Efficient Code Offloading Techniques for Mobile Applications

Von der Fakultät Informatik, Elektrotechnik und
Informationstechnik der Universität Stuttgart
zur Erlangung der Würde eines Doktors der Naturwissenschaften
(Dr. rer. nat.) genehmigte Abhandlung

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Tag der mündlichen Prüfung: 20.12.2017

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der Universität Stuttgart
2017

Acknowledgements

At this point, I take the opportunity to thank all the people that continuously supported and encouraged me during my research making this dissertation possible.

Above all, I express my special thanks and appreciation to my doctoral supervisor, Prof. Dr. Kurt Rothermel, who give me the opportunity to conduct my research in his group. His appropriate guidance, excellent support, and prolific discussions during my whole time at the University of Stuttgart were invaluable contributions for the success of my research presented in this thesis. He always gave helpful feedback and advice, asking the right questions whenever necessary. The great conditions provided in his group for learning and enhancing fundamental skills let me grow as a research scientist.

Furthermore, my thanks also go to the co-advisor of my thesis, Prof. Dr. Christian Becker, for his time and effort to review my dissertation giving me appropriate feedback.

Special thanks also go to my great project supervisor, Dr. Frank Dürr, for his encouragement, support, and (technical as well as personal) help during my research with many inspiring discussions and constructive feedback, sometimes to the detriment of his full schedule. His love and dedication to research like pursuing new ideas inspired not only me but also the approaches presented in this dissertation significantly.

During my research in the Distributed Systems group at the University of Stuttgart, I met exceptional colleagues, creating an amazing atmosphere within the institute. The productive and friendly working environment was both inspiring and fun, why I had a great time as a doctoral researcher – not only due to the countless matches at the soccer table. The brilliant, enthusiastic colleagues inspired me with new ideas, provided to me insightful feedback, and improved my research work a lot. In particular, I want to mention (in alphabetical order) Thomas Bach, Dr. Patrick Baier, Dr. Andreas Benzing, Ben Carabelli, Christoph Dibak, Dr. Stefan Föll, Hannes Hannak, Thomas Kohler, Dr. Boris Koldehofe, Christian Mayer, Ruben Mayer, Naresh Nayak, Dr. Damian Philipp, Stephan Schnitzer, David Schäfer, and of course all the other members of the research group. Having worked in the ARAMiS project – Automotive, Railway and Avionics Multicore Systems – over several years, I enjoyed very much the collaboration with researchers from other universities and employees from companies

all across Germany, elaborating on interesting research problems. In this context, I also express my gratitude towards the "Bundesministerium für Bildung und Forschung" for partially funding my research through the ARAMiS project. This funding enabled my research in the first place and allowed me to present my results to the research community on various international conferences. Also, I am grateful to Annemarie Rösler, Eva Strähle, and Martin Brodbeck for supporting me in administrative matters and thus, allowing me to focus on my research.

Finally, I thank my family and friends for their strong support, encouragement, and patience over all these years, sharing with me the joy of good times and supporting me through hard times. Special thanks go to my parents Günther and Regina, my brother Markus, and my sisters Franziska and Julia for their care and love. I am very happy to know that I can count on them not only during this important stage of my life but also in the future whatever happens next.

The last "thank you" goes out to my wife Corinna and my son Jonas, who were and are always there for me, why I am deeply grateful for having you both in my life.

Thank you all very much!

Florian Andreas Berg, December 20, 2017

Contents

List of Figures

List of Tables

List of Algorithms

Abstract

Since the release of the first smart phone from Apple in the year 2007, smart phones in general experience a fast growth of rising popularity. A smart phone typically possesses among others a touchscreen display as user interface, a mobile communication for accessing the Internet, and a System-on-a-Chip as an integrated circuit of required components like a central processing unit. This pervasive computing platform derives its required power from a battery, where an end user runs upon it different kinds of applications like a calendar application or a high-end mobile game. Differing in the usage of the local resources from a battery-operated smart phone, a heavy utilization of local resources like playing a resource-demanding application drains the limited resource of energy in few hours. Despite the constant increase of memory, communication, or processing capabilities of a smart phone since the release in 2007, applications are also getting more and more sophisticated and demanding. As a result, the energy consumed on a smart phone was, still is, and will be its main limiting factor.

To prevent the limited resource of energy from a quick exhaustion, researchers propose *code offloading* for (resource-constrained) mobile devices like smart phones. Code offloading strives for increasing the energy efficiency and execution speed of applications by utilizing a server instance in the infrastructure. To this end, a code offloading approach executes dynamically resource-intensive parts from an application on powerful remote servers in the infrastructure on behalf of a (resource-constrained) mobile device. During the remote execution of a resource-intensive application part on a remote server, a mobile device only waits in idle mode until it receives the result of the application part executed remotely. Instead of executing an application part on its local resources, a (resource-constrained) mobile device benefits from the more powerful resources of a remote server by sending the information required for a remote execution, waiting in idle mode, and receiving the result of the remote execution.

The process of offloading code from a (resource-constrained) mobile device to a powerful remote server in the infrastructure, however, faces different problems. For instance, code offloading introduces some overhead for additional computation and communication on a mobile device. Moreover, spontaneous disconnections during a remote execution can cause a higher energy consumption and execution time than a

local execution on a mobile device without code offloading. To this end, this dissertation addresses the whole process of offloading code from a mobile device not only to one but also to multiple remote resources, comprising the following steps:

1) First, code offloading has to identify feasible parts from an application for a remote execution, where the distributed execution of the identified application part is more beneficial than its local execution. A feasible part for a remote execution typically has the following properties: A low size of information required for transmission before a remote execution, a resource-intensive computation not accessing local sensors, and a low size of information required for transmission after a remote execution. In the area of identification of application parts for a remote execution, this dissertation presents an approach based on code annotations from application developers that automatically transforms a monolithic execution on a mobile device to a distributed execution on multiple heterogeneous resources. In contrast to related approaches in the literature, the annotation-based approach requires least interventions from application developers and end users, keeping the overhead introduced on a mobile device low.

2) For an application part identified for a remote execution, code offloading has to determine its execution side, executing the application part either on the local resources of a mobile device or on the remote resource at the infrastructure. In the area of determining the execution side for an application part, this dissertation presents the offloading problem, where a mobile device decides whether to execute an application part locally or remotely. Furthermore, this dissertation also presents an approach called "code bubbling" that shifts the decision making into the infrastructure. In contrast to related approaches in the literature, the decision-based approach on a mobile device and the bubbling-based approach minimize the execution time, energy consumption, and monetary cost for an application.

3) To determine the execution side for an application part identified for a remote execution, code offloading has to obtain different parameters from the application, participating resources, and utilized links. In the area of obtaining the information required from an application, this dissertation presents a bit-flipping approach that dynamically flips a bit at the modification of application-related information. Furthermore, this dissertation also presents an offload-aware Application Programming Interface (API) that encapsulates the application-related information required for code offloading. In contrast to related approaches in the literature, the bit-flipping approach and the offload-aware API provide an efficient gathering of information at run-time, keeping the overhead introduced on a mobile device low.

4) Beside the information from an application, code offloading has to obtain further information from participating resources and utilized links. In the area of obtaining the

information required from participating resources and utilized links, this dissertation presents the approach of code bubbling, already mentioned above. In contrast to related approaches in the literature, the bubbling-based approach makes the offload decision at the place where the related information occurs, keeping the overhead introduced on a mobile device, participating resources, and utilized links low.

5) In case of a remote execution of an application part, code offloading has to send the information required for a remote execution to the remote resource that subsequently executes the application part on behalf of the mobile device. In the area of sending the required information and executing an application part remotely, this dissertation presents code offloading with a cache on the remote side. The cache on the remote side serves as a collective storage of results for already executed application parts, avoiding a repeated execution of previously run application parts. In contrast to related approaches in the literature, the caching-aware approach increases the efficiency of code offloading, keeping the energy consumption, execution time, and monetary cost low.

6) While a remote resource executes an application part, code offloading has to handle the occurrence of failures like a failure of the remote resource or a disconnection. In the area of handling the occurrence of failures, this dissertation presents a preemptable offloading of code with safe-points. The preemptable offloading of code with safe-points enables an interruption of an offloading process and a corresponding continuation of a remote execution on a mobile device, without abandoning the complete result calculated remotely so far. Based on a preemptable offloading of code with safe-points, this dissertation further presents a predictive offloading of code with safe-points that minimizes the overhead introduced by safe-point'ing and maximizes the efficiency of a deadline-aware offloading. In contrast to related approaches in the literature, the preemptable approach with safe-point'ing increases the robustness of code offloading in case of failures. Furthermore, the predictive approach for safe-point'ing ensures a minimal responsiveness and a maximal efficiency of applications despite failures.

7) At the end of a remote execution of an application part, code offloading has to gather on the remote resource the required information after the execution and send this information to the mobile device. In the area of gathering the required information, a remote resource utilizes the same approaches as a mobile device, already mentioned above (cf. the bit-flipping approach and the offload-aware API).

8) Last, code offloading has to receive on the mobile device the information from a remote resource, install the information on the mobile device, and continue the execution of the application on the mobile device. In the area of installing the information and continuing the execution locally, a mobile device utilizes the approaches already mentioned above (cf. the bit-flipping approach and the offload-aware API).

Deutsche Zusammenfassung

Im Jahre 2007 stellte die Firma Apple ihr erstes Smartphone, das iPhone, vor und ebnete damit den Weg für den Siegeszug der "smarten" Mobiltelefone. Heutzutage sind die Smartphones aus unserem Alltag und der Geschäftswelt nicht mehr wegzudenken, da ein Smartphone ein klassisches Mobiltelefon mit computerähnlichen Funktionalitäten und Konnektivität verknüpft. Typischerweise besitzt ein Smartphone einen großen, berührungsempfindlichen Bildschirm für die Eingabe von Benutzerdaten über Gesten, eine mobile Breitbandverbindung für die Kommunikation mit dem Internet sowie einen leistungsstarken System-on-a-Chip, der die computerrelevanten Komponenten vereint. Im Alltag oder der Geschäftswelt führen Endanwender auf solch einer mobilen Computerplattform verschiedene Anwendungen, wie zum Beispiel eine Kalenderanwendung oder ein hochauflösendes Videospiel, aus. Die Ausführung von Anwendungen beansprucht die lokalen Ressourcen eines batteriebetriebenen Smartphones unterschiedlich stark. Durch eine starke Beanspruchung der lokalen Ressourcen aufgrund der Ausführung einer ressourcenintensiven Anwendung auf dem Smartphone wird die begrenzte Energiekapazität der Batterie in nur wenigen Stunden entladen. Im Laufe der Zeit erfuhren durch Forschung und Entwicklung in der Kommunikationsbranche die Hardwarekomponenten eines Smartphones stetige Verbesserungen, wodurch sich die Leistungsfähigkeit des Speichers, der mobilen Breitbandverbindung oder des Prozessors stetig erhöhte. Mit der voranschreitenden Weiterentwicklung der Hardwarekomponenten entwickelten sich ebenfalls die mobilen Endanwendungen stetig weiter und bieten beispielsweise eine verbesserte Grafikauflösung an, die wiederum die leistungsstärkeren, lokalen Ressourcen eines Smartphones stärker beanspruchen. Aus diesen Gründen war, ist und wird die Benutzung eines Smartphones durch den benötigten Energieverbrauch stark beeinflusst und stellt das größte Hindernis bei der mobilen Nutzung im Alltag oder der Geschäftswelt dar.

Um einer allzu schnellen Entladung der begrenzten Energiekapazität eines batteriebetriebenen mobilen Endgerätes, beispielsweise eines Smartphones, entgegen zu wirken, schlagen Forscher in der Literatur den Ansatz des *Code Offloadings* vor. Der Ansatz des Code Offloadings strebt nach einer verbesserten Energieeffizienz und einer schnelleren

Ausführungsgeschwindigkeit von Endanwendungen durch die Nutzung von entfernten Serverinstanzen innerhalb der Infrastruktur. Dies spiegelt den Grundgedanken des Code Offloadings wieder, welches ressourcenintensive Teile einer Endanwendung nicht auf einem (ressourcenschwachen) mobilen Endgerät sondern auf entfernten, leistungsstarken Serverinstanzen innerhalb der Infrastruktur ausführt. Während einer solchen entfernten Ausführung eines ressourcenintensiven Anwendungsteil auf einem entfernten Server wartet das mobile Endgerät nur auf den Empfang des Ergebnisses der entfernten Ausführung ohne selbst den Anwendungsteil auszuführen. Aufgrund der leistungsstärkeren Ressourcen eines entfernten Servers ist eine entfernte Ausführung für ein (ressourcenschwaches) mobiles Endgerät im Vergleich zu einer lokalen Ausführung profitabler, wobei eine entfernte Ausführung das Senden der benötigten Information, das Warten während der entfernten Ausführung und das Empfangen des Ergebnisses der entfernten Ausführung beinhaltet.

Dieser Prozess einer entfernten Ausführung von Anwendungsteilen auf einer entfernten, leistungsstarken Serverinstanz innerhalb der Infrastruktur anstelle auf einem (ressourcenschwachen) mobilen Endgerät umfasst jedoch verschiedene Herausforderungen. Zum Beispiel birgt das Code Offloading zusätzlichen Berechnungs- und Kommunikationsmehraufwand, den es auszugleichen gilt. Des Weiteren kann durch spontane Verbindungsabbrüche während einer entfernten Ausführung eines Anwendungsteil der Energieverbrauch und die Ausführungszeit einer verteilten Anwendungsausführung höher sein als für eine lokale Ausführung des Anwendungsteils auf dem mobilen Endgerät. Zu diesem Zweck behandelt die vorliegende Dissertation den gesamten Prozess des Code Offloadings von einem mobilen Endgerät zu nicht nur einer entfernten Ressource sondern auch zu mehreren entfernten Ressourcen, wobei im Einzelnen die folgenden Prozessabschnitte behandelt werden:

1) Zuallererst muss das Code Offloading geeignete Anwendungsteile identifizieren, bei denen eine verteilte Ausführung gegenüber einer lokalen Ausführung des Anwendungsteil vorzuziehen ist. Ein geeigneter Anwendungsteil besitzt hierbei eine geringe Menge an benötigten Informationen, die für eine entfernte Ausführung übertragen werden müssen, eine ressourcenintensive Berechnung, die keine lokalen Ressourcen wie zum Beispiel einen Sensor benötigt, und eine geringe Menge an benötigten Informationen, die nach einer entfernten Ausführung übertragen werden müssen. Auf dem Gebiet der Identifikation von geeigneten Anwendungsteilen präsentiert die vorliegende Dissertation einen Ansatz, der auf Annotationen des Quellcodes vom Anwendungsentwickler basiert. Dieser Ansatz mit Hilfe von Annotationen ermöglicht es, automatisch eine monolithische Ausführung auf einem mobilen Endgerät in eine verteilte Ausführung auf mehreren verschiedenartigen Ressourcen zu transformieren. Im Gegensatz zu ver-

wandten Arbeiten in der Literatur benötigt der präsentierte Ansatz basierend auf Codeannotationen nur sehr geringe Hilfe vom Anwendungsentwickler und Benutzer des mobilen Endgerätes, wobei der Ansatz nur einen sehr geringen Mehraufwand auf dem mobilen Endgerät verursacht.

2) Nach der Identifizierung eines geeigneten Anwendungsteil muss das Code Offloading den Ausführungsort des Anwendungsteils bestimmen, wobei der geeignete Anwendungsteil entweder auf den lokalen Ressourcen des mobilen Endgerätes oder auf den entfernten Ressourcen innerhalb der Infrastruktur ausgeführt wird. Auf dem Gebiert der Bestimmung des Ausführungsortes für einen identifizierten Anwendungsteil präsentiert die vorliegende Dissertation einerseits ein Optimierungsproblem, mit dessen Hilfe entschieden wird, ob der Anwendungsteil lokal oder entfernt ausgeführt wird, und andererseits den "Code Bubbling" Ansatz, der die Entscheidung über den Ausführungsort innerhalb der Infrastruktur trifft. Im Gegensatz zu verwandten Arbeiten in der Literatur minimieren die Ansätze des Optimierungsproblems sowie Code Bubblings die Ausführungszeit, den Energieverbrauch und die monetären Kosten einer Anwendung.

3) Zur Bestimmung des Ausführungsortes eines geeigneten Anwendungsteils muss das Code Offloading verschiedene Parameter bezüglich der Anwendung, der beteiligten Ressourcen sowie des Netzwerks in Erfahrung bringen. Auf dem Gebiet der Beschaffung von Informationen über die Anwendung präsentiert die vorliegende Dissertation einerseits einen Ansatz, welcher geänderte Anwendungsinformationen basierend auf Bitflipping beschafft, und andererseits einen Ansatz, welcher eine erweiterte Programmierschnittstelle für das Code Offloading bereitstellt. Im Gegensatz zu verwandten Arbeiten in der Literatur stellen die Ansätze des Bitflippings sowie der erweiterten Programmierschnittstelle eine effiziente Beschaffung der Information zur Laufzeit bereit, die beide nur einen sehr geringen Mehraufwand auf dem mobilen Endgerät verursachen.

4) Neben den zu beschaffenden Informationen bezüglich der Anwendung muss das Code Offloading weitere Informationen über die beteiligten Ressourcen sowie des Netzwerks beschaffen, um den Ausführungsort eines Anwendungsteil zu bestimmen. Auf dem Gebiet der Beschaffung von Informationen über die beteiligten Ressourcen sowie des Netzwerks präsentiert die vorliegende Dissertation den bereits weiter oben erwähnten Ansatz des Code Bubblings. Im Gegensatz zu verwandten Arbeiten in der Literatur trifft der Ansatz des Code Bubblings die Entscheidung über eine entfernte Ausführung nicht auf einem (ressourcenschwachen) mobilen Endgerät sondern an dem Ort, an welchem die hierfür benötigten Informationen vorliegen, wodurch der Ansatz den verursachten Mehraufwand auf dem mobilen Endgerät, den beteiligten Ressourcen sowie dem Netzwerk gering hält.

5) Im Falle einer entfernten Ausführung eines Anwendungsteils muss das Code Of-

floading die benötigten Informationen für eine entfernte Ausführung zur gewählten, entfernten Ressource senden, welche anschließend den Anwendungsteil anstelle des mobilen Endgerätes ausführt. Auf dem Gebiet des Senden von benötigten Informationen und des entfernten Ausführens von Anwendungsteilen präsentiert die vorliegende Dissertation einen Ansatz, der einen entfernten Cache für das Code Offloading nutzt. Der entfernte Cache dient hierbei zur gemeinschaftlichen Speicherung von Ergebnissen von bereits ausgeführten Anwendungsteilen und vermeidet somit ein wiederholtes Ausführen von bereits ausgeführten Anwendungsteilen. Im Gegensatz zu verwandten Arbeiten in der Literatur erhöht ein Code Offloading mit einem entfernten Cache die Effizienz des Code Offloadings, wodurch der Energieverbrauch, die Ausführungszeit sowie die monetären Kosten gering gehalten werden.

6) Während einer entfernten Ausführung eines Anwendungsteils muss das Code Offloading das Auftreten von Fehlern wie beispielsweise einem Serverausfall oder einem Verbindungsabbruch handhaben. Auf dem Gebiet der Handhabung von Fehlern präsentiert die vorliegende Dissertation ein unterbrechbares Code Offloading, welches auf sogenannten Safe-points basiert. Die Verwendung von Safe-points ermöglicht die Unterbrechung des Prozesses der entfernten Ausführung mit einer einhergehenden lokalen Fortsetzung der entfernten Ausführung auf dem mobilen Endgerät, wobei die bereits errechneten Zwischenergebnisse der entfernten Ausführung auf dem mobilen Endgerät zur Ausführung weitergenutzt werden. Des Weiteren präsentiert die vorliegende Dissertation basierend auf einem unterbrechbaren Code Offloading ein vorausschauendes Code Offloading, welches den einhergehenden Mehraufwand durch die Verwendung von Safe-points minimiert und gleichzeitig die Effizienz eines Code Offloadings mit einer gesetzten Deadline maximiert. Im Gegensatz zu verwandten Arbeiten in der Literatur erhöht der unterbrechbare Ansatz mit Safe-points die Robustheit von Code Offloading im Fehlerfall. Außerdem stellt der vorausschauende Ansatz mit Safe-points eine minimale Ansprechbarkeit und eine maximale Effizienz einer verteilten Anwendungsausführung trotz dem Aufkommen von Fehlern sicher.

7) Am Ende einer entfernten Ausführung eines Anwendungsteils muss das Code Offloading die benötigten Informationen einer entfernten Ausführung für das mobile Endgerät beschaffen und diese Informationen zu dem mobilen Endgerät senden. Auf dem Gebiet der Beschaffung von benötigten Informationen benutzen die entfernten Ressourcen die gleichen Ansätze, die ein mobiles Endgerät für die Beschaffung von Informationen benutzt, und bereits weiter oben beschrieben wurden (vgl. den Ansatz des Bitflippings und der erweiterten Programmierschnittstelle für das Code Offloading).

8) Zuletzt muss das Code Offloading die benötigten Informationen von einer entfernten Ressource nach der Ausführung eines Anwendungsteil auf dem mobilen Endgerät

empfangen, die entsprechenden Informationen auf dem mobilen Endgerät installieren und darauf basierend die Anwendungsausführung auf dem mobilen Endgerät fortsetzen. Auf dem Gebiet der Installation von benötigten Informationen sowie der lokalen Fortsetzung einer Anwendungsausführung benutzt ein mobiles Endgerät die gleichen Ansätze des Bitflippings und der erweiterten Programmierschnittstelle für das Code Offloading, die bereits weiter oben beschrieben wurden.

Chapter 1

Introduction

In the year 2007, Apple released the first model of its iPhone series, "going to reinvent the phone" [Inf07a]. Compared to popular phones at this time like the mobile phone Q from Motorola or the E62 from Nokia, the first iPhone combines a revolutionary user interface with exceeding hardware components like a wide multi-touch touchscreen, plenty of sensors, and a powerful processing unit. Furthermore, the iPhone (1^{st} generation) acquires, disseminates, and shares information with services in the Internet based on multiple connectivity for data transfer like a Wireless Fidelity (Wi-Fi) or cellular connection. This new interplay of the revolutionary software together with the exceeding hardware from the first iPhone extended the typical functionality of a "traditional" mobile phone at this time, changing significantly the everyday use of mobile phones. Due to the "smarter" functionality compared to traditional mobile phones, the community calls such mobile phones as *smart phones*.

A smart phone is a ubiquitous computing platform with Internet access, powered by a battery. An end user executes on the hardware different applications like a web browser or a mobile game. Apart from a couple of applications pre-installed by default, a mobile operating system like iOS on the first iPhone enables an end user to individualize the functionality of the smart phone to its need. An end user can install and execute further applications from an application store like the Apple App Store, where the execution of (resource-friendly and resource-intensive) applications on a smart phone utilizes local resources differently. A heavy utilization of the constrained resources from a battery-operated smart phone drains its limited energy in few hours. For instance, Apple announced 5 hours of talk time, Internet use, or video playback or 16 hours of audio playback for the preliminary version of the first iPhone [Inf07b]. For the final version, Apple further increased the battery life of the first iPhone, shipping it with 8 hours of talk time, 6 hours of Internet use, 7 hours of video playback, or 24 hours of audio playback. This fact clearly shows that already at the time of delivery the main limiting factor of the first smart phone from Apple was its constrained battery life.

Ten years later, the hardware and software of smart phones improved significantly. Regarding the current flagship smart phone from Samsung presented in March 2017,

the Samsung Galaxy S8 [Sam17] possesses, for instance, a 3D multi-touch touchscreen with a higher resolution, additional sensors with higher accuracy, and a more powerful processing unit compared to the iPhone (1st generation). Furthermore, the capabilities of the connectivity for data transfer also improved significantly, where an end user now accesses services in the Internet via a high-bandwidth and low-latency connection – e.g., up to 1 Gbit/s for the down link, up to 500 Mbit/s for the up link, and a latency less than 10 ms based on LTE-Advanced[1] [NK16]. Associated with the improvements to the hardware of smart phones, the software steadily improved as well, enabling an execution of more sophisticated and more demanding applications. An execution of more sophisticated software on more sophisticated hardware overall increases the energy demands on a battery-operated smart phone. Thus, an execution of a resource-intensive application like a high-end video game still drains the battery of today's smart phones in few hours (cf. [CH10]). Like for the first iPhone released in 2007, the main limiting factor of a today's smart phone is still its constrained battery life. An end user typically has to charge its smart phone every day. According to Sekar [Sek13], the power consumption of mobile devices "remains and will remain a first-class design constraint". Consequently, a battery-operated mobile device like a smart phone requires techniques to minimize its energy consumption without sacrificing the computational power available for an execution of an application.

1.1. Motivation

A corresponding technique for a smart phone arose with the rise of cloud computing that dramatically changed the landscape of Information Technology (IT) over the last years [AFG+10]. Cloud providers like Amazon, Google, or Microsoft offer services like computing infrastructure, platforms, or software to customers in a pay-as-you-go manner (cf. Amazon Web Services, Google Cloud Platform, or Microsoft Azure). Empowered by this new computing paradigm of cloud computing, end users now lease on-demand reliable, elastic, and cost-effective resources from commercial data centers at the cloud. As a result, the technique of *Code Offloading* emerged both from academic researchers and industrial pioneers, striving to increase the energy efficiency of a (resource-constrained) mobile device and the execution speed of a (resource-intensive) application. Code offloading bridges the gap between *Mobile Computing* and *Cloud Computing* with computation offloading via a *Wireless Network*, called *Mobile Cloud Computing (MCC)* [SGKB13, uRKOMK14]. In detail, mobile computing comprises

[1] Long-Term-Evolution-Advanced (LTE-Advanced)

(battery-operated) mobile devices like a smart phone, providing a ubiquitous platform with sensing, communicating, and computing capabilities. The rise of cloud computing in the last years brought powerful resources from the cloud closer to mobile computing, typically paid in a pay-as-you-go manner. Last, a mobile device communicates with resources at the cloud via a Wi-Fi or cellular connection (wireless network), providing a high-bandwidth and low-latency link to remote resources.

Due to the combination of mobile computing with cloud computing via a wireless network, code offloading overcomes the energy limitation of a (resource-constrained) mobile device by executing resource-intensive parts from applications on powerful server instances at the cloud. To this end, code offloading regards the cost for an execution of an application part on local resources of a mobile device and on remote resources at the cloud. The local cost includes the execution time and energy consumption for a local execution of an application part on a mobile device. The remote cost includes the execution time, energy consumption, and monetary cost for a remote execution of an application part on a server instance at the cloud. Compared to a local execution, a remote execution takes time and consumes energy on a mobile device for sending information to a remote resource, waiting in idle mode during the execution on a remote resource, and receiving the execution state of a remote resource after the execution. It causes monetary cost for sending bytes to a remote resource, utilizing a remote resource for an execution, and receiving bytes from a remote resource. Regarding the trade-off between the local cost and the remote cost, the challenge is now to find an optimal distribution of application parts between the local resources on a mobile device and the remote resources at the cloud, resulting in a minimum execution time, energy consumption, and monetary cost.

Beside the remote resources at the cloud for code offloading, technological trends like *Big Data* [JBD+14, Cen12], *Cyber-Physical Systems* [RLSS10, KM15], and *Internet of Things* [BLMN13, AFGM+15] made multiple classes of highly distributed heterogeneous resources available for code offloading. As a result, multiple resources augment an execution of an application on a (resource-constrained) mobile device, where a mobile device has to distribute optimally an execution of application parts between multiple resources. For instance, *Fog Computing* brings the cloud closer to end users, providing powerful, elastic resources to mobile devices at the edge of the network [BMZA12, VRM14]. An exemplary environment for code offloading with multiple resources consists of a smart watch that a Bluetooth link connects to a smart phone. Further, a Wi-Fi link connects the smart phone to a smart car that again an LTE-Advanced link connects to a server instance at the edge. Finally, a fixed link connects the server instance at the edge to a server instance in a data center at the cloud. These

heterogeneous devices in such an environment differ significantly in terms of resources for energy, computation, and communication, increasing typically from very limited (e.g., a smart watch) to virtually unlimited (e.g., the cloud). Code offloading in such environments with multiple resources will become relevant in future, where a plenty of highly distributed heterogeneous resources with different performance characteristics and cost implications surround a (resource-constrained) mobile device.

Summarizing, code offloading can increase the energy efficiency of a mobile device and the execution speed of an application by distributing an execution of application parts from a mobile device to remote resources in the infrastructure, causing monetary cost for a utilization of remote resources. Regarding the whole process of offloading code from a mobile device to a remote resource, an optimal distribution of application parts from a (resource-constrained) mobile device to a or multiple remote resources arises challenging research questions like feasibility, robustness, or adaptability.

1.2. Research Focus

To optimally distribute parts from an application, a realization of an efficient system for code offloading has to address several challenging research questions. The key challenges for a realization of an efficient system directly result from the distributed execution of an application to multiple resources. Accordingly, the whole process of code offloading from the identification of application parts – that can be distributed – to the receive of the result from a remote execution classifies the scope of this dissertation, where prior research does not sufficiently address the key challenges. The following paragraphs give a more detailed view on the research focus of this dissertation that encompasses the whole process for a distribution of an application execution between a mobile device and remote resources.

First of all, code offloading has to identify parts from an application for a remote execution. It divides an application into application parts that a mobile device has to execute locally and into application parts that can be distributed to a remote resource (offloadable). An application part that is offloadable only utilizes the processing capabilities on a mobile device, without accessing further local capabilities like taking a photo via a camera. A good candidate for a remote execution of an application part that is offloadable has a long running computation, utilizing the computing capabilities on the remote resource heavily. Moreover, it has a small size of information required for a remote execution and a small size of information received on a mobile device after a remote execution, utilizing the uplink and downlink from a communication network to a remote resource sparingly. Thus, the arising question is how to (efficiently) *identify*

application parts that are offloadable, keeping the burden on application developers together with the overhead introduced to a mobile device low.

After the identification of an application part that is offloadable, code offloading has to determine the execution side for this application part. To this end, it regards for the application part the trade-off between the cost for a local execution on a mobile device and the cost for a remote execution on a remote resource, typically formulated as an optimization problem like an Integer Linear Program. The solution of the optimization problem determines whether a mobile device executes the application part that is offloadable locally on its resources or distributes it to a remote resource for a remote execution. Thus, the arising question is how to (efficiently) *determine* the execution side for an application part identified as offloadable, keeping the time taken for solving the optimization problem minimal.

To solve the optimization problem related to code offloading for an application part that is offloadable, code offloading has to obtain a set of parameters required for the solution of the optimization problem. The required parameters result from the cost – the time taken and energy consumed – for a local execution and – the time taken, energy consumed, and monetary cost caused – for a remote execution. In detail, the parameters comprise information about the application like its execution state, local and remote resources like the performance, and network links like the bandwidth. Thus, the arising question is how to (efficiently) *obtain* parameters required to solve the optimization problem for code offloading, keeping the overhead introduced to a mobile device, participating resources, and network links low.

After the determination of the execution side for an application part identified as offloadable, code offloading has to execute an application part remotely if a remote execution is more beneficial compared to a local execution. To this end, it sends the execution state gathered locally from a mobile device to a remote resource and waits subsequently for the end of a remote execution on a remote resource, to finally receive the execution state on the remote resource after the remote execution. Due to the utilization of the uplink, the remote resource, and the downlink in case of a remote execution, an end user has to pay a corresponding fee for the utilization charged by (link and resource) providers. Thus, the arising question is how to (efficiently) *optimize* the process of sending, waiting, and receiving for a remote execution, keeping the introduced overhead together with the charged monetary cost low.

While a remote resource executes an application part on behalf of a mobile device, code offloading has to handle an occurrence of failures on participating nodes or connecting links. For instance, in case of a failure of a remote resource near the end of a remote execution, the occurrence of the failure delays – e.g., due to a node recovery

and a subsequent re-execution – the receive on a mobile device of the execution state after the remote execution. It gets even worse in case of a long-lasting disconnection between a mobile device and a remote resource near the end of a remote execution, where a local execution of the application part would be retrospectively more beneficial. Thus, the arising question is how to (efficiently) *handle* an occurrence of failures during a remote execution, keeping the efficiency of code offloading high.

Summarizing, this dissertation tackles a couple of challenging research questions that prior research does not sufficiently address. It regards the whole process of a distribution from an efficient identification to failure handling to a receive of a remote result, proposing different concepts, algorithms, and approaches. In detail, this dissertation realizes an efficient, scalable, and applicable system for code offloading that distributes application parts between a mobile device and multiple remote resources.

1.3. Contributions

The dissertation investigates the challenging research questions described above, contributing concepts, algorithms, and approaches for the investigated questions. We published the contributions of this dissertation at international conferences [BDR14a, BDR14b, BDR15, BDR16] and in an international journal [BDR18], where all publications were peer-reviewed. Concepts, algorithms, and implementations of the approaches presented in [BDR14a, BDR14b, BDR15, BDR16, BDR18] are original work of the author, where a thesis of a student supervised by the author provided prelimary understanding of the work proposed in [BDR15]. At all times, Kurt Rothermel and Frank Dürr helped to improve the presentation of concepts, algorithms, and results, where the author of this thesis contributed about 75 %, 80 %, 85 %, 90 %, and 95 % of the scientific content for the papers [BDR14a], [BDR14b], [BDR15], [BDR16], and [BDR18]. In particular, this dissertation has the following individual contributions:

1. To *identify* at run-time application parts that are offloadable, this dissertation proposes an annotation-based distribution with least interventions from an application developer as well as end user. An application developer only annotates at development-time application parts that are offloadable, where an offload-aware compiler inserts at compile-time instructions for an application part annotated as offloadable. Based on the offload-specific instructions inserted at compile-time, the approach automatically partitions at run-time an application to parts that have to be executed locally and to parts that are offloadable. Thus, it does not require any interventions from an application developer or end user. In contrast

to related approaches in the literature, the annotation-based distribution with offload-specific instructions keeps the burden on application developers and end users low. Moreover, it also keeps the overhead introduced to the run-time system on a (resource-constrained) mobile device low.

2. To *determine* the execution side for an application part that is offloadable, this dissertation proposes a distribution with the concept of "code bubbling". Code bubbling shifts the offload decision – determining whether to execute an application part locally or remotely – from a (resource-constrained) mobile device into the infrastructure. Based on the concept of code bubbling, the approach dynamically determines the best available resource for an execution of an application part at run-time, especially in case of multiple remote resources participating in code offloading. In contrast to related approaches in the literature, code bubbling does not require a global view onto all resources of an environment, keeping the overhead introduced to a run-time system on a mobile device low.

3. To *obtain* from an application the parameters required for the offload decision, this dissertation proposes a bit-flipping approach. The bit-flipping approach marks information from an execution state modified during run-time by flipping a corresponding bit in the information header. Based on the dynamic flipping of a bit at run-time, the bit-flipping approach minimizes the execution state synchronized between a mobile device and a remote resource. It only includes information from an execution state that is modified during run-time. In contrast to related approaches in the literature, the dynamic flipping of a bit does not require a resource-intensive monitoring of information for an execution state in parallel of an execution. As a result, the dynamic flipping of a bit keeps the overhead introduced to a run-time system on a mobile device low.

4. To *obtain* from an application part the parameters required for the offload decision, this dissertation also proposes an offload-aware Application Programming Interface (API) for the Java programming language beside the dynamic flipping of a bit. The offload-aware Java API extends the Java core class libraries with additional classes for code offloading, making the Java programming language directly aware for offloading code. Based on the additional Java core classes, an application developer only extends a corresponding Java core class, enabling code offloading for its Java application. In contrast to related approaches in the literature, the offload-aware Java API provides an ease of use and an efficient processing of code offloading that keeps the overhead introduced to a run-time

system on a mobile device and on a remote resource low.

5. To *obtain* from participating resources and network links the parameters required for the offload decision, this dissertation proposes the distribution with code bubbling. The distribution with code bubbling makes a decision to offload an application part at the point where the information required for an offload decision occurs, namely at the infrastructure. Due to an offload decision on remote resources at the infrastructure, a (resource-constrained) mobile device only submits an offload request into the infrastructure. Afterwards, it automatically receives offers from participating remote resources, where a remote execution is more beneficial compared to a local execution. In contrast to related approaches in the literature, the distribution with code bubbling does not obtain all parameters required for the offloading decision at a (resource-constrained) mobile device, keeping the overhead introduced to a mobile device, participating remote resource(s), and related network link(s) low.

6. To *optimize* the offloading process of sending, waiting, and receiving in case of a remote execution, this dissertation proposes a caching-aware distribution. It extends a distribution of application parts with a cache on the remote side. The cache on the remote side stores collectively execution states after a local execution or a remote execution of application parts. A mobile device queries the cache for a corresponding entry just before offloading an application part to a remote resource. Based on the cache on the remote side, a mobile device immediately receives a queried execution state in case of a cache hit, whereas in case of a cache miss it starts a distribution of the application part to a remote resource. In contrast to related approaches in the literature, the caching-aware distribution avoids a repeated execution of previously run application parts, keeping the time taken, energy consumed, and monetary cost charged for a remote execution low.

7. To *handle* the occurrence of failures (e.g., node or link failures) during a remote execution, this dissertation proposes a preemptable distribution with safe-point'ing and a predictive distribution with safe-point'ing. The preemptable distribution stores at different points in time the execution state on a remote resource during a remote execution called safe-points. It also transmits these safe-points during a remote execution to a mobile device, enabling an interruption of an offloading process and a continuation of a remote execution on a mobile device in case of a failure. Thus, safe-point'ing does not abandon the intermediate result calculated remotely so far. The predictive distribution extends the preemptable

distribution with an adaptive scheduler that predicts the optimal times for a creation and transmission of a safe-point during a remote execution. For instance, in the optimal case, it only transmits one safe-point just before a disconnection occurs. In contrast to related approaches in the literature, the preemptable distribution based on safe-point'ing increases the robustness of code offloading in case of a failure, keeping the efficiency of code offloading high. Additionally, the predictive distribution based on safe-point'ing ensures a minimal responsiveness and a maximal efficiency of distributed applications despite link failures.

1.4. Structure of the Thesis

Now, this section describes the structure of the dissertation which is as follows:

The current chapter, **Chapter 1**, shows the ropes and starts with an introduction about resource limitation of smart phones in the past and present time. Afterwards, Section 1.1 gives a motivation for the technique of code offloading that augments a (resource-constrained) mobile device with powerful remote resources. Section 1.2 details about the research focus within code offloading, where Section 1.3 highlights the research contributions of this dissertation, both comprising the whole process of distribution for code offloading. Finally, Section 1.4 outlines the structure of the thesis.

The next chapter, **Chapter 2**, describes in detail the background information required for this dissertation. It starts with a description of mobile computing in Section 2.1 that communicates with other devices and the Internet via different wireless networks described in Section 2.2. A mobile computing environment accesses via a wireless network computing resources from cloud computing, described in Section 2.3. It also accesses nearby computing resources at the edge of a network, favored by different technological trends described in Section 2.4. The combination of mobile computing with cloud computing enables mobile cloud computing described in Section 2.5, providing services like computation offloading. Last, Section 2.6 presents a summary.

The next chapter, **Chapter 3**, gives a system overview for code offloading in the landscape of Mobile Cloud Computing (MCC). First, Section 3.1 outlines a related system model before Section 3.2 formulates the problem statement. Related to the system model and problem statement, Section 3.3 describes the system components involved in code offloading. As each component of the system might fail, Section 3.4 highlights the underlying failure model for this dissertation, including crash failures with eventually recovery of nodes and links. Then, Section 3.5 presents the system requirements of a system for code offloading. Last, Section 3.6 presents a summary.

The next chapter, **Chapter 4**, presents an efficient code offloading with annotations,

where a (resource-poor) mobile device offloads computation to a (powerful) remote resource. Section 4.1 introduces this basic distribution and Section 4.2 gives its related system overview. Utilizing a runtime environment for code offloading, Section 4.3 describes the functionality of a runtime-layer offloading. Section 4.4 outlines the offloading timeline for a basic distribution and Section 4.5 the functionality provided by an offloading framework. Afterwards, Section 4.6 highlights the implementation of the offloading framework in different prototypes, before Section 4.7 presents the evaluation. Last, Section 4.8 presents a summary.

The next chapter, **Chapter 5**, presents a robust code offloading through safe-point'ing. The preemptable distribution described in Section 5.1 reuses, in case of a failure, intermediate states of a remote execution, without abandoning the remote result achieved so far. To this end, Section 5.2 gives a related system overview, Section 5.3 outlines the offloading timeline for the preemptable distribution, and Section 5.4 describes the functionality provided by an offloading framework. Afterwards, Section 5.5 presents the evaluation of the preemptable distribution in multiple scenarios, where failures occur at different point in times. Last, Section 5.6 presents a summary.

The next chapter, **Chapter 6**, presents a deadline-aware code offloading with predictive safe-point'ing. The predictive distribution described in Section 6.1 utilizes an adaptive algorithm based on prediction models to dynamically adapt the point in times for a creation and transmission of safe-points. To this end, Section 6.2 gives a related system overview before Section 6.3 describes the optimal schedule for safe-point'ing that minimizes the number of safe-points received on a mobile device. Afterwards, Section 6.4 presents the evaluation of a MATLAB simulation in different scenarios. Last, Section 6.5 presents a summary.

The next chapter, **Chapter 7**, presents an optimized code offloading through cooperative caching. The caching-aware distribution described in Section 7.1 optimizes a basic distribution with a cache on the remote side. The cache stores execution states from application parts executed previously. To this end, Section 7.2 gives a related system overview, Section 7.3 outlines the offloading timeline for a caching-aware distribution, and Section 7.4 describes the functionality provided by an offloading framework. To evaluate the overhead and benefits for a caching-aware distribution, Section 7.5 presents the evaluation of an OpenJDK prototype on different mobile devices running different mobile applications. Last, Section 7.6 presents a summary.

The next chapter, **Chapter 8**, presents a code offloading in environments with multiple tiers. The distribution with code bubbling described in Section 8.1 enables a basic distribution to efficiently offload computation in environments with highly distributed heterogeneous resources. To this end, Section 8.2 gives a related system overview, Sec-

tion 8.3 outlines the offloading timeline for a distribution, and Section 8.4 describes the functionality provided by an offloading framework. To evaluate the overhead and benefits for a distribution with code bubbling, Section 8.5 describes the evaluation of a prototype based on Android and OpenJDK. Last, Section 8.6 presents a summary.

The next chapter, **Chapter 9**, presents the work related to this dissertation. The discussion includes the work related to an efficient code offloading with annotations described in Section 9.1 (cf. the basic distribution in Chapter 4), to a robust code offloading through safe-point'ing described in Section 9.2 (cf. the preemptable distribution in Chapter 5), to a deadline-aware code offloading with predictive safe-point'ing described in Section 9.3 (cf. the predictive distribution in Chapter 6), to an optimized code offloading through cooperative caching described in Section 9.4 (cf. the caching-aware distribution in Chapter 7), and to a code offloading in environments with multiple tiers described in Section 9.5 (cf. the distribution with code bubbling in Chapter 8). Last, Section 9.6 presents a summary.

The last chapter, **Chapter 10**, presents the conclusion of this dissertation by giving a summary described in Section 10.1 on the topics covered in this dissertation and an outlook described in Section 10.2 on remaining open research questions.

Chapter 2

Background

This chapter presents the background information for code offloading in the scope of Mobile Cloud Computing (MCC). As the name *Mobile Cloud Computing* suggests, MCC combines mobile computing with cloud computing via a wireless network. To this end, Section 2.1 gives a brief overview of the typical environment, classic architecture, and inherent limitations related to mobile computing. Due to the portability of a device from mobile computing, a wireless network described in Section 2.2 connects the mobile computing environment with resources in an intranet or the Internet. Typically connected via a Wi-Fi, cellular, or Bluetooth link, a device from mobile computing can access powerful resources from cloud computing described in Section 2.3 with its essential characteristics, service models, and deployment models. Different technological trends described in Section 2.4 like Big Data, Internet of Things, and Cyber-Physical System bring the resources from a distant cloud closer to a device from mobile computing, providing nearby resources at the edge of a network. The augmentation of mobile computing with nearby and distant resources via a wireless network enables code offloading in the field of Mobile Cloud Computing. To this end, Section 2.5 first gives an overview of MCC, before it describes the related architectures, requirements for a framework, and arising challenges. Finally, Section 2.6 summarizes the main facts from the background information presented in this chapter.

2.1. Mobile Computing

This section gives a brief overview of mobile computing, where devices from mobile computing transmit data via a wireless link according to Koudounas and Iqbal [KI96]. Improvements in energy-efficient but powerful hardware, wireless telecommunication, and adaptive software enabled this portable computing [Sat10]. To this end, Subsection 2.1.1 characterizes the typical environment of mobile computing, Subsection 2.1.2 the classic architecture of client-server and an extended architecture of client-interlayers-server, and Subsection 2.1.3 the inherent limitations from mobility.

2.1.1. Environment

Mobile computing provides an environment to an end user for sensing, communicating, and processing, where the end user is physically on the move and not stationary in front of a static computer at a single location. The mobile computing environment deploys a portable device with sensing and processing resources that connects via a wireless network to other portable and/or static devices, moving along with a mobile end user. Due to the portability of a computing environment, inherent issues from mobility – e.g., the size, weight, or battery life of the environment – characterize the hardware for a mobile computing environment. For instance, the small size of a mobile computing environment requires an alternate interface for user Input/Output (user IO) like speech recognition compared to classic user IO of static computers. [Sat10, TAY10]

A mobile end user of a mobile computing environment collects, processes, stores, accesses, and spreads information anywhere and anytime via a communication network, avoiding the spatial and temporal constraint from static computers like a desktop computer. This (spatial and temporal) flexibility enables the vision of "information at your fingertips anywhere, anytime" [Sat10], driving academic researchers and industrial pioneers in the past, present, and future. To perform anywhere at anytime a task like spreading information via a mobile computing environment, a corresponding device is a condensed modification of multipurpose computers, where a battery powers the downgraded hardware of a mobile device. Owing to the mobility, a mobile device communicates via a wireless communication link at a low bandwidth and high latency compared to a wired communication link of a static computer. [Sat10, TAY10]

The availability of computation and connectivity irrespective of time and place quickly raised the popularity and importance of devices from mobile computing in today's mobile systems of networked computing. Furthermore, sensing, communicating, and computing capabilities of devices from mobile computing like wireless sensors, Personal Digital Assistants (PDAs), cellular phones, laptops, and many others are nowadays seamlessly integrated into the world of everyday life. Being not distinguishable from physical objects in the world, people accomplish nowadays ordinary tasks by unconsciously using ubiquitous computers – e.g., compare Weiser's seminal paper [Wei99] on the vision of ubiquitous computing. [Sat10, TAY10]

2.1.2. Architecture

The typical architecture in mobile computing is a hierarchy with two tiers, where a transient infrastructure consists of a "client" (first tier) and a "server" (second tier) – the classic model of client-server. To indicate the presence of resources from multiple

servers, nowadays "cloud" is also a name for the second tier (cf. Section 2.3). The first tier, a client, of the two-tier hierarchy corresponds to a mobile computing environment described above, limited by the mobility concerns like downgraded hardware or limited battery life. The second tier, a server or the cloud, of the two-tier hierarchy corresponds to a well-managed, stationary environment, being free of mobility concerns. This classic model of client-server or client-cloud exists from the very beginning of mobile computing. Nowadays, future architectures extend this two-tier hierarchy for mobile computing with one or more interlayers between a client and a server (cf. Section 2.4). For instance, Satyanarayanan et al. [SBCD09] propose an intermediate layer called "cloudlet" as a remote resource at, for instance, a Wi-Fi access point. Compared to resources in a distant cloud, it provides a lower latency and higher bandwidth of a network link, offering its resources for processing and storage to nearby devices. [Sat10]

2.1.3. Limitations

The mobility of mobile computing – not being spatial and temporal constraint – is also responsible for its intrinsic limitations, where technological issues are not bearing the blame. Due to the mobility of a device from mobile computing, it has poor, vulnerable, and variable resources compared to static resources from multipurpose computers or the cloud. The device's mobility defines its acceptable weight and compact size, also affecting the performance from sensing, communicating, and computing resources like processor speed or memory size. Additionally, end users always want to have a smaller, lighter, faster, longer-running mobile device. Despite past or future progress and improvement to mobile devices in absolute ability[1], performance on mobile devices were, are, and will be always a compromise, making a mobile device resource-poor in relation to static resources. Especially as a limited source of energy primarily powers the hardware and software of a mobile device[2], where the battery technology evolves and improves at a slow pace. Thus, energy concerns accompany the flexibility of mobile computing, limiting its usage to the charge cycles of the limited source of energy. Associated with the mobility of a device, the mobile device itself and the communication from or to a mobile device via a wireless link are exposed to a higher danger for loss, damage, or attack in relation to static resources, for instance, locked in the office and communicating via a wired link. The quality of a wireless link – especially while

[1] For instance, the iPhone (1st generation) executes applications on a Samsung 32-bit RISC ARM processor running at 620 MHz with a 128 MB memory. The Samsung Galaxy S7 executes applications on the Samsung Exynos 8 Octa 8890 System-on-a-Chip (SoC) with a big.LITLE 64-bit architecture of eight cores (maximum frequency: 2.6 GHz) and 4 GB memory. [Sam16]

[2] The iPhone (1st generation) has a battery capacity of 1400 mAh, whereas the Samsung Galaxy S7 has a battery capacity of 3000 mAh.

on the move – is also highly variable in relation to static resources. For instance, a Wi-Fi network within a building provides a reliable, high-bandwidth and low-latency connection, whereas a cellular network provides an unreliable, low-bandwidth and high-latency connection, suffering under transient outages. [Sat96]

2.2. Wireless Network

To provide information anywhere at anytime for ubiquitous computing, communicating via a wireless link with other mobile or static devices in an intranet or the Internet is a key characteristic of mobile computing. As a result, properties like coverage, data rates, or latency from a wireless link of a communication network impact significantly the performance of mobile computing and thus, its acceptance. Due to the rapid improvements[3] and vast number of different technologies available in mobile computing for a wireless communication network, this section gives a brief overview on the network technologies utilized in this dissertation. In detail, this dissertation utilizes Wireless Fidelity networks described in Subsection 2.2.1, cellular networks described in Subsection 2.2.2, and Bluetooth networks described in Subsection 2.2.3.

2.2.1. Wireless Fidelity Network

Wireless Fidelity (Wi-Fi) is a brand name for a family of standards that implements a Wireless Local Area Network (WLAN) communication. It specifies techniques for Media Access Control (MAC) and physical layer, administrated by the Institute of Electrical and Electronics Engineers (IEEE) LAN/MAN Standards Committee (IEEE 802) in IEEE 802.11. IEEE 802.11 is a mobile communication network via a wireless link. It connects two or more mobile devices – also with the wider Internet – in a limited area like a building, where an end user can walk around and stay connected as long as being in the local coverage of a Wi-Fi Access Point (AP). Typically, the coverage of a Wi-Fi AP depends on different properties like radio frequency, output power, or receiver sensitivity. IEEE released the first version of IEEE 802.11 in the year 1997, improved and extended by multiple amendments over the years (cf. [Soc12]). The following paragraphs describe the amendments utilized in this dissertation.

802.11-1997: In the year 1997, IEEE released the standard 802.11-1997 that provides a raw data rate of 1 Mbit/s or 2 Mbit/s with a local coverage of approximately

[3] For a cellular link, the iPhone (1st generation) offers a peak data rate of 220 kbit/s [Inf07c], whereas the Samsung Galaxy S7 offers a peak data rate of 150 Mbit/s (uplink) and of 600 Mbit/s (downlink) with a latency less than 10 ms owing to LTE-Advanced [NK16, Sam16].

20 m indoor and 100 m outdoor. It transmits signals either via infrared or in the ISM[4] frequency band of 2.4 GHz – like other network technologies as Bluetooth (cf. Subsection 2.2.3) causing interference – with a frequency bandwidth of 22 MHz. [Soc12]

802.11b: In the year 1999, IEEE released the standard 802.11b that extends the modulation method of 802.11-1997. It increases the raw data rate to up to 11 Mbit/s with a local coverage of approximately 35 m indoor and 140 m outdoor. [Soc12]

802.11a: In the year 1999, IEEE also released the standard 802.11a that utilizes the same protocols on the data link layer (Layer 2[5]) and frame format as 802.11-1997, but changes the modulation technique on the physical layer (Layer 1[5]). It operates in the relatively unused frequency band of 5.8 GHz with a bandwidth of 20 MHz, enabling raw data rates of up to 54 Mbit/s. Due to the higher carrier frequency, a solid object like a wall absorbs the signal strongly. As a result, it lowers the data rates and local coverage, being approximately 35 m indoor and 120 m outdoor. [Soc12]

802.11g: In the year 2003, IEEE released the standard 802.11g that improves the modulation technique of 802.11b (2.4 GHz), enabling a raw data rate of up to 54 Mbit/s and a local coverage of approximately 38 m indoor and 140 m outdoor. [Soc12]

802.11n: In the year 2009, IEEE released the standard 802.11n that enhances the previous standards of 802.11a and 802.11g with the extensions of frame aggregation on the data link layer, $4x4$ Multiple Input Multiple Output (MIMO) transmission on the physical layer, and security improvements. It operates in both frequency bands of 2.4 GHz or 5.8 GHz with a bandwidth of 20 MHz or 40 MHz. The maximum raw data rates with a frequency bandwidth of 40 MHz is 600 Mbit/s with a local coverage for both frequency bands of approximately 70 m indoor and 250 m outdoor. [Soc12]

2.2.2. Cellular Network

A cellular network provides a wireless link for mobile devices, usually available within a huge range provided by (commercial) cell towers. Developed in the early 1980s, the first cellular network only transmitted analog signals for voice calls, whereas nowadays it supports IP[6]-based connectivity with a high bandwidth, low latency, and extensive

[4] Industrial, Scientific and Medical (ISM)
[5] Corresponding to the model from International Organization for Standardization (ISO)/Open Systems Interconnection (OSI)
[6] Internet Protocol (IP)

coverage. Thus, communication ubiquity for mobile computing comes nowadays true, being available anywhere and anytime. The following paragraphs give a brief overview for the evolution of cellular networks utilized in this dissertation.

First Generation: The 1st generation (1G) of cellular network is only an analog system for voice services to cellular phones, where the underlying architecture is a circuit-switched network. In detail, Bell Labs developed the system standard of Advanced Mobile Phone Service (AMPS) for analog mobile cellular phones [Ehr79, You79] – deployed in the year 1983. In the spectrum range of 869 - 894 MHz, cell sites transmit voice to mobiles (forward channel), whereas in the spectrum range of 824 - 849 MHz mobiles transmit voice to cell sites (reverse channel) [Com81]. The main limitations are its low data rates of about 2 kbit/s and limited services. [PSMM04, Akh09, KS11, KSK14]

Second Generation: The 2nd generation (2G) of cellular network introduces the wireless technology of Global Systems for Mobile Communications (GSM) in the year 1991, still used today in many countries all over the world. The main focus of GSM was the transmission of voice *and* data with digital signals – still based on a circuit-switched architecture. It provides higher spectrum efficiency, better data services, and a seamless roaming in different countries compared to 1G. In detail, next generations of cellular network are only an evolution to the architecture of GSM. GSM – more precisely P-GSM – technically uses the frequency band of 890-915 MHz for the reverse channel and of 935-960 MHz for the forward channel. Each channel is segmented into 124 carrier frequencies of 200 kHz and each carrier frequency is further fragmented into eight time slots. As a result, GSM enables eight voice or data calls at the same time, increasing the capacity of the network. The data rate for each channel increased to 9.6 kbit/s – and with an improved channel encoding to 14.4 kbit/s. The main limitations of 2G are a lack of security and its low data rate for web browsing. [PSMM04, Akh09, KSK14]

The 2.5th generation introduces different techniques like High Speed Circuit Switched Data (HSCSD) or General Packet Radio Services (GPRS) in the year 1995. HSCSD enhances circuit-switched data by improving the encoding methods and aggregating multiple time slots for data transmission. Theoretically, the data rate increases to 115.2 kbit/s with eight combined channels. By providing circuit-switched data *and* packet-switched data, GPRS enables simultaneously a phone call and data transmission, further increasing the data rate to theoretically 171.2 kbit/s.

The 2.75th generation changes the modulation scheme in the year 1999, called Enhanced Data rates for Global Evolution (EDGE)[7]. It further increases the data rates per

[7]The original name was Enhanced Data rates for GSM Evolution

time slot with an unchanged baud rate (sending more bits per symbol) to 59.2 kbit/s. Realistically, a mobile phone gets maximally four time slots for the downlink and two time slots for the uplink, resulting in 263.8 kbit/s and 118.4 kbit/s, respectively.

Third Generation: The 3rd generation (3G) of cellular network divides the core network into a circuit-switched part and packet-switched part in the year 2000. It enables IP-based services, higher data rates, increased system capacity, and worldwide roaming. 3G is a set of international-accepted standards, where ITU[8] defined the requirements of 3G in IMT-2000[9]. The 3GPP[10] organization developed Universal Terrestrial Mobile System (UMTS) as a European variant. It utilizes the frequency bands of 800/900 MHz, 1.7 - 1.9 GHz, and 2.5 - 2.69 GHz with a carrier frequency per channel of 5 MHz. UMTS achieves a data rate of 144 kbit/s in rural regions, 384 kbit/s in suburban regions, and 2 Mbit/s in low range outdoor. The main limitations of 3G are its still lower data rates compared to Wi-Fi at this time (cf. Subsection 2.2.1), high latency of at least 30 ms, high complexity of the terminals, and high cost of the infrastructure. [DA97, ITU97, PSMM04, Akh09, KSK14]

The 3.5th generation improves 3G with lower latency, higher data rates, and extended capacity by applying the protocols High-Speed Downlink Packet Access (HSDPA) and High-Speed Uplink Packet Access (HSUPA) combined in High-Speed Packet Access (HSPA). The key features are, for instance, shared channel and multi-code transmission, higher-order modulation, and fast link adaptation and scheduling. The maximum channel rate for HSDPA is 14.4 Mbit/s and for HSUPA 5.8 Mbit/s. HSPA evolution (HSPA+) further increases the data rates to 21 Mbit/s for the downlink and 11 Mbit/s for the uplink. The subsequent improvements like a combination of higher order modulation with spatial multiplexing enable a theoretical peak data rate for the downlink of 672 Mbit/s and for the uplink of 168 Mbit/s. [fG00]

2.2.3. Bluetooth Network

Bluetooth is a packet-based protocol that implements a Wireless Personal Area Network (WPAN) communication with a master-slave structure over a short range based on low-power consumption, invented by Ericsson in the year 1994. The Bluetooth Special Interest Group specifies nowadays the Bluetooth standards, where IEEE specified a Bluetooth standard in IEEE 802.15.1, not maintaining it anymore. Bluetooth transmits signals in the ISM frequency band of 2.4 GHz with a bandwidth of 1 MHz. The

[8] International Telecommunication Union (ITU)
[9] International Mobile Telecommunications-2000 (IMT-2000)
[10] 3rd Generation Partnership Project (3GPP)

range of a Bluetooth communication depends on a power-class, where Class 1 has a maximum permitted power of 100 mW and a typical range of 100 m, Class 2 of 2.5 mW and 10 m, Class 3 of 1 mW and 1 m, and Class 4 of 0.5 mW and 0.5 m.

Bluetooth 1: The Bluetooth versions 1.0, 1.1[11], and 1.2[11] improve step-wise the new standard by fixing errors and introducing, for instance, non-encrypted channels or faster discovery and connection, having a raw data rate of up to 1 Mbit/s. [Soc05]

Bluetooth 2: The Bluetooth versions 2.0 released in the year 2004 and 2.1 released in the year 2007 introduce further improvements like Secure Simple Pairing and utilizes a combined modulation, enabling raw data rates of up to 3 Mbit/s.

Bluetooth 3: The Bluetooth version 3.0 released in the year 2009 has the main key feature of Alternative MAC/PHY. It enables raw data rates of up to 24 Mbit/s, where the Bluetooth radio discovers a device and initiates a connection and a parallel 802.11 radio transports the data at a high speed.

2.3. Cloud Computing

The rise of cloud computing started in the early 2000s, where, for instance, Amazon announced its Elastic Compute Cloud in the year 2006 [Ama06]. Four years later, Microsoft also announced the general availability of its cloud computing platform, called Azure [Hau10]. In the late 2000s, cloud computing experienced a further increase, mainly based on the availability of high-capacity networks, low-cost devices, virtualization techniques, and service-oriented architectures. The National Institute of Standards and Technology (NIST) defines cloud computing as a model that offers to end-users "... on-demand network access to a shared pool of configurable computing resources [...] rapidly provisioned and released ..." [BGPCV12], where configurable resources include resources like storage, processing, or network. To this end, Subsection 2.3.1 outlines the essential characteristics, Subsection 2.3.2 the different service models, and Subsection 2.3.3 the different deployment models of cloud computing.

2.3.1. Essential Characteristics

Following the definition from NIST, an end user utilizes cloud computing as an on-demand self-service, where he or she autonomously allocates and releases resources

[11] IEEE specified version 1.1 as IEEE 802.15.1-2002 and version 1.2 as IEEE 802.15.1-2005

from a shared pool of configurable resources without an intervention from the cloud provider. An end user allocates and releases capabilities from a cloud provider via a network access, utilizing its client platform like a mobile phone or workstation. A cloud provider uses a multi-tenant model and pools its computing resources with dynamic re-/assignment of physical and virtual resources to serve the demands from multiple end users. Typically, an end user does not know the exact location of its allocated resources (location independence), defining only the resource's location at a higher level of abstraction like a region. An allocation and release of resources from a cloud provider take place rapidly and elastically, scaling automatically up and down based on the user demand. For an end user, available resources seem to be virtually unlimited, provided in any quantity at any time. A system of cloud computing automatically controls, meters, and optimizes the usage of its resources, providing transparency to its provider and to end users. A cloud provider typically charges fees for utilized resources based on a "pay-as-you-go" model. [AFG+10, BGPCV12]

2.3.2. Service Models

Cloud computing offers different service models, where common service models are Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS), increasing step-wise the level of abstraction. The service model IaaS provides to an end user the "plain" resource like processing, storage, or network. An end user can run arbitrary software on the resources like an operating system on a processing resource. To this end, an end user has the highest flexibility on the total software stack associated with the responsibility to manage the total software stack. The service model PaaS provides to an end user the ability to deploy software onto the infrastructure from cloud computing, where a cloud provider supports a set of programming languages and tools. To this end, an end user does not manage the software stack provided for software development but controls the environment for deployment as well as the deployed software. Last, the service model SaaS provides to an end user the utilization of applications supported by a cloud provider, where the supported applications are accessible from various interfaces like a Web browser. To this end, an end user does not manage the total software stack required to execute an application and just utilizes an application as and when required. [AFG+10, BGPCV12]

2.3.3. Deployment Models

Cloud computing offers different deployment models, where common deployment models are a private cloud, a community cloud, a public cloud, and a hybrid cloud. The

deployment model of a private cloud provides an infrastructure exclusively used by a single organization, where an organization, a third-party, or a combination owns, operates, manages, and/or hosts the cloud infrastructure internally or externally. The deployment model of a community cloud provides an infrastructure exclusively used by a specific community from organizations – e.g., sharing a common concern, where one or more organization(s) from a community, a third party, or a combination owns, operates, manages, and/or hosts the cloud infrastructure internally or externally. The deployment model of a public cloud provides an infrastructure for the general public, where a company owns, operates, manages, and hosts the cloud infrastructure internally. The deployment model of a hybrid cloud bounds together two or more different infrastructures from a private cloud, community cloud, and/or public cloud that remain unique but provide portability. [AFG+10, BGPCV12]

2.4. Technological Trends

Technological trends like Big Data, Internet of Things (IoT), or Cyber-Physical System (CPS) pave the way for powerful computing resources at the edge of a network, to rapidly manage and process a large amount of data. For instance, computing resources from cloud computing (cf. Section 2.3) reside in distant data centers at a few location all over the world, being too far-away for related applications.

Commonly, the four dimensions of volume, velocity, variety, and veracity distinguish solutions for Big Data from conventional IT. Big Data has to manage, process, and validate (veracity) rapidly (velocity) a large amount (volume) of structured and unstructured data (variety). Jewell et al. characterize in [JBD+14] solutions for Big Data as a real-time complex processing. Thus, the utilization of computing resources at a distant data center from cloud computing is not always preferable, requiring in-network computing resources where data arises. [Cen12, JBD+14]

IoT includes a wide variety of physical objects from everyday life, integrating the physical world into computer-assisted systems. Augmented by sensors, actuators, and connectivity, an everyday object becomes a so-called "smart object" that autonomously collects, exchanges, and retrieves data with other smart objects and the Internet. This advanced interconnection improves the efficiency, accuracy, and economic benefit from everyday objects, generating a large amount of data at an exponential rate. This generation of a large amount of data introduces new challenges like the demand of very low end-to-end latency and very high network bandwidth. Thus, it requires distant computing resources from cloud computing together with in-network computing resources where data arises. [BLMN13, AFGM+15, CZ16]

With the embedding of sensing, communicating, and processing capabilities to everyday objects in the physical world, CPS bridges the cyber-world with the physical world by monitoring and controlling the physical world with a computer-assisted system. A CPS influences the interaction and control of the physical world by humans, coupling embedded real-time systems of distributed sensors and actuators with controls. Thus, it requires the distant computing resources from cloud computing together with in-network computing resources. [RLSS10, KM15]

Regarding the technological trends of Big Data, IoT, and CPS, the requirement for closer computing resources at the edge of a network is omnipresent. For instance, fog computing offers powerful computing resources like processing or storage at the edge of a network [BMZA12]. It rapidly processes data where it arises due to its location in the near proximity to end devices and its dense geographical distribution. Compared to distant computing resources from cloud computing (cf. Section 2.3), fog computing connects an end device with its in-network resources via a link with a higher bandwidth and a lower latency. [BMZA12, VRM14, YLL15]

2.5. Mobile Cloud Computing

Mobile Cloud Computing (MCC) integrates the powerful computing resources from cloud computing (cf. Section 2.3) into the environment of mobile computing (cf. Section 2.1) via wireless networks (cf. Section 2.2) to overcome the limitations of a (resource-poor) mobile device (cf. Subsection 2.1.3). The service of code offloading from MCC is a potential technique that augments (resource-poor) devices from mobile computing with powerful, remote resources from cloud computing. The idea of code offloading is to execute resource-intensive parts from an application on a powerful, remote resource on behalf of a mobile device. The related benefits for a mobile device are shorter execution times and lower energy consumption for an application execution, paying a monetary cost for the utilization of the remote resource. To this end, Subsection 2.5.1 gives a brief overview of code offloading within MCC before Subsection 2.5.2 characterizes its typical architectures of two tiers and multiple tiers. Afterwards, Subsection 2.5.3 discusses requirements to a framework for code offloading before Subsection 2.5.4 outlines related challenges.

2.5.1. Overview

The driving force behind an offloading of code from a mobile device to a powerful, remote resource is the resource poverty of mobile devices. The hardware of a mobile

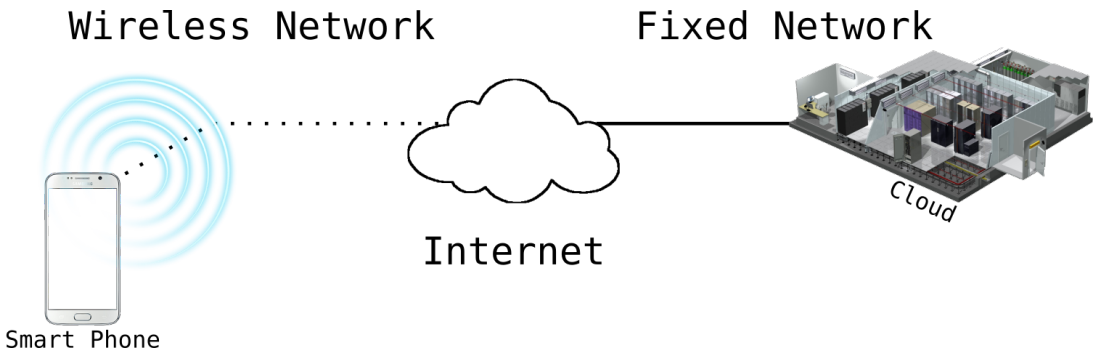


Figure 2.1.: A typical two-tier architecture from Mobile Cloud Computing, where a smart phone communicates via the Internet with the cloud.

device is unavoidably resource-poor in relation to static workstations or server instances (cf. Subsection 2.1.3). Cloud services offer on-demand computing resources with a high performance, availability (24/7), scalability, elasticity, and accessibility (anywhere at anytime) at a low cost (cf. Section 2.3). By offloading computation from a resource-poor device to remote resources, the advantages for a mobile device are, for instance, a reduced consumption of power increasing its battery life. However, the mobility in mobile computing blurs the classic model of client-server (cf. Subsection 2.1.2), where, for instance, a client statically executes predefined parts of an application on a well-known remote server based on Remote Procedure Calls (RPCs). Due to the mobility in mobile computing, the current situation on a client about user, device, application, network, and environment changes constantly. Thus, a client requires a more dynamic system for a distributed execution of application parts. Dependent on information from the current situation, the system should adaptively react and reassign application parts during the execution to the local resources of the client and to a remote resource like a server instance at a nearby fog or a distant cloud to fit the current situation. Especially, uncertain connectivity from a wireless network like a cellular network (cf. Subsection 2.2.2) requires high adaptation, reacting rapidly on its high-varying performance and reliability. [Sat96, Sat10, TAY10]

2.5.2. Architectures

In general, code offloading supports manifold architectures, where the most popular architecture consists of two tiers (cf. Figure 2.1): A mobile device (first tier) and the cloud (second tier). Categorized by the number of tiers within the architecture, this kind of architecture is called a two-tier architecture. Beside a two-tier architecture, there are also multiple tiers possible in today's MCC (cf. Figure 2.2), where multiple tiers surround a mobile device and participate in code offloading like smart wearable

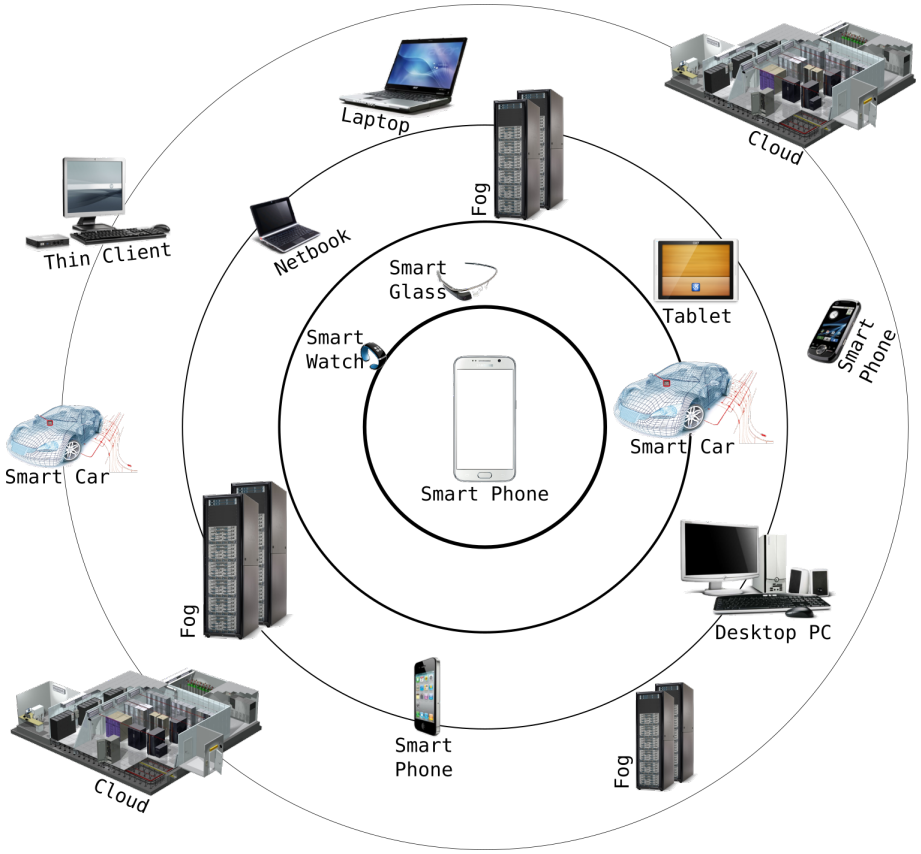


Figure 2.2.: A multi-tier architecture from Mobile Cloud Computing, where multiple resources like smart wearables, smart phones, ..., and server instances at the cloud surround a smart phone, communicating via different networks with each other.

(first tier), smart phone (second tier), ..., and the cloud (last tier). As a result, this kind of architecture is called a multi-tier architecture.

Two-tier Architecture: Figure 2.1 shows the most popular architecture with two tiers from Mobile Cloud Computing. It consists of a mobile device like a smart phone (first tier), wireless and fixed networks, and remote resources like server instances at the cloud (second tier). In detail, a mobile device communicates via a wireless network with the Internet and thus, with remote resources located in a data center at the cloud. A wireless network is either a Wi-Fi network or a cellular network from a network provider that peers its wireless network with the Internet at Internet exchange nodes like the DE-CIX in Frankfurt[12], providing connectivity to the infrastructures of cloud providers. The network within the Internet and to the cloud infrastructures is typically a fixed network, providing high bandwidth, low latency, and high reliability.

[12] `https://www.de-cix.net/en/locations/germany/frankfurt`

Multi-tier Architecture: Figure 2.2 shows an architecture with multiple tiers from Mobile Cloud Computing. It consists of multiple classes of highly distributed heterogeneous resources like smart wearables, smart phones, tablets, smart cars, workstations, server instances at the fog, and server instances at the cloud. In detail, different kind of (mobile and fixed) networks like a Bluetooth network, a Wi-Fi network, a cellular network, or the Internet connect the multiple resources with each other. Thus, multiple resources surround a mobile device like a smart phone, differing significantly in terms of capabilities like energy, computation, and communication. The capabilities from the multiple resources increase typically from very limited (cf. smart wearable) to virtually unlimited (cf. server instances at the cloud). An exemplary scenario for an architecture with multiple tiers consists of a smart watch that a Bluetooth link connects to a smart phone. The smart phone again communicates via a Wi-Fi link to a resource on a smart car that provides connectivity via a 3G mobile communication to an in-network server at the edge of the network. The 3G mobile communication also provides connectivity to a server instance at the cloud, where the network from the peering node to the cloud is a fixed network.

2.5.3. Framework

To provide code offloading for an architecture with two or multiple tiers, participating resources like the mobile device and the remote resource require an efficient framework that enables a dynamic distribution of application parts.

For the mobile device, a framework has to answer the following Five Ws and one H: What does it offload, who does the offloading, when does the offloading happen, where does it offload to, why does it offload, and how to offload. The question *what does it offload* defines the type of an application part like a thread or a method. The question *who does the offloading* defines the layer within the software stack of a mobile device that is responsible for the offloading like at application layer, at run-time layer, or at system layer. The question *when does the offloading happen* defines the point in time of the decision making like at development-time or at run-time. The question *where does it offload to* defines the number of remote resources that are available for code offloading like resources at the cloud, the fog, and/or further resources from smart devices. The question *why does it offload* defines the decision problem of code offloading like increasing energy efficiency and/or execution speed and/or decreasing monetary cost. The question *how to offload* defines the behavior of a mobile device during code offloading like an execution of a mechanism to handle failures.

For the remote resource, a framework has to answer the following Five Ws and one H:

What does it execute, who does the execution, when does the execution happen, where does it execute on, why does it execute, and how to execute. The question *what does it execute* defines the software stack on a remote resource like a virtualization environment, a mobile operating system, or a lightweight runtime environment. The question *who does the execution* defines the re-distribution from a remote resource to another remote resource or to the client due to, for instance, a long-lasting disconnection. The question *when does the execution happen* defines the point in time of the start for an execution on a remote resource like for an execution of time-uncritical parts. The question *where does it execute on* defines the number of remote executions for code offloading like a parallel execution of an application part. The question *why does it execute* defines the monetary cost charged for an execution on a remote resource like a "pay-as-you-go" model from cloud computing. The question *how to execute* defines the performance of a remote resource like the different kind of virtual machines offered in today's cloud computing.

2.5.4. Challenges

Combining the two different fields of mobile computing and cloud computing, code offloading from MCC faces a number of challenges for a distribution of application parts between a mobile device and a remote resource. Due to the resource poverty of a mobile device like a smart phone, code offloading should sparingly use resources like the limited resources of a mobile device, keeping the overhead introduced to the system low. For instance, a resource-efficient monitoring of information related to the current situation is essential for an effective distribution of an application. Due to an uncertain connectivity of a wireless network like high-varying bandwidth, latency, and reliability, code offloading should provide a seamless connectivity to remote resources, handling dynamically network failures like disconnections. Regarding the low bandwidth and high latency of a Wide Area Network (WAN) link compared to, for instance, a Wi-Fi link, code offloading should utilize computing resources not only from distant data centers at the cloud but also from nearby in-network data centers at the fog. Even more, code offloading should also utilize closer computing resources from static workstations or smart devices like a smart car. Due to the advantages from cloud computing or fog computing like elasticity and scalability, code offloading should adapt dynamically the usage of computing resources at the cloud or at the fog to current workload by an adaptive provisioning and de-provisioning of computing resources. Moreover, code offloading should also turn its attention to challenges inherited from cloud computing and fog computing like challenges related to trust, security, or privacy, because a remote

execution of application parts from an end user can contain user-related information. Summarizing, a resource-efficient situation-aware system for code offloading is essential to face the outlined challenges.

2.6. Summary

Mobile computing described in Section 2.1 provides a portable environment that possesses capabilities for sensing, processing, and communicating of data, where a transmission of data happens via a wireless link. A mobile computing environment enables its end user to have information at its fingertips, anywhere at anytime, accessing data in the Internet mainly on the classic architecture of client-server. The issue of "mobility" in mobile computing, however, also limits the usage of a mobile computing environment, restricted by its lower performance like the limited battery life or the varying wireless connectivity compared to a static workstation. To weaken the limitations of a mobile computing environment, steady improvements to its hardware and communication like the underlying technology of a mobile wireless network increased its performance significantly. The current versions of *wireless networks* described in Section 2.2 provide a wireless link from a Wi-Fi network, a cellular network, or a Bluetooth network with a high performance like a high bandwidth, a low latency, a high reliability, and a high coverage, enabling the communication ubiquity. Based on this communication ubiquity, a mobile computing environment utilizes the field of *cloud computing* described in Section 2.3 that provides powerful services in infrastructures at a few locations all over the world. The essential characteristics of cloud computing are an on-demand provisioning of powerful, virtually unlimited computing resources like processing or storage, automatically charged in a "pay-as-you-go" manner. The utilization of computing resources from cloud computing happens typically based on different service models like IaaS, PaaS, and SaaS and deployment models like private cloud, community cloud, public cloud, or hybrid cloud. Beside computing resources in a distant cloud infrastructure, *technological trends* like Big Data, IoT, and CPS described in Section 2.4 moved the distant cloud closer to end terminals, offering nearby computing resources at the edge of a network like fog computing. The integration of cloud computing – and, for instance, fog computing – into mobile computing created the field of *mobile cloud computing* described in Section 2.5, providing new areas of application like code offloading. Code offloading augments a resource-poor device from mobile computing with powerful, remote resources at the fog or at the cloud. It dynamically executes resource-intensive parts from an application on remote resources dependent on the current situation of the user, device, application, network, and envi-

ronment. Due to the vast number of available resources for code offloading in today's landscape of MCC, different architectures are common like a two-tier architecture or a multi-tier architecture. To this end, a related framework for code offloading between two or multiple tiers arises a number of challenges like resource efficiency or situation awareness, requiring a resource-efficient situation-aware system to offload code.

Chapter 3

System Overview

This chapter presents code offloading in the landscape of Mobile Cloud Computing. In general, code offloading augments a (resource-poor) mobile device with (powerful) remote resources by executing (resource-intensive) parts of an application remotely. To this end, Section 3.1 describes the underlying system model for code offloading with multiple tiers before Section 3.2 outlines the general problem statement to be solved for offloading code. Based on the system model and the problem statement, Section 3.3 outlines the system components involved in code offloading, including an offloading client, an offloading service, and a communication network. As each system component can fail at any point in time, Section 3.4 describes the underlying failure model for this dissertation and Section 3.5 the key requirements for an offloading system. Finally, Section 3.6 summarizes the main facts of code offloading presented in this chapter.

3.1. System Model

Today's landscape of Mobile Cloud Computing comprises multiple classes of highly distributed heterogeneous resources that differ in performance characteristics and cost implications (cf. Subsection 2.5.2 and especially Figure 2.2). To this end, this dissertation formulates a general system model for code offloading based on multiple resources (multi-tier architecture). The general system model for a multi-tier architecture also includes the system model for the classic two-tier architecture presented in Subsection 2.5.2. The general system model is as follows:

Multiple highly distributed heterogeneous resources are available for code offloading, where each resource $\Xi(\xi)$ with $\xi = 0, 1, \ldots, n_\xi - 1$ is capable of executing portable code (p-code) with the help of a runtime environment. The performance characteristic $P_{ppwr}^{\Xi(\xi)}$ is the processing power of a resource $\Xi(\xi)$, indicating how many p-code (e.g., instructions) the resource executes per second.

Utilizing other resources, the performance characteristics $E_{send}^{\Xi(\xi_l)}$, $E_{wait}^{\Xi(\xi_l)}$, $E_{recv}^{\Xi(\xi_l)}$, and $E_{exec}^{\Xi(\xi_l)}$ for a resource $\Xi(\xi_l)$ are energy factors of sending bytes, waiting in idle mode,

receiving bytes, and executing p-code, indicating how much energy the operation consumes per second. Providing its computing power to other resources, the cost implication $C_{exec}^{\Xi(\xi_r)}$ for a resource $\Xi(\xi_r)$ is the monetary cost of a resource, indicating how much monetary cost a resource charges per executed p-code.

A resource $\Xi(\xi_l)$ and a resource $\Xi(\xi_r)$ communicate with each other via a bidirectional link $\Lambda(\xi_l;\xi_r)$. For a link $\Lambda(\xi_l;\xi_r)$, the performance characteristics $B_{up}^{\Lambda(\xi_l;\xi_r)}$ and $B_{down}^{\Lambda(\xi_l;\xi_r)}$ are the up and down bandwidth of a link, indicating how many bytes a link transmits per second. The performance characteristics $L_{up}^{\Lambda(\xi_l;\xi_r)}$ and $L_{down}^{\Lambda(\xi_l;\xi_r)}$ are the up and down latency of a link, indicating the network delay of a link in seconds. The cost implications $C_{send}^{\Lambda(\xi_l;\xi_r)}$ and $C_{recv}^{\Lambda(\xi_l;\xi_r)}$ are the monetary cost of a link for sending and receiving bytes, indicating how much monetary cost a link charges per sent or received byte.

A mobile application A consists of application parts A_α with $\alpha = 0, 1, \ldots, n_\alpha - 1$ like methods. To offload an application part A_α from a resource $\Xi(\xi_l)$ to a resource $\Xi(\xi_r)$, the execution of the application part A_α must only rely on the processing power of resources, not accessing further capabilities from a resource like a local sensor. Thus, the application parts A_α consist of application parts A_{α_o} that can be offloaded ("offloadable") and application parts A_{α_l} that must be executed locally.

Each application part A_α comprises an input execution state $I_{state}(A_\alpha)$ like method parameters, portable code $P_{pcode}(A_\alpha)$ like method instructions, and an output execution state $O_{state}(A_\alpha)$ like the return value of the method. An execution of $P_{pcode}(A_\alpha)$ only depends on $I_{state}(A_\alpha)$ and transforms $I_{state}(A_\alpha)$ into $O_{state}(A_\alpha)$. The load metric $P_{pcode}^{exe}(I_{state}(A_\alpha), P_{pcode}(A_\alpha))$ indicates the number and kind of p-code a resource $\Xi(\xi)$ has to actually execute from $P_{pcode}(A_\alpha)$ for an execution. Furthermore, the load metrics $I_{state}^{size}(A_\alpha)$ and $O_{state}^{size}(A_\alpha)$ indicates the total number of bytes for an input execution state $I_{state}(A_\alpha)$ and an output execution state $O_{state}(A_\alpha)$, respectively.

3.2. Problem Statement

The call graph $G(V, E)$ of an application A represents the call stack of the application parts A_α (cf. Figure 3.1). Each vertex $A_{\alpha_v} \in V$ represents an application part and each edge $e(A_{\alpha_u}, A_{\alpha_v}) \in E$ with $A_{\alpha_u}, A_{\alpha_v} \in V$ represents an invocation of the application part A_{α_v} from the application part A_{α_u}. A resource $\Xi(\xi_l)$ executes an application A by invoking its application parts A_α and determines the optimal resource within $\Xi(\xi)$ for an application part $A_{\alpha_o} \in V$ that is offloadable by minimizing the cost function f_w:

$$\min_{\xi} f_w(A_{\alpha_o}, \Xi(\xi)) \tag{3.1}$$

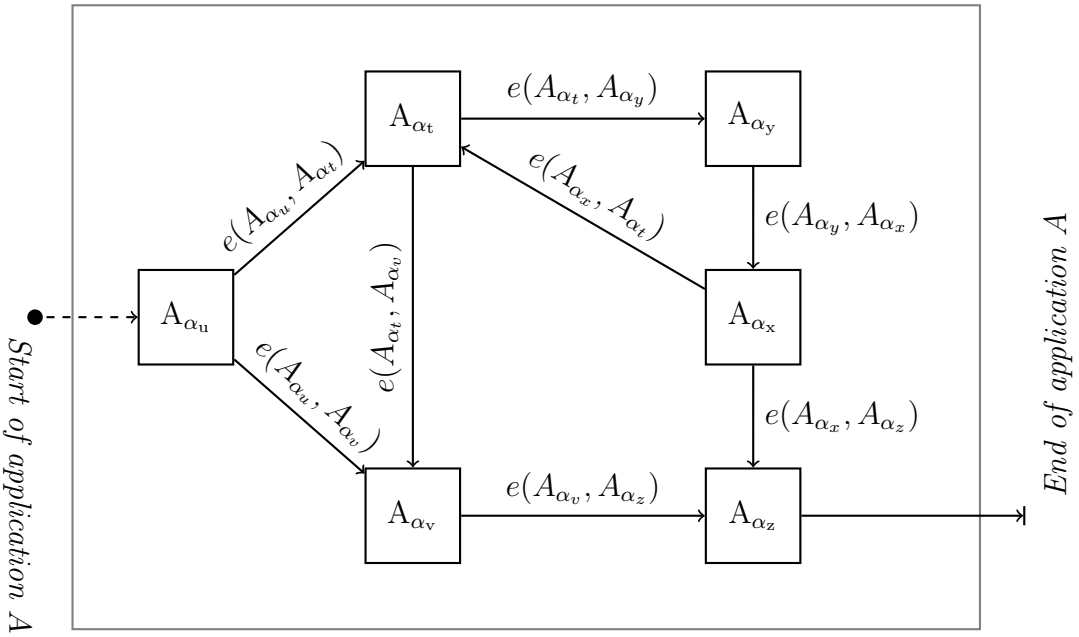


Figure 3.1.: An exemplary call graph $G(V, E)$ for an application A, where the set V of vertexes contains the application parts A_α of an application A and the set E of edges contains the invocations of the application parts.

where the cost function f_w is the weighted sum of the execution time T, the energy consumption E, and the monetary cost C of the application part A_{α_o}:

$$f_w(A_{\alpha_o}, \Xi(\xi)) = w_t \cdot T(A_{\alpha_o}, \Xi(\xi)) + w_e \cdot E(A_{\alpha_o}, \Xi(\xi)) + w_c \cdot C(A_{\alpha_o}, \Xi(\xi))$$

with the weight w_t for the execution time T, the weight w_e for the energy consumption E, and the weight w_c for the monetary cost C. Utilizing a weighted sum for the cost function f_w, an end user or an offloading system can specify its current preference of the execution time, energy consumption, and monetary cost. For instance, if a mobile device is plugged in, an offloading system sets automatically the weight w_e to 0, neglecting temporarily the energy consumption of the mobile device and benefiting from shorter execution times through code offloading.

The execution time $T(A_{\alpha_o}, \Xi(\xi))$ depends on the resource $\Xi(\xi)$ that executes the application part A_{α_o}. In case of a local execution of the application part A_{α_o} on the resource $\Xi(\xi_l)$, the execution time $T(A_{\alpha_o}, \Xi(\xi))$ with $\Xi(\xi) = \Xi(\xi_l)$ evaluates to:

$$T(A_{\alpha_o}, \Xi(\xi)) = T_{local}(A_{\alpha_o}, \Xi(\xi_l)) = \frac{P^{exe}_{pcode}(I_{state}(A_\alpha), P_{pcode}(A_\alpha))}{P_{ppwr}(\Xi(\xi_l))}$$

In case of a remote execution of the application part A_{α_o} on the resource $\Xi(\xi_r)$, the

execution time $T(A_{\alpha_o}, \Xi(\xi))$ with $\Xi(\xi) = \Xi(\xi_r) \neq \Xi(\xi_l)$ sums up the execution time $T_{send}(A_{\alpha_o}, \Xi(\xi_r))$ of sending the input execution state $I_{state}(A_{\alpha_o})$ to the resource $\Xi(\xi_r)$, $T_{wait}(A_{\alpha_o}, \Xi(\xi_r))$ of waiting in idle mode until the resource $\Xi(\xi_r)$ executed the p-code $P^{exe}_{pcode}(I_{state}(A_{\alpha_o}), P_{pcode}(A_{\alpha_o}))$, and $T_{recv}(A_{\alpha_o}, \Xi(\xi_r))$ of receiving the output execution state $O_{state}(A_{\alpha_o})$ from the resource $\Xi(\xi_r)$:

$$\begin{aligned} T(A_{\alpha_o}, \Xi(\xi)) = T_{remote}(A_{\alpha_o}, \Xi(\xi_r)) \quad &= T_{send}(A_{\alpha_o}, \Xi(\xi_r)) + \\ &\quad T_{wait}(A_{\alpha_o}, \Xi(\xi_r)) + \\ &\quad T_{recv}(A_{\alpha_o}, \Xi(\xi_r)) \end{aligned}$$

with

$$\begin{aligned} T_{send}(A_{\alpha_o}, \Xi(\xi_r)) &= \frac{I^{size}_{state}(A_{\alpha_o})}{B^{\Lambda(\xi_l;\xi_r)}_{up}} + L^{\Lambda(\xi_l;\xi_r)}_{up} \\ T_{wait}(A_{\alpha_o}, \Xi(\xi_r)) &= \frac{P^{exe}_{pcode}(I_{state}(A_{\alpha_o}), P_{pcode}(A_{\alpha_o}))}{P_{ppwr}(\Xi(\xi_r))} \\ T_{recv}(A_{\alpha_o}, \Xi(\xi_r)) &= \frac{O^{size}_{state}(A_{\alpha_o})}{B^{\Lambda(\xi_l;\xi_r)}_{down}} + L^{\Lambda(\xi_l;\xi_r)}_{down} \end{aligned}$$

The energy consumption $E(A_{\alpha_o}, \Xi(\xi))$ also depends on the resource $\Xi(\xi)$ that executes the application part A_{α_o} and evolves in case of a local execution of the application part A_{α_o} on the resource $\Xi(\xi_l)$ with $\Xi(\xi) = \Xi(\xi_l)$ to:

$$E(A_{\alpha_o}, \Xi(\xi)) = E_{local}(A_{\alpha_o}, \Xi(\xi_l)) = T_{local}(A_{\alpha_o}, \Xi(\xi_l)) \cdot E^{\Xi(\xi_l)}_{exec}$$

In case of a remote execution of the application part A_{α_o} on the resource $\Xi(\xi_r)$ with $\Xi(\xi) = \Xi(\xi_r) \neq \Xi(\xi_l)$, the energy consumption $E(A_{\alpha_o}, \Xi(\xi))$ sums up the energy consumption $E_{send}(A_{\alpha_o}, \Xi(\xi_r))$ of sending the input execution state $I_{state}(A_{\alpha_o})$ to the resource $\Xi(\xi_r)$, $E_{wait}(A_{\alpha_o}, \Xi(\xi_r))$ of waiting in idle mode until the resource $\Xi(\xi_r)$ executed the p-code $P^{exe}_{pcode}(I_{state}(A_{\alpha_o}), P_{pcode}(A_{\alpha_o}))$, and $E_{recv}(A_{\alpha_o}, \Xi(\xi_r))$ of receiving the output execution state $O_{state}(A_{\alpha_o})$ from the resource $\Xi(\xi_r)$:

$$\begin{aligned} E(A_{\alpha_o}, \Xi(\xi)) = E_{remote}(A_{\alpha_o}, \Xi(\xi_r)) \quad &= E_{send}(A_{\alpha_o}, \Xi(\xi_r)) + \\ &\quad E_{wait}(A_{\alpha_o}, \Xi(\xi_r)) + \\ &\quad E_{recv}(A_{\alpha_o}, \Xi(\xi_r)) \end{aligned}$$

with

$$\begin{aligned} E_{send}(A_{\alpha_o}, \Xi(\xi_r)) &= T_{send}(A_{\alpha_o}, \Xi(\xi_r)) \cdot E^{\Xi(\xi_l)}_{send} \\ E_{wait}(A_{\alpha_o}, \Xi(\xi_r)) &= T_{wait}(A_{\alpha_o}, \Xi(\xi_r)) \cdot E^{\Xi(\xi_l)}_{wait} \\ E_{recv}(A_{\alpha_o}, \Xi(\xi_r)) &= T_{recv}(A_{\alpha_o}, \Xi(\xi_r)) \cdot E^{\Xi(\xi_l)}_{recv} \end{aligned}$$

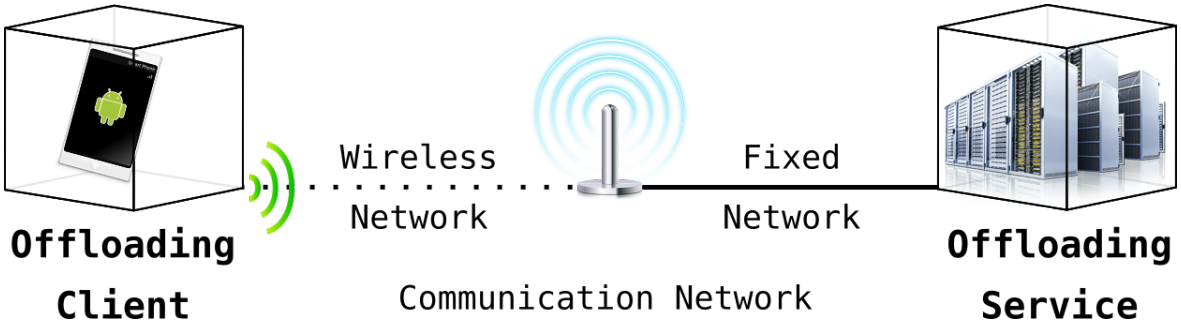


Figure 3.2.: The system components for code offloading, where an offloading client offloads code via a communication network – consisting of a wireless network and a fixed network – to an offloading service.

The monetary cost $C(A_{\alpha_o}, \Xi(\xi))$ also depends on the resource $\Xi(\xi)$ that executes the application part A_{α_o}. It only applies in case of a remote execution, utilizing the resource $\Xi(\xi_r)$ with $\Xi(\xi) = \Xi(\xi_r) \neq \Xi(\xi_l)$ and the link $\Lambda_{\xi_l \leftrightarrow \xi_r}$ to the resource $\Xi(\xi_r)$. The monetary cost $C(A_{\alpha_o}, \Xi(\xi))$ sums up the monetary cost $C_{recv}(A_{\alpha_o}, \Xi(\xi_r))$ of receiving the input execution state $I_{state}(A_{\alpha_o})$ from the resource $\Xi(\xi_l)$, $C_{exec}(A_{\alpha_o}, \Xi(\xi_r))$ of executing the p-code $P^{exe}_{pcode}(I_{state}(A_{\alpha_o}), P_{pcode}(A_{\alpha_o}))$ on the resource $\Xi(\xi_r)$, and $C_{send}(A_{\alpha_o}, \Xi(\xi_r))$ of sending the output execution state $O_{state}(A_{\alpha_o})$ to the resource $\Xi(\xi_l)$:

$$\begin{aligned} C(A_{\alpha_o}, \Xi(\xi)) = C_{remote}(A_{\alpha_o}, \Xi(\xi_r)) \quad &= C_{recv}(A_{\alpha_o}, \Xi(\xi_r)) + \\ &C_{exec}(A_{\alpha_o}, \Xi(\xi_r)) + \\ &C_{send}(A_{\alpha_o}, \Xi(\xi_r)) \end{aligned}$$

with

$$\begin{aligned} C_{recv}(A_{\alpha_o}, \Xi(\xi_r)) &= I^{size}_{state}(A_{\alpha_o}) \cdot C^{\Lambda(\xi_l;\xi_r)}_{recv} \\ C_{wait}(A_{\alpha_o}, \Xi(\xi_r)) &= P^{exe}_{pcode}(I_{state}(A_\alpha), P_{pcode}(A_\alpha)) \cdot C^{\Xi(\xi_r)}_{exec} \\ C_{send}(A_{\alpha_o}, \Xi(\xi_r)) &= O^{size}_{state}(A_{\alpha_o}) \cdot C^{\Lambda(\xi_l;\xi_r)}_{send} \end{aligned}$$

Summarizing, the problem for a resource $\Xi(\xi_l)$ that distributes an application part A_{α_o} to resources that offer their computing power is to determine the right resource $\Xi(\xi)$ for an execution of A_{α_o} by minimizing the cost function f_w (cf. Equation 3.1).

3.3. System Components

Related to the system model and the problem statement described above, a distribution of an application from a resource like a smart phone to another resource like a server instance at the cloud includes three main components (cf. Figure 3.2): An offloading client that offloads application parts (cf. Subsection 3.3.1), an offloading service

that executes offloaded application parts (cf. Subsection 3.3.2), and a communication network that connects both with each other (cf. Subsection 3.3.3).

3.3.1. Offloading Client

To distribute application parts to other resources, a resource runs an offloading client upon its local hardware. It provides the functionality required on the client side for code offloading to other resources. The offloading client is capable to execute portable code from an application part on the local hardware and to monitor a related execution of the portable code. Based on monitoring a local execution of an application part, the offloading client is capable to identify an application part as offloadable and to gather both its input execution state and portable code. At the invocation of an application part that is offloadable, the offloading client minimizes the cost function in Equation 3.1 to determine the optimal resource for an execution under the current situation. To obtain the parameters required for Equation 3.1, the offloading client retrieves the energy factors, samples the links to remote resources, and queries remote resources for the cost implications (cf. Section 3.1). In case of a local execution, the offloading client just continues the local execution of the application on the local hardware. In case of a remote execution, the offloading client is capable to send the input execution state and the related p-code from the application part to the remote resource, to wait in idle mode for the end of a remote execution of the application part, and to receive the output execution state from the remote resource. It is also capable to install the received output execution state on the local hardware and to continue subsequently the execution of the application.

3.3.2. Offloading Service

To execute an application part distributed by an offloading client, a resource runs an offloading service upon its local hardware. The offloading service provides the required functionality on the service side for an execution of offloaded code. To this end, the offloading service is capable to receive an input execution state and the related portable code from an offloading client, to install both on its local hardware, and to start an execution of the portable code based on the received input execution state. At the end of an execution for a distributed application part, the offloading service is capable to gather the output execution state of the execution and to send the gathered output execution state to the offloading client.

3.3.3. Communication Network

To enable resources for communicating with each other, a communication network connects an offloading client with an offloading service. A typical resource that distributes application parts to other resources is a (resource-constrained) mobile device like a smart phone, equipped with multiple connectivity for data transfer like a Wi-Fi network, a cellular network, or a Bluetooth network (cf. Section 2.2). Based on a Bluetooth link, a mobile device communicates directly via a wireless link with other resources. Based on a Wi-Fi link, a mobile device communicates via a wireless link with a Wi-Fi AP that again provides either a tethered connection or a wireless connection to other resources. Furthermore, a Wi-Fi AP typically provides via a WAN connectivity to the Internet. Last, based on a cellular link, a mobile device communicates with the Internet via a mobile communication network like the Third Generation (3G) and via fixed networks like the backbone network of a network provider.

3.4. Failure Model

Regarding the system components and their interplay for code offloading, each system component can fail at any time influencing differently the process of code offloading. The underlying failure model of this dissertation includes crash failures with eventually recovery of the offloading client, the offloading service, and the communication network.

For the offloading client, an occurrence of a crash failure disturbs a current execution of an application with its application parts. At a disturbance of a current execution of an application, an end user has to restart the application execution. Restarting an application in case of an unexpected interruption, recovery mechanisms of an operating system have to handle an occurrence of such failures. Due to recovery mechanisms implemented on an operating system, crash failures on an offloading client are out of scope of this dissertation and thus not considered in the design of a related system for code offloading. Please note that despite the occurrence of a crash failure on the offloading client during a remote execution of an application part, an end user has to pay for the utilization of the offloading service and the communication network.

For the offloading service, an occurrence of a crash failure also disturbs a current execution of an application part. Executing an application part on behalf of an offloading client, the quality of recovery mechanisms influence the efficiency of an offloading service. Owing to a failure near the end of a remote execution, for instance, a total restart of a remote execution almost doubles the waiting time, energy consumption, and monetary cost for an offloading client. To this end, the design of a related system

for code offloading considers crash failures for the offloading service.

For the communication network, an occurrence of a crash failure on a link that connects an offloading client and an offloading service disturbs the communication between both. Disturbing the communication between an offloading client and an offloading service also influences the efficiency of an offloading client. Owing to the mobility of an offloading client, for instance, an interference due to incomplete network coverage that last for several seconds or longer delays a sending of an input execution state or a receive of an output execution state. To this end, the design of a related system for code offloading considers crash failures for the communication network.

3.5. System Requirements

The realization of a system for code offloading that distributes application parts from an offloading client like a (resource-poor) mobile device to an offloading service like a (powerful) remote server instance at the cloud arises the following key requirements:

Adaptation: Due to the mobility of mobile devices, the current situation for code offloading changes constantly. Thus, a system for code offloading should adapt dynamically to varying parameters related to device, user, environment, application, or network by re-considering a made offload decision.

Efficiency: Due to the resource poverty of mobile devices, a system for code offloading should use sparingly local resources on an offloading client and links from a communication network, keeping the overhead introduced low. The sparing utilization of resources and links includes, for instance, an efficient monitoring of the current situation and the transmission of only required data.

Experience: Due to the general correlation of success for a system and the user experience, a system for code offloading should keep the burden for end users and application developers low, relying on least interventions from both developers and end users. A high level of automation combined with minimal information where necessary convince developers and end users, creating acceptance and applicability for a system.

Feasibility: For the feasibility of code offloading, a system for code offloading should guarantee the equality of a distributed execution for an application on an offloading client and offloading services with a monolithic execution for an application on an

offloading client. A location-transparent execution of applications results in equal execution states, no matter whether it is a monolithic execution or a distributed execution.

Heterogeneity: Due to the heterogeneity of participating offloading clients and offloading services, a system for code offloading should support different hardware platforms like smart phones, laptops, or server instances at the fog or at the cloud. The abstraction from different Instruction Set Architectures (ISAs) like x86 vs. ARM and 32-bit vs. 64-bit is fundamentally to support a vast number of participants.

Scalability: Due to the availability of multiple offloading services at different tiers, a system for code offloading should scale horizontally and vertically. To this end, it scales not only offloading services at one layer like the cloud but also supports multiple offloading services from different tiers like the fog and the cloud. The support of multi-tier architectures on behalf of only the classic two-tier architectures increases the efficiency of code offloading.

Seamless Execution: Due to the distributed nature of code offloading, a system for code offloading should enable a seamless execution of distributed application parts, handling automatically the occurrence of failures. An applicable failure handling increases not only the efficiency but also the acceptance of code offloading.

3.6. Summary

To provide code offloading in the landscape of Mobile Cloud Computing, the *system model* described in Section 3.1 presents a general system model for a distribution with multiple resources. It includes performance characteristics and cost implications for resources that distribute application parts to other resources and resources that offer the processing power to other resources. Based on the system model, the *problem statement* described in Section 3.2 minimizes a cost function to determine the optimal resource for an execution of an application part that is offloadable. The cost function is a weighted sum of the execution time, energy consumption, and monetary cost for an application part on a resource. Thus, it regards the trade-off between the cost for a local execution and for a remote execution. The local cost comprises the execution time and energy consumption for a local execution on an offloading client, whereas the remote cost comprises the execution time, energy consumption, and monetary cost for a remote execution on an offloading service. Both the offloading client and the offloading service are parts of the *system components* described in Section 3.3,

communicating via a communication network with each other. The communication network typically consists of a wireless network and fixed networks, where an offloading client offloads computation via the communication network to an offloading service. Following Finagle's Law of Dynamic Negatives "If anything can go wrong, it will." [Chi63], each system component might fail. To this end, the *failure model* for code offloading presented in Section 3.4 involves crash failures with eventually recovery for an offloading client, an offloading service, and the communication network. Resulting from previous discussions, the *system requirements* described in Section 3.5 include key features and functionality of a system for code offloading.

Chapter 4

Efficient Code Offloading with Annotations

This chapter presents a basic distribution for code offloading with annotations. It supports the offloading of computation from an offloading client running on a (resource-poor) mobile device to an offloading service running on a (powerful) remote resource. As the mobile device runs the system for the basic distribution on its hardware platform, the system has to use sparingly local resources, keeping the overhead introduced low. It also has to keep the burden on application developers and end users low, being applicable with a high user experience. To this end, Section 4.1 first gives a brief overview of a basic distribution between a mobile device and a remote resource before Section 4.2 gives the system overview for the basic distribution, including the system model, the problem statement, and the system components. Due to the utilization of a runtime-layer distribution for code offloading, Section 4.3 describes the typical software stack and functionality for a runtime environment, utilized by the offloading client and offloading service. The offloading timeline in Section 4.4 outlines the interplay between an offloading client and an offloading service to realize the basic distribution for computation offloading. Providing the corresponding functionality for an offloading client and an offloading service, Section 4.5 describes the offloading framework required for the basic distribution. To evaluate the performance of the basic distribution, Section 4.6 presents the implementation of prototypes based on the Java platform, where this dissertation utilizes different Java implementations. Afterwards, Section 4.7 presents the evaluation of the basic distribution based on three prototypes, including the evaluation setup and the evaluation results. Last, Section 4.8 summarizes the main facts of the efficient code offloading with annotations presented in this chapter.

4.1. Basic Distribution

The key feature of "mobility" from mobile computing is simultaneously its main challenge, requiring techniques like code offloading. It also influences the design and per-

formance of a mobile device and of the systems running on a mobile device. Compared to stationary computing devices like workstations or server instances, a mobile device is a resource-poor computing environment related to performance like execution speed and battery. As a result, energy efficiency plays an important role for a mobile device and thus, for its systems like a distribution system for code offloading.

In the literature, approaches for code offloading propose either an automatic partitioning of an application at development-time (cf. CloneCloud from Chun et al. [CIM+11]), an annotation of application parts by an application developer (cf. MAUI from Cuervo et al. [CBC+10]), or a manual distribution of application parts by an application developer based, for instance, on a Remote Procedure Call (cf. RPC from Kristensen [Kri10]). An automatic partitioning of an application at development-time keeps an application developer out of business but puts a high complexity on a distribution system. It requires a full-automatic system-layer distribution that plans a huge set of possible future situations in advance. An annotation of application parts that are feasible for a distribution increases the burden on an application developer but reduces the complexity of a distribution system. It requires an half-automatic runtime-layer distribution that profits from application knowledge of an application developer. Last, a manual distribution of application parts has the highest burden on an application developer but the lowest complexity on a distribution system. It requires a developer-manual application-layer distribution that fully depends on the knowledge from an application developer.

To this end, our deployment of a distribution system for code offloading faces the trade-off between the overhead introduced to a system and the interventions required from an application developer. It utilizes a runtime-layer distribution with the annotation of application parts that are offloadable by the application developer like Cuervo et al. [CBC+10]. This little application-specific knowledge from an application developer goes far [FSS02], reducing noticeably the complexity of our distribution system. In detail, it relies on an annotation-based instrumentation of the portable code (instructions) from an application part based on a runtime environment. An application developer annotates at development-time an application part that is offloadable, marking it as a suitable candidate for a remote execution. A suitable candidate does not rely on further resources like a local sensor except the processing power for an execution of its portable code. Furthermore, it possesses a low size of information required for a remote execution, a long running remote execution, and a low size of output information received after the remote execution. During the compilation of the source code to platform-independent portable code at development-time, an offload-aware compiler introduces offload-specific portable code for application parts annotated as offloadable

from an application developer. At run-time, the offload-specific portable code invokes at its execution an offload-aware controller that afterwards handles a distribution of the application part that is offloadable.

Summarizing, the annotation-based instrumentation of the portable code (instructions) for a distribution system keeps both the overhead introduced to a mobile device and the burden on an application developer low. In detail, our deployment invokes automatically an offload-aware controller for application parts that are feasible for a distribution based on the offload-specific portable codes introduced by the offload-aware compiler. The automatic invocation avoids, for instance, a monitoring of system information while a mobile device executes an application. Just relying on the annotation of an application part that is feasible for a distribution, our deployment hides the distributed and parallel nature of a remote execution from an application developer by automatically distributing application parts without further interventions. Nevertheless, it keeps an application developer aware of a possible distribution benefiting from application-specific knowledge from the application developer.

4.2. System Overview

The basic distribution offloads computation in the two-tier architecture (cf. Subsection 2.5.2), where each tier has one resource. The first tier consists of a (resource-poor) mobile device $\Xi(\xi_k)$ and the second tier consists of a (powerful) server instance at the cloud $\Xi(\xi_m)$. Thus, it reduces the system model of multiple tiers with multiple resources into two tiers with a resource each. The performance characteristics and cost implications for the two resources stay the same from the general system model defined in Section 3.1. The same applies to the definition for an application, where the basic distribution utilizes the model defined in Section 3.1.

Like the system model, the problem statement for the basic distribution also reduces from multiple tiers with multiple resources into two tiers with a resource each. Thus, it still minimizes the cost function f_w from Equation 3.1 but only for two resources resulting in the trade-off between cost for a local execution on resource $\Xi(\xi_k)$ and cost for a remote execution on resource $\Xi(\xi_m)$:

$$\min \; I \cdot f_w(A_{\alpha_o}, \Xi(\xi_k)) + (1 - I) \cdot f_w(A_{\alpha_o}, \Xi(\xi_m)) \tag{4.1}$$

where I equals 1 in case of a local execution and I equals 0 in case of a remote execution.

The system components for the basic distribution corresponds to the system components described in Section 3.3 – namely an offloading client (cf. Subsection 3.3.1),

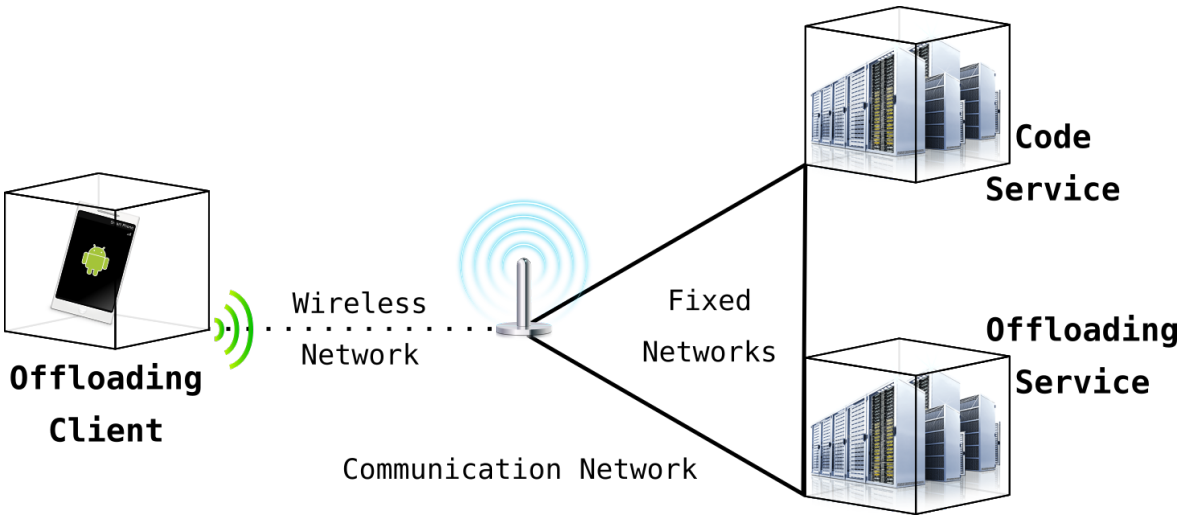
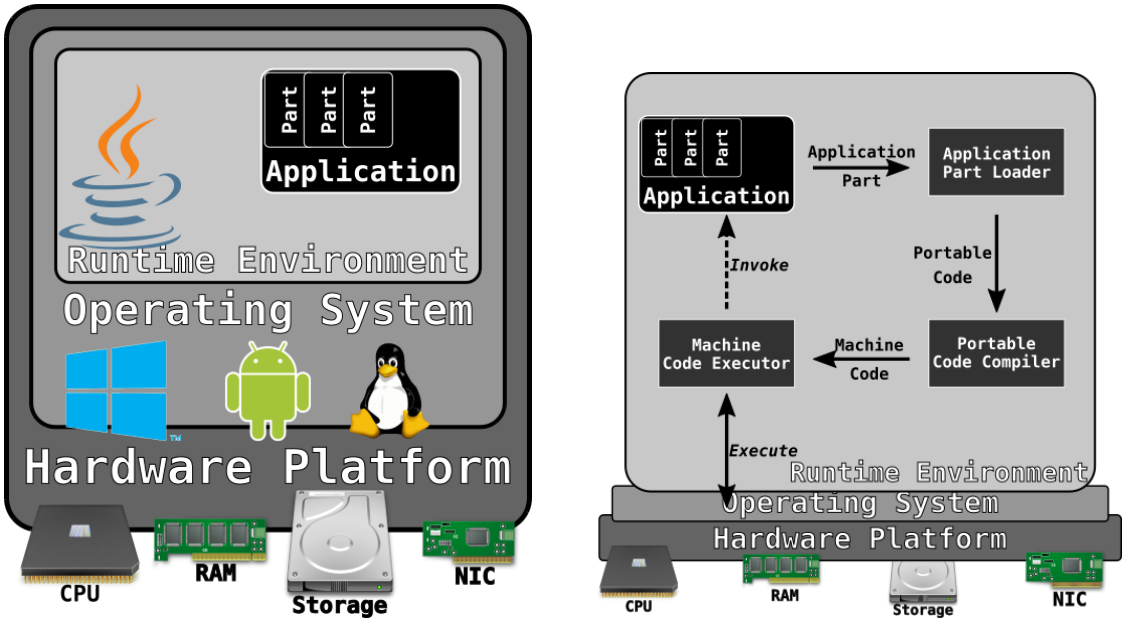


Figure 4.1.: The system components for the basic distribution, where an offloading client offloads computation via a communication network to an offloading service. Moreover, a code service disseminates portable code of applications to clients and services.

an offloading service (cf. Subsection 3.3.2), and a communication network (cf. Subsection 3.3.3) – and an additional code service (cf. Figure 4.1). A code service stores portable code of applications for dissemination among mobile devices (cf. the Google Play Store), hosted at a server instance at the cloud. An end user downloads the portable code for an application from the code service and installs the application on its mobile device only once. In order to relieve an offloading client on a mobile device from sending the portable code for an application part via the communication network, an offloading service also downloads the portable code for an application from the code service. To this end, an offloading service either downloads pro-actively the portable code for an application from the code service or downloads it from the code service at the first time an offloading client distributes an application part for a related application. As a fixed network connects an offloading service and a code service with each other, an offloading service downloads the portable code for an application very fast, where the download time is negligible. Like an offloading service, a code service might suffer from crash failures with eventually recovery, resulting in an unavailability of the service (cf. Section 3.4). Due to the location at the cloud, a code service utilizes automated failover mechanisms like service redundancy, typically found in a (cloud) data center. Such failover mechanisms are commonly applied and automatically handle crash failures, being out of scope of this dissertation and not considered subsequently.



(a) The software stack of a resource executing portable code from an application.

(b) The essential components of a runtime environment to execute portable code.

Figure 4.2.: Overview of (a) the software stack and (b) the run-time environment on a resource to execute portable code from an application.

4.3. Runtime-layer Offloading

The basic distribution presented in this chapter utilizes a runtime-layer distribution with annotations to offload computation from an offloading client to an offloading service. As both the offloading client and the offloading service extends the basic functionality provided by a runtime environment, this section introduces the typical functionality provided by a runtime environment to execute portable code on a resource. To this end, Subsection 4.3.1 first gives an overview of the software stack and functionality of a runtime environment, before Subsection 4.3.2 describes the functionality for an offloading client and Subsection 4.3.3 for an offloading service. Last, Subsection 4.3.4 gives an overview of the Java platform with its Java Runtime Environment (JRE), extended in this dissertation for code offloading.

4.3.1. Overview

Figure 4.2a shows the software stack of a resource like a smart phone, a laptop, or a server machine, running on the hardware platform. The hardware platform typically consists of multiple components like a Central Processing Unit (CPU), a Random Access Memory (RAM), storage, and a Network Interface Card (NIC). These underlying components of the hardware platform differ in capabilities and properties like the ISA

of a CPU (e.g., an x86 vs. ARM vs. PowerPC architecture with a 32-bit vs. 64-bit instruction set). To manage the hardware platform and enable the execution of software components, a resource executes an operating system like Windows, Linux, or Android, specialized to the components of the hardware platform. Due to different capabilities and properties of the hardware platform as well as the operating system, an application developer has to explicitly compile its application for a combination of a hardware platform and an operating system. To avoid an explicit compilation and abstract from an actual combination of a hardware platform and an operating system, the operating system executes a runtime environment like the Java Runtime Environment (JRE). The runtime environment enables an execution of applications written in platform-independent portable code, where an application consists of (multiple) parts like threads, components, or methods.

To execute the platform-independent portable code of an application part on a resource (cf. Figure 4.2b), the runtime environment has an application part loader. The application part loader loads an application part by extracting its portable code and forwarding it to the portable code compiler. The portable code compiler compiles the platform-independent portable code to platform-dependent machine code and forwards it to the machine code executor. The machine code executor executes the machine code on the actual hardware platform, where the execution of an application part can require further application parts. In this case, the machine code executor invokes the required application part, again starting its loading, compilation, and execution.

To offload an application part from a hardware platform (e.g., mobile device) to another hardware platform (e.g., server instance at the cloud) based on a runtime environment, the offloading client as well as the offloading service extend the above-described functionality of a basic runtime environment.

4.3.2. Offloading Client

Figure 4.3 shows the runtime environment of the offloading client, where a decision maker, a monitor, and a communicator extend the functionality required to distribute an execution of application parts to an offloading service. To this end, the application part loader forwards the platform-independent portable code from an application part to the decision maker. The decision maker decides whether to execute an application part on the local hardware platform or on the remote hardware platform of an offloading service. To determine the execution side of an application part, the decision maker minimizes the cost function f_w from Equation 4.1, where the decision requires parameters about the current situation like network quality. As a result, the monitor

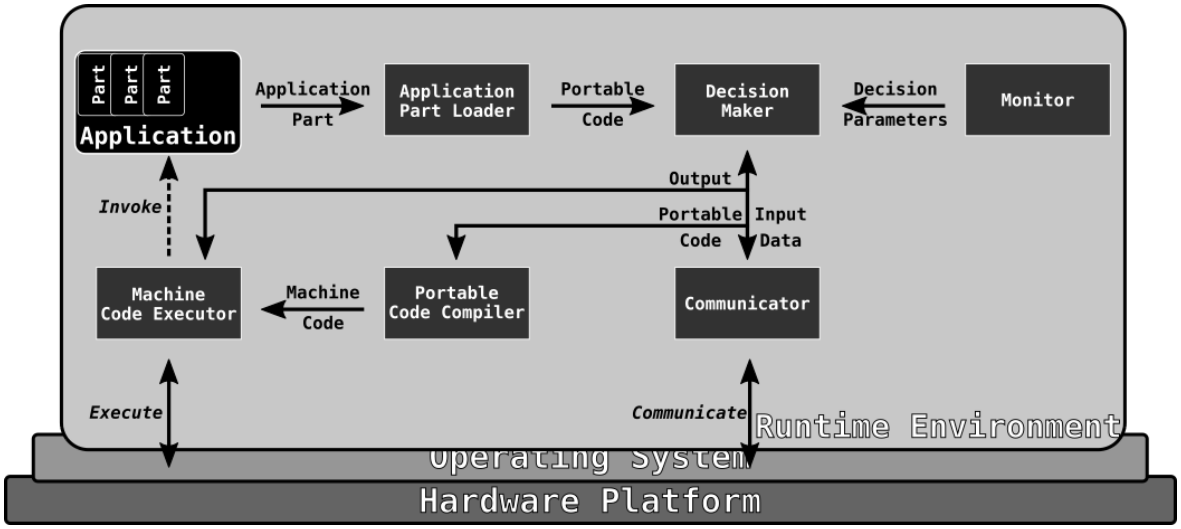


Figure 4.3.: The extended runtime environment for the offloading client enabling code offloading by utilizing a decision maker, a monitor, and a communicator.

monitors the parameters required for a decision and forwards them to the decision maker to determine the execution side. In case of a local execution of an application part, the decision maker forwards the platform-independent portable code to the portable code compiler, entering the process of compilation and execution on the local hardware platform. In case of a remote execution of an application part, the decision maker forwards the platform-independent portable code and the input execution state to the communicator. The communicator is responsible for the communication to an offloading service, sending the portable code and the input execution state to the offloading service. During a remote execution of an application part on an offloading service, the communicator waits for the end of a remote execution, receiving the output execution state of a remote execution. Receiving an output execution state of a remote execution from an offloading service, the communicator forwards it to the machine code executor. Afterwards, the machine code executor installs the output execution state of a remote execution on the local hardware platform and continues the execution of the application just as for a local execution of the application part.

4.3.3. Offloading Service

Figure 4.4 shows the runtime environment of the offloading service, where a communicator extends the functionality required to execute an application part on behalf of an offloading client. To this end, the communicator receives the platform-independent portable code and the input execution state of an application part from an offloading client. Possessing the portable code and the input execution state required for a remote

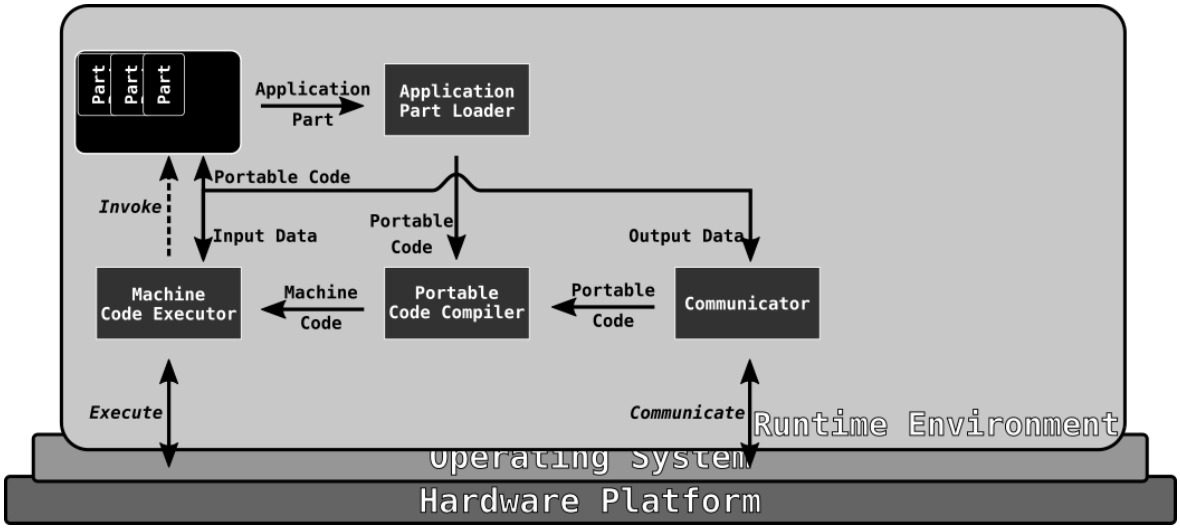


Figure 4.4.: The extended runtime environment for the offloading service enabling code offloading by utilizing a communicator.

execution, it forwards the portable code to the portable code compiler and the input execution state to the machine code executor. The portable code compiler compiles the platform-independent portable code to platform-dependent machine code and forwards it to the machine code executor. The machine code executor first installs the received input execution state, before it starts an execution of the machine code on its hardware platform based on the input execution state. At the end of an execution of an application part on the offloading service, the machine code executor forwards the output execution state to the communicator that sends it to the waiting offloading client. Afterwards, the offloading service waits for further requests from offloading clients, starting again a remote execution of an application part.

4.3.4. Java Platform

The Java programming language is a general-purpose programming language with key properties like an object-oriented design, safety, concurrency, and portability. Taking a closer look at the portability, the famous slogan “write once, run everywhere” [Tim97] from Sun Microsystems emphasizes the design goal of platform independence of the Java programming language. In detail, a Java application compiled once from an application developer runs without a recompilation on any combination of hardware platforms and operating systems that support an adequate Java platform. Achieving this platform independence of the Java programming language, a Java platform compiles the code of a Java application to Java bytecode instructions. The Java bytecode instructions are an intermediate representation of code that runs on any architecture

compared to architecture-specific machine code. Due to the intermediate representation of Java bytecode instructions, a Java platform executes the cross-platform instructions on a run-time environment, compiling the intermediate representation of Java bytecode instructions to architecture-specific machine code at run-time.

A Java platform is responsible for the development of a Java application written in the Java programming language as well as the execution of its cross-platform instructions. For the execution of the cross-platform instructions, an end user utilizes a JRE, particularly implemented for a combination of a hardware platform and an operating system. The JRE comprises a set of components required for an execution like an implementation of a Java Virtual Machine (JVM) and Java class libraries. An application developer utilizes a Java Development Kit (JDK) that extends the functionality of a JRE with development tools. Based on the development tools like the Java Compiler `javac`, an application developer compiles Java source code to Java bytecode instructions at development-time. At run-time, a Just-In-Time (JIT) compiler from a JVM of a JRE compiles on demand the intermediate Java bytecode instructions to native machine code. Due to an extensive set of Java class libraries, a Java application can access particular features from hardware platforms or operating systems.

To this end, a Java platform abstracts from the actual hardware platform and software stack, providing a platform-independent execution of applications written in the Java programming language. At development-time, it compiles a Java application to the intermediate representation of Java bytecode instructions that it further compiles to architecture-specific machine code at run-time. To provide a platform-independent execution of Java bytecode instructions, a Java platform consists of a Java Virtual Machine, a predefined set of Java bytecode instructions, and Java class libraries.

Java Virtual Machine: Although the Java bytecode instructions are platform-independent, each particular combination of a hardware platform and an operating system requires its own implementation of a Java Virtual Machine (JVM). To ensure a semantic interpretation of Java bytecode instructions in the same way, different implementations of a JVM have to meet the formal requirements of the JVM specification [LYBB15]. Due to the utilization of a single specification, all implementations are interoperable no matter of underlying hardware or software. Thus, each JVM is able to execute a Java application due to the execution of the intermediate Java bytecode instructions.

Figure 4.5 shows the internal architecture for a JVM to execute an application written in the Java programming language. Typically, a Java application consists of (multiple) Java classes, where a Java class is an organizational unit possessing a number of Java bytecode instructions as well as auxiliary information for its processing like a symbol

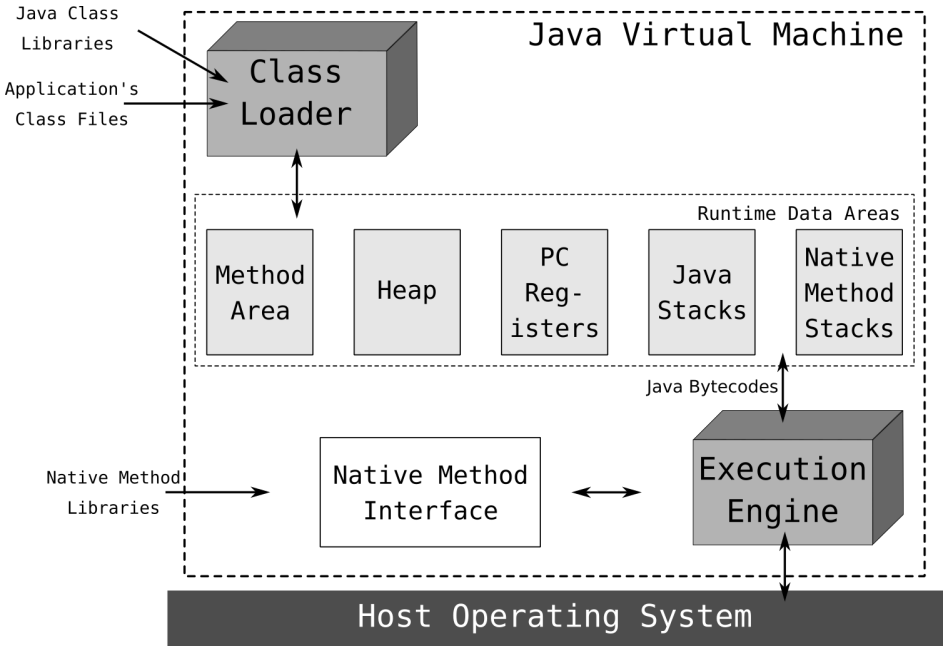


Figure 4.5.: Overview of the internal architecture for a Java Virtual Machine. [Venry]

table. At development-time, the Java compiler `javac` compiles a Java class to a binary format, representing the Java class independently from the underlying platform. At run-time, a JVM dynamically loads a Java class – that confirms to the Java class file format – from a Java application with the help of a class loader. Beside loading classes from a Java application, the class loader is also responsible for locating a Java class library, reading its content and loading the related classes within the library. Notice that the class loader only loads a Java class on demand, once a Java application calls a corresponding Java class. Possessing the Java bytecode instructions for a Java class, a JVM executes the Java bytecode instructions with the help of an execution engine. The execution engine corresponds to an abstract computing machine that translates at run-time the Java bytecode instructions to native machine code instructions based on, for instance, a JIT compiler. Afterwards, it executes the machine code instructions on the host operating system. The execution engine stores required information like translated instructions, instantiated objects, method parameters, or intermediate results in the runtime data areas. The runtime data areas include one method area, one heap, pc (program counter) registers, Java stacks, and native method stacks. A JVM has only one method area and one heap, shared by all Java threads from a Java application. It stores information from a loaded Java class file like type information in the method area and allocates memory in the heap for new objects like class instances or arrays. Each Java thread has its own pc register and Java stack. A pc register indicates the execution of the next Java bytecode instruction for a Java method and the Java stack

stores state information for an execution of a Java method. The state information includes method parameters, local variables, return value, intermediate computations, and further data. In detail, the Java stack comprises for each Java method a stack frame containing the state information for a Java method. A JVM pushes a new stack frame at the call of a Java method onto the Java stack and pops the current stack frame at the end of a Java method discarding its state information. A Java method completes either by returning properly or by throwing an exception. Last, a JVM has native method stacks to store information about the state for native methods executed through a native method interface. The native method interface provides the capability for a JVM to execute platform-dependent native methods on host operating systems.

Java Bytecode Instructions: The Java bytecode instructions are platform-independent instructions, representing the instruction set of a JVM. A Java bytecode consists of one or more bytes. The first byte identifies uniquely the instruction (opcode) and the further bytes, if any, are parameters for the instruction. Thus, there are in total 255 Java bytecode instructions available, of which a JVM uses currently 198 instructions (cf. Appendix A). In detail, they provide functionality like loading and storing of data (cf. Table A.1), arithmetic operations, logic operations, and type conversions (cf. Table A.2), and object creation, object manipulation, operand stack management, control transfer, method invocation, method return, exception throwing, and monitor-based concurrency (cf. Table A.3). Out of the other 57 instructions, the JVM specification reserves 54 for future use and set 3 as permanently unimplemented. [LYBB15]

The Java bytecode instructions operate on certain data types, categorized into a set of *primitive types* and a *reference type*, holding primitive values and reference values, respectively. The primitive types are `boolean` (8-bit signed), `byte` (8-bit signed), `char` (16-bit signed), `short` (16-bit signed), `int` (32-bit signed), `long` (64-bit signed), `float` (32-bit signed), and `double` (64-bit signed). The reference type is a reference (32-bit or 64-bit) for class types, interface types, array types, and so on.

Java Class Libraries: Due to the platform independence of a Java platform, a Java application cannot rely on specific functions of a platform-native library. To this end, the Java class libraries provide to a Java application the common functionality of modern operating systems. They are a comprehensive, well-known set of reusable functions, relying heavily on the underlying hardware platform and operating system. At run-time, a JVM loads dynamically the Java class libraries on demand to realize common tasks like networking or file handling. For an application developer, the Java class libraries are an abstract interface to platform-dependent tasks.

4.4. Offloading Timeline

First of all, an application developer implements a Java application that consists at least of a Java class with a `main` method (cf. Subsection 4.3.4). Commonly, a Java application consists of multiple Java classes containing multiple Java methods (application parts). A Java method typically encapsulates a required functionality of a Java application. Possessing a Java method that is feasible for a remote execution, an application developer annotates it with the annotation `Offloadable` (cf. Listing 4.1):

```
1  public class HelloWorld {
2     public static void main(String[] args) {
3        // Prints the String "Hello, World!" to the console
4        System.out.println("Hello, World!");
5
6        float flt = dstrbtblMthd(args);
7        System.out.println("Computation finished: " + flt);
8     }
9
10    @Offloadable
11    public static float dstrbtblMthd(String[] args) {
12       float result = 0.0F;
13
14       // Long running computation
15       ...
16
17       return result;
18    }
19 }
```

Listing 4.1: The Java source code of an extended "Hello, World"-application that contains a Java method that is offloadable.

After the implementation of a Java application and a (possible) annotation of Java methods as "offloadable", an application developer compiles the Java source code of an application with the program `javac`, the JAVA Compiler. It translates Java source code from an application into platform-independent Java bytecode instructions. To this end, we extended `javac` to introduce at development-time offload-specific Java bytecode instructions for a Java method annotated with `offloadable`. During this translation of Java source code into Java bytecode instructions, it introduces an offload-specific Java bytecode instruction at the start of a Java method annotated with `offloadable` and another one at each end of the Java method (cf. Subsection 4.5.1).

After the compilation of a Java application and a dissemination via a code service to mobile devices, an end user can start an execution of a Java application on its mobile device. Please note that usually an end user downloads and installs an application on its mobile device from a code service only once, before the first execution of an application (cf. Figure 4.6). Through a start of a Java application, an operating system on a mobile device runs a JRE extended for the basic distribution by an offloading framework (cf.

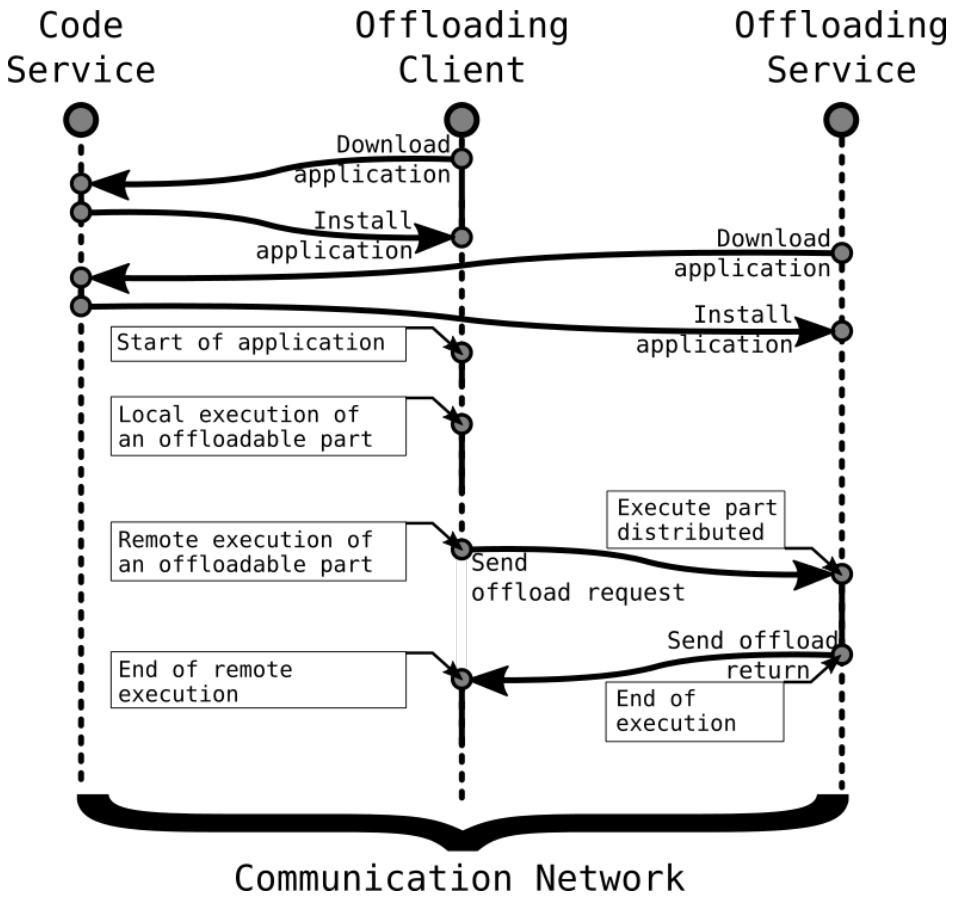


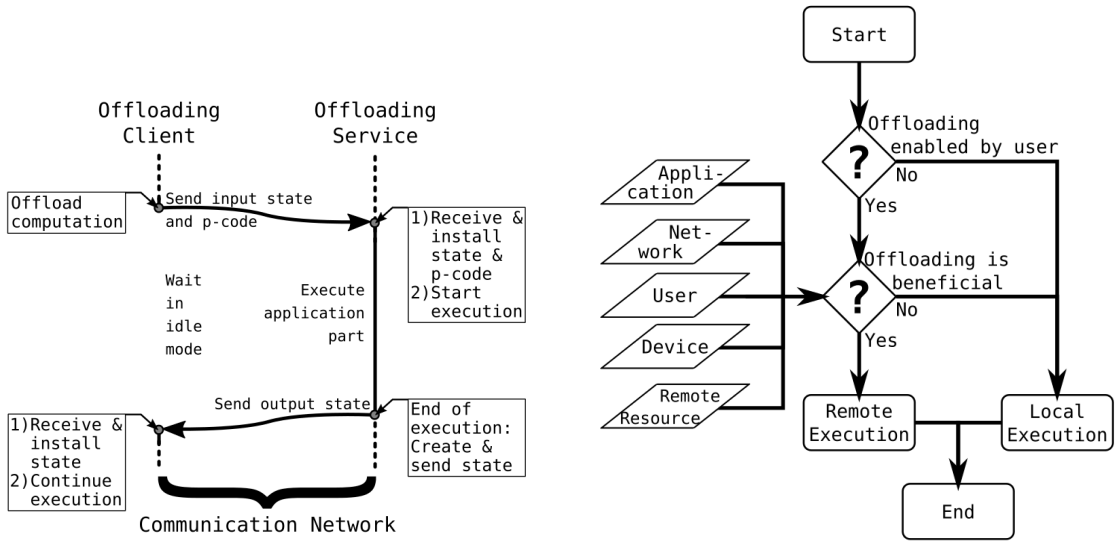
Figure 4.6.: Offloading timeline of the basic distribution for an application part between an offloading client and an offloading service via a communication network. Both download and install the application from a code service.

Section 4.5). Beside typical components of a JRE for an execution of a Java application (cf. Subsection 4.3.4), the extended JRE also starts the additional components of the offloading client required for the basic distribution (cf. Subsection 4.5.2). Afterwards, it executes the Java application by invoking its `main` method that again invokes further Java methods, communicating with each other.

After the invocation of a Java method on the offloading client, an execution of platform-independent Java bytecode instructions requires a compiler that translates Java bytecode instructions to platform-dependent machine code during run-time. Due to the introduction of offload-specific Java bytecode instructions at development-time, we extended the standard Java compiler of a Java Virtual Machine (cf. Subsection 4.5.1). The extension comprises the translation of offload-specific Java bytecode instruction to platform-dependent machine code at run-time. The execution of translated machine code invokes the execution controller of the offloading client (cf. Section 4.5.2). Subsequently, the execution controller invokes the offload controller of the

offloading client, informing the offload controller of the call of a Java method annotated with `offloadable` by an application developer.

After the invocation of the offload controller on the offloading client, the offload controller decides whether to distribute the called Java method to an offloading service (cf. Figure 4.6). To this end, it minimizes the cost function in Equation 4.1, requiring information about the application, the network, the user, the device, and the remote resource (cf. Figure 4.7b). The information about the application comprises the input execution state of the Java method, the execution time of the Java method on the local resource and on the remote resource, as well as the size of the output execution state of the Java method. To retrieve the input execution state, the execution controller on the offloading client gathers the input execution state from the local resource, having direct access to the Java stack (cf. Subsection 4.5.2). The input execution state comprises the method parameters, the member values of the class declaring the method, and the static members of all classes reachable. To retrieve the execution time on the local and remote resource, the app profiler on the offloading client builds a profile model based on past invocations. To this end, it requires the input execution state together with the Java bytecode instructions of the called Java method. The app profiler retrieves the Java bytecode instructions from the execution controller that has access to the declaring class of a Java method. Based on the profile model built, the offload controller on the offloading client predicts the execution time for an execution on the local resource and on the remote resource. The same applies to the prediction for the size of the output execution state, where the app profiler builds another profile model based on past invocations. For this, it requires the input execution state together with the size of the output execution state. The information about the network comprises the link bandwidth and link latency to the remote resource. Possessing the link bandwidth and link latency, the offload controller on the offloading client determines the duration for sending the input execution state to the remote resource as well as for receiving the output execution state from the remote resource. To retrieve the link bandwidth and link latency, the network monitor on the offloading client monitors both to the remote resource. The information about the user comprises the user-defined weights for the execution time, the energy consumption, and the monetary cost. To retrieve the user-defined weights, the user interface on the offloading client provides an interface for the user to enter the weights. The information about the device comprises factors for the energy consumption and for the performance of the mobile device. To retrieve the factors for the energy consumption, the device interface on the offloading client provides an interface for the device manufacturer to enter the device-specific factors. To retrieve the factor for the performance, the device benchmark on the offloading client



(a) Detailed timeline for a remote execution of an offloadable application part.

(b) Flow of decision making for code offloading of an offloadable application part.

Figure 4.7.: Overview of (a) the timeline and (b) decision making for code offloading.

benchmarks the local performance of executing Java bytecode instructions. Last, the information about the remote resource comprises factors for its monetary cost and for its performance. To retrieve the factors for the monetary cost and the performance, the service monitor on the offloading client creates a resource request, requesting the factors from an offloading service. Afterwards, it forwards the resource request to the service connector on the offloading client. The service connector handles the communication to the remote resource and thus, sends the resource request to the offloading service.

Upon the receipt of a resource request at the client connector on the offloading service, the client connector requests the factors of the performance and the monetary cost from the offload controller (cf. Subsection 4.5.3). The offload controller on the offloading service retrieves the factor for the performance from the device benchmark and the factors of the monetary cost from the provider interface. To retrieve the factor for the performance, the device benchmark on the offloading service benchmarks the local performance of executing Java bytecode instructions. To retrieve the factors for the monetary cost, the provider interface on the offloading service provides an interface for the provider of the remote resource to enter the resource-specific factors. Possessing the factors for the performance and the monetary cost of the remote resource, the offload controller on the offloading service forwards the factors to the requesting client connector. The client connector on the offloading service first creates a resource response that contains the factors, before it sends the resource response to the service connector of the offloading client.

After the offload controller on the offloading client possesses all of the information required to minimize the cost function, it determines the execution side of the called Java method. In case of a local execution of the Java method, the offload controller on the offloading client just continues the local execution of the Java method by returning its invocation that again returns the invocation of the execution controller. In case of a remote execution of the Java method (cf. Figure 4.6), the offload controller forwards the input execution state of the Java method to the service connector and waits for a response from it. Receiving the input execution state from the offload controller, the service connector creates an offload request – containing the input execution state of the Java method – and sends it to the client connector on the offloading service.

Upon the receipt of an offload request on the client connector of the offloading service, the client connector forwards the input execution state to the offload controller (cf. Subsection 4.5.3). The offload controller on the offloading service forwards the input execution state to the execution controller that installs the state on the computing resource and starts the execution of the Java method by calling the Java method with its method parameters contained in the input execution state.

After the execution of the offload request on the offloading service, the execution of the offload-specific Java bytecode instruction invokes the execution controller. The execution controller gathers the output execution state of the Java method. It comprises the information of an input execution state, the return value of the Java method, and the value for the register with the "ByteCode Index" (`bci`) for the execution. The `bci` register indicates the index of the Java bytecode instruction executed next. It holds at the end of the execution the Java bytecode instruction executed last like a `return` instruction. Possessing the output execution state of the Java method, the execution controller forwards it to the offload controller that again forwards it together with the monetary cost of the execution to the client connector. The client connector creates an offload response – containing the output execution state and the monetary cost – and sends it to the service connector of the offloading client.

Upon the receipt of an offload response on the service connector of the offloading client, the service connector forwards the output execution state and the monetary cost to the offload controller (cf. Subsection 4.5.2). The offload controller forwards the output execution state to the execution controller and pays the monetary cost charged from the offloading service. The execution controller installs the information in the output execution state on the Java stack and jumps to the last Java bytecode instruction of the Java method. Due to the jump to the last Java bytecode instruction, the local execution returns the Java method with the return value contained in the output execution state and continues the execution of the Java application.

4.5. Offloading Framework

The offloading framework provides the functionality for the basic distribution between an offloading client and an offloading service on the Java platform. The offloading framework requires an extension of the standard Java compiler of the Java platform to translate the offload-specific Java bytecode instructions at development-time as well as at run-time (cf. Subsection 4.5.1). Moreover, the offloading client (Subsection 4.5.2) as well as the offloading service (Subsection 4.5.3) of the offloading framework extend the functionality provided by a JRE.

4.5.1. Extended Java Compiler

The JAVA Compiler (`javac`) is responsible to translate the Java source code of a Java application into platform-independent Java bytecode instructions at development-time (cf. Subsection 4.3.4). As an application developer marks Java methods feasible for a remote execution with the annotation `offloadable`, `javac` has to know this offload-specific annotation and how to handle it. To this end, we extended `javac` to instrument Java bytecode instructions for an efficient identification of annotated Java methods. For an annotated Java method, it introduces the offload-specific Java bytecode instructions `offload` and `offload_end` during the translation of Java source code into Java bytecode. In detail, it inserts `offload` at the start of the method body as the first executed Java bytecode instruction. Knowing the start of an execution of a Java method that is offloadable, the Java bytecode instruction `offload_end` marks the end of its execution. Thus, `javac` inserts it before each end of the method body. Execution ends are a return Java bytecode instruction – `return`, `ireturn`, `lreturn`, `freturn`, `dreturn`, or `areturn` – or a Java bytecode instruction throwing an exception like `athrow` (cf. Appendix A). Executing `offload_end` right before the last Java bytecode instruction of a Java method, the offloading framework gathers the execution state just before the execution of the last instruction destroys the execution state.

4.5.2. Offloading Client

Figure 4.8 shows the runtime environment of the offloading client, providing the client-side functionality for the basic distribution. It consists of an offload compiler, an execution controller, a state generator, an app profiler, a network monitor, a network interface, a user interface, a device interface, a device benchmark, a service monitor, a service connector, and an offload controller.

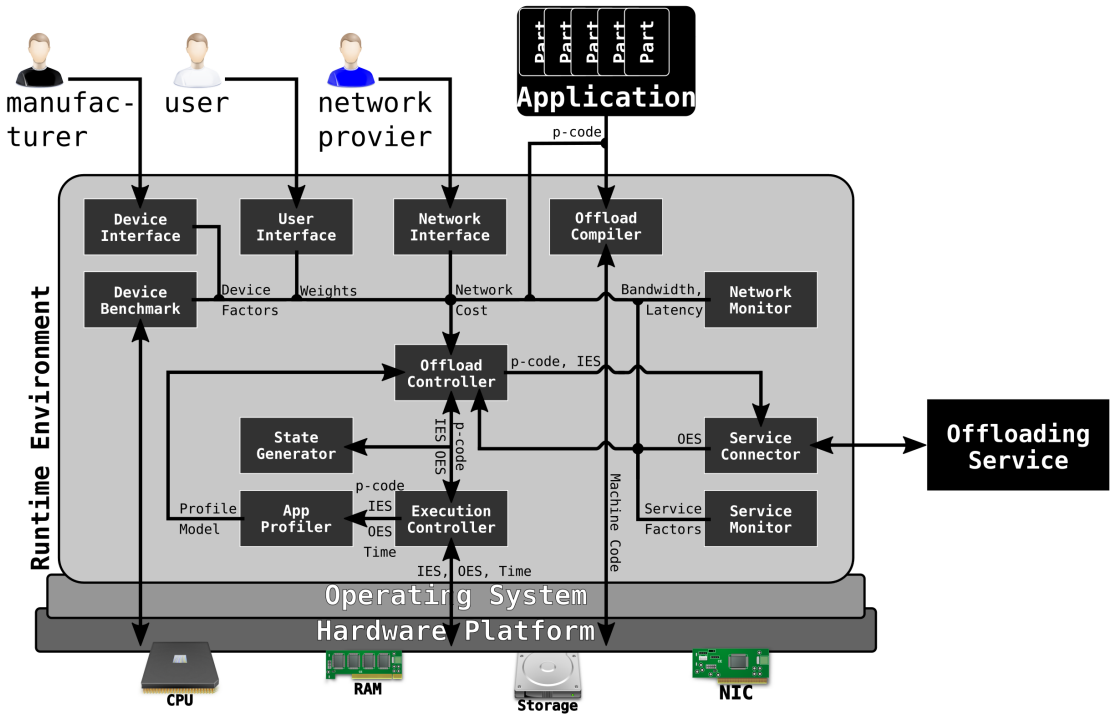


Figure 4.8.: The runtime environment on the offloading client for the basic distribution of an application part to an offloading service.

Offload Compiler: The standard Java compiler is responsible to translate platform-independent Java bytecode instructions into platform-dependent machine code at runtime (cf. Subsection 4.3.4). As `javac` introduces the offload-specific Java bytecode instructions `offload` and `offload_end` at development-time, a standard Java compiler of a Java implementation has to know how to translate these Java bytecode instructions to machine code. To this end, we extended the standard Java compiler to an offload compiler. It translates the two offload-specific Java bytecode instructions into offload-specific machine code that internally invokes the execution controller at its execution.

Execution Controller: The execution controller of the offloading client is an interface between the execution engine and the offloading components within a JVM (cf. Subsection 4.3.4). An execution of the assembler code for the offload-specific Java bytecode instructions `offload` and `offload_end` invokes the execution controller. Only at an execution of `offload`, the execution controller invokes the offload controller to inform it of the call of a Java method that is feasible for a remote execution. The main tasks of the execution controller are the installation of an output execution state after a remote execution of a Java method and the manipulation of an execution of a Java method. Moreover, it also interacts with the state generator to obtain an input execution state and an output execution state for a called Java method.

To install an output execution state after an execution of a Java method on a remote resource, the execution controller replaces the member values of the declaring Java class with the related values contained in an output execution state. It also pushes the return value contained in an output execution state on the stack frame of the Java stack. Notice that the execution controller only replaces the member values and pushes the return value, because further values on the stack frame of the Java stack have only a local scope and thus, are only valid during an execution of the Java method. Due to the immediate return of an execution of the Java method after the Java bytecode instruction `offload_end`, the execution engine destroys the created stack frame.

To manipulate an execution of a Java method, the execution controller changes the values of the registers from the execution engine (cf. Subsection 4.3.4), holding state information during an execution of a Java method. For instance, it has a register that holds the "ByteCode Index" (`bci`) indicating an index to the next Java bytecode instruction executed by the execution engine (cf. pc registers). By setting the `bci` register to the last Java bytecode instruction of a Java method, the execution engine immediately returns the call of a Java method.

State Generator: The state generator of the offloading client is an interface between the runtime data areas and the offloading components within a JVM (cf. Subsection 4.3.4). To this end, the main tasks of the state generator are the marshaling of Java data types, the gathering of execution state information before an execution of a Java method, the gathering of execution state information after an execution of a Java method, and the gathering of Java bytecode instructions of a Java method.

To marshal Java data types, the state generator distinguishes between Java primitives, Java objects, and Java arrays (cf. Subsection 4.3.4). For a Java primitive, it just copies the Java identifier of the data type together with related data into a platform-independent representation. For a Java object, it visits each member value of the Java class and stores the Java primitives. In case of the member value of the Java object corresponds itself to a Java object or a Java array, the state generator marshals recursively this member value. For an one-dimensional Java array, the state generator visits each entry and stores the related data of a Java primitive or a Java object. For a multi-dimensional Java array, it visits recursively each entry of each dimension, reaching at the end an one-dimensional Java array that it marshals.

To gather the execution state information before the execution of a called Java method, the state generator copies the parameters of a Java method from the Java stack and from the Java heap (cf. Section 4.3.4). On the execution of the first Java bytecode instruction `offload`, the execution engine initialized a new stack frame on

the Java stack for the invocation of a Java method. The stack frame contains the parameters of a Java method in ascending order, where the values of Java primitives are on the stack and the values of Java objects or Java arrays are on the heap linked by a reference on the stack frame. To this end, the state generator directly copies the values of a Java primitive from the stack frame on the Java stack, whereas it first marshals the Java object or Java array from the Java heap linked by a reference. Beside the parameters of a Java method, the first value at the stack frame on the Java stack is a reference to the `this` object[1], corresponding to the declaring Java class of the Java method. Visiting the declaring Java class, the state generator directly copies its member values. Last, the state generator requires the static members of all classes reachable. It visits all loaded Java classes from the class loader stored in a list within the JVM (cf. Section 4.3.4), copying the static members of the reachable Java classes. Thus, it possesses the information required to create an input execution state.

To gather the execution state information after the execution of a Java method, the state generator first creates an input execution state. Afterwards, it further requires the return value for the Java method, corresponding to the last value on the stack frame of the Java stack due to the execution of the Java bytecode instruction `offload_end`. In case the last value on the stack frame of the Java stack is a Java primitive, the state generator just copies it. In case of the last value on the stack frame of the Java stack is a Java object or a Java array, the state generator marshals the Java object or Java array referenced by the last value on the stack frame. Thus, it possesses the information required to create an output execution state.

To gather the Java bytecode instructions of a called Java method, the state generator visits the declaring Java class of a Java method through the reference to the `this` object on the frame stack on the Java stack. The declaring Java class of the Java method possesses the Java bytecode instructions of a Java method. Thus, the state generator directly copies the Java bytecode instructions from the declaring Java class.

App Profiler: The offload controller of the offloading client invokes the app profiler to retrieve two profile models built from past invocations of a Java method (history-based approach). One model profiles the execution time for a local execution of a Java method on the hardware platform, where the other model profiles the size of the output execution state after an execution of a Java method. To build the two profile models, the app profiler retrieves from the execution controller after a local

[1] In case of a static call of a Java method (e.g., `invokestatic`), the reference to the `this` object is missing on the related Java stack. Due to the static invocation of the Java method, however, the member values of the declaring Java class correspond to the static member values of the declaring Java class, accessed through the class definition.

execution of a Java method its input execution state, its output execution state, and its execution time. Afterwards, the app profiler creates a data sample for each profile model. The first data sample consists of the input execution state together with the execution time. The second data sample consists of the input execution state together with the output execution state. Creating data samples after a local execution for a Java method, the training set on the offloading client increases over time. Thus, the app profiler trains from time to time new profile models due to an increased set of training data. Notice that the offloading client does not rely on a specific algorithm to profile the execution time or the size, being out of scope of this dissertation. In detail, the basic distribution utilizes two k-Nearest Neighbors[2] algorithms like in [MF10] for regression-based machine learning, building and training both models.

Network Monitor: The offload controller of the offloading client invokes the network monitor to retrieve the link bandwidth and the link latency from the offloading client to an offloading service and vice versa. To this end, the network monitor probes the uplink and downlink in five iterations each, where an iteration comprises a ping followed by a packet with 10 kB of data. Afterwards, the network monitor takes the average, possessing the actual link bandwidth and link latency.

Network Interface: The offload controller of the offloading client invokes the network interface to retrieve the factors for the monetary cost of the network. The factors are the monetary cost for a utilization of the communication network to and from an offloading service. To this end, the network interface provides an interface – more precisely a configuration file, where a network provider defines the static or dynamic factors of the monetary cost of the communication network.

User Interface: The offload controller of the offloading client invokes the user interface to retrieve the user-defined weights for the execution time, the energy consumption, and the monetary cost of the cost function (cf. Section 3.2). To this end, the user interface provides a graphical interface – more precisely three bars, where an end user of a mobile device defines its preference for each weight. Based on the weights defined by an end user, the end user influences the solution of the cost function.

Device Interface: The offload controller of the offloading client invokes the device interface to retrieve static factors for the energy consumption. The static factors are the energy consumption for executing code on the hardware platform, sending and

[2]For a detailed explanation of the k-Nearest Neighbor algorithm, please take a look at [WFHP16].

receiving bytes via the communication network to and from an offloading service, and waiting in idle mode during a remote execution. To this end, the device interface provides an interface – more precisely a configuration file, where a device manufacturer defines the static factors of the energy consumption.

Device Benchmark: The offload controller of the offloading client invokes the device benchmark to retrieve the performance factor of executing Java bytecode instructions. To this end, the device benchmark benchmarks the computing speed of a hardware platform by measuring the execution time for a predefined number of Java bytecode instructions. In detail, the benchmark comprises measurements of Java bytecode instructions for the manipulation of Java primitives (`Integer`, `Long`, `Float`, and `Double`), Java objects, and Java arrays (cf. Subsection 4.3.4). Based on the measurements of Java bytecode instructions, the device benchmark calculates the performance factor, possessing a comparative value for the performance of hardware platforms.

Service Monitor: The offload controller of the offloading client invokes the service monitor to retrieve the factors of the performance and the monetary cost for a remote execution on an offloading service. To this end, it creates a resource request that is actually a packet containing only an identifier for requesting the factors. After the creation of the resource request, the service monitor forwards it to the service connector of the offloading client and waits for a resource response from the offloading service. A resource response is a packet with a related identifier and the requested factors.

Service Connector: The offload controller and the service monitor of the offloading client invoke the service connector to handle the communication between the offloading client and an offloading service. To this end, it receives the input execution state from the offload controller, creating an offload request and sending it to the client connector on an offloading service. Afterwards, the service connector waits for a receive of an offload response at the end of a remote execution. Receiving an offload response from a client connector on an offloading service, the service connector on the offloading client extracts the output execution state and the monetary cost of a remote execution, forwarding both to the offload controller. Beside sending of offload requests and receiving of offload responses, the service connector receives resource requests from the service monitor. To this end, it sends a resource request to the client connector on an offloading service and waits for a receive of a resource response. Afterwards, the service connector on the offloading client extracts the factors of the performance and the monetary cost of an offloading service and forwards both to the offload controller.

Offload Controller: The execution controller of the offloading client invokes the offload controller at the execution of the offload-specific Java bytecode instruction `offload`. This indicates the call of a Java method that is feasible for a remote execution. Thus, the offload controller minimizes the cost function from Equation 4.1, requiring the information about the application, the network, the user, the device, and the offloading service. For the information about the application, the offload controller invokes the execution controller retrieving the input execution state of the called Java method. Furthermore, it invokes the app profiler retrieving the profile models for the execution time on the hardware platform and for the size of the output execution state. Based on the profile models built from the app profiler, the offload controller predicts the execution time on the hardware platform and the size of the output execution state based on the input execution state of the called Java method. To retrieve the execution time on an offloading service, the offload controller multiplies the execution time predicted for the local hardware platform by a speedup factor. It calculates the speedup factor based on the factor for the performance of the local hardware platform and of the offloading service. For the information about the network, the offload controller invokes the network monitor retrieving the link bandwidth and the link latency to an offloading service. For the information about the user, the offload controller invokes the user interface retrieving the user-defined weights for the execution time, the energy consumption, and the monetary cost. For the information about the device, the offload controller invokes the device interface retrieving the factors for the energy consumption and for the performance of the hardware platform. For the information about the offloading service, the offload controller invokes the service monitor retrieving the factors for the monetary cost and for the performance of the offloading service.

By minimizing the cost function with the retrieved information, the offload controller decides whether it executes the called Java method on the hardware platform of the offloading client or distributes the execution of the called Java method to the hardware platform of the offloading service. In case of a local execution on the offloading client, the offload controller just returns its invocation – and thus, the invocation of the execution controller – continuing the execution of the Java method locally on the offloading client. In case of a remote execution on the offloading service, the offloading client forwards the input execution state to the service connector. Afterwards, it waits for the output execution state and the monetary cost of a remote execution on the offloading service from the service connector. Receiving the output execution state and the monetary cost from the service connector, the offload controller forwards the output execution state to the execution controller. It also pays the monetary cost charged from the offloading service for the remote execution of the Java method.

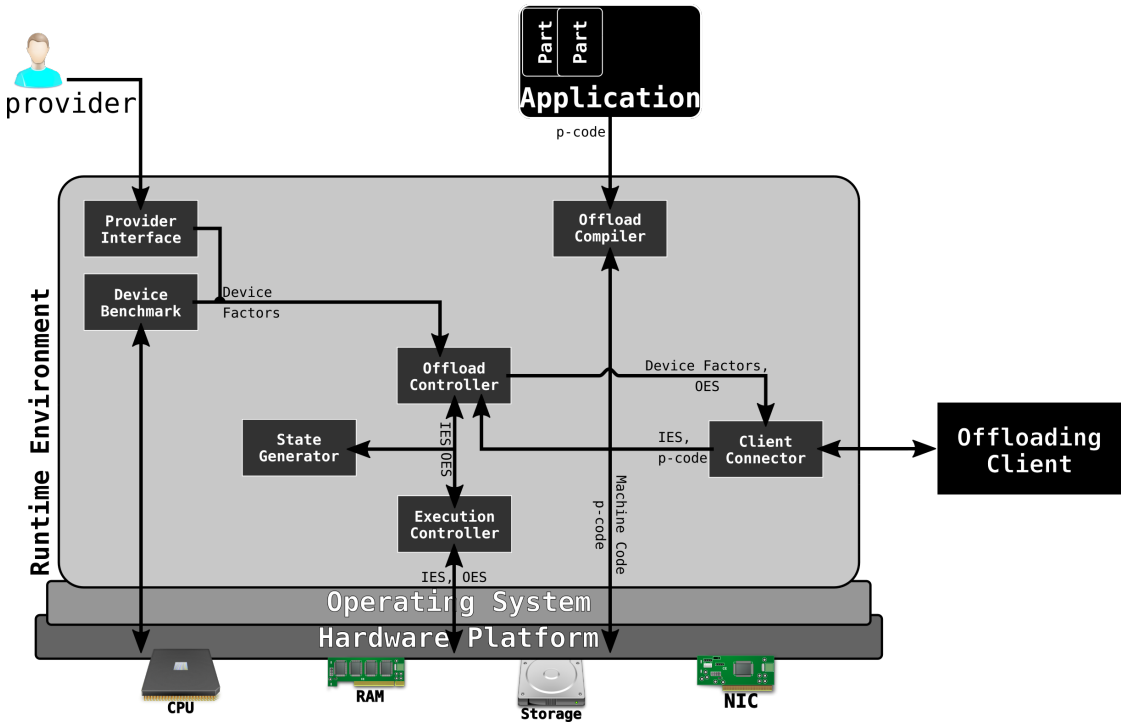


Figure 4.9.: The runtime environment on the offloading service for the basic distribution to execute application parts distributed from an offloading client.

4.5.3. Offloading Service

Figure 4.9 shows the runtime environment of the offloading service, providing the service-side functionality for the basic distribution. It consists of an offload compiler, an execution controller, a state generator, a provider interface, a device benchmark, a client connector, and an offload controller.

Offload Compiler: The offload compiler of the offloading service corresponds to the offload compiler on the offloading client (cf. Subsection 4.5.2), translating both offload-specific Java bytecode instructions into offload-specific machine code.

Execution Controller: The execution controller of the offloading service corresponds to the execution controller on the offloading client (cf. Subsection 4.5.2). Only the execution of the offload-specific Java bytecode instruction `offload_end` invokes the execution controller that invokes the offload controller, informing it about the execution end of a Java method and forwarding the output execution state to it.

State Generator: The state generator on the offloading service provides the same functionality as the state generator on the offloading client (cf. Subsection 4.5.2),

extended with the functionality to install an execution state for an invocation of a Java method. To install an execution state for an invocation of a Java method, the state generator replaces the member values of the declaring Java class with the related values contained in the execution state. Notice that the state generator only replaces the member values, because the offload controller calls a Java method with the right parameters contained in the execution state. For the replacement of the member values, the state generator visits the declaring Java class through the reference to the `this` object on the stack frame on the Java stack. Afterwards, it replaces the member values in memory with the values contained in the execution state.

Provider Interface: The offload controller of the offloading service calls the provider interface to retrieve dynamic factors. The dynamic factors are the monetary cost for executing code on the hardware platform, and sending and receiving bytes via the communication network to and from an offloading client. To this end, the provider interface provides an interface – more precisely text entry boxes, where a provider of a remote resource defines the resource-specific factors for the monetary cost.

Device Benchmark: The device benchmark of the offloading service corresponds to the device benchmark on the offloading client (cf. Subsection 4.5.2), benchmarking the performance of the hardware platform.

Client Connector: According to the basic distribution (cf. Section 4.4), the receive of a resource request or an offload request invokes the client connector of the offloading service. By receiving a resource request from the service connector of an offloading client, the client connector on the offloading service invokes the offload controller to retrieve the factors for the performance and the monetary cost of executing, sending, and receiving. Retrieving the factors from the offload controller, the client connector creates a resource response – containing the factors – and sends it to the requesting service connector on the offloading client. By receiving an offload request from the service connector of the offloading client, the client connector on the offloading service extracts the input execution state from the offload request. Afterwards, the client connector forwards it to the offload controller that starts the execution of the Java method. After the execution of the Java bytecode instructions of the Java method, the offload controller invokes the client connector, forwarding the output execution state and the monetary cost of the remote execution. The client connector creates an offload response – containing the output execution state and the monetary cost of the remote execution – and sends it to the service connector of the offloading client.

Offload Controller: The client connector of the offloading service invokes the offload controller due to the receive of an offload request. To this end, the client connector forwards the input execution state of a Java method to the offload controller. The offload controller forwards it to the execution controller that installs the input execution state for an invocation of the Java method (cf. Subsection 4.5.2). Afterwards, the offload controller starts the execution of the Java method. At the end of an execution of a Java method, the execution controller invokes the offload controller and forwards the output execution state gathered due to the execution of the offload-specific Java bytecode instruction `offload_end`. Based on the time elapsed for the execution of the Java method, the offload controller calculates the monetary cost for the execution. Possessing the output execution state and the monetary cost for the execution of a Java method, the offload controller forwards both to the client connector.

4.6. Implementation

The basic distribution is the basis for the concepts and algorithms presented in this dissertation. Thus, we implemented the functionality required for the basic distribution on the Java platform (cf. Subsection 4.3.4). For the Java platform, there are different implementations available, where this dissertation deploys a prototype for code offloading based on the Jikes Research Virtual Machine (cf. Subsection 4.6.1), the Open Java Development Kit (cf. Subsection 4.6.2), and the Android Open-Source Project (cf. Subsection 4.6.3). Beside the implementation of prototypes based on the Java platform, this dissertation utilizes two self-designed measurement boards (cf. Subsection 4.6.5) that measure the energy consumption of the offloading clients.

4.6.1. Jikes Research Virtual Machine

The Jikes Research Virtual Machine (RVM) is an open-source implementation of a JVM, written in the Java programming language (meta-circular). Despite the meta-circular implementation style, the Jikes RVM is self-hosted, where it executes its Java bytecode instructions on itself. In November 1997, the development of the Jikes RVM started as an internal research project at IBM's Thomas J. Watson Research Center. At 2012, the Jikes RVM won the ACM SIGPLAN Software award [SIG12]. The citation of the award says that "The high quality and modular design of Jikes has made it easy for researchers to develop, share, and compare advances in programming language implementation." At the year 2015, the Jikes RVM possesses a large community of researchers and scientific publications, spawning more than 200 papers and at least 40

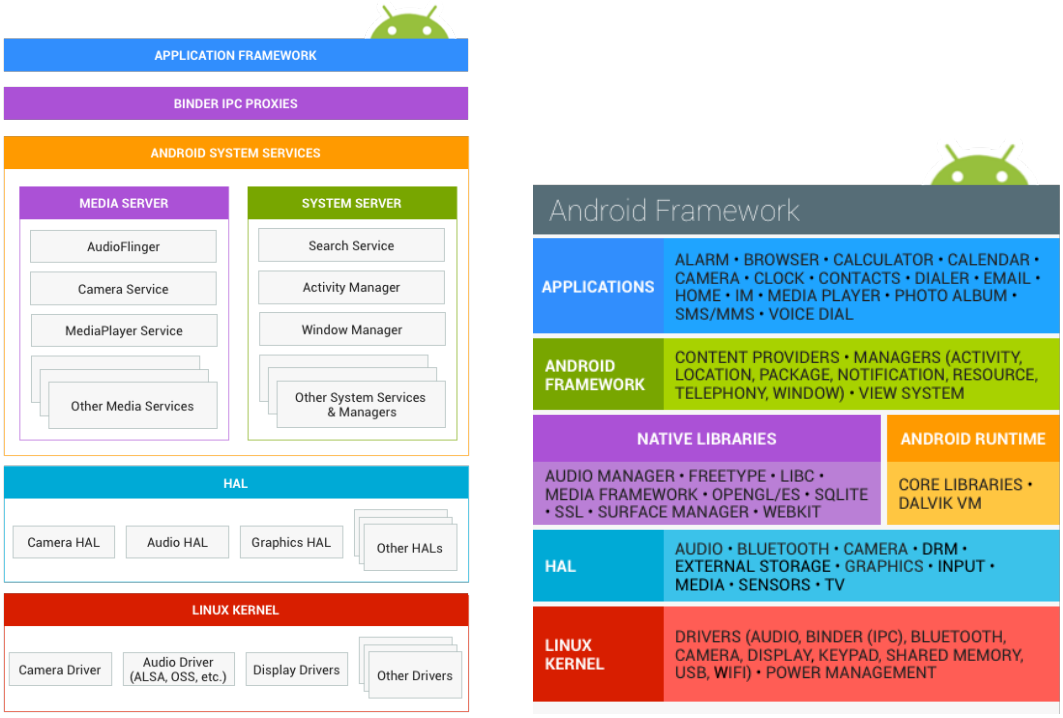


Figure 4.10.: The software stack from the Android OS. [And16a, And16b]

dissertations at almost 100 universities [Mac16]. Focusing on the research of new techniques, the Jikes RVM offers a rapid prototyping for a JVM, supporting the PowerPC and the Intel $x86$ 32-bit ISAs with a Linux operating system. As Java class libraries, it utilizes either the implementation from Apache Harmony or from GNU Classpath.

4.6.2. Open Java Development Kit

The Open Java Development Kit (OpenJDK) is a free and open-source implementation of the Java Platform, Standard Edition (Java SE). The main components of the OpenJDK project are an implementation of the JVM named HotSpot, the Java class libraries, and the Java compiler `javac`. The OpenJDK project implements its components mainly in the `C++` programming language and the Java programming language. Back to 2006, Sun Microsystems announced that Java would become open-source and released main parts like the Java HotSpot virtual machine as free software. To provide a JDK as free software, Sun Microsystems released at the year 2007 the Java class libraries as open-source code. Today, the Java platform of OpenJDK is the standard Java installation on many Linux distributions like Ubuntu.

4.6.3. Android Open-Source Project

The Android Open-Source Project (AOSP) is a mobile Operating System (OS) and application environment for mobile devices like smart phones or tablets. It supports multiple architectures like ARM, x86, and MIPS[3] architecture in 32-bit and 64-bit variants. Initially developed by Android Inc. and later bought by Google in the year 2005, it provides an open-source software stack. The commercial version Android OS from Google had 1.4 billion active devices in September 2015 [Goo15]. Thus, it is the most widespread (mobile) OS. Due to the open nature of AOSP, it has a large community of developers that utilizes AOSP for own projects. The software stack of AOSP runs above a device hardware and comprises a Linux kernel, a Hardware Abstraction Layer (HAL), an Android platform that consists of the Android runtime, the native libraries, and the Android framework, the Binder Inter-Process Communication (IPC), and the applications (cf. Figure 4.10). Depending on the actual hardware platform of a mobile device, AOSP utilizes a Linux kernel specialized with important additions (cf. the Binder IPC driver in Figure 4.10) for a (mobile) embedded platform. Through the Linux kernel and the HAL, AOSP accesses device resources like camera, audio, or network functions. To this end, the HAL provides a standard interface for software hooks between the higher-level Android platform and the lower-level drivers. The Android platform consists of the Android runtime, the native libraries, and the Android framework. The Android runtime includes the Dalvik Virtual Machine (DVM) and Java-compatible core libraries to execute applications written in the Java programming language. The DVM contains a JIT compiler that executes dex-code (Dalvik EXecutable), compiled from Java bytecode at development-time. With Android version 5.0, Google replaced the JIT compiler with an Ahead-Of-Time (AOT) compiler that compiles the entire code of an application into machine code at the installation of an application. The Java-compatible core libraries correspond to a subset of the discontinued Apache Harmony. Since Android version 7.0, OpenJDK replaces Apache Harmony. The native libraries provide access to particular features of a hardware platform. For instance, OpenGL ES provides an application programming interface to render graphics on an embedded device. The Android framework summarizes system services like the Window Manager or the MediaPlayer Service that access the hardware platform of a mobile device. In detail, AOSP groups system services under the System Server and the Media Server (cf. Figure 4.10). The System Server contains services involved in the system like the Window Manager. The Media Server contains services involved in playing and recording media like the MediaPlayer Service. The Binder

[3]Microprocessor without Interlocked Pipeline Stages (MIPS)

IPC provides mechanism for a communication across process boundaries, enabling an interaction between system services as well as between system services and higher-level applications. Actually, there are two sources for applications in the software stack. The first source is the pre-installation of applications, providing key capabilities of mobile devices like calling or browsing. The second source is the user-driven installation of applications, customizing the functionality of a mobile device with third-party applications. To this end, Android offers the Android Software Development Kit (SDK), supporting an environment for an open development of applications. It is a comprehensive set of development tools like a debugger or software libraries for application developers to deploy applications written in the Java programming language. Until December 2014, Google provided the Android SDK based on a plugin – namely the Android Development Tools (ADT) plugin – for the Eclipse Integrated Development Environment (IDE). Nowadays, the Android Studio from Google is the primary IDE for the deployment of Android applications.

4.6.4. Modifications

Jikes RVM and OpenJDK: The changes to the Jikes RVM (cf. Subsection 4.6.1) and to the OpenJDK (cf. Subsection 4.6.2) comprise modifications to the JAVA Compiler (`javac`), the implementation of the JVM, and the Java core class libraries (cf. Subsection 4.3.4). The changes to `javac` include the integration of the offload-specific annotation and the offload-specific Java bytecode instructions. The integration enables the compilation of offload-specific Java source code to offload-specific Java bytecode instructions at development-time (cf. Subsection 4.5.1). The changes to the implementation of the JVMs include the execution of the offload-specific Java bytecode instructions and the functionality required for the offloading client and for the offloading service. Thus, the JVM provides either the execution as an offloading client or as an offloading service. The changes to the Java core class libraries include the integration of the offload-specific annotation in the `java.lang` package.

AOSP: The modification to the AOSP comprises changes to the Android runtime and an additional system service to the Android application framework (cf. Subsection 4.6.3). The changes to the Android runtime include the integration of the offload-specific annotation, the offload-specific Java bytecode instructions, and the functionality required for the offloading client (cf. Subsection 4.5.2). To this end, we adapted among others the DVM corresponding to an implementation of a JVM that executes the Dalvik Bytecode on the hardware platform. In detail, we enabled the DVM to

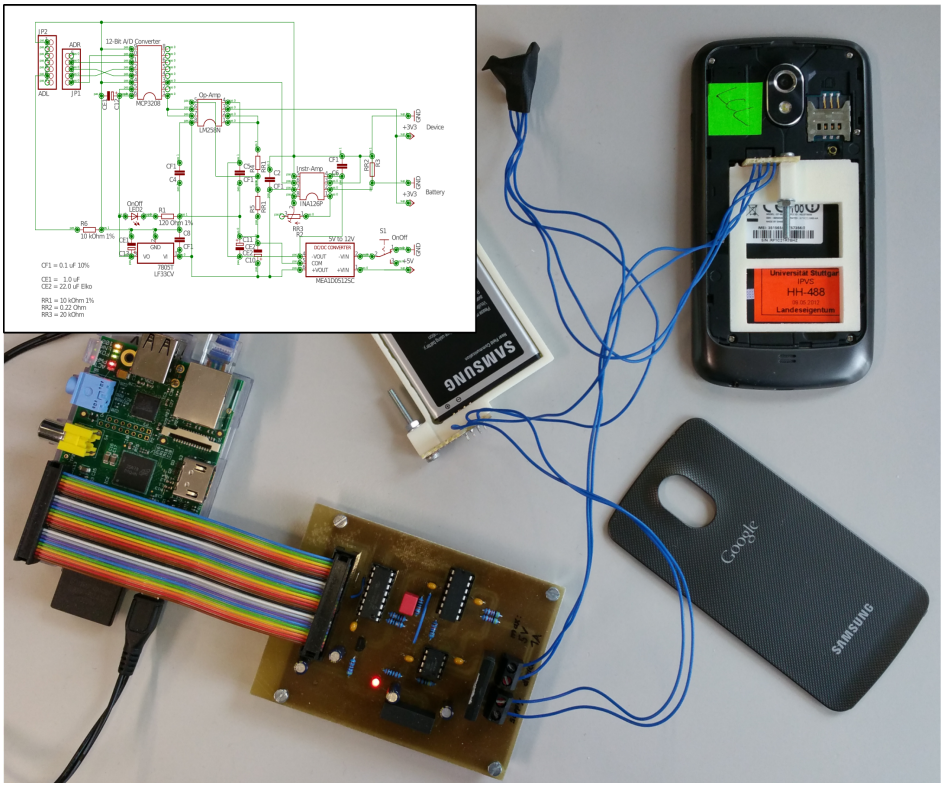


Figure 4.11.: The measurement board for the Samsung Galaxy Nexus, consisting of a Raspberry Pi and a self-designed extension board.

execute the two offload-specific Dalvik bytecodes `offload` and `offload_end`. Moreover, we enabled it to gather an input execution state of a Java method, install an output execution state received from an offloading service, and skip a local execution. Through the execution of `offload`, the DVM informs an additional system service, namely the Offload Manager, from the Android application framework of the current execution of a Java method that is offloadable. Like other managers (e.g., Activity Manager or Location Manager) from the Android application framework, the Offload Manager also possesses a category in the Android settings. Via this Android setting, an end user easily controls the system service of the Offload Manager like starting the service, stopping the service, or changing the user-defined weights.

4.6.5. Measurement Boards

To measure the energy consumption of an offloading client that offloads computation to an offloading service, this subsection provides an insight about the self-designed measurement boards for this dissertation. Due to mobile and stationary measurements of the hardware platforms from a smart phone (cf. Section C.1), a netbook (cf. Section C.2), and a laptop (cf. Section C.3), this dissertation designs two different

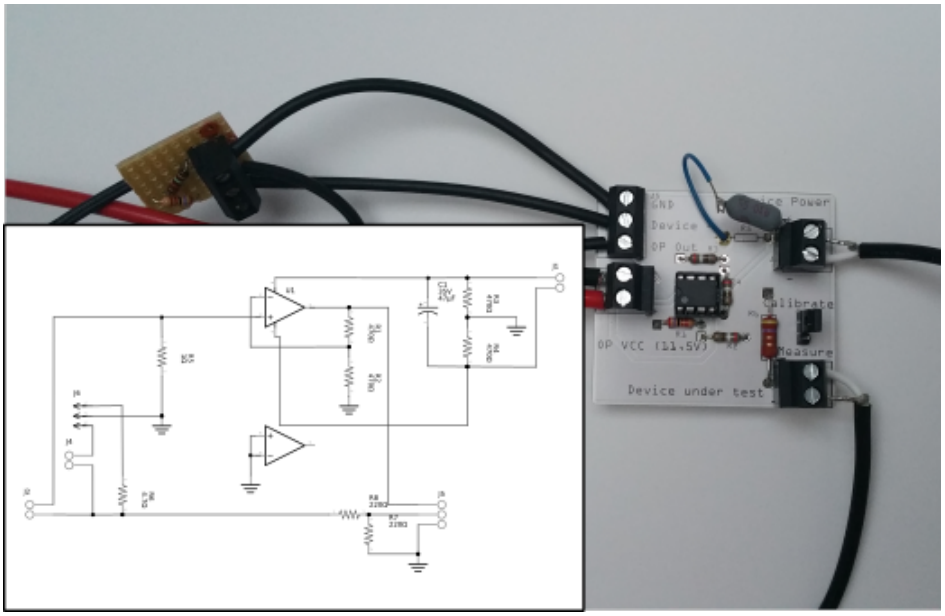


Figure 4.12.: The measurement board for the Dell Inspiron Mini 10v and the Lenovo ThinkPad T61, consisting of a self-designed board and a 16-bit Analog Data Acquisition Board from Meilhaus Electronic [Ele17].

measurement boards, namely one for the Samsung Galaxy Nexus and another one for the Dell Inspiron Mini 10v & Lenovo ThinkPad T61.

Samsung Galaxy Nexus: A Raspberry Pi and a self-designed extension board measures the power consumption of the battery-operated smart phone (cf. Figure 4.11). The Raspberry Pi runs a real-time operating system – a Linux with RT PREEMPT patch – polling concurrently samples from a 12 bit Analog-to-Digital Converter (ADC) on the extension board. The ADC samples the continuous voltage U and current I of the device under test, namely the Samsung Galaxy Nexus. To this end, the ADC measures the voltage drop along a 0.01 Ohm shunt resistor, connected in series with the device under test. The measured voltage drop is proportional to the current I flowing through the shunt (Ohm's law $R = \frac{U}{I}$). Furthermore, the extension board measures the voltage U directly at the device under test. Last, the extension board amplifies the voltage of the shunt resistor with the help of an instrumentation amplifier for precise measurements. The corresponding design of hardware and software are open-source[4].

Dell Inspiron Mini v10 & Lenovo ThinkPad T61: A self-designed board together with the ME-Jekyll ME-4610 PCI 16-bit Analog Data Acquisition Board from Meilhaus Electronic (cf. [Ele17]) measures the power consumption of the power-supplied

[4] `github.com/duerrfk/rpi-powermeter`

netbook and laptop (cf. Figure 4.12). The self-designed board amplifies the voltage drop along a 0.1 Ohm shunt resistor with the help of an operational amplifier for precise measurements. It connects the shunt resistor in series with the device under test, either the Dell Inspiron Mini 10v or the Lenovo ThinkPad T61. Moreover, it also measure the voltage U directly at the device under test. Both the voltage and the voltage drop are analog inputs to the 16-bit Analog Data Acquisition Board that does a high-precision 16 bit/500 kHz A/D conversion. As the analog inputs from the Data Acquisition Board have a voltage range of ±10 V, the self-designed board has a preceding voltage divider for the power input of 19 V/20 V from the netbook/laptop.

4.7. Evaluation

To evaluate the performance of the basic distribution, a mobile device executes a Java application on an unaltered Java Runtime Environment (JRE) and on an offload-aware JRE. To this end, Subsection 4.7.1 describes the evaluation setup before Subsection 4.7.2 presents the evaluation results.

4.7.1. Setup

The different implementations of the prototype for the basic distribution categorize the evaluation setup (cf. Section 4.6), where this subsection describes the setup for the prototypes of the Jikes RVM, the OpenJDK, and the AOSP.

Jikes Research Virtual Machine

For the Jikes RVM, the netbook Dell Inspiron Mini 10v (cf. Section C.2) and the laptop Lenovo ThinkPad T61 (cf. Section C.3) execute the offloading client of the Jikes RVM prototype, representing two heterogeneous mobile devices. The netbook is a resource-poor and energy-efficient device, whereas the laptop is a more powerful device with higher energy consumption. To measure the power consumption of the netbook or of the laptop, we utilized the measurement board described in detail in Subsection 4.6.5. The desktop computer HP Compaq 8200 Elite (cf. Section C.4) executes the offloading service of the Jikes RVM prototype, being the most powerful device and having a power connection. As an underutilized desktop computer in the vicinity executes the offloading service, it does not charge a monetary cost for its utilization (cf. $C_{exec}^{\Xi(\xi_r)}$ in Section 3.1). The netbook and the laptop communicate via a 3.5 Generation (3.5G) mobile communication network to the desktop computer with a varying bandwidth of round about 1 Mbit/s and a varying latency of round about

100 ms. The Huawei E1750 Surf Stick (cf. Section C.6) provides the link to the mobile communication network. It does not charge a monetary cost for its utilization (cf. $C_{send}^{\Lambda(\xi_l;\xi_r)}$ and $C_{recv}^{\Lambda(\xi_l;\xi_r)}$ in Section 3.1), because an end user has today typically a flat-rate data plan. The application evaluated on the netbook and on the laptop is the Chesspresso application (cf. Section B.2), where the end user sets the weight for the time w_t, the energy w_e, and the cost w_c to 1 (cf. Section 3.1).

Open Java Development Kit

For the OpenJDK, the evaluated mobile devices are also the resource-poor netbook and the more powerful laptop (cf. Section C.2 and Section C.3). Both mobile devices execute the offloading client of the OpenJDK prototype for the basic distribution. We also measured the power consumption of the netbook or of the laptop with the measurement board described in detail in Subsection 4.6.5. The desktop computer (cf. Section C.4) executes the offloading service of the OpenJDK prototype being the most powerful device and having a power connection. For the monetary cost charged by the offloading service (cf. $C_{exec}^{\Xi(\xi_r)}$ in Section 3.1), we consider the price charged by Amazon[5] for an *m3.medium* machine type from its cloud, causing a monetary cost of 0.070 $ per hour. For the communication network, the netbook and the laptop communicate via a Wi-Fi link to the desktop computer, not charging a monetary cost for its utilization (cf. $C_{send}^{\Lambda(\xi_l;\xi_r)}$ and $C_{recv}^{\Lambda(\xi_l;\xi_r)}$ in Section 3.1). The Wi-Fi link has a varying bandwidth of round about 3 Mbit/s and a varying latency of round about 5 ms, provided by the Linksys WRT54GL wireless router (cf. Section C.7). The applications evaluated on the netbook and on the laptop are a chess game (cf. Section B.2) and a text-to-voice application (cf. Section B.2), differing in the computational complexity and the communication required for code offloading. For the user-defined weights, the end user sets the weight w_t for the time, w_e for the energy, and w_c for the cost to 1 (cf. Section 3.1).

Android Open-Source Project

For the AOSP, the evaluated mobile device is the Samsung Galaxy Nexus (cf. Section C.1), executing the offloading client of the AOSP prototype. This smart phone is a resource-constrained device with a high energy consumption for the execution of resource-intensive application parts. To measure the power consumption on the smart phone, we utilize the measurement board described in detail in Subsection 4.6.5. A t2.micro instance from the Amazon Web Services (AWS) Elastic Compute Cloud (EC2) (cf. Section C.5) executes the offloading service from the OpenJDK prototype, being

[5] `https://aws.amazon.com/ec2/pricing/?nc1=h_ls`

the most powerful device. As a result, we consider the price charged by Amazon[6] for a t2.micro instance from its cloud, causing a monetary cost of 0.012 $ per hour (cf. $C_{exec}^{\Xi(\xi_r)}$ in Section 3.1). For the communication network, the smart phone communicates via a Wi-Fi network and fixed networks to the t2.micro instance, not charging a monetary cost for the utilization (cf. $C_{send}^{\Lambda(\xi_l;\xi_r)}$ and $C_{recv}^{\Lambda(\xi_l;\xi_r)}$ in Section 3.1). The networks have a varying bandwidth of round about 2.5 Mbit/s and a varying latency of round about 10 ms. The Linksys WRT54GL wireless router provides the Wi-Fi AP to the Internet (cf. Section C.7). The mobile application evaluated on the smart phone consists of resource-friendly and resource-intensive parts, where the resource-friendly parts are graphical user input and output. The resource-intensive parts are a best chess move engine (cf. Section B.3), a human face recognition engine (cf. Section B.4), and a text-to-voice engine (cf. Section B.5), differing in the computational complexity and the communication required for code offloading. Beside the standard applications always started on an Android OS, the end user only starts the implemented application for a better comparison and sets the weight w_t for the time, w_e for the energy, and w_c for the cost to 1 (cf. Section 3.1).

4.7.2. Results

The different implementations of the prototypes for the basic distribution also categorize the evaluation results (cf. Section 4.6), where this subsection describes the results for the prototypes of the Jikes RVM, the OpenJDK, and the AOSP.

Jikes Research Virtual Machine

The netbook consumes in idle mode 8.40 W on average (cf. power consumption at 35 s in Figure 4.13). Executing the Chesspresso application totally on the netbook with an unaltered Jikes RVM, this local execution takes in total 29.542 s and consumes in total 294.07 J, resulting in a power consumption of 9.95 W on average (cf. Figure 4.13). Now, executing the Chesspresso application on the netbook with the Jikes RVM enabled for the basic distribution, it takes in total 16.825 s (cf. Figure 4.13). The remote execution starts at 14.59 s and ends at 18.69 s, taking 4.10 s. The netbook consumes for the basic distribution in total 178.00 J resulting in a power consumption of 10.58 W on average. Thus, an execution of the Chesspresso application on the netbook benefits significantly from the basic distribution, taking 12.717 s less time and consuming 116.07 J less energy.

Compared to the power consumption of the netbook, the absolute power consumption on the laptop is in total higher due to the smaller energy efficiency. The laptop

[6] `https://aws.amazon.com/ec2/pricing/?nc1=h_ls`

Figure 4.13.: Power consumption on the netbook for a local execution and the basic distribution of the Chesspresso application.

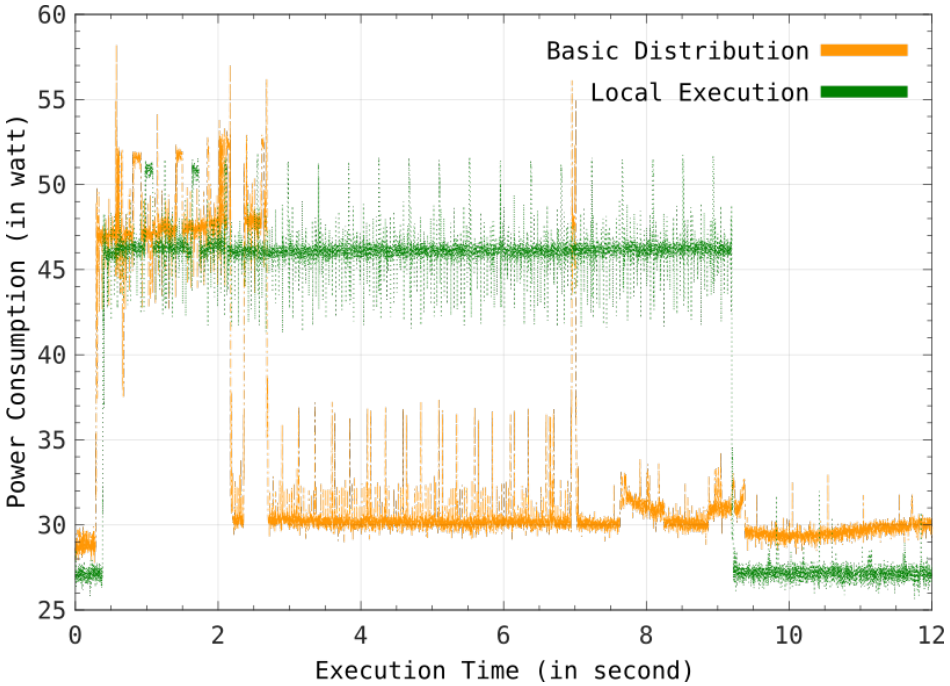


Figure 4.14.: Power consumption on the laptop for a local execution and the basic distribution of the Chesspresso application.

consumes in idle mode 27.29 W on average (cf. power consumption at 10 s Figure 4.14). Executing the Chesspresso application totally on the laptop with an unaltered Jikes RVM, this local execution in total takes 8.841 s and consumes 408.97 J, resulting in a power consumption of 46.25 W on average (cf. Figure 4.14). Now, executing the Chesspresso application on the laptop with the Jikes RVM enabled for the basic distribution, it takes in total 6.737 s. The remote execution starts at 2.695 s and ends at 6.963 s taking 4.268 s. The laptop consumes for the basic distribution in total 244.89 J resulting in a power consumption of 36.34 W on average. Thus, an execution of the Chesspresso application on the laptop also benefits from the basic distribution, taking 2.104 s less time and consuming 164.08 J less energy.

Summarizing, the basic distribution increases on both devices the energy efficiency of the devices as well as the execution speed of the Chesspresso application.

OpenJDK

Chess Game: For the chess game, each mobile device plays 10 rounds with the different opening moves from Figure B.2 and a chess difficulty of 2 (cf. Section B.3).

For the netbook, Table 4.1 summarizes the execution time, energy consumption, and monetary cost for a local execution and the basic distribution after 10 rounds of chess moves for each opening move. A local execution of the chess game totally on the netbook takes the longest time and consumes the most energy for every opening move. In detail, the execution time for a local execution is between 134.70 s and 345.03 s with an energy consumption between 1450.38 J and 3715.22 J. Comparing the time taken and the energy consumed of a local execution with the basic distribution (cf. Table 4.1), the basic distribution of the Java method that is offloadable from the chess game reduces both the execution time and the energy consumption significantly. In detail, it requires at least 24.44 s and 241.10 J and at most 45.31 s and 433.51 J. Due to the utilization of the offloading service, it reduces the execution time by up to 86.87% and energy consumption by up to 88.33%, causing monetary cost between 0.05273 $ and 0.12995 $.

For the laptop, Table 4.1 also summarizes the execution time, energy consumption, and monetary cost for a local execution and the basic distribution after 10 rounds of chess moves for each opening move. Overall, the results for the evaluation on the laptop follow the same characteristics as the results for the evaluation on the netbook. Due to the fact that the laptop is a more powerful device with a higher energy consumption compared to the netbook, the laptop halves the time taken and more than duplicates the energy consumed for a local execution of the chess game, still taking the longest

Netbook	**1 a4**	**1 b4**	**1 c4**	**1 d4**	**1 h4**	**1 a3**	**1 g3**
Local Execution							
Execution Time:	235.02	345.03	204.06	163.70	134.70	162.985	214.958
Energy Consumption:	2530.61	3715.22	2197.30	1762.68	1450.38	1754.99	2314.62
Monetary Cost:	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Basic Distribution							
Execution Time:	35.03	45.31	31.81	27.79	24.44	27.64	34.60
Energy Consumption:	338.78	433.51	309.07	272.00	241.10	270.68	337.66
Monetary Cost:	0.09181	0.12995	0.07993	0.06497	0.05273	0.06442	0.08348
Laptop	**1 a4**	**1 b4**	**1 c4**	**1 d4**	**1 h4**	**1 a3**	**1 g3**
Local Execution							
Execution Time:	122.85	178.61	106.37	89.32	69.02	89.98	110.03
Energy Consumption:	5673.35	8248.12	4912.35	4124.71	3187.30	4155.23	5081.14
Monetary Cost:	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Basic Distribution							
Execution Time:	34.57	44.89	31.22	27.27	23.91	27.06	32.42
Energy Consumption:	1203.06	1519.67	1110.34	988.40	890.93	993.11	1138.24
Monetary Cost:	0.09216	0.12966	0.07769	0.06350	0.04997	0.06005	0.08414

Table 4.1.: Overview of execution time, energy consumption, and monetary cost on the netbook and on the laptop for the evaluation of the chess game with different opening moves.

time and consuming the most energy (cf. Table 4.1). In detail, the execution time for a local execution is between 69.019 s and 178.608 s with an energy consumption between 3187.30 J and 8248.12 J. Despite the higher performance of the laptop, the benefits of the basic distribution to the offloading service are still notable (cf. Table 4.1). Compared to a local execution, the basic distribution reduces the execution time and the energy consumption by up to 74.87% and 81.58%. It requires at least 23.912 s and 890.93 J and at most 44.889 s and 1519.67 J with a monetary cost of at least 0.04997 $ and at most 0.12966 $.

Summarizing, the basic distribution increases on the netbook and on the laptop the energy efficiency of the devices as well as the execution speed of the chess game.

Text-to-Voice Application: For the text-to-voice application, each mobile device transforms either from the beginning the next 15 words (*Idx*=0 *Cnt*=15) or from the word at position 15 the next 20 words (*Idx*=15 *Cnt*=20) from ThinkAir or MAUI with the voice "Alan" to voice (cf. Section B.5).

For the netbook, Table 4.2 shows the execution time, energy consumption, and monetary cost for a local execution and the basic distribution, transforming 15 or 20 words from ThinkAir or MAUI to voice. A local execution transforms the words to voice totally on the netbook, taking the longest time (minimum: 65.532 s; maximum: 85.024 s) and consuming the most energy (minimum: 705.64 J; maximum: 915.52 J) compared to the basic distribution (cf. Table 4.2). As the text-to-voice application is on the netbook a good candidate for a distribution, the basic distribution reduces significantly the execution time and energy consumption by up to 51.48% and 54.00% (cf. Table 4.2). In detail, it takes at least 32.519 s and at most 41.472 s, consumes at least 332.97 J and at most 423.29 J, and raises at least 0.03867 $ and at most 0.05560 $.

For the laptop, Table 4.2 shows the execution time, energy consumption, and monetary cost for a local execution and the basic distribution, transforming the words to voice. A local execution of the text-to-voice application takes between 26.083 s and 33.731 s and consumes between 280.86 J and 363.21 J (cf. Table 4.2). Due to the fact that, on the one hand, the laptop is a more powerful device with a higher energy consumption and, on the other hand, the text-to-voice application has a big size of the output execution state, a local execution on the laptop is better than a remote execution on the offloading service. As a result, the basic distribution does not distribute the Java method that is offloadable of the text-to-voice application. Regarding a naive basic distribution that still distributes the Java method that is offloadable, it increases the execution time (minimum: 29.304 s; maximum: 38.508 s) by up to 16.16%, the energy consumption (minimum: 298.35 J; maximum: 392.98 J) by up to 10.09%, and

Netbook	**ThinkAir: Idx=0 Cnt=15**	**ThinkAir: Idx=15 Cnt=20**	**MAUI: Idx=0 Cnt=15**	**MAUI: Idx=15 Cnt=20**
Local Execution				
Execution Time:	65.53	84.45	65.93	85.02
Energy Consumption:	705.64	909.34	709.88	915.52
Monetary Cost:	0.00	0.00	0.00	0.00
Basic Distribution				
Execution Time:	32.53	41.47	32.52	41.25
Energy Consumption:	332.97	423.29	333.98	421.17
Monetary Cost:	0.04144	0.05560	0.03867	0.05498
Laptop	**ThinkAir: Idx=0 Cnt=15**	**ThinkAir: Idx=15 Cnt=20**	**MAUI: Idx=0 Cnt=15**	**MAUI: Idx=15 Cnt=20**
Local Execution				
Execution Time:	26.08	33.73	26.55	33.15
Energy Consumption:	280.86	363.21	285.89	356.96
Monetary Cost:	0.00	0.00	0.00	0.00
Naive Distribution				
Execution Time:	29.30	37.91	29.99	38.51
Energy Consumption:	298.35	385.29	307.03	392.98
Monetary Cost:	0.04107	0.05479	0.03803	0.05178

Table 4.2.: Overview of execution time, energy consumption, and monetary cost on the netbook and on the laptop for the evaluation of the text-to-voice application.

Figure 4.15.: Power consumption on the smart phone for a local execution and the basic distribution of the mobile application.

causes monetary cost between 0.03803 $ and 0.05479 $ compared to a local execution.

Summarizing, the basic distribution increases on the netbook and on the laptop the energy efficiency of the device as well as the execution speed of the chess game. The basic distribution only offloads the Java method that is offloadable from the text-to-voice application on the netbook, benefiting from computation offloading. On the laptop, the basic distribution does not offload the Java method that is offloadable from the text-to-voice application due to its big size of the output execution state. The evaluation results of a naive basic distribution that still offloads the Java method that is offloadable would decrease the energy efficiency of the device as well as the execution speed of the text-to-voice application on the laptop, highlighting the importance of proper decisions for computation offloading.

Android Open-Source Project

Figure 4.15 shows the power consumption on the smart phone for a local execution of the application on its hardware platform in airplane mode. On average, the smart phone consumes 1.107 W in idle mode, 3.612 W for utilizing the cellular link, and 2.412 W during the execution of the resource-intensive application parts. Once an end user starts the application on the smart phone, the smart phone starts the execution of the best chess move engine with configuration 0 of the chess board (cf. Figure B.2i) and a chess difficulty of 2. The best chess move engine takes in total 37.216 s caused by

its high code complexity. After a short period of time for user input and output (0.5 s), the application executes the human face recognition engine with a minimum scale of 1, a maximum scale of 100, and an image size of 1258 pixels times 1024 pixels. It takes 11.431 s caused by its moderate code complexity. After another period of time for user input and output (0.5 s), the application executes the text-to-voice engine that finishes the execution. The text-to-voice engine transforms all words from *OWN* with the voice "Alan" (cf. Section B.5). The text-to-voice engine takes 18.624 s caused by a higher code complexity than the human face recognition engine but a lower code complexity than the best chess move engine. In total, the local execution of the application on the smart phone takes 68.853 s and consumes 173.159 J.

Figure 4.15 also shows the power consumption on the smart phone for the basic distribution of the application via a Wi-Fi link to the Internet and thus, to an offloading service at the cloud. The Wi-Fi link between the smart phone and the server instance at the cloud has a bandwidth of 1.5 MB/s and a latency of 8.605 ms. As a result, the basic distribution executes the best chess move engine, the human face recognition engine, and the text-to-voice engine on the offloading service, reducing its execution time to 4.208 s, to 7.654 s, and to 2.084 s, respectively. In total, the basic distribution results in an execution time of 15.705 s and an energy consumption of 45.301 J.

Summarizing, the basic distribution increases significantly on the smart phone the energy efficiency of the device as well as the execution speed of the application.

4.8. Summary

To offload computation from a (resource-poor) mobile device to a (powerful) remote resource like a server instance at the cloud, the *basic distribution* described in Section 4.1 provides an efficient code offloading with annotations. An efficient code offloading uses sparingly resources from both a mobile device and a remote resource relying on least interventions from both an application developer and an end user. To this end, it utilizes an annotation-based instrumentation of portable code, requiring a little application-specific knowledge from an application developer. The *system overview* described in Section 4.2 specifies the system model, the problem statement, and the system components of the basic distribution between a mobile device and a remote resource (two-tier architecture). As features like a dynamic adaptation, resource efficiency, or a seamless execution are necessarily for the basic distribution, it utilizes a *runtime-layer offloading* described in Section 4.3. It runs a runtime environment on the hardware platform of participating resources to abstract from actual capabilities and properties from different hardware platforms and software stacks in the landscape

of Mobile Cloud Computing (MCC). In detail, the offloading client and the offloading service extends the functionality provided from a runtime environment like the Java platform to enable an efficient code offloading based on portable code. The *offloading timeline* described in Section 4.4 for the basic distribution between an offloading client and an offloading service via a communication network describes each step from an identification of application parts for a remote execution to a receive of an output execution state after a remote execution. Each step described in the timeline from the basic distribution requires specific functionality on the offloading client and on the offloading service provided by the *offloading framework* described in Section 4.5. The functionality provided by the offloading framework are interfaces for the device manufacturer, end user, and resource provider, benchmark of the hardware, controllers for the distribution and execution, monitors for the network and service, connectors to the client and the service, an application profiler, a state generator, and a compiler. To analyze the interplay of the functionality required for the basic distribution, this dissertation deploys different *implementations* described in Section 4.6 of a prototype based on the Jikes Research Virtual Machine, the OpenJDK (Java Development Kit), and the Android Open-Source Project. Furthermore, each prototype performs an *evaluation* described in Section 4.7 of the performance for the basic distribution between a mobile device like a smart phone, netbook, or laptop to a server instance at a desktop or the Amazon cloud. In summary, the evaluation results for the basic distribution of an application like a chess game, a face recognition application, or a text-to-voice application outperform significantly a related execution of the applications locally on the hardware platform of the mobile devices.

Chapter 5

Robust Code Offloading through Safe-point'ing

A mobile device might suffer from crash failures of the communication network that last for longer periods of seconds to minutes during the basic distribution presented in detail in Chapter 4. To make the basic distribution robust against crash failures, this chapter presents a robust code offloading of application parts through safe-point'ing. To this end, Section 5.1 describes a preemptable distribution of application parts between an offloading client on a (resource-poor) mobile device and an offloading service on a (powerful) remote resource. The preemptable distribution enables an offloading client to react on failures by interrupting a remote execution on an offloading service and continuing the remote execution locally based on the execution state of the offloading service. First, Section 5.2 gives the system overview for the preemptable distribution, including the system model, the problem statement, and the system components, before Section 5.3 highlights a related offloading timeline. The basic idea of the preemptable distribution is the creation and transmission of safe-points of a remote execution, where a safe-point conceptually corresponds to a snapshot of the state of a remote execution. The offloading framework described in Section 5.4 enables an offloading client on a mobile device to continue a remote execution locally from the safe-point received most recently, containing the intermediate state of the remote execution on an offloading service. To evaluate the benefit and overhead of the preemptable distribution compared to the basic distribution, Section 5.5 presents the evaluation of a prototype, including the evaluation setup and the evaluation results. Last, Section 5.6 summarizes the main facts of a robust code offloading through safe-point'ing presented in this chapter.

5.1. Preemptable Distribution

The basic distribution – presented in detail in Chapter 4 – of applications parts comprises an offloading client that distributes application parts, an offloading service that executes the distributed application parts, and a (wireless) link that connects both

(communication network). Corresponding to the failure model in Section 3.4, the offloading service as well as the (wireless) link suffer from crash failures. Multiple evaluations in the literature show that mobile connections are error-prone, causing (temporary) disconnections between an offloading client and an offloading service. For instance, Ding et al. [DWC+13] measure the signal strength of a 3G mobile communication network from smart phones with Android OS based on a data set from 3785 volunteers worldwide. The measurements show that over 80% (60%) of the end users have a poor signal strength for over 15% (32%) of their active usage time. As end users of smart phones move frequently in an area with a poor coverage of cellular networks, Ding et al. [DWC+13] identify geographic variations of network coverage as the major reason for temporary disconnections.

Approaches proposed in the literature only consider very limited strategies to handle failures during a remote execution of application parts. Popular strategies either start a local re-execution of an application part or wait for a re-connection to the remote site in case of failures. Both strategies have adverse effects for the efficiency of the energy consumption as well as for the execution time of an application: On the one hand, a distribution plus a re-execution of an application part consume more energy and take more time than a local execution of the application part. Aborting a distribution of an application part due to a failure wastes the energy consumed and the time spent so far for the distribution plus the waiting in idle mode for the end of the remote execution. On the other hand, a distribution plus waiting for a re-connection block an offloading client for an (arbitrary) long time. Moreover, an offloading client again consumes energy and spends time while waiting, possible beyond the point in time, where a local execution would be more efficient.

In order to solve the dilemma of either waiting for a re-connection or starting a local re-execution in case of a failure, we propose the approach of a preemptable distribution. The preemptable distribution enables an offloading client to re-use the intermediate state of a remote execution on an offloading service for a local continuation in case of a failure. To this end, an offloading service creates from time to time the intermediate states for an execution of an application part and transmits these intermediate states to the offloading client. In case of a failure, the offloading client does not need to either wait for a re-connection or start a local re-execution, because it now continues the execution locally based on the intermediate state received most recently. We call such an intermediate state of a remote execution a safe-point, containing the information required on an offloading client for a continuation of the partial remote execution of an application part. The challenge of the preemptable distribution is to determine the right times of creating and transmitting safe-points such that it increases the energy

efficiency on the offloading client and the execution speed of an application. In detail, if the preemptable distribution utilizes too many safe-points, the communication overhead and thus, the energy consumption increases. If it utilizes too few safe-points, the risk of falling back to a very old intermediate state in case of a failure increases ultimately. At worst, it converges into the basic distribution without safe-points, just waiting for a re-connection or starting a local re-execution. The computation complexity of an application part together with the size of a safe-point influence the decision for creating and transmitting a safe-point. For instance, if a local re-execution of an application part is inexpensive with regard to energy, fewer safe-points are sufficient. To this end, the preemptable distribution estimates the energy saved by a safe-point based on online measurements to calculate the right time for safe-points such that it reduces effectively the energy consumption of an offloading client in average.

Summarizing, we make the following contributions: (1) A framework for the preemptable distribution based on safe-points for applications written in the Java programming language; (2) an adaptive algorithm with online measurements that schedules the creation and transmission of safe-points such that it minimizes the energy consumption and increases the robustness under failures; (3) an implementation of the offloading framework for the preemptable distribution on the Java platform; and (4) an evaluation with state of the art mobile devices that shows the efficiency of the preemptable distribution based on safe-points.

5.2. System Overview

The preemptable distribution increases the robustness of the basic distribution by re-using intermediate states of a remote execution. Thus, the system model and the system components of the preemptable distribution are same as before (cf. Section 4.2).

Beside the minimization of the cost function f_w for the basic distribution, the preemptable distribution additionally increases the robustness of an application under crash failures. While increasing the robustness of an application, the execution time and energy consumption should stay small in cases with failures. Regarding the cost function f_w of Equation 4.1, the creation and transmission of safe-points influence the execution time $T(A_{\alpha_o}, \Xi(\xi))$, the energy consumption $E(A_{\alpha_o}, \Xi(\xi))$, and the monetary cost $C(A_{\alpha_o}, \Xi(\xi))$ of a remote execution. We assume that safe-point'ing is an additional feature offered by the provider of an offloading service and, for instance, financed by advertising (cf. Google with Android OS), not charging additional monetary cost. However, safe-point'ing increases the execution time $T_{wait}(A_{\alpha_o}, \Xi(\xi_r))$ on an offloading client due to the time for creating safe-points on an offloading service. It also causes

the execution time $T_{sfpt}(A_{\alpha_o}, \Xi(\xi_r))$ on an offloading client due to receiving safe-points from an offloading service. Thus, the execution time $T(A_{\alpha_o}, \Xi(\xi))$ is defined as:

$$\begin{aligned} T(A_{\alpha_o}, \Xi(\xi)) = T_{remote}(A_{\alpha_o}, \Xi(\xi_r)) \quad &= T_{send}(A_{\alpha_o}, \Xi(\xi_r)) + T_{wait}(A_{\alpha_o}, \Xi(\xi_r)) \\ &+ \; T_{sfpt}(A_{\alpha_o}, \Xi(\xi_r)) + T_{recv}(A_{\alpha_o}, \Xi(\xi_r)) \end{aligned}$$

with

$$T_{wait}(A_{\alpha_o}, \Xi(\xi_r)) \quad = \frac{P^{exe}_{pcode}(I_{state}(A_{\alpha_o}), P_{pcode}(A_{\alpha_o}))}{P_{ppwr}(\Xi(\xi_r))} + \sum_{s}^{N(SP)-1} T_{crtn}(SP_i)$$

$$T_{sfpt}(A_{\alpha_o}, \Xi(\xi_r)) \quad = \quad \sum_{s}^{N(SP)-1} (\frac{SP^{size}_i(A_{\alpha_o})}{B^{\Lambda(\xi_l;\xi_r)}_{down}} + L^{\Lambda(\xi_l;\xi_r)}_{down})$$

Please note that the time $T_{crtn}(SP_i)$ spent for creating a safe-point depends on the current execution state of the remote execution and thus, is unknown in advance.

Beside increasing the execution time on an offloading client, safe-point'ing also consumes energy, causing the energy consumption $E_{sfpt}(A_{\alpha_o}, \Xi(\xi_r))$ for receiving safe-points. Please note that the energy consumption $E_{wait}(A_{\alpha_o}, \Xi(\xi_r))$ includes the increase of the energy consumption caused by creating safe-points on the remote side. Thus, the energy consumption $E(A_{\alpha_o}, \Xi(\xi))$ is defined as:

$$\begin{aligned} E(A_{\alpha_o}, \Xi(\xi)) = E_{remote}(A_{\alpha_o}, \Xi(\xi_r)) \quad &= E_{send}(A_{\alpha_o}, \Xi(\xi_r)) + E_{wait}(A_{\alpha_o}, \Xi(\xi_r)) \\ &+ \; E_{sfpt}(A_{\alpha_o}, \Xi(\xi_r)) + E_{recv}(A_{\alpha_o}, \Xi(\xi_r)) \end{aligned}$$

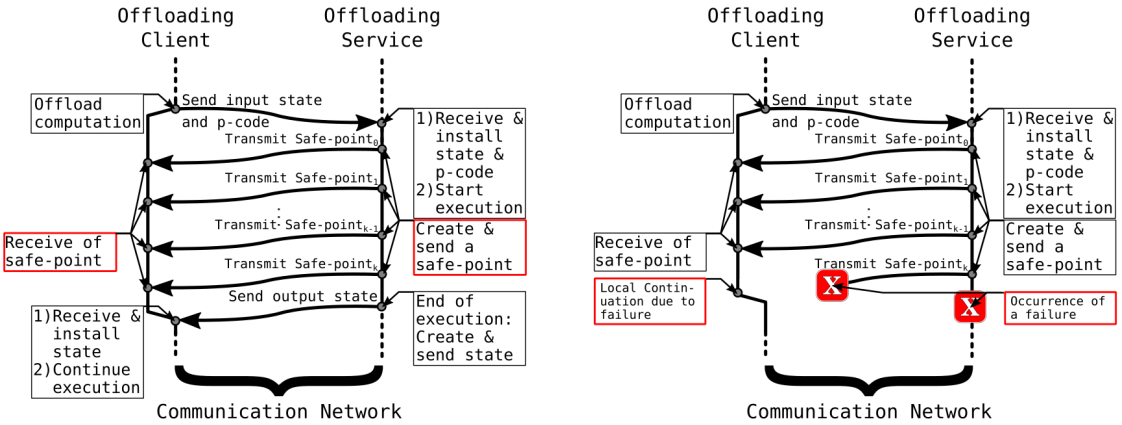
with

$$E_{sfpt}(A_{\alpha_o}, \Xi(\xi_r)) = T_{sfpt}(A_{\alpha_o}, \Xi(\xi_r)) \cdot E^{\Xi(\xi_l)}_{recv}$$

As the total number $N(SP) - 1$ of created and received safe-points as well as the time for creating each safe-point $T_{crtn}(SP_i)$ are unknown in advance, $T_{wait}(A_{\alpha_o}, \Xi(\xi_r))$, $T_{sfpt}(A_{\alpha_o}, \Xi(\xi_r))$, $E_{wait}(A_{\alpha_o}, \Xi(\xi_r))$, and $E_{sfpt}(A_{\alpha_o}, \Xi(\xi_r))$ are also unknown in advance.

5.3. Offloading Timeline

Figure 5.1a shows the preemptable distribution with safe-point'ing of an application part between an offloading client and an offloading service, where no failures occur during the remote execution. Compared to the basic distribution of an application



(a) No failures during the remote execution.

(b) Failures during the remote execution.

Figure 5.1.: The preemptable distribution of an application part between an offloading client and an offloading service via a communication network, where (a) no failures occur during the remote execution and (b) failures occur during the remote execution, where the offloading client continues the execution locally.

part (cf. Section 4.4), an offloading service creates and transmits safe-points to an offloading client during an execution of an application part. In detail, in case of a remote execution, the offload controller invokes a safe-point generator to create a safe-point on the offloading client (cf. Subsection 5.4.1). A safe-point includes the parameters of the method, all reachable values of heap objects, declared class member objects, and static objects, corresponding to the input execution state of the basic distribution. After the creation of a safe-point on the safe-point generator, the offload controller forwards the created safe-point to the service connector and waits for the output execution state. The service connector creates the offload request that contains among others the safe-point and sends it to the offloading service.

Due to the receive of an offload request, the offloading service installs the contained information and calls the Java method, starting a remote execution just like for the basic distribution. To execute the Java method, the Java Runtime Environment (JRE) invokes the offload compiler to translate the platform-independent Java bytecode instructions into platform-dependent machine code. During the translation of Java bytecode instructions into machine code, the offload compiler instruments the machine code with breakpoints to interrupt the execution of the Java method at certain points detailed below. The introduced breakpoints invokes the execution controller that again invokes the offload controller. Due to the invocation of the offload controller, it decides whether to create a safe-point at this point in time and transmit it to the offloading client. During the execution of the Java method on the offloading service, the offload

controller might create several safe-points, but not transmitting each. It only transmits a safe-point to the offloading client if the energy consumption on the offloading client to locally reach the execution state contained in a safe-point is higher than a transmission of the safe-point from the offloading service to the offloading client.

While the offloading service executes the Java method, the offloading client runs a failure handler. The failure handler decides whether to preempt the distribution and continue the remote execution on the offloading service locally based on the safe-point received most recently (cf. Figure 5.1b). To this end, the failure handler on the offloading client monitors via the service connector the link to the offloading service as well as the remote service itself (cf. Subsection 4.5.2). In case of the failure handler detects a connection failure or a node failure, it invokes the offload controller to continue the remote execution locally on the offloading client.

5.4. Offloading Framework

The preemptable distribution extends the functionality provided from the offloading framework of the basic distribution (cf. Section 4.5), adapting the offloading client (cf. Subsection 5.4.1) and the offloading service (cf. Subsection 5.4.2).

5.4.1. Offloading Client

Figure 5.2 shows the runtime environment on the offloading client that enables the preemptable distribution with safe-point'ing. Compared to the runtime environment of the basic distribution (cf. Subsection 4.5.2), the changes comprise the offload controller and the state generator – now named safe-point generator – and a failure handler.

Offload Controller: The execution controller on the offloading client invokes the offload controller due to the execution of the Java bytecode instruction `offload`, marking the call of the Java method as feasible for a distribution. To this end, the offload controller on the offloading client invokes the safe-point generator to create a safe-point of the current execution state. The generated safe-point corresponds to the input execution state of the basic distribution. Thus, the safe-point generator forwards it after the creation to the offload controller that again forwards it to the service connector just like for the basic distribution. The failure handler on the offloading client invokes the offload controller due to the occurrence of a connection failure to or a node failure of the offloading service. To this end, the offload controller invokes the safe-point generator to retrieve the execution state last known of the remote execution. The

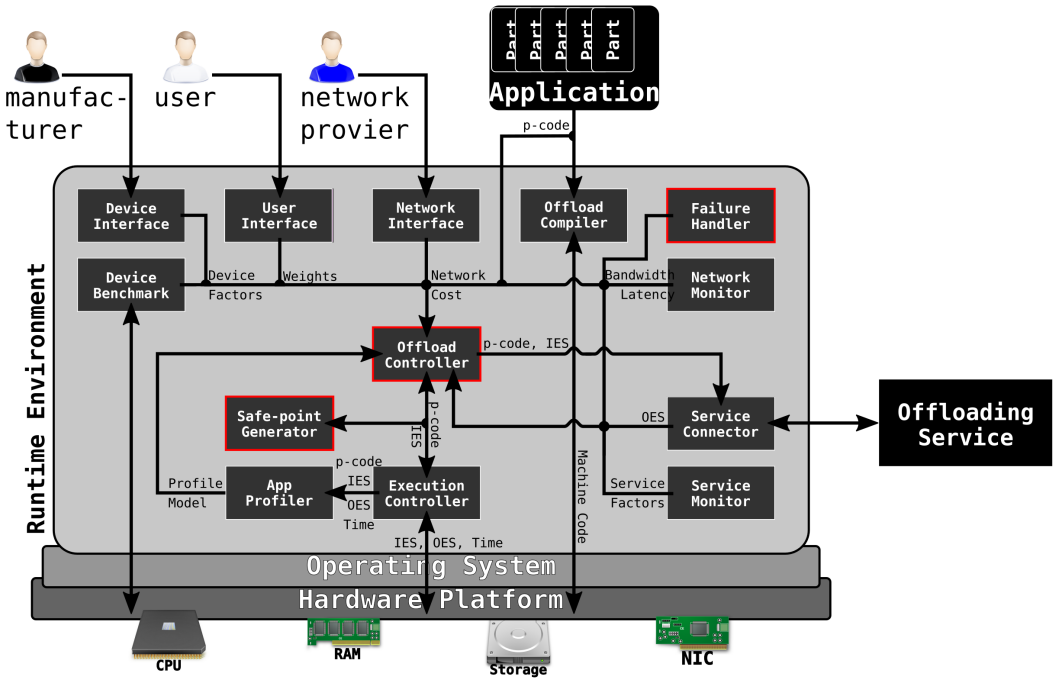


Figure 5.2.: Overview of the runtime environment on the offloading client enabling the preemptable distribution based on safe-point'ing with an adapted offload controller and an added safe-point generator and failure handler.

safe-point generator generates the execution state last known based on the safe-point created locally (input execution state) together with the safe-point(s) received from the offloading service. Retrieving the execution state last known, the offload controller forwards it to the execution controller that installs it and continues the execution of the remote execution locally.

Safe-point Generator: The safe-point generator on the offloading client extends the state generator from the basic distribution (cf. Subsection 5.4.1) by providing functionality for safe-point'ing. It creates the first safe-point before the execution of a Java method that is offloadable. This first safe-point corresponds to the input execution state of the basic distribution that contains all of the information required for a remote execution. Furthermore, the safe-point generator is responsible to generate the execution state last known of the remote execution on the offloading service. To this end, it combines all incremental safe-points received from the offloading service into a single safe-point. This combined safe-point contains the execution state last known from a remote execution like all variables required and modified during a remote execution.

Failure Handler: The failure handler on the offloading client decides whether to preempt the distribution of the Java method and continue its remote execution on the

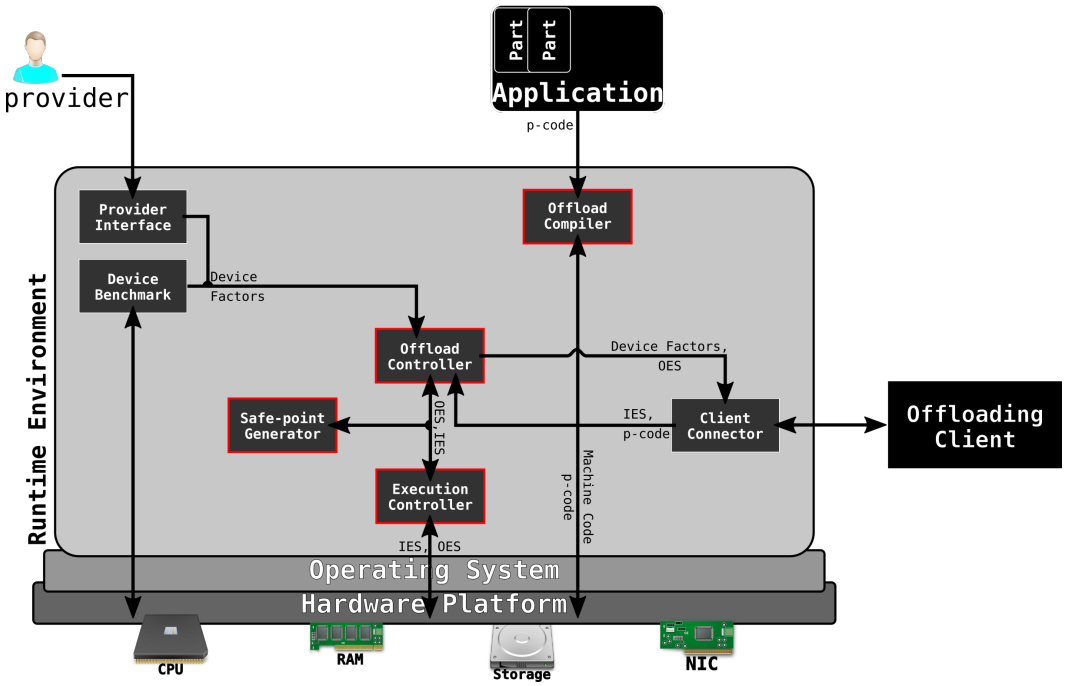


Figure 5.3.: Overview of the runtime environment on the offloading service enabling the preemptable distribution based on safe-point'ing with an adapted offload compiler, execution controller, and offload controller and an added safe-point generator.

offloading service locally based on the execution state last known. To this end, it monitors via the service connector the link to the offloading service as well as the remote service itself by sending periodically heartbeat messages. Due to the periodically pinging of the offloading service, the failure handler invokes the offload controller in case of receiving no heartbeat message after a timeout period. Receiving no heartbeat message after a timeout period corresponds to the occurrence of a failure.

5.4.2. Offloading Service

Figure 5.3 shows the runtime environment on the offloading service that enables the preemptable distribution with safe-point'ing. Compared to the runtime environment of the basic distribution (cf. Subsection 4.5.3), the changes comprise the offload compiler, the execution controller, the offload controller, and the safe-point generator.

Offload Compiler: The offload compiler on the offloading service inserts breakpoints at each Java bytecode instruction, where an execution of the Java bytecode instruction branches an execution of a Java method. Java bytecode instructions that branch an execution of a Java method are `goto`, `goto_w`, `jsr`, `jsr_w`, `ret`, `tableswitch`, and

`lookupswitch` (cf. Appendix A). These Java bytecode instructions are particularly well-suited for safe-point'ing, because the execution state at these branching instructions has a small footprint of memory. As variables with a local scope – e.g., inside the body of a loop – are typically not visible after the branch, a safe-point does not include such variables with a local scope and thus, has a small footprint of memory.

Furthermore, the offload compiler on the offloading service inserts additional Assembler code to efficiently keep track of modifications to the Java stack, the Java heap, and static Java objects during an execution of a Java method (cf. Subsection 4.3.4). To track modifications during an execution, the offload compiler inserts the additional Assembler code at each Java bytecode instruction that modifies a value of the Java stack, the Java heap, or a static Java object. Java bytecode instructions that change a value of the Java stack are `istore`, `lstore`, `fstore`, `dstore`, `astore`, `istore_0`, `istore_1`, `istore_2`, `istore_3`, `lstore_0`, `lstore_1`, `lstore_2`, `lstore_3`, `fstore_0`, `fstore_1`, `fstore_2`, `fstore_3`, `dstore_0`, `dstore_1`, `dstore_2`, `dstore_3`, `astore_0`, `astore_1`, `astore_2`, `astore_3`, `iastore`, `lastore`, `fastore`, `dastore`, `aastore`, `bastore`, `castore`, and `sastore` (cf. Appendix A). The Java bytecode instruction that changes a value of the Java heap is `putfield` and the Java bytecode instruction that changes a value of a static Java object is `putstatic` (cf. Appendix A). At execution, the inserted Assembler code flips a certain Bit in the Java header of the corresponding Java object, where a Bit flipped in the Java header indicates the modification of a Java object during an execution.

Execution Controller: Each time the execution of a Java method reaches the additional Assembler code inserted by the offload compiler for Java bytecode instructions that branches an execution of a Java method, the inserted Assembler code invokes the execution controller on the offloading service. On the one hand, the execution controller counts the number of Assembler code executed since the safe-point created last and, on the other hand, invokes the offload controller to create and transmit a safe-point to the offloading client at the current state of an execution.

Offload Controller: The execution controller on the offloading service invokes the offload controller due to the execution of the additional Assembler code inserted by the offload compiler for Java bytecode instructions that branches an execution of a Java method. The offload controller decides whether to create a safe-point at this point in time and transmit it to the offloading client by evaluating the energy savings for the offloading client through receiving a safe-point.

In order to evaluate the energy savings of a safe-point, the offload controller estimates

the energy consumption on the offloading client to reach the execution state contained in the safe-point through a local execution. To this end, it estimates the execution time required on the offloading client to execute the Assembler code counted since the last safe-point by the execution controller. Multiplying the estimated execution time with the energy factor for executing portable code (cf. Section 3.1), the offload controller calculates the energy consumption spent on the offloading client for this partial execution. In detail, the estimation of the energy consumption for a local execution includes the following parameters: (1) The number $P^{exe}_{asm}(S_i(A_{\alpha_o}), P_{pcode}(A_{\alpha_o}))$ with $S_0(A_{\alpha_o}) = I_{state}(A_{\alpha_o})$ of Assembler code executed since the last safe-point to reach the execution state contained in the current safe-point. The offload controller obtains the number $P^{exe}_{asm}(S_i(A_{\alpha_o}), P_{pcode}(A_{\alpha_o}))$ from the execution controller that counts the number of executed Assembler code based on the additional Assembler code inserted by the offload compiler. (2) The performance characteristic $P^{\Xi(\xi_k)}_{ppwr}(asm)$ of the offloading client $\Xi(\xi_k)$ that indicates how many Assembler code the offloading client executes per second. (3) The performance characteristic $E^{\Xi(\xi_k)}_{exec}(asm)$ of the offloading client $\Xi(\xi_k)$ that indicates an energy factor of how much energy the execution of Assembler code consumes per second. Please note that an offload request contains both performance characteristics of the offloading client. Thus, the energy consumption for a local execution $E^{\Xi(\xi_k)}_{exec}(S_i(A_{\alpha_o})$ is defined as:

$$E^{\Xi(\xi_k)}_{exec}(S_i(A_{\alpha_o}), P_{pcode}(A_{\alpha_o})) = \frac{P^{exe}_{asm}(S_i(A_{\alpha_o}), P_{pcode}(A_{\alpha_o}))}{P^{\Xi(\xi_k)}_{ppwr}(asm)} \cdot E^{\Xi(\xi_k)}_{exec}(asm) \tag{5.1}$$

Beside the estimation of the energy consumption on the offloading client for a local execution, the offload controller on the offloading service also estimates the energy consumption for a transmission of the safe-point to the offloading client. To this end, it invokes the safe-point generator to create a safe-point at the current state of the execution. Based on the created safe-point, the offload controller determines the size of it and multiplies the size with the energy factor for receiving bytes (cf. Section 3.1). In detail, the estimation of the energy consumption for a transmission includes the following parameters: (1) The size S^{size}_i in bytes of the safe-point. In order to calculate the size S^{size}_i of a safe-point, the safe-point generator creates a safe-point that the offloading service might not sent if it is not beneficial for the offloading client. (2) The performance characteristic $B^{\Lambda(\xi_k;\xi_m)}_{down}$ and $L^{\Lambda(\xi_k;\xi_m)}_{down}$ for a link $\Lambda(\xi_k;\xi_m)$ between the offloading service $\Xi(\xi_m)$ and the offloading client $\Xi(\xi_k)$ that indicates the number of bytes the link transmits per second and the network delay of the link in seconds, respectively (cf. Section 3.1). (3) The performance characteristic $E^{\Xi(\xi_k)}_{recv}$ that indicates an energy factor for receiving bytes on the offloading client (cf. Section 3.1). Please note

that an offload request contains the three performance characteristics of the offloading client. Thus, the energy consumption for a transmission $E^{\Xi(\xi_k)}_{trnsmt}(S_i(A_{\alpha_o})$ is defined as:

$$E^{\Xi(\xi_k)}_{trnsmt}(S_i(A_{\alpha_o})) = \left(\frac{S^{size}_i}{B^{\Lambda(\xi_k;\xi_m)}_{down}} + L^{\Lambda(\xi_k;\xi_m)}_{down} \right) \cdot E^{\Xi(\xi_k)}_{recv} \tag{5.2}$$

Finally, the offload controller only sends the created safe-point to the offloading client if the transmission of the safe-point saves energy on the offloading client compared to a local execution: $E^{\Xi(\xi_k)}_{exec}(S_i(A_{\alpha_o}), P_{pcode}(A_{\alpha_o})) > E^{\Xi(\xi_k)}_{trnsmt}(S_i(A_{\alpha_o}))$. Therefore, the offloading service ensures for a safe-point that the energy consumption for a transmission is lower than for a local execution.

Algorithm 5.1 summarizes the decision making for safe-points on the offload controller. Keeping the overhead on the offloading service low, the offload controller only generates a new safe-point if $\frac{P^{exe}_{asm}(S_i(A_{\alpha_o}),P_{pcode}(A_{\alpha_o}))}{P^{\Xi(\xi_k)}_{ppwr}(asm)}$ is greater than a time threshold $T^{exe}_{thrshld}$ (cf. Line 3). As a result, the time threshold $T^{exe}_{thrshld}$ defines the rate at which the offloading service generates potential safe-points for a transmission, avoiding a too-frequent generation of safe-points for a code sequence with closely-spaced breakpoints. Furthermore, it only sends a safe-point if the sum of the energy consumption for a transmission $E^{\Xi(\xi_k)}_{trnsmt}(S_i(A_{\alpha_o}))$ plus an energy threshold $E^{trnsmt}_{thrshld}$ is smaller than for a local execution $E^{\Xi(\xi_k)}_{exec}(S_i(A_{\alpha_o}), P_{pcode}(A_{\alpha_o}))$ (cf. Line 9). Please note that the energy threshold $E^{trnsmt}_{thrshld}$ functions as a parameter for the accuracy of the estimations to include, for instance, bandwidth or latency variations in the network link.

Last, the execution controller on the offloading service invokes the offload controller due to the execution of the Assembler code for the Java bytecode instruction `offload_end`. To this end, the offload controller always invokes the safe-point generator to create a last safe-point due to the end of the remote execution of the Java method. The offload controller forwards the safe-point created last to the client connector that transmits it to the offloading client.

Safe-point Generator: The safe-point generator on the offloading service is responsible for an efficient creation of safe-points. Thus, the safe-point generator utilizes its own serialization and deserialization of Java objects. Utilizing its own serialization and deserialization, it does not require from an application developer the implementation of an individual serialization and deserialization for each Java class based on the Java interface `serializable`. Not relying on the Java interface `serializable` keeps the generation of safe-points from Java classes transparent to application developers. To this end, the safe-point generator implements a memory module for the Java Virtual

Constant: JBC_{brnch} # *Branching Java ByteCode (JBC) instructions*
Constant: JBC_{ofldnd} # *Java bytecode instruction* `offload_end`
Input: JBC_{nxt} # *Java bytecode instruction executed NeXT*
Input: $T^{cur}_{thrshld}$ # *Current time threshold, initialized to* $T^{exe}_{thrshld}$

1: **if** $JBC_{nxt} \in JBC_{brnch}$ **then**
2: $t_{\text{tmp}} := \frac{P^{exe}_{asm}(S_i(A_{\alpha_o}), P_{pcode}(A_{\alpha_o}))}{P^{\Xi(\xi_k)}_{ppwr}(asm)}$;
3: **if** $t_{\text{tmp}} > T^{cur}_{thrshld}$ **then**
4: $T^{cur}_{thrshld} := T^{cur}_{thrshld} + T^{exe}_{thrshld}$;
5: $S_i :=$ gnrtSfPnt(); # *Generate a safe-point ...*
6: $S^{size}_i :=$ sizeof(S_i); # *... and determine the size of it*
7: $E^{\Xi(\xi_k)}_{trnsmt}(S_i(A_{\alpha_o})) := \left(\frac{S^{size}_i}{B^{\Lambda(\xi_k;\xi_m)}_{down}} + L^{\Lambda(\xi_k;\xi_m)}_{down}\right) \cdot E^{\Xi(\xi_k)}_{recv}$;
8: $E^{\Xi(\xi_k)}_{exec}(S_i(A_{\alpha_o}), P_{pcode}(A_{\alpha_o})) := t_{\text{tmp}} \cdot E^{\Xi(\xi_k)}_{exec}(asm)$;
9: **if** $E^{\Xi(\xi_k)}_{exec}(S_i(A_{\alpha_o}), P_{pcode}(A_{\alpha_o})) > \left(E^{\Xi(\xi_k)}_{trnsmt}(S_i(A_{\alpha_o})) + E^{trnsmt}_{thrshld}\right)$ **then**
10: sndSfPnt(S_i); # *Send safe-point to the offloading client*
11: $T^{cur}_{thrshld} := T^{exe}_{thrshld}$;
12: **end if**
13: **end if**
14: **else if** $JBC_{nxt} == JBC_{ofldnd}$ **then**
15: $S_i :=$ gnrtSfPnt(); # *Generate last safe-point ...*
16: sndSfPnt(S_i); # *... and send it to the offloading client*
17: **end if**

Algorithm 5.1: Algorithm of the decision making for safe-point'ing from the offload controller on the offloading service.

Machine (JVM) that transforms Java primitives, objects, and arrays into a platform-independent representation and vice versa (cf. Subsection 4.3.4). In order to minimize the size of a safe-point, the safe-point generator only serializes objects required and modified since the safe-point transmitted last (incremental safe-point'ing). It identifies the required and modified Java objects by visiting all Java objects that are reachable from an execution of a Java method and inspects their flag of modification. The set of reachable objects includes all visible static objects, members from the declaring class of the method, local values on the stack, and accessible objects on the heap (cf. Subsection 4.3.4). As the offload compiler inserts additional Assembler code that flips a Bit in the Java header on a modification of a related Java object, the offloading service only monitors modifications at the level of Java bytecode instructions. In detail, it cannot detect modifications outside the JVM, for instance, due to an execution of a native method. However, the tracking of modifications based on Bit flipping keeps the overhead introduced to the runtime environment low.

5.5. Evaluation

To evaluate the performance of the preemptable distribution compared to the basic distribution, a mobile device executes a Java application on an unaltered JRE (local execution), on an offload-aware JRE (basic distribution), and on a preemptable-aware JRE (preemptable distribution). To this end, we extended the implementation of the Jikes RVM prototype for the basic distribution (cf. Subsection 4.6.1) to provide the functionality required for the preemptable distribution. The extensions to the Jikes RVM prototype comprise changes to the implementation of the JVM to provide the functionality required for the preemptable distribution on the offloading client and on the offloading service. Next, Subsection 5.5.1 describes the evaluation setup before Subsection 5.5.2 presents the evaluation results.

5.5.1. Setup

The evaluation setup for the preemptable distribution extends the evaluation setup for the basic distribution on the Jikes RVM described in Subsection 4.7.1 as follows:

The evaluation compares the preemptable distribution with two basic approaches found in the literature (cf. Section 9.2). Both approaches provide a non-preemptable distribution based on different strategies at the occurrence of a failure. The first approach – named *Basic Distribution with a Re-Execution (BDwRE)* – starts a re-execution of the Java method on the offloading client as soon as the failure occurs. As

only the input execution state is available at the occurrence of a failure, the offloading client must re-execute the complete Java method locally again. The second approach – named *Basic Distribution waiting for a Re-Connection (BDwRC)* – waits for a re-connection to the offloading service at the occurrence of a failure to receive the last safe-point of a remote execution from the offloading service.

5.5.2. Results

Now, this subsection describes the results for the evaluation of the preemptable distribution. As the creation and transmission of safe-points introduce some overhead, the evaluation compares first the different approaches in a scenario, where no failures occur during a distribution of a Java method. Afterwards, it compares the different approaches in scenarios, where failures occur during a distribution at different points in time, highlighting the benefits of the creation and transmission of safe-points.

Distributing the Java method without failures: The creation and transmission of safe-points for the preemptable distribution introduces a certain overhead that only pays off in case of the occurrence of failures. Thus, for a distribution of the Java method without the occurrence of a failure, we expect that the preemptable distribution is less efficient due to the usage of safe-points than the other approaches not using safe-points. Note that in a scenario without failures, the approaches *BDwRE* and *BDwRC* behave identically and perform like the basic distribution, because the only difference of the approaches is the reaction on failures. To evaluate the overhead introduced by safe-point'ing, we compare the preemptable distribution with the basic distribution – corresponding to *BDwRE* and *BDwRC* – and both approaches with a local execution in a scenario without failures. Ideally, the overhead introduced by safe-point'ing does not affect the overall performance of the preemptable distribution significantly.

To give an insight of the introduced overhead, we start with the comparison of the different approaches on the netbook, where Subsection 4.7.2 describes the evaluation results for a local execution (29.542 s; 294.07 J) and the basic distribution (16.825 s; 178.00 J) of the Chesspresso application on the Jikes RVM. To this end, Figure 5.4 shows the power consumption on the netbook for the preemptable distribution of the Chesspresso application. It takes in total 16.746 s, where the remote execution takes 4.500 s and the netbook receives five safe-points. During the preemptable distribution, the netbook consumes in total 181.45 J resulting in a power consumption of 10.84 W on average. Thus, the preemptable distribution and basic distribution perform similar for the scenario without the occurrence of failures, virtually resulting in the same

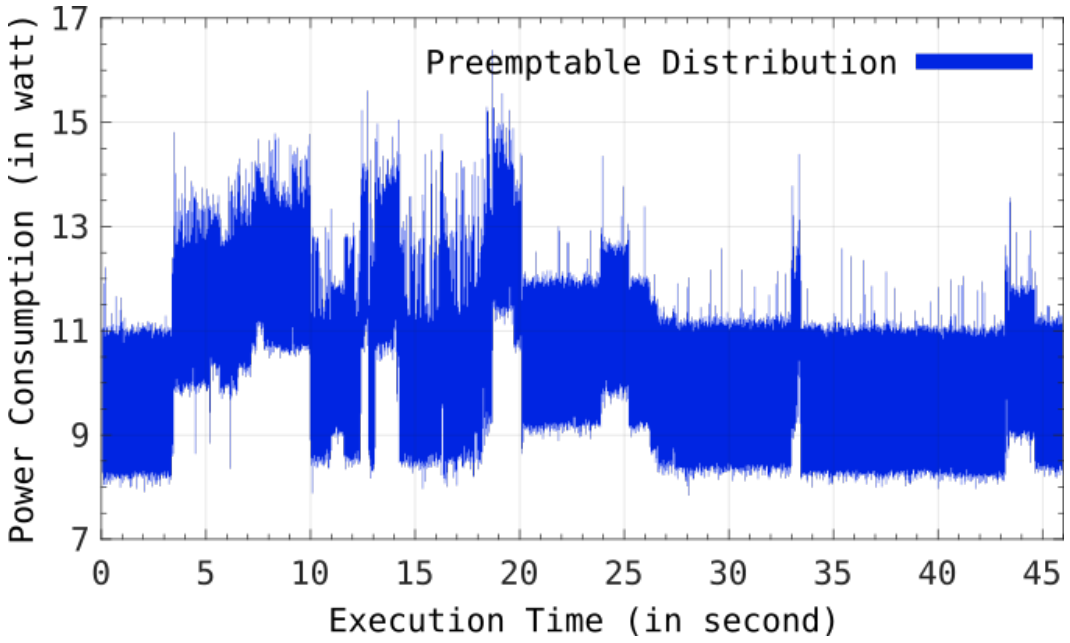


Figure 5.4.: Power consumption on the netbook for the preemptable distribution of the Chesspresso application.

execution time and energy consumption. Compared to the energy consumption of the basic distribution, the overhead of the preemptable distribution is smaller than 2%.

Now, we compare the different approaches on the laptop, giving an insight of the introduced overhead, where Subsection 4.7.2 also describes the evaluation results for a local execution (8.841 s; 408.97 J) and the basic distribution (6.737 s; 244.89 J) of the Chesspresso application on the Jikes RVM. To this end, Figure 5.5 shows the power consumption on the laptop for a preemptable distribution of the Chesspresso application. It takes in total 6.914 s, where the remote execution takes 4.428 s and the laptop receives five safe-points. During the preemptable distribution, the laptop consumes in total 253.85 J resulting in a power consumption of 36.71 W on average. Thus, the preemptable distribution and basic distribution also perform on the laptop similar for the scenario without the occurrence of failures, virtually resulting in the same execution time and power consumption. The relative difference of the preemptable distribution compared to the basic distribution for the consumed energy is only 3.66%.

Summarizing, the relative difference of the basic distribution and the preemptable distribution is very small in a scenario without the occurrence of failures. The reason for the small overhead introduced by safe-point'ing is primarily the small number and size of received safe-points (cf. Algorithm 5.1). As a result, the preemptable distribution still saves a lot of energy compared to a local execution of the Chesspresso application.

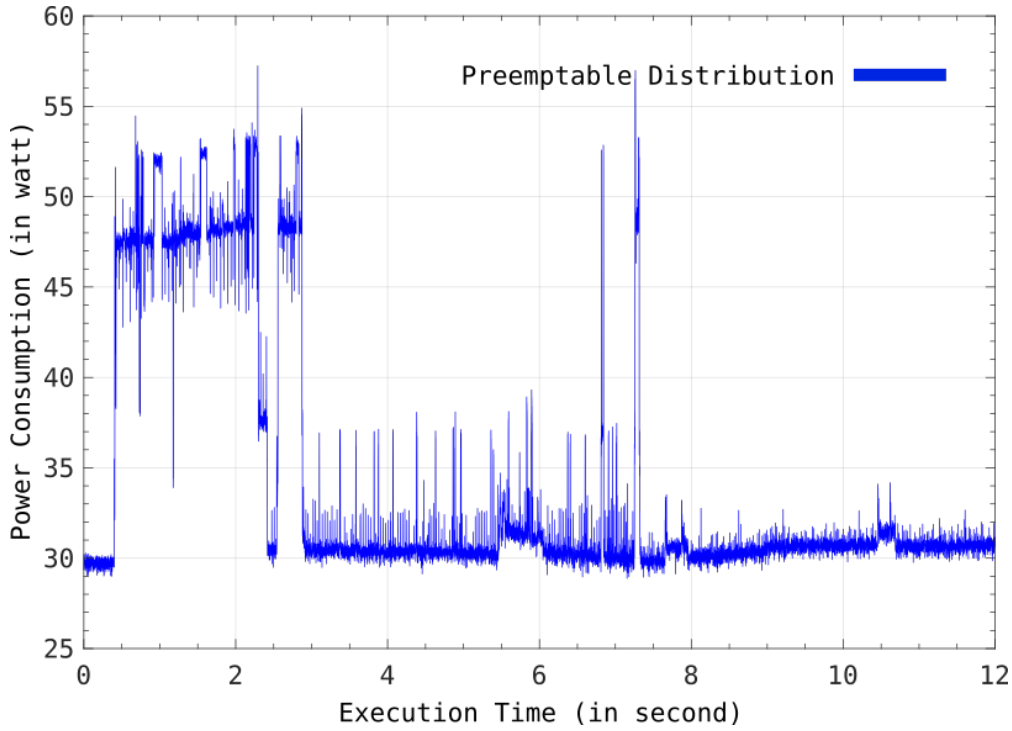
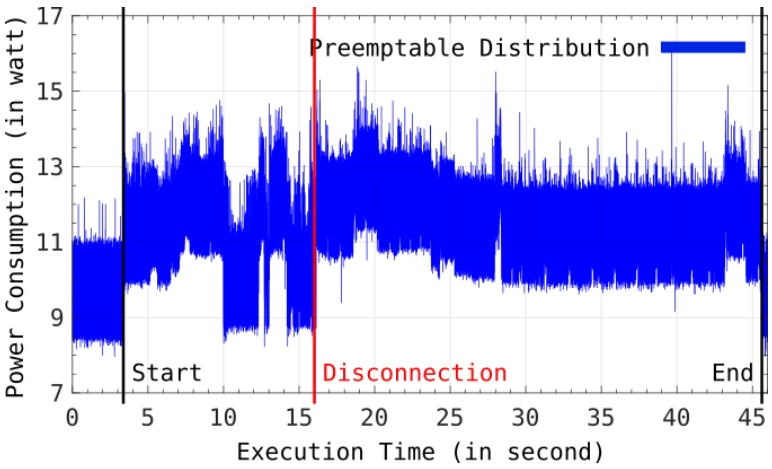


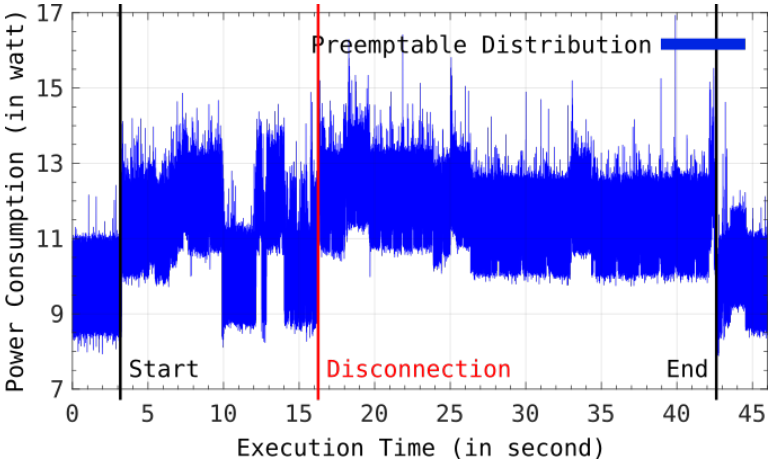
Figure 5.5.: Power consumption on the laptop for the preemptable distribution of the Chesspresso application.

Distributing the Java method with failures: The creation and transmission of safe-points for the preemptable distribution pay off in case of the occurrence of failures, where we consider now different scenarios with the occurrence of failures. Thus, for a distribution of the Java method with the occurrence of failures, we expect the preemptable distribution to be more efficient due to the usage of safe-points than the other approaches not using safe-points. To evaluate the benefits of the preemptable distribution with safe-points, we compare all approaches in multiple scenarios, where disconnections happen at different points in time.

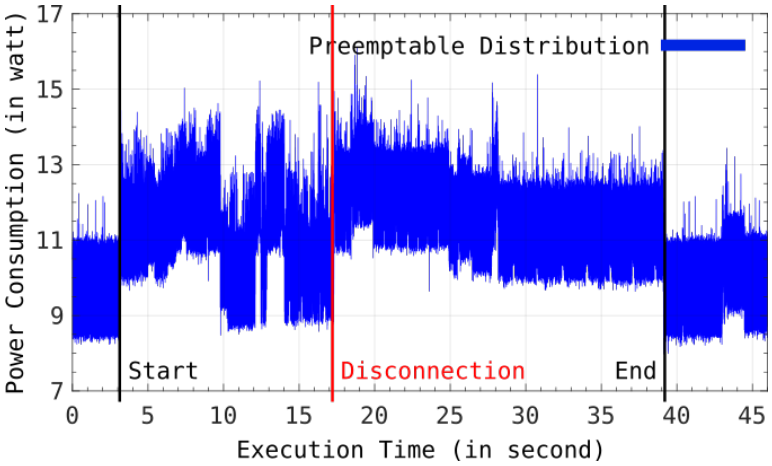
As *BDwRC* waits until a re-connection in case of a failure, it performs equally than the basic distribution described in Subsection 4.7.2 if a disconnection together with a re-connection occurs before the end of a remote execution. In such a scenario, *BDwRC* and the preemptable distribution receive the last safe-point at the end of the remote execution from the offloading service. Receiving the last safe-point from the offloading service, *BDwRC* (basic distribution) performs better than the preemptable distribution, because the preemptable distribution continues the remote execution locally based on the safe-point received last and stops the continuation in case of a re-connection. Depending on the point in time the failure occurs, the duration of the disconnection increases the energy consumption but not the execution time of the preemptable dis-



(a) Failure occurs at $t_e = 16.14\,\text{s}$ with 0 safe-points received.

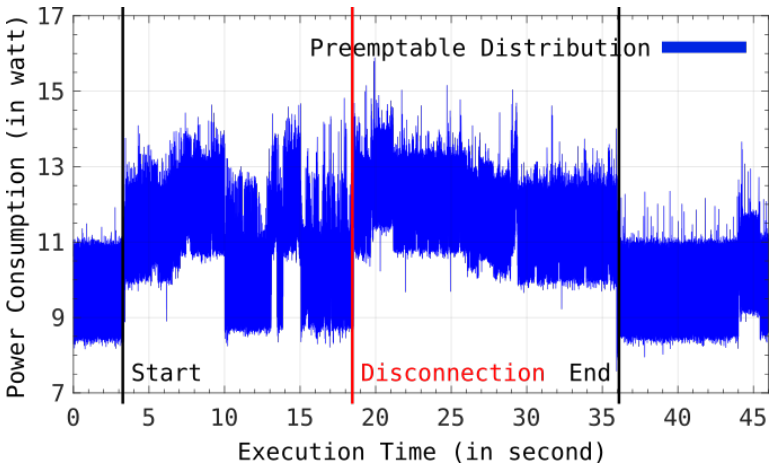


(b) Failure occurs at $t_e = 16.31\,\text{s}$ with 1 safe-point received.

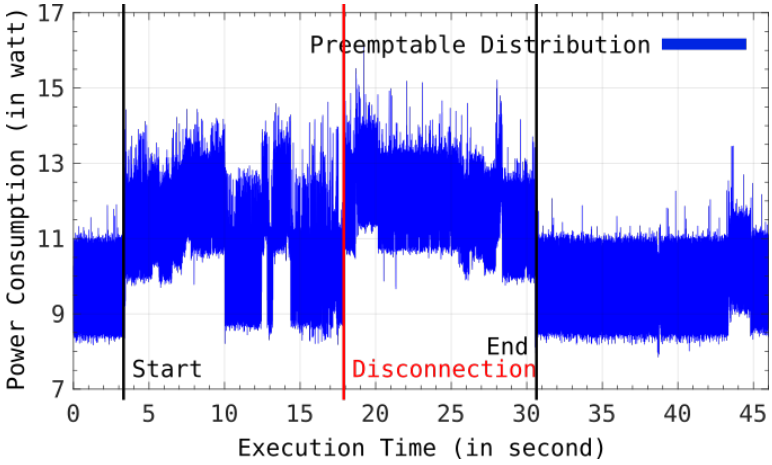


(c) Failure occurs at $t_e = 17.31\,\text{s}$ with 2 safe-points received.

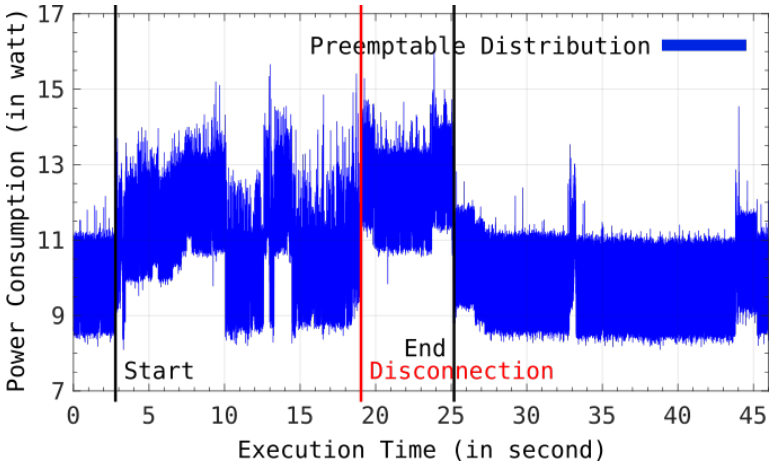
Figure 5.6.: Power consumption on the netbook for a remote execution of the Chesspresso application based on the preemptable distribution, where failures occur at different points in time ($t_e = 16.14\,\text{s}, 16.31\,\text{s}, \text{and } 17.31\,\text{s}$) during the remote execution.



(a) Failure occurs at $t_e = 18.54\,\text{s}$ with 3 safe-points received.



(b) Failure occurs at $t_e = 17.97\,\text{s}$ with 3 safe-points received.



(c) Failure occurs at $t_e = 19.02\,\text{s}$ with 4 safe-points received.

Figure 5.7.: Power consumption on the netbook for a remote execution of the Chesspresso application based on the preemptable distribution, where failures occur at different points in time (t_e = 18.54 s, 17.97 s, and 19.02 s) during the remote execution.

tribution. For instance, in a worst-case scenario for the preemptable distribution on the netbook, a disconnection occurs at 14.60 s and a re-connection at 18.60 s. *BDwRC* (basic distribution) consumes in total 178.00 J, whereas the preemptable distribution consumes in total 221.25 J instead of 181.45 J. The same applies to a disconnection before the end of a remote execution with a re-connection after the end of a remote execution but before the end of a local continuation (preemptable distribution). Depending on the point in time of the re-connection, the continuation of the remote execution on the netbook increases the energy consumption of the preemptable distribution but not the execution time. Actually, the point in time of the re-connection determines whether *BDwRC* and the preemptable distribution stay below the time for a local execution. In contrast to *BDwRC*, the duration of the local continuation and thus, the number of received safe-points determine for the preemptable distribution whether it stays below the time for a local execution. For instance, if the local continuation finishes before 30.00 s and the disconnection is still long in coming, the preemptable distribution stays below the time for a local execution instead of *BDwRC*. To this end, Figure 5.6 and Figure 5.7 show in total six scenarios, where a disconnection occurs at 16.14 s, 16.31 s, 17.31 s, 18.54 s, 17.97 s, and 19.02 s and the offloading client receives 0, 1, 2, 3, 3, and 4 safe-points. Regarding the worst-case scenarios for the preemptable distribution, a re-connection happens just before the local continuation finishes at 45.63 s, 42.55 s, 39.15 s, 36.02 s, 30.55 s, and 25.14 s, where it consumes 81.68 J, 76.43 J, 62.42 J, 51.65 J, 39.34 J, and 21.55 J more energy compared to *BDwRC*.

BDwRE starts a re-execution in case of a failure, where only failures are interesting that occur before the remote execution finishes and last for a longer period. Otherwise, *BDwRE* and the preemptable distribution perform similar apart from safe-point'ing, because both start a local continuation – *BDwRE* from the start and the preemptable distribution from the safe-point received last – and receive the last safe-point at the end of the remote execution. Regarding the scenario with a disconnection at 16.14 s (cf. Figure 5.6a), the preemptable distribution does not receive a safe-point due to the short time of the remote execution. Thus, *BDwRE* and the preemptable distribution perform equally, taking 42.23 s and consuming 467.34 J. For a disconnection at 16.31 s, the preemptable distribution only generates one intermediate safe-point before it continues the execution locally. It takes 39.29 s and consumes 437.83 J compared to 42.54 s and 434.41 J for *BDwRE*. Due to the short period of the remote execution of 2.3 s, the preemptable distribution consumes still more energy than *BDwRE* or a local execution (294.07 J). The preemptable distribution generates more safe-points due to a longer period of the remote execution if the disconnection occurs later. Thus, the energy efficiency of the preemptable distribution further increases while the execution

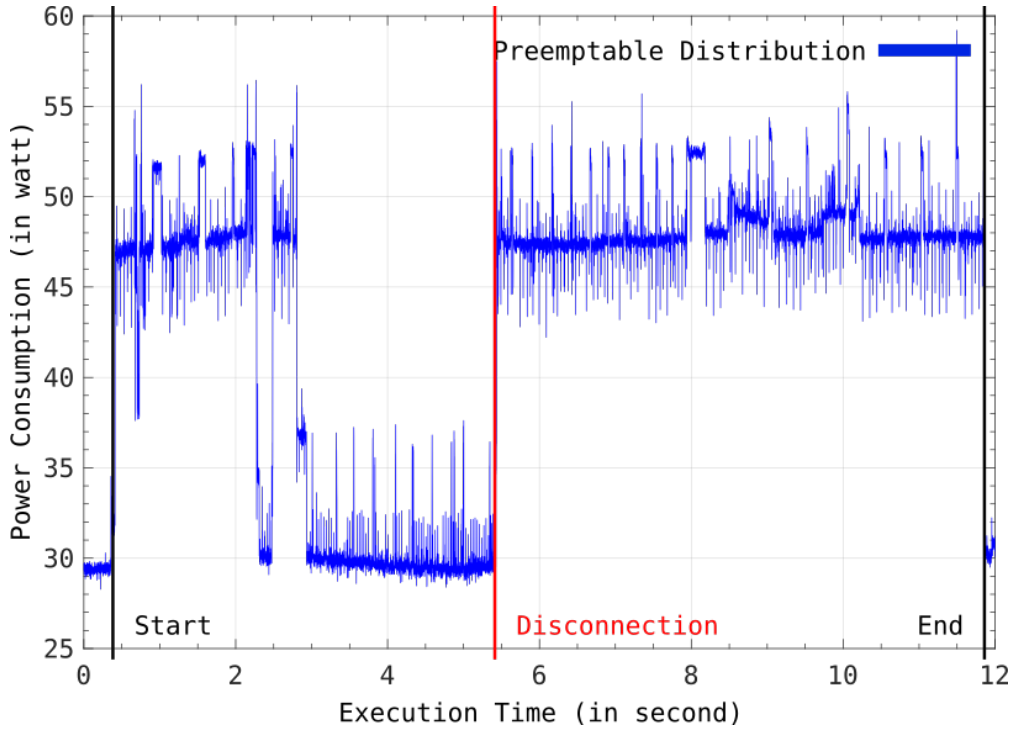


Figure 5.8.: Power consumption on the laptop for a remote execution of the Chesspresso application based on the preemptable distribution, where a failure occurs at $t_e = 5.424\,\text{s}$ with 1 safe-point received.

time further decreases. For a disconnection at 17.31 s, it generates two intermediate safe-points before it continues the execution locally. Based on the two intermediate safe-points, the execution time as well as the energy consumption of the preemptable distribution are smaller than *BDwRE* (36.03 s vs. 43.68 s and 399.59 J vs. 447.14 J), but are higher than a local execution (36.03 s vs. 29.54 s and 399.59 J vs. 294.07 J). Generating four intermediate safe-points for a disconnection at 19.02 s, the preemptable distribution now performs better than a local execution with an execution time of 22.36 s vs. 29.54 s and an energy consumption of 246.14 J vs. 294.07 J. Compared to *BDwRE*, the preemptable distribution reduces the execution time by 23.34 s and the energy consumption by 220.47 J.

On the laptop, the same applies for *BDwRC* and *BDwRE* as for the netbook, described above. In case of a disconnection together with a re-connection before the end of a remote execution, the only difference between *BDwRC* and the preemptable distribution is the local continuation of the remote execution of the preemptable distribution. As a result, the execution time of *BDwRC* and the preemptable distribution is equal, whereas the energy consumption of the preemptable distribution is higher due to the local continuation. For instance, in a worst-case scenario for the preemptable distribution, a disconnection occurs at 2.90 s and a re-connection at 4.40 s, where

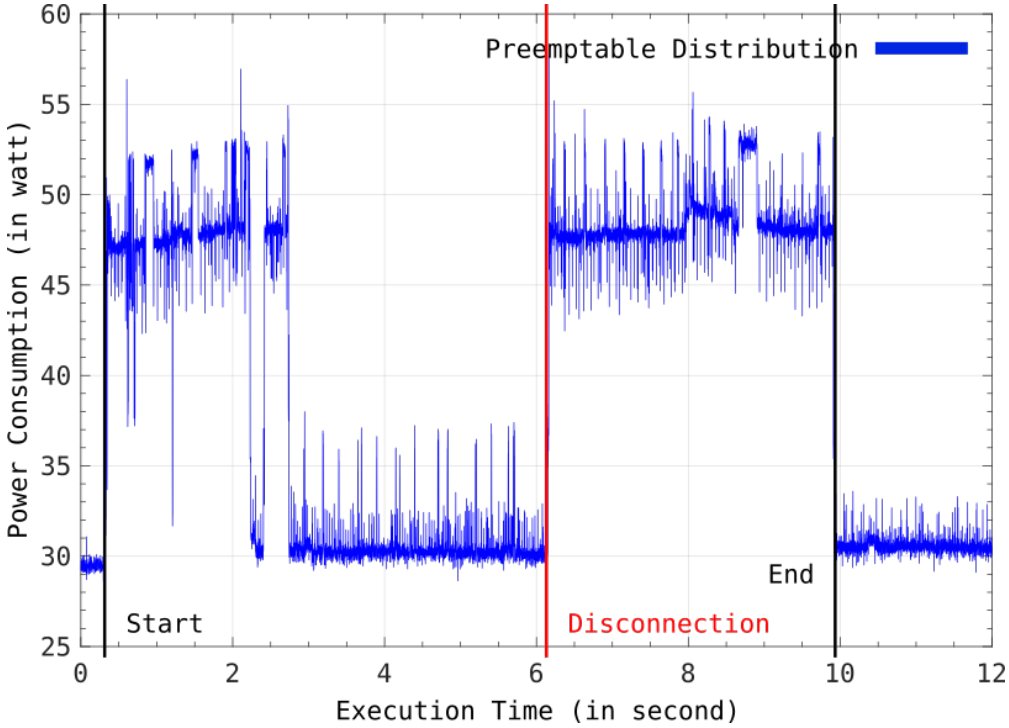


Figure 5.9.: Power consumption on the laptop for a remote execution of the Chesspresso application based on the preemptable distribution, where a failure occurs at $t_e = 6.146\,\mathrm{s}$ with 2 safe-points received.

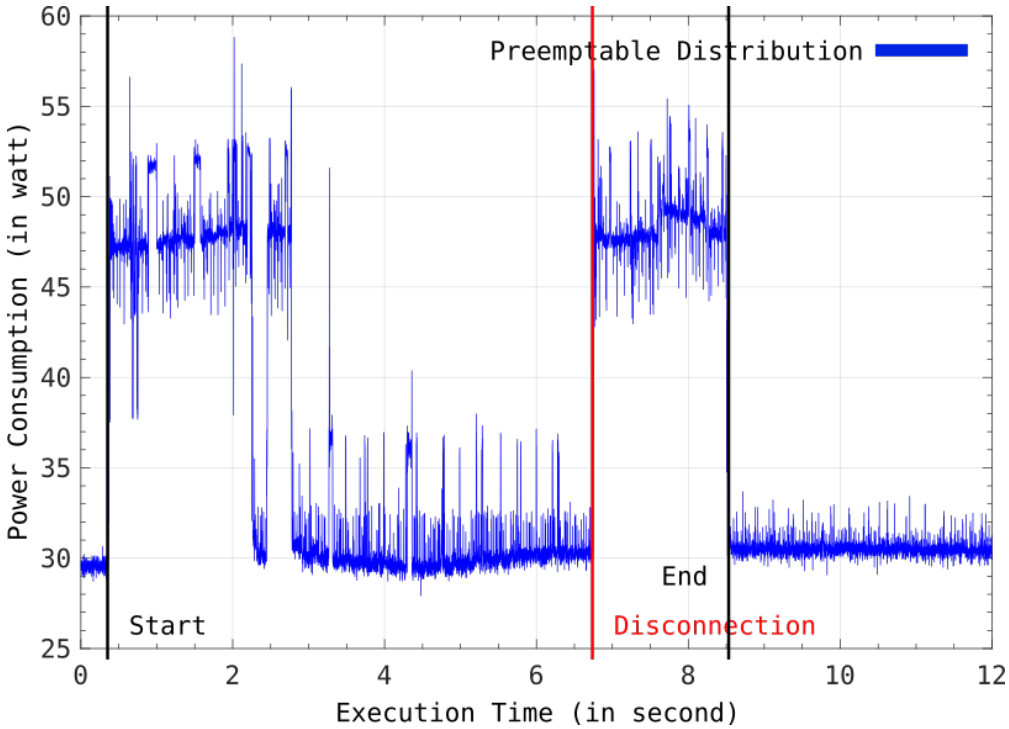


Figure 5.10.: Power consumption on the laptop for a remote execution of the Chesspresso application based on the preemptable distribution, where a failure occurs at $t_e = 6.749\,\mathrm{s}$ with 3 safe-points received.

BDwRC consumes 244.89 J and the preemptable distribution 282.35 J (local execution: 8.841 s and 408.97 J). In case of a disconnection before and a re-connection after the end of a remote execution, the worst-case scenarios for the preemptable distribution against *BDwRC* contain a re-connection just before the local continuation finishes (cf. Figure 5.8 - 5.10). In detail, a re-connection happens just before the local continuation finishes at 11.87 s, 9.93 s, and 8.51 s, where the preemptable distribution consumes 135.25 J, 80.33 J, and 37.42 J more energy.

To this end, we concentrate on disconnections that occur before the remote execution ends and last for a longer period. Figure 5.8, Figure 5.9, and Figure 5.10 show three scenarios, where a disconnection occur at 5.42 s, 6.16 s, and 6.75 s and the offloading client receives 1, 2, and 3 safe-points. In general, the results for the laptop follow the same trend as for the netbook. For short periods of a remote execution until the disconnection, the preemptable distribution is more energy efficient than *BDwRE*. Actually, the preemptable distribution generates one intermediate safe-point for a disconnection at 5.42 s that already leads to a smaller execution time and energy consumption than *BDwRE* (11.46 s vs. 12.56 s and 501.85 J vs. 513.12 J). Compared to a local execution (8.841 s and 408.97 J), the execution time and energy consumption of the preemptable distribution is higher. Again, longer periods of a remote execution pronounce more the savings of the energy consumption and the execution time. For a disconnection at 6.75 s, the preemptable distribution generates three safe-points resulting in an execution time of 8.14 s and an energy consumption of 318.85 J. Thus, it performs better than a local execution and *BDwRE* with an execution time of 8.841 s and 13.88 s and an energy consumption of 408.97 J and 533.65 J, respectively.

Summarizing, for scenarios with the occurrence of failures, the preemptable distribution with safe-points reduces the execution time on the netbook and on the laptop. The reduction of the execution time results from the creation and transmission of safe-points together with a continuation of the local execution. Furthermore, the preemptable distribution stays below the time for a local execution, whereas the two basic approaches *BDwRC* and *BDwRE* do not meet it.

5.6. Summary

To provide a robust code offloading through safe-point'ing, the *preemptable distribution* described in Section 5.1 extends the basic distribution described in Section 4.1. The preemptable distribution re-uses – in case of a failure – the intermediate state of a remote execution so far without abandoning the complete progress executed remotely. As a result, it increases the energy efficiency and responsiveness of the basic distribution

under failures. The *system overview* described in Section 5.2 with the system model, problem statement, and system components corresponds almost to the system overview of the basic distribution, considering safe-point'ing in the problem statement. The basic idea of the preemptable distribution is the interruption and local continuation of a current distribution in case of a failure without losing the partial result calculated remotely so far and avoiding a local re-execution of the complete application part, described in the *offloading timeline* in Section 5.3. A safe-point contains from a remote execution all of the information required to continue a remote execution locally on the offloading client. Thus, an offloading service creates and transmits safe-points to the offloading client during a remote execution whenever it is beneficial in terms of energy consumption. The *offloading framework* described in Section 5.4 provides the additional functionality required for the preemptable distribution on an offloading client and an offloading service. Compared to the offloading framework for the basic distribution (cf. Section 4.5), the changes are mainly on the offload compiler, offload controller, state generator, and failure handler. To evaluate the introduced overhead and gained benefit by the preemptable distribution compared to the basic distribution with common mechanism to handle failures, the *evaluation* described in Section 5.5 presents the evaluation setup and the evaluation results. In detail, a prototype based on the Jikes RVM runs in multiple scenarios, where failures occur at different point in times. Although the creation and transmission of safe-points introduce communication and energy overhead, the evaluation results show that this overhead quickly pays off. Especially, in scenarios with failures, safe-point'ing leads to a lower energy consumption on the evaluated mobile device like a netbook and a laptop. Moreover, the utilization of safe-points for the preemptable distribution also improves the responsiveness of an application by staying below the corresponding time for a local execution under failures.

Chapter 6
Deadline-aware Code Offloading with Predictive Safe-point'ing

The preemptable distribution presented in detail in Chapter 5 improves the efficiency of the basic distribution under failures through the utilization of safe-points. However, the scheduling strategy that determines the point in times for the creation and transmission of a safe-point is not always optimal with regard to efficiency. To improve the efficiency of the preemptable distribution, this chapter presents a predictive distribution described in Section 6.1 that optimizes the schedule of creating and transmitting safe-points. The system overview in Section 6.2 describes the system model, problem statement, and system components for the predictive distribution. On the one hand, the predictive distribution tries to avoid the creation and transmission of safe-points that – considered afterwards – are not needed. In the optimal case, an offloading client only receives one safe-point just before the occurrence of a failure. On the other hand, the predictive distribution ensures a minimal responsiveness of an application execution by adding an additional constraint for the execution time to meet a predefined deadline for the application execution. To this end, the predictive distribution improves the preemptable distribution with an optimal schedule for safe-point'ing described in Section 6.3 by predicting the link connectivity and the remaining runtime. To evaluate the performance of the predictive distribution compared to the preemptable distribution, Section 6.4 presents the evaluation of a simulation, including the evaluation setup and the evaluation results. Last, Section 6.5 summarizes the main facts for a deadline-aware code offloading with predictive safe-point'ing presented in this chapter.

6.1. Predictive Distribution

The approach of the preemptable distribution based on safe-points – described in Chapter 5 – shows the benefits of safe-point'ing the intermediate states of a remote execution. The preemptable distribution uses a scheduling strategy of creating and transmitting

safe-points that is not always optimal with regard to the efficiency of the energy consumed on an offloading client. To improve the basic approach of the preemptable distribution based on safe-points, we propose an optimized schedule of creating and transmitting safe-points based on the following two improvements: First, the optimized schedule tries to avoid the creation and transmission of safe-points that – considered afterwards – are not needed on the offloading client. For instance, receiving two safe-points on the offloading client, the receive of the first safe-point is needless, because no failure occurred in the meanwhile. In the optimal case, an offloading client only receives during a remote execution one safe-point to continue the execution locally just before the occurrence of a failure like a disconnection. Second, the optimized schedule ensures a minimal responsiveness of an application execution by adding an additional constraint for the execution time to meet a predefined deadline for the application execution. These two improvements related to the preemptable approach comprise the design of an adaptive algorithm for scheduling safe-points that adapts dynamically the point in time of creating and transmitting safe-points due to dynamic conditions of the communication network. On the one hand, the optimized schedule creates and transmits fewer safe-points for a communication network where communication failures are less frequent. On the other hand, it creates and transmits more safe-points for a communication network where communication failures are more frequent, being prepared for impending failures. To this end, the improved approach solves a constrained optimization problem. The problem minimizes the overhead for safe-point'ing under a deadline constraint for the execution by using a predictive approach that forecasts the link quality of the communication network and the remaining runtime of the execution.

During the remote execution of an application part that is offloadable, the offload controller on the offloading service determines at the breakpoints introduced for safe-point'ing (cf. Subsection 5.4.2) whether it creates and transmits a safe-point to the offloading client. To improve the decision making for safe-point'ing on the offload controller, it solves a scheduling problem of optimal safe-point'ing under a constraint of the maximum time for the execution using an Integer Linear Program (ILP). The solution of the scheduling problem requires a prediction of the link connectivity and a prediction of the remaining runtime for the execution. The offload controller on the offloading service should intuitively create and transmit a safe-point to the offloading client at the current breakpoint if the probability of a connection loss is high and the remaining runtime for an execution lasts too long until reaching the next breakpoint. Otherwise, it takes the risk to wait until it reaches the next breakpoint and again decides about the creation and transmission of a safe-point. Thus, the offload controller waits for the next breakpoint without the creation and/or transmission of a safe-point if either the

probability of a connection loss is low or the probability of reaching the maximum time for the execution is high. As the creation and transmission of a safe-point is ideally equivalent to switch the execution side from the offloading service to the offloading client, the offload controller only creates and transmits a safe-point if – according to the prediction models – it does not reach the next breakpoint. Subsequently, if the offloading client receives a safe-point from the offloading service, it continues the local execution of an application part based on the safe-point received. The offloading client can theoretically re-distribute the application part – that it continued locally – again to the offloading service after the disconnection. Regarding the typical duration of a disconnection that lasts longer than the typical duration of the remaining execution for an application part, however, a re-distribution is very unlikely.

At the same time, during a remote execution of an application part, the failure handler on the offloading client monitors via the service connector the link to the offloading service as well as the remote service itself. To monitor the link and the service, the failure handler utilizes message probing as well as the receipt of safe-points. Based on the prediction of the remaining runtime for the execution, the failure handler sets a deadline until it has to receive a response or a safe-point from the offloading service to meet the constraint of the maximum time for the execution. Please note that the failure handler sets adaptively the deadline such that a local continuation of a remote execution based on a safe-point received most recently will end before the maximum time for the execution. Thus, if the failure handler does not receive a further safe-point until the deadline set, it invokes the offload controller to continue the remote execution locally based on the safe-point received most recently.

Summarizing, we make the following contributions: (1) A formulation of the problem to optimally schedule safe-point'ing under temporal disconnections of the communication network together with a given deadline constraint for the execution time; (2) an adaptive algorithm that solves the formulated problem with the help of an ILP and a prediction model for the link quality of the communication network and the remaining time of the execution; (3) an implementation of the predictive approach for the preemptable distribution; and (4) an evaluation of the efficiency of the predictive distribution based on simulations, calibrated through energy measurements on mobile devices and through connectivity traces of mobile devices.

6.2. System Overview

The predictive distribution adds to the preemptable distribution an adaptive algorithm based on prediction models for safe-point'ing. Thus, the system model as well as the

system components are same as before (cf. Section 5.2).

The scheduling problem of the predictive distribution improves the preemptable distribution with an adaptive approach for safe-point'ing based on prediction models. Regarding the problem statement of the preemptable distribution (cf. Section 5.2), the predictive distribution adds the additional constraint $T^{max}(A_{\alpha_o}, \Xi(\xi))$ for the execution time. $T^{max}(A_{\alpha_o}, \Xi(\xi))$ is the maximum time tolerated for an execution of the application part A_{α_o} on $\Xi(\xi)$. Due to the constraint added to the problem statement, it meets a deadline predefined for an execution of an application part, ensuring a minimal responsiveness of an application. The offload controller searches for a strategy of the creation and transmission of safe-point(s) that selects the optimal times and numbers for safe-point'ing such that the total consumed energy is minimal under the given time constraint. Formally, the objective is to minimize the cost function f_w under the given constraint of the maximum time for the execution:

$$\begin{aligned} \min_{\xi} \quad & f_w(A_{\alpha_o}, \Xi(\xi)) \\ s.t. \quad & T(A_{\alpha_o}, \Xi(\xi)) \leq T^{max}(A_{\alpha_o}, \Xi(\xi)) \end{aligned} \tag{6.1}$$

As an end user sets the constraint $T^{max}(A_{\alpha_o}, \Xi(\xi))$ of the maximum time for the execution, we set the user-defined weight w_t for the execution time to 0. Moreover, we also set the monetary cost $C(A_{\alpha_o}, \Xi(\xi))$ to 0, because the question of monetary cost charged in case of a failure is left as a remaining open research question[1]. This simplifies the equation as follows:

$$\begin{aligned} \min_{\xi} \quad & w_e \cdot E(A_{\alpha_o}, \Xi(\xi)) \\ s.t. \quad & T(A_{\alpha_o}, \Xi(\xi)) \leq T^{max}(A_{\alpha_o}, \Xi(\xi)) \end{aligned} \tag{6.2}$$

Summarizing, the goal is to find an optimal schedule for the creation and transmission of safe-points that solves the given constrained optimization problem under dynamic network conditions like link failures or varying bandwidth. Please note that both the number of safe-points and the points in time of the creation and transmission of safe-points influence the constrained optimization problem.

[1] For instance, based on a received safe-point, an offloading client has continued the execution locally due to the occurrence of a failure and receives later on the last safe-point of the remote execution from the offloading service due to a re-connection. In case of the offloading client did not finish the execution yet, it utilizes the last safe-point and pays for the whole remote execution as well. In case of the offloading client already finished the execution, it only pays for the partial remote execution for receiving the safe-point to continue the execution locally. As a result, an offloading service may not continue a remote execution in case of the occurrence of a failure, because the offloading client will not pay for it if the result of the remote execution receives too late.

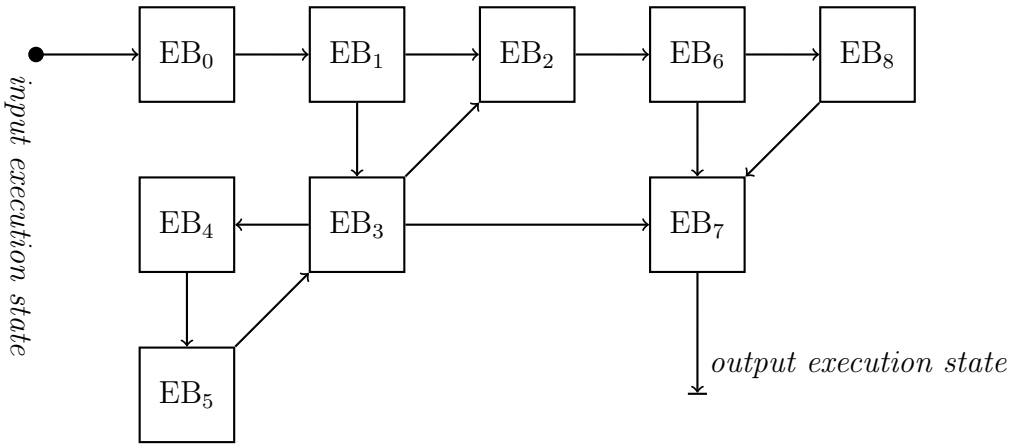


Figure 6.1.: An exemplary execution graph for a Java method at compile-time, divided into nine execution blocks by the offload compiler.

6.3. Optimal Schedule for Safe-point'ing

The goal of the optimal schedule for the creation and transmission of safe-points is to minimize the cost function under the given constraint of the maximum time for an execution. To this end, it models an execution of a Java method (application part) as an execution graph $G = \left(V, E, \varepsilon^v, \varepsilon^{e(u,v)}, \tau^v, \tau^{e(u,v)}\right)$ being a vertex-weighted and edge-weighted graph. The graph-based execution model consists of a set of vertices V, where each $v \in V$ represents an execution block. An execution block corresponds to a sequential execution of code between two breakpoints. Please note that the offload compiler presented in Subsection 5.4.2 inserts a breakpoint before each Java bytecode instruction that branches the execution of a Java method. An edge $e(u, v) \in E$ with $u, v \in V$ defines a transition between execution blocks according to the execution flow of a Java method. Figure 6.1 shows an exemplary execution graph of a Java method that the offload compiler divided into nine execution blocks EB_i with $i = 0, 1, 2, \ldots, 8$. At run-time, a possible execution path is $EB_0 \rightarrow EB_1 \rightarrow EB_2 \rightarrow EB_6 \rightarrow EB_7$.

The execution graph G further defines two weights ε^v and τ^v with $v \in V$ for a vertex and two weights $\varepsilon^{e(u,v)}$ and $\tau^{e(u,v)}$ with $e(u, v) \in E$ and $u, v \in V$ for an edge. The function $\varepsilon^v : V \rightarrow \mathbb{R}$ denotes the energy consumed for an execution of the related execution block. The function $\varepsilon^{e(u,v)} : E \rightarrow \mathbb{R}$ denotes the energy consumed between two execution blocks for distributing the Java method from the offloading client to the offloading service and vice versa (i.e., switching the execution side again). The function $\tau^v : V \rightarrow \mathbb{R}$ denotes the execution time of the related execution block according to the prediction model for the execution time. The function $\tau^{e(u,v)} : E \rightarrow \mathbb{R}$ denotes the time for switching the execution from the offloading client to the offloading service and vice versa, depending on the bandwidth and latency of the network link.

Based on the vertex-weighted and edge-weighted execution graph G, we formulate the problem of the optimal schedule for safe-point'ing as an Integer Linear Program (ILP). Intuitively, the ILP searches for the placement of each execution block from the execution graph G either on the offloading client or on the offloading service, minimizing the cost function and not violating the constraint of the maximum time for the execution of the Java method. To define the placement of an execution block, the ILP uses a binary vector $B \in \{0,1\}^{|V|}$. $B_v = 0$ means an execution of $v \in V$ on the offloading service and $B_v = 1$ means an execution of $v \in V$ on the offloading client. Thus, the optimal solution of the ILP is the placement vector that minimizes the cost function without a constraint violation. Using this placement vector, the following equation expresses the execution time $T(A_{\alpha_o}, \Xi(\xi))$:

$$\begin{aligned} T(A_{\alpha_o}, \Xi(\xi)) \quad = \quad & \sum_{v \in V} \left(B_v \cdot \tau^v_{\Xi(\xi_k)} + (1 - B_v) \cdot \tau^v_{\Xi(\xi_m)} \right) + \\ & \sum_{e(u,v) \in E} |B_u - B_v| \cdot \tau^{e(u,v)}_{B_u, B_v} \end{aligned} \tag{6.3}$$

where $\tau^v_{\Xi(\xi_k)}$ is the time for a local execution if the optimal solution places the execution block v on the offloading client $\Xi(\xi_k)$. Otherwise, it adds the time $\tau^v_{\Xi(\xi_m)}$ for a remote execution if the offloading service $\Xi(\xi_m)$ executes the execution block v. The second term defines the time for switching the execution side, where the optimal solution adds this switching time if the execution blocks $u, v \in V$ are on different sides. Beside the execution time, the ILP also requires the energy consumption $E(A_{\alpha_o}, \Xi(\xi))$:

$$\begin{aligned} E(A_{\alpha_o}, \Xi(\xi)) \quad = \quad & \sum_{v \in V} \left(B_v \cdot \varepsilon^v_{\Xi(\xi_k)} + (1 - B_v) \cdot (\tau^v_{\Xi(\xi_m)} \cdot E^{\Xi(\xi_k)}_{wait}) \right) + \\ & \sum_{e(u,v) \in E} |B_u - B_v| \cdot \varepsilon^{e(u,v)}_{B_u, B_v} \end{aligned} \tag{6.4}$$

where $\varepsilon^v_{\Xi(\xi_k)}$ is the energy consumed for a local execution if the optimal solution places the execution block v on the offloading client $\Xi(\xi_k)$. Otherwise, it adds the energy consumed of the offloading client waiting in idle mode if the offloading service $\Xi(\xi_m)$ executes the execution block v. The second term of the equation defines the energy consumed for switching the execution side from u to v that includes the creation and transmission of a safe-point. Thus, if the block placement of $u, v \in V$ differs – for instance, u on the offloading client and v on the offloading service, or vice versa, the optimal solution has to add the energy cost for switching the execution side.

Regarding Equation 6.3 and Equation 6.4, the execution time and the energy consumption depend on the time taken and the energy consumed for each individual

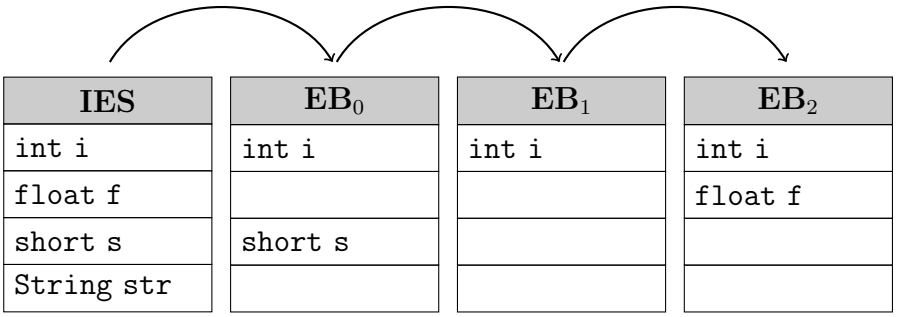


Figure 6.2.: An exemplary modification of variables for each execution block.

execution block $v \in V$. The execution blocks differ in the number and kind of the executed Java bytecode instructions (computational complexity), where the execution time of the same execution block differs on the offloading client and on the offloading service. Thus, we express the energy consumed and the time taken for an execution block $v \in V$ as follows:

$$\begin{aligned} \tau^{v}_{\Xi(\xi)} &= \frac{P^{exe}_{pcode}\left(I_{state}(A_\alpha), P^{v}_{pcode}(A_\alpha)\right)}{P^{\Xi(\xi)}_{ppwr}} \\ \varepsilon^{v}_{\Xi(\xi)} &= \tau^{v}_{\Xi(\xi)} \cdot E^{\Xi(\xi_k)}_{exec} \end{aligned} \tag{6.5}$$

where $P^{\Xi(\xi)}_{ppwr}$ is the processing power of a resource $\Xi(\xi)$, $E^{\Xi(\xi_k)}_{exec}$ the energy factor for executing code, and $P^{exe}_{pcode}(I_{state}(A_\alpha), P_{pcode}(A_\alpha))$ the load metric (cf. Section 3.1). Please note that the offloading framework calibrates $P^{\Xi(\xi)}_{ppwr}$ through online benchmarks, where we calibrate $E^{\Xi(\xi_k)}_{exec}$ for the offloading framework through offline measurements.

Beside the energy consumed and the time taken for each individual execution block, Equation 6.3 and Equation 6.4 require the time taken and the energy consumed for a switch of the execution side. The size of a safe-point determines the consumed energy and the taken time, where the size depends on the variables modified since the safe-point transmitted last (incremental safe-point'ing). For instance, the offloading client distributes a Java method (cf. Figure 6.1), sending the input execution state (first safe-point) to the offloading service. The offloading service starts the execution of the Java method based on the first safe-point (at node *input execution state*). Now, the optimal schedule for safe-point'ing determines to switch the execution side from the offloading service to the offloading client between the execution blocks EB_2 and EB_6. To this end, it requires all variables modified since the offloading service started the execution ($EB_0 \rightarrow EB_2$). Figure 6.2 shows an exemplary modification of variables, where a safe-point contains the variables `i` (EB_2), `f` (EB_2), and `s` (EB_0).

As a result, the last synchronization of the execution state through safe-point'ing S_{i-1} with $i \geq 1$ determines the energy consumed and the time taken for a switch of the execution side. Please note that S_0 equals to the execution state contained in the first safe-point at the start of the execution on the offloading service (input execution state). The following equation defines the time taken $\tau_{B_u,B_v}^{e=(u,v)}$ for a switch of the execution side, where the offloading service executes $u \in V$ and the offloading client $v \in V$:

$$\tau_{B_u,B_v}^{e=(u,v)} = \delta(S_i, S_{i-1}) \cdot B_{down}^{\Lambda(\xi_k;\xi_m)} + L_{down}^{\Lambda(\xi_k;\xi_m)} \tag{6.6}$$

The function $\delta(S_i, S_{i-1})$ calculates the size of the incremental safe-point'ing. Moreover, $B_{down}^{\Lambda(\xi_k;\xi_m)}$ is the bandwidth and $L_{down}^{\Lambda(\xi_k;\xi_m)}$ the latency of the link $\Lambda(\xi_k;\xi_m)$ between the offloading client and the offloading service (cf. Section 3.1). Please note that for a switch of the execution side from the offloading client to the offloading service only the bandwidth $B_{up}^{\Lambda(\xi_k;\xi_m)}$ and the latency $L_{up}^{\Lambda(\xi_k;\xi_m)}$ changes.

The following equation defines the energy consumed $\varepsilon_{B_u,B_v}^{e=(u,v)}$ for a switch of the execution side between the execution blocks $u, v \in V$. The offloading service executes u and the offloading client v, hence receiving a safe-point on the offloading client:

$$\varepsilon_{B_u,B_v}^{e=(u,v)} = \tau_{B_u,B_v}^{e=(u,v)} \cdot E_{recv}^{\Xi(\xi_k)} \tag{6.7}$$

where $E_{recv}^{\Xi(\xi_k)}$ is the energy consumed for receiving bytes (cf. Section 3.1).
Summarizing, the optimal schedule solves the following ILP for the creation and transmission of safe-points on the offloading service:

$$\begin{aligned}
\min \quad & \sum_{v \in V} \left(B_v \cdot \frac{P_{pcode}^{exe}\left(I_{state}(A_\alpha), P_{pcode}^{v}(A_\alpha)\right)}{P_{ppwr}^{\Xi(\xi_k)}} \cdot E_{exec}^{\Xi(\xi_k)} + \right. \\
& \qquad \left. (1 - B_v) \cdot \frac{P_{pcode}^{exe}\left(I_{state}(A_\alpha), P_{pcode}^{v}(A_\alpha)\right)}{P_{ppwr}^{\Xi(\xi_m)}} \cdot E_{wait}^{\Xi(\xi_k)} \right) + \\
& \sum_{e(u,v) \in E} \left(|B_u - B_v| \cdot \left(\delta(S_i, S_{i-1}) \cdot B_{down}^{\Lambda(\xi_k;\xi_m)} + L_{down}^{\Lambda(\xi_k;\xi_m)} \right) \cdot E_{recv}^{\Xi(\xi_k)} \right) \\
s.t. \quad & \sum_{v \in V} \left(B_v \cdot \frac{P_{pcode}^{exe}\left(I_{state}(A_\alpha), P_{pcode}^{v}(A_\alpha)\right)}{P_{ppwr}^{\Xi(\xi_k)}} + \right. \\
& \qquad \left. (1 - B_v) \cdot \frac{P_{pcode}^{exe}\left(I_{state}(A_\alpha), P_{pcode}^{v}(A_\alpha)\right)}{P_{ppwr}^{\Xi(\xi_m)}} \right) + \\
& \sum_{e(u,v) \in E} \left(|B_u - B_v| \cdot \left(\delta(S_i, S_{i-1}) \cdot B_{down}^{\Lambda(\xi_k;\xi_m)} + L_{down}^{\Lambda(\xi_k;\xi_m)} \right) \right) \\
& \leq T^{max}(A_{\alpha_o}, \Xi(\xi))
\end{aligned} \tag{6.8}$$

6.3.1. Prediction of Link Connectivity

The solution of the ILP presented above depends on the knowledge of the bandwidth $B^{\Lambda(\xi_k;\xi_m)}$ and the latency $L^{\Lambda(\xi_k;\xi_m)}$ of the link $\Lambda(\xi_k;\xi_m)$ between the offloading client and the offloading service. To this end, the optimal schedule uses a prediction model of the link based on Markov chains. Researchers widely use Markov chains for the prediction of the link quality like in [ZWG+13], because a Markov chain requires a low memory space together with a low computational complexity. A Markov chain is a stochastic process with an initial state of a state space, where a transition describes the change from a state to another state based on a transition probability. A transition matrix outlines the transition probabilities of a Markov chain that satisfies the Markov property. Fulfilling the Markov property, a Markov chain predicts the future of a stochastic process solely based on its current state. Thus, the transition probability for switching from a state into another state only depends on the current state and not on the state history of past transitions. Formally, let the pair $(\Omega, \mathcal{F})$ be a measurable space with the sample space Ω and the σ-algebra $\mathcal{F}$. The set Ω contains all possible outcomes, where an outcome represents for a single execution the output. The collection $\mathcal{F}$ is a subset of Ω that contains the considered events, where an event is a set of zero or more outcomes. Moreover, let the triplet $(\Omega, \mathcal{F}, \mathbb{P})$ be the probability space with the probability measure $\mathbb{P}$ that returns an event's probability and thus, is the function $\mathbb{P} : \mathcal{F} \to [0, 1]$. Based on the measurable space $(\Omega, \mathcal{F})$, the filtration $\{\mathcal{F}_t\}_{t\geq 0}$ with $\mathcal{F}_t \subseteq \mathcal{F}$ and $t \in T$ fulfills $t_1 \leq t_2 \implies \mathcal{F}_{t_1} \subseteq \mathcal{F}_{t_2}$, where the index set T equals $\mathbb{R}_{\geq 0} = \{r \in \mathbb{R} | r \geq 0\}$. [Ste94, Str13]

An $(\Omega, \mathcal{F})$-valued stochastic process $X = (X_t, t \in T)$ fulfills the Markov property if

$$\mathbb{P}(X_l \in A | \mathcal{F}_k) = \mathbb{P}(X_l \in A | X_k) \tag{6.9}$$

is true $\forall\ A \in \mathcal{F}$ and $\forall\ k, l \in T$ with $k < l$. For a Markov chain with a discrete time where T equals $\mathbb{N}^0 = \{0, 1, 2, \dots\}$ and a finite space of discrete states where $\mathcal{F}$ is a discrete set (called a Discrete-Time Markov Chain (DTMC)) the Markov property is:

$$\mathbb{P}(X_n = x_n | X_{n-1} = x_{n-1}, X_{n-2} = x_{n-2}, \dots, X_0 = x_0) = \mathbb{P}(X_n = x_n | X_{n-1} = x_{n-1})$$

To build the prediction model of the link based on a Markov chain, the optimal schedule considers the bandwidth and latency of past connections from the offloading client. As a result, the offloading client does not measure in parallel the bandwidth and latency to an offloading service, keeping the (energy) overhead introduced to the system low. The optimal schedule maps the continuous values for the bandwidth and latency moni-

tored from past connections onto n discrete quality classes of the link. For instance, an interpretation of the mapping to the five latency classes $[0\,\text{ms}, 50\,\text{ms}]$, $(50\,\text{ms}, 100\,\text{ms}]$, $(100\,\text{ms}, 200\,\text{ms}]$, $(200\,\text{ms}, 300\,\text{ms}]$, and $(300\,\text{ms}, \infty]$ is "very low latency", "low latency", "medium latency", "high latency", and "disconnected". Likewise, possible quality classes for the link bandwidth are, for instance, $[0\,\text{kbit/s}, 50\,\text{kbit/s}]$, $(50\,\text{kbit/s}, 350\,\text{kbit/s}]$, $(350\,\text{kbit/s}, 700\,\text{kbit/s}]$, $(700\,\text{kbit/s}, 1050\,\text{kbit/s}]$, and $(1050\,\text{kbit/s}, \infty]$, interpreted as "disconnected", "very low bandwidth", "low bandwidth", "medium bandwidth", and "high bandwidth". Based on the discrete quality classes for the bandwidth and for the latency of the link, the optimal schedule models each direction (downstream and upstream) of the link as an DTMC with a finite state space $Q^{B,L}$ of n^2 states. For instance, the finite state space for the above-described quality classes consists of 25 states. The variable p_{ij} with $i, j = [0, 1, \ldots, m]$ and $m = n - 1$ represents the transition probabilities between a state $Q_i^{B,L}$ and a state $Q_j^{B,L}$, resulting in the following transition matrix P:

$$P = \begin{pmatrix} p_{00} & p_{01} & \cdots & p_{0m} \\ p_{10} & p_{11} & \cdots & p_{1m} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m0} & p_{m1} & \cdots & p_{mm} \end{pmatrix} \tag{6.10}$$

where the time duration spent in each state is a non-negative natural number (e.g., with a time step size of 500 ms). Moreover, we assume that the probability of a link failure and a corresponding link recovery is exponentially distributed, fulfilling the Markov property (cf. Nicholson et al. [NN08]). Based on the transition rates, we calculate iteratively the mean recurrence time M_{ii} and the mean first passage time M_{ij}. The mean first passage time M_{ij} represents the number of steps expected that the stochastic process takes for reaching node j from node i for the first time:

$$M^{(k+1)} = E + P * (M^{(k)} - diag\{M^{(k)}\}) \tag{6.11}$$

with

$$M^{(k)} = \begin{pmatrix} m_{00}^{(k)} & m_{01}^{(k)} & \cdots & m_{0s}^{(k)} \\ m_{10}^{(k)} & m_{11}^{(k)} & \cdots & m_{1s}^{(k)} \\ \vdots & \vdots & \ddots & \vdots \\ m_{s0}^{(k)} & m_{s1}^{(k)} & \cdots & m_{ss}^{(k)} \end{pmatrix} \qquad diag\{M^{(k)}\} = \begin{pmatrix} m_{00}^{(k)} & 0 & \cdots & 0 \\ 0 & m_{11}^{(k)} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & m_{ss}^{(k)} \end{pmatrix}$$

where $M^{(0)} = E$ and E denote the identity matrix. [Ste94]

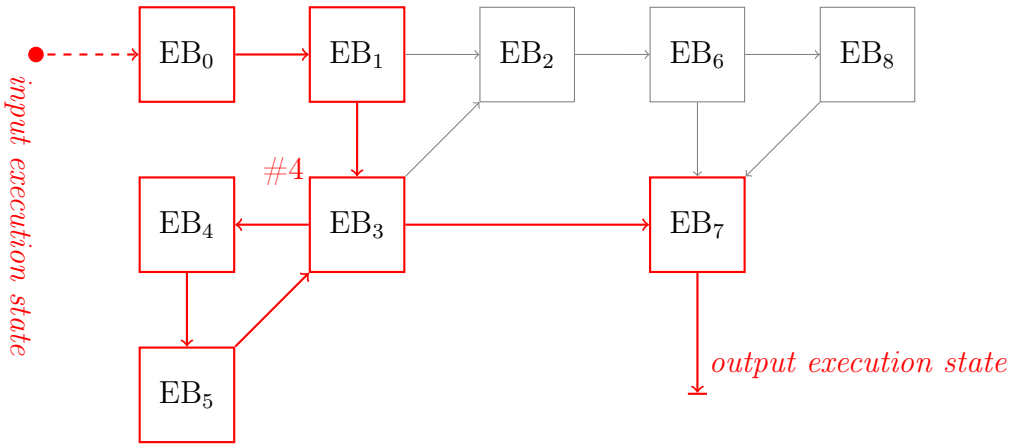


Figure 6.3.: An exemplary execution graph (red flow) for a Java method at run-time, executing a loop four times.

Summarizing, the offload controller on the offloading service predicts the time-dependent connectivity factors of the bandwidth $B^{\Lambda(\xi_k;\xi_m)}$ and the latency $L^{\Lambda(\xi_k;\xi_m)}$ based on the prediction models from Markov chains. By summing up the values for the bandwidth and for the latency, it results in the time-invariant factors for the quality class b with $b = 0, 1, \ldots, m$ of the bandwidth and l with $l = 0, 1, \ldots, m$ of the latency:

$$B^{\Lambda(\xi_k;\xi_m)} = \sum_{c=0}^{m} m_{bc}^{\infty} \qquad L^{\Lambda(\xi_k;\xi_m)} = \sum_{c=0}^{m} m_{cl}^{\infty}$$

6.3.2. Prediction of Remaining Runtime

Beside the prediction of the link connectivity for the solution of the ILP presented above, the solution of the ILP also depends on the prediction of the remaining runtime for an execution of a Java method on the offloading client as well as on the offloading service. To this end, the optimal schedule uses a prediction model of the execution time to satisfy the constraint of the maximum time for the execution. The prediction model predicts the path for an execution – more precisely, the sequence of execution blocks – of a Java method based on the input execution state. To build the prediction model of execution paths, the optimal schedule monitors past executions of the Java method, retrieving the sequence of blocks executed for the input execution state (history-based approach). Like the app profiler for the basic distribution (cf. Subsection 4.5.2), it utilizes a k-Nearest Neighbors algorithm to profile the sequence of blocks executed for a Java method based on the input execution state. For instance, Figure 6.3 highlights an exemplary execution graph executed at run-time for a Java method (cf. Figure 6.1)

that executes the loop $EB_3 \rightarrow EB_4 \rightarrow EB_5$ four times. Based on the prediction model of execution paths, the optimal schedule predicts the sequence of execution blocks for a Java method. During the execution of the Java method, the offload controller on the offloading service keeps track of execution blocks already executed, knowing at each breakpoint the number and kind of individual execution blocks that the offloading service or the offloading client still has to execute. As a result, it calculates the remaining time for an execution of remaining execution blocks on the offloading service or on the offloading client based on Equation 6.5.

6.4. Evaluation

The performance of the predictive distribution relies on multiple parameters like network quality, energy characteristics of mobile devices, or application complexity. To this end, we implemented a simulation in MATLAB[2] to analyze the performance for a wide range of parameter combinations. To provide a realistic evaluation based on the MATLAB simulation, however, real-world measurements of the connectivity quality from communication networks, energy consumed on mobile devices, and execution times of applications calibrate the parameters used within the MATLAB simulation. Thus, the evaluation gains results under realistic circumstances, where the MATLAB simulation runs different scenarios. First, Subsection 6.4.1 describes the evaluation setup before Subsection 6.4.2 presents the evaluation results.

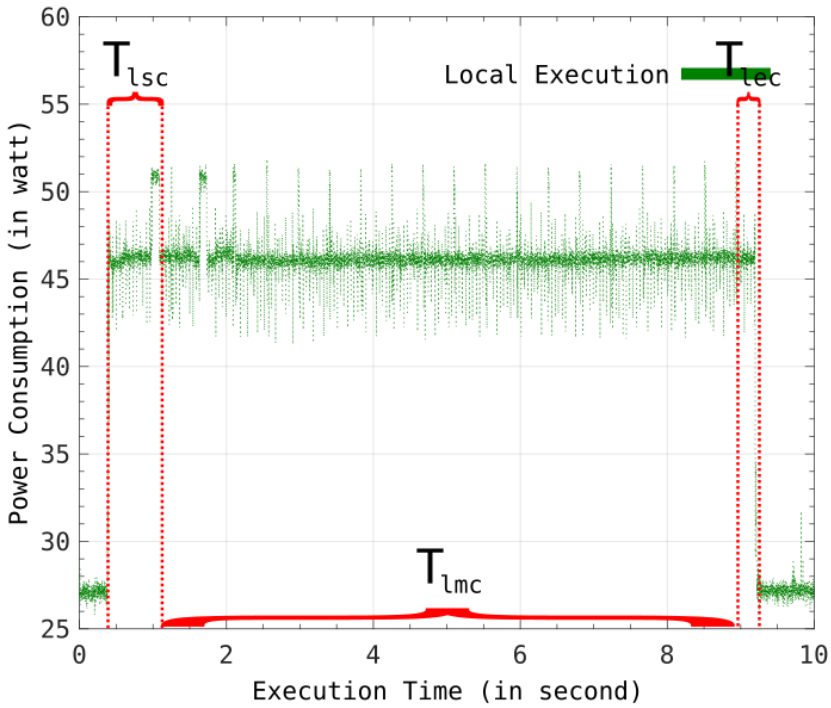
6.4.1. Setup

The evaluation of the optimal schedule for the predictive distribution with safe-points uses the same setup presented in Subsection 5.5.1 with the following differences.

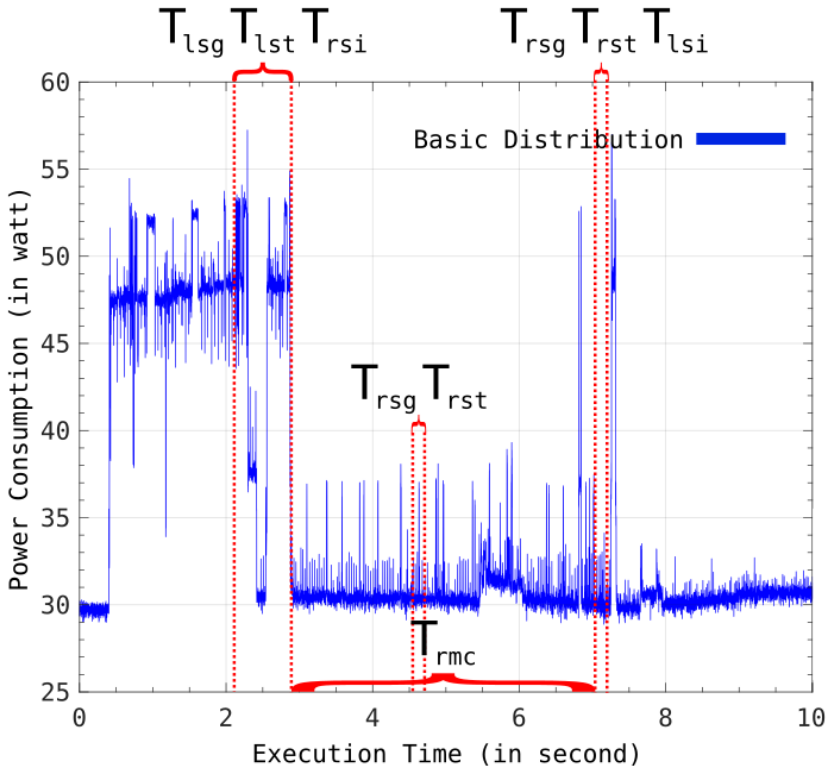
Beside the Chesspresso application already considered for the preemptable distribution (cf. Section B.2), the evaluation further considers a face recognition application presented in detail in Section B.4. The face recognition application recognizes human faces in an image. In detail, it is a good candidate for a distribution, because it has a high complexity of computation, a huge size of the input execution state, a small size of safe-points, and a small size of the output execution state.

In order to solve the given ILP in Equation 6.8, the offloading service uses the standard solver from MATLAB that is highly optimized and quickly solves the problem in a few milliseconds keeping the overhead introduced to the offloading service small. In detail, the time overhead of the standard solver from MATLAB executed on the

[2] `https://www.mathworks.com/products/matlab.html`



(a) Power consumption on the laptop for a local execution of the Chesspresso application.



(b) Power consumption on the laptop for a remote execution of the Chesspresso application.

Figure 6.4.: Power consumption on the laptop for (a) a local execution and (b) a remote execution of the Chesspresso application, highlighting the timing parameters for the predictive distribution.

Figure 6.5.: A section of the topographic map from the public transport of Stuttgart (Germany), where the red line highlights the rail between the station "Universität Stuttgart" and "Schwabstraße".

offloading service for solving the ILP is less than 50 ms for the Chesspresso application or for the face recognition application. The MATLAB simulation takes several timing parameters into account, basically depending on the processor speed of the device, the computational complexity of the application, and the data rate of the communication link. To this end, we calibrated the timing parameters through the execution of both applications on the Jikes RVM prototype for the preemptable distribution on both devices. Beside the timing parameters, we also measured the energy consumed for the execution of the application code on the offloading client and on the offloading service (cf. Section 4.7). The measurements of the timing parameters and the energy consumption on the physical devices provide a realistic basis for the simulation. Table 6.1 summarizes and Figure 6.4 outlines the timing parameters. In detail, T_{lsc} is the time until the execution reaches the Java method that is offloadable. T_{lec} and T_{rmc} are the time for an execution of the Java method on the offloading client and on the offloading service. T_{lsg} and T_{lst} are the time for the creation of the input execution state (first safe-point) on the offloading client and the transmission of the first safe-point from the offloading client to the offloading service. Similarly, T_{rsg} and T_{rst} are the time for the creation of a safe-point on the offloading service and the transmission of a safe-point from the offloading service to the offloading client. T_{lsi} and T_{rsi} are the time for the installation of a safe-point on the offloading client and on the offloading service. Finally, T_h defines the constraint of the maximum time for the application execution, which we set lower for the Chesspresso application than for the face recognition application. We set T_h according to the execution time of the applications on the offloading client.

Table 6.1.: Timing parameters calibrated on real-world measurements for the evaluation of the predictive distribution with safe-points.

Name	**Description**	**Chesspresso Application**		**Face Recognition Application**	
		Netbook	Laptop	Netbook	Laptop
T_h	Maximum time for the application execution	40.000 s	10.000 s	50.000 s	30.000 s
t_s	Granularity of the time slot	0.001 s			
T_{lsc}	Execution time for reaching the offloadable Java method	5.797 s	1.421 s	2.903 s	1.684 s
T_{lmc}	Execution time for a local execution of the Java method	27.705 s	7.307 s	39.158 s	21.728 s
T_{rmc}	Execution time for a remote execution of the Java method	4.249 s		6.594 s	
T_{lec}	Execution time for reaching the end of the application	0.778 s	0.110 s	5.806 s	3.261 s
T_{lsg}	Time of generating the input execution state	1.146 s	0.655 s	3.182 s	1.746 s
T_{lst}	Time of transmitting the input execution state to remote side	0.100 s		3.385 s	
T_{lsi}	Time of installing a safe-point locally	0.157 s	0.014 s	0.128 s	0.015 s
T_{rsg}	Time of generating a safe-point on the remote side	0.029 s		0.024 s	
T_{rst}	Time of transmitting a safe-point to the client	0.010 s		0.009 s	
T_{rsi}	Time of installing the input execution state remotely	0.327 s		0.083 s	

Beside the execution time and energy consumption, the simulation requires connectivity parameters of the network link. To this end, we measured the network connectivity in the cellular networks of the providers O_2 and T-Mobile. We measured the connectivity traces at different days while riding a train of the public transport from Stuttgart, Germany (cf. Figure 6.5). To retrieve the connectivity traces, a mobile device pings periodically via a cellular connection a server at the University of Stuttgart connected to the Internet through the fixed university network. Based on the connectivity traces measured for the cellular network of O_2 and T-Mobile, the offloading service builds the prediction models with the help of Markov chains. Equation 6.12 outlines the prediction model for the cellular network of T-Mobile and Equation 6.13 of O_2, differing significantly in the occurrence and duration of disconnections:

$$P = \begin{pmatrix} 0.8861 & 0.1139 \\ 0.1950 & 0.8051 \end{pmatrix} \qquad M_{ij}^{(\infty)} = \begin{pmatrix} 1.5842 & 8.7826 \\ 5.1304 & 2.7119 \end{pmatrix} \tag{6.12}$$

$$P = \begin{pmatrix} 0.9859 & 0.0141 \\ 0.1081 & 0.8919 \end{pmatrix} \qquad M_{ij}^{(\infty)} = \begin{pmatrix} 1.1307 & 70.7500 \\ 9.2500 & 8.6486 \end{pmatrix} \tag{6.13}$$

Informally, the quality of the cellular network is higher for T-Mobile in comparison to O_2 (cf. $M_{01}^{(\infty)}$ of Equation 6.12 and 6.13). Due to the significance of the prediction models for the connectivity, we evaluated the accuracy of the applied Markovian model, dividing the real-world traces of the connectivity into a training set and a test set. Based on the training set and the test set, we built the Markov model on the training set and evaluated it against the test set. In average, the (simple) stochastic model based on Markov chains predict the quality of the cellular network in 65% properly.

To evaluate the performance and efficiency of the predictive distribution called *Predictive*, the evaluation compares it with a local execution, the basic distribution with a re-execution in case of a failure called *Baseline*, the preemptable distribution with periodic safe-point'ing called *Periodic*, and an optimal distribution called *Optimal*. A local execution executes the application locally on the mobile device without code offloading. *Baseline* uses a basic strategy at the occurrence of a failure by re-executing the offloaded Java method as soon as a disconnection occurs like in [KT12]. *Periodic* uses a static schedule (i.e., non-predictive and non-optimized) for the creation and transmission of safe-points, where the offloading client receives from the offloading service a safe-point at an application-specific time interval predefined to 1 s for the evaluation. As a reference, *Optimal* uses a perfect schedule for safe-point'ing knowing in advance the point in times for a disconnection as well as its duration. Please note that an optimal distribution with a perfect schedule is only achieved theoretically.

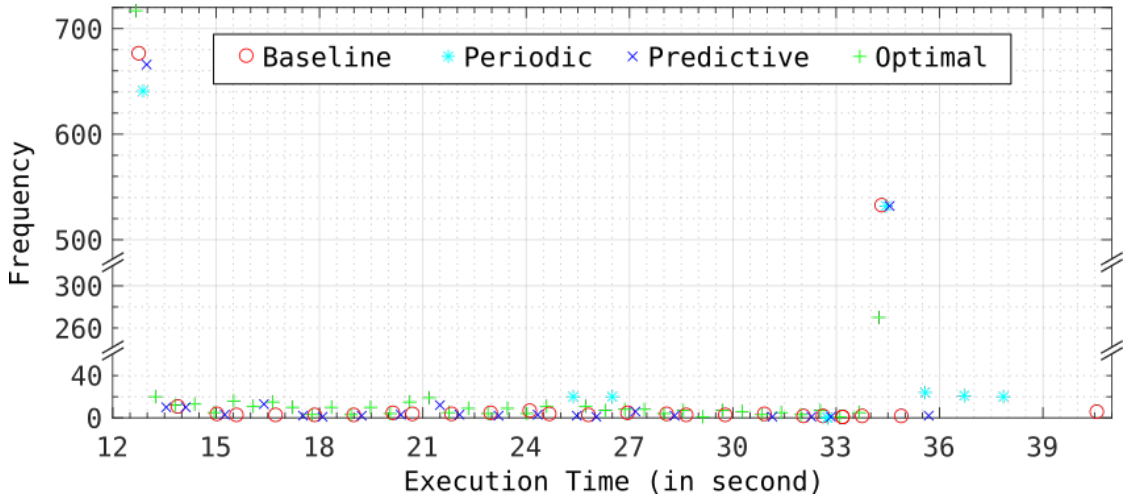


Figure 6.6.: Frequency of execution times for the Chesspresso application on the netbook based on the connectivity traces for T-Mobile.

6.4.2. Results

This subsection describes the results for the evaluation of the predictive distribution, categorized into the evaluated applications.

Chesspresso Application

Now, we present the evaluation results of the execution time and the energy consumption on the netbook and on the laptop, distributing the Java method of the Chesspresso application. Please note that, for a better overview, each following figure only shows the frequencies of the execution time or the energy consumption that are greater than 0. Due to the heterogeneity of the hardware platform from the netbook and the laptop, the execution time for a local execution of the Chesspresso application differs significantly on both hardware platforms, taking 29.542 s on the netbook and 8.841 s on the laptop. We define the maximum time for the execution of the Chesspresso application slightly higher than a local execution, setting it to 40 s on the netbook and to 10 s on the laptop (cf. Table 6.1).

For the netbook, Figure 6.6 shows the frequency of execution times for the different approaches, distributing the Java method to the offloading service based on 1278 connectivity traces of the cellular network of T-Mobile. Regarding the frequencies in the figure for the different approaches, the different approaches result in execution times, centered around two peeks at 12.60 s and 34.28 s. The execution time 12.60 s (first peek) corresponds to the duration of a distribution, where no disconnections occur during the remote execution and the offloading service executes completely the Java method.

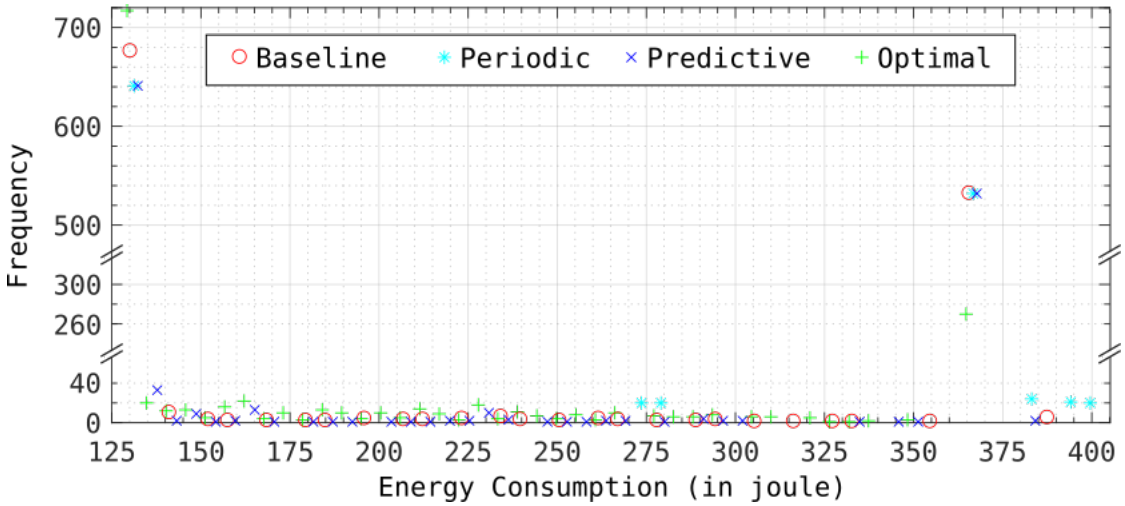


Figure 6.7.: Frequency of energy consumption for the Chesspresso application on the netbook based on the connectivity traces for T-Mobile.

In detail, the frequency of the execution time for the first peek counts for *Baseline* 676, for *Periodic* 641, for *Predictive* 666, and for *Optimal* 717. The execution time 34.28 s (second peek) corresponds to the duration of a local execution for the Java method on the netbook, where *Baseline*, *Periodic*, and *Predictive* counts 532 and *Optimal* counts 270. The reduction of the execution time about 21.68 s shows the benefits for the distribution of the Java method, utilizing the faster hardware platform of the desktop on behalf of the slower hardware platform of the netbook. Having a closer look at the execution times between the two peeks, *Baseline* finishes an execution of the Java method 63 times, *Periodic* 40 times, *Predictive* 78 times, and *Optimal* 291 times between the two peeks. Thus, the execution times for *Optimal* stay totally between the two peeks, where the execution time for the worst case corresponds to a local execution of the Java method on the netbook (34.28 s). *Predictive* results in 2 execution times that are higher than the execution time for a local execution, *Periodic* in 65, and *Baseline* in 7. The lowest number of execution times between the two peeks together with the highest number of execution times after the second peek causes the highest execution time for *Periodic* of 23.27 s on average. *Baseline* results on average in a slightly smaller execution time of 22.26 s, which *Predictive* further reduces to 22.09 s. However, *Optimal* has on average an execution time of 19.20 s and thus, a 13.08% lower execution time than *Predictive*. Regarding the latest time the execution of the Java method finishes, *Baseline* violates 5-times the maximum time set for an execution, whereas *Periodic* stays below the maximum time set and finishes an execution not later than 38.00 s. This shows the positive effect of safe-point'ing in general. *Predictive* also stays below the maximum time set with a maximum time for an execution of 36.00 s.

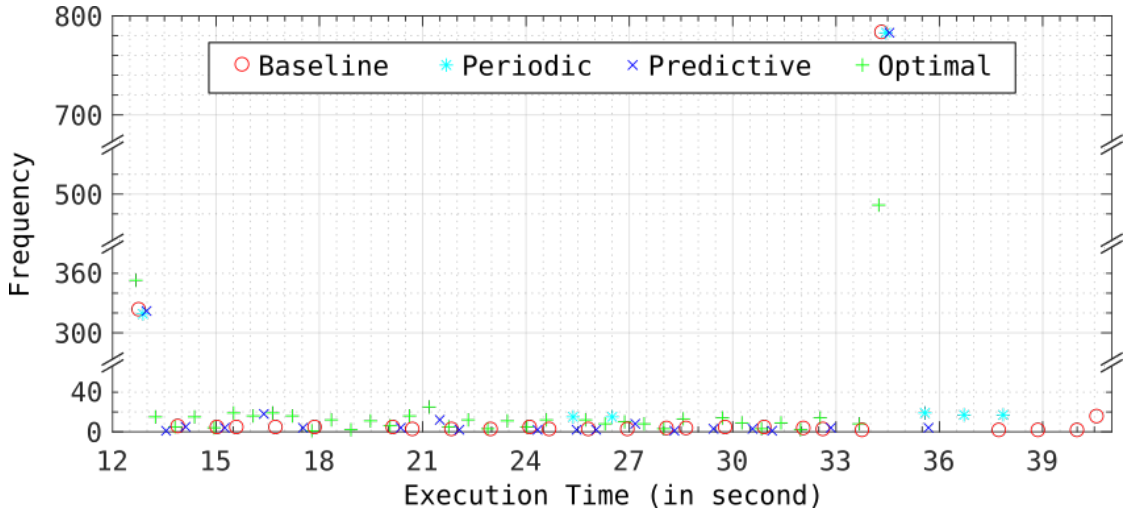


Figure 6.8.: Frequency of execution times for the Chesspresso application on the netbook based on the connectivity traces for O_2.

Regarding the energy consumption caused by the different approaches for a distribution of the Java method on the netbook (cf. Figure 6.7), a total execution of the Java method on the offloading service consumes 128.53 J (first peek) and on the offloading client 369.12 J (second peek). So, the first peek corresponds to a remote execution, where no disconnections occur. The second peek corresponds to a local execution on the netbook due to the occurrence of failures. Thus, the netbook saves energy of 240.59 J by distributing the Java method to the desktop. In detail, the average energy consumed for *Baseline* and *Predictive* are similar, consuming in average 234.43 J and 233.95 J, respectively. Due to the improved schedule for safe-point'ing, the average energy consumed for *Predictive* is lower than *Periodic* that causes a higher energy consumption of 13.00 J. The lowest energy consumed in average causes *Optimal* with 198.76 J, resulting in a 15.04% lower energy consumption compared to *Predictive*.

Figure 6.8 shows the frequency of execution time for 1185 connectivity traces of the cellular network of O_2. Like for the cellular network of T-Mobile, the frequency of execution times has two peeks at 12.60 s and at 34.28 s, where the execution time of a local execution dominates over the execution time for a remote execution. In detail, *Baseline* counts 323 at the first peek and 783 at the second peek, *Periodic* 319 and 783, *Predictive* 322 and 783, and *Optimal* 353 and 489. The main reason for the decrease of the first peek together with the increase of the second peek for all approaches is the higher likelihood of a disconnection for O_2. As a result, the failure handler of the approaches starts more often a local execution in case of the occurrence of a failure. As a result, the average time for an execution increases for *Baseline* to 27.87 s (an increase of 5.61 s), *Periodic* to 28.32 s (an increase of 5.05 s), *Predictive* to 27.55 s (an

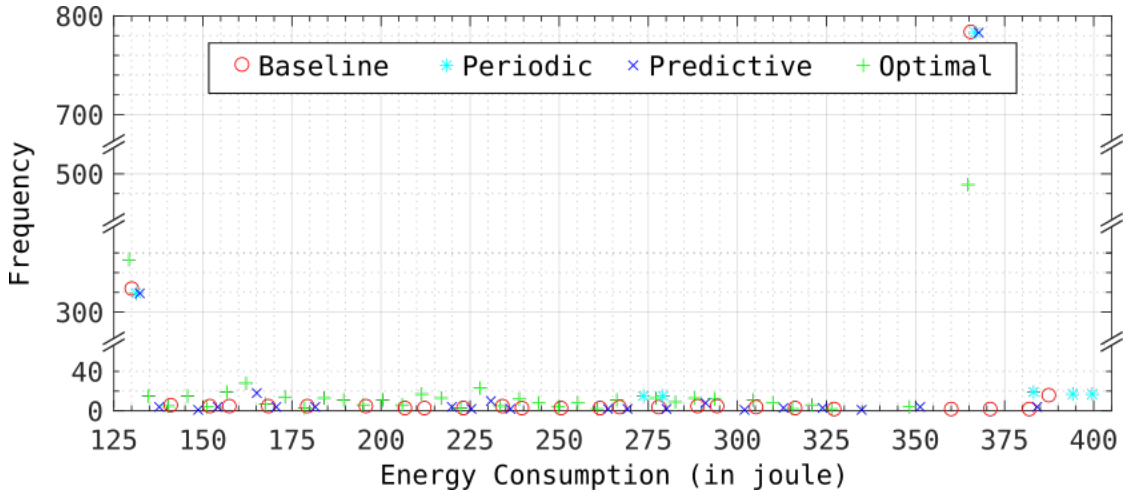


Figure 6.9.: Frequency of energy consumption for the Chesspresso application on the netbook based on the connectivity traces for O_2.

increase of 5.46 s), and *Optimal* to 24.31 s (an increase of 5.11 s). Beside the increase of the average time for an execution, the connectivity traces of the cellular network of O_2 leads to the same characteristics as of T-Mobile. *Periodic* has the highest average time with 30 execution times between the two peeks and 53 execution times after the second peek. In detail, it finishes an execution not later than 38.00 s and thus, does not violate the maximum time for an execution, showing the benefits of safe-point'ing. Due to 61 execution times between the two peeks and 18 execution times after the second peek, *Baseline* reduces the average time compared to *Periodic*, however, violating the maximum time for an execution 16 times. *Predictive* further decreases the maximum time for an execution. Due to 76 execution times between the two peeks and 4 execution times after the second peek, it finishes an execution not later than 35.50 s and thus, staying below the maximum time set. Only *Optimal* keeps the time for an execution below 34.28 s, counting 343 execution times between the two peeks. As a result, the average time for an execution of *Optimal* is 11.76% lower compared to *Predictive*.

Regarding the energy consumption caused by the different approaches for a distribution of the Java method with the cellular network of O_2 (cf. Figure 6.9), the consumed energy is proportionally similar to the cellular network of T-Mobile. It is only increased in general by the higher execution times due to the higher likelihood for the occurrence of a failure. In detail, the average energy consumed for *Baseline* is 273.14 J, for *Periodic* 279.27 J, for *Predictive* 271.53 J, and for *Optimal* 234.79 J, where the average energy consumed for *Predictive* is lower than *Periodic* as well as *Baseline*. However, *Optimal* consumes in average the lowest energy, resulting in a 13.53% lower energy consumption compared to *Predictive*.

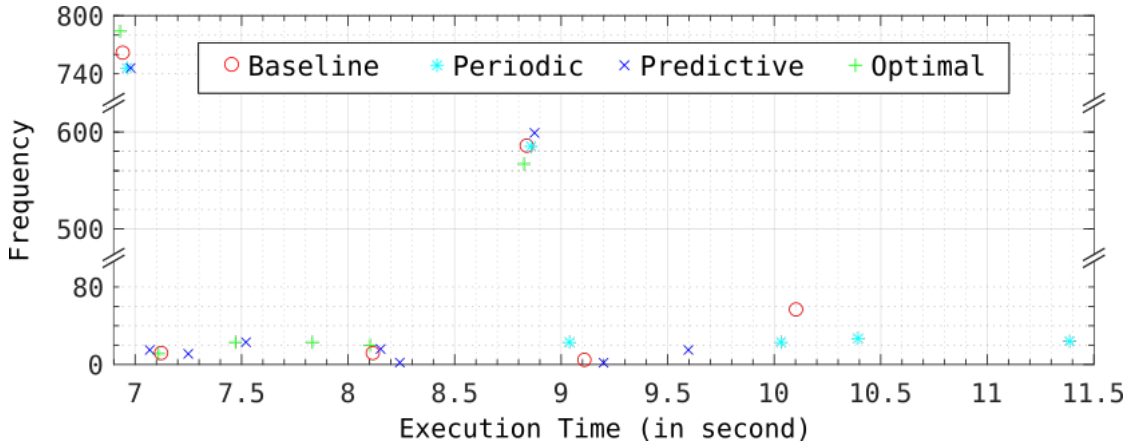


Figure 6.10.: Frequency of execution times for the Chesspresso application on the laptop based on the connectivity traces for T-Mobile.

Now, we consider the execution times (cf. Figure 6.10 and Figure 6.12) and energy consumption (cf. Figure 6.11 and Figure 6.13) for the different approaches on the laptop. The laptop also distributes the Chesspresso application to the offloading service based on the connectivity traces of the cellular network for T-Mobile and O_2. Compared to the hardware platform of the netbook, the hardware platform of the laptop is more powerful and thus, closer to the performance of the desktop. As a result, the time (and energy) benefit for a distribution of the Java method is smaller, where also a short duration of a disconnection matters significantly.

For the laptop, Figure 6.10 shows the frequency of execution times for the different approaches based on 1428 connectivity traces of the cellular network for T-Mobile. Here, the execution times settle around the two peeks of 6.92 s and 8.84 s. The first peek at 6.92 s corresponds to a remote execution of the Java method, where the offloading service executes it totally without the occurrence of a failure. For the first peek, *Baseline* counts to 761, *Periodic* and *Predictive* to 746, and *Optimal* to 784. The second peek at 8.84 s corresponds to the execution time for a local execution on the offloading client due to the occurrence of failures. For the second peek, *Baseline* and *Periodic* counts to 585, *Predictive* to 599, and *Optimal* to 567. The reduction of the execution time by 1.92 s is the benefit for a distribution of the Java method. Due to the smaller benefit of a distribution for the laptop, the number of executions times between the two peeks is for *Baseline* and *Periodic* low (22 and 0, respectively), reacting too late on the occurrence of a failure. Utilizing the predictive scheduler for safe-point'ing, *Predictive* results in 67 execution times between the two peeks, only 10 execution times lower than *Optimal*. Furthermore, *Optimal* finishes an execution of the Java method not later than the execution time for a local execution (second peek: 8.84 s), where

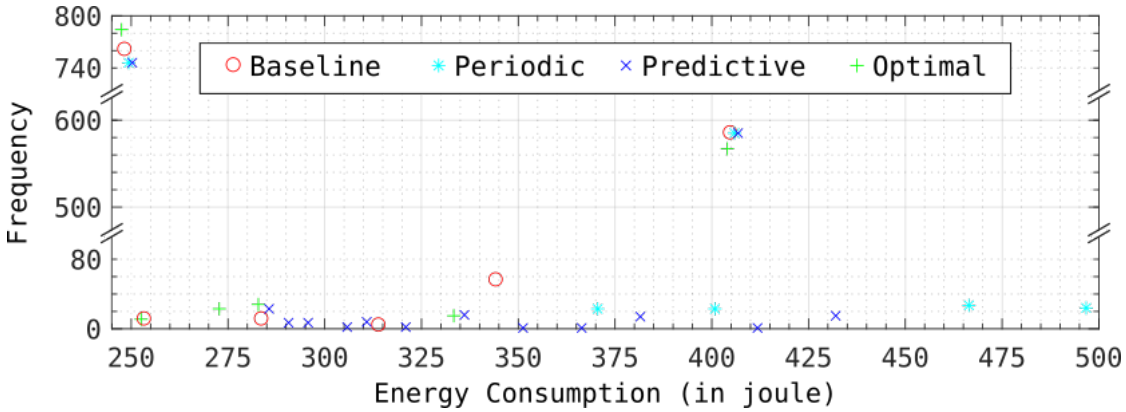


Figure 6.11.: Frequency of energy consumption for the Chesspresso application on the laptop based on the connectivity traces for T-Mobile.

Predictive results in 16 execution times that are higher than 8.84 s but lower than the maximum time set to 10 s for the laptop. Both *Baseline* and *Periodic* violate several times the maximum time set (56 and 74, respectively), highlighting the positive effect of the utilization of the prediction models. On average, *Predictive* leads to lower times for an execution (7.78 s) compared to *Baseline* (7.85 s) as well as *Periodic* (7.93 s). Compared to *Optimal*, *Predictive* leads only to a 0.77% higher average time for an execution, i.e., being very close to optimal.

Figure 6.11 shows the energy consumption for the connectivity traces of the cellular network for T-Mobile on the laptop, corresponding to 250.26 J (first peek) for a remote execution and 406.78 J (second peek) for a local execution. Thus, a distribution of the Java method reduces the energy consumption on the laptop by 156.52 J. Regarding the average energy consumed of the different approaches for T-Mobile, *Predictive* (317.56 J) consumes in average less energy than *Periodic* (324.28 J), whereas it consumes in average more energy than *Baseline* (315.88 J). As the energy consumed by *Baseline* is not higher than 406.78 J (energy for a local execution), the 16 energy consumption for *Predictive* that are higher than 406.78 J are responsible for the higher average energy consumed by *Predictive* (cf. Figure 6.11). Having a closer look at the 16 connectivity traces for T-Mobile that cause the higher energy consumption for *Predictive*, they correspond to the worst-case scenario of the preemptable distribution. Compared to *Optimal* (311.69 J), *Predictive* consumes in average only 1.85% more energy.

The higher likelihood of a disconnection for the 1335 connectivity traces of O_2 increases in general the execution times of the different approaches like for the netbook (cf. Figure 6.12). It shifts the execution times towards the second peek (8.84 s) of a local execution, because the failure handler of the different approaches starts a local execution or continues a remote execution locally in case of the occurrence of a fail-

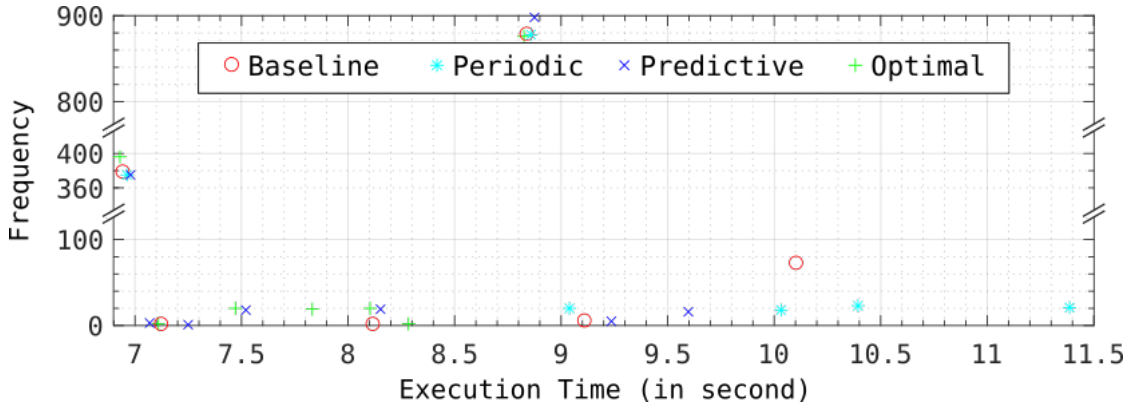


Figure 6.12.: Frequency of execution times for the Chesspresso application on the laptop based on the connectivity traces for O_2.

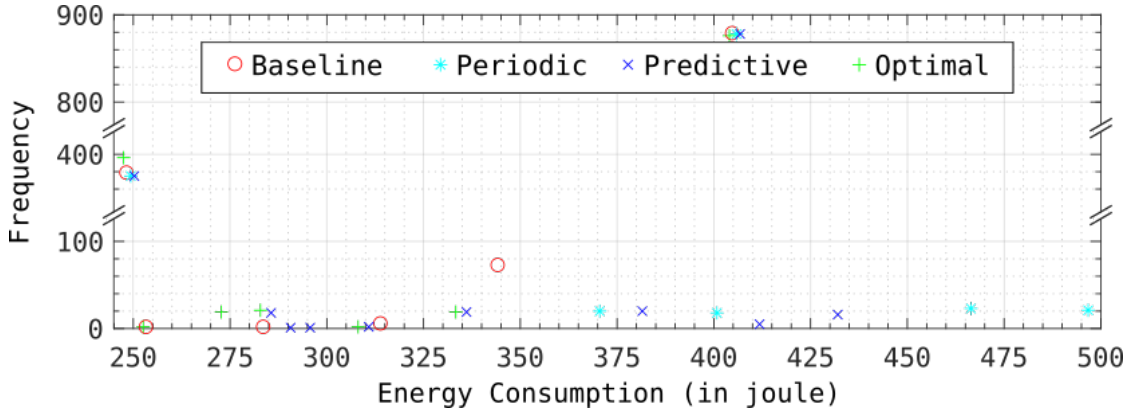


Figure 6.13.: Frequency of energy consumption for the Chesspresso application on the laptop based on the connectivity traces for O_2.

ure. The increase of the average time for an execution is roughly 6%, resulting in an average time of 8.36 s for *Baseline*, 8.38 s for *Periodic*, 8.27 s for *Predictive*, and 8.21 s for *Optimal*. In detail, *Baseline* counts to 378 for the first peek and 878 for the second peek, *Periodic* to 375 and 878, *Predictive* to 375 and 898, and *Optimal* to 396 and 876. Regarding the number of execution times between the two peeks, *Baseline* and *Periodic* reacts too late at the occurrence of a failure (2 and 0, respectively), whereas the utilization of the prediction models improves the reaction to failures and increases the number to 41 for *Predictive*, being only 22 less than *Optimal*. Moreover, *Baseline* and *Periodic* violate in total 72 and 62 times the maximum time set for an execution, whereas *Predictive* (and *Optimal*) never violates the maximum time set (10 s).

The energy consumption of the different approaches on the connectivity for O_2 has the same characteristics as for T-Mobile, only increased by roughly 11% owing to the higher likelihood for the occurrence of a failure (cf. Figure 6.13). In detail, the average energy consumed for *Baseline* is 355.89 J, for *Periodic* 361.93 J, for *Predictive* 357.05 J,

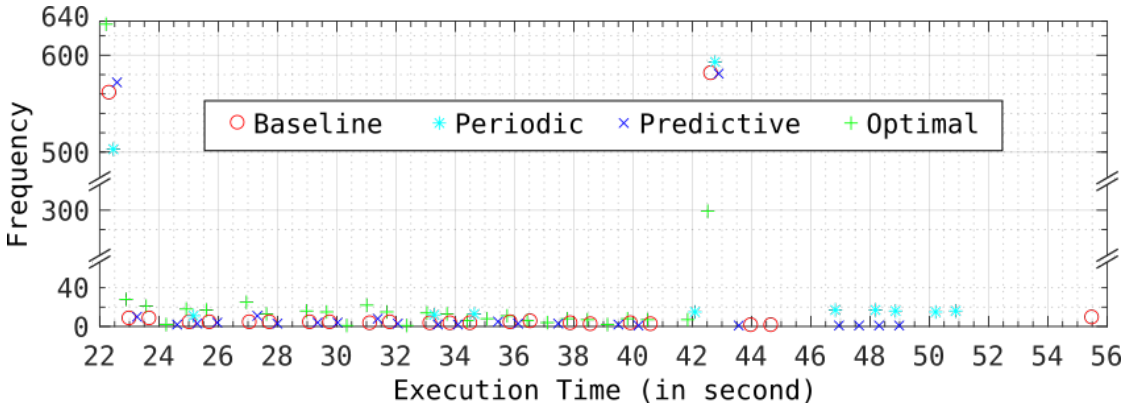


Figure 6.14.: Frequency of execution time for the face recognition application on the netbook based on the connectivity traces for T-Mobile.

and for *Optimal* 352.44 J, where *Predictive* consumes 1.16 J more energy than *Baseline* due to the worst-case scenarios like for T-Mobile. Compared to *Optimal*, *Predictive* consumes only 1.29% more energy.

Summarizing, the basic strategy of failure handling from *Baseline* violates a maximum time set for a distribution of the Java method from the Chesspresso application. The utilization of the preemptable distribution with safe-points improves the results, however, still violating the maximum time set. Only the improvement with a predictive schedule for safe-point'ing does not violate the maximum time set despite the occurrence of failures due to the utilization of the prediction models. In comparison with an optimal approach that knows in advance the point in time as well as the duration of a failure, the predictive schedule only performs slightly worse.

Face Recognition Application

Now, we present the evaluation results of the execution time and the energy consumption on the netbook and on the laptop, distributing the Java method of the face recognition application. Like for the evaluation results of the chess game, each following figure only shows the frequencies that are greater than 0. Moreover, due to the heterogeneity of the hardware platform from the netbook and the laptop, we also set the maximum time to 50 s on the netbook and to 30 s on the laptop related to the execution time for a local execution of 42.89 s and 24.64 s, respectively (cf. Table 6.1).

For the netbook, Figure 6.14 shows the frequency of execution times and Figure 6.15 of the energy consumption for the different approaches. The different approaches distribute the Java method of the face recognition application to the offloading service based on 1228 connectivity traces of the cellular network of T-Mobile. Like for the distribution of the chess game, the two peeks of a remote execution and of a local exe-

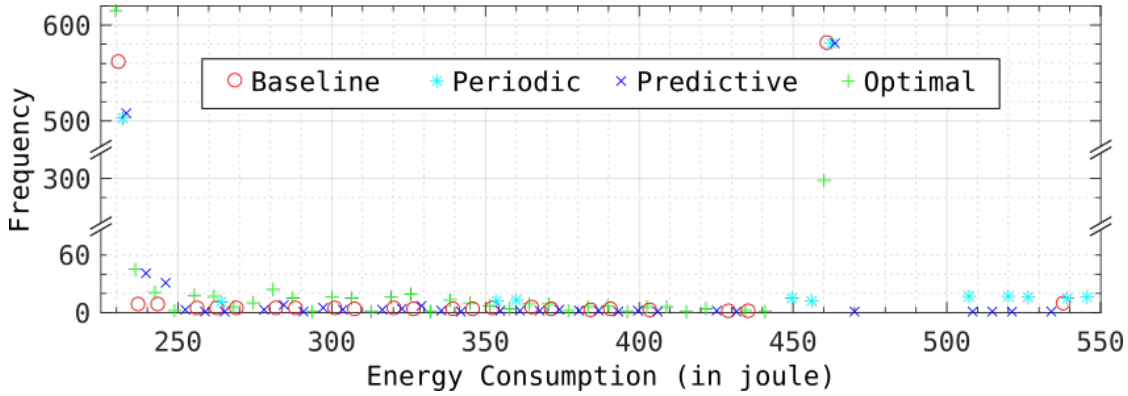


Figure 6.15.: Frequency of energy consumption for the face recognition application on the netbook based on the connectivity traces for T-Mobile.

cution dominate the frequencies of the execution time (22.59 s and 42.89 s) and of the energy consumption (233.19 J and 463.60 J) for the different approaches. The difference between the two peeks highlights the benefits of a distribution without the occurrence of a failure, reducing the execution time by 20.30 s and the energy consumption by 230.41 J. For the execution time (and for the energy consumption), *Baseline* counts for the first peek and for the second peek to 561 and 581 (561 and 581), *Periodic* to 503 and 593 (503 and 581), *Predictive* to 572 and 581 (508 and 581), and *Optimal* to 632 and 299 (615 and 298). The execution time (energy consumption) between the two peeks sums up for *Baseline* to 75 (77), for *Periodic* to 51 (63), for *Predictive* to 70 (134), and for *Optimal* to 297 (315). Moreover, *Baseline* causes 11-times (9-times) a higher execution time (energy consumption) than a local execution, *Periodic* 81-times (81-times), and *Predictive* 5-times (5-times), whereas *Optimal* takes not longer than and consumes not more than a local execution. *Baseline* as well as *Periodic* violate in total 9-times and 31-times the maximum time set, whereas *Predictive* as well as *Optimal* do not violate it. Due to the similarity of the frequencies for *Baseline* and *Predictive*, the average taken time as well as the average consumed energy are similar for both approaches, where the results are slightly lower for *Predictive* (time: 0.79%; energy: 1.78%). In detail, *Baseline* results in 32.96 s and 349.28 J and *Predictive* in 32.70 s and 348.66 J. Compared to the average taken time (29.46 s) and the average consumed energy (307.63 J) for *Optimal*, *Predictive* leads to a higher average taken time of 9.91% and a higher average consumed energy of 11.77%.

Figure 6.16 shows the frequency of the execution time and Figure 6.17 of the energy consumption on the netbook from 1335 connectivity traces for the cellular network of O_2. The evaluation results are comparatively similar to the connectivity traces for the cellular network of T-Mobile, only increased by the higher likelihood of the occurrence

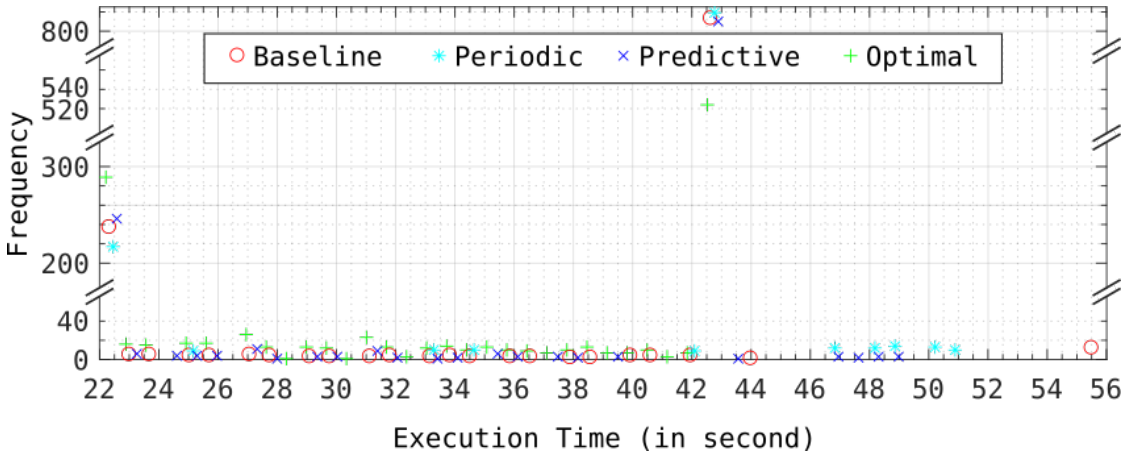


Figure 6.16.: Frequency of execution time for the face recognition application on the netbook based on the connectivity traces for O_2.

of a disconnection. In detail, the higher likelihood roughly halves the frequency at the first peek and mainly adds it to the second peek, resulting for the execution time (the energy consumption) in 237 and 813 (237 and 810) for *Baseline*, 217 and 819 (217 and 810) for *Periodic*, 246 and 810 (218 and 810) for *Predictive*, and 289 and 544 (277 and 540) for *Optimal*. The frequency between the two peeks as well as after the second peek stays similar for the execution time (and the energy consumption), where *Baseline* sums up to 72 and 13 (76 and 12), *Periodic* to 38 and 61 (47 and 61), *Predictive* to 67 and 12 (95 and 12), and *Optimal* to 302 and 0 (318 and 0). Due to the simple strategy of failure handling in case of a disconnection, *Baseline* violates 12 times the maximum time set, where *Periodic* violates it 23 times despite the utilization of safe-point'ing. Only *Predictive* (and thus, *Optimal*) does not violate the maximum time set due to the utilization of a predictive schedule for safe-point'ing. On average, the execution time and energy consumption for *Baseline* (38.09 s and 406.99 J) and *Predictive* (37.79 s and 406.11 J) are similar, whereas the execution time and energy consumption for *Periodic* is roughly 1.00 s and 12.50 J higher. Compared to *Optimal*, the average time and the average energy for an execution of *Predictive* is 7.94% and 9.52% higher.

For the laptop, Figure 6.18 shows the frequency of the execution time and Figure 6.19 of the energy consumption on the laptop from 1328 connectivity traces for the cellular network of T-Mobile. The time taken as well as the energy consumed for a remote execution (16.04 s and 654.70 J) and for a local execution (24.64 s and 1148.20 J) dominate the frequencies for all approaches like 637 and 585 of the time as well as 647 and 588 of the energy for *Baseline*, 575 and 585 as well as 575 and 603 for *Periodic*, 637 and 590 as well as 575 and 586 for *Predictive*, and 675 and 428 as well as 706 and 419 for *Optimal*. Thus, the benefit for a distribution of the face recognition application is on

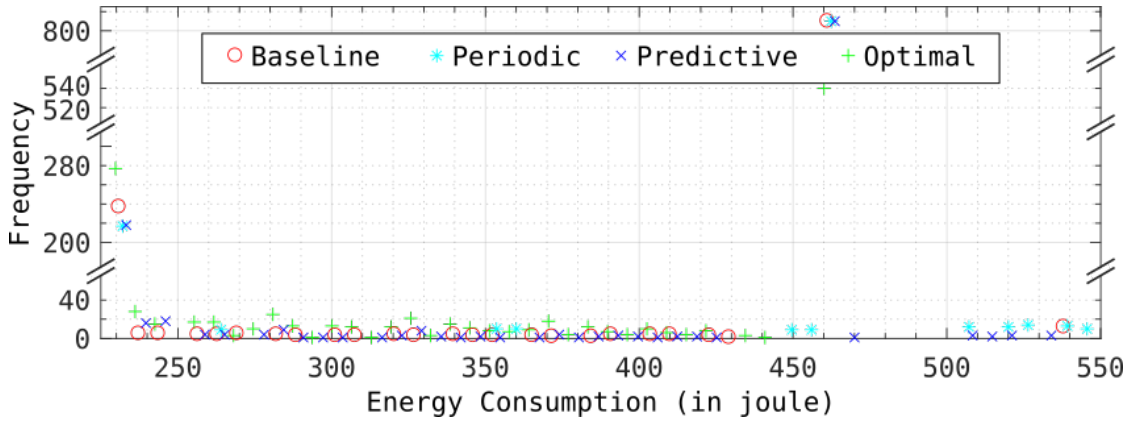


Figure 6.17.: Frequency of energy consumption for the face recognition application on the netbook based on the connectivity traces for O_2.

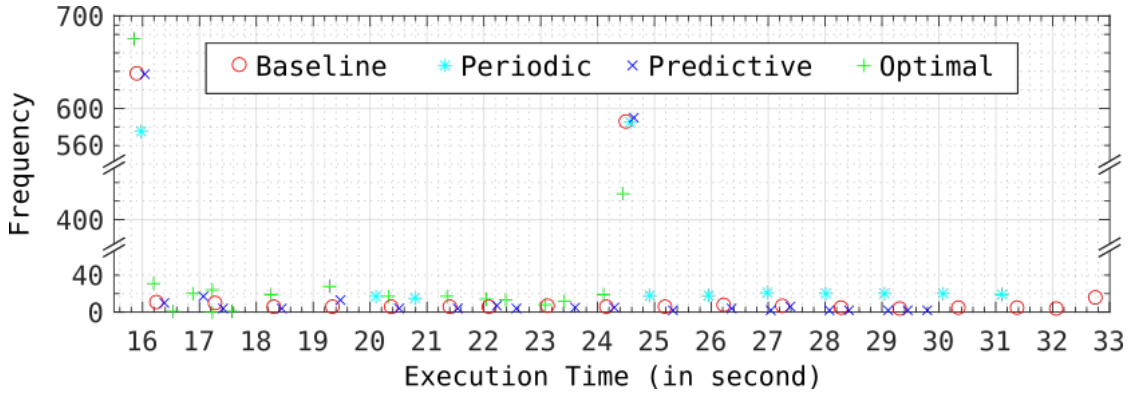


Figure 6.18.: Frequency of execution time for the face recognition application on the laptop based on the connectivity traces for T-Mobile.

the laptop 8.60 s and 493.50 J. For the taken time and the consumed energy between the two peeks, *Baseline* results in 55 and 78, *Periodic* in 32 and 50, *Predictive* in 77 and 142, and *Optimal* in 225 and 203. The taken time and the consumed energy are for *Baseline* 51 times and 15 times higher than for a local execution, 136 times and 100 times for *Periodic*, 24 times and 25 times for *Predictive*, and 0 times and 0 times for *Optimal*. As a consequence of the frequencies, the average time for an execution is similar for *Baseline* (20.51 s) and *Predictive* (20.27 s), whereas the average energy consumed for *Baseline* (896.51 J) is slightly lower than for *Predictive* (901.69 J). However, *Baseline* violates 26 times the maximum time set, where *Predictive* stays below it for all the connectivity traces. The average time taken and the average energy consumed for an execution is for *Periodic* higher (21.17 s and 941.89 J), violating 39 times the maximum time set. Compared to *Optimal* (19.46 s and 834.47 J), *Predictive* has in average a 4.0% higher execution time and a 7.46% higher energy consumption.

Figure 6.20 shows the frequency of the execution time and Figure 6.21 of the energy

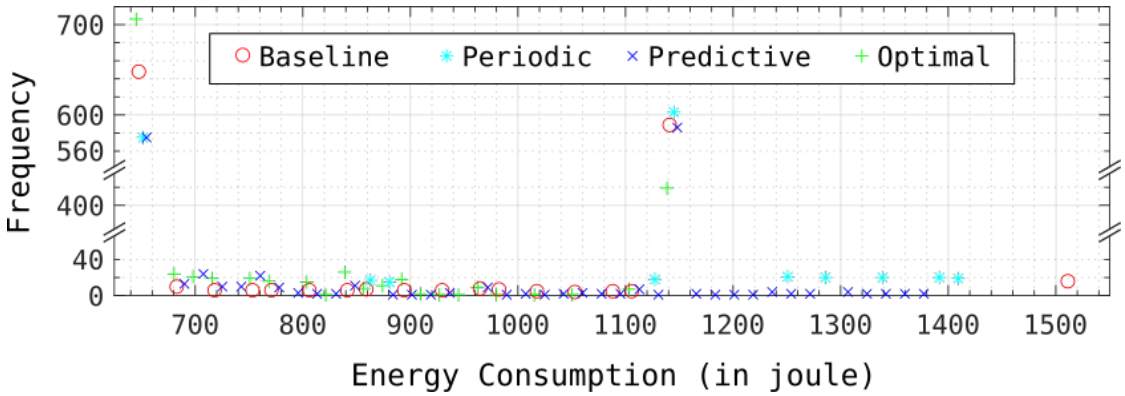


Figure 6.19.: Frequency of energy consumption for the face recognition application on the laptop based on the connectivity traces for T-Mobile.

consumption on the laptop from 1235 connectivity traces for the cellular network of O_2. Due to the higher likelihood of a disconnection for the cellular network of O_2, it increases the frequencies for both the execution time and the energy consumption towards a local execution (second peek) compared to the cellular network of T-Mobile. The frequencies for the first peek and the second peek are 283 and 841 (288 and 844) for *Baseline*, 266 and 841 (266 and 853) for *Periodic*, 283 and 848 (266 and 841) for *Predictive*, and 307 and 725 (324 and 715) for *Optimal*. The frequencies between the two peeks as well as after the second peek are similar for O_2 and T-Mobile. *Baseline* results in 42 and 69 for the execution time as well as 68 and 35 for the energy consumption, *Periodic* in 22 and 106 as well as 36 and 80, *Predictive* in 64 and 40 as well as 86 and 42, and *Optimal* in 203 and 0 as well as 225 and 0. Moreover, *Baseline* and *Periodic* violate 46 times and 30 times the maximum time set, whereas *Predictive* and *Optimal* stay below it for all the connectivity traces. In average, *Baseline* takes 22.86 s and consumes 1029.80 J, taking 0.34 s longer and consuming 2.90 J more energy than *Predictive*. Due to the static strategy of periodic safe-point'ing, *Periodic* takes the longest average time (23.01 s) and consumes the highest average energy (1048.90 J). Knowing in advance the point in time and the duration of a disconnection, *Optimal* reduces the average taken time and the average consumed energy by 3.33% and 5.82% compared to *Predictive*.

Summarizing, like for the Chesspresso application, *Baseline* and *Predictive* perform for the face recognition application similar on the netbook as well as on the laptop. Both result in a similar execution time and energy consumption for the connectivity traces of T-Mobile and of O_2. However, the basic strategy of failure handling from *Baseline* violates the maximum time set for a distribution of the face recognition application, whereas *Predictive* stays below it for all the connectivity traces. In many cases, *Periodic* takes the longest time and consumes the highest energy compared to the other

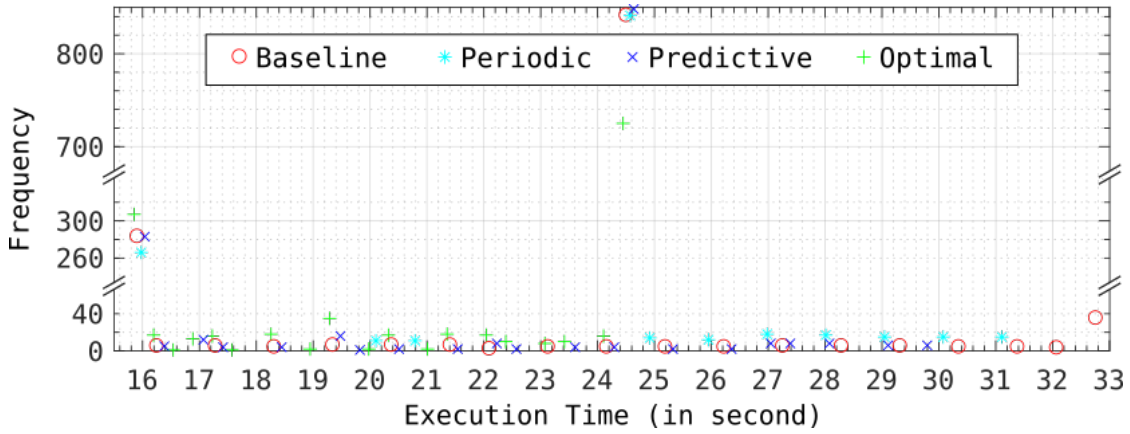


Figure 6.20.: Frequency of execution time for the face recognition application on the laptop based on the connectivity traces for O_2.

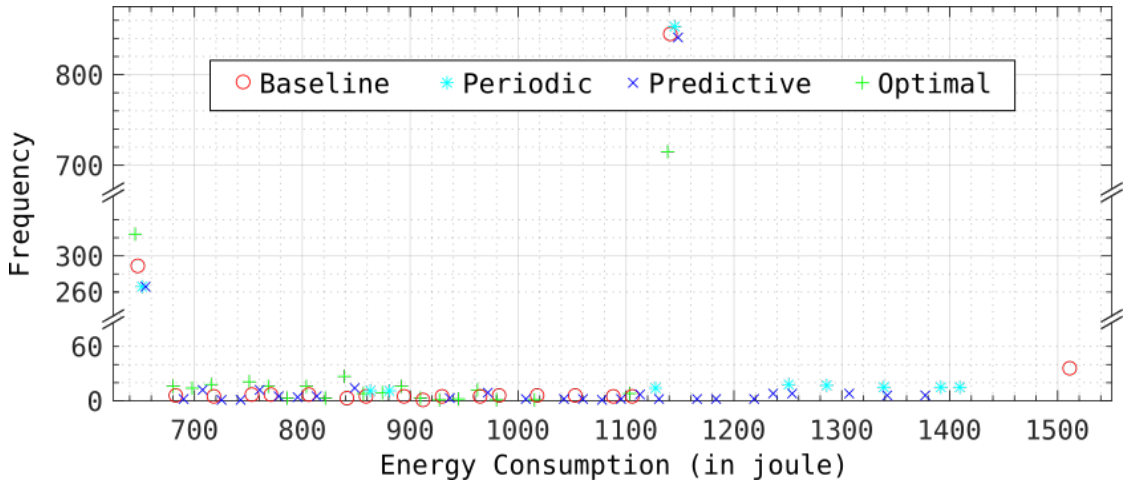


Figure 6.21.: Frequency of energy consumption for the face recognition application on the laptop based on the connectivity traces for O_2.

approaches, emphasizing the utilization of a predictive schedule for safe-point'ing from *Predictive*. For instance, the static schedule for safe-point'ing from *Periodic* violates several times the maximum time set. Knowing in advance the point in time and the duration of a failure, *Optimal* performs best, reducing the average taken time and the average consumed energy only slightly compared to *Predictive*.

6.5. Summary

The *predictive distribution* described in Section 6.1 improves the safe-point schedule of the preemptable distribution described in Section 5.1 with an adaptive algorithm based on prediction models. It dynamically adapts the point in times for a creation and transmission of safe-points due to dynamic conditions of the communication net-

work. During a remote execution of an application part, the adaptive algorithm on the offloading service predicts impending link failures to minimize the number of safe-points received on an offloading client. In the optimal case, the offloading client only receives one safe-point from the offloading service just before a disconnection happens that lasts longer than the remaining time from a time constraint set for the execution. The underlying *system overview* described in Section 6.2 with the system model, problem statement, and system components extends the preemptable distribution with an additional constraint for the maximum time of an execution. To optimize the efficiency of the preemptable distribution with safe-point'ing under the constraint, the predictive distribution utilizes an *optimal schedule for safe-point'ing* described in Section 6.3. It selects the optimal time to send a safe-point from the offloading service to the offloading client by using a predictive approach that takes future network connectivity into account. To evaluate the efficiency of the predictive distribution compared to the preemptable distribution, the *evaluation* described in Section 6.4 presents the evaluation setup and the evaluation results of multiple MATLAB simulations calibrated with real-world measurements. The evaluation of the predictive distribution shows that it significantly increases the efficiency – often tending the optimal performance – compared to other distribution approaches and additionally guarantees a maximum time for an execution under network failures. In detail, application parts that are computational-intensive and have a small execution state like the Chesspresso application pronounce more the benefits for a predictive distribution. These kind of application parts naturally lend themselves better for code offloading than application parts with a larger execution state transferred between an offloading client and an offloading service.

Chapter 7
Optimized Code Offloading through Cooperative Caching

The basic distribution presented in detail in Chapter 4 causes computation and communication overhead due to, for instance, executing the offloading framework or sending and receiving execution states. Moreover, an end user has to pay monetary cost for a remote execution of an application part distributed to an offloading service at a commercial cloud. To this end, this chapter presents a caching-aware distribution described in Section 7.1 that extends the offloading framework of the basic distribution with a cache on the remote side. The addition of a cache on the remote side changes the system overview described in Section 7.2 related to the basic distribution. The offloading timeline described in Section 7.3 highlights the function of the cache on the remote side. A remote-side cache serves as a collective storage for output execution states from already executed application parts, avoiding a repeated execution of previously run application parts. Making the offloading framework described in Section 7.4 aware of a cache on the remote side, the offloading client queries the introduced cache for a related output execution state of an application part instead of executing it on an offloading service. In case of a cache hit, the caching service that provides the cache immediately sends the output execution state to the offloading client. Otherwise, in case of a cache miss, the offloading client distributes the application part to an offloading service just like the basic distribution. To evaluate the introduced overhead and gained benefits of the caching-aware distribution compared to the basic distribution, Section 7.5 presents the evaluation of an implemented prototype, including the evaluation setup and the evaluation results. Last, Section 7.6 summarizes the main facts of an optimized code offloading through cooperative caching presented in this chapter.

7.1. Caching-aware Distribution

The offloading client of the basic distribution presented in detail in Subsection 4.5.2 identifies an application part for a distribution, gathers its input execution state, and

determines its execution side. Afterwards, in case of a remote execution on an offloading service, the offloading client sends the required information to the offloading service and waits in idle mode during the remote execution. Finally, it receives the output execution state from the offloading service, installs the contained information on its hardware platform, and continues the execution of the application. Regarding these eight substeps – identify, gather, determine, send, wait, receive, install, and continue – on the offloading client for the basic distribution, each substep introduces either computation or communication overhead to the offloading client. In case of a distribution of an application part, the process of code offloading – including the eight substeps – significantly increases the efficiency of the offloading client. In case of a local execution of an application part, the process of code offloading – now, only including the first three substeps – introduces an overhead to the offloading system. Please note that the basic distribution proposed in Chapter 4 improves these first three substeps, keeping the overhead low. Regarding the remaining five substeps – send, wait, receive, install, and continue – on the offloading client, the offloading client has to perform immutably the last two substeps of installing and continuing. Consequently, we propose the approach of a caching-aware distribution. The caching-aware distribution improves on the offloading client the substeps of sending, waiting, and receiving from the basic distribution with a cache. The cache serves as a collective storage for output execution states from already executed application parts on an offloading client or an offloading service to avoid a repeated execution of previously run application parts.

Before the substep of sending the input execution state to an offloading service, the offloading client just queries the introduced cache. Querying the cache for an output execution state of an application part, the cache starts a lookup in its storage of output execution states from already executed application parts. In case of a cache hit, the cache responses to the offloading client with the related output execution state, avoiding a repeated execution of a previously run application part on the offloading service. As the offloading client immediately receives the output execution state for the application part, it skips the substeps of sending, waiting, and receiving and proceeds with the substeps of installing and continuing. In case of a cache miss, the cache does not possess the related output execution state for an application part. Thus, the offloading client has to proceed with the substeps of sending, waiting, receiving, installing, and continuing. The caching-aware distribution benefits from previous executions of application parts by replacing the time cost of distribution – send, wait, and receive – with the space cost of caching – query, wait, and receive.

In general, there are multiple locations possible for the cache of the caching-aware distribution like directly on the hardware platform of an offloading client, at any place

in the infrastructure (cf. at the Fog [BMZA12]), or at a commercial cloud data center. A cache located on the hardware platform of an offloading client has the lowest delay of querying the cache, but introduces computation and storage overhead for a local processing and storing of the cache. Due to the single usage by an offloading client, only one client fills the cache with output execution states after an execution or a distribution of application parts. Moving the location of the cache to the infrastructure, the delay of communicating with the cache increases dependent on the link quality of the network. However, a cache located in the infrastructure replaces the computation and storage overhead for a cache located on the hardware platform of an offloading client with the communication overhead and monetary cost. The monetary cost arises due to the utilization of resources located in the infrastructure. Now, several offloading clients fill the cache with output execution states, increasing the probability for a cache hit. Going one step further, a cache located at a commercial cloud data center differs from a cache located in the infrastructure in the delay of communicating with the cache and the number of offloading clients filling the cache. However, the communication delay increases slightly and the number of participants considerably.

As the benefits of the caching-aware distribution directly depends on the fill level of the cache, the caching-aware distribution utilizes a cache located at a commercial cloud data center. Thus, the caching-aware distribution benefits from a collective sharing of output execution states cached on the remote side, where multiple offloading clients distribute application parts, filling the remote cache over time. Summarizing, we make the following contributions: (1) A formulation of the problem to make the basic distribution aware of a collective sharing of output execution states based on a cache; (2) an adaptive algorithm that solves the caching-aware problem increasing the efficiency of the basic distribution; (3) an implementation of the adaptive approach for the caching-aware distribution; and (4) an evaluation of the overhead and benefit for the caching-aware distribution based on real-world measurements, where different mobile devices execute different mobile applications.

7.2. System Overview

The caching-aware distribution extends the basic distribution with a cache on the remote side. To this end, Subsection 7.2.1 describes the changes to the system model, Subsection 7.2.2 to the problem statement, and Subsection 7.2.3 to the system components related to the basic distribution (cf. Section 4.2).

7.2.1. System Model

The system model of the caching-aware distribution extends the basic distribution with a cache on the remote side. Thus, an offloading client on a resource $\Xi(\xi_l)$ distributes application parts to an offloading service on a resource $\Xi(\xi_r)$ and queries a cache on a resource $\Xi(\xi_c)$. Providing a cache to offloading clients and offloading services, the performance characteristic $Q_{chlu}^{\Xi(\xi_c)}$ for a resource $\Xi(\xi_c)$ is a performance factor, indicating how much time the resource requires for processing a cache query. Moreover, the cost implication $Q_{qury}^{\Xi(\xi_c)}$ for a resource $\Xi(\xi_c)$ is the processing fee, indicating how much monetary cost the resource charges per cache query. Utilizing a cache provided by a resource $\Xi(\xi_c)$, the load metrics $Q_{I_{state}}^{size}(A_{\alpha_o})$ and $Q_{chms}^{\Xi(\xi)}$ indicates the total number of bytes for a cache query of the input execution state $I_{state}(A_{\alpha_o})$ and for the information about the cache miss. For the communication network, the offloading client communicates with the cache via a bidirectional link $\Lambda(\xi_l;\xi_c)$, where the offloading service and the cache communicate with each other via a bidirectional link $\Lambda(\xi_r;\xi_c)$. Please note that the communication network consists for $\Lambda(\xi_l;\xi_c)$ of wireless and fixed networks, whereas it consists for $\Lambda(\xi_r;\xi_c)$ of a fixed network.

7.2.2. Problem Statement

A remote execution from the basic distribution – identifying, gathering, determining, sending, waiting, receiving, installing, and continuing – replaces a local execution of an application part if it is worthwhile. The caching-aware distribution introduces the substep of "querying" a cache before "sending" information to an offloading service, substituting "sending" in case of a cache hit. To keep the resource efficiency and the user experience high, the caching-aware distribution minimizes the cost function f_w (cf. Section 3.2) subject to the additional constraint $T^{max}(A_{\alpha_o}, \Xi(\xi))$ on the maximum time for an execution of an application part. $T^{max}(A_{\alpha_o}, \Xi(\xi))$ is the maximum time tolerated for an execution of the application part A_{α_o} on $\Xi(\xi)$, ensuring a minimal responsiveness of an application. For instance, a distribution in case of a limited quality of the communication network keeps the energy consumed on the offloading client low but increases the overall time for an execution of an application part. Formally, the caching-aware distribution changes the problem stated in Equation 3.1 as follows:

$$\begin{aligned} \min_{\xi} \quad & f_w(A_{\alpha_o}, \Xi(\xi)) \\ s.t. \quad & T(A_{\alpha_o}, \Xi(\xi)) \leq T^{max}(A_{\alpha_o}, \Xi(\xi)) \end{aligned} \tag{7.1}$$

As an end user sets the constraint $T^{max}(A_{\alpha_o}, \Xi(\xi))$ of the maximum time for the execution, we set the user-defined weight w_t for the execution time to 0. Thus, the cost function f_w is the sum of the energy consumption multiplied by the weight w_e and the monetary cost multiplied by the weight w_c, simplifying the equation as follows:

$$\begin{aligned} \min_{\xi} \quad & w_e \cdot E(A_{\alpha_o}, \Xi(\xi)) + w_c \cdot C(A_{\alpha_o}, \Xi(\xi)) \\ s.t. \quad & T(A_{\alpha_o}, \Xi(\xi)) \leq T^{max}(A_{\alpha_o}, \Xi(\xi)) \end{aligned} \tag{7.2}$$

Having a closer look on the execution time $T(A_{\alpha_o}, \Xi(\xi))$, each substep of a remote execution with caching – identifying, gathering, determining, sending/querying, waiting, receiving, installing, and continuing – takes time on the offloading client. In detail, a local execution of the application part on the offloading client takes time for identifying, gathering, determining, and continuing. A cache hit from the cache takes time for the eight substeps with "querying", where a remote execution on the offloading service takes time for the eight substeps with "sending". A cache miss from the cache takes time for the eight substeps of a cache hit, but receives a small message about the cache miss instead of the output execution state. Thus, it additionally takes time for a remote execution on the offloading service after the receive of the message about the cache miss. As a result, the execution time $T(A_{\alpha_o}, \Xi(\xi))$ is either the time for a local execution on the resource $\Xi(\xi_l)$, a cache hit from the cache on the resource $\Xi(\xi_c)$, a remote execution on the resource $\Xi(\xi_r)$, or a cache miss from the cache on the resource $\Xi(\xi_c)$. Please note that Section 3.2 defines the time $T_{local}(A_{\alpha_o}, \Xi(\xi_l))$ for an execution on a resource $\Xi(\xi_l)$ and $T_{remote}(A_{\alpha_o}, \Xi(\xi_r))$ for a distribution to a resource $\Xi(\xi_r)$, consisting of the execution time $T_{send}(A_{\alpha_o}, \Xi(\xi_r))$, $T_{wait}(A_{\alpha_o}, \Xi(\xi_r))$, and $T_{recv}(A_{\alpha_o}, \Xi(\xi_r))$. For a cache hit, $T_{chht}(A_{\alpha_o}, \Xi(\xi))$ sums up the execution time $T_{qury}(A_{\alpha_o}, \Xi(\xi_c))$ for querying the cache, $T_{chlu}(A_{\alpha_o}, \Xi(\xi_c))$ for waiting until the cache processed the cache query, and $T_{recv}(A_{\alpha_o}, \Xi(\xi_c))$ for receiving the output execution state from the cache. For a cache miss, $T_{chms}(A_{\alpha_o}, \Xi(\xi))$ sums up the execution time $T_{qury}(A_{\alpha_o}, \Xi(\xi_c))$ for querying the cache, $T_{chlu}(A_{\alpha_o}, \Xi(\xi_c))$ for processing the cache query at the cache, $T^{chms}_{recv}(A_{\alpha_o}, \Xi(\xi_c))$ for receiving the information about the cache miss, and $T_{remote}(A_{\alpha_o}, \Xi(\xi_r))$ for executing the application part A_{α_o} remotely on the resource $\Xi(\xi_r)$.

$$\begin{aligned} T_{qury}(A_{\alpha_o}, \Xi(\xi_c)) &= \frac{Q^{size}_{I_{state}}(A_{\alpha_o})}{B^{\Lambda(\xi_l;\xi_c)}_{up}} + L^{\Lambda(\xi_l;\xi_c)}_{up} \\ T_{chlu}(A_{\alpha_o}, \Xi(\xi_c)) &= Q^{\Xi(\xi_c)}_{chlu} \\ T^{chms}_{recv}(A_{\alpha_o}, \Xi(\xi_c)) &= \frac{Q^{\Xi(\xi_c)}_{chms}}{B^{\Lambda(\xi_l;\xi_c)}_{down}} + L^{\Lambda(\xi_l;\xi_c)}_{down} \end{aligned}$$

Like the time taken for each substep, each substep also consumes energy on the offloading client. In detail, the energy consumption $E(A_{\alpha_o}, \Xi(\xi))$ is the energy consumed for a local execution on the resource $\Xi(\xi_l)$, a cache hit from the cache on the resource $\Xi(\xi_c)$, a remote execution on the resource $\Xi(\xi_r)$, or a cache miss from the cache on the resource $\Xi(\xi_c)$. Again, please note that Section 3.2 defines the energy $E_{local}(A_{\alpha_o}, \Xi(\xi_l))$ consumed for an execution on a resource $\Xi(\xi_l)$ and $E_{remote}(A_{\alpha_o}, \Xi(\xi_r))$ for a distribution to a resource $\Xi(\xi_r)$, consisting of the energy consumption $E_{send}(A_{\alpha_o}, \Xi(\xi_r))$, $E_{wait}(A_{\alpha_o}, \Xi(\xi_r))$, and $E_{recv}(A_{\alpha_o}, \Xi(\xi_r))$. For a cache hit, $E_{chht}(A_{\alpha_o}, \Xi(\xi))$ sums up the energy consumption $E_{qury}(A_{\alpha_o}, \Xi(\xi_c))$ for querying the cache, $E_{chlu}(A_{\alpha_o}, \Xi(\xi_c))$ for waiting until the cache processed the query, and $E_{recv}(A_{\alpha_o}, \Xi(\xi_v))$ for receiving from the cache the output execution state. For a cache miss, $E_{chms}(A_{\alpha_o}, \Xi(\xi))$ sums up the energy consumption $E_{qury}(A_{\alpha_o}, \Xi(\xi_c))$ for querying the cache, $E_{chlu}(A_{\alpha_o}, \Xi(\xi_c))$ for waiting until the cache processed the query, $E^{chms}_{recv}(A_{\alpha_o}, \Xi(\xi_c))$ for receiving the cache miss, and $E_{remote}(A_{\alpha_o}, \Xi(\xi_r))$ for executing A_{α_o} remotely on the resource $\Xi(\xi_r)$.

$$
\begin{aligned}
E_{qury}(A_{\alpha_o}, \Xi(\xi_c)) &= T_{qury}(A_{\alpha_o}, \Xi(\xi_c)) \cdot E^{\Xi(\xi_l)}_{send} \\
E_{chlu}(A_{\alpha_o}, \Xi(\xi_c)) &= T_{chwt}(A_{\alpha_o}, \Xi(\xi_c)) \cdot E^{\Xi(\xi_l)}_{wait} \\
E^{chms}_{recv}(A_{\alpha_o}, \Xi(\xi_c)) &= T^{chms}_{recv}(A_{\alpha_o}, \Xi(\xi_c)) \cdot E^{\Xi(\xi_l)}_{recv}
\end{aligned}
$$

Having a closer look on the monetary cost $C(A_{\alpha_o}, \Xi(\xi))$, a cache hit from the cache on the resource $\Xi(\xi_c)$ (querying, waiting, and receiving), a remote execution on the resource $\Xi(\xi_r)$ (sending, waiting, and receiving), and a cache miss from the cache on the resource $\Xi(\xi_c)$ (querying, waiting, receiving, sending, waiting, and receiving) raise monetary cost for the offloading client. Again, please note that Section 3.2 defines the monetary cost $C_{remote}(A_{\alpha_o}, \Xi(\xi_r))$ raised for a distribution to a resource $\Xi(\xi_r)$, consisting of the monetary cost $C_{recv}(A_{\alpha_o}, \Xi(\xi_r))$, $C_{wait}(A_{\alpha_o}, \Xi(\xi_r))$, and $C_{send}(A_{\alpha_o}, \Xi(\xi_r))$. For a cache hit, $C_{chht}(A_{\alpha_o}, \Xi(\xi))$ sums up the monetary cost $C_{qury}(A_{\alpha_o}, \Xi(\xi_c))$ for querying the cache, $C_{chlu}(A_{\alpha_o}, \Xi(\xi_c))$ for processing the query on the cache, and $C_{send}(A_{\alpha_o}, \Xi(\xi_c))$ for receiving the output execution state from the cache. For a cache miss, $C_{chms}(A_{\alpha_o}, \Xi(\xi))$ sums up the monetary cost $C_{qury}(A_{\alpha_o}, \Xi(\xi_c))$ for querying the cache, $C_{chlu}(A_{\alpha_o}, \Xi(\xi_c))$ for processing the query on the cache, $C^{chms}_{send}(A_{\alpha_o}, \Xi(\xi_c))$ for receiving the information about the cache miss from the cache, and $C_{remote}(A_{\alpha_o}, \Xi(\xi_r))$ for executing A_{α_o} remotely on the resource $\Xi(\xi_r)$.

$$
\begin{aligned}
C_{qury}(A_{\alpha_o}, \Xi(\xi_c)) &= Q^{size}_{I_{state}}(A_{\alpha_o}) \cdot C^{\Lambda(\xi_l;\xi_c)}_{recv} \\
C_{chlu}(A_{\alpha_o}, \Xi(\xi_c)) &= Q^{\Xi(\xi_c)}_{qury} \\
C^{chms}_{send}(A_{\alpha_o}, \Xi(\xi_c)) &= Q^{\Xi(\xi_c)}_{chms} \cdot C^{\Lambda(\xi_l;\xi_c)}_{send}
\end{aligned}
$$

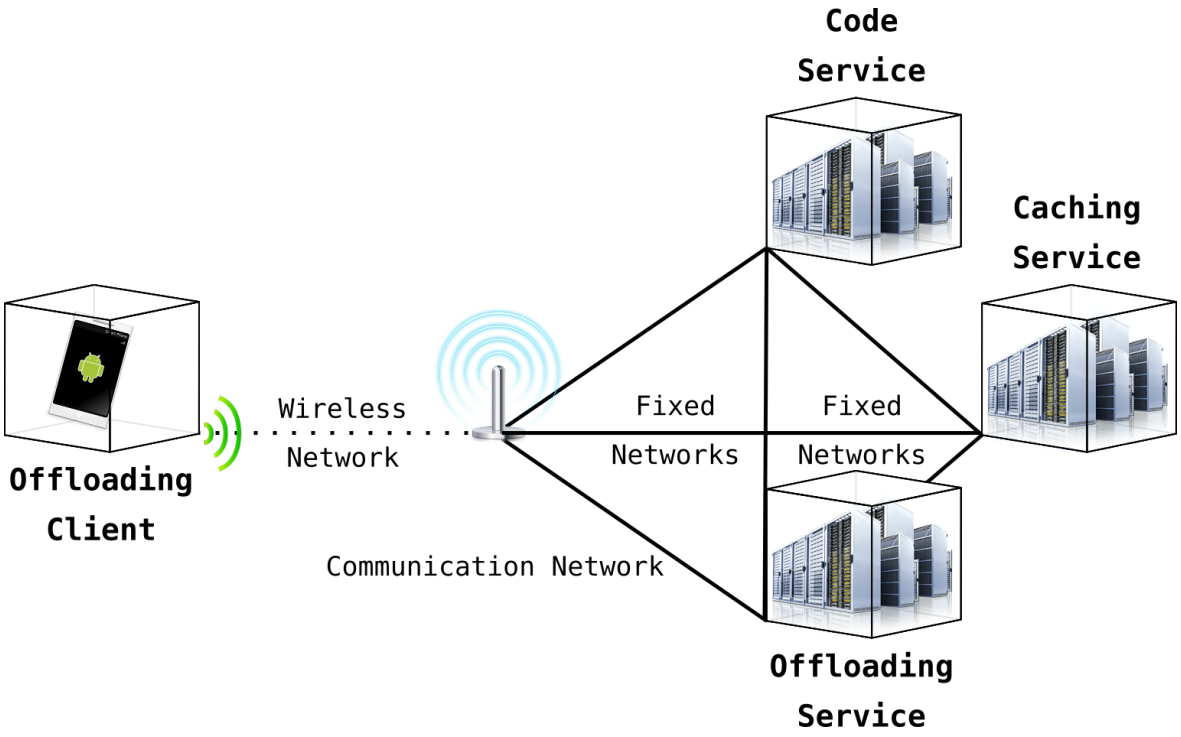


Figure 7.1.: The system components for the caching-aware distribution, where an offloading client offloads code via a communication network to an offloading service. A caching service provides a cache of output execution states.

Summarizing, the caching-aware distribution may increase the efficiency of the offloading client compared to the basic distribution by querying a cache for an application part instead of executing it on an offloading service. If the cache possesses a corresponding value in its storage (cache hit), it responses to the offloading client with the output execution state. Optimally, each query of an offloading client to the cache corresponds to a cache hit that significantly reduces the execution time, energy consumption, and monetary cost for an application part. In case of a cache miss, additional time, energy, and money arise for caching *and* distributing. Thus, the substeps required for caching introduces some overhead compared to the basic distribution.

7.2.3. System Components

Figure 7.1 shows the integration of a caching service to the system components of the basic distribution, where the caching service functions as a cache on the remote side. It is a classic server machine, hosted in a (commercial) cloud data center, providing Caching as a Service (CaaS) to offloading clients and offloading services with a pay-as-you-go cost model. Due to the pay-as-you-go cost model, each cache query or cache insert causes monetary cost for an offloading client or an offloading service that queries

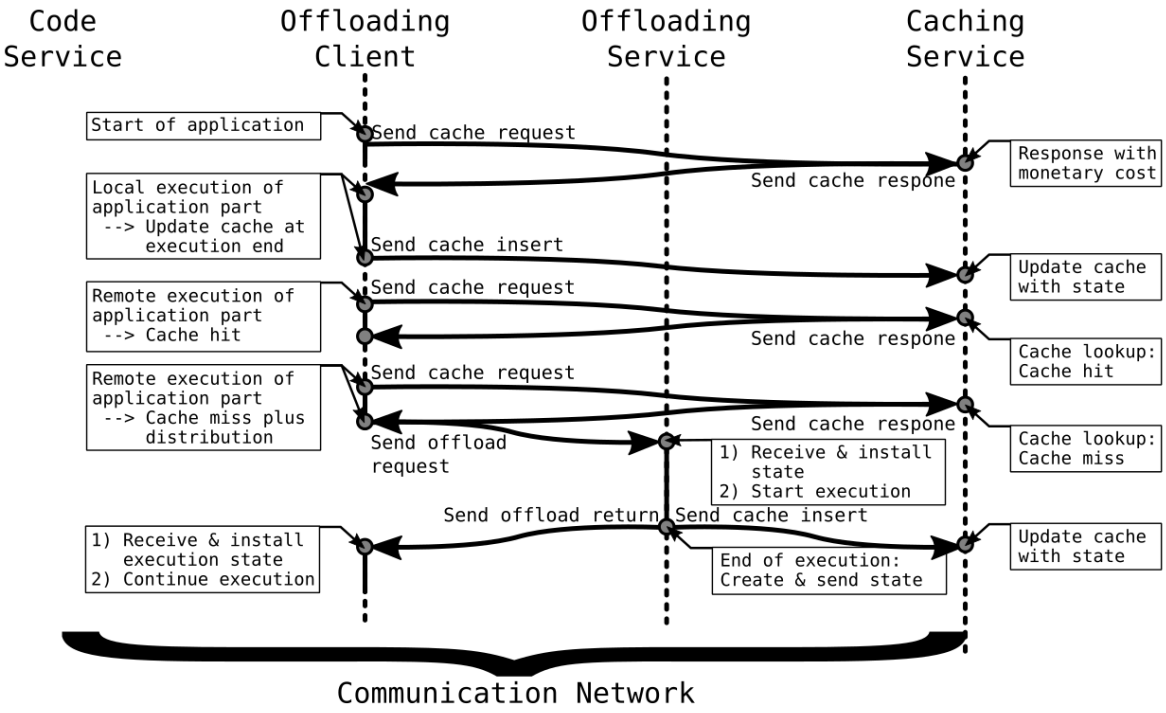


Figure 7.2.: Offloading timeline of the caching-aware distribution for an application part between an offloading client and an offloading service via a communication network, where the offloading client inserts and requests the output execution state from the caching service for application parts.

or inserts values (cf. Google's Memcache [Pla16]). To handle cache queries or cache inserts, the caching service stores key-value pairs in a database, where a key identifies globally uniquely its corresponding value. Offloading clients and offloading services query the caching service for key-value pairs and/or insert key-value pairs into it.

7.3. Offloading Timeline

Figure 7.2 shows a timeline for the caching-aware distribution that extends the basic distribution described in Section 4.4 with a cache on the remote side (caching service). First, an offloading client sends a cache request to the caching service, requesting the monetary cost charged for a utilization of the caching service. On a receive of a cache request, the caching service creates a cache response that contains the monetary cost for its utilization and sends the cache response to the offloading client. Like for the basic distribution, the offloading client identifies an application part that is feasible for a distribution based on the offload-specific annotation `offloadable`. Invoking an annotated application part, the offloading client gathers the input execution state of

the Java method and creates an offload request containing the input execution state. Afterwards, the offloading client determines the execution side for the Java method.

To make the basic distribution aware of caching, the caching-aware distribution additionally determines whether to query the caching service before either executing the Java method locally or distributing it to the offloading service. In case of querying the caching service, the offloading client creates three hash values for a Java method: (1) A hash value from the complete name of the application like `app_name-v1.3`, (2) a hash value from the entire signature of the Java method like `d.s.Klass.call(Ljava.lang.String;J[F)S`, and (3) a hash value of the offload request. For the computation of the hash values, the offloading client utilizes the efficient function DJB (Daniel Julius Bernstein)[1] for hash computation (cf. Henke et al. [HSZ08]). These three hash values provide a proper mapping between the call of a Java method within an application and its right output execution state, constituting an Identifier (ID) for the call of a Java method within an application. To this end, a cache request only consists of the three hash values that the offloading client sends to the caching service querying for a corresponding output execution state.

Each time the caching service receives a cache request from an offloading client, it starts a cache lookup in its local database based on the received ID (*key*). The local database is a (huge) hash map that stores key-value pairs requiring $\mathcal{O}(n)$ for the storage space and in average $\mathcal{O}(1)$ (in worst case $\mathcal{O}(n)$) for searching, inserting, or deleting values [CSRL09]. If the database contains a corresponding output execution state (*value*) for the received key (cache hit), the caching service immediately sends the offload response to the offloading client. Otherwise, it sends a small message to the offloading client indicating the non-existence of a key-value pair (cache miss).

In case of a cache hit, the offloading client receives the offload response, installs the contained information, and continues the execution of the application. In case of a cache miss, the offloading client receives the information of a cache miss and starts either an execution of the Java method locally or a distribution of the Java method to the offloading service as the basic distribution (Figure 7.2).

To fill the cache of the caching service with key-value pairs, offloading clients and offloading services send after a local execution of a Java method its ID together with the offload response to the caching service (cache insert). Then, the caching service updates its local database with the key-value pairs proactively, inserting the appropriate entries into the hash map. Regarding the memory limit of a cache storage, a caching service has to start a replacement strategy in case of running out of space, where the caching service utilizes the common replacement strategy of Least-Recently-Used (LRU) [JS94].

[1] Professor Daniel J. Bernstein invented the algorithm for the hash function.

7.4. Offloading Framework

The caching-aware distribution extends the offloading framework of the basic distribution described in Section 4.5 by modifying the offloading client (cf. Subsection 7.4.1) and the offloading service (cf. Subsection 7.4.2). Beside the modifications to the offloading client and the offloading service, it adds the caching service (cf. Subsection 7.4.3).

7.4.1. Offloading Client

On the offloading client, the caching-aware distribution only adjusts the offload controller to send cache inserts and cache requests (cf. Subsection 4.5.2). To send a cache insert after a local execution of an application part that is offloadable, the execution controller on the offloading client invokes the offload controller due to the execution of the offload-specific Java bytecode instruction `offload_end`. Afterwards, the offload controller generates a cache insert for the application part and sends it via the service connector to the caching service. To send a cache request before a local execution or the basic distribution of an application part that is offloadable, the offload controller on the offloading client minimizes the cost function from Equation 7.1 at its invocation from the execution controller due to the execution of the offload-specific Java bytecode instruction `offload`. Please note that the execution time $T(A_{\alpha_o}, \Xi(\xi))$, the energy consumption $E(A_{\alpha_o}, \Xi(\xi))$, and the monetary cost $C(A_{\alpha_o}, \Xi(\xi))$ depend in general on dynamic parameters that the offload controller only knows at run-time. For instance, an end user playing a chess game determines the parameters of the Java method that is offloadable by moving a chess piece during the play. Thus, the offload controller has to minimize online the cost function at run-time based on the current parameters.

Algorithm 7.1 visualizes the decision making of the offload controller on the offloading client minimizing the cost function at run-time. To this end, it first considers for a Java method A_{α_o} the tradeoff between a local execution on the hardware platform of the offloading client or receiving an offload response from the caching service due to a cache request (cf. Line 4). The offload controller executes the Java method locally in two cases: (1) If the sum of the energy consumption W^E_{chht} and the monetary cost W^C_{chht} for a cache hit is equal or higher than the energy consumption W^E_{lcl} for a local execution or (2) the execution time W^T_{chht} for a cache hit is equal or higher than the maximum time $T^{max}(A_{\alpha_o}, \Xi(\xi))$ for its execution. For instance, in case of a bad quality of the communication network (e.g., due to a high latency of the wireless link), a local execution is more beneficial than querying the caching service for an offload response. In case the `if-statement` in Line 4 of Algorithm 7.1 is `true`, the offloading client sends

1: $W^T_{lcl} = w_t \cdot T(A_{\alpha_o}, \Xi(\xi_l))$ $W^T_{chht} = T_{chht}(A_{\alpha_o}, \Xi(\xi_c))$
2: $W^E_{lcl} = w_e \cdot E(A_{\alpha_o}, \Xi(\xi_l))$ $W^E_{chht} = w_e \cdot E(A_{\alpha_o}, \Xi(\xi_c))$
3: $W^C_{chht} = w_c \cdot C(A_{\alpha_o}, \Xi(\xi_c))$
4: **if** $(W^E_{chht} + W^C_{chht}) < W^E_{lcl}$ && $W^T_{chht} < T^{max}(A_{\alpha_o}, \Xi(\xi))$ **then**
5: **if** sndCchRqstAndRcvCchRspns() == Cache Hit **then**
6: **return** offldRspns
7: **else**
8: $W^T_{rmt} = T_{chht}(A_{\alpha_o}, \Xi(\xi_r))$
9: $W^E_{rmt} = w_e \cdot E(A_{\alpha_o}, \Xi(\xi_r))$
10: $W^C_{rmt} = w_c \cdot C(A_{\alpha_o}, \Xi(\xi_r))$
11: **if** $(W^E_{rmt} + W^C_{rmt}) < W^E_{lcl}$ && $W^T_{rmt} < T^{max}(A_{\alpha_o}, \Xi(\xi))$ **then**
12: **return** sndOffldRqustAndRcvOffldRspn()
13: **end if**
14: **end if**
15: **end if**
16: exctLcl()

Algorithm 7.1: Algorithm of the decision making for the caching-aware distribution on the offload controller of the offloading client.

a cache request to the caching service. The caching service responses to the offloading client with the cache response containing either the offload response (cache hit) or the information about the cache miss. In case of a cache hit, the offload controller on the offloading client installs the contained information and continues the execution of the application (cf. Line 6). In case of a cache miss, the offload controller considers a further tradeoff between a local execution on the offloading client or a remote execution on the offloading service (cf. Line 11). Like for the first tradeoff, the offload controller executes the Java method locally in two cases: (1) If the sum of the energy consumption W^E_{rmt} and the monetary cost W^C_{rmt} for a remote execution is equal or higher than the energy consumption W^E_{lcl} for a local execution or (2) the execution time W^T_{rmt} for a remote execution is equal or higher than the maximum time $T^{max}(A_{\alpha_o}, \Xi(\xi))$ for its execution. In case the `if-statement` in Line 11 is `true`, the offloading client sends an offload request to the offloading service. After the remote execution of the offload request on the offloading service, the offloading service responses to the offloading client with the offload response. On receiving the offload response, the offloading client installs the contained information and continues the execution of the application (cf. Line 12).

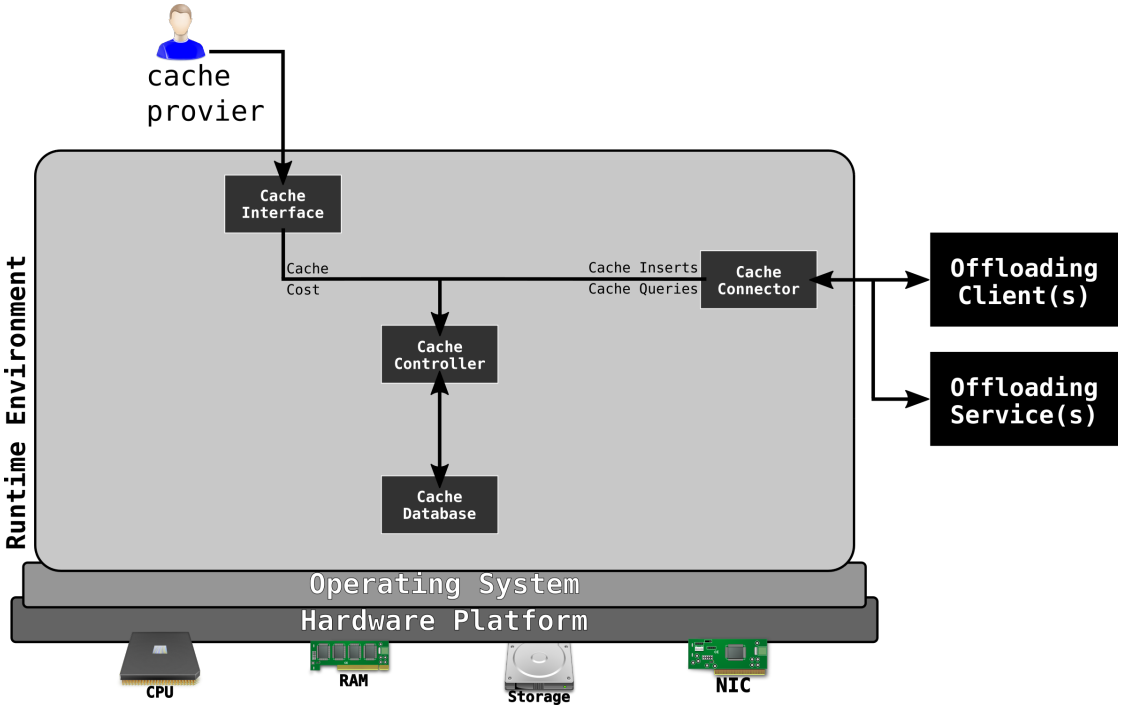


Figure 7.3.: The runtime environment on the caching service for the caching-aware distribution.

7.4.2. Offloading Service

For the offloading service, the caching-aware distribution only adjusts the offload controller and adds a service connector to send cache inserts (cf. Subsection 4.5.3). To send a cache insert after an execution of an application part that is offloadable, the execution controller invokes the offload controller due to the execution of the offload-specific Java bytecode instruction `offload_end`. Afterwards, the offload controller generates a cache insert for the application part and sends it via the service connector to the caching service. Please note that the service connector corresponds to a service connector on an offloading client, providing the same functionality.

7.4.3. Caching Service

Figure 7.3 shows the runtime environment of the caching service, providing the cache-side functionality for the caching-aware distribution. It consists of a cache interface, a cache connector, a cache controller, and a cache database.

Cache Interface The cache controller of the caching service invokes the cache interface to retrieve the monetary cost for querying the caching service of an output execution state and inserting an input execution state to the caching service. To this

end, the cache interface provides an interface – more precisely text entry boxes, where a provider of the cache defines the monetary cost.

Cache Connector The cache connector of the caching service receives cache requests, cache inserts, and cache queries from offloading clients and offloading services. Moreover, it sends cache responses to offloading clients and offloading services. Receiving a cache request, an offloading client or an offloading service requests the monetary cost for querying and inserting of the caching service. To this end, the cache connector forwards the cache request to the cache controller. Receiving a cache insert, an offloading client or an offloading service updates the caching service with an output execution state after an execution of an application part. Thus, the cache connector forwards the cache insert to the cache controller. Receiving a cache query, an offloading client or an offloading service queries the caching service for an output execution state before an execution of an application part. To this end, the cache connector forwards the cache query to the cache controller. Receiving a cache response, the cache controller responses to a cache request, cache insert, or a cache query. Thus, the cache connector forwards it to the corresponding offloading client or offloading service.

Cache Controller The cache connector of the caching service invokes the cache controller due to the receive of a cache request, a cache insert, or a cache query. In case of a cache request, the cache controller creates a cache response – that contains the monetary cost of the caching service requested from an offloading client or an offloading service – and forwards the cache response to the cache connector. In case of a cache insert, the cache controller updates the cache database if it does not possess the key-value pair from the cache insert. In case of a cache query, the cache controller starts a lookup on the cache database if it possesses a corresponding value (output execution state) for the queried key. Afterwards, the cache controller creates a cache response – that contains either a corresponding value of the output execution state (cache hit) or the information about the cache miss – and forwards it the the cache connector.

Cache Database The cache database is a hash map that provides an efficient insert and lookup of key-value pairs for the caching service.

7.5. Evaluation

To evaluate the introduced overhead and gained benefits of the caching-aware distribution, we extended the implementation of the OpenJDK prototype for the basic

distribution (cf. Subsection 4.6.2). The extensions to the OpenJDK prototype comprise changes to the implementation of the JVM to provide the functionality required for the caching-aware distribution on the offloading client and the offloading service (cf. Section 7.4). Moreover, we implemented the caching service in a Java application, executed on an unaltered OpenJDK JRE. For the evaluation, mobile devices execute Java applications on an unaltered OpenJDK JRE (local execution), on an offload-aware OpenJDK JRE (basic distribution), and on a caching-aware OpenJDK JRE (caching-aware distribution). To this end, Subsection 7.5.1 describes the evaluation setup before Subsection 7.5.2 presents the evaluation results.

7.5.1. Setup

The evaluation setup for the caching-aware distribution extends the evaluation setup for the basic distribution on the OpenJDK described in Subsection 4.7.1 as follows:

The desktop computer that executes the offloading service also executes the Java application for a caching service on its hardware platform, possessing enough processing power for the execution of both services (cf. Section C.4).

The application evaluated for the caching-aware distribution are the chess game (cf. Section B.3) and the text-to-voice application (cf. Subsection B.5). The Java method that is offloadable from the chess game occupies only a small amount of memory on the cache of the caching service due to its small size of the output execution state. Regarding the huge number of possible configurations of the chess board[2], however, the hit ratio of a cache for chess decreases fast with the number of rounds played for chess. Today's chess engines also look up favorable chess moves from a chess opening book in place of actually calculating the next best move on hardware. The Java method that is offloadable from the text-to-voice application occupies a large amount of memory on the cache of the caching service due to its big size of the output execution state. Regarding the general frequency of a word in a text (cf. Zipf's law [Pow98]), however, the hit ratio of a cache for text-to-voice is significantly higher than for chess. For instance, Fagan and Gençay analyzed in [FG10] the Brown University Standard Corpus of Present-Day American English (text collection)[3] that consists of $1,014,312$ words in total. Remarkably, half of the text collection only requires 135 different words.

For the monetary cost charged by the offloading service or the caching service, we

[2] In the year 1950, Claude E. Shannon estimated the number of possible positions of chess pieces in the general order of roughly 10^{43}. [Sha50]

[3] `http://clu.uni.no/icame/manuals/BROWN/INDEX.HTM`

consider the prices charged by Google[4] or Amazon[5] for the utilization of instances from their cloud platform. Both providers of cloud instances do not charge for data sent to the data center as well as data received from the data center. Together with the availability of a flat-rate data plans for end users, we set $C_{recv}^{\Lambda(\xi_l;\xi_c)}$ – and thus $C_{qury}(A_{\alpha_o}, \Xi(\xi_c))$ and $C_{recv}(A_{\alpha_o}, \Xi(\xi_r))$ – as well as $C_{send}^{\Lambda(\xi_l;\xi_c)}$ – and thus $C_{send}^{chms}(A_{\alpha_o}, \Xi(\xi_c))$ and $C_{send}(A_{\alpha_o}, \Xi(\xi_r))$ – to 0 (cf. Subsection 7.2.2). Typically, a cloud instance from Google or Amazon executes either the offloading service or the caching service. As the desktop computer executes both services, the monetary cost for $C_{wait}(A_{\alpha_o}, \Xi(\xi_r))$ or $C_{chlu}(A_{\alpha_o}, \Xi(\xi_c))$ equals the prices for an *m3.medium* machine type from Amazon as well as an *n1-standard-1* machine type from Google. The utilization of an *m3.medium* machine type from Amazon causes a monetary cost of 0.070 $ per hour and an *n1-standard-1* machine type from Google 0.063 $ per hour. As a provider of an offloading service or a caching service want to earn money with its service running on a cloud instance, we assume the sum of the price for a cloud instance from Amazon and Google, resulting in a monetary cost of $3.69 \cdot 10^{-5}$ $\left(= \frac{0.070+0.063}{60 \cdot 60}\right)$ $ per second for $C_{wait}(A_{\alpha_o}, \Xi(\xi_r))$ and $C_{chlu}(A_{\alpha_o}, \Xi(\xi_c))$. For instance, utilizing a Google *n1-standard-1* instance, a provider amortizes the leasing cost of an hour (3600 s) for the Google instance after 1705.26 s of consecutive execution of application parts distributed to its service. As a provider of a caching service wants its cache to be filled by many participants, it does not charge monetary cost for cache inserts.

The evaluation compares the caching-aware distribution – named *Cached* – in two configurations – named $Cached_{Empty}$ and $Cached_{Full}$ – differing in the fill level of the cache on the caching service with the two approaches *Local* and *Baseline*. The approach *Local* totally executes an application on an unaltered OpenJDK JRE, not distributing or caching a Java method that is offloadable. The approach *Baseline* utilizes the basic distribution (cf. Section 4.1) distributing but not caching a Java method that is offloadable. The configuration $Cached_{Empty}$ of *Cached* represents the worst case of the caching-aware distribution. The fill level of the cache from the caching service is empty and thus, the caching service responses to an offloading client that queries the caching service every time with a cache miss. The configuration $Cached_{Full}$ of *Cached* represents the optimal case of the caching-aware distribution. The cache from the caching service possesses each corresponding value for a key queried from an offloading client and thus, responses to an offloading client that queries the caching service every time with a cache hit. Based on the two configurations of $Cached_{Empty}$ and $Cached_{Full}$, the evaluation highlights for the caching-aware distribution its overhead and benefit.

[4] `https://cloud.google.com/compute`
[5] `https://aws.amazon.com/ec2/pricing/?nc1=h_ls`

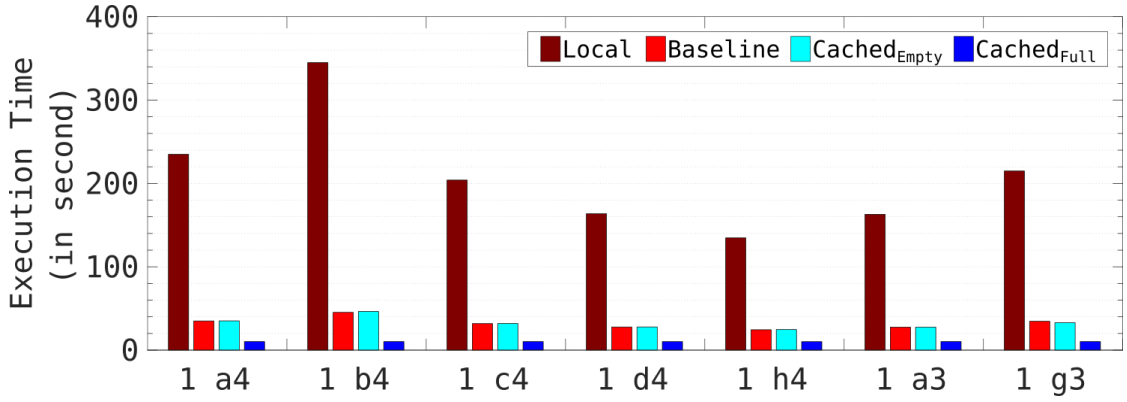
Beside the evaluation of the overhead and benefit for the caching-aware distribution, the evaluation further gives an insight into the actual performance of the caching-aware distribution (*Cached*) with the help of a mobile scenario. To this end, each mobile device executes alternately on its hardware platform either the chess game or the text-to-voice application with different parameters like the configuration of the chess board or the transformed sentence. Both mobile devices utilize the same cache for the chess game and the text-to-voice application, where the fill level of the cache is empty at the start of the mobile scenario. To keep the results of *Cached* comparable with *Baseline*, only two mobile devices fill the cache of the caching service, because the hit ratio of the cache increases with the number of participating devices. The total space of the cache amounts to 1 GB that is large enough to store all of the values filled from the two mobile devices during the mobile scenario.

7.5.2. Results

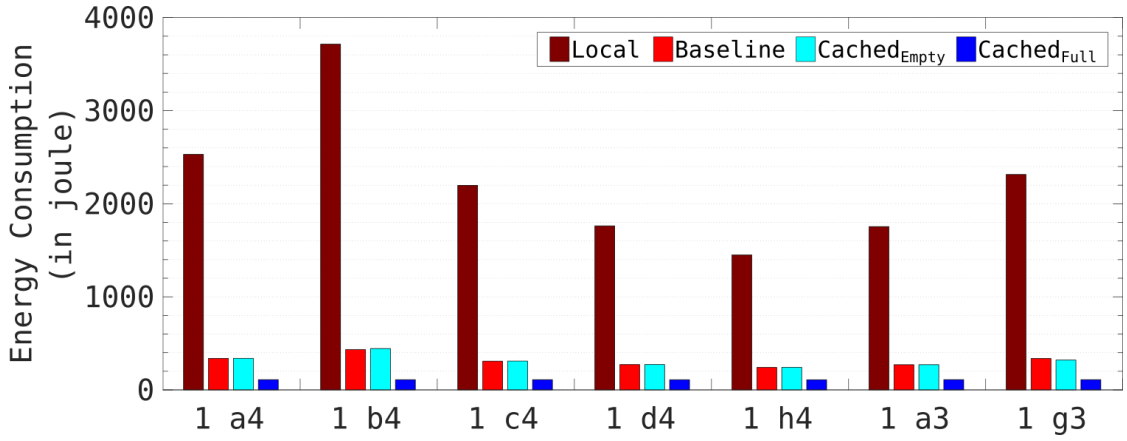
Now, the following subsection presents the evaluation results, first describing the evaluation results for the chess game and afterwards the evaluation results for the text-to-voice application. Last, it describes the evaluation results for the mobile scenario.

Chess Game

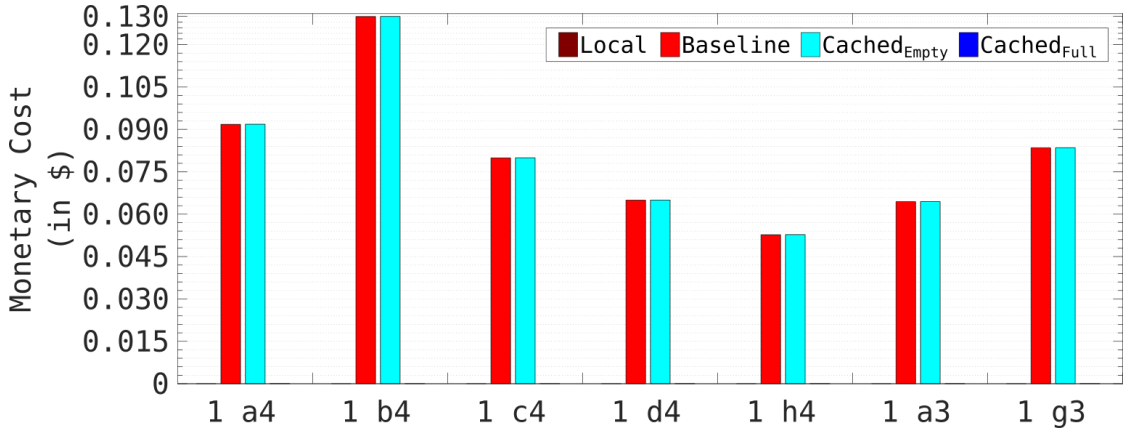
For the netbook, Figure 7.4 shows the execution time, energy consumption, and monetary cost of the different approaches after 10 rounds of chess moves for each opening move. Subsection 4.7.2 describes the evaluation results for a local execution (134.70 s and 345.03 s; 1450.38 J and 3715.22 J; 0 $) and the basic distribution (24.44 s and 45.31 s; 241.10 J and 433.51 J; 0.0527260 $ and 0.1299504 $) of the chess game on the related OpenJDK JRE (cf. dark-red and red bars in Figure 7.4a, Figure 7.4b, and Figure 7.4c). Regarding the execution time, energy consumption, and monetary cost of $Cached_{Empty}$ (cf. cyan bars in Figure 7.4a, Figure 7.4b, and Figure 7.4c), the caching-aware distribution keeps the (computation and communication) overhead introduced by caching low. Compared to the evaluation results of *Baseline*, the differences are minimal resulting in similar results for *Baseline* and $Cached_{Empty}$. For instance, the difference of the execution time is in the order of ten milliseconds owing to the additional queries to the caching service. The benefits of a cache that possesses all values queried in advance are significantly (cf. blue bars in Figure 7.4a, Figure 7.4b, and Figure 7.4c), because the time taken, the energy consumed, or the money raised for a cache query compared to a remote execution is very small. In detail, $Cached_{Full}$ takes at least 10.156 s and at most 10.255 s, consumes at least 109.34 J and at most



(a) Execution time on the netbook for the chess game.



(b) Energy consumption on the netbook for the chess game.



(c) Monetary cost on the netbook for the chess game.

Figure 7.4.: Execution time, energy consumption, and monetary cost on the netbook for the evaluation of the chess game with the different opening moves.

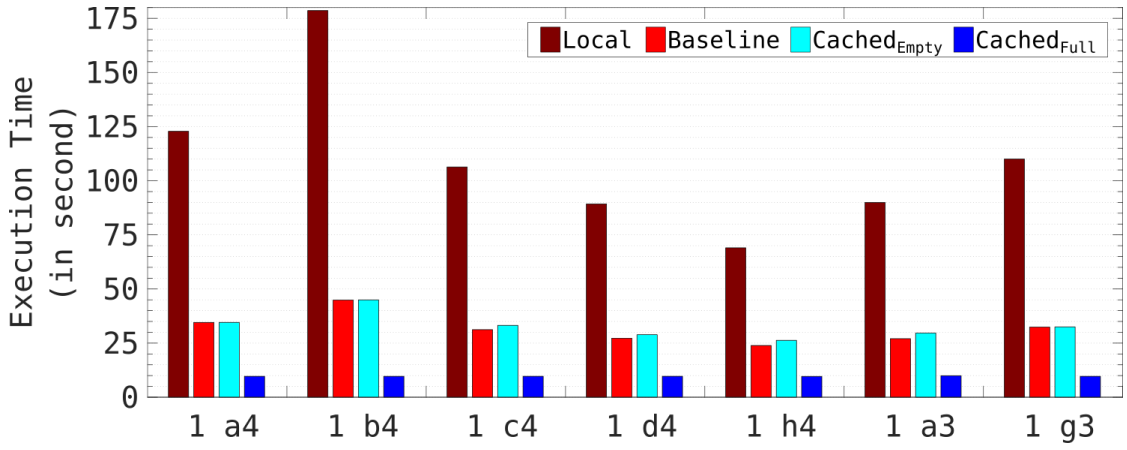
110.41 J, and raises at least 0.0000242 $ and at most 0.0000402 $. Compared to *Baseline*, $Cached_{Full}$ reduces the execution time, energy consumption, and monetary cost by up to 77.45%, 74.62%, and 99.98%, respectively. Compared to *Local*, it further reduces both execution time and energy consumption by up to 97.04%.

For the laptop, Figure 7.5 shows the execution time, energy consumption, and monetary cost of the different approaches after 10 rounds of chess moves for each opening move. Subsection 4.7.2 also describes the evaluation results for a local execution (69.019 s and 178.608 s; 3187.30 J and 8248.12 J; 0 $) and the basic distribution (23.912 s and 44.889 s; 890.93 J and 1519.67 J; 0.0499715 $ and 0.1296594 $) of the chess game on the related OpenJDK JRE (cf. dark-red and red bars in Figure 7.5a, Figure 7.5b, and Figure 7.5c). Like for the netbook, the caching-aware distribution keeps the introduced (computation and communication) overhead low (cf. cyan bars in Figure 7.5a, Figure 7.5b, and Figure 7.5c), where the maximum overhead of $Cached_{Empty}$ for the execution time is in average 0.237 s and for the energy consumption 10.964 J compared to *Baseline*. Regarding the benefits produced from $Cached_{Full}$ (cf. blue bars in Figure 7.5a, Figure 7.5b, and Figure 7.5c), it reduces the execution time (minimum: 9.637 s; maximum: 9.968 s), energy consumption (minimum: 444.89 J; maximum: 460.18 J), and monetary cost (minimum: 0.0000239 $; maximum: 0.0000479 $) by up to 78.46%, 70.63%, and 99.97% compared to *Baseline*. Compared to *Local*, it further reduces both execution time and energy consumption by up to 94.59%.

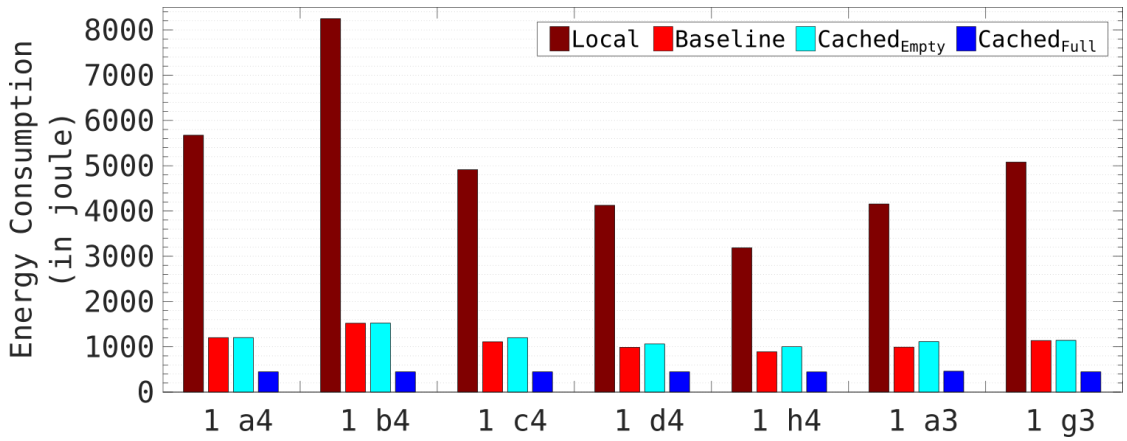
Summarizing, the caching-aware distribution further increases the benefits of the basic distribution that already improves a local execution of applications. As it only sends the ID to a caching service to query the cache, the total number of bytes transferred is low, especially compared to sending the offload request to the offloading service for a remote execution (order of bytes vs. multiple kilobytes or even megabytes). Thus, the caching-aware distribution outperforms the basic distribution in the optimal case ($Cached_{Full}$), also keeping the introduced overhead low in the worst case ($Cached_{Empty}$).

Text-to-Voice Application

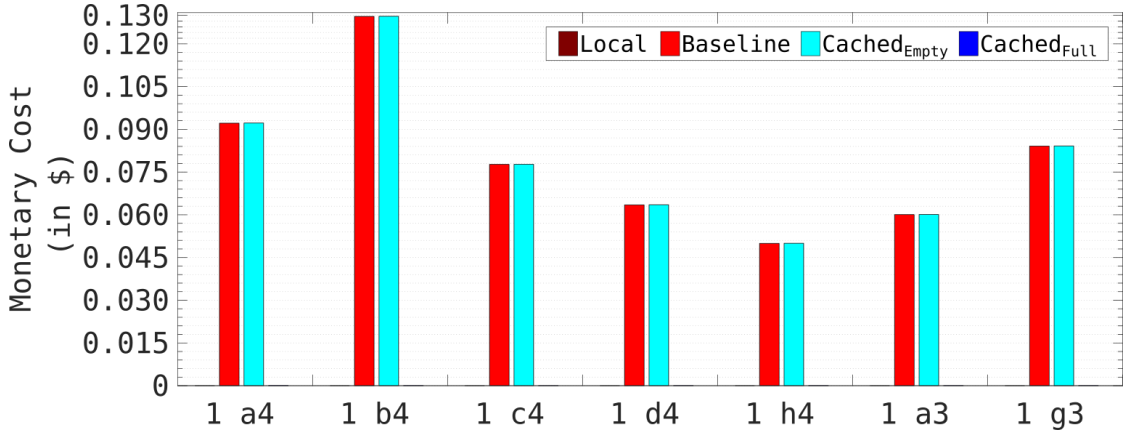
For the netbook, Figure 7.6 shows the execution time, energy consumption, and monetary cost of the different approaches transforming 15 or 20 words from ThinkAir or MAUI to voice. Subsection 4.7.2 also describes the evaluation results for a local execution (65.532 s and 85.024 s; 705.64 J and 915.52 J; 0 $) and the basic distribution (32.519 s and 41.472 s; 332.97 J and 423.29 J; 0.0386653 $ and 0.0555976 $) of the text-to-voice application on the related OpenJDK JRE (cf. dark-red and red bars in Figure 7.6a, Figure 7.6b, and Figure 7.6c). The difference of the results between



(a) Execution time on the laptop for the chess game.

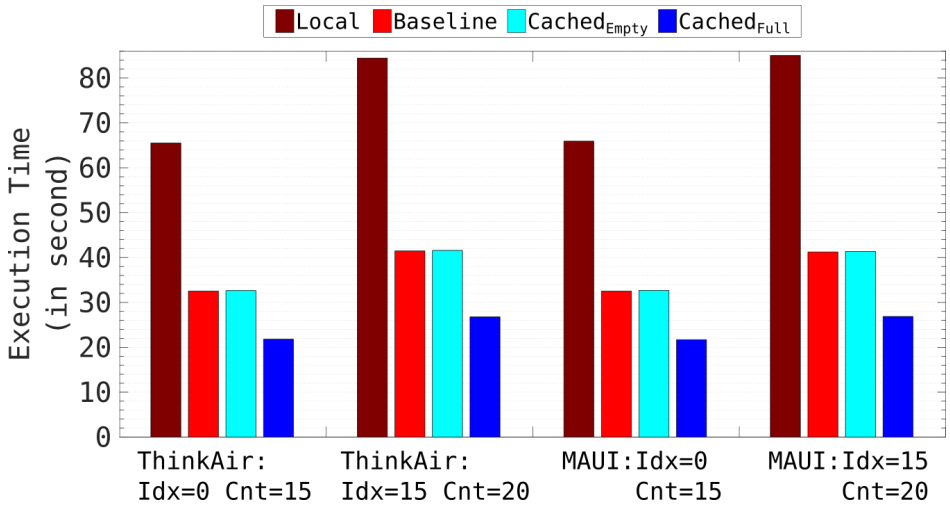


(b) Energy consumption on the laptop for the chess game.

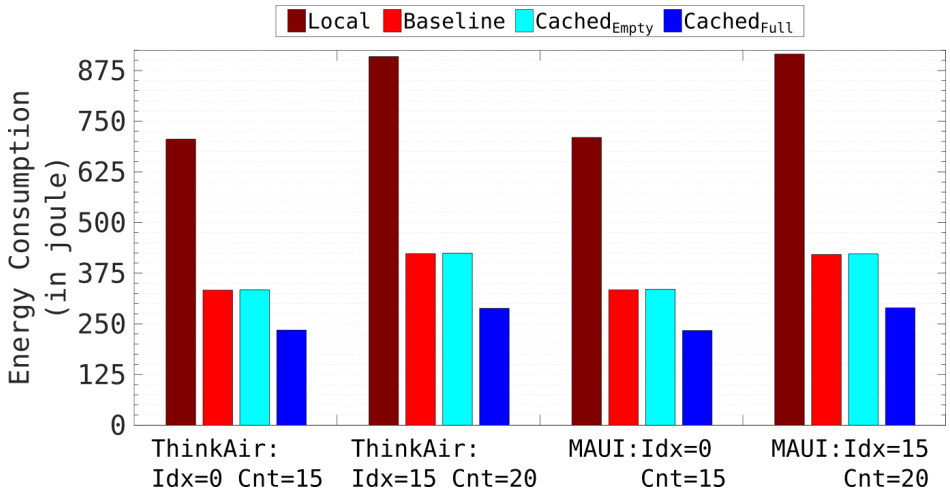


(c) Monetary cost on the laptop for the chess game.

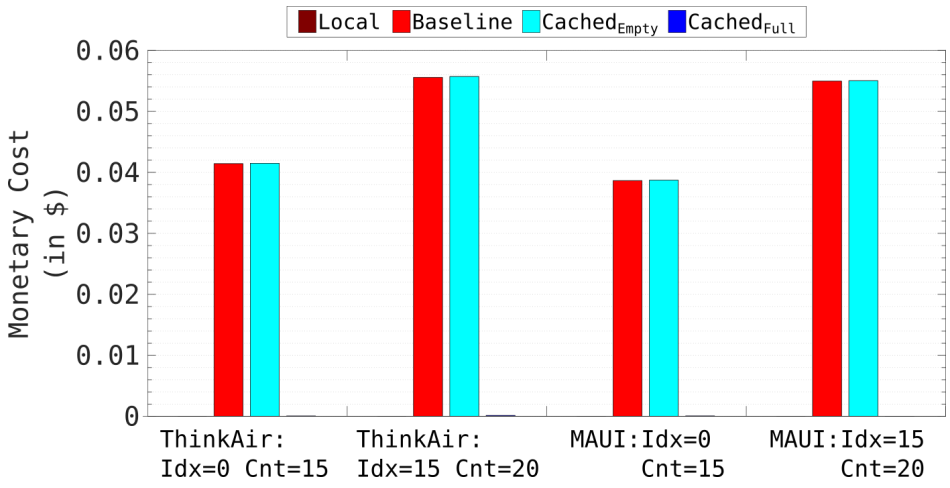
Figure 7.5.: Execution time, energy consumption, and monetary cost on the laptop for the evaluation of the chess game with the different opening moves.



(a) Execution time on the netbook for the text-to-voice application.



(b) Energy consumption on the netbook for the text-to-voice application.



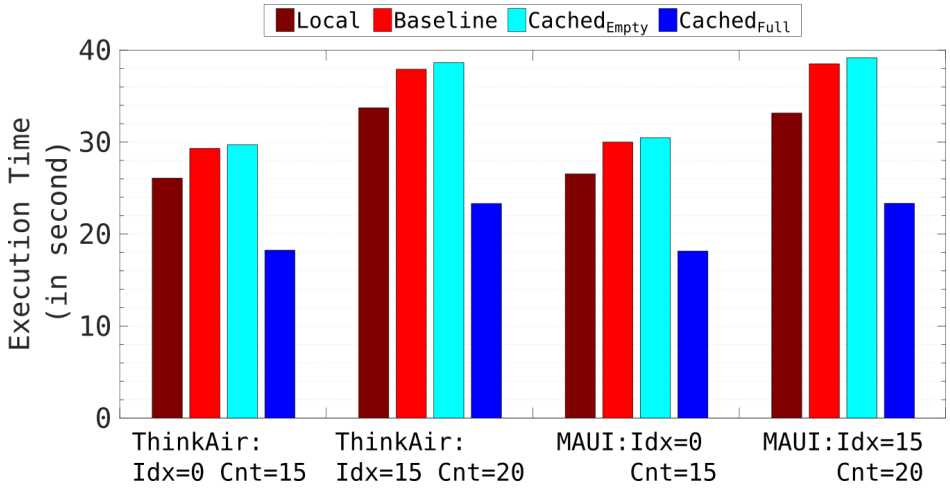
(c) Monetary cost on the netbook for the text-to-voice application.

Figure 7.6.: Execution time, energy consumption, and monetary cost on the netbook for the evaluation of the text-to-voice application.

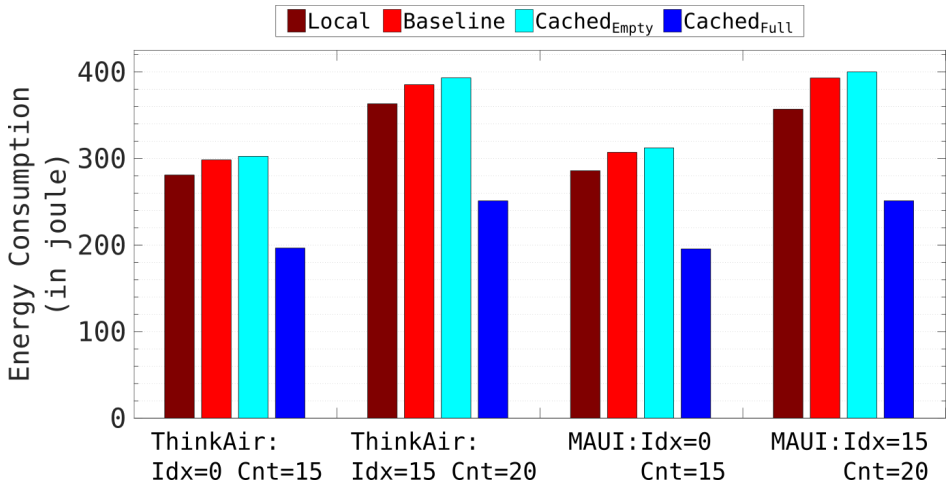
Baseline and $Cached_{Empty}$ highlights the (computation and communication) overhead introduced by caching, being for the execution time, energy consumption, and monetary cost very low (cf. cyan bars in Figure 7.6a, Figure 7.6b, and Figure 7.6c). Thus, the basic distribution (*Baseline*) and the caching-aware distribution ($Cached_{Empty}$) results in similar execution time (in the order of 100 milliseconds), energy consumption (in the order of 2 joules), and monetary cost (in the order of 0.1 cent). Regarding the benefits of a cache that possesses all values queried in advance (cf. blue bars in Figure 7.6a, Figure 7.6b, and Figure 7.6c), $Cached_{Full}$ takes the shortest time (minimum: 21.686 s; maximum: 26.872 s), consumes the least energy (minimum: 233.48 J; maximum: 289.32 J), and raises the lowest monetary cost (minimum: 0.0000596 $; maximum: 0.0001426 $) compared to the other approaches. $Cached_{Full}$ reduces the execution time, energy consumption, and monetary cost compared to *Baseline* by up to 35.39%, 31.85%, and 99.86%, respectively. Compared to *Local*, it further reduces both execution time and energy consumption by up to 68.39% and 68.40%.

For the laptop, Figure 7.7 shows the execution time, energy consumption, and monetary cost of the different approaches transforming the words to voice. Subsection 4.7.2 also describes the evaluation results for a local execution (26.083 s and 33.731 s; 280.86 J and 363.21 J; 0 $) and the naive basic distribution (29.304 s and 38.508 s; 298.35 J and 392.98 J; 0.03803 $ and 0.05479 $) of the text-to-voice application on the related OpenJDK JRE (cf. dark-red and red bars in Figure 7.7a, Figure 7.7b, and Figure 7.7c). Please note that the basic distribution would not distribute the Java method that is offloadable from the text-to-voice application just like $Cached_{Empty}$ or $Cached_{Full}$. However, both $Cached_{Empty}$ and $Cached_{Full}$ can still send a query to the caching service. As a result, *Baseline* corresponds on the laptop to the naive basic distribution that still distributes the Java method that is offloadable. Regarding the (computation and communication) overhead introduced by caching, the caching-aware distribution also keeps the overhead on the laptop low (cf. cyan bars in Figure 7.7a, Figure 7.7b, and Figure 7.7c), resulting in an average increase of the execution time and energy consumption by up to 0.033 s and 0.35 J. Despite the fact that the Java method that is offloadable is a bad candidate for a distribution, $Cached_{Full}$ reduces the execution time (minimum: 18.156 s; maximum: 23.333 s) and energy consumption (minimum: 195.48 J; maximum: 251.18 J) compared to *Local* and thus, to *Baseline* (cf. blue bars in Figure 7.7a, Figure 7.7b, and Figure 7.7c). Raising monetary cost between 0.0000417 $ and 0.0001527 $, $Cached_{Full}$ lowers the execution time and energy consumption by up to 39.46% and 36.33% compared to *Baseline*. Compared to *Local*, it has a lower execution time and energy consumption of up to 31.62% and 31.62%.

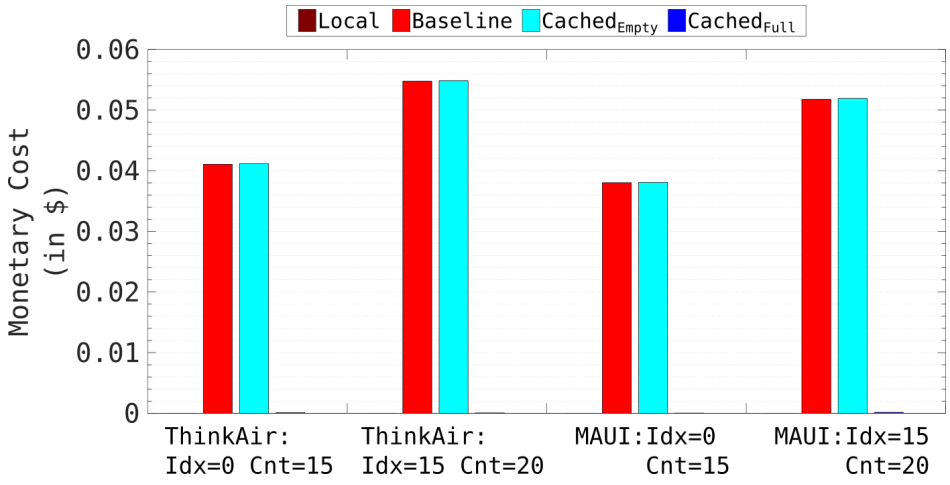
Summarizing, the caching-aware distribution on the netbook further increases the



(a) Execution time on the laptop for the text-to-voice application.

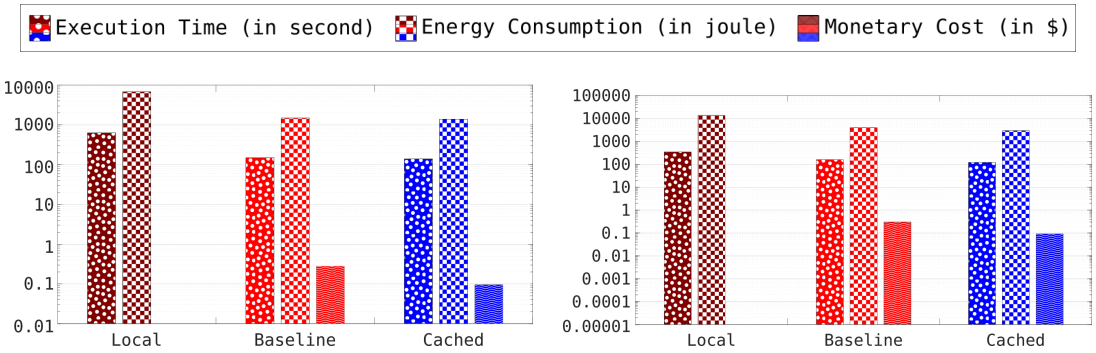


(b) Energy consumption on the laptop for the text-to-voice application.



(c) Monetary cost on the laptop for the text-to-voice application.

Figure 7.7.: Execution time, energy consumption, and monetary cost on the laptop for the evaluation of the text-to-voice application.



(a) Execution time, energy consumption, and monetary cost on the netbook.

(b) Execution time, energy consumption, and monetary cost on the laptop.

Figure 7.8.: Execution time, energy consumption, and monetary cost (a) on the netbook and (b) on the laptop for the evaluation of the mobile scenario.

benefits of the basic distribution that already improves a local execution of applications. Due to the fact that, on the one hand, the laptop is a more powerful device with a higher energy consumption and, on the other hand, the text-to-voice application has a big size of the output execution state, only the additional utilization of a caching service ($Cached_{Full}$) reduces the execution time and energy consumption on the laptop lower than a local execution. Thus, on both mobile devices, the caching-aware distribution outperforms the basic distribution in the optimal case ($Cached_{Full}$), also keeping the introduced overhead in the worst case low ($Cached_{Empty}$).

Mobile Scenario

For the mobile scenario, each mobile device executes in parallel five times either the chess game or the text-to-voice application as follows. The randomly selected sequence on the netbook is a chess game with **1 d4**, a text-to-voice application with **ThinkAir: Idx=0 Cnt=15**, a text-to-voice application with **ThinkAir: Idx=0 Cnt=15**, a chess game with **1 h4**, and a chess game with **1 c4**. On the laptop, the randomly selected sequence is a text-to-voice application with **MAUI: Idx=15 Cnt=20**, a text-to-voice application with **ThinkAir: Idx=0 Cnt=15**, a chess game with **1 a4**, a chess game with **1 h4**, and a chess game with **1 d4**.

Figure 7.8 shows the execution time, energy consumption, and monetary cost on the netbook (cf. Figure 7.8a) and on the laptop (cf. Figure 7.8b) for the different approaches executing the sequence of applications for the mobile scenario. Regarding the execution time of *Local*, *Baseline*, and *Cached* on both devices (cf. white-dotted bars in Figure 7.8), *Local* takes the longest time for the execution, namely on the netbook 633.521 s and on the laptop 340.424 s. Compared to *Local*, *Baseline* reduces

the execution time by 76.46% on the netbook and by 53.72% on the laptop, resulting in 149.102 s and 157.562 s, respectively. At the start of the mobile scenario, the cache on the caching service is empty, where both mobile devices fill it up during the evaluation of the mobile scenario. As a result, the execution time of *Baseline* and *Cached* are similar, where *Cached* further reduces the execution time of *Baseline* by 6.41% on the netbook and 23.89% on the laptop as well as of *Local* by 97.95% on the netbook and 98.24% on the laptop. It takes on the netbook 139.550 s and on the laptop 119.913 s. The same applies to the energy consumption of the three approaches (cf. white-squared bars in Figure 7.8), where *Local* consumes the most energy with 6821.63 J on the netbook and 13623.17 J on the laptop. *Baseline* reduces the energy consumption of*Local* by 78.19% on the netbook and 70.94% on the laptop (1488.11 J and 3958.74 J, respectively), where *Cached* reduces it by 79.56% on the netbook and 78.60% on the laptop (1394.30 J and 2914.73 J). Regarding the monetary cost of *Local*, *Baseline*, and *Cached* on both devices (cf. white-waved bars in Figure 7.8), *Local* raises no monetary cost, executing the sequence of applications totally on the mobile devices. To reduce the execution time and energy consumption of *Local*, *Baseline* raises monetary cost of 0.2805151 $ on the netbook and 0.2984818 $ on the laptop due to the remote execution of the Java methods on the Distribution Service. Due to the cache hits during the mobile scenario, *Cached* reduces the monetary cost raised by 65.64% on the netbook and 69.81% on the laptop, resulting in 0.0963923 $ and 0.0901089 $.

Summarizing, the netbook and the laptop benefits significantly from the basic distribution of the Java methods that are offloadable in the mobile scenario. Extending the basic distribution with a cache on the remote side, however, the execution time and energy consumption reduces slightly due to an increased hit ratio of the cache during the mobile scenario. Moreover, the cache hits from the caching-aware distribution reduces significantly the monetary cost raised during the mobile scenario.

7.6. Summary

To provide an optimized code offloading through cooperative caching, the *caching-aware distribution* described in Section 7.1 extends the basic distribution with a cache on the remote side. The cache stores output execution states (value) of application parts previously executed on offloading clients or offloading services. As stated by Satyanarayanan in [Sat96], “caching plays a key role in mobile computing”, the caching-aware distribution adds a caching service to the *system overview* described in Section 7.2, adapting the system model, problem statement, and system components of the basic distribution. Regarding the *offloading timeline* described Section 7.3 the ad-

ditional utilization of a caching service for the basic distribution enables an offloading client to query the cache on the remote side for a corresponding output execution state of an application part that is offloadable. To this end, the offloading client just sends a cache query either before the local execution of the application part or the basic distribution of it. In case of a cache hit, the cache queries, on the one hand, avoids a repeated execution of application parts previously executed, and, on the other hand, reduces significantly the execution time required to get an output execution state. In case of a cache miss, the overhead introduced for cache queries is small, consisting only of hash values that identify the call of an application part. The *offloading framework* described in Section 7.4 provides the functionality required for the caching-aware distribution on the offloading client, on the offloading service, and on the caching service. To evaluate the overhead introduced and benefit gained by the caching-aware distribution compared to the basic distribution, the *evaluation* described in Section 7.5 analyzes different mobile devices with different applications based on the implemented prototype on the OpenJDK JRE. The evaluation results show that the caching-aware distribution increases the efficiency of the basic distribution. It reduces the execution time, energy consumption, and monetary cost for an application part that is offloadable compared to the basic distribution as well as to a local execution.

Chapter 8

Code Offloading in Environments with Multiple Tiers

The basic distribution presented in detail in Chapter 4 offloads computation between a mobile device and a remote resource (two-tier architecture). It increases the efficiency on a mobile device and the execution speed of a mobile application. A common environment in today's Mobile Cloud Computing (MCC), however, comprises highly distributed heterogeneous resources that can participate in code offloading. Such environments enlarge the number of available resources for a remote execution of application parts that are offloadable. To this end, this chapter presents a bubbling distribution in environments with multiple tiers described in Section 8.1. The bubbling distribution makes the basic distribution aware of an efficient and applicable code offloading to multiple resources with different performance characteristics and cost implications (multi-tier architecture). Thus, the system overview described in Section 8.2 with the system model, problem statement, and system components changes now from a two-tier architecture (basic distribution) to a multi-tier architecture (bubbling distribution). For a multi-tier architecture with multiple resources, it is very costly for a resource-poor mobile device to gather a global view of all available resources in all available tiers. For this reason, the bubbling distribution utilizes the concept of code bubbling. Code bubbling moves application parts that are offloadable dynamically and adaptively towards more powerful and more distant tiers, described in the offloading timeline in Section 8.3. Each tier makes autonomous decisions either to execute an application part in the tier or to forward it further to the next tier. To support such a recursive escalation of application parts along autonomous tiers, the bubbling distribution extends the offloading framework described in Section 8.4. The offloading framework provides a corresponding Application Programming Interface for the Java programming language to support code bubbling. Moreover, it also extends the offloading client and offloading service to support code bubbling and introduces a tier service to manage tiers. To evaluate the efficiency and applicability of a distribution with code bubbling compared to the basic distribution, Section 8.5 presents the evaluation of a

prototype, including the evaluation setup and the evaluation results. Last, Section 8.6 summarizes the main facts of a code offloading in environments with multiple tiers through code bubbling presented in this chapter.

8.1. Bubbling Distribution

The basic distribution presented in Section 4.1 of applications parts comprises an offloading client (first tier), an offloading service (second tier), and a (wireless) communication network that connects both tiers. In such a two-tier environment, the basic distribution can increase the energy efficiency of devices and execution speed of applications by executing resource-intensive application parts on more powerful resources (offloading service) in the infrastructure. To ensure a minimum execution time, energy consumption, and monetary cost, an offloading client regards the trade-off between the cost for a local execution and the cost for a remote execution of an application part (cf. Section 4.2). The cost for a local execution comprises the energy and time for an execution on the offloading client, whereas the cost for a remote execution comprises the energy, time, and monetary cost for an execution on an offloading service.

In the literature, researchers propose different approaches for offloading computation considering mostly two-tier environments or (seldom) three-tier environments. Compared to a two-tier environment, a three-tier environment, for instance, considers additionally a server instance at the edge of a network being close to the offloading client (cf. Fog Computing [BMZA12]). We assume that in the future, environments with multiple tiers will become relevant, where multiple classes of highly distributed heterogeneous resources are available for code offloading. Figure 8.1 shows such an environment with multiple tiers as an exemplary scenario. It consists of a smart watch (Tier 1) connected via Bluetooth to a smart phone (Tier 2). The smart phone in turn is connected via Wi-Fi to a smart car (Tier 3) that is connected to a server at the edge of the network (Tier 4) via a 3G cellular network. The server at the edge is finally connected to a server in a cloud data center (Tier 5) via a fixed network. In such a multi-tier environment, the heterogeneous devices differ significantly in terms of energy, compute, and communication resources, increasing typically from very limited (Tier 1) to virtually unlimited (Tier n).

The bubbling distribution targets such environments with multiple tiers that consists of highly distributed heterogeneous resources with different performance characteristics and cost implications. It utilizes a distributed architecture of autonomous tiers to fully exploit the capabilities of environments with multiple tiers. Each tier manages participating resources within its tier independently and decides autonomously whether

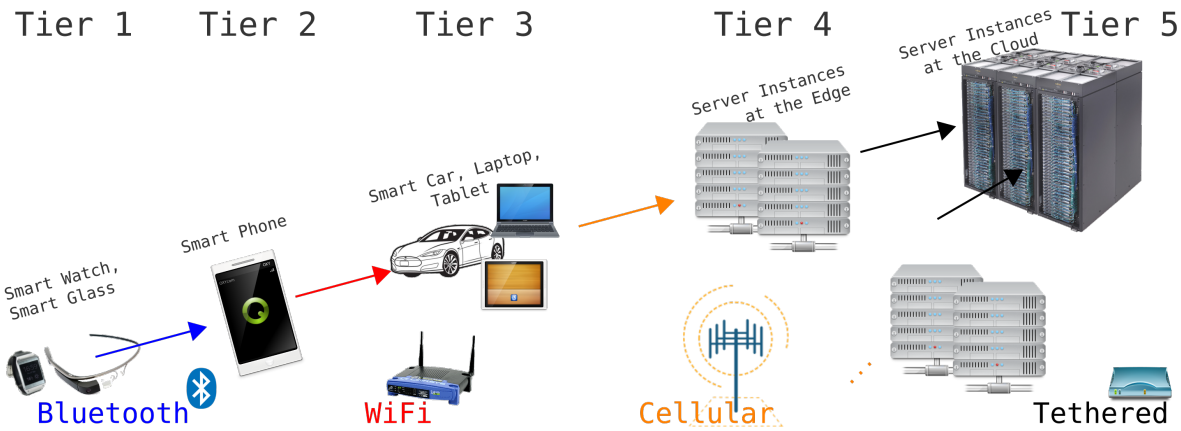


Figure 8.1.: An exemplary environment of multiple tiers. It consists of a smart watch (Tier 1) connected via Bluetooth to a smart phone (Tier 2). The smart phone in turn is connected via Wi-Fi to a smart car (Tier 3) that is connected to an edge server (Tier 4) via a 3G cellular network. The edge server is finally connected to a cloud server (Tier 5) via a fixed network.

to execute an application part within the tier or to forward it to the next upper tier. Due to the recursive escalation of application parts along autonomous tiers, an offloading client only interacts with its neighboring tier. At run-time, the offloading client forwards to its neighboring tier the request of offloading an application part and continues asynchronously the local execution of this application part (pessimistic approach). This decoupled and non-blocking distribution of application parts keeps the overhead on the offloading client low, not requiring a global view on the environment with multiple tiers. Moreover, the decentralized architecture based on autonomous tiers handles the increasingly connected environment in a simple, scalable, and flexible way. We call this concept of a recursive distribution of application parts within autonomous tiers code bubbling, since code rises towards higher tiers like bubbles towards the surface. Code bubbling keeps the distribution of application parts for an offloading client efficient, because it neither requires the interaction nor the exchange of state information with all tiers or resources in the environment. Moreover, the distribution decision on an offloading client is rather simple compared to the question on which resource to execute which application part, requiring a global view onto multiple tiers.

Summarizing, we make the following key contributions: (1) A framework for a distribution based on code bubbling in environments with multiple tiers that supports highly distributed heterogeneous resources with different performance characteristics and cost implications; (2) the concept of code bubbling that dynamically and adaptively distributes application parts in environments with multiple tiers based on a recursive escalation of code along autonomous tiers, where participating resources are unknown

a priori; (3) an extension of the Application Programming Interface (API) from the Java programming language that, on the one hand, requires least interventions from application developers or end users and, on the other hand, keeps the overhead introduced on participating resources low; (4) a mechanism to prove if an a priori unknown resource really executed an application part, not fooling an offloading client with inactivity; (5) an implementation of the framework and the extended Java API for the bubbling distribution on the Android OS and the OpenJDK Java platform; and (6) an extensive evaluation of the operational system including real-world measurements in environments with two tiers and multiple tiers.

8.2. System Overview

The bubbling distribution is applicable in environments with multiple tiers, where each tier has zero or more resources available for code offloading. To this end, the system model for the bubbling distribution extends the general system model for multiple resources described in detail in Section 3.1 with tiers. It structures the multiple classes of highly distributed heterogeneous resources in several tiers $\Gamma(\gamma)$ with $\gamma = 0, 1, \ldots, n_\gamma - 1$. Each tier $\Gamma(\gamma)$ comprises a number of resources $\Xi(\gamma, \xi)$ with $\xi = 0, 1, \ldots, n_{\gamma,\xi} - 1$, where the performance characteristics and cost implications of a resource are the same as in the general system model. Thus, compared to the basic distribution, the problem statement of the bubbling distribution changes as follows:

$$\min_{\gamma,\xi} f_w(A_{\alpha_o}, \Xi(\gamma, \xi)) \tag{8.1}$$

with

$$f_w(A_{\alpha_o}, \Xi(\gamma, \xi)) = w_t \cdot T(A_{\alpha_o}, \Xi(\gamma, \xi)) + w_e \cdot E(A_{\alpha_o}, \Xi(\gamma, \xi)) + w_c \cdot C(A_{\alpha_o}, \Xi(\gamma, \xi))$$

The execution time $T(A_{\alpha_o}, \Xi(\gamma, \xi))$, the energy consumption $E(A_{\alpha_o}, \Xi(\gamma, \xi))$, and the monetary cost $C(A_{\alpha_o}, \Xi(\gamma, \xi))$ for a resource $\Xi(\gamma, \xi)$ are calculated like the execution time $T(A_{\alpha_o}, \Xi(\xi))$, the energy consumption $E(A_{\alpha_o}, \Xi(\xi))$, and the monetary cost $C(A_{\alpha_o}, \Xi(\xi))$ for a resource $\Xi(\xi)$ (cf. Section 3.2).

To efficiently provide the bubbling distribution for environments with multiple tiers, the architecture of the bubbling distribution uses a multi-tiered hierarchy (cf. Figure 8.2), consisting of an offloading client, a tier service on each tier, an offloading service on each resource within a tier, and a communication network.

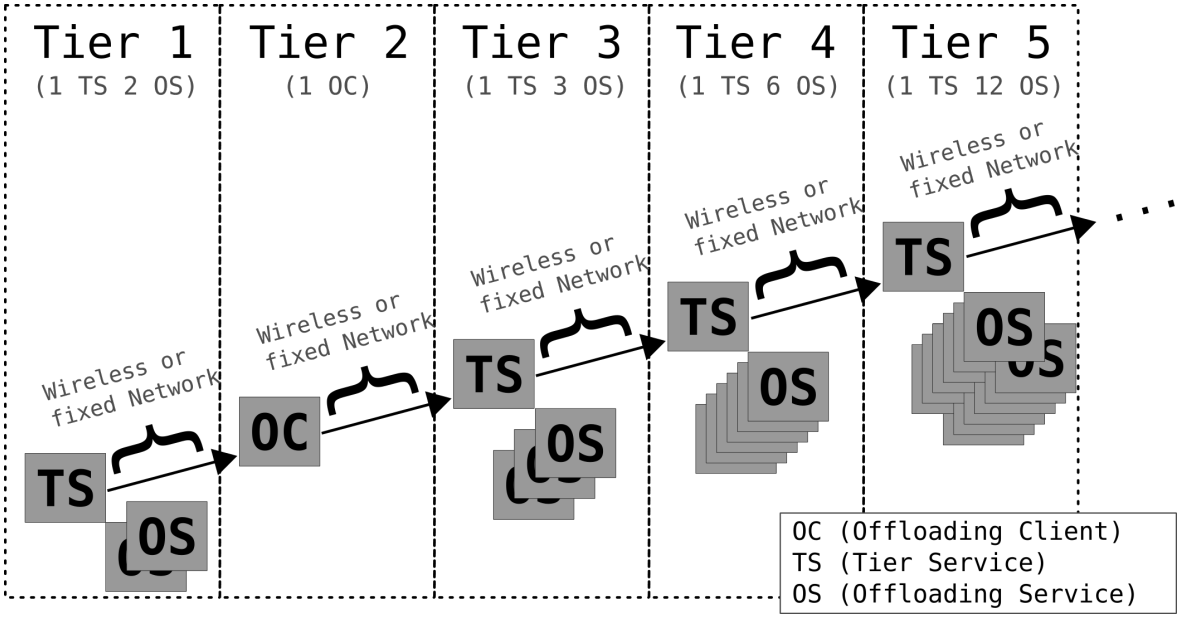


Figure 8.2.: The system components for the bubbling distribution, where an offloading client (OC) offloads computation via a communication network to tier services (TSs) and accordingly to offloading services (OSs).

Offloading Client: The offloading client on a resource $\Xi(\gamma_i, \xi_k)$ controls the local execution of an application (cf. Subsection 3.3.1). Each time an execution of an application reaches an application part A_{α_o} that is offloadable, the offloading client gathers the input execution state $I_{state}(A_{\alpha_o})$ and the portable code $P_{pcode}(A_\alpha)$ of the application part A_{α_o}. Beside the application-related information of $I_{state}(A_{\alpha_o})$ and $P_{pcode}(A_\alpha)$, the offloading client further gathers resource-related and user-related information. The resource-related information are the energy factors of sending bytes $E_{send}^{\Xi(\gamma_i,\xi_k)}$, waiting in idle mode $E_{wait}^{\Xi(\gamma_i,\xi_k)}$, and receiving bytes $E_{recv}^{\Xi(\gamma_i,\xi_k)}$ on the resource $\Xi(\gamma_i, \xi_k)$. The user-related information are the user-defined weights of w_t for the execution time, w_e for the energy consumption, and w_c for the monetary cost. Based on the application-related, resource-related, and user-related information, the offloading client creates an offload request. The offload request contains all of the information required, on the one hand, to minimize the cost function f_w on a tier service and, on the other hand, to execute the application part remotely on an offloading service.

Tier Service: A tier service manages centrally participating resources within its tier. For instance, in Figure 8.1, a smart car provides for its passengers a Wi-Fi Access Point (AP) and runs a tier service that possesses a direct connection to each (participating) resource within its tier. On the one hand, a tier service monitors the non-varying performance characteristic (cf. $P_{ppwr}^{\Xi(\gamma,\xi)}$) and cost implications (cf. $C_{exec}^{\Xi(\gamma_j,\xi_m)}$,

$C_{send}^{\Lambda(\gamma_i,\xi_k;\gamma_j,\xi_m)}$, and $C_{recv}^{\Lambda(\gamma_i,\xi_k;\gamma_j,\xi_m)}$) as well as the time-varying performance characteristics (cf. $B_{up}^{\Lambda(\gamma_i,\xi_k;\gamma_j,\xi_m)}$, $B_{down}^{\Lambda(\gamma_i,\xi_k;\gamma_j,\xi_m)}$, $L_{up}^{\Lambda(\gamma_i,\xi_k;\gamma_j,\xi_m)}$, and $L_{down}^{\Lambda(\gamma_i,\xi_k;\gamma_j,\xi_m)}$) of participating resources (cf. Section 3.1). On the other hand, a tier service functions as a gateway to other tiers and plans the execution of offload requests for participating resources within its tier. Receiving an offload request, the tier service regards the application-related, resource-related, and user-related information, determining dynamically the best available resource within its tier.

Offloading Service: The offloading service on participating resources executes an offload request on its hardware platform (cf. Subsection 3.3.2), providing a lightweight execution engine for portable code. It transforms an input execution state $I_{state}(A_{\alpha_o})$ into an output execution state $O_{state}(A_{\alpha_o})$ based on the execution of portable code $P_{pcode}(A_{\alpha_o})$ on its hardware platform. As an offloading client distributes an application part to unknown remote resources, an offloading service guarantees the "real" execution of an application part based on a further instrumentation of Java bytecode instructions.

Communication Network: The communication network connects each offloading service with its tier service, each tier service with its neighboring tier service(s), and an offloading client with its neighboring tier service(s). Thus, the communication network consists of multiple wireless network(s) and/or fixed network(s).

8.3. Offloading Timeline

A resource that wants to distribute application parts to other resources runs an offloading client. If it also functions as an Access Point (AP) for other resources (cf. the smart phone in Figure 8.1 that a Bluetooth link connects to the smart watch), the distributing resource also runs a tier service managing offloading services from connected resources. Each time the execution of an application A reaches an application part A_{α_o} that is offloadable, the execution of the application part annotated with `offloadable` invokes the offloading client that creates a corresponding offload request for A_{α_o}. Based on the cost function f_w (cf. Equation 8.1), the offloading client calculates the cost for a local execution of A_{α_o} and adds it to the offload request. To keep the communication overhead and the waiting time low, the offloading client only submits a downgraded version of the offload request to the next tier service and continues the local execution of A_{α_o}. The downgraded offload request only contains the input size $I_{state}^{size}(A_\alpha)$, the output size $O_{state}^{size}(A_\alpha)$, and the code complexity $P_{pcode}^{exe}(I_{state}(A_\alpha), P_{pcode}(A_\alpha))$ instead of the actual values of $I_{state}(A_{\alpha_o})$ and $P_{pcode}(A_{\alpha_o})$. The asynchronous submission of a

downgraded offload request decouples the decision of a distribution from the offloading client into the infrastructure.

Managing offloading services from participating resources within a tier, each time a tier service receives a downgraded offload request, it determines the best available offloading service within its tier. To this end, it first calculates the value of the cost function for the available offloading services within its tier. As it currently does not know the actual bandwidth and latency of the link between the offloading client and its tier, it assumes an infinite bandwidth and a zero latency. Later on, the offloading client replaces these optimistic values for the bandwidth and latency with the proper bandwidth and latency. After the calculation of the value of the cost function, a tier service compares it with the value of the cost function for a local execution contained in the downgraded offload request. Only in case of a smaller value, the tier service sends to the offloading client a resource offer containing the performance characteristics and cost implications for an execution on the offloading service within its tier. Independently from the calculated value of the cost function, the tier service forwards the downgraded offload request to its next upper tier service. It finds its next upper tier service with the help of a service discovery, where the bubbling distribution does not rely on a specific service discovery protocol. Thus, an efficient and optimal discovery is out of scope of this dissertation. Forwarding the downgraded offload request to the next tier service, the offload request bubbles up the tiers, visiting recursively multiple tier services until it reaches the highest tier (cf. the cloud resources in Figure 8.1).

Due to the code bubbling of the bubbling distribution, an offloading client receives from multiple tier services at different points in time a resource offer. Receiving a resource offer, an offloading client measures simultaneously the bidirectional latency of the link to the corresponding tier service. Possessing the actual latency of the link, an offloading client incorporates the measured latency and a profiled bandwidth of the link into the value of the cost function offered from a tier service. Due to the local continuation of the application execution, an offloading client also recalculates the value of the cost function for finishing the execution of the application locally. Comparing the recalculated values, an offloading client decides whether to continue the local execution or to distribute the application part A_{α_o} to the offloading service in the tier. In case of a distribution of A_{α_o}, an offloading client sends the input execution state $I_{state}(A_{\alpha_o})$ and the portable code $P_{pcode}(A_{\alpha_o})$ to the corresponding tier service, waiting for the output execution state $O_{state}(A_{\alpha_o})$ from the remote execution of A_{α_o}.

Receiving the actual $I_{state}(A_{\alpha_o})$ and $P_{pcode}(A_{\alpha_o})$ of an offload request, a tier service allocates the offloading service offered from the resource offer and forwards the offload request to the offloading service. Moreover, it starts a monitoring of the execution on

the offloading service, to react on varying conditions in its tier like a crash failure with a redistribution of the offload request to another resource.

Receiving an offload request, an offloading service installs the input execution state $I_{state}(A_{\alpha_o})$ and starts the execution of the portable code $P_{pcode}(A_{\alpha_o})$. At the end of the execution, it sends the output execution state $O_{state}(A_{\alpha_o})$ to its tier service that subsequently sends $O_{state}(A_{\alpha_o})$ to the offloading client.

Receiving an output execution state $O_{state}(A_{\alpha_o})$, an offloading client interrupts the local execution of the portable code $P_{pcode}(A_{\alpha_o})$ and installs the output execution state $O_{state}(A_{\alpha_o})$. After the installation of $O_{state}(A_{\alpha_o})$, the offloading client jumps to the end of the local execution of $P_{pcode}(A_{\alpha_o})$ and continues the execution of the application.

8.4. Offloading Framework

The offloading framework for the bubbling distribution adjusts the offloading framework for the basic distribution described in Section 4.5. To provide the functionality required for the bubbling distribution, Subsection 8.4.1 describes the Application Programming Interface (API) for the Java programming language extended for the bubbling distribution. Afterwards, Subsection 8.4.2 and Subsection 8.4.3 presents the changes to the offloading client and to the offloading service, respectively. Last, Subsection 8.4.4 outlines the tier service for the bubbling distribution.

8.4.1. Application Programming Interface

The bubbling distribution utilizes an extended Application Programming Interface (API) for the Java programming language (cf. Subsection 4.3.4) to abstract from the actual hardware architectures of smart phones, laptops, or server machines (e.g., x86 vs. ARM and 32-bit vs. 64-bit). Due to the extension of the Java technology for a distribution with code bubbling, the extended Java platform provides a platform-independent execution of Java bytecode instructions on different hardware architectures.

To keep the complexity for end users as well as application developers low, the extended Java API of the bubbling distribution hides the distributed and parallel nature of environments with multiple tiers. It relies on least interventions from an end user and an application developer. An end user only specifies the user-related information for the weights of execution time, energy consumption, and monetary cost (cf. Equation 8.1) via the user interface of the offloading client (cf. Subsection 4.5.2). An application developer simple extends a provided Java core class at development-time to enable the distribution of a Java method. The Java core class libraries like `java.lang.*` are essential

```
1 package java.lang;
  import  java.io.Serializable;
3
  public abstract class OffloadExecution implements Serializable {
5    private static final long serialVersionUID = 42L;

7    @Offloadable
     public abstract OffloadIO execute(OffloadIO inputs);
9 }
```

Listing 8.1: The source code of the `abstract` Java class `OffloadExecution` from the Java core package `java.lang`. The class `OffloadExecution` has an `abstract` Java method `execute` with the annotation `Offloadable` that utilizes the Java class `OffloadIO` as input and output.

libraries for using a Java Virtual Machine (JVM) of a Java Runtime Environment (JRE) (cf. Subsection 4.3.4). The additional core classes `Offloadable`, `OffloadExecution`, and `OffloadIO` in the core class library `java.lang` enable the bubbling distribution of application parts from an offloading client to offloading services. In detail, an application developer only extends the `abstract` Java class `OffloadExecution` that possesses the `abstract` Java method `execute` (cf. Listing 8.1). This method possesses the annotation `Offloadable` (cf. Section 4.4), marking a Java method as a suitable candidate for a remote execution. For instance, a suitable candidate only relies on the processing resource of a hardware platform not accessing a local sensor like Global Positioning System (GPS) for localization. Due to the annotation of Java methods that are offloadable, the extended Java compiler instruments the Java bytecode instructions of the Java method with `offload` and `offload_end` at development-time (cf. Subsection 4.5.1). At run-time, the execution of the Java bytecode instructions `offload` or `offload_end` invokes the execution controller (cf. Subsection 4.5.2), creating an offload request for the Java method. Thus, an application developer implements an offload request by simply implementing the method `execute` of the Java core class `OffloadExecution`. The parameter and the return value of the Java method `execute` of the Java core class `OffloadExecution` correspond both to the Java core class `OffloadIO` (cf. Listing 8.1). This core class serves as an efficient storage of the data for Java primitives, arrays, and objects of the parameters or the return value for a Java method (cf. Subsection 4.3.4). For an efficient serialization and deserialization of the Java data types stored in the Java core class `OffloadIO`, it implements the standard Java `Serializable` interface of the Java core class libraries (cf. Subsection 4.3.4).

The execution of an offload request on an offloading service only utilizes data from the input execution state – e.g., the parameters of the Java method or the members of its declaring Java class. As a result, an application developer only references data

from the declaring Java class of the Java method `execute` during its execution. Based on this *Input* → *Execution* → *Output* processing of the extended Java API, an execution does not alter the execution state of an application outside of an offload request beside the resulting output. This guarantees the equality of a monolithic execution of an application on a local resource with a distributed execution of an application on multiple resources. Moreover, the *Input* → *Execution* → *Output* processing offers a resource-friendly execution on an offloading service, not needing to trace or monitor changes to the execution state during an execution.

8.4.2. Offloading Client

For a dynamic distribution of application parts, an offloading client has to obtain the application-related, resource-related, and network-related information.

Application-related Information: The application-related information required for an offload request comprises from an application part A_{α_o} the input execution state $I_{state}(A_{\alpha_o})$ and its size $I^{size}_{state}(A_{\alpha_o})$, the Java bytecode instructions $P_{pcode}(A_{\alpha_o})$ and its code complexity $P^{exe}_{pcode}(I_{state}(A_{\alpha_o}), P_{pcode}(A_{\alpha_o}))$, and the size of the output execution state $O_{state}(A_{\alpha_o})$ and its size $O^{size}_{state}(A_{\alpha_o})$ (cf. Section 8.3). At the call of a Java method A_{α_o} that is offloadable, its input execution state $I_{state}(A_{\alpha_o})$ and its Java bytecode instructions $P_{pcode}(A_{\alpha_o})$ are immediately available from the state generator (cf. Subsection 4.5.2). Due to the implementation of the standard Java serialization of the Java core class `OffloadIO`, the size of the input execution state $I^{size}_{state}(A_{\alpha_o})$ is also directly available by serializing the input execution state $I_{state}(A_{\alpha_o})$. To obtain the code complexity $P^{exe}_{pcode}(I_{state}(A_{\alpha_o}), P_{pcode}(A_{\alpha_o}))$ of the Java bytecode instructions $P_{pcode}(A_{\alpha_o})$ as well as the size of the output execution state $O_{state}(A_{\alpha_o})$, the offload controller predicts the code complexity $P^{exe}_{pcode}(I_{state}(A_{\alpha_o}), P_{pcode}(A_{\alpha_o}))$ or the size $O^{size}_{state}(A_{\alpha_o})$ with the help of the profile models built by the app profiler (cf. Subsection 4.5.2).

Resource-related Information: The resource-related information required for an offload request comprises on an offloading client on the resource $\Xi(\gamma_i, \xi_k)$ its execution speed of Java bytecode instructions $P^{\Xi(\gamma_i,\xi_k)}_{ppwr}$ and its energy factors $E^{\Xi(\gamma_i,\xi_k)}_{exec}$, $E^{\Xi(\gamma_i,\xi_k)}_{send}$, $E^{\Xi(\gamma_i,\xi_k)}_{recv}$, and $E^{\Xi(\gamma_i,\xi_k)}_{wait}$. Moreover, the resource-related information comprises the monetary cost $C^{\Xi(\gamma_j,\xi_m)}_{exec}$ for an offloading service on the resource $\Xi(\gamma_j, \xi_m)$. To obtain the performance characteristic $P^{\Xi(\gamma_i,\xi_k)}_{ppwr}$, an offloading client as well as an offloading service support an execution mode for the JVM that benchmarks the underlying capabilities of a resource including the architectural differences of participating resources (cf. Subsec-

tion 4.5.2). This specific execution mode determines the execution speed of simple Java bytecode instructions like `add` or `mod` for Java primitive data types, array data types, and object data types (cf. Subsection 4.3.4). The outcome of this specific execution mode is a profile of a resource based on Java bytecode instructions, where this performance model determines the execution speed of Java bytecode instructions on the resource. To obtain the performance characteristics $E_{exec}^{\Xi(\gamma_i,\xi_k)}$, $E_{send}^{\Xi(\gamma_i,\xi_k)}$, $E_{recv}^{\Xi(\gamma_i,\xi_k)}$, and $E_{wait}^{\Xi(\gamma_i,\xi_k)}$, an offloading client provides the device interface (cf. Subsection 4.5.2), where a device manufacturer defines these resource-specific factors of the energy consumption offline. To obtain the cost implication $C_{exec}^{\Xi(\gamma_j,\xi_m)}$, an offloading service provides the provider interface (cf. Subsection 4.5.3), where a resource provider defines this resource-specific factor of the monetary cost either offline or online.

Network-related Information: The network-related information required for an offload request comprises for a link between two resources $\Xi(\gamma_i, \xi_k)$ (offloading client) and $\Xi(\gamma_j, \xi_m)$ (offloading service) the up and down latency $L_{up}^{\Lambda(\gamma_i,\xi_k;\gamma_j,\xi_m)}$ and $L_{down}^{\Lambda(\gamma_i,\xi_k;\gamma_j,\xi_m)}$, the up and down bandwidth $B_{up}^{\Lambda(\gamma_i,\xi_k;\gamma_j,\xi_m)}$ and $B_{down}^{\Lambda(\gamma_i,\xi_k;\gamma_j,\xi_m)}$, and the monetary cost $C_{send}^{\Lambda(\gamma_i,\xi_k;\gamma_j,\xi_m)}$ and $C_{recv}^{\Lambda(\gamma_i,\xi_k;\gamma_j,\xi_m)}$. To obtain the performance characteristic of the up and down latency and use sparingly link resources, the network monitor on an offloading client measures the up and down latency associated with the resource offers from available resources within a tier (cf. Section 8.3). Moreover, it measures the up and down bandwidth for each connection type (e.g., GSM, UMTS, LTE, or WiFi) in the background while an end user utilizes its resource like a smart phone during the day. Based on the bandwidth measured for each connection type, it calculates a weighted average based on the occurrence of the measured bandwidth. This avoids a periodic lavish measurement of the up and down bandwidth with message probing to multiple tiers (cf. Subsection 4.5.2). Combining the actual latency with the history-based bandwidth, the offload controller determines a profiled duration for the transmission of an input execution state and an output execution state. During the sending or receiving of the data for an input execution state or an output execution state, the network monitor monitors the actual bandwidth and reacts, for instance, in case of a too low bandwidth by invoking the offload controller. Subsequently, the offload controller reacts on the too low quality of the link for a distribution with, for instance, a re-distribution to another resource or a local completion of the execution. To obtain the cost implications $C_{send}^{\Lambda(\gamma_i,\xi_k;\gamma_j,\xi_m)}$ and $C_{recv}^{\Lambda(\gamma_i,\xi_k;\gamma_j,\xi_m)}$, an offloading client provides the network interface (cf. Subsection 4.5.2), where a network provider defines the link-specific factor of the monetary cost either offline or online.

8.4.3. Offloading Service

The functionality provided by the offloading service is nearly the same as for the basic distribution described in detail in Subsection 4.5.3. As an offloading client does not know a priori – and maybe does not trust – the resource that executes the offloading service, the bubbling distribution extends the offloading service with a mechanism that provides the prove for an offloading client if the offloading service really executed an application part. To guarantee the "real" execution of an application part on an unknown resource, the bubbling distribution secures a remote execution based on the extended API for the Java programming language (cf. Subsection 8.4.1). To this end, the bubbling distribution utilizes a shared secret at the run-time level between an offloading client and offloading services. It utilizes a shared secret at the run-time level, because an attacker possibly knows the Java bytecode instructions of a Java method (application level) and can intercept the machine code produced by an offloading service during an execution of the Java method (system level). The shared secret is a large set of mathematical functions $f^i(x)$ with $i = 0, 1, \ldots$ only known to the run-time environments of an offloading client and an offloading service. During an execution of a Java method on an unknown remote resource, its offloading service calculates $f^i(x)$ in parallel. At the end of a remote execution, an offloading service hashes the result of $f^i(x)$, the values chosen for i and x, the input execution state $I_{state}(A_{a_o})$, the portable code $P_{pcode}(A_{a_o})$, and the output execution state $O_{state}(A_{a_o})$ based on the cryptographic hash function SHA-3[1] (Secure Hash Algorithm 3). After the hashing of the corresponding values, an offloading service sends the hash value, the values of i and x, and the output execution state to the offloading client. The offloading client verifies the correctness of the output execution state by recalculating the result of $f^i(x)$ requiring i and x, hashing the six values, and comparing the equality of the two hash values. Due to the inclusion of the result from $f^i(x)$ and the values of i and x, an attacker cannot intercept the hash value and replace it with an own generated hash value due to the shared secret of $f^i(x)$. Due to the inclusion of $I_{state}(A_{a_o})$, $P_{pcode}(A_{a_o})$, and $O_{state}(A_{a_o})$, an attacker cannot produce a valid hash value based on the "wrong" execution of a resource-friendlier Java method, sparing its resources. As an attacker can trace the machine codes executed by an offloading service for a Java method and the mathematical function, an offloading service executes additionally from time to time unused machine codes to circumvent the comparison with a code trace from an execution on an unaltered JRE. Technically, the offload-aware Java compiler further inserts at development-time before branching instructions the offload-specific Java bytecode

[1] `https://www.nist.gov/node/555116?pub_id=919061`

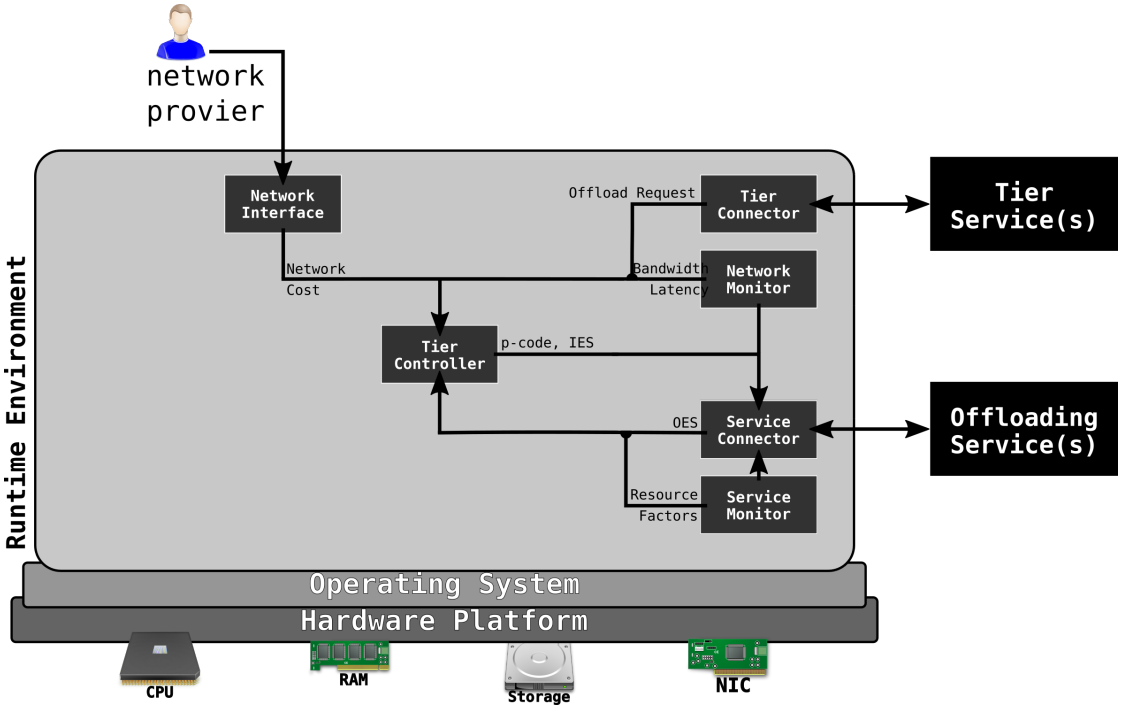


Figure 8.3.: The runtime environment on the tier service for the bubbling distribution.

instruction `offload_branch`. At run-time, the execution of `offload_branch` invokes either the next step of the calculation for the mathematical function or unused machine codes. Summarizing, a remote resource has to actually execute the Java method to obtain the correct hash value. It cannot just fool an offloading client with an arbitrary output execution state, charging monetary cost for an execution that never happened.

8.4.4. Tier Service

Figure 8.3 shows the runtime environment of the tier service, providing the tier-side functionality for the bubbling distribution. It consists of a network monitor, a network interface, a service monitor, a service connector, a tier connector, and a tier controller. The network interface, service monitor, and service connector provides the same functionality as for the basic distribution described in detail in Subsection 4.5.3.

Network Monitor: The network monitor for the bubbling distribution is the same as the network monitor of the basic distribution described in detail in Subsection 4.5.3, offering to a tier service the capability to measure the link bandwidth and link latency.

Tier Connector: The tier controller of the tier service invokes the tier connector to handle the communication between the tier service and its neighboring tier service(s).

Moreover, it also invokes the tier connector to handle the communication between the tier service and an offloading client being also a tier. Receiving an offload request from its next lower tier service, the tier service forwards the offload request to the tier controller and to its next upper neighboring tier service. Receiving an input execution state and the Java bytecode instructions for an application part from an offloading client, the tier connector forwards both to the tier controller. Last, receiving from the tier controller a resource offer or an output execution state, the tier connector sends both to the corresponding offloading client.

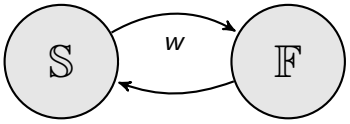
Tier Controller: The tier controller of the tier service manages the participating offloading services within its tier, functioning as a gateway to other tiers. To this end, it plans the execution of received offload requests by minimizing Equation 8.1 with the application-related, resource-related, and user-related information contained in an offload request. To determine dynamically the best available offloading service within its tier, the tier controller requires from participating offloading services further parameters. First, it requires from an offloading service the non-varying parameters of the processing power and monetary cost retrieved via the service monitor. Second, it requires from the utilized links to offloading services the non-varying parameters of the monetary cost retrieved via the network interface as well as the time-varying parameters of the up and down bandwidth and latency retrieved via the network monitor. Possessing the required parameters to minimize Equation 8.1, the tier controller sends a resource offer for the best available offloading service within its tier via the tier connector to the service connector on the offloading client that sent the offload request.

Receiving an input execution state and the Java bytecode instructions for an application part from the tier connector – because the tier service sent a resource offer to an offloading client, the tier controller forwards both via the service connector to the corresponding offloading service. During the execution of an application part on an offloading service, the tier controller monitors via the service monitor the execution, to react, for instance, on crash failures of the offloading service.

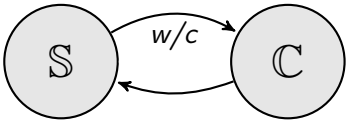
Receiving from the service connector an output execution state from an offloading service after the execution of an application part, the tier controller forwards the output execution state to the tier connector.

8.5. Evaluation

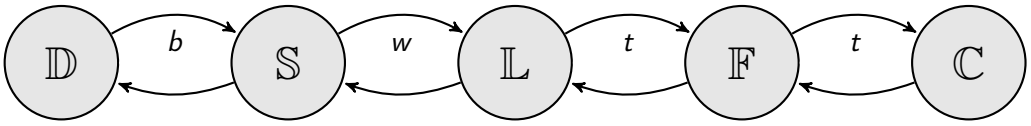
This section evaluates the overhead and benefit for the operational system of the bubbling distribution in real-world environments compared to related approaches from the



(a) A smart phone (𝕊) and the fog (𝔽) communicate via a Wi-Fi link (w) with each other.



(b) A smart phone (𝕊) and the cloud (ℂ) communicate either via a Wi-Fi link (w) or a cellular link (c) with each other.



(c) A smart wearable (𝔻) and a smart phone (𝕊) communicate via a Bluetooth link (b) with each other, the smart phone (𝕊) and a laptop (𝕃) via a Wi-Fi link (w), the laptop (𝕃) and the fog (𝔽) via a tethered link (t), and the fog (𝔽) and the cloud (ℂ) via a tethered link (t).

Figure 8.4.: Overview of the different environments evaluated for the bubbling distribution, where (a) and (b) shows the environments with two tiers and (c) the environment with multiple tiers.

literature. In detail, the evaluation considers two different environments, namely an environment with two tiers and an environment with multiple tiers. To this end, we extended the implementation of the AOSP prototype for the basic distribution (cf. Subsection 4.6.3) to provide the functionality required on the offloading client for the bubbling distribution. Moreover, we extended the implementation of the OpenJDK prototype for the basic distribution (cf. Subsection 4.6.2) to provide the functionality required on the offloading service for the bubbling distribution. Please note that through the execution of an adapted OpenJDK JRE instead of a complete Android OS on the hardware platform of an offloading service, the bubbling distribution keeps the overhead introduced on participating resources very low. The extension to the AOSP prototype as well as to the OpenJDK prototype comprises changes to the implementation of the JVM and the Java core class libraries. Last, we implemented the functionality required for a tier service (cf. Subsection 8.4.4) in a Java application, executed on an unaltered OpenJDK JRE. The following subsections describe the evaluation setup (cf. Subsection 8.5.1) and the evaluation results (cf. Subsection 8.5.2).

8.5.1. Setup

The evaluation setup for thea bubbling distribution extends the evaluation setup for the basic distribution on the AOSP described in Subsection 4.7.1 as follows:

Figure 8.4 shows the environments with two tiers (cf. Figure 8.4a and Figure 8.4b) and the environment with multiple tiers (cf. Figure 8.4c) evaluated for the bubbling distribution. The environments with two tiers consist of a smart phone (𝕊) that dis-

tributes code to a remote tier, where the remote tier is either a fog distribution tier ($\mathbb{F}$) or a cloud distribution tier ($\mathbb{C}$). Both tiers differ in the performance of the participating resources. The smart phone and the remote tier communicate either via a Wi-Fi connection (w) or a cellular connection (c) with each other, differing in the latency as well as the bandwidth of the link. In total, the environments with two tiers result in $\mathbb{S}w\mathbb{F}$, $\mathbb{S}w\mathbb{C}$, and $\mathbb{S}c\mathbb{C}$. The environment with multiple tiers consists of a smart phone ($\mathbb{S}$), a device distribution tier ($\mathbb{D}$), a local distribution tier ($\mathbb{L}$), a fog distribution tier ($\mathbb{F}$), and a cloud distribution tier ($\mathbb{C}$) (cf. Figure 8.4c). The smart phone communicates via a Bluetooth connection (b) with the device distribution tier and via a Wi-Fi connection (w) with the local distribution tier. The local distribution tier communicates via a tethered connection (t) with the fog distribution tier that again communicates via a tethered connection (t) with the cloud distribution tier. Thus, the environment with multiple tiers results in $\mathbb{D}b\mathbb{S}w\mathbb{L}t\mathbb{F}t\mathbb{C}$.

The device distribution tier ($\mathbb{D}$) consists of the netbook Dell Inspiron Mini 10v (cf. Section C.2). It runs a tier service and an offloading service on its resources, possessing a benchmark value of 1.305, and raises no monetary cost. The smart phone ($\mathbb{S}$) is the Samsung Galaxy Nexus (cf. Section C.1). It runs an offloading client on its resources with a benchmark value of 3.106. The local distribution tier ($\mathbb{L}$) consists of the laptop Lenovo ThinkPad T61 (cf. Section C.3). It runs a tier service and an offloading service on its resources, possessing a benchmark value of 0.989, and also raises no monetary cost. The fog distribution tier ($\mathbb{F}$) consists of the desktop HP Compaq 8200 Elite (cf. Section C.4). It runs a tier service and three offloading services on its resources, possessing a benchmark value of 0.434, and raises half the prices of the cloud distribution tier ($\mathbb{C}$). Last, the cloud distribution tier ($\mathbb{C}$) consists of the server instance t2.micro from the AWS EC2 (cf. Section C.5). It runs a tier service and an offloading service on its resources, possessing a benchmark value of 0.335, and raises the prices[2] from the AWS EC2.

The smart phone ($\mathbb{S}$) establishes the Bluetooth link (b) to the netbook ($\mathbb{D}$) based on the Bluetooth version 2.1, having an average latency and bandwidth of 7.751 ms and 235 kB/s. The Linksys WRT54GL wireless router (cf. Section C.7) establishes a wireless Access Point (AP) based on IEEE 802.11g connecting the smart phone ($\mathbb{S}$) either with the laptop ($\mathbb{L}$), the desktop computer ($\mathbb{F}$), or the cloud ($\mathbb{C}$) with an average latency and bandwidth of 3.681 ms and 752 kB/s, 3.712 ms and 2.7 MB/s, or 8.562 ms and 2.6 MB/s, respectively. Moreover, the smart phone ($\mathbb{S}$) communicates via a 3.5G mobile communication network with the cloud ($\mathbb{C}$) having an average latency and bandwidth of 43.964 ms and 200 kB/s. The LevelOne GSW-0809 Gigabit Ethernet

[2]Prices of the AWS for the utilization of instances from its EC2: `aws.amazon.com/de/ec2/pricing`

Switch (cf. Section C.8) connects the laptop ($\mathbb{L}$) and the desktop computer ($\mathbb{F}$) with each other, where the average latency and bandwidth of a link between the smart phone ($\mathbb{S}$) and the desktop computer ($\mathbb{F}$) is 4.936 ms and 2.1 MB/s. Last, a 10 Gigabit Ethernet link[3] connects the desktop computer ($\mathbb{F}$) and the cloud ($\mathbb{C}$) with each other, where the average latency and bandwidth of a link between the smart phone ($\mathbb{S}$) and the cloud ($\mathbb{C}$) is 7.614 ms and 2.0 MB/s.

The evaluation compares the bubbling distribution with two approaches from the literature: An approach for a distribution regarding two tiers – named *Two-tier Distribution* – and an approach for a distribution regarding multiple tiers – named *Multi-tier Distribution*. The two-tier distribution distributes application parts from the smart phone to resources in the vicinity (fog distribution tier) or in a far-away cloud (cloud distribution tier) like MAUI [CBC+10]. To this end, it utilizes an offload-enabled Android OS for code offloading in environments with two tiers. The multi-tier distribution distributes code to resources organized into multiple tiers like Cloudlets [SBCD09]. To this end, it utilizes an offload-enabled Android OS for code offloading in environments with multiple tiers. We also compared the two-tier distribution, the multi-tier distribution, and the bubbling distribution with a local execution of the application. A local execution serves as a baseline, where the smart phone executes everything on its local resources in airplane mode. To this end, it utilizes an unaltered Android OS.

8.5.2. Results

The following subsection presents the evaluation results. First, it describes the overhead and benefit for a distribution in the environments with two tiers and for a distribution in the environment with multiple tiers. Afterwards, it presents the overhead introduced for securing a remote execution on an a priori unknown resource.

Environments with two tiers

The evaluation result of a local execution, the two-tier distribution, and the bubbling distribution are categorized into the overhead and benefit of a distribution.

Overhead of a Distribution: Figure 8.5 shows the execution time, Figure 8.6 the energy consumption, and Figure 8.7 the monetary cost of the local execution, the two-

[3]The University of Stuttgart is part of the network "Baden-Württembergs extended LAN (BelWü)" that connects scientific organizations in Baden-Württemberg with low-latency and high-bandwidth links (`https://www.belwue.de/netz/topologie/aktuell.html`). The BelWü network peers with DE-CIX Frankfurt (`https://www.de-cix.net/de/locations/germany/frankfurt`), where the data center of the server instance from the Amazon Web Service is located in Frankfurt.

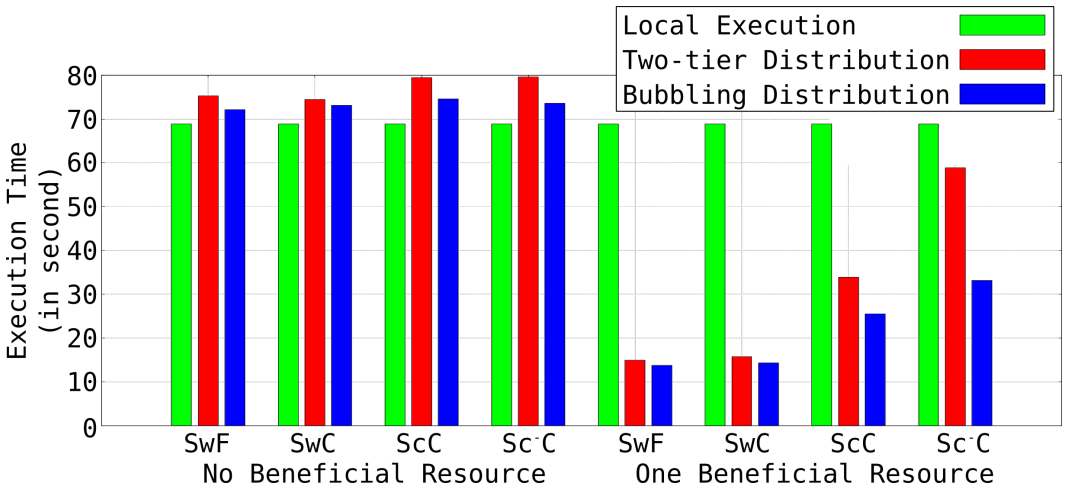


Figure 8.5.: Execution time of a local execution, the two-tier distribution, and the bubbling distribution evaluated in the environments with two tiers.

tier distribution, and the bubbling distribution evaluated in the environments $\mathbb{S}w\mathbb{F}$, $\mathbb{S}w\mathbb{C}$, $\mathbb{S}c\mathbb{C}$, and $\mathbb{S}c^{-}\mathbb{C}$. For the first four group of bars in Figure 8.5 and Figure 8.6, the offloading service on the remote side does not possess a beneficial resource for a remote execution, indicating the overhead introduced by each approach. Please note that Table 8.1 outlines each value for the execution time, energy consumption, and monetary cost of the approaches evaluated in the environments with two tiers.

To make the decision of distributing a Java method that is offloadable, the two-tier distribution probes periodically the link to and monitors the state of the remote tier like in MAUI from Cuervo et al. [CBC+10]. Due to the missing beneficial resource in the remote tier, the two-tier distribution decides each time to execute the offloadable Java method locally on the smart phone. Compared to a local execution of the mobile application on the smart phone, the periodic link probing and state monitoring increase the execution time as well as the energy consumption of the two-tier distribution. For a latency of the Wi-Fi link between the smart phone and the fog distribution tier of 6.669 ms ($\mathbb{S}w\mathbb{F}$), the two-tier distribution takes 6.380 s longer and consumes 17.017 J more energy than a local execution. In case of a distant tier with a bad quality of the cellular link between the smart phone and the cloud distribution tier (cf. $\mathbb{S}c^{-}\mathbb{C}$ in Figure 8.5 and Figure 8.6), the overhead of the two-tier distribution increases heavily with a latency of the cellular link of 294.197 ms. In detail, it takes 10.729 s longer and consumes 56.636 J more energy compared to a local execution.

In contrast to the periodic link probing and state monitoring, the bubbling distribution only submits the downgraded offload requests into the infrastructure and continues the local execution on the smart phone. As the gathering of a downgraded

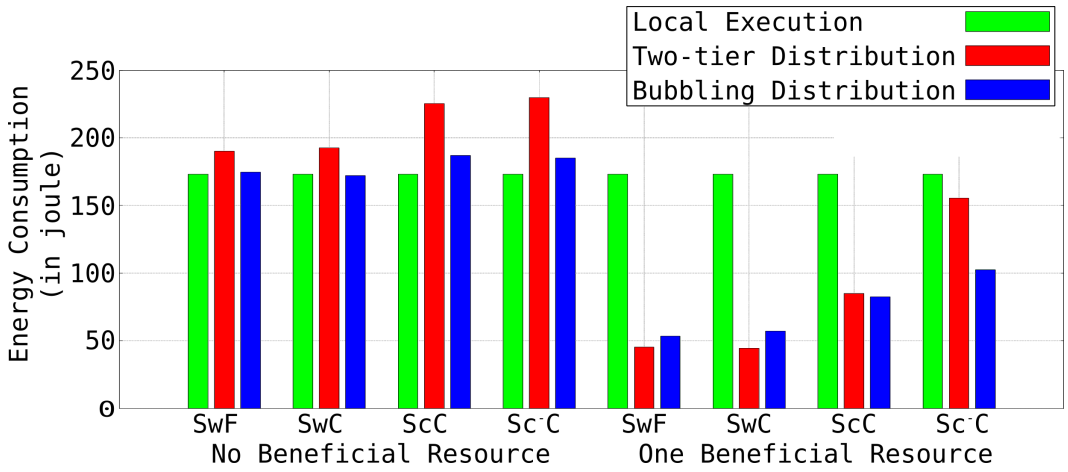


Figure 8.6.: Energy consumption of a local execution, the two-tier distribution, and the bubbling distribution evaluated in the environments with two tiers.

offload request interrupts a pure local execution, the evaluation results of the bubbling distribution are worse than for a local execution. For the environment $\mathbb{S}w\mathbb{F}$, a local execution and the bubbling distribution have in average a similar power consumption of 2.5 W. However, the bubbling distribution finishes the local execution of the mobile application on the smart phone later at 72.139 s (cf. Figure 8.5) and thus, consumes more energy (cf. Figure 8.6). Compared to the two-tier distribution, the bubbling distribution performs better with a shorter execution time of 3.094 s and a lower energy consumption of 15.493 J. Distributing the Java methods that are offloadable to a distant cloud with a bad quality of the link (cf. $\mathbb{S}c\text{-}\mathbb{C}$ in Figure 8.5 and Figure 8.6), the execution time and the energy consumption for the bubbling distribution only minor increase by 1.460 s and 10.495 J, respectively. As the high latency to the cloud distribution tier does not influence the bubbling distribution much, it performs better than the two-tier distribution. In detail, it reduces the execution time by 5.983 s and the energy consumption by 44.671 J.

Summarizing, the two-tier distribution as well as the bubbling distribution introduce some overhead in the environments with two tiers, increasing the execution time and the energy consumption compared to a local execution. Due to the distribution without a beneficial resource on the remote side, both approaches cause no monetary cost at all. In detail, the overhead introduced by the two-tier distribution is higher than for the bubbling distribution, because the two-tier distribution probes periodically the link to and monitors the state of the remote tier. The decoupled submission of downgraded offload requests keeps the overhead introduced by the bubbling distribution low, especially in case of a bad quality of the link between the smart phone and the remote tier.

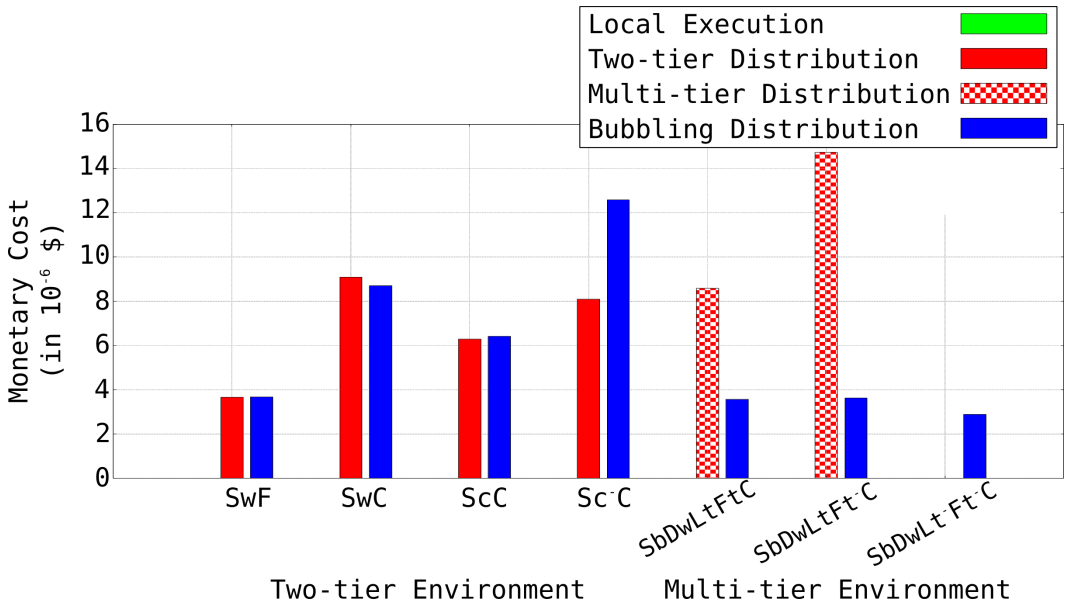


Figure 8.7.: Monetary cost of a local execution, the two-tier distribution, the multi-tier distribution, and the bubbling distribution evaluated in the environments with two tiers and the environment with multiple tiers, respectively.

Benefit of a Distribution: Figure 8.5 shows the execution time, Figure 8.6 the energy consumption, and Figure 8.7 the monetary cost of a local execution, the two-tier distribution, and the bubbling distribution evaluated in the environments $\mathbb{S}w\mathbb{F}$, $\mathbb{S}w\mathbb{C}$, $\mathbb{S}c\mathbb{C}$, and $\mathbb{S}c^{-}\mathbb{C}$. For the last four group of bars in Figure 8.5 and Figure 8.6 and the first four group of bars in Figure 8.7, the offloading service on the remote side possesses a beneficial resource for a remote execution, indicating the benefit gained.

The environment $\mathbb{S}w\mathbb{F}$ corresponds to a perfect environment for a distribution of the Java methods that are offloadable, providing a sufficient link with a latency of 4.679 ms and a bandwidth of 1.9 MB/s between the smart phone and the remote tier with the beneficial resource. As a result, the two-tier distribution distributes all three Java methods that are offloadable, where the execution time of the best chess move engine decreases to 4.217 s, of the human face recognition engine to 7.456 s, and of the text-to-voice engine to 1.589 s. In total, it takes 14.900 s and consumes 44.518 J with a monetary cost of 3.653 E-6 $, outperforming significantly a local execution on the smart phone. Changing the environment to a distant tier with a cellular link (cf. $\mathbb{S}c\mathbb{C}$ in Figure 8.5 and Figure 8.6), the bandwidth decreases to 185 kB/s. Thus, the two-tier distribution does not distribute the human face recognition engine due to its huge size of the input execution state. The local execution of the human face recognition engine on the smart phone increases the execution time and the energy consumption of the two-tier distribution, however, still resulting in a shorter execution time of 33.860 s

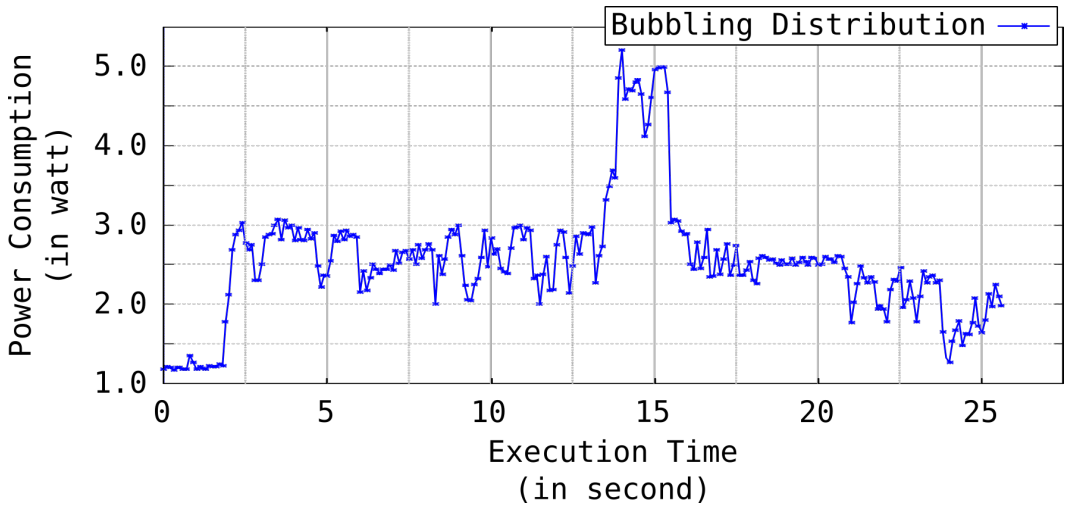


Figure 8.8.: The power consumption of the bubbling distribution evaluated in the environment $\mathbb{S}c\mathbb{C}$. The bubbling distribution recognizes the too bad bandwidth of the link between the smart phone and the remote tier after the transmission of 250 kB to the cloud distribution tier.

and a lower energy consumption of 84.882 J compared to a total local execution of the application on the smart phone. Increasing simultaneously the latency of the cellular link to 253.772 ms (cf. $\mathbb{S}c^{-}\mathbb{C}$ in Figure 8.5 and Figure 8.6), the two-tier distribution only distributes the best chess move engine to the remote tier. Despite the local execution of the two Java methods that are offloadable, it still performs better than a total local execution of the application on the smart phone. In detail, the two-tier distribution results in an execution time of 58.831 s and an energy consumption of 155.566 J with a monetary cost of 8.088 E-6 $.

For the environment $\mathbb{S}w\mathbb{F}$, the bubbling distribution results in a similar execution time, energy consumption, and monetary cost as the two-tier distribution. Due to the huge size of the input execution state, the bubbling distribution also does not distribute the human face recognition engine for the environment $\mathbb{S}c\mathbb{C}$. It recognizes the too bad bandwidth of the link between the smart phone and the remote tier by sending the first 250 kB to the cloud distribution tier (cf. the peak at 14 s in Figure 8.8). As the bubbling distribution executes in parallel the human face recognition engine on the smart phone, however, the evaluation results of the bubbling distribution are better than of the two-tier distribution. The bubbling distribution reduces the execution time by 8.333 s and the energy consumption by 2.282 J with a similar monetary cost. Increasing simultaneously the latency of the cellular link to the cloud distribution tier (cf. $\mathbb{S}c^{-}\mathbb{C}$ in Figure 8.5 and Figure 8.6), the bubbling distribution also does not distribute the text-to-voice engine like the two-tier distribution. It executes the

text-to-voice engine locally based on the bandwidth and latency measured during the evaluation, not sending any bytes for the input execution state to the remote tier unlike for the human face recognition engine. Thus, the evaluation results of the bubbling distribution evaluated in $\mathbb{S}c\text{-}\mathbb{C}$ are better than of the two-tier distribution, reducing the execution time by 25.711 s and the energy consumption by 53.097 J. Compared to a local execution, the bubbling distribution reduces the execution time by 35.733 s and the energy consumption by 70.690 J with a monetary cost of 12.582 E-6 $.

Summarizing, the benefits gained of the two-tier distribution and the bubbling distribution for a distribution are high for the environments with two tiers possessing a sufficient link to the remote tier with a beneficial resource. Due to the distribution with a beneficial resource, both approaches reduce the execution time and the energy consumption compared to a local execution, causing monetary cost for the remote execution on an offloading service. In detail, the benefit gained of the two-tier distribution is lower than of the bubbling distribution, because the two-tier distribution probes periodically the link to and monitors the state of the remote tier. Especially in case of a link with a high latency and a low bandwidth, the decoupled submission of downgraded offload requests keeps the benefit of the bubbling distribution high.

Environment with Multiple Tiers

The evaluation result of a local execution, the multi-tier distribution, and the bubbling distribution are categorized into the overhead and benefit of a distribution.

Overhead of a Distribution: Figure 8.5 shows the execution time, Figure 8.6 the energy consumption, and Figure 8.7 the monetary cost of a local execution, the multi-tier distribution, and the bubbling distribution evaluated in the environments $\mathbb{D}b\mathbb{S}w\mathbb{L}t\mathbb{F}t\mathbb{C}$, $\mathbb{D}b\mathbb{S}w\mathbb{L}t\mathbb{F}t\text{-}\mathbb{C}$, and $\mathbb{D}b\mathbb{S}w\mathbb{L}t\text{-}\mathbb{F}t\text{-}\mathbb{C}$. For the first three group of bars in Figure 8.5 and Figure 8.6, the offloading services at the multiple tiers do not possess a beneficial resource for a remote execution, indicating the introduced overhead. Please note that Table 8.1 outlines each value for the execution time, energy consumption, and monetary cost of the approaches evaluated in the environment with multiple tiers.

The multi-tier distribution also makes its decision for a distribution in the environment with multiple tiers by periodically probing the link to and monitoring the state of the tiers. Due to the missing beneficial resources in each tier, the multi-tier distribution executes all of the Java methods that are offloadable on the smart phone. Thus, the periodic probing and monitoring together with the local execution of the mobile application increases the execution time and the energy consumption of the

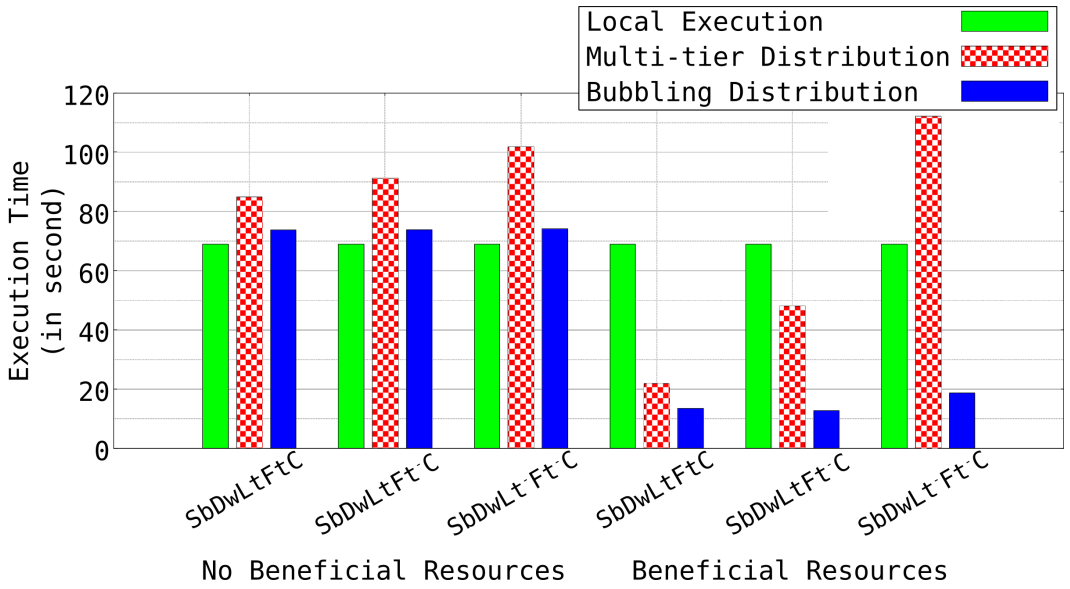


Figure 8.9.: Execution time of a local execution, the multi-tier distribution, and the bubbling distribution evaluated in the environment with multiple tiers.

multi-tier distribution compared to a local execution without code offloading. In detail, it takes 15.932 s longer and consumes 28.141 J more energy (cf. $\mathbb{D}b\mathbb{S}w\mathbb{L}t\mathbb{F}t\mathbb{C}$ in Figure 8.5 and Figure 8.6). Increasing the latency of the tethered link between the fog distribution tier and the cloud distribution tier to 268.189 ms, the evaluation results for the multi-tier distribution are getting worse. In detail, it takes 22.362 s longer and consumes 44.986 J more energy compared to a local execution without code offloading (cf. $\mathbb{D}b\mathbb{S}w\mathbb{L}t\mathbb{F}t\text{-}\mathbb{C}$ in Figure 8.5 and Figure 8.6). Increasing simultaneously the latency of the tethered link between the local distribution tier and the fog distribution tier to 154.686 ms and between the fog distribution tier and the cloud distribution tier to 402.399 ms, it takes 32.937 s longer and consumes 58.891 J more energy compared to a local execution without code offloading (cf. $\mathbb{D}b\mathbb{S}w\mathbb{L}t\text{-}\mathbb{F}t\text{-}\mathbb{C}$ in Figure 8.5 and Figure 8.6).

Due to the gathering and submitting of the downgraded offload requests, the bubbling distribution results in worse results compared to a local execution without code offloading. In detail, it takes 4.835 s longer and consumes 1.360 J more energy for the environment $\mathbb{D}b\mathbb{S}w\mathbb{L}t\mathbb{F}t\mathbb{C}$ (cf. Figure 8.5 and Figure 8.6). However, both increases of the latency of the links do not affect the results of the bubbling distribution, keeping the execution time and the energy consumption constant (cf. $\mathbb{D}b\mathbb{S}w\mathbb{L}t\mathbb{F}t\text{-}\mathbb{C}$ and $\mathbb{D}b\mathbb{S}w\mathbb{L}t\text{-}\mathbb{F}t\text{-}\mathbb{C}$ in Figure 8.5 and Figure 8.6). Compared to the execution time and the energy consumption of the multi-tier distribution, the bubbling distribution performs better for the environment with multiple tiers with and without a bad quality of a link. In detail, it reduces the execution time by 11.097 s, 17.403 s, and 27.711 s as well as the

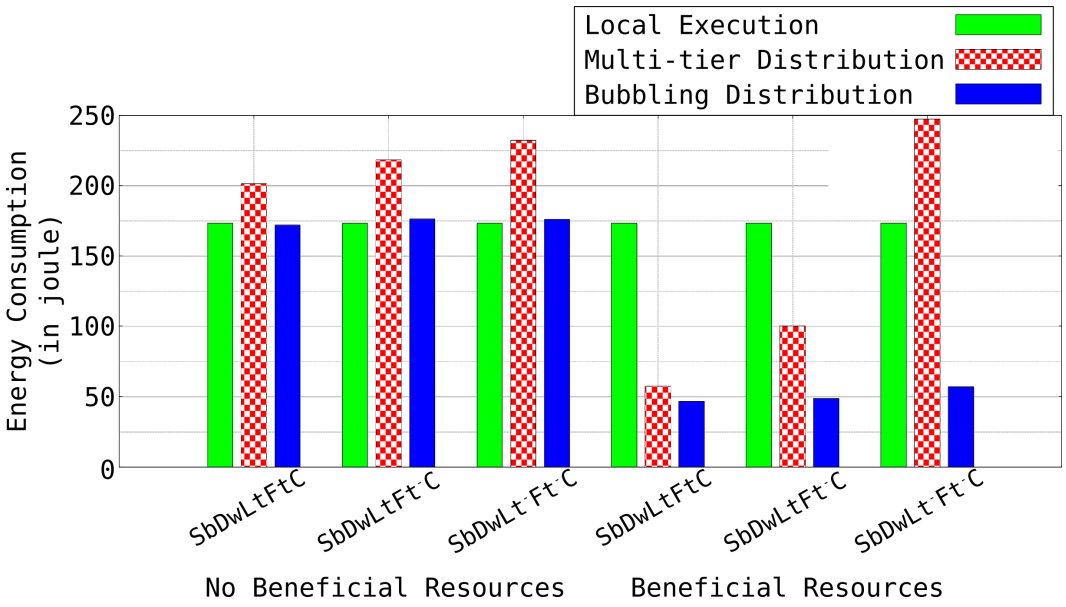


Figure 8.10.: Energy consumption of a local execution, multi-tier distribution, and bubbling distribution evaluated in the environment with multiple tiers.

energy consumption by 29.501 J, 41.962 J, and 56.216 J (cf. Figure 8.5 and Figure 8.6).

Summarizing, the multi-tier distribution as well as the bubbling distribution introduce some overhead in the environment with multiple tiers, increasing the execution time and the energy consumption compared to a local execution without code offloading. Due to the distribution without a beneficial resource in the multiple tiers, both approaches cause no monetary cost at all. However, the overhead introduced for the multi-tier distribution is higher than for the bubbling distribution. The decoupled submission of downgraded offload requests also keeps the overhead introduced in the environment with multiple tiers for the bubbling distribution low.

Benefit of a Distribution: Figure 8.5 shows the execution time, Figure 8.6 the energy consumption, and Figure 8.7 the monetary cost of a local execution, the multi-tier distribution, and the bubbling distribution evaluated in the environments $\mathbb{D}b\mathbb{S}w\mathbb{L}t\mathbb{F}t\mathbb{C}$, $\mathbb{D}b\mathbb{S}w\mathbb{L}t\mathbb{F}t\text{-}\mathbb{C}$, and $\mathbb{D}b\mathbb{S}w\mathbb{L}t\text{-}\mathbb{F}t\text{-}\mathbb{C}$. For the last three group of bars in the figures, the offloading services at the multiple tiers possess beneficial resources for a remote execution, indicating the benefit gained by the approaches.

The environment $\mathbb{D}b\mathbb{S}w\mathbb{L}t\mathbb{F}t\mathbb{C}$ corresponds to an optimal environment for a distribution. Thus, the multi-tier distribution distributes all three Java methods that are offloadable to the cloud distribution tier. The distribution of the three Java methods that are offloadable decreases the execution time by 47.049 s and the energy consump-

tion by 115.694 J with a monetary cost of 8.587 E-6 $ compared to a local execution without code offloading (cf. Figure 8.5, Figure 8.6, and Figure 8.7). Increasing the latency of the tethered link between the fog distribution tier and the cloud distribution tier, the evaluation results are getting worse but still performing better than a local execution without code offloading (cf. $\mathbb{D}b\mathbb{S}w\mathbb{L}t\mathbb{F}t\mathbb{C}$ in Figure 8.5, Figure 8.6, and Figure 8.7). In detail, the multi-tier distribution distributes the best chess move engine to the cloud distribution tier, executes the human face recognition engine locally on the smart phone, and distributes the text-to-voice engine to the fog distribution tier. It results in a reduction of the execution time by 20.869 s and the energy consumption by 73.187 J compared to a local execution without code offloading. However, increasing both the latency of the tethered link between the local distribution tier and the fog distribution tier as well as between the fog distribution tier and the cloud distribution tier, the multi-tier distribution executes all three Java methods that are distributable locally on the smart phone (cf. $\mathbb{D}b\mathbb{S}w\mathbb{L}t\mathbb{F}t\mathbb{C}$ in Figure 8.5, Figure 8.6, and Figure 8.7). As a result, the evaluation results of the multi-tier distribution are worse than a local execution without code offloading with an increase of the execution time by 43.266 s and the energy consumption by 73.937 J.

For the environment $\mathbb{D}b\mathbb{S}w\mathbb{L}t\mathbb{F}t\mathbb{C}$, the bubbling distribution distributes all three Java methods that are distributable to the fog distribution tier, reducing the execution time by 8.418 s and the energy consumption by 10.971 J compared to the multi-tier distribution. Increasing the latency of the tethered link between the local distribution tier and the fog distribution tier as well as between the fog distribution tier and the cloud distribution tier, the evaluation results for the bubbling distribution remain constant (cf. $\mathbb{D}b\mathbb{S}w\mathbb{L}t\mathbb{F}t\mathbb{C}$ and $\mathbb{D}b\mathbb{S}w\mathbb{L}t\mathbb{F}t\mathbb{C}$ in Figure 8.5, Figure 8.6, and Figure 8.7). Due to the high link latency, the bubbling distribution distributes the text-to-voice engine to the local distribution tier. In total, it performs better than the multi-tier distribution and a local execution without code offloading for the environment with multiple tiers.

Summarizing, the benefits of the multi-tier distribution and the bubbling distribution for a distribution are high for the environment with multiple tiers possessing suitable links to the multiple tiers with beneficial resources. Due to the distribution with beneficial resources, both approaches reduce the execution time and the energy consumption compared to a local execution without code offloading, causing monetary cost for the remote execution on the offloading services. In detail, the benefit gained of the bubbling distribution is higher than of the multi-tier distribution due to the decoupled submission of downgraded offload requests instead of the periodic probing of the links to and monitoring of the state from the multiple tiers. Especially in case of links with a high latency, the bubbling distribution keeps the related benefit high.

		Lcl	$\mathbb{S}w\mathbb{F}$		$\mathbb{S}w\mathbb{C}$		$\mathbb{S}c\mathbb{C}$		$\mathbb{S}c^{-}\mathbb{C}$	
			TtD	BlD	TtD	BlD	TtD	BlD	TtD	BlD
Without Beneficial Resources:										
Energy	(in Joule)	173.159	190.176	174.683	192.557	172.203	225.415	187.065	229.795	185.178
Time	(in Seconds)	68.853	75.233	72.139	74.448	73.149	79.423	74.583	79.582	73.599
Cost	(in 10^{-6} \$)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
With Beneficial Resources:										
Energy	(in Joule)	173.159	44.518	57.215	45.301	53.340	84.882	82.600	155.566	102.469
Time	(in Seconds)	68.853	14.900	13.738	15.705	14.345	33.860	25.527	58.831	33.120
Cost	(in 10^{-6} \$)	0.000	3.653	3.665	9.083	8.701	6.282	6.411	8.088	12.582

Table 8.1.: Overview of the execution time, the energy consumption, and the monetary cost for a local execution (*Lcl*), the two-tier distribution (*TtD*), and the bubbling distribution (*BlD*) evaluated in the environments with two tiers with and without beneficial resources.

		Lcl	$\mathbb{D}b\mathbb{S}w\mathbb{L}t\mathbb{F}t\mathbb{C}$		$\mathbb{D}b\mathbb{S}w\mathbb{L}t\mathbb{F}t^{-}\mathbb{C}$		$\mathbb{D}b\mathbb{S}w\mathbb{L}t^{-}\mathbb{F}t^{-}\mathbb{C}$	
			MtD	BlD	MtD	BlD	MtD	BlD
Without Beneficial Resources:								
Energy	(in Joule)	173.159	201.300	171.799	218.145	176.183	232.050	175.834
Time	(in Seconds)	68.853	84.785	73.688	91.215	73.812	101.790	74.079
Cost	(in 10^{-6} \$)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
With Beneficial Resources:								
Energy	(in Joule)	173.159	57.465	46.494	99.972	48.514	247.096	57.014
Time	(in Seconds)	68.853	21.804	13.386	47.984	12.651	112.119	18.706
Cost	(in 10^{-6} \$)	0.000	8.587	3.559	14.736	3.617	0.000	2.882

Table 8.2.: Overview of the execution time, the energy consumption, and the monetary cost for a local execution (*Lcl*), the multi-tier distribution (*MtD*), and the bubbling distribution (*BlD*) evaluated in the environment with multiple tiers with and without beneficial resources.

Application Part	Distribution Tier	Offloading Service		Time Overhead
		Basic	Bubbling	
Best Chess Move Engine	$\mathbb{D}$	18.386 s	18.446 s	0.33%
	$\mathbb{L}$	5.014 s	5.028 s	0.28%
	$\mathbb{F}$	1.800 s	1.801 s	0.06%
	$\mathbb{C}$	2.461 s	2.463 s	0.08%
Human Face Recognition Engine	$\mathbb{D}$	2.579 s	2.627 s	1.86%
	$\mathbb{L}$	0.582 s	0.591 s	1.55%
	$\mathbb{F}$	0.248 s	0.249 s	0.40%
	$\mathbb{C}$	0.616 s	0.620 s	0.65%
Text-to-Voice Engine	$\mathbb{D}$	5.228 s	5.659 s	8.24%
	$\mathbb{L}$	1.216 s	1.276 s	4.93%
	$\mathbb{F}$	0.534 s	0.538 s	0.75%
	$\mathbb{C}$	0.821 s	0.834 s	1.58%

Table 8.3.: Overview of execution time on an offloading service for the basic distribution and the bubbling distribution for each resource-intensive application part. The distribution tiers that executes the application parts are the device distribution tier ($\mathbb{D}$), the local distribution tier ($\mathbb{L}$), the fog distribution tier ($\mathbb{F}$), and the cloud distribution tier ($\mathbb{C}$).

8.5.3. Securing Overhead

Table 8.3 shows the time and transmission overhead introduced for securing a remote execution of application parts on an a priori unknown resource. To this end, participating resources in the device distribution tier ($\mathbb{D}$), the local distribution tier ($\mathbb{L}$), the fog distribution tier ($\mathbb{F}$), and the cloud distribution tier ($\mathbb{C}$) execute each resource-intensive application part – namely the best chess move engine, the human face recognition engine, and the text-to-voice engine – 10 times on an unaltered offloading service from the basic distribution (cf. Subsection 4.5.3) and 10 times on an offloading service for the bubbling distribution (cf. Subsection 8.4.3).

For the best chess move engine, the time overhead introduced for the execution of the additional Java bytecode instruction `offload_branch` ranges between 0.06% and 0.35% for the participating resources in $\mathbb{D}$, $\mathbb{L}$, $\mathbb{F}$, and $\mathbb{C}$ (cf. Table 8.3). In detail, the execution time for the best chess move engine in $\mathbb{F}$ differs only by 1 ms and in $\mathbb{C}$ by 2 ms, being very similar. The execution time in the device distribution tier ($\mathbb{D}$) differs by 60 ms, also resulting in a very low time overhead. Regarding the time overhead, the tier with the most powerful resources ($\mathbb{F}$) induces the lowest overhead and the tier with the poorest resources ($\mathbb{D}$) has the highest overhead. The same characteristic applies for the human face recognition engine and the text-to-voice engine. The time overhead for

$\mathbb{D}$, $\mathbb{L}$, $\mathbb{F}$, and $\mathbb{C}$ ranges between 0.40% and 1.86% for the human face recognition engine and between 0.75% ($\mathbb{F}$) and 8.24% ($\mathbb{D}$) for the text-to-voice engine (cf. Table 8.3). However, the absolute values for the additional time from the text-to-voice engine ranges between 0.004 ms ($\mathbb{F}$) and 0.431 ms ($\mathbb{D}$), still being acceptable with regard to the local execution time of 18.624 ms on the smart phone (cf. Subsection 4.7.2).

Beside the time overhead for the additional execution of the Java bytecode instruction `offload_branch`, the offloading service for the bubbling distribution also induces a transmission overhead. In detail, it is independent from the actual resource at the distribution tier (cf. $\mathbb{D}$, $\mathbb{L}$, $\mathbb{F}$, or $\mathbb{C}$) that executes a Java method as well as from the distributed Java method itself. Regarding the additional transmission, an offloading service for the bubbling distribution transfers additionally to an offloading client the calculated hash value and the integer values of i and x compared to an offloading service for the basic distribution. In total, the additional number of bytes transferred is 64 byte for the hash value plus 8 byte for the two integer values, resulting in total in a very low transmission overhead of 72 byte.

8.6. Summary

To provide a code offloading in environments with multiple tiers through code bubbling, the *bubbling distribution* described in Section 8.1 extends the basic distribution. The bubbling distribution offloads computation not only between a mobile device (first tier) and a remote resource (second tier) but also between multiple tiers with highly distributed heterogeneous resources. To this end, the bubbling distribution utilizes a *system overview* described in Section 8.2 of multiple tiers, adjusting accordingly the system model, problem statement, and system components of the basic distribution. For the bubbling distribution, an offloading client can distribute an application part that is offloadable among heterogeneous resources on many tiers (e.g., wearable device $\leftrightarrow$ smart phone $\leftrightarrow$ edge servers $\leftrightarrow$ cloud servers, etc.). Thus, the decision making for code offloading in environments with multiple tiers is more complex. Keeping code offloading in environments with multiple tiers also applicable, the bubbling distribution introduces the concept of code bubbling – *offloading timeline* described in Section 7.3. Code bubbling enables each tier to make autonomous decisions for code offloading without the need to gather a global view onto all resources of all tiers. As a result, the usage of code bubbling potentially scales to an arbitrary number of tiers since the decision making for code offloading only involves neighboring tiers. The *offloading framework* described in Section 8.4 provides the functionality required for the bubbling distribution, extending the API of the Java programming language. Moreover,

it extends the offloading client and the offloading service with the functionality for the bubbling distribution, and adds a tier service for managing participating resources within a tier. To evaluate the overhead introduced and benefit gained by the bubbling distribution compared to the basic distribution, the *evaluation* described in Section 8.5 of a prototype based on the Android OS and the OpenJDK JRE analyzes multiple approaches in different environments. The evaluation results show that a distribution with code bubbling keeps the introduced overhead low and gained benefit high due to the submission of downgraded offload requests and the local continuation of the application execution. Especially, in case of a network link with a bad quality, the bubbling distribution significantly performs better than related approaches from the literature.

Chapter 9

Related Work

This chapter presents the work related to the contributions previously described in this dissertation. The related work comprises computation offloading in the landscape of Mobile Cloud Computing (MCC) that covers both code offloading and cyber foraging. Both augment a (resource-poor) mobile device with (powerful) remote resources, where cyber foraging locates a remote resource in the vicinity like an underutilized desktop computer and code offloading locates it at a distant data center at the cloud. To this end, Section 9.1 discusses the work related to an efficient code offloading with annotations described in Chapter 4. It provides the basic distribution of application parts between a mobile device and a remote resource, keeping the efficiency of a distribution high and at the same time the burden on application developers and end users low. During a remote execution of application parts distributed to a remote resource, crash failures like a disconnection might occur. To this end, Section 9.2 discusses the work related to a robust code offloading through safe-point'ing described in Chapter 5. It provides the preemptable distribution of application parts improving the basic distribution to locally reuse intermediate states – so-called safe-points – from the remote side, not abandoning partial computations achieved remotely so far. Section 9.3 discusses the work related to a deadline-aware code offloading with predictive safe-point'ing described in Chapter 6 that provides the predictive distribution. It improves the preemptable distribution with an adaptive algorithm based on prediction models to dynamically adapt the point in times for safe-point'ing due to dynamic conditions of the communication network. Next, Section 9.4 discusses the work related to an optimized code offloading through cooperative caching described in Chapter 7 that provides the caching-aware distribution of application parts. It increases the efficiency of the basic distribution with a cache on the remote side that stores the result of application parts previously executed, avoiding a repeated execution. As highly distributed heterogeneous resources surround nowadays a mobile device in the landscape of MCC, Section 9.5 discusses the work related to a code offloading in environments with multiple tiers described in Chapter 8. It provides the bubbling distribution of application parts to remote resources in multiple tiers, shifting the decision making for code of-

floading from a (resource-poor) mobile device into the infrastructure, not requiring to gather a global view onto all resources of all tiers. Last, Section 9.6 summarizes the main facts for the related work of this dissertation presented in this chapter.

9.1. Efficient Code Offloading with Annotations

In the literature, several approaches show the capabilities of a distribution of application parts from a (resource-constrained) mobile device like a smart phone to a (powerful) remote resource in the infrastructure like a server instance at the cloud.

Cuervo et al. [CBC+10] propose an offloading approach called MAUI that improves the energy efficiency of a mobile device. MAUI distributes application parts at the granularity of methods from a mobile device to a remote server located in a data center at the cloud. MAUI identifies application parts that are offloadable based on an annotation from an application developer annotated at development-time. To this end, they formulate an Integer Linear Program (ILP) that minimizes the energy consumption of a mobile application on the mobile device subjected to a maximum time for an execution of an application. The ILP considers the network parameters like the bandwidth and latency of the link between the mobile device and the server.

CloneCloud from Chun et al. [CIM+11] also improves the energy efficiency of a mobile device by distributing application parts from a mobile device to a remote server at the cloud. CloneCloud distributes application parts at the granularity of threads, where a so-called device clone for each mobile device runs at the cloud. A main goal for the design of CloneCloud is a transparent distribution of application parts for an application developer by automatically transforming and partitioning the code of an application to enable a distributed execution. To automatically distribute threads from a mobile device to its clone, it partitions applications based on a static analysis of the application at development-time together with a profiling of the application at runtime. Thereupon, CloneCloud determines the execution side for an application part by formulating an optimization problem that minimizes the energy consumption of the mobile device subjected to a maximal time for an execution of an application.

Giurgiu et al. [GRA12] propose an approach that distributes application parts at the granularity of modules. To this end, the approach partitions applications into modules based on the technology of remote OSGi (Open Services Gateway initiative) [RAR07]. After the partitioning of an application, the approach distributes dynamically the partitioned modules between a mobile device and a remote server based on profiling the mobile device as well as the application.

Gitzenis et al. [GB09] propose an approach that considers the local management

for the power consumption of a mobile device for a distribution of application parts by adjusting, for instance, the processor speed. The approach focuses on the trade-off between the execution time of an application and the energy saving on the mobile device, modeling the decision problem of a distribution as a controlled Markov chain. The solution of the problem is a policy that determines the execution side as well as the power consumption of the mobile device.

ThinkAir from Kosta et al. [KAH+12] also distributes application parts from a mobile device to a remote server at the cloud reducing the execution time and energy consumption on the mobile device for an execution of an application. Beside the execution time and energy consumption, ThinkAir explicitly includes the monetary cost for a remote execution at the cloud. To this end, it dynamically scales the computational power at the cloud to achieve an optimal performance, allocating on-demand server instances at the cloud and mapping the application parts to the allocated server instances. Furthermore, it allows a parallel execution of application parts on multiple server instances at the cloud.

The middleware proposed from Ferber et al. [FRTH12] augments the execution of compute-intensive applications on a resource-constrained mobile device with cloud resources. It provisions on-demand the utilization of server instances at the cloud and thus, considers the costs arose for a remote execution by accounting end users.

Shi et al. [SHP+14] present the distribution system COSMOS that minimizes the execution time, energy consumption, and monetary cost of an application on a mobile device. COSMOS also allocates resources at the cloud to schedule efficiently the remote execution of distributed application parts. It offers the distribution of computation as a service mapping dynamically application parts from mobile devices to compute resources in a commercial data center at the cloud. As a result, its optimization problem for a distribution additionally minimizes the leasing costs of cloud resources while handling variable network connectivity.

Tasklet from Paluska et al. [PPS+12, SEV+16] provides a lightweight abstraction for best-effort computation at the granularity of threads to migrate computation, for instance, from local resources of a mobile device to resources in the cloud. In detail, a Tasklet is a fine-grained and self-contained computation unit created dynamically at run-time that includes everything for its processing like instructions, data, and state. The underlying representation of instructions and data are chunks, building a graph of linked chunks as a Tasklet. A Tasklet container consists of a virtual machine to execute Tasklets, running on any suitable hardware connected to the Internet.

Summarizing, multiple approaches proposed in the literature show the benefits of computation offloading increasing significantly the energy efficiency on a (resource-

constrained) mobile device and the execution speed for a (resource-intensive) application. However, MAUI from Cuervo et al. [CBC+10] and CloneCloud from Chun et al. [CIM+11] focuses on the improvement of the energy efficiency of a mobile device and the execution speed of an application. They do not regard monetary cost for a remote execution of application parts distributed to a server instance, hosted, for instance, in a commercial data center at the cloud. In detail, MAUI is similar to the basic distribution presented in Chapter 4, where an application developer annotates methods that are offloadable. However, MAUI does not instrument bytecodes for the efficient identification of methods that are offloadable. ThinkAir from Kosta et al. [KAH+12] and COSMOS from Shi et al. [SHP+14] focuses on improvements on the remote side like resource allocation and execution parallelism, executing on a server instance at the cloud a virtual machine of a complete system from a smart phone. Tasklet from Paluska et al. [PPS+12] focuses on the issue of best-effort computation, utilizing at the system core an own virtual machine for thread migration implemented in a new programming language. In contrast to the related approaches proposed in the literature, the basic distribution presented in Chapter 4 minimizes the execution time, energy consumption, and monetary cost for a computation offloading of application parts between a mobile device and a remote resource. It utilizes an annotation-based instrumentation of Java bytecode instructions that keeps both the overhead introduced to a mobile device and the burden on application developers and end users low.

9.2. Robust Code Offloading through Safe-point'ing

The approaches related to the basic distribution of application parts described in Section 9.1 show the benefits for a distribution of application parts between a mobile device and a remote server. The execution of application parts on a remote server on behalf of a mobile device reduces significantly the energy consumption and execution time on the mobile device. Due to the utilization of a remote resource, the remote execution causes monetary cost for an end user. Although these approaches increase the efficiency on a mobile device, they assume a permanent link between a mobile device and a remote resource as well as a permanent availability of a remote resource. They do not consider the adverse effects from the occurrence of failures like a link disconnection, especially as the occurrence of failures can result in a higher execution time and/or energy consumption than a local execution on a mobile device.

Kwon et al. [KT12] propose a basic mechanism handling the occurrence of failures. The approach creates a single safe-point before the distribution of application parts that are offloadable, annotated by an application developer. In case of an occurrence

of a failure during a remote execution of an application part, it starts a complete re-execution of the application part on the mobile device based on the single safe-point.

The ENDA system from Li et al. [LBLX13] also considers the occurrence of failures. ENDA distributes application parts that are offloadable from a mobile device either to small servers called cloudlets via a Wi-Fi connection or to server instances at the cloud via a 3G mobile communication network. Based on historic traces of a mobile device, it selects Wi-Fi access points along the predicted route that connect the mobile device to the cloudlets. In case of the unavailability of a cloudlet, it uses the 3G mobile communication to distribute an application part to a server instances at the cloud. Furthermore, it simply waits for a re-connection to a cloudlet or a server instance if a failure occurs during a remote execution of an application part.

The COMET system from Gordon et al. [GJM+12] also focuses on the robustness for a distribution of an application part – more precisely, a thread – between a mobile device and a remote server. To handle the occurrence of failures from the network or the server, COMET utilizes the techniques of Distributed Shared Memory (DSM) and Virtual Machine Synchronization (VMS), already utilized for the offloading of threads. Based on DSM and VMS, COMET synchronizes threads distributed between a mobile device and a remote sever, where this fine-grained heap and stack synchronization between a (resource-constrained) mobile device and a remote server induces a high overhead of communication. For instance, COMET has to synchronize the complete initial state at the start of an application, resulting in a typical size of 750-810 kB.

Summarizing, multiple approaches proposed in the literature show techniques for computation offloading that handles the occurrence of failures during a distribution of an application part. However, the approach from Kwon et al. [KT12] starts in case of a failure a complete re-execution on a mobile device of an application part. It abandons the intermediate state achieved on the remote side so far resulting in a higher execution time and energy consumption in case of a failure. ENDA from Li et al. [LBLX13] waits in case of a failure for a re-connection to the remote resource that executes the application part, also resulting in a higher execution time and energy consumption, especially, for instance, for long lasting disconnections. COMET from Gordon et al. [GJM+12] utilizes a fine-grained synchronization of threads distributed between a mobile device and a remote resource, introducing a large communication overhead. In contrast to the related approaches proposed in the literature, the preemptable distribution presented in Chapter 5 utilizes incremental safe-point'ing, where a safe-point corresponds to the intermediate state on the remote side. It re-uses locally the intermediate states of the remote side to continue the remote execution locally, leading to a much smaller amount of data that a remote resource transfers to a mobile device.

9.3. Deadline-aware Code Offloading with Predictive Safe-point'ing

The approaches related to the preemptable distribution of application parts described in Section 9.2 handle the occurrence of failures during a remote execution of application parts distributed between a mobile device and a remote resource. In case of an occurrence of a failure, the approaches either re-executes a (resource-intensive) application part on a (resource-constrained) mobile device (cf. Kwon et al. [KT12]) or waits for a re-connection to the remote resource (cf. Li et al. [LBLX13]). Handling an occurrence of failures by re-executing application parts or waiting for a re-connection reduces the efficiency on a mobile device of a distribution in case of a failure. Furthermore, both strategies of re-executing and re-connecting might not be optimal with regard to energy efficiency and execution speed, giving no guarantees about an execution deadline for an application. The preemptable distribution with safe-point'ing presented in Chapter 5 re-uses locally partial results (intermediate states) from the remote side in case of a failure to continue a remote execution on the mobile device. To this end, the preemptable distribution creates safe-points – that captures the temporal execution state of an application part executed on a remote resource – and transmits these safe-points to the mobile device during a remote execution of an application part. After an occurrence of a failure, a mobile device continues the remote execution locally based on the safe-point received most recently. Summarizing, the preemptable distribution with safe-point'ing proposed from Berg et al. [BDR14a] uses a non-predictive schedule to determine the points in time to create and transmits safe-points. The strategy that determines the points in time for safe-point'ing does not always perform optimally under dynamic conditions of the network. In contrast to the related approaches proposed in the literature, the predictive distribution presented in Chapter 6 utilizes an adaptive schedule based on prediction models. It dynamically adapt the point in times for a creation and transmission of safe-points due to dynamic conditions of the communication network, increasing the efficiency of code offloading.

9.4. Optimized Code Offloading through Cooperative Caching

The approaches related to the basic distribution of application parts described in Section 9.1 show the benefits related to the basic distribution augmenting a (resource-constrained) mobile device with a remote resource. The execution of application parts

distributed to a remote resource causes monetary cost due to the utilization, for instance, of cloud resources (basic distribution). To this end, the caching-aware distribution improves the basic distribution with a cache. Today, many computing systems utilize different types of a cache for data and function as, for instance, nodes in a distributed system that utilize a cache for Domain Name System (DNS) to speed-up the lookup of a name resolution. In general, the basic idea behind the concept of caching is that a cache stores information of current requests, speeding up future requests in case of a cache hit. In case of a cache miss, a cache needs to obtain the information elsewhere, which is comparatively slower.

WhereStore from Stuedi et al. [SMT10] is a data cache for mobile devices that replicates cloud data on the limited memory of a mobile device based on the device's history of location. WhereStore distributes the data between mobile devices and the cloud based on filtered replication together with the device's history of location. As a result, it decreases the access times for the data and improves availability of the data, especially in case of a disconnection between a mobile device and the cloud. The main idea of this location-aware caching between mobile devices and the cloud is that a mobile device typically accesses only specific data at certain places (e.g., restaurant recommendations at downtown).

Michie [Mic68] proposes a run-time optimization for a local execution related to function calls, avoiding the overhead for a redundant execution of a function locally called Memoization. To this end, a local cache for functions stores the arguments and the corresponding result from a previous call of a function. In case of the local cache for functions has a corresponding result (cache hit), it returns immediately a call of a function with the corresponding result. This avoids the local execution of the function's body once again, reducing the execution time of a function.

ADEOM from Jiang et al. [JHLX14] consider a cache on the remote side for a distribution of application parts between a mobile device and a remote server. The cache stores an input execution state of an application part required for its execution on a remote resource. Through the integration of a cache, it reduces the time for a transmission of an input execution state for an application part distributed between a mobile device and a remote server. In case of a repeated execution on a remote resource of an application part previously distributed, a mobile device does not have to sent the input execution state already stored in the cache on the remote side. Thus, ADEOM decreases the memory size of migrated data and accelerates the transmission time.

Summarizing, multiple approaches proposed in the literature show the benefits related to the utilization of caching. WhereStore from Stuedi et al. [SMT10] provides a location-aware caching for information related to the location of a mobile device,

replicating cloud data on the mobile device. “Memoization” from Michie [Mic68] is a local cache for functions, avoiding a redundant execution of a function in case of a cache hit. ADEOM from Jiang et al. [JHLX14] provides for computation offloading a cache on the remote side storing input execution states for application parts, avoiding a repeated transmission of information required for an execution on a remote resource. In contrast to the related approaches proposed in the literature, the caching-aware distribution presented in Chapter 7 utilizes for computation offloading a cache on the remote side. The cache stores output execution states to (further) speed up the time and energy required for a remote execution of an application part that is offloadable.

9.5. Code Offloading in Environments with Multiple Tiers

The approaches related to the basic distribution of application parts described in Section 9.1 show the benefits related to the basic distribution of application parts between a mobile device (first tier) and a remote resource (second tier). Although these approaches increase the energy efficiency on a mobile device and the execution speed for an application in environments with two tiers, they largely neglect a distribution of application parts in environments with multiple tiers, typically found in today’s landscape of MCC. Compared to an environment with two tiers, highly distributed heterogeneous resources from multiple tiers surround a mobile device, differing in performance characteristics and cost implications.

Scavenger from Kristensen [Kri10] distributes application parts in mobile, heterogeneous environments. Scavenger enables a resource-constrained mobile device to execute tasks – more precisely RPCs – from Python applications on underutilized, unknown devices in the vicinity called surrogates like a desktop computer. Scavenger selects the best available surrogate for a task with the help of its “strength”, determined from a CPU benchmark. To retrieve the execution time for a task on a surrogate, it utilizes a history-based profiling of tasks and of (task, surrogate)-pairs, where an application developer defines the task complexity.

Cheng et al. [CLWG15] propose a three-layer architecture for a distribution of application parts. A wearable device (first layer) distributes application parts to mobile devices like smart phones (middle layer) or to the remote cloud (third layer). To this end, they formulate an optimization problem that maximizes the number of distributed parts subjected to a given delay of the execution time. Cheng et al. provide a proof that the formulated optimization problem is NP-hard and approximate the optimal

solution based on a genetic algorithm.

Satyanarayanan et al. [SBCD09] propose with cloudlet a nearby cloud of underutilized devices for the distribution of application parts. A cloudlet comprises computing infrastructure co-located with a Wi-Fi AP, where an agent manages the nodes within its cloudlet. The utilization of a cloudlet avoids the high latency and low bandwidth of a cellular network to a distant elastic cloud. A mobile device distributes application parts on the basis of virtual machine synthesis [SBCD09] or at component level [VSTD12]. Besides the nearby, ad hoc cloudlet, the approach also considers computation power from a distant elastic cloud, for instance, as a fallback to provide more powerful servers or to avoid interruptions while on the move.

Summarizing, multiple approaches proposed in the literature provides computation offloading in environments with two tiers and seldom with three tiers. Scavenger from Kristensen [Kri10] enables computation offloading in unknown environments, relying on high developer interventions and keeping a partial global view onto the environment. Cheng et al. [CLWG15] enable computation offloading in a known environment with three tiers based on a centralized algorithm. Satyanarayanan et al. [SBCD09] propose with cloudlet an approach that distributes application parts to nearby clouds – and as a fallback to distant clouds – by calculating "a global optimum for all the devices in the cloudlet" [VSTD12]. In contrast to the related approaches proposed in the literature, the bubbling distribution presented in Chapter 8 enables computation offloading in unknown environments with multiple tiers. It utilizes a recursive distribution of application parts to autonomous tiers, not requiring a global view.

9.6. Summary

In the literature, multiple approaches propose techniques for computation offloading related to the contributions in this dissertation. In detail, the work related to an *efficient code offloading with annotations* described in Section 9.1 also proposes computation offloading between a mobile device and a remote resource. However, the related work does not provide an efficient distribution that minimizes the execution time, energy consumption, and monetary cost for application parts that are offloadable with least interventions from application developers and end users based on an annotation-based instrumentation of Java bytecode instructions (cf. Chapter 4). The work related to a *robust code offloading through safe-point'ing* described in Section 9.2 also proposes for computation offloading approaches to handle (network or node) failures during a remote execution of application parts on a remote resource. However, the related work does not provide a robust distribution with safe-point'ing that locally

re-uses intermediate states from the remote side to continue a remote execution on a mobile device, not abandoning partial results achieved on a remote resource so far (cf. Chapter 5). The work related to a *deadline-aware code offloading with predictive safe-point'ing* described in Section 9.3 also proposes scheduling strategies for a local re-use of intermediate states from the remote side (safe-points). However, the related work does not provide an adaptive approach based on prediction models for the scheduling strategy to dynamically adapt the point in times for a creation and transmission of safe-points due to dynamic conditions of the communication network (cf. Chapter 6). The work related to an *optimized code offloading through cooperative caching* described in Section 9.4 also proposes for computation offloading an integration of a cache to speed up the time required, for instance, for a transmission of an input execution state. However, the related work does not provide a cooperative cache on the remote side storing output execution states from mobile devices and remote resources to speed up the total time and energy required for an execution of an application part distributed to a remote resource (cf. Chapter 7). The work related to a *code offloading in environments with multiple tiers* described in Section 9.5 also proposes computation offloading in environments with two tiers like a mobile device and a remote resource and seldom in environments with three tiers like a mobile device, a fog resource, and a cloud resource. However, the related work does not provide computation offloading in unknown environments with multiple tires, not requiring a global view (cf. Chapter 8).

Chapter 10

Conclusion

By offloading computation from a (resource-constrained) mobile device to a (powerful) remote resource, a mobile device benefits significantly through a higher energy efficiency and a faster execution speed. In the area of code offloading, this dissertation covers different topics like a basic distribution for an efficient offloading of computation, a preemptable distribution for an efficient failure handling, or a bubbling distribution for and efficient computation offloading in future environments with multiple tiers. This chapter concludes this dissertation, first presenting a summary described in Section 10.1 on the topics covered in this dissertation together with concluding remarks on key results. Afterwards, it gives an outlook described in Section 10.2 on research questions remained open, guiding future work in the domain of code offloading.

10.1. Summary

Mobile devices like smart phones, tablets, or laptops have become an integral part in daily life, where an end user, for instance, works on a project, plays a mobile game, or surfs the web on its way. To this end, an end user executes on its battery-operated mobile device different applications like an office suite, a high-end video game, or a web browser, to accomplish a desired task. Due to the mobility provided to end users by a battery-operated mobile device, however, a mobile device faces fast its main limiting factor, the energy consumption. A heavy utilization of a mobile device via, for instance, an execution of a resource-intensive application like a high-end video game drains its limited battery in few hours. Beside the limited battery capacity of a mobile device, the issue of mobility also influences further hardware resources like its processing unit, making a mobile device a resource-constrained computing environment – especially compared with the virtual unlimited performance of cloud platforms.

To handle the resource limitation of mobile devices, code offloading augments a (resource-constrained) mobile computing environment like a smart phone via a wireless network like Wi-Fi with a (powerful) remote resource like a server instance at a (commercial) data center of a cloud provider. Thus, code offloading combines mobile

computing with cloud computing to mobile cloud computing, bringing the cloud closer to end users together with its advantages like virtual unlimited resources (e.g., storage, processing, ...), flexibility (e.g., on-demand up or down scale), or cost efficiency (e.g., pay-as-you-go manner). The augmentation involves the offloading of resource-intensive computations from a mobile computing environment to a remote resource, where the remote execution increases the energy efficiency of a mobile computing environment and the execution speed of an application. Due to the utilization of remote resources like a server instance at the cloud, an end user has to pay a monetary cost. Please note that in today's landscape of mobile cloud computing, highly distributed heterogeneous resources like smart wearables, laptops, desktops, smart cars, or resources at the fog and the cloud surround a mobile device like a smart phone, differing in performance characteristics and cost implications.

To offload computation from a mobile computing environment (client) to a remote resource (service), a distribution process on the client comprises the eight steps of identifying, gathering, determining, sending, waiting, receiving, installing, and continuing. First, a client has to identify application parts that are offloadable, where a remote execution on a service is more beneficial than a local execution on the client. An application part that is offloadable only utilizes a processing unit – without accessing further resources like a local sensor. After identifying an application part for a remote execution, a client gathers the input information required for a remote execution like method parameters or global variables. Moreover, it also has to gather further parameters about the current situation like network quality or performance of a service, to determine the execution side of an application part. To this end, the client regards the cost for a local execution and the cost for a remote execution. For an application part, the cost for a local execution includes the execution time and energy consumption for a local execution, where the cost for a remote execution includes the execution time, energy consumption, and monetary cost for a remote execution. In case of a local execution, a client just continues the execution of an application locally, whereas it sends the input information required for a remote execution to a remote service in case of a remote execution. During a remote execution of an application part, a client waits in idle mode for the end to receive the output information of the execution on the remote service. After receiving an output information resulted from a remote execution, a client installs the output information locally and continues the execution of an application just like in case of a local execution of the application part.

Regarding the distribution process described above, an offloading framework – that enables a client to offload computation to a remote resource – has to keep the overhead introduced by the steps for a computation offloading on a client and on a service

low, providing a high energy efficiency and a fast execution speed. Moreover, it also has to keep the interventions required by an application developer or an end user low, providing an ease of use computation offloading. To this end, this dissertation presented the basic distribution for an efficient code offloading with least interventions, where a (resource-poor) mobile computing environment offloads code to a (powerful) remote resource. It utilizes an annotation-based instrumentation of Java bytecode instructions to efficiently identify feasible parts from an application for a remote execution. As a result, an application developer only annotates feasible parts at development-time, where this little application-specific knowledge is enough that the offloading framework does the rest of the distribution process at run-time on its own. The same applies to an end user which only specifies weights for the execution time, energy consumption, and monetary cost. The evaluation results of different prototypes implemented on the Jikes Research Virtual Machine, the OpenJDK, and the Android Open-Source Project show the efficiency and performance of the basic distribution, outperforming significantly a local execution on a mobile computing environment.

Regarding the distribution process described above, an offloading framework has to handle the occurrence of failures like node or network failures. For instance, a long-lasting disconnection between a client and a remote service near the end of a remote execution prevents a receive of the output information on the client. Due to the occurrence of failures, a client starts mechanisms for error handling like a local re-execution. To this end, this dissertation presented the preemptable distribution for a robust code offloading through safe-point'ing to increase the energy efficiency and responsiveness also under (node or/and network) failures. The preemptable distribution allows an interruption of computation offloading after a failure without losing the intermediate result calculated remotely so far until the occurrence of a failure. This avoids a complete re-execution of an application part locally or an (undefined long) waiting for a re-connection to a remote service. The interruption of computation offloading relies on safe-points that contain all information required to continue a remote execution locally. Thus, a remote service creates and transmits such safe-points to a client during a remote execution whenever it is beneficial in terms of energy. Although the creation and transmission of safe-points introduce some overhead, the evaluation results show that this overhead is small and quickly pays off in scenarios with link failures. As a result, the preemptable distribution leads to lower execution time and energy consumption.

Regarding the preemptable distribution described above, an offloading framework has to determine optimal points in time for the creation and transmission of safe-points. For instance, fewer safe-points are sufficient for a communication network with less frequent failures reducing the communication overhead, whereas a communica-

tion network with more frequent failures require more safe-points to be prepared for impending network failures. To this end, this dissertation presented the predictive distribution for a deadline-aware code offloading with predictive safe-point'ing. It optimizes the schedule for the creation and transmission of safe-points to minimize the introduced overhead and guarantee a maximum time of an execution for a minimal responsiveness. The predictive distribution utilizes an adaptive algorithm for scheduling safe-points that adapts dynamically the point in time of creating and transmitting safe-points due to dynamic conditions of the communication network. To determine the optimal points in time for safe-point'ing, it predicts the quality of the network link and solves a given constrained optimization problem (minimum overhead for safe-point'ing under a constraint for the execution deadline). The evaluation results show that the predictive distribution increases the energy efficiency and execution speed compared to the basic distribution and the preemptable distribution by additionally guaranteeing a maximum time for an execution under failures (improved responsiveness).

Regarding the distribution process described above, an offloading framework has to speed up a remote execution (e.g., the three steps of sending, waiting, and receiving) from an application part, to keep the energy efficiency and execution speed high. In computer science, many distributed systems utilize a cache for data and function to speed up future requests by storing information of current requests in a cache. To this end, this dissertation presented the caching-aware distribution for an optimized code offloading through cooperative caching. A cache on the remote side stores output information from local executions on mobile computing environments or remote executions on services. In case of a distribution of an application part that is offloadable, a mobile computing environment queries a cache on the remote side, avoiding, on the one hand, a repeated execution of application parts already executed previously, and reducing, on the other hand, the time required for a remote execution in case of a cache hit. As a result, a mobile computing environment benefits not only from shorter execution times for application parts but also from lower monetary cost, not utilizing a remote service for an execution in case of a cache hit. The evaluation results show that the caching-aware distribution increases the energy efficiency and execution speed as well as decreases the monetary cost compared to the basic distribution, keeping the overhead introduced for caching low.

Regarding the distribution process described above, an offloading framework nowadays has to offload computation not only between a mobile computing environment (first tier) and a remote service (second tier) but also between a mobile computing environment (first tier) and multiple highly distributed heterogeneous resources (multiple tiers) with different performance characteristics and cost implications. For instance,

a mobile computing environment can offload application parts among heterogeneous compute resources on many tiers (e.g., smart wearables ↔ laptops ↔ desktops ↔ edge servers ↔ cloud servers, etc.), making a decision for code offloading more complex. To this end, this dissertation presented the bubbling distribution for a code offloading in environments with multiple tiers. The concept of code bubbling enables each tier to make autonomous decisions for code offloading without the need to gather a global view onto all resources of all tiers. Using the concept of code bubbling, code offloading potentially scales to an arbitrary number of tiers since decisions for code offloading only involve neighboring tiers. The evaluation results show that the bubbling distribution enables an efficient code offloading for environments with multiple tiers in today's landscape of mobile cloud computing, keeping the introduced overhead low as well as the energy efficiency and execution speed high.

10.2. Outlook

Apart from a direct improvement to the basic distribution, the preemptable distribution, the predictive distribution, the caching-aware distribution, or the bubbling distribution presented in this dissertation, additional information, optimization, and functionality improves each distribution as follows.

For the basic distribution, an application developer annotates feasible parts from an application as "offloadable" for an execution on a remote service, relying on a little application-specific knowledge from an application developer. An application part that is offloadable only requires a processing unit, not accessing further resources like a local sensor. Moreover, a suitable candidate for a remote execution is offloadable and has a long running computation with a small size of input information required for a remote execution and of output information received on a client. Thus, an improvement to the basic distribution can be an approach that automatically identifies and proposes suitable application parts at development-time based on criteria for a suitable candidate. This supports an application developer in its decision to annotate suitable application parts with "offloadable".

For the preemptable distribution and the predictive distribution, a remote service at the cloud creates and transmits safe-points during an execution of an application part, enabling an interruption of a remote execution and a local continuation on a client based on the safe-point received most recently. Despite the low overhead introduced on a client and a remote service, the main overhead for a client constitutes the communication cost of receiving safe-points while waiting in idle mode during a remote execution. Thus, an improvement to the preemptable distribution and the predictive

distribution can be a buffer of safe-points at, for instance, the last communication hop (access point) to a client. Only in case of the occurrence of a failure the buffer sends the safe-points to the client increasing the energy efficiency on the client.

For the caching-aware distribution, a cache on the remote side stores output information from application parts previously executed on clients or remote services. Thus, a client queries the cache for corresponding output information for application parts that are offloadable. The significant increase of the energy efficiency and execution speed on a client depends mainly on the hit ratio at the cache on the remote side. Thus, an improvement to the caching-aware distribution can be a hierarchical composition of multiple caches at a client, an access point, the fog, and the cloud, where an important entry of a cache flows up the hierarchy improving the overall hit ratio of caching and thus, further increasing the energy efficiency and execution speed.

For the bubbling distribution, a client gathers the input information required for a remote execution creating an offload request. Thus, it has to interrupt the local execution of a corresponding application part. Due to the interruption of a local execution to gather and create an offload request, the execution time (and energy consumption) is worse compared to a pure local execution. Thus, an improvement to the bubbling distribution can be an optimization to the local creation of an offload request that first only copies the input information from an application part, continues the local execution, and then starts the steps required for code bubbling.

For all distributions, a remote service, for instance, at an underutilized desktop, a server instance at the fog or the cloud executes an application part from a client. Thus, an end user has to trust a corresponding (personal, fog, or cloud) provider of a remote service. The remote processing of information like an execution of application parts or a caching of output information raises the question of privacy and security implications to an end user. For instance, an execution of an application part requires personal information or a caching of output information from a specific client reveals its execution flow. Thus, an improvement to all distributions can be the consideration of privacy and security implications on the remote side that prevents an end user from misuse of, for instance, its personal information.

Appendix

A. Java Bytecode Instructions

Table A.1, Table A.2, and Table A.3 outline the Java bytecode instructions:

Constants:			**Loads:**			**Stores:**		
00	(0x00)	nop	21	(0x15)	iload	54	(0x36)	istore
01	(0x01)	aconst_null	22	(0x16)	lload	55	(0x37)	lstore
02	(0x02)	iconst_m1	23	(0x17)	fload	56	(0x38)	fstore
03	(0x03)	iconst_0	24	(0x18)	dload	57	(0x39)	dstore
04	(0x04)	iconst_1	25	(0x19)	aload	58	(0x3a)	astore
05	(0x05)	iconst_2	26	(0x1a)	iload_0	59	(0x3b)	istore_0
06	(0x06)	iconst_3	27	(0x1b)	iload_1	60	(0x3c)	istore_1
07	(0x07)	iconst_4	28	(0x1c)	iload_2	61	(0x3d)	istore_2
08	(0x08)	iconst_5	29	(0x1d)	iload_3	62	(0x3e)	istore_3
09	(0x09)	lconst_0	30	(0x1e)	lload_0	63	(0x3f)	lstore_0
10	(0x0a)	lconst_1	31	(0x1f)	lload_1	64	(0x40)	lstore_1
11	(0x0b)	fconst_0	32	(0x20)	lload_2	65	(0x41)	lstore_2
12	(0x0c)	fconst_1	33	(0x21)	lload_3	66	(0x42)	lstore_3
13	(0x0d)	fconst_2	34	(0x22)	fload_0	67	(0x43)	fstore_0
14	(0x0e)	dconst_0	35	(0x23)	fload_1	68	(0x44)	fstore_1
15	(0x0f)	dconst_1	36	(0x24)	fload_2	69	(0x45)	fstore_2
16	(0x10)	bipush	37	(0x25)	fload_3	70	(0x46)	fstore_3
17	(0x11)	sipush	38	(0x26)	dload_0	71	(0x47)	dstore_0
18	(0x12)	ldc	39	(0x27)	dload_1	72	(0x48)	dstore_1
19	(0x13)	ldc_w	40	(0x28)	dload_2	73	(0x49)	dstore_2
20	(0x14)	ldc2_w	41	(0x29)	dload_3	74	(0x4a)	dstore_3
			42	(0x2a)	aload_0	75	(0x4v)	astore_0
			43	(0x2b)	aload_1	76	(0x4c)	astore_1
			44	(0x2c)	aload_2	77	(0x4d)	astore_2
			45	(0x2d)	aload_3	78	(0x4e)	astore_3
			46	(0x2e)	iaload	79	(0x4f)	iastore
			47	(0x2f)	laload	80	(0x50)	lastore
			48	(0x30)	faload	81	(0x51)	fastore
			49	(0x31)	daload	82	(0x52)	dastore
			50	(0x32)	aaload	83	(0x53)	aastore
			51	(0x33)	baload	84	(0x54)	bastore
			52	(0x34)	caload	85	(0x55)	castore
			53	(0x35)	saload	86	(0x56)	sastore

Table A.1.: Part I of the Java bytecode instructions from 00 to 86. [LYBB15]

Stack:

87	(0x57)	pop
88	(0x58)	pop2
89	(0x59)	dup
90	(0x5a)	dup_x1
91	(0x5b)	dup_x2
92	(0x5c)	dup2
93	(0x5d)	dup2_x1
94	(0x5e)	dup2_x2
95	(0x5f)	swap

Math:

96	(0x60)	iadd
97	(0x61)	ladd
98	(0x62)	fadd
99	(0x63)	dadd
100	(0x64)	isub
101	(0x65)	lsub
102	(0x66)	fsub
103	(0x67)	dsub
104	(0x68)	imul
105	(0x69)	lmul
106	(0x6a)	fmul
107	(0x6b)	dmul
108	(0x6c)	idiv
109	(0x6d)	ldiv
110	(0x6e)	fdiv
111	(0x6f)	ddiv
112	(0x70)	irem
113	(0x71)	lrem
114	(0x72)	frem
115	(0x73)	drem
116	(0x74)	ineg
117	(0x75)	lneg
118	(0x76)	fneg
119	(0x77)	dneg
120	(0x78)	ishl
121	(0x79)	lshl
122	(0x7a)	ishr
123	(0x7b)	lshr
124	(0x7c)	iushr
125	(0x7d)	lushr
126	(0x7e)	iand
127	(0x7f)	land
128	(0x80)	ior
129	(0x81)	lor
130	(0x82)	ixor
131	(0x83)	lxor
132	(0x84)	iinc

Conversions:

133	(0x85)	i2l
134	(0x86)	i2f
135	(0x87)	i2d
136	(0x88)	l2i
137	(0x89)	l2f
138	(0x8a)	l2d
139	(0x8b)	f2i
140	(0x8c)	f2l
141	(0x8d)	f2d
142	(0x8e)	d2i
143	(0x8f)	d2l
144	(0x90)	d2f
145	(0x91)	i2b
146	(0x92)	i2c
147	(0x93)	i2s

Table A.2.: Part II of the Java bytecode instructions from 87 to 147. [LYBB15]

Comparisons:

148	(0x94)	lcmp
149	(0x95)	fcmpl
150	(0x96)	fcmpg
151	(0x97)	dcmpl
152	(0x98)	dcmpg
153	(0x99)	ifeq
154	(0x9a)	ifne
155	(0x9b)	iflt
156	(0x9c)	ifge
157	(0x9d)	ifgt
158	(0x9e)	ifle
159	(0x9f)	if_icmpeq
160	(0xa0)	if_icmpne
161	(0xa1)	if_icmplt
162	(0xa2)	if_icmpge
163	(0xa3)	if_icmpgt
164	(0xa4)	if_icmple
165	(0xa5)	if_acmpeq
166	(0xa6)	if_acmpne

Control:

167	(0xa7)	goto
168	(0xa8)	jsr
169	(0xa9)	ret
170	(0xaa)	tableswitch
171	(0xab)	lookupswitch
172	(0xac)	ireturn
173	(0xad)	lreturn
174	(0xae)	freturn
175	(0xaf)	dreturn
176	(0xb0)	areturn
177	(0xb1)	return

References:

178	(0xb2)	getstatic
179	(0xb3)	putstatic
180	(0xb4)	getfield
181	(0xb5)	putfield
182	(0xb6)	invokevirtual
183	(0xb7)	invokespecial
184	(0xb8)	invokestatic
185	(0xb9)	invokeinterface
186	(0xba)	invokedynamic
187	(0xbb)	new
188	(0xbc)	newarray
189	(0xbd)	anewarray
190	(0xbe)	arraylength
191	(0xbf)	athrow
192	(0xc0)	checkcast
193	(0xc1)	instanceof
194	(0xc2)	monitorenter
195	(0xc3)	monitorexit

Extended:

196	(0xc4)	wide
197	(0xc5)	multianewarray
198	(0xc6)	ifnull
199	(0xc7)	ifnonnull
200	(0xc8)	goto_w
201	(0xc9)	jsr_w

Reserved:

202	(0xca)	breakpoint
254	(0xfe)	impdep1
255	(0xff)	impdep2

Table A.3.: Part III of the Java bytecode instructions from 148 to 255. [LYBB15]

B. Mobile Applications

An end user executes nowadays different mobile applications on its mobile device like high-end video games. To this end, this chapter highlights capabilities of the mobile applications utilized in this dissertation for code offloading. Due to significant differences with regard to computational complexity and communication overhead of the mobile applications (cf. Table B.1), each mobile application benefits differently from code offloading. In detail, this dissertation utilizes a Chesspresso application (cf. Section B.2), a chess game (cf. Section B.3), a face recognition application (cf. Section B.4), and a text-to-voice application (cf. Section B.5).

B.1. "Hello, World!" Application

The Java programming language is object-oriented, where every data is an object except the Java primitive types `boolean`, `char`, `short`, `integer`, `float`, and `double` owing to performance issues. An application developer writes the application code inside classes, where the public class contained in a source file plus the suffix `.java` define its file name. The following listing, Listing B.1 "HelloWorld.java", shows the popular "Hello, World!" application written in the Java programming language:

```
1 class HelloWorld {
2
3     public static void main(String[] args) {
4         // Prints the String "Hello, World!" to the console
5         System.out.println("Hello, World!");
6     }
7
8 }
```

Listing B.1: The Java source code for the "Hello, World!" application.

B.2. Chesspresso Application

The Chesspresso application is a chess program that searches iteratively for the best move of the black player after the white player moved its pawn two steps ahead (cf. Figure B.1). It utilizes the Java library Chesspresso from Bernhard Seybold [Sey03] that is

	Size of Input Execution State	Code Complexity	Size of Output Execution State
Chesspresso Application	6050 bytes ⇒ constant small size	High computational complexity	3023 bytes ⇒ constant small size
Chess Game	$80 + (n \cdot 80) + 1$ integers ⇒ small size	With a chess difficulty of 3 very high, with 2 moderate, and with 1 low	5 integers ⇒ very small, constant size
Face Recognition Application	Width times height times color space ⇒ huge size (in the magnitude of megabytes)	High computational complexity	$4 \cdot n$ integers, where n is the number of detected faces
Text-to-Voice Application	Written sentence and voice name ⇒ moderate size (in the magnitude of kilobytes)	High computational complexity	Audio file ⇒ moderate size (in the magnitude of hundred kilobytes)

Table B.1.: Comparison of the main facts from the Java applications evaluated for code offloading on the prototypes.

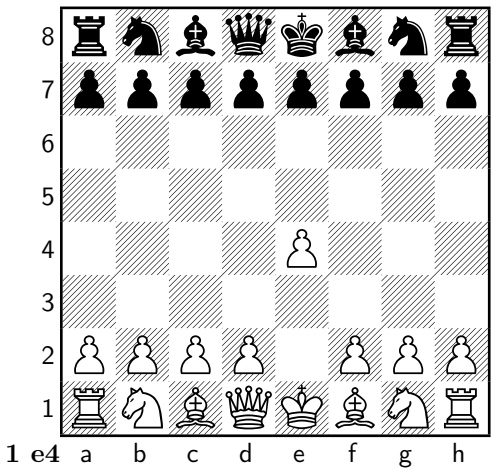


Figure B.1.: The opening move for the Chesspresso application.

open-source and provides the necessary functionality like data structures and rules to implement a chess game. After an initialization part, the Chesspresso application calls the Java method `iterativeChessCalls(...)` of the Java class `ChessDetectPosition` that is offloadable. It has the input parameters of the current chess board (cf. Figure B.1) and an array of empty Strings (cf. Listing B.2). As output, the Java method has an Integer value indicating the number of calls for the Java method `check(...)` (cf. Listing B.2). Regarding the size of the input parameters, the Java class Position has a size of 2951 bytes and the array of Strings a size of 72 bytes, summing up to 3023 bytes (cf. Listing B.2). As both input parameters are Java objects, the output includes both input parameters – now with a size of 5902 bytes and 144 bytes – as well as the 4 bytes for the return of an integer value, summing up to 6050 bytes. Summarizing, the search algorithm from the Chesspresso application is an optimal candidate for a computation offloading. It possesses a constant, small size of input and a constant, small size of output with a high computational complexity. The following listing shows the relevant code for the Chesspresso application:

```
/*
 * Copyright (c) 2014 Florian Berg
   <Florian.Berg@ipvs.uni-stuttgart.de>
 * All rights reserved.
 *
 * ...
 */

package chesspresso;

import chesspresso.Chess;
import chesspresso.move.IllegalMoveException;
import chesspresso.move.Move;
import chesspresso.position.Position;

public class ChessDetectPosition {

   public int iterativeChessCalls(Position position, String[] game) {
      short[] nm1 = position.getAllMoves();
      short[] nm2; short[] nm3; short[] nm4;

      // record
      int ply = position.getPlyNumber();
      Move lastMove = position.getLastMove();
      game[ply - 1] = lastMove.getSAN();

      MainChess.TEST = game.length;

      boolean found = false;
      int counter   = 0;
      try {
         for (int i1=0; i1<nm1.length; i1++) {
            System.out.println("i1: " + i1);

            position.doMove(nm1[i1]);
            nm2 = position.getAllMoves();
```

```
36
                // record
38              ply = position.getPlyNumber();
                lastMove = position.getLastMove();
40              game[ply - 1] = lastMove.getSAN();

42              // check and count
                found = check(position, lastMove, ply, game);
44              counter++;

46              // one down
                for (int i2=0; i2<nm2.length; i2++) {
48                 System.out.println(" - i2: " + i2);

50                 position.doMove(nm2[i2]);
                   nm3 = position.getAllMoves();
52
                   // record
54                 ply = position.getPlyNumber();
                   lastMove = position.getLastMove();
56                 game[ply - 1] = lastMove.getSAN();

58                 // one down
                   for (int i3=0; i3<nm3.length; i3++) {
60                    System.out.println("i3: " + i3);

62                    position.doMove(nm3[i3]);
                      nm4 = position.getAllMoves();
64
                      // record
66                    ply = position.getPlyNumber();
                      lastMove = position.getLastMove();
68                    game[ply - 1] = lastMove.getSAN();

70                    // one down
                      for (int i4=0; i4<nm4.length; i4 += 2) {
72                       System.out.println("i4: " + i4);

74                       position.doMove(nm4[i4]);
                         nm5 = position.getAllMoves();
76
                         // record
78                       ply = position.getPlyNumber();
                         lastMove = position.getLastMove();
80                       game[ply - 1] = lastMove.getSAN();

82                       // check and count
                         found = check(position, lastMove, ply, game);
84                       counter++;

86                       position.undoMove();
                      }
88
                      position.undoMove();
90                 }

92                 position.undoMove();
                }
94
                boolean debug = position.undoMove();
96              if (debug) counter++;
```

```
            }
98          } catch (IllegalMoveException e) {
               e.printStackTrace();
100         }

102         if (!found) return counter;

104         return -1;
        }
106
        private boolean check(Position position, Move lastMove, int ply,
        String[] game) {
108         return (position.isMate() &&
                    lastMove.isCapturing() &&
110                 lastMove.getMovingPiece() == Chess.KNIGHT &&
                    position.getPiece(lastMove.getToSqi()) == Chess.ROOK);
112     }

114 ...

116 }
```

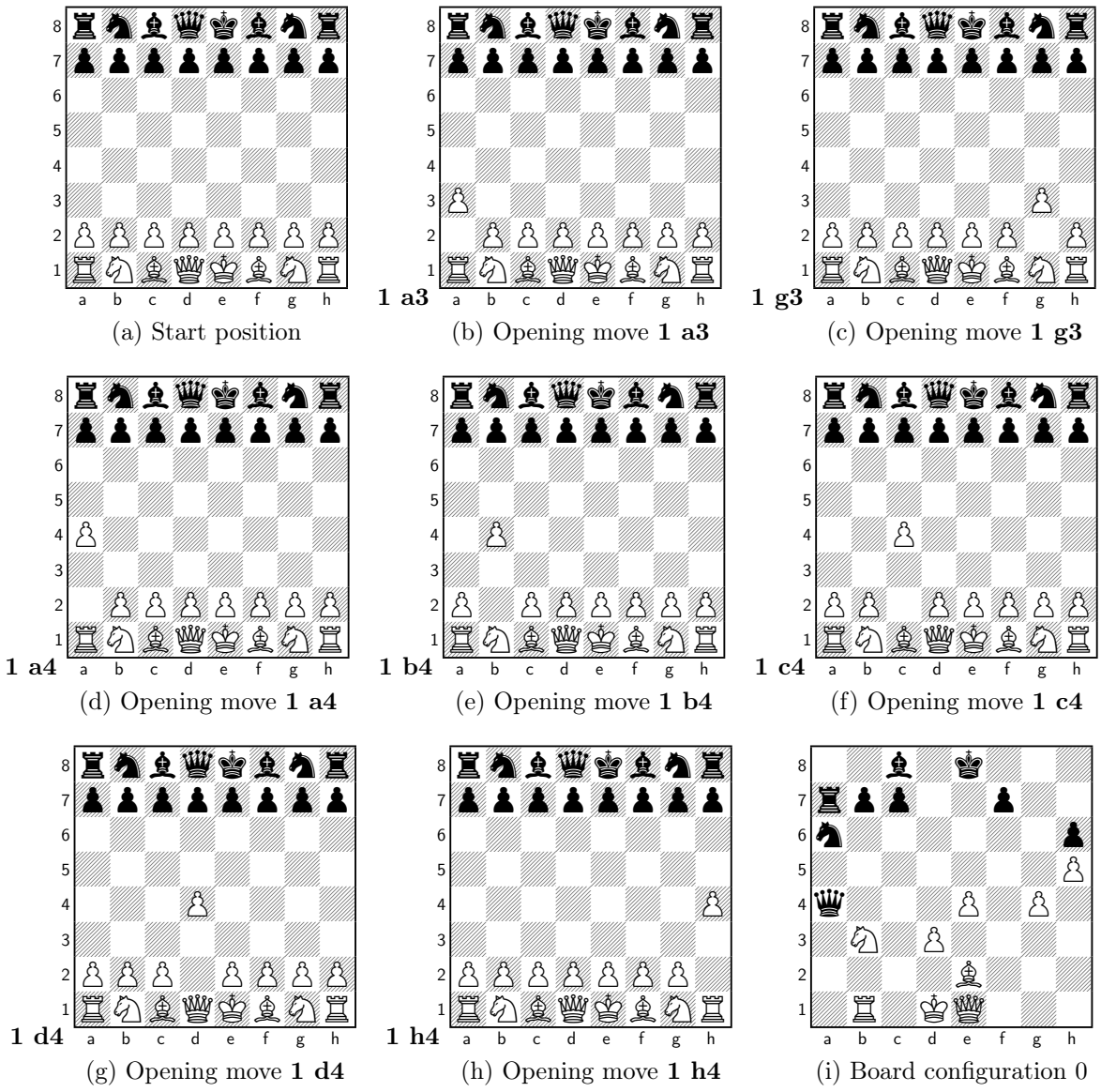
Listing B.2: The Java Source Code of the Chesspresso Application [Sey03]

B.3. Chess Game

The chess game enables an end user to play a chess game against a computer opponent, where the source code of the chess game is from Ulf Ochsenfahrt [Och08].

The Graphical User Input (GUI) of the chess game displays the current configuration of the chess board, takes the next move of the user, and displays the determined move of the computer opponent. To determine the next best chess move of the computer opponent, the search algorithm uses an Alpha-beta pruning. The input parameters are the current configuration of the chess board, the chess history of past moves, and the search depth (cf. Listing B.3). Notice that the search depth defines the chess difficulty of the computer opponent, influencing significantly the code complexity of the search algorithm. As output, the search algorithm returns the next best chess move of the computer opponent based on the given input parameters (cf. Listing B.3). Regarding the size of the input parameters, the chess board results in $8 \cdot 8 + 16 = 80$ integers, the chess history of n past moves in $80 \cdot n$ integers, and the chess difficulty in 1 integer. Regarding the size of the output, the chess return sums up to 5 integers.

For the evaluations in this dissertation, a mobile device plays multiple rounds with different opening moves, namely **1 a3**, **1 g3**, **1 a4**, **1 b4**, **1 c4**, **1 d4**, and **1 h4**. Figure B.2 shows in the first row the chess board at the start of a new chess game (cf. Figure B.2a) and the opening moves that move a pawn one-step further (cf. Figure B.2b and B.2c). Moreover, Figure B.2 shows in the second and the third row the opening



(a) Start position (b) Opening move **1 a3** (c) Opening move **1 g3**

(d) Opening move **1 a4** (e) Opening move **1 b4** (f) Opening move **1 c4**

(g) Opening move **1 d4** (h) Opening move **1 h4** (i) Board configuration 0

Figure B.2.: The different configurations of the chess board evaluated for a chess game.

moves that move a pawn two-steps further (cf. Figure B.2d - B.2h).

Summarizing, the search algorithm from the chess game is an optimal candidate for a computation offloading. It possesses a small size of input and a very small, constant size of output with a high computational complexity that depends on the chess difficulty chosen and the current configuration of the chess board.

The following listing shows the relevant code for the chess game:

```
/*
 * Copyright (c) 2005-2008 Ulf Ochsenfahrt <ulf@ofahrt.de>
 * All rights reserved.
 *
 * ...
 */

import ...

public final class aichess4k extends JComponent implements Runnable {
// board:
// 0-7  board
// 8    0-3 lastmove source x,y & dest x,y
//      4 activeplayer 5 leftrookmoved 6 kingmoved 7 rightrookmoved
// 9    0 movenum 1 movessincetake 2 check
// ply:
// 0-1 source position x,y
// 2-3 dest position x,y
// 4   target figure (only used for transformation moves)

// current board
private int[][] myboard;

// move including transformation target if pawn ends up on final row
private int[] myply;

// all previous board configurations
private int[][][] undo;

// ai result
private int[] resply;

// ai difficulty (modifies search depth)
private int difficulty;

private void init() { ... }

private boolean isCastleing(final int[][] board, final int sx, final
    int sy, final int dx, final int dy) { ... }

private boolean isEnPassant(int[][] board, int sx, int sy, int dx,
    int dy) { ... }

private boolean isNormal(int[][] board, int sx, int sy, int dx, int
    dy) { ... }

void copy(int[][] from, int[][] to) { ... }

boolean move(int[][] board, int[] ply) { ... }

int search(int[][] board, final int steps, final int maxsteps, int
```

```
    alpha, int beta) {
    // Check for a draw
50  ...

52  // Evaluate board if search depth is reached
    ...
54
    // Start alpha-beta-search
56  for (int x = 0; x < 8; x++)
       for (int y = 0; y < 8; y++) {
58        int figure = board[x][y];
          int type = figure & FIGURE;
60        if ((figure & COLOR) == side) {
             for (int dx = 0; dx < 8; dx++) {
62              for (int dy = 0; dy < 8; dy++) {
                   if (((board[dx][dy] & COLOR) != side) &&
64                 (isEnPassant(board, x, y, dx, dy) ||
                    isCastleing(board, x, y, dx, dy) ||
66                  isNormal(board, x, y, dx, dy))) {
                      int newsteps = steps;
68                    if ((board[dx][dy] != EMPTY) && (steps <
    maxsteps)) newsteps++;

70                 int min = QUEEN;
                   if ((type == PAWN) && ((dy == 0) || (dy == 7)))
    min = BISHOP;
72                 for (int k = min; k <= QUEEN; k++) {
                      int[] p = new int[] {x, y, dx, dy, k};
74                    copy(board, save);
                      if (move(save, p)) {
76                       int val = -search(save, newsteps-1,
    maxsteps-1, -beta, -alpha);
                         if (val >= beta) return beta;
78                       if (val > alpha) {
                            alpha = val;
80                          bestply = p;
                         }
82                    }
                   }
84              }
             }
86        }
       }
88  }

90  // Return resply
    ...
92}

94...

96}
```

Listing B.3: The Java Source Code of the Chess Game [Och08]

B.4. Face Recognition Application

The face recognition application enables an end user to recognize faces on an image, where the source code of the face recognition is from Jon's Java Imaging Library (JJIL) [Web08], containing various tasks for image processing.

The GUI loads or takes an image, displays it, and highlights, if any, faces recognized by rectangles. The algorithm for face detection applies a Haar cascade to the image based on multiple scales. The input parameters are the image together with a minimum (finest) scale and a maximum (coarsest) scale (cf. Listing B.4). As output, the algorithm for face detection returns an array of enclosing rectangles, locating the faces detected in an image (cf. Listing B.4). Regarding the size of the input parameters, the number of bytes of an image depends on its pixel resolution, whereas the minimum scale and the maximum scale are an integer each. Regarding the size of the output, the number of rectangles depends on the number of detected faces, where each rectangle has 4 integers, namely x, y, w (width), and h (height).

For the evaluations in this dissertation, a mobile device recognizes faces either in a color image with a width of 1258 pixel and a height of 1024 pixel or in a color image with a width of 960 pixel and a height of 1280 pixel.

Summarizing, the algorithm for face detection from the face recognition application is only a good candidate for a computation offloading in case of a good quality of the network up-link. It possesses a huge size of input and a small size of output with a high computational complexity.

The following listing shows the relevant code for the face recognition application:

```
package jjil.algorithm;

/*
 * Gray8DetectHaarMultiScale.java
 *
 * Created on August 19, 2007, 7:33 PM
 *
 * Copyright 2007 by Jon A. Webb
 *
 * ...
 */

import ...

public class Gray8DetectHaarMultiScale extends PipelineStage {
    private HaarClassifierCascade hcc;

   // maximum scale is the largest factor the image is divided by
   private int nMaxScale = 10;

   // minimum scale is the smallest factor the image is divided by
   private int nMinScale = 5;
```

```
24    // scale change is the change in scale from one search to the next
      times 256
      private int nScaleChange = 12 * 256 / 10;
26
      public Gray8DetectHaarMultiScale(InputStream is, int nMinScale,
      int nMaxScale) throws jjil.core.Error, IOException { ... }
28
      // Apply multi-scale Haar cascade and prepare a mask image showing
      where features were detected.
30    public void push(Image image) throws jjil.core.Error {
         // Check image
32       ...

34       int nScale = Math.min(this.nMaxScale, Math.min(image.getWidth()
      / this.hcc.getWidth(), image.getHeight() / this.hcc.getHeight()));
         Gray8Image imMask = new Gray8Image(1,1,Byte.MIN_VALUE);
36       while (nScale >= this.nMinScale) {
            // shrink the input image
38          int nTargetWidth = imGray.getWidth() / nScale;
            int nTargetHeight = imGray.getHeight() / nScale;
40          Gray8Shrink gs = new Gray8Shrink(nTargetWidth,
      nTargetHeight);
            gs.push(imGray);
42          Gray8Image imShrunk = (Gray8Image) gs.getFront();
            // scale the mask to the new size
44          Gray8RectStretch grs = new Gray8RectStretch(nTargetWidth,
      nTargetHeight);
            grs.push(imMask);
46          imMask = (Gray8Image) grs.getFront();
            // combine the image and mask to make a masked image
48          Gray8MaskedImage gmi = new Gray8MaskedImage(imShrunk,
      imMask);
            // pass the masked image to a subimage generator
50          MaskedGray8SubImgGen mgsi = new MaskedGray8SubImgGen( ... );
            mgsi.push(gmi);
52          // now run Haar detection on each scaled image
            int nxLastFound = -hcc.getWidth();
54          int nyLastFound = -hcc.getHeight();
            while (!mgsi.isEmpty()) {
56             Gray8OffsetImage imSub = (Gray8OffsetImage)
      mgsi.getFront();
               // if we've found a feature recently we skip forward
      until we're outside the masked region. There's no point rerunning
      the detector
58             if (imSub.getXOffset() > nxLastFound + hcc.getWidth() &&
                  imSub.getYOffset() > nyLastFound + hcc.getHeight()) {
60                if (hcc.eval(imSub)) {
                     // Found something.
62                   nxLastFound = imSub.getXOffset();
                     nyLastFound = imSub.getYOffset();
64                   // assign Byte.MAX_VALUE to the feature area so we
      don't search it again
                     Gray8Rect gr = new Gray8Rect( ... );
66                   gr.push(imMask);
                     imMask = (Gray8Image) gr.getFront();
68                      }
                  }
70          }
            nScale = nScale * 256 / this.nScaleChange;
72       }
         // Stretch imMask to original image size; this is the result
```

```
74          Gray8RectStretch grs = new Gray8RectStretch(image.getWidth(),
        image.getHeight());
            grs.push(imMask);
76          super.setOutput(grs.getFront());
         }
78
        ...
80  }

82  ...

84  }
```

Listing B.4: The Java Source Code of the Face Recognition Application [Web08]

B.5. Text-to-Voice Application

The text-to-voice application enables an end user to synthesize a written sentence to spoken speech, where the source code of the text-to-voice application is from FreeTTS [Lab09]. It is an open-source implementation of a speech synthesis engine, totally written in the Java programming language.

The GUI has a field to enter a sentence and a button to start the speech synthesis. The input parameters of the algorithm for text-to-speech are the written sentence and the name of the utilized voice, both as a String (cf. Listing B.5). As output, the algorithm for text-to-speech returns an audio file of the sentence spoken by the voice (cf. Listing B.5). Regarding the size of the input parameters, the number of bytes of a written sentence as well as the name of the voice depends on the number of characters. Regarding the size of the output, the number of bytes of an audio file depends on both the length of a sentence and the chosen voice.

For the evaluations in this dissertation, a mobile device transforms words from different text passages to voice, where the text passages correspond to the abstracts from [KAH+12] (*ThinkAir*), [CBC+10] (*MAUI*), and an own sentence (*OWN*). In detail, the relevant words from *ThinkAir* are

"***Smartphones have exploded in popularity in recent years, becoming ever more sophisticated and capable. As a result, developers worldwide are building increasingly complex applications that require ever increasing amounts of computational power and energy. In ...***" [KAH+12]

from *MAUI*

"***This paper presents MAUI, a system that enables fine-grained energy-aware offload of mobile code to the infrastructure. Previous approaches to these problems either relied heavily on programmer support to partition an application, or ...***" [CBC+10].

and from *OWN*

"***This is a very long sentence where FreeTTS has to transform written text into spoken voice!***".

Summarizing, the algorithm for text-to-voice from the text-to-voice application is only a good candidate for a computation offloading in case of a good quality of the network down-link. It possesses a small size of input and a big size of output with a high computation complexity.

The following listing shows the relevant code for the text-to-voice application:

```
/**
 * Copyright 2003 Sun Microsystems, Inc.
 *
 * ...
 */

import ...

public class FreeTTSHelloWorld {

public static void main(String[] args) {
    ...
    // The VoiceManager manages all the voices for FreeTTS.
    VoiceManager voiceManager = VoiceManager.getInstance();
    Voice helloVoice = voiceManager.getVoice(voiceName);

    // Allocates the resources for the voice.
    helloVoice.allocate();

    // Synthesize speech.
    helloVoice.speak("Thank you for giving me a voice. "
       + "I'm so glad to say hello to this world.");

    // Clean up and leave.
    helloVoice.deallocate();
    System.exit(0);
}

...

}
```

Listing B.5: The Java Source Code from of the Text-to-Voice Application [Lab09]

C. System Devices

The landscape of today's Mobile Cloud Computing includes plenty of different resources like smart phones, tablets, laptops, workstations, or server instances at the fog or the cloud. To this end, this chapter highlights capabilities of the system devices utilized in this dissertation for code offloading. Due to differences in the performance characteristics of the system devices (cf. Table C.1), each system device benefits differently from code offloading. In detail, this dissertation utilizes as an offloading client a smart phone – namely a Samsung Galaxy Nexus (cf. Subsection C.1) – a netbook – namely a Dell Inspiron Mini 10v (cf. Subsection C.2) – and a laptop – namely a Lenovo ThinkPad T61 (cf. Subsection C.3). Moreover, this dissertation utilizes as an offloading service a workstation – namely an HP Compaq 8200 Elite (cf. Subsection C.4) – and a server instance at the AWS EC2 – namely a t2.micro instance (cf. Subsection C.5). As the system devices connect via further devices like a Wi-Fi AP to other system devices and the Internet, this dissertation utilizes as network devices a Huawei E1750 Surf Stick (cf. Subsection C.6), a Linksys WRT54GL Wireless Router (cf. Subsection C.7), and a LevelOne GSW-0809 Gigabit Ethernet Switch (cf. Subsection C.8).

C.1. Samsung Galaxy Nexus

The Samsung Galaxy Nexus (GT-i9250) is a smart phone from the Google Nexus series, running the Android OS as mobile operating system (cf. Subsection 4.6.3). Released in the year 2011, it possesses the OMAP[1] 4460 System-on-a-Chip (SoC) from Texas Instruments [Ins12]. The OMAP 4460 SoC has a dual-core CPU of ARM Cortex-A9, where each 32-bit core runs at 1.2 - 1.5 GHz. Beside the OMAP 4460 SoC, it has a memory of 1 GB and a storage of 16 GB. It communicates via Near Field Communication (NFC), Bluetooth 3.0 (cf. Subsection 2.2.3), Wi-Fi IEEE 802.11 a,b,g,n (cf. Subsection 2.2.1), or a 3.5 Generation cellular network (cf. Subsection 2.2.2). Last, a battery of 1750 mAh powers the Samsung Galaxy Nexus. [Sam11]

[1] Open Multimedia Application Platform (OMAP)

System Device	Central Processing Unit (CPU)	Communication Network	Software Stack
Samsung Galaxy Nexus	Dual-core CPU running at 1.2 GHz	Bluetooth 3.0 + IEEE 802.11 a,b,g, n + 3.5 Generation	Android OS, 32-bit
Dell Inspiron Mini 10v	Single-core CPU running at 1.6 GHz	Bluetooth 2.1 + IEEE 802.11 b,g + 3.5 Generation	Linux + OpenJDK, 32-bit
Lenovo ThinkPad T61	Dual-core CPU running at 2.4 GHz	IEEE 802.11 a,b,g,n + 3.5 Generation	Linux + OpenJDK, 64-bit
HP Compaq 8200 Elite	Quad-core CPU running at 3.4 GHz	up to 1 Gbit/s	Linux + OpenJDK, 64-bit
AWS EC2 t2.micro	single-core CPU running at 2.4 GHz	at least 10 Mbit/s	Linux + OpenJDK, 64-bit

Table C.1.: Overview of the capabilities from the system devices utilized for performance measurements of code offloading.

C.2. Dell Inspiron Mini 10v

The Dell Inspiron Mini 10v (1011) is a netbook from Dell Technologies, running a minimal Linux 32-bit version based on Debian Wheezy as operating system. Released in the year 2009, the Dell Inspiron Mini 10v (1011) possesses an Intel Atom N270 processor, where the single-core 32-bit CPU runs at 1.6 GHz. It has a memory of 1 GB and communicates via 100 Mbit Ethernet, Bluetooth 2.1 (cf. Subsection 2.2.3), and Wi-Fi IEEE 802.11 b,g (cf. Subsection 2.2.1). [Inc09] As the Dell Inspiron Mini 10v (1011) has no built-in connectivity for a cellular network, it utilizes the Huawei E1750 surf stick connected via Universal Serial Bus (cf. Subsection C.6), providing connectivity for a 3.5 Generation cellular network.

C.3. Lenovo ThinkPad T61

The Lenovo ThinkPad T61 is a laptop from Lenovo, running a minimal Linux 64-bit version based on Debian Wheezy as operating system. Released in the year 2007, the Lenovo ThinkPad T61 possesses an Intel Core 2 Duo T7300 processor, where the dual-core 64-bit CPU runs at 2.0 GHz. It has a memory of 2 GB and communicates via 1 Gbit Ethernet, Bluetooth 2.1 (cf. Subsection 2.2.3), and Wi-Fi IEEE 802.11 a,b,g

(cf. Subsection 2.2.1). [Len07] Like the Dell Inspiron Mini 10v (1011), the Lenovo ThinkPad T61 has no built-in connectivity for a cellular network, why it also utilizes the Huawei E1750 surf stick connected via Universal Serial Bus (cf. Subsection C.6), providing connectivity for a 3.5 Generation cellular network.

C.4. HP Compaq 8200 Elite

The HP Compaq 8200 Elite Microtower PC is a desktop computer from Hewlett Packard, running a minimal Linux 64-bit version based on Debian Wheezy as operating system. Released in the year 2011, the HP Compaq 8200 Elite Microtower PC possesses an Intel Core i7-2600 processor, where the quad-core 64-bit CPU runs at 3.4 GHz. It has a memory of 8 GB and communicates via 1 Gbit Ethernet. [Pac11]

C.5. AWS EC2 t2.micro

The Amazon Elastic Compute Cloud (EC2) is the web service for cloud computing from Amazon (cf. Section 2.3), where an end user obtains resizable capacity of computing resources at the cloud. Due to resizing the capacity, the computing resources quickly scale up and down depending on changes in the user (computing) demands. Moreover, an end user only pays for the capacity that he or she actually used (pay-as-you-go manner). The Amazon EC2 provides different types of instances (cf. T2, M4, or C4 [Ama14]) fitting multiple use cases. This dissertation uses a t2.micro instance that possesses one virtual CPU (vCPU) running at 2.4 GHz and a memory of 1 GB. As operating system, it runs an adapted Linux 64-bit version from Amazon. [Ama14]

C.6. Huawei E1750 Surf Stick

The Huawei E1750 surf stick works in the mobile communication networks of GSM and UMTS, supporting the frequency bands for GSM of 850/900/1800/1900 MHz and for UMTS of 2100 MHz. Due to the utilization of the Qualcomm MSM7200 SoC [Qua06], the surf stick provides for GSM the improvements of GPRS (2.5 Generation) and EDGE (2.75 Generation) and for UMTS the improvement of HSPA (3.5 Generation). Thus, it downloads data with a peak data rate of 7.2 Mbit/s and uploads data with a peak data rate of 5.76 Mbit/s. [Hua17]

C.7. Linksys WRT54GL Wireless Router

The Linksys WRT54GL wireless router provides a Wi-Fi AP, supporting IEEE 802.11 g,b and thus, a peak data rate of 54 Mbit/s. Beside the Wi-Fi network, the wireless router possesses a 10/100 Mbit/s WAN port and four 10/100 Mbit/s switched Local Area Network (LAN) ports based on Fast Ethernet standard IEEE 802.3u. [Lin02]

C.8. LevelOne GSW-0809 Gigabit Ethernet Switch

The LevelOne GSW-0809 Gigabit Ethernet Switch provides reliable high-performance networking with auto-learning and auto-aging of MAC addresses, where it has 8 Gigabit Ethernet ports with a wire data rate of 10/100/1000 Mbit/s. Moreover, it also supports techniques like IEEE 802.3x flow control or IEEE 802.3az energy efficiency. [Lev17]

Bibliography

[AFG+10] Michael Armbrust, Armando Fox, Rean Griffith, Anthony D. Joseph, Randy Katz, Andy Konwinski, Gunho Lee, David Patterson, Ariel Rabkin, Ion Stoica, and Matei Zaharia. A View of Cloud Computing. *Communications of the ACM*, 53(4):50–58, April 2010.

[AFGM+15] Ala Al-Fuqaha, Mohsen Guizani, Mehdi Mohammadi, Mohammed Aledhari, and Moussa Ayyash. Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications. *IEEE Communications Surveys Tutorials*, 17(4):2347–2376, Fourthquarter 2015.

[Akh09] Shakil Akhtar. Evolution of Technologies, Standards, and Deployment of 2G-5G Networks. In Margherita Pagani, editor, *Encyclopedia of Multimedia Technology and Networking, Second Edition*, chapter 70, pages 522–532. Information Science Reference, 2009.

[Ama06] Amazon. Announcing Amazon Elastic Compute Cloud (Amazon EC2) - beta. `https://aws.amazon.com/de/about-aws/whats-new/2006/08/24/announcing-amazon-elastic-compute-cloud-amazon-ec2---beta/`, 2006. Accessed: 2017-10-01.

[Ama14] Amazon. Amazon Web Services Elastic Compute Cloud. `https://aws.amazon.com/ec2/?nc1=h_ls`, 2014. Accessed: 2017-10-01.

[And16a] Android. Android Software Stack. `https://source.android.com/devices/images/ape_fwk_all.png`, 2016. Accessed: 2017-10-01.

[And16b] Android. Android Software Stack. `https://source.android.com/security/images/android_software_stack.png`, 2016. Accessed: 2017-10-01.

[BDR14a] Florian Berg, Frank Dürr, and Kurt Rothermel. Increasing the Efficiency and Responsiveness of Mobile Applications with Preemptable

Code Offloading. In *Proc. 3rd Intl. Conf. Mobile Services*, MS'14, pages 76–83, June 2014.

[BDR14b] Florian Berg, Frank Dürr, and Kurt Rothermel. Optimal Predictive Code Offloading. In *Proc. 11th Intl. Conf. Mobile and Ubiquitous Systems: Computing, Networking and Services*, Mobiquitous'14, pages 1–10, December 2014.

[BDR15] Florian Berg, Frank Dürr, and Kurt Rothermel. Increasing the Efficiency of Code Offloading through Remote-side Caching. In *Proc. IEEE 11th Intl. Conf. Wireless and Mobile Computing, Networking and Communications*, WiMob'15, pages 573–580, October 2015.

[BDR16] Florian Berg, Frank Dürr, and Kurt Rothermel. Increasing the Efficiency of Code Offloading in n-tier Environments with Code Bubbling. In *Proc. 13th Intl. Conf. Mobile and Ubiquitous Systems: Computing, Networking and Service*, Mobiquitous'16, pages 170–179, November 2016.

[BDR18] Florian Berg, Frank Dürr, and Kurt Rothermel. Increasing the Efficiency of Code Offloading in n-tier Environments with Code Bubbling. *Mobile Networks and Applications*, pages 1–12, February 2018.

[BGPCV12] Mark L. Badger, Timothy Grance, Robert Patt-Corner, and Jeffrey M. Voas. Cloud Computing Synopsis and Recommendations. Technical Report Special Publication (NIST SP) - 800-146, The National Institute of Standards and Technology (NIST), Gaithersburg, Maryland, USA, May 2012.

[BLMN13] Joseph Bradley, Jeff Loucks, James Macaulay, and Andy Noronha. White Paper: Internet of Everything (IoE) Value Index - How Much Value Are Private-Sector Firms Capturing from IoE in 2013? Technical report, Cisco Systems, San Jose, California, USA, June 2013.

[BMZA12] Flavio Bonomi, Rodolfo Milito, Jiang Zhu, and Sateesh Addepalli. Fog Computing and Its Role in the Internet of Things. In *Proc. 1st MCC Workshop on Mobile Cloud Computing*, MCC'12, pages 13–16, August 2012.

[CBC+10] Eduardo Cuervo, Aruna Balasubramanian, Dae Cho, Alec Wolman, Stefan Saroiu, Ranveer Chandra, and Paramvir Bahl. MAUI: Making

Smartphones Last Longer with Code Offload. In *Proc. 8th Intl. Conf. Mobile Systems, Applications, and Services*, MobiSys'10, pages 49–62, March 2010.

[Cen12] Intel IT Center. Vision Paper: Distributed Data Mining and Big Data - Intel's Perspective on Data at the Edge. Technical Report 0812/RF/ME/PDF-USA 327826-001, Intel Corporation, Santa Clara, California, USA, August 2012.

[CH10] Aaron Carroll and Gernot Heiser. An Analysis of Power Consumption in a Smartphone. In *Proceedings of the 2010 USENIX Conference on USENIX Annual Technical Conference*, USENIX ATC'10, pages 21–21, June 2010.

[Chi63] Francis P. Chisholm. The Chisholm Effect. *Motive Magazine*, 1963.

[CIM+11] Byung-Gon Chun, Sunghwan Ihm, Petros Maniatis, Mayur Naik, and Ashwin Patti. CloneCloud: Elastic Execution between Mobile Device and Cloud. In *Proc. 6th Conf. Computer Systems*, EuroSys'11, pages 301–314, March 2011.

[CLWG15] Zixue Cheng, Peng Li, Junbo Wang, and Song Guo. Just-in-Time Code Offloading for Wearable Computing. *Emerging Topics in Computing, IEEE Transactions on*, 3(1):74–83, March 2015.

[Com81] Federal Communications Commission. Cellular Service. `https://www.fcc.gov/general/cellular-service`, 1981. Accessed: 2017-10-01.

[CSRL09] Thomas H. Cormen, Clifford Stein, Ronald L. Rivest, and Charles E. Leiserson. *Introduction to Algorithms*. MIT Press, 3rd edition, 2009.

[CZ16] Mung Chiang and Tao Zhang. Fog and IoT: An Overview of Research Opportunities. *IEEE Internet of Things Journal*, 3(6):854–864, December 2016.

[DA97] Ian Doig and Niels Peter Skov Andersen. Universal Mobile Telecommunications System (UMTS); Requirements for the UMTS Terrestrial Radio Access system (UTRA). Technical Report UMTS 21.01 version 3.0.1, European Telecommunications Standards Institute (ETSI), Sophia Antipolis Cedex, France, November 1997.

[DWC+13] Ning Ding, Daniel Wagner, Xiaomeng Chen, Abhinav Pathak, Y. Charlie Hu, and Andrew Rice. Characterizing and Modeling the Impact of Wireless Signal Strength on Smartphone Battery Drain. In *Proc. ACM SIGMETRICS/Intl. Conf. Measurement and Modeling of Computer Systems*, SIGMETRICS'13, pages 29–40, June 2013.

[Ehr79] Nathan Ehrlich. The Advanced Mobile Phone Service. *IEEE Communications Magazine*, 17(2):9–16, March 1979.

[Ele17] Meilhaus Electronic. ME-Jekyll ME-4610 PCI 16-bit Analog Data Acquisition Board. `http://www.meilhaus.de/en/me-4610+pci.htm`, 2017. Accessed: 2017-10-01.

[fG00] Jeanette Wannstrom (for 3GPP). HSPA. `http://www.3gpp.org/technologies/keywords-acronyms/99-hspa`, 2000. Accessed: 2017-10-01.

[FG10] Stephen Fagan and Ramazan Gençay. *An Introduction to Textual Econometrics*, pages 133–153. Chapman and Hall/CRC, 2010.

[FRTH12] Marvin Ferber, Thomas Rauber, Mario Henrique Cruz Torres, and Tom Holvoet. Resource Allocation for Cloud-Assisted Mobile Applications. In *Proc. IEEE 5th Intl. Conf. Cloud Computing*, CLOUD'12, pages 400–407, June 2012.

[FSS02] Jason Flinn, Park SoYoung, and Mahadev Satyanarayanan. Balancing Performance, Energy, and Quality in Pervasive Computing. In *Proc. 22nd Intl. Conf. Distributed Computing Systems*, ICDCS'02, pages 217–226, July 2002.

[GB09] Savvas Gitzenis and Nicholas Bambos. Joint Task Migration and Power Management in Wireless Computing. *IEEE Transactions on Mobile Computing*, 8(9):1189–1204, September 2009.

[GJM+12] Mark S. Gordon, D. Anoushe Jamshidi, Scott Mahlke, Z. Morley Mao, and Xu Chen. COMET: Code Offload by Migrating Execution Transparently. In *Proc. 10th USENIX Conf. Operating Systems Design and Implementation*, OSDI'12, pages 93–106, October 2012.

[Goo15] Google. September Press Event 2015. `https://www.youtube.com/watch?v=Jc-LEG0T_4c`, 2015. Accessed: 2017-10-01.

[GRA12] Ioana Giurgiu, Oriana Riva, and Gustavo Alonso. Dynamic Software Deployment from Clouds to Mobile Devices. In *Proc. 13th Intl. Middleware Conference*, Middleware'12, pages 394–414, December 2012.

[Hau10] Doug Hauger. Windows Azure General Availability. `https://blogs.technet.microsoft.com/microsoft_blog/2010/02/01/windows-azure-general-availability/`, 2010. Accessed: 2017-10-01.

[HSZ08] Christian Henke, Carsten Schmoll, and Tanja Zseby. Empirical Evaluation of Hash Functions for Multipoint Measurements. *SIGCOMM Comput. Commun. Rev.*, 38(3):39–50, July 2008.

[Hua17] Huawei. Huawei E1750 Surf Stick. `http://www.surfsticks.de/modelle/huawei/e1750.html`, 2017. Accessed: 2017-10-01.

[Inc09] Dell Technologies Inc. Dell Inspiron Mini 10v. `http://www.dell.com/content/products/productdetails.aspx/laptop-inspiron-10?c=us&l=en&s=corp&`, 2009. Accessed: 2017-10-01.

[Inf07a] Apple Press Info. Apple Reinvents the Phone with iPhone. `http://www.apple.com/pr/library/2007/01/09Apple-Reinvents-the-Phone-with-iPhone.html`, 2007. Accessed: 2017-10-01.

[Inf07b] Apple Press Info. iPhone Delivers Up to Eight Hours of Talk Time. `http://www.apple.com/pr/library/2007/06/18iPhone-Delivers-Up-to-Eight-Hours-of-Talk-Time.html`, 2007. Accessed: 2017-10-01.

[Inf07c] Apple Press Info. T-Mobile and Apple Announce Rate Plans for iPhone in Germany, Starting at Just 49 Euro per Month. `http://www.apple.com/pr/library/2007/10/29T-Mobile-and-Apple-Announce-Rate-Plans-for-iPhone-in-Germany-Starting-at-Just-49-per-Month.html`, 2007. Accessed: 2017-10-01.

[Ins12] Texas Instruments. OMAP4460. `http://www.ti.com/lit/ml/swpt034b/swpt034b.pdf`, 2012. Accessed: 2017-10-01.

[ITU97] ITU. International Mobile Telecommunications-2000 (IMT-2000). Technical Report M.687-2 (02/97), International Telecommunication Union (ITU), Geneva, Switzerland, February 1997.

[JBD+14] Dave Jewell, Ricardo Dobelin Barros, Stefan Diederichs, Lydia M. Duijvestijn, Michael Hammersley, Arindam Hazra, Corneliu Holban, Yan Li, Osai Osaigbovo, Andreas Plach, Ivan Portilla, Mukerji Saptarshi, Harinder P. Seera, Elisabeth Stahl, and Clea Zolotow. Performance and Capacity Implications for Big Data. Technical Report REDP-5070-00, International Business Machines Corporation, Armonk, New York, USA, January 2014.

[JHLX14] Yong Jiang, Juhua He, Qing Li, and Xi Xiao. A Dynamic Execution Offloading Model for Efficient Mobile Cloud Computing. In *Global Communications Conference, 2014 IEEE*, Globecom'14, pages 2302–2307, December 2014.

[JS94] Theodore Johnson and Dennis Shasha. 2Q: A Low Overhead High Performance Buffer Management Replacement Algorithm. In *Proc. 20th Intl. Conf. on Very Large Data Bases*, VLDB '94, pages 439–450, September 1994.

[KAH+12] S. Kosta, A. Aucinas, Pan Hui, R. Mortier, and Xinwen Zhang. ThinkAir: Dynamic Resource Allocation and Parallel Execution in the Cloud for Mobile Code Offloading. In *Proc. IEEE INFOCOM*, INFOCOM'12, pages 945–953, March 2012.

[KI96] Vasilis Koudounas and Omar Iqbal. Mobile Computing: Past, Present, and Future, Volume 4 1996.

[KM15] Siddhartha Kumar Khaitan and James D. McCalley. Design Techniques and Applications of Cyberphysical Systems: A Survey. *IEEE Systems Journal*, 9(2):350–365, June 2015.

[Kri10] Mads Darø Kristensen. Scavenger: Transparent Development of Efficient Cyber Foraging Applications. In *Proc. IEEE Intl. Conf. Pervasive Computing and Communications*, PerCom'10, pages 217–226, March 2010.

[KS11] Evgenii Krouk and Sergei Semenov, editors. *Modulation and Coding Techniques in Wireless Communications*. Wiley, 1st edition, January 2011.

[KSK14] Pratik Kanani, Kamal Shah, and Vikas Kaul. A Survey on Evolution of Mobile Networks: 1G to 4G. *International Journal of Engineering*

Sciences & Research Technology (IJESRT) (Vol.3, No. 2), 3(2):803–810, February 2014.

[KT12] Young-Woo Kwon and Eli Tilevich. Energy-Efficient and Fault-Tolerant Distributed Mobile Execution. In *Proc. IEEE 32nd Intl. Conf. Distributed Computing Systems*, ICDCS'12, pages 586–595, June 2012.

[Lab09] Sun Microsystems Laboratories. FreeTTS. `http://freetts.sourceforge.net/docs/index.php`, 2009. Accessed: 2017-10-01.

[LBLX13] Jiwei Li, Kai Bu, Xuan Liu, and Bin Xiao. ENDA: Embracing Network Inconsistency for Dynamic Application Offloading in Mobile Cloud Computing. In *Proc. 2nd ACM SIGCOMM Workshop on Mobile Cloud Computing*, MCC'13, pages 39–44, 2013.

[Len07] Lenovo. Lenovo ThinkPad T61. `https://support.lenovo.com/us/en/documents/pd008989`, 2007. Accessed: 2017-10-01.

[Lev17] LevelOne. LevelOne GSW-0809 Gigabit Ethernet Switch. `http://uk.level1.com/Switch/GSW-0809/p-3748.htm`, 2017. Accessed: 2017-10-01.

[Lin02] Linksys. Linksys WRT54GL Wireless-G Wireless Router. `http://www.linksys.com/us/p/P-WRT54GL/`, 2002. Accessed: 2017-10-01.

[LYBB15] Tim Lindholm, Frank Yellin, Gilad Bracha, and Alex Buckley. The Java Virtual Machine Specification - Java SE 8 Edition. `https://docs.oracle.com/javase/specs/jvms/se8/html/index.html`, 2015. Accessed: 2017-10-01.

[Mac16] Jikes Research Virtual Machine. Publications. `http://www.jikesrvm.org/Resources/Publications/`, 2016. Accessed: 2017-10-01.

[MF10] Andrea Matsunaga and Jose Fortes. On the Use of Machine Learning to Predict the Time and Resources Consumed by Applications. In *Proc. 10th Intl. Conf. Cluster, Cloud and Grid Computing*, CCGrid'10, pages 495–504, May 2010.

[Mic68] Donald Michie. Memo Functions and Machine Learning. *Nature*, 218(5136):19–22, April 1968.

[NK16] Takehiro Nakamura and Joern Krause. Requirements for further advancements for Evolved Universal Terrestrial Radio Access (E-UTRA) (LTE-Advanced). Technical Report 3GPP TR 36.913 version 13.0.0 Release 13, European Telecommunications Standards Institute (ETSI), Sophia Antipolis Cedex, France, January 2016.

[NN08] Anthony J. Nicholson and Brian D. Noble. BreadCrumbs: Forecasting Mobile Connectivity. In *Proc. 14th ACM Intl. Conf. on Mobile Computing and Networking*, MobiCom'08, pages 46–57, September 2008.

[Och08] Ulf Ochsenfahrt. aichess4k. `http://ulf.ofahrt.de/aichess4k/`, 2008. Accessed: 2017-10-01.

[Pac11] Hewlett Packard. HP Compaq 8200 Elite. `https://support.hp.com/us-en/document/c02779501`, 2011. Accessed: 2017-10-01.

[Pla16] Google Cloud Platform. Memcache Overview. `https://cloud.google.com/appengine/docs/java/memcache`, 2016. Accessed: 2017-10-01.

[Pow98] David M. W. Powers. Applications and Explanations of Zipf's Law. In *Proc. Joint Conf. on New Methods in Language Processing and Computational Natural Language Learning*, NeMLaP3/CoNLL'98, pages 151–160, January 1998.

[PPS+12] Justin Mazzola Paluska, Hubert Pham, Gregor Schiele, Christian Becker, and Steve Ward. Vision: A Lightweight Computing Model for Fine-grained Cloud Computing. In *Proceedings of the Third ACM Workshop on Mobile Cloud Computing and Services*, MCS'12, pages 3–8, June 2012.

[PSMM04] Vasco Pereira, Tiago Sousa, Paulo Mendes, and Edmundo Monteiro. Evaluation of Mobile Communications: From Voice Calls to Ubiquitous Multimedia Group Communications. In *Proc. 2nd Intl. Working Conf. on Performance Modeling and Evaluation of Heterogeneous Networks*, HET-NETs'04, pages 4–10, July 2004.

[Qua06] Qualcomm. Qualcomm Paves the Way for Next-Generation Services on HSUPA. `https://www.qualcomm.com/news/releases/2006/05/04/qualcomm-paves-way-next-generation-services-hsupa`, 2006. Accessed: 2017-10-01.

[RAR07] Jan S. Rellermeyer, Gustavo Alonso, and Timothy Roscoe. R-OSGi: Distributed Applications Through Software Modularization. In *Proc. ACM/IFIP/USENIX Intl. Conf. on Middleware*, Middleware'07, pages 1–20, November 2007.

[RLSS10] Ragunathan (Raj) Rajkumar, Insup Lee, Lui Sha, and John Stankovic. Cyber-physical Systems: The Next Computing Revolution. In *Proceedings of the 47th Design Automation Conference*, DAC'10, pages 731–736, June 2010.

[Sam11] Samsung. Samsung Galaxy Nexus. `http://www.samsung.com/us/support/owners/product/GT-I9250TSGGEN`, 2011. Accessed: 2017-10-01.

[Sam16] Samsung. Samsung Exynos 8 Octa. `http://www.samsung.com/semiconductor/minisite/Exynos/w/solution/mod_ap/8890`, 2016. Accessed: 2017-10-01.

[Sam17] Samsung. Samsung Galaxy S8. `http://www.samsung.com/global/galaxy/galaxy-s8`, 2017. Accessed: 2017-10-01.

[Sat96] Mahadev Satyanarayanan. Fundamental Challenges in Mobile Computing. In *Proceedings of the Fifteenth Annual ACM Symposium on Principles of Distributed Computing*, PODC'96, pages 1–7, May 1996.

[Sat10] Mahadev Satyanarayanan. Mobile Computing: The Next Decade. In *Proceedings of the 1st ACM Workshop on Mobile Cloud Computing & Services: Social Networks and Beyond*, MCS '10, pages 5:1–5:6, June 2010.

[SBCD09] Mahadev Satyanarayanan, Paramvir Bahl, Ramón Cáceres, and Nigel Davies. The Case for VM-Based Cloudlets in Mobile Computing. *Pervasive Computing, IEEE*, 8(4):14–23, October 2009.

[Sek13] Krishna Sekar. Power and Thermal Challenges in Mobile Devices. In *Proc. 19th Intl. Conf. Mobile Computing and Networking*, MobiCom'13, pages 363–368, September 2013.

[SEV+16] Dominik Schäfer, Janick Edinger, Sebastian VanSyckel, Justin Mazzola Paluska, and Christian Becker. Tasklets: Overcoming heterogeneity in distributed computing systems. In *Proceedings of the 2016 IEEE*

36th International Conference on Distributed Computing Systems Workshops, ICDCSW'16, pages 156–161, June 2016.

[Sey03] Bernhard Seybold. Chesspresso. `http://www.chesspresso.org/`, 2003. Accessed: 2017-10-01.

[SGKB13] Muhammad Shiraz, Abdullah Gani, Rashid Hafeez Khokhar, and Rajkumar Buyya. A Review on Distributed Application Processing Frameworks in Smart Mobile Devices for Mobile Cloud Computing. *IEEE Communications Surveys Tutorials*, 15(3):1294–1313, Third 2013.

[Sha50] Claude E. Shannon. XXII. Programming a Computer for Playing Chess. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, 7(41:314):256–275, 1950.

[SHP+14] Cong Shi, Karim Habak, Pranesh Pandurangan, Mostafa Ammar, Mayur Naik, and Ellen Zegura. COSMOS: Computation Offloading As a Service for Mobile Devices. In *Proc. 15th ACM Intl. Symposium on Mobile Ad Hoc Networking and Computing*, MobiHoc'14, pages 287–296, August 2014.

[SIG12] ACM SIGPLAN. Programming Languages Software Award. `http://www.sigplan.org/Awards/Software/`, 2012. Accessed: 2017-10-01.

[SMT10] Patrick Stuedi, Iqbal Mohomed, and Doug Terry. WhereStore: Location-based Data Storage for Mobile Devices Interacting with the Cloud. In *Proc. 1st ACM Workshop on Mobile Cloud Computing & Services: Social Networks and Beyond*, MCS'10, pages 1:1–1:8, June 2010.

[Soc05] IEEE Computer Society. IEEE Standard for Information Technology - Telecommunications and Information Exchange between Systems - Local and Metropolitan Area Networks - Specific Requirements. Part 15.1: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Wireless Personal Area Networks (WPANs). Technical Report IEEE Std 802.15.1-2005, Institute of Electrical and Electronics Engineers (IEEE), New York, NY, USA, March 2005.

[Soc12] IEEE Computer Society. IEEE Standard for Information Technology – Telecommunications and Information Exchange between Systems Local

and Metropolitan Area Networks – Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. Technical Report IEEE Std 802.11-2012, Institute of Electrical and Electronics Engineers (IEEE), New York, NY, USA, March 2012.

[Ste94] William J. Stewart. *Introduction to the Numerical Solution of Markov Chains*. Princeton University Press, 1st edition, 1994.

[Str13] Daniel W. Stroock. *Mathematics of Probability*. American Mathematical Society, 1st edition, 2013.

[TAY10] Asoke K. Talukder, Hasan Ahmed, and Roopa R Yavagal. *Mobile Computing - Technology, Applications and Service Creation (Second Edition)*. Tata McGraw Hill Education Private Limited, 2nd edition, 2010.

[Tim97] The New York Times. Sun Sues Microsoft on Use of Java System. `http://www.nytimes.com/1997/10/08/business/sun-sues-microsoft-on-use-of-java-system.html`, 1997. Accessed: 2017-10-01.

[uRKOMK14] Atta ur Rehman Khan, Mazliza Othman, Sajjad Ahmad Madani, and Samee Ullah Khan. A Survey of Mobile Cloud Computing Application Models. *IEEE Communications Surveys Tutorials*, 16(1):393–413, First Quarter 2014.

[Venry] Bill Venners. *Inside the Java 2 Virtual Machine*. McGraw-Hill Professional, 2nd edition, January January.

[VRM14] Luis M. Vaquero and Luis Rodero-Merino. Finding Your Way in the Fog: Towards a Comprehensive Definition of Fog Computing. *SIGCOMM Comput. Commun. Rev.*, 44(5):27–32, October 2014.

[VSTD12] Tim Verbelen, Pieter Simoens, Filip De Turck, and Bart Dhoedt. Cloudlets: Bringing the Cloud to the Mobile User. In *Proc. 3rd ACM Workshop on Mobile Cloud Computing and Services*, MCS'12, pages 29–36, June 2012.

[Web08] Jon A. Webb. Jon's Java Imaging Library (JJIL). `https://code.google.com/archive/p/jjil/`, 2008. Accessed: 2017-10-01.

[Wei99] Mark Weiser. The Computer for the 21st Century. *SIGMOBILE Mob. Comput. Commun. Rev.*, 3(3):3–11, July 1999.

[WFHP16] Ian H. Witten, Eibe Frank, Mark A. Hall, and Christopher J. Pal. *Data Mining: Practical Machine Learning Tools and Techniques*. Morgan Kaufmann, 4th edition, December 2016.

[YLL15] Shanhe Yi, Cheng Li, and Qun Li. A Survey of Fog Computing: Concepts, Applications and Issues. In *Proceedings of the 2015 Workshop on Mobile Big Data*, Mobidata'15, pages 37–42, June 2015.

[You79] W. Rae Young. Advanced Mobile Phone Service: Introduction, Background, and Objectives. *The Bell System Technical Journal*, 58(1):1–14, January 1979.

[ZWG+13] Weiwen Zhang, Yonggang Wen, Kyle Guan, Dan Kilper, Haiyun Luo, and Dapeng Oliver Wu. Energy-Optimal Mobile Cloud Computing under Stochastic Wireless Channel. *Wireless Communications, IEEE Transactions on*, 12(9):4569–4581, September 2013.

Erklärung

Ich erkläre hiermit, dass ich, abgesehen von den ausdrücklich bezeichneten Hilfsmitteln und den Ratschlägen von jeweils namentlich aufgeführten Personen, die Dissertation selbstständig verfasst habe.

(Ort, Datum) (Florian Andreas Berg)