Institute of Architecture of Application Systems

University of Stuttgart
Universitätsstraße 38
D–70569 Stuttgart

Master Thesis

IoT based monitoring and control for energy management system

Karim, Ahmad

Course of Study:	INFOTECH
Examiner:	Prof. Dr. Dr. h.c. Frank Leymann
Supervisor:	Dipl.-Inf. Michael Hahn, Dr. Dirk Pietruschka (Enisyst GmbH)
Commenced:	October 19, 2017
Completed:	April 19, 2018

Abstract

The world economy is growing rapidly, and global energy demands are predicted to increase even more in the future. Energy is expected to get more expensive, in turn affecting the economic development. Energy demand can be reduced by employing efficient Energy Management Systems (EMS). The required infrastructure cost for EMS is often quite high, making it an unviable solution. However, new Internet of Things (IoT) based solutions can help to reduce the installation effort as well as cost significantly. Low-Power Wide-Area Networks (LPWAN) hold the solution to this problem. The goal of an LPWAN is to provide cheap nodes and communication distances of a few kilometers (5-10 km) with a low battery consumption rate (5-10 years). The data transfer rate is low, but the range and power consumption make it ideal for environmental data acquisition (samples per few minutes). The current wireless technologies, such as ZigBee, Bluetooth, and Wi-Fi, that are being used for wireless sensors are not suitable for industrial use where the number of connected devices is significantly higher, and reliability is of dire need. Therefore, in this work, a study of available LPWAN technologies is carried out which concludes in the selection of LoRa technology for communication in an EMS. Furthermore, we evaluate possible communication distances of the LoRa technology in an industrial area by conducting several range tests which result in significantly higher communication distances as compared to legacy WAN technologies. LoRa has proved to be a good start for adopting LPWAN, especially in applications such as energy management systems. Based on that, we present a system architecture for an EMS using LoRa as the underlying communication technology as well as a prototypical implementation of it. This implementation is furthermore integrated into the current EMS of Enisyst. LoRa-modulation combined with LoRaWAN communication protocol proves to be a base for a reliable and scalable system.

Contents

List of Figures

List of Tables

1 Introduction

The world economy is growing rapidly, and global energy demands are predicted to get higher in the future. Even though the energy industry is moving from conventional sources (oil, gas, and coal) to clean and renewable sources, fossil fuels still dominate this industry, which in turn is a cause of rising CO2 levels in the environment and also results in other environmental problems. Energy is expected to get more expensive and thereby relevant for the economic development. The increase in efficiency holds a very high potential to reduce energy demand, decoupling economic growth from energy demand. This effect is visible in Germany, where already substantial efforts have been taken to increase energy efficiency in all sectors; however, the building sector in Germany holds even more potential regarding energy efficiency. Apart from insulation measures on the buildings, intelligent and efficient control has the potential to increase the energy efficiency of buildings by low energy heating and cooling systems, this requires active energy management systems for optimized control and observation to avoid inefficient energy use.

1.1 Motivation

Active energy management systems (EMS) comprise of a sensor network and control units collecting a huge amount of data, which is then analyzed and used for optimization. On the other hand, installation of sensors and the required cabling is expensive, and therefore in some cases, it is not economically viable to install an EMS; however, new IoT based solutions can help to reduce the installation effort as well as cost significantly. A wireless sensor network (WSN) can be employed to tackle this issue. Yinbiao et al. [43] define WSN as follows:

> "A WSN is a network formed by a large number of sensor nodes where each node is equipped with a sensor to detect physical phenomena such as light, heat, pressure, etc. WSNs are regarded as a revolutionary information gathering method to build the information and communication system which will greatly improve the reliability and efficiency of infrastructure systems. Compared with the wired solution, WSNs feature easier deployment and better flexibility of devices."

The data collected from these sensors can be directly transferred to a cloud server where it can be stored and used by control systems for efficient control. Such solutions are emerging, but they suffer from low range, low data transfer rate, or short battery cycles. A wireless communication network known as Low-Power Wide-Area Network (LPWAN) holds the solution to this problem. The goal of an LPWAN is to provide cheap nodes and communication distances of a few kilometers (5-10 km) with a low battery consumption rate (5-10 years) [27]. Undeterred by the low data transfer its range and power consumption makes it ideal for environmental data acquisition where data is gathered in samples per few minutes. The current wireless technologies such as ZigBee [45], Bluetooth [4] and Wi-Fi [14] that are being used for conventional WSN [37] are not suitable for industrial use, where the number of connected devices is significantly higher and reliability is of dire need. The major difference between a conventional WSN and an LPWAN is of the network topology; WSN consists of a mesh or ad-hoc topology, whereas LPWAN employs a star topology. The nodes are connected to one base station which is further connected to a wired network, and this scheme enables LPWAN to extend the network coverage to the order of dozens of kilometers [27]. Examples of such networks are "LoRaWAN" [23], "Sigfox" [34] and "Weightless" [41]. State of the art LPWAN technologies will be thoroughly discussed in Section 2.4.

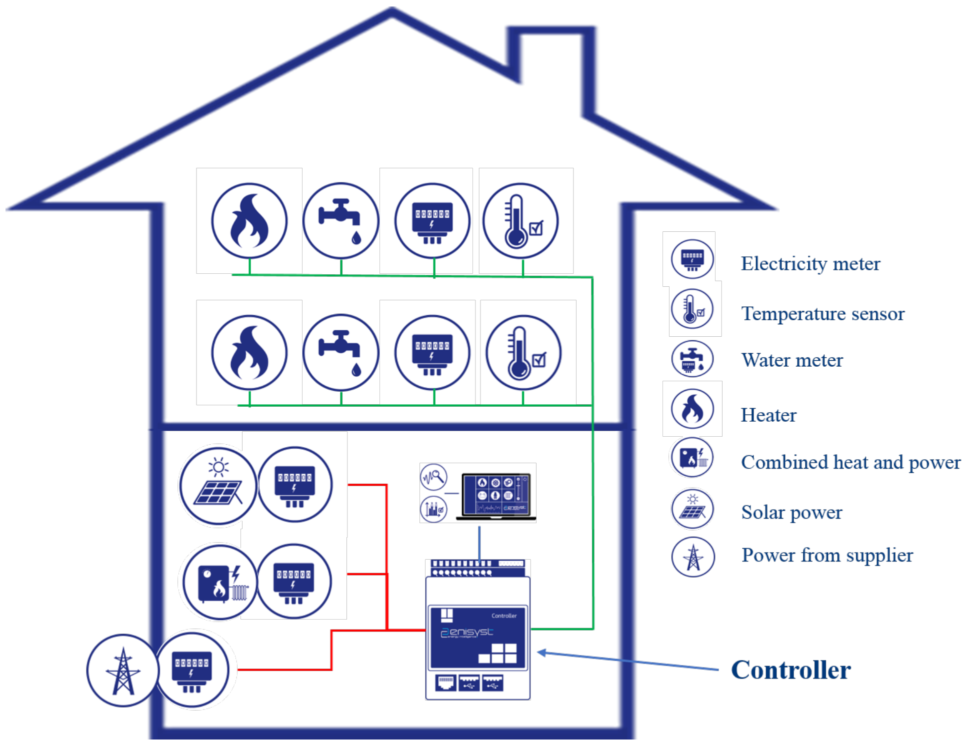

Figure 1.1: Over view of an EMS.

EMS relies on the sensor network to acquire environmental data be it indoors or outdoors. This data is crucial for efficient energy use. A building's heating and cooling are managed by reading the sensor data. These sensors are located at various points of interests in the building. The EMS actively adjusts the temperature to maintain a pleasant atmosphere during active hours, and it can be scheduled to turn off the heating system during idle hours, e.g., night or weekends. Using an EMS is not just environment-friendly but also has its economic benefits. These economic benefits are notably prominent on the high scale projects, e.g., malls, multi-storied buildings, and commercial buildings, etc. In an overview of the currently employed EMS shown in Figure 1.1, inputs from various sensors and meters are read by the controller and corresponding decisions are made. Creating the infrastructure for EMS is an integral part of a building's construction work. The construction plans are analyzed by project engineers months before construction begins. They provide the construction firm with the locations of sensors. These sensors and their required cabling are then installed during the construction of the building. There are major problems in this scenario. The sensors are connected to the controller in a star topology, which increases the installation effort; this scenario is difficult to implement for already constructed buildings with residents in them. Apart from these problems, cable length can easily increase from a few meters to several hundred meters in a multi-storied building, requiring repeaters and signal amplifiers hence further increasing cost and effort.

Enisyst is an energy solution provider with the focus on smart energy management. They offer an EMS based on industrial grade hardware assuring reliability and robustness. They offer clients a 30% reduction in energy cost by using energy smartly. Enisyst's current solution is comprised of a wired system, as described above. Enisyst is also facing the problem of increased effort and difficulties in deployment for already constructed buildings. All these problems can be addressed by switching to wireless sensors.

In the area of wireless communication, significant advancements have been made in the past few decades, providing consumers with various options. It is, therefore, an integral part of this thesis to carry out a study on the wireless communication technologies and selecting one for implementation an EMS.

1.2 Document layout

A significant part of this document is dedicated to communications technology. To make it easier for the readers to understand Chapter 2 will be focused on terminologies and basic concepts of communication systems. Section 2.4 of Chapter 2 will present the state of the art of LPWAN technologies. A comparison of the available technologies is carried out in Chapter 3. Based on the results of the comparison, one of the introduced LPWAN technologies is selected for implementing an EMS. In Chapter 4 a standard EMS is discussed with its various components. In Chapter 5, hardware components and their interconnections required for realizing an EMS with LPWAN technology will be explained. Chapter 5 will also present the system architecture of the EMS as well as the detailed working of the entire system and its internal modules. Results of the range tests will be discussed in Chapter 6 with Chapter 7 concluding this thesis.

2 Background

In principle, any system that transmits information from one location to another location without the use of wires is considered as a wireless system. Wireless communication is achieved by using electromagnetic waves as a medium to transmit electrical signals instead of wires. A wireless system is a vast topic, and a complete explanation of all the internal workings are out of scope for this thesis, only the terms and concepts which are relevant will be discussed in this chapter.

Wireless transmission uses waves to transmit information. In the realm of physics, waves can be categorized by two kinds, mechanical waves, and electromagnetic waves. Mechanical waves are those waves which need a medium to travel and cannot propagate through the vacuum, for example, sound waves. Electromagnetic (EM) waves, on the other hand, do not require a medium to propagate for instance visible light, radio waves, microwaves, x-rays, etc. Communication systems use EM waves as a communication medium as their ability to move through objects is far more than mechanical waves.

The characteristics and behavior of EM waves depend directly on their operating frequency, i.e., wavelength. Low-frequency radio waves have a longer wavelength and can travel long distances without attenuation, but they cannot carry much information. Contrarily, high-frequency waves (shorter wavelength), like microwaves, are susceptible to interference and prone to attenuation for long distances, but they can carry more information.

Digital signals cannot be directly transmitted wirelessly. They need to be converted to a different form to be transmitted. As discussed earlier EM waves are used as a communication medium for wireless systems, and conversion of information from digital bits to EM waves is a process that is called modulation. There are several different techniques for modulation. The operating frequency and modulation technique actively govern the characteristics of any wireless technology. For example, Radio stations use 76 MHz-108 MHz as the base frequency for transmission and "Frequency-Modulation" as modulation technique to transmit voice or songs over the air. Whereas cellular services use microwaves ($>$ 1 GHz) as the base frequency for transmission and shift keying as their modulation technique. More information can be transmitted on the same operating frequency by just changing the modulation technique, e.g., GSM, GPRS and EDGE. All are cellular technologies that use same base frequency, but EDGE is capable of three times data capacity as that of GPRS due to its more advanced modulation technique.

An ideal wireless system would be one that has the most extended range, consumes the least amount of power, is resistant to interferences, and has the highest possible data throughput while consuming the lowest possible bandwidth. All these parameters are interlinked, some inversely and some directly; high data throughput requires more bandwidth, more bandwidth introduces more noise, and long range requires more power.

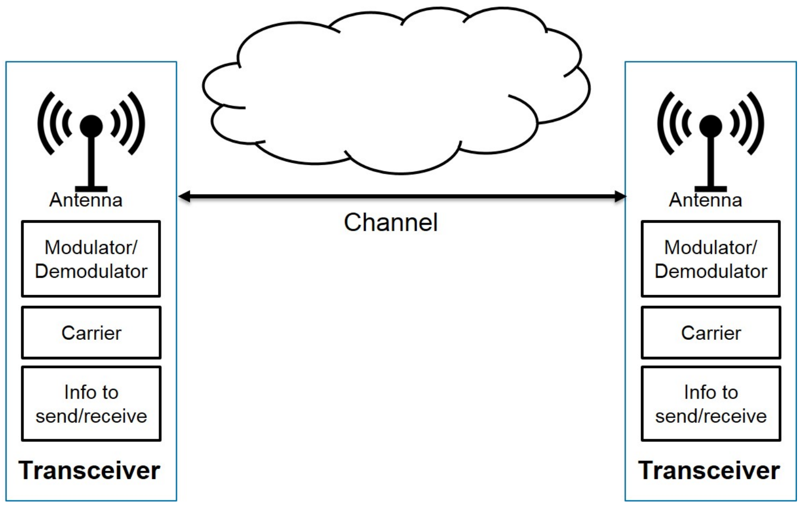

Figure 2.1: A basic wireless system.

Figure 2.1 shows a primary wireless communication system with two transceivers communicating over the air. A transceiver is a device that is capable of both transmitting and receiving data. A basic transceiver has an antenna and a modulator. An antenna is an electrical device that converts electric current to EM energy and vice versa; a modulator is a device that converts the raw information into a form that can be transmitted through EM waves.

2.1 Communication terms

This section will be focused on the physical properties of a communications system. The subsections will include a brief description of relevant terminologies.

2.1.1 Channel

The medium through which signals travel is known as the channel. In wired communication, it is the copper wire, in space communication, it is the vacuum of space, and in wireless communication, the communication channel is the air. A channel is modeled by the calculation of processes that cause changes to the signal. In a wireless communication system, this can be achieved by calculating the signals strength before and after it reflects off any surface or object.

2.1.2 Decibel (dBm)

dBm is a logarithmic way of describing a signal and is the most common unit in communication systems. It is a ratio of the power of desired signal compared to 1 milliwatt of power. The difference in decibels between two quantities is defined by Equation (2.1).

$$[10 * \log \frac{P_1}{P_2}] \tag{2.1}$$

In communication systems, numerical values tend to get minute, and it is best to describe them in terms of logarithms for more comfortable usability and readability. Table 2.1 shows generic dBm values used in a communication system; not only does the dBm scale provide ease of use but it is also the norm for expressing values in communication systems.

P (dBm)	P (mW)	
50	100000	strong transmitter
40	10000	
30	1000	
20	100	
10	10	
0	1	
-10	0.1	
-20	0.01	
-30	0.001	
-40	0.0001	
-50	0.00001	
-60	0.000001	
-70	0.0000001	
-80	0.00000001	sensitive receiver
-90	0.000000001	

Table 2.1: Generic dBm values for transmitter and receiver.

2.1.3 Bandwidth

The range of frequencies that is used for transmission is known as bandwidth. Signal bandwidth also refers to the frequency range in which a signal's spectral density is nonzero. Spectral density is the region of frequencies where the average power of a signal is distributed.

2.1.4 Antenna gain

Antenna gain is a performance parameter. It quantifies an antennas directivity and efficiency. Directivity is a measure of the strength of radiation emitted in a particular direction. Efficiency is a measure of conversion of electrical energy into radio waves and vice versa in case of a receiving antenna.

2.1.5 Modulation

Modulation is a process of converting information to a form that can travel farther with a lesser loss. A prime example of analog modulation is AM and FM radio. Sound waves are converted into electrical signals and propagated through air. There are also digital modulation techniques where discrete signals are converted to transmissible EM waves. Some examples of digital modulation are PSK (phase-shift keying), FSK (frequency-shift keying), ASK (amplitude-shift keying) and QAM (quadrature amplitude modulation).

2.1.6 Link budget

Transmitting information in terms of EM waves is subject to many losses. These losses are at the transmission end, receiving end, in the channel, due to weather, etc. All these losses when accounted together are known as link budget. Equation (2.2) depicts a simple version of a link budget equation.

$$\text{Received Power (dB)} = \text{Transmitted Power (dB)} + \text{Gains (dB)} * \text{Losses (dB)} \tag{2.2}$$

Link budget can be referred to as a quality parameter for a communication system. It is one value portrayed in dBm that gives an overview of the entire system.

2.1.7 Signal to Noise Ratio

Signal to noise ratio (SNR) is one of the most important parameters when it comes to a communication system. SNR is the power level of the desired signal when compared with the background noise. An SNR of less then one would mean that noise power is higher than the desired signal hence making the signal hard to detect. SNR of a signal can be calculated by Equation (2.3).

$$\text{SNR}_{db} = 10 * \log(\frac{P_{signal}}{P_{noise}}) \tag{2.3}$$

Figure 2.2 shows a signal in the frequency domain in comparison with the background noise. It can be seen that background noise is present in all the frequencies whereas the desired signal has a power level higher than the noise, showing an SNR of greater than one.

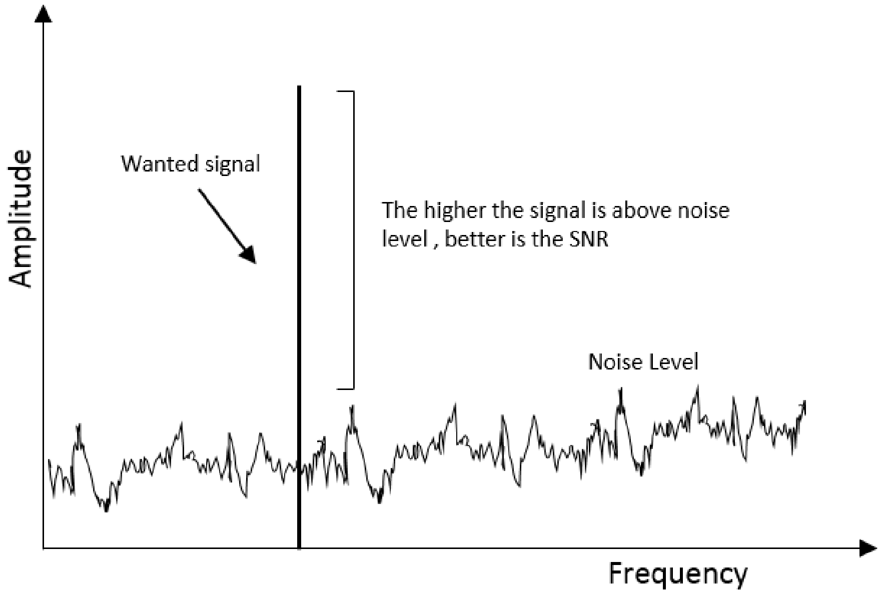

Figure 2.2: A signal with an SNR of higher than one.

In general an SNR of greater then one is a measure of good signal strength. Lower SNRs, notably less than one, may not always mean that signal is undetectable. There are special techniques through which a signal whose power level is even below noise can be detected, and communication can be carried out.

2.2 Network

In the previous section, physical properties of communication systems were discussed. This section will cover networks and standardization in network technologies, communication between devices on a higher abstraction level and different network topologies.

2.2.1 OSI Layer Model

Interconnected paths for exchanging information between heterogeneous devices is known as a network. All the communication performed in a network is easily explained by the Open System Interconnect (OSI) model [46]. The OSI model is a network framework that provides an abstract view of the communication processes by dividing the various tasks into seven layers. Each layer describes a small task in the longspun process of communication. The lower layers of this model deal with the electrical signals, whereas the higher layers deal with applications and network protocols. Figure 2.3 gives an overview of the OSI layer model, which will be briefly described next.

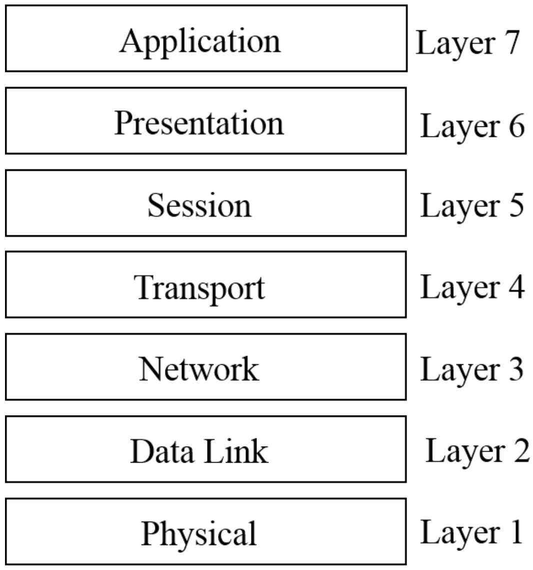

Figure 2.3: OSI layer model [46].

Application Layer

The application layer specifies shared interface methods and protocols. Hypertext Transfer Protocol (HTTP), File Transfer Protocol (FTP) and Simple Mail Transfer Protocol (SMTP) are a few examples of application layer protocols.

Presentation Layer

Operating systems such as (Windows, Linux and MacOS) reside on this layer and provide basic services to the application layer.

Session Layer

This layer is responsible for creating communication between network devices, e.g., a network session between an end user and a server.

Transport Layer

The transport layer enables communication between different applications. Each application uses its own communication channel, making it possible to communicate with applications running on different systems. The Transmission Control Protocol (TCP) is the common transport layer protocol.

Network Layer

All the routing of data is performed at the network layer. The network protocol for the internet is known as IP, which is responsible for providing addresses to the devices and carrying data from one device to another.

Data Link Layer

The link layer is responsible for converting digital signals, such as bits into transmittable signals. It also manages data encapsulation for reliable transmission.

Physical Layer

The physical layer is the bottom layer of the OSI model. It specifies the physical properties of a communication channel. This layer is responsible for transmitting data from the data link layer through a communication channel.

A layered network is scalable and flexible, but it is intricate and requires more memory and processing power because every layer puts on additional information that causes data overhead. A layer-less network design would be a proprietary application protocol, communicating directly on the physical layer like a temperature sensor in a wireless sensor network. This is a very efficient implementation, but it can only be used for simple applications and will not be able to handle a complex network configuration.

2.2.2 Network types

On a very basic level, networks are divided into the following three classes:

- Personal Area Network (PAN),
- Local Area Network (LAN),
- Wide Area Network (WAN).

Each of these networks differ in respect to range, data throughput and application.

Personal Area Network

This kind of network only covers a small area also referred to as personal space. Bluetooth [4] is one of the prime examples of protocols that conform to PAN, other examples include wired USB and Wi-Fi [14].

Local Area Network

LAN is one of the most common types of networks. Modern-day LAN is based on Ethernet and its coverage area includes homes and buildings.

Wide Area Network

WAN is a term used to describe networks that cover a wider area as compared to LAN, which is a very generic description. A WAN could be a network connecting multiple buildings to multiple continents. The Internet is the most prominent example of a WAN.

2.2.3 Network Topologies

Network components have to be connected with each other for them to communicate. This arrangement of network components is known as a network topology. The network topology is one of the core design elements in communication systems. It is one of the factors that govern the primary features of a network including scalability, robustness, data throughput, flexibility, and complexity.

Star Topology

One central server manages all the communication between all the network components in a star topology. A star topology has low complexity is easy to setup and modify, and requires less effort for upgrades. Figure 2.4 shows a star topology network.

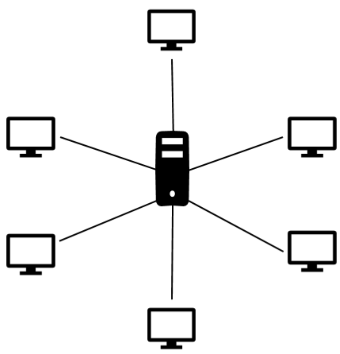

Figure 2.4: Star topology.

The downside of the star topology is its complete dependency on the server; the performance of the whole system is reliant on the server, i.e., the whole network fails if the server crashes.

Bus Topology

In a bus topology all the network components are connected to one single cable making it cost-effective, it also requires less infrastructure compared to other topologies. Bus topologies are more suited to small networks with low traffic.

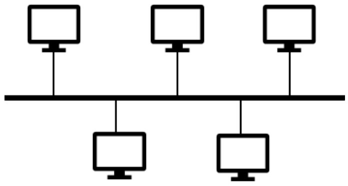

Figure 2.5: Bus topology.

The drawbacks of a bus topology are, slower speeds in case of high traffic and dependence on one central link. Figure 2.5 depicts a bus topology network.

Ring Topology

In a ring topology, the network components are connected to each other in a ring fashion as shown in Figure 2.6. Every single component in a ring topology has precisely two neighbors eliminating the need for a router.

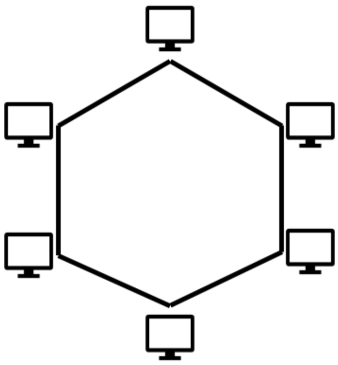

Figure 2.6: Ring topology.

Transmission is unidirectional, with the sequential transfer of data. It is cheap to install and expand. All the components are interdependent, hence the failure of one component causes the whole network to crash.

Mesh Topology

In a mesh topology, every network component is connected to all the other components. There are two modes of operation for data transfer: routing and broadcast.

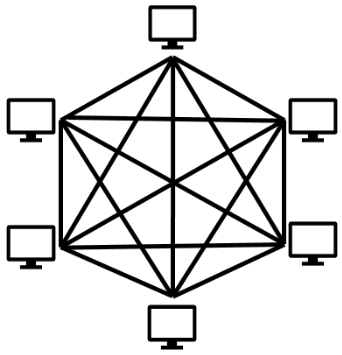

Figure 2.7: Mesh topology.

In case of routing, devices are configured to send data to the required destination. This operation requires some routing logic at target device, whereas the broadcast mechanism transmits data to all the network components. The broadcast mode is easy to implement, but adds overhead in the network traffic. Figure 2.7 depicts a mesh topology network.

2.3 Hardware Communication Protocols

The three most extensively used protocols for the implementation are RS232, 1-wire protocol, and SPI (Serial Peripheral Interface). These protocols are briefly discussed further.

2.3.1 Serial Peripheral Interface

The Serial Peripheral Interface bus (SPI) is a synchronous serial communication interface used for short distance communication in embedded systems. SPI devices communicate in full duplex mode using a master-slave architecture with a single master. The master device originates the frame for reading and writing.

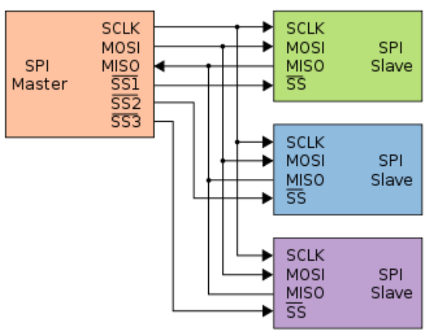

Figure 2.8: SPI Master-slave configuration.

Multiple slave devices are supported through selection with individual slave select (SS) lines as shown in Figure 2.8. SPI is used for communication between the 1611 and RFM95W at the node end, and between the concentrator board and 1613 at the gateway end (see Section 5.2).

2.3.2 1-Wire Protocol

As the name suggests, devices conforming to the 1-wire protocol use only one wire plus a ground wire to transmit signals. This communication protocol is used by the DS18B20 temperature sensor (see Section 5.1.4).

2.3.3 RS232

RS232 is an asynchronous serial communication protocol that is used for communication between 1613 and a PC (see Section 5.1). Though communication with the 1613 can be established via an ssh client program, for initial board setup RS232 is used.

2.4 LPWAN

LPWAN is an acronym for "Low-Power Wide-Area Network" and is conceived to identify particular kinds of networks, with unique operating capabilities. LPWANs tend to have a long range and low power consumption as opposed to the conventional networks. This advantage of long range and low power consumption comes at the expense of low data rates. The sensors operating on this technology could run for 5 to 10 years without replacing battery.

Beecham that is an analyst firm has forecasted LPWANs to be the backbone of IoT market. It is predicted to hold a quarter of the total IoT connectivity market. Beecham stated that by 2020 there would be approximately 345 million IoT connections. The use of unlicensed frequency and open source technologies will end the mobile network operators monopoly in IoT networks [39].

LPWAN is a new technology. The rapid growth in the IoT sector is the cause of the sudden increase in the device count, creating a demand for LPWAN networks. The term LPWAN was coined somewhere in the 2000s, but the idea behind it was first seen in the late 1980s [29].

2.5 History

Networks similar to LPWAN already existed in the end 1980s. One such network was “AlarmNet” which was created by Alarm Device Manufacturing Company (ADEMCO), one of the biggest producer of alarm panels and systems. ADEMCO built a 900 MHz network for monitoring of the alarm panels, and as the data sent by the alarms was minimal, low data rates were acceptable [29].

With the birth of 2G in the late 1990s, it was possible to transmit voice and data on the same network, and it was no longer necessary to have a dedicated network for alarm systems. Thus the need for such long-range and low data transfer rate networks died out [29].

Another Motorola owned network known as ARDIS had a similar fate. ARDIS was also a low-speed network designed for sales automation, fleet tracking, e-mail, transaction processing and messaging [29].

This concept of long range and low power disappeared in the 80s because there were never enough users and IoT was nonexistent. The use of this concept resurfaced with the introduction of IoT and increasing number of devices to be connected. Today the requirement for low cost and low data devices has increased even more.

SIGFOX [34], Ingenu (formerly OnRamp) [16], members of LoRa Alliance [23] etc. are current active contributors to the LPWAN technology each with their own respective approach, some targeting the open frequencies with open standards while others operating in licensed frequencies and offer proprietary solutions.

2.6 State of the art in LPWAN

LPWAN technologies are classified regarding the frequency spectrum they use, i.e., two basic subcategories: licensed spectrum and unlicensed spectrum. Figure 2.9 depicts graphically how the categories are made and includes the subcategories.

Cellular service providers use technologies that fall into the category of licensed spectrum. Services offered by the mobile network operators are expensive and it would be counter-productive to use them for IoT. LTE is the prevalent cellular technology and has a high data throughput, but it is expensive and LTE-based devices consume much power. NB-IoT is the new proposed technology for IoT applications in the licensed spectrum. It is promised to be cheap and power efficient. In the following, we will have a look at technologies from both categories, starting with the ones operating on unlicensed frequencies.

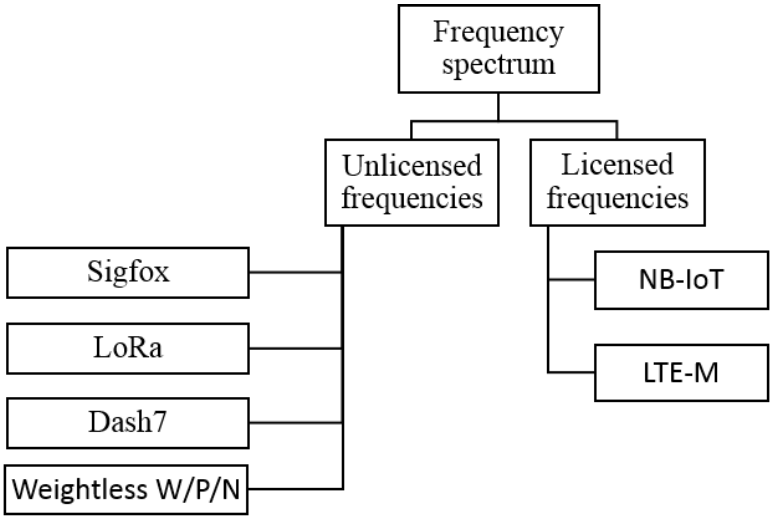

Figure 2.9: Classification of LPWAN.

2.6.1 Sigfox

Sigfox is a French company that provides communication solutions for IoT. It is Europe's leading company that provides IoT connectivity solutions based on LPWAN. Sigfox follows the business model of a cellular service provider despite the fact that it operates in the unlicensed frequency spectrum.

Ultra Narrow Band (UNB)

Sigfox uses ultra-narrow band (UNB) and binary phase-shift keying (BPSK) to achieve the extended range of an LPWAN. In UNB communication, the spectral density (see Section 2.1.3) of signal is concentrated in a narrow band of frequencies, the energy density of noise is distributed along the whole spectrum instead of being concentrated, which makes the signal in any narrow portion of spectrum always above the noise floor. The drawback is interference if noise peaks exist in the communication band.

The UNB is 192 KHz wide between 868 and 868.2 MHz in Europe, and between 902 and 928 MHz in the rest of the world. Each message on the air occupies 100 Hz as shown in Figure 2.10.

Transmission between an end device and the network is unsynchronized, the device transmits data on a random frequency and then sends two additional copies of the same message at another point in time on another frequency. This feature is known as "random access" depicted in Figure 2.11. On the other end, base stations scan the whole 192 kHz searching for UNB signals for demodulation [36].

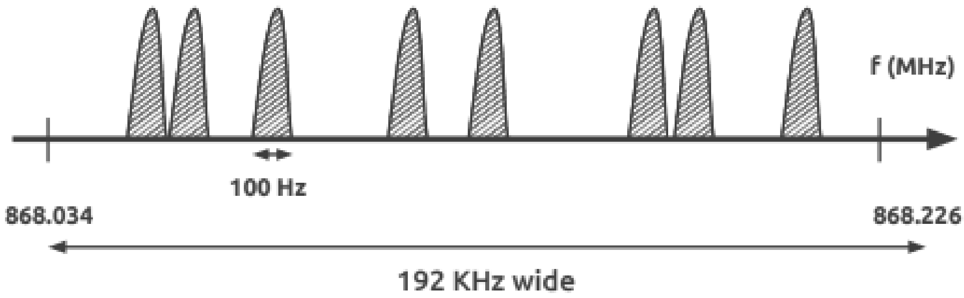

Figure 2.10: Sigfox band specification [35].

Sigfox offers "cooperative reception", which is a resource sharing technique that increases the robustness of the network by using minimum redundancies. The network element is not attached to one permanent base station; instead, the message is broadcasted and picked up by several stations and filtered at the back end. On average, Sigfox offers three base stations per device.

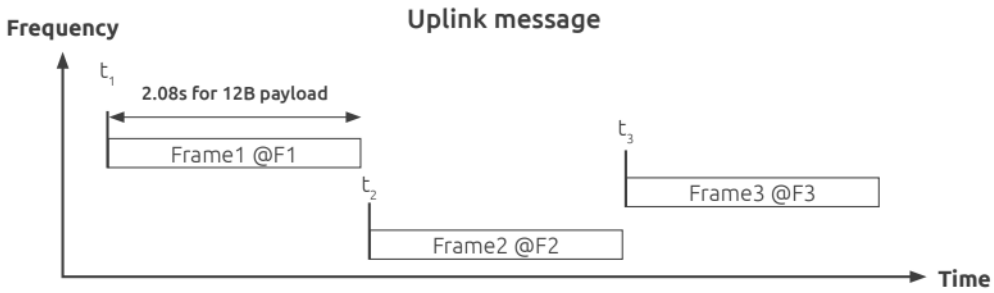

Figure 2.11: Random access [35].

Figure 2.12 shows the standard network architecture of the Sigfox network. The end devices send data to base stations over the air using the UNB and BPSK modulation technique. The base stations communicate with the backend via DSL and 3G. The backend handles all the message processing, redundant messages are discarded, and only the relevant messages are stored in the database. The web interface allows customers to access their messages by using the browser or a REST API [35].

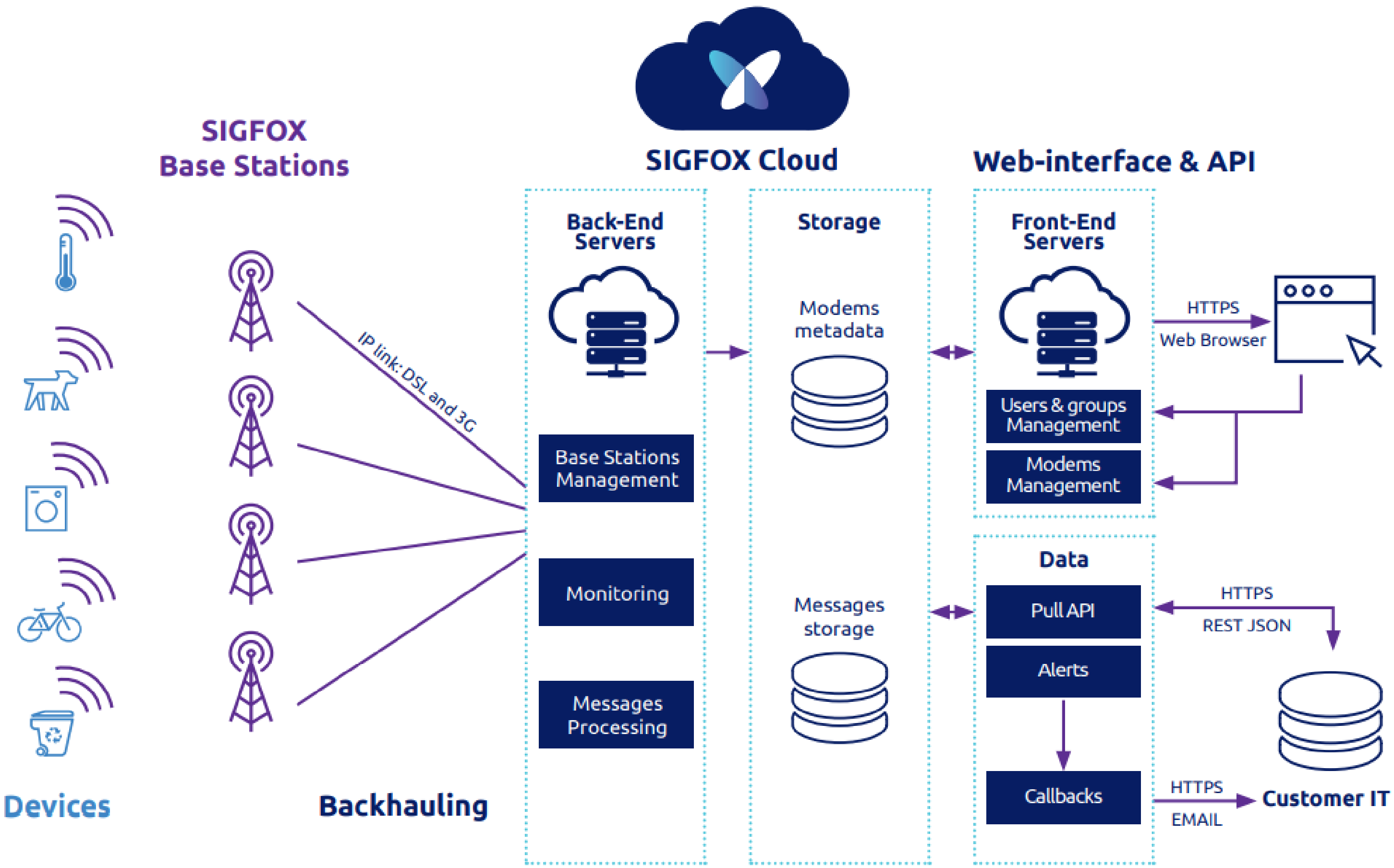

Figure 2.12: Sigfox network architecture [35].

2.6.2 LoRa

LoRa is a new modulation technique that offers long-range communication. This modulation technique can be described as a "frequency modulated (FM) chirp" or "Chirp spread spectrum" [22, 30, 33]. Chirp spread spectrum has already been in use by the military and space communication for decades because of its significant long range and robustness against interferences. However, LoRa is the first commercial use of chirp spread spectrum.

LoRaWAN Protocol

LoRaWAN is developed by the LoRa Alliance, which is an open, non-profit organization. LoRa is a link layer protocol and does not specify the network architecture. LoRaWAN, on the other hand, is a Media Access Control (MAC) layer protocol which specifies the network architecture. The protocol and network architecture are amongst the key elements that govern battery lifetime of a node, the network capacity, the quality of service, the security, and the variety of applications served by the network [22].

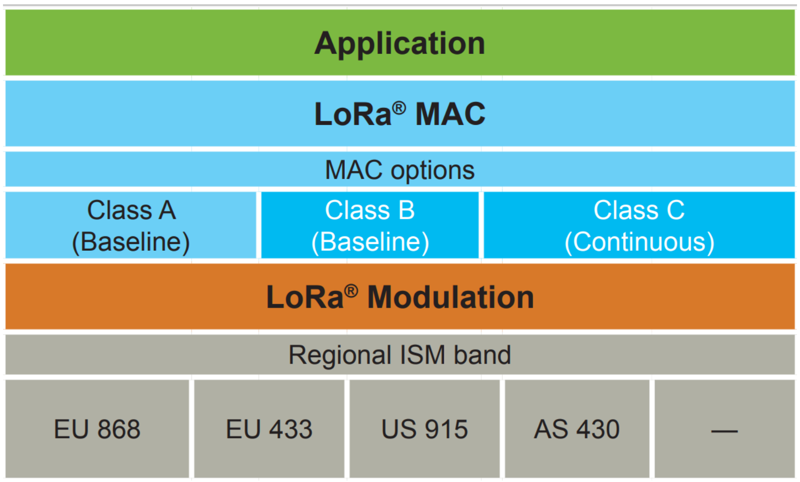

Figure 2.13: LoRa and LoRaWAN stack [22].

Mesh topology variants offer extended network range by using network elements as routers. Extension of the range is as simple as adding more devices to the network where every device acts as a repeater. This range extension adds complexity and processing overhead to the network and also reduces the battery life and network capacity [22]. Zigbee [45] is a prime example of such topology.

LoRaWAN offers "cooperative reception" where end nodes are not specified to one gateway. Instead, a node transmits the data packet to multiple gateways as shown in Figure 2.14. Each gateway then pushes packets to the server via Ethernet, Wi-Fi or some other backhaul. Message filtering and storage is done at the server side, reducing complexity from the end device and gateway.

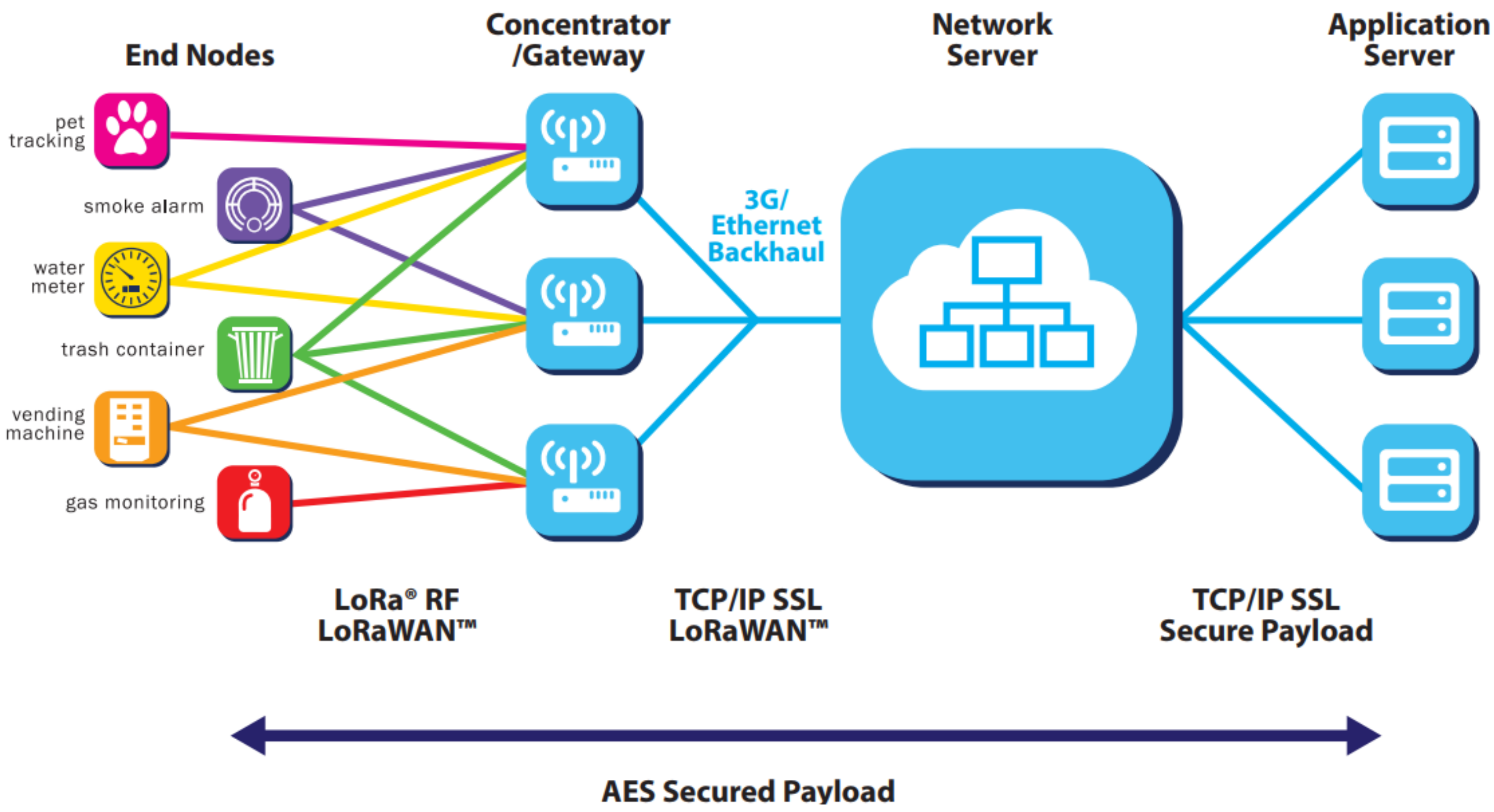

Figure 2.14: LoRaWAN network topology [22].

Cooperative reception is quite helpful in case of a mobile node; as the node does not need to switch from gateway to gateway, it keeps on broadcasting the signal and its position can be determined by monitoring the signal strength [22].

LoRaWAN Device Classes

LoRaWAN provides three device classes for various applications. These classes have trade-offs between network downlink, communication latency, and battery life as shown in Figure 2.15. Communication latency is crucial in a control application, where timely control of specific actuators is required.

Bi-directional end-devices (Class A): Class A devices allow bi-directional communication. Up-link transmission of an end device is followed by two short downlink receive windows. The Class A operation requires the lowest power as it requires downlink communication from the server only for a short interval after an uplink transmission. Downlink communication will need to wait till the next up-link transmission in any other case.

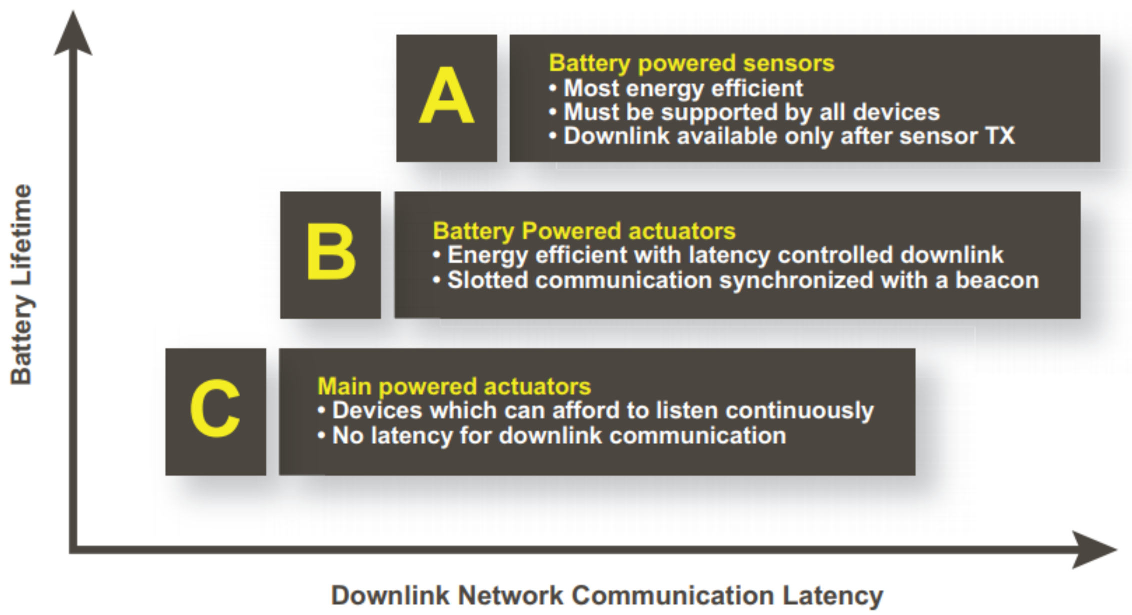

Figure 2.15: LoRaWAN device classes [22].

Bi-directional end-devices with scheduled receive slots (Class B): Class B devices have all the features of the class A devices, and they support the feature of extra receive windows at scheduled times.

Bi-directional end-devices with maximal receive slots (Class C): End-devices of Class C have almost continuously open receive windows, only closed when transmitting.

2.6.3 DASH7

DASH7 is an LPWAN communication standard. It offers extended range at low data rates for monitoring applications. DASH7 is an open source standard, and it operates in the sub-1 GHz frequency band (315 MHz and 915 MHz). The DASH7 Alliance is a nonprofit organization that is responsible for maintaining the DASH7 protocol. The protocol, officially known as the DASH7 Alliance Protocol (D7AP), has various versions, where version 1.0 is focused on wireless sensors and actuators. D7AP is a variant of the ISO/IEC 18000-7 standard [19] which was designed for 433 MHz band only, but D7AP extends it to all sub-GHz Industrial Scientific and Medical (ISM) and Short Range Device (SRD) bands (433, 868 and 915 MHz). These radio bands are reserved internationally for the use of radio frequency (RF) energy for industrial, scientific and medical purposes other than telecommunications

D7AP is an asynchronous network protocol with medium range when compared to other LPWAN technologies, following a request-response style of communication. To decrease complexity in the network, it uses a star topology, but to extend the range it allows a maximum of one hop between the node and gateway. Nodes have the option to enforce the acknowledgment from at least one gateway [11].

D7AP extends to all OSI-layers (see Section 2.2.1), from physical to application layer, as shown in Figure 2.16. D7AP has its own file system with data elements and their properties, such as permissions and storage classes. Some data elements define various parameters, while others are for sensor data storage; these data elements can be managed via the D7AP Application Layer Programming Interface (ALP). The ALP consists of commands that perform actions such as read, write, execute, etc. These ALP commands are used by the gateway or a sub-controller to manage and communicate with the end nodes [11].

The D7AP physical layer (PHY in Figure 2.16) supports 433, 868 and 915 MHz unlicensed ISM/SRD bands with three channel classes, i.e., Lo-Rate, Normal and Hi-Rate, each with a symbol rate of 9.6, 55.555 and 166.667 kbps respectively [10]. All the channels use Gaussian frequency shift keying (GFSK) as the modulation technique, but with different frequency deviations and channel spacings. Parameters, such as frequency band, data rate, transmit power, coding parameters, and constraints, such as range, antenna size, cost, and energy consumption, create a trade-off which depends on the application. For instance, using the 868 MHz instead of the 433 MHz band will decrease the antenna size, but will also affect negatively on the range as well [11].

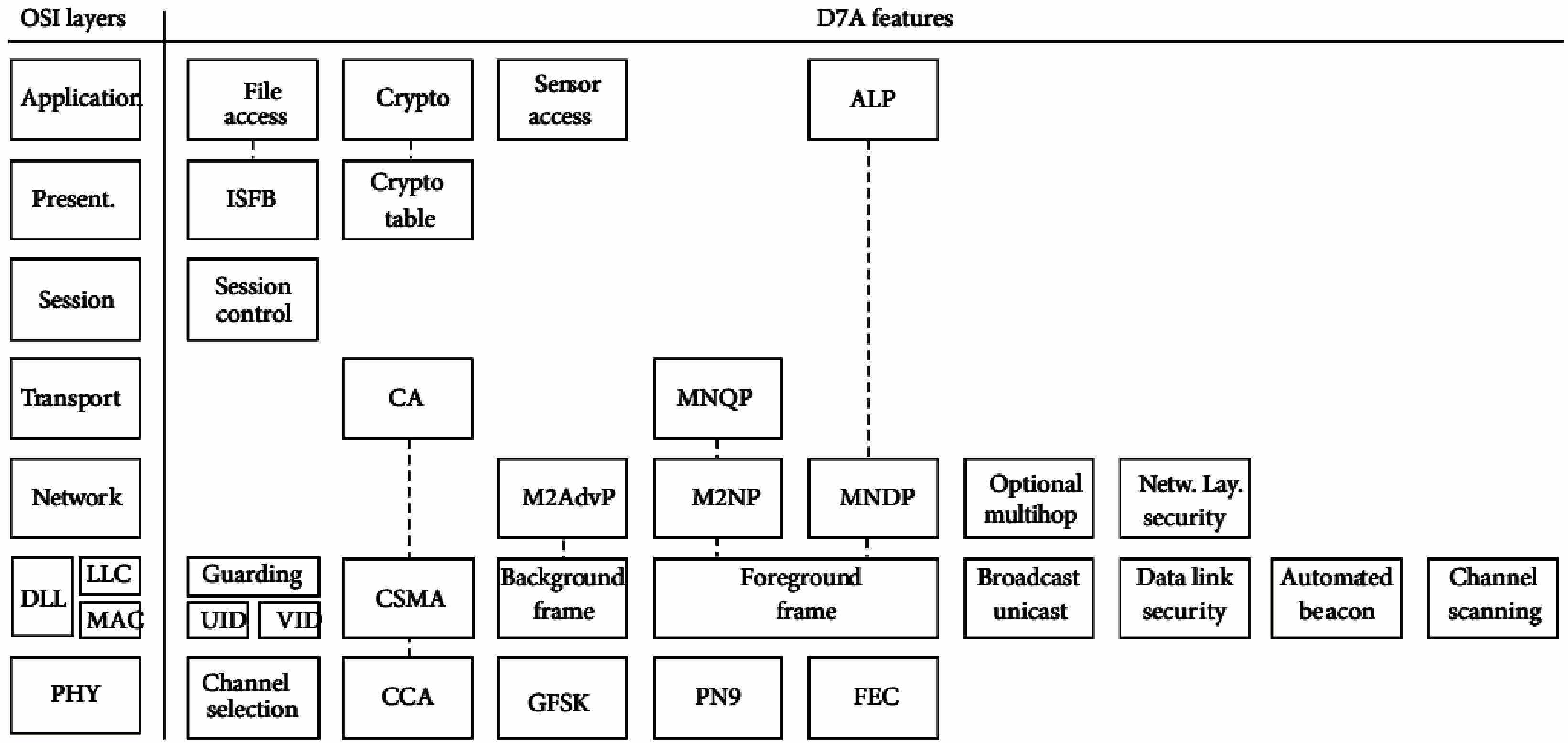

Figure 2.16: Excerpt of OSI layers based on [42].

D7AP Communication Schemes

For various application scenarios, D7AP provides three communication schemes. The schemes are as follows:

Polling data using the D7AP Advertising Protocol: A gateway can query a node using ALP commands, but the node is power constrained, it does not continuously scan for requests. D7AP has a low-power wake-up mechanism called D7AP Advertising protocol (D7AAdvP), which performs synchronization only when a request is queued [11].

Pushing data using the D7AP Action Protocol: By using the D7AP Action Protocol (D7AActP), it is possible to push data instead of querying it, as pushing data is far more efficient than querying. D7AActP allows the sensor to push data to the gateway, eliminating the need for polling. This scheme is efficient for both, event-driven and periodic data acquisition; it also provides an advantage in reduced power consumption and spectrum usage [11].

Dormant Sessions: In use cases where nodes continuously push data to the gateway (D7AActP), there might arise situations where data is to be transferred to the node, e.g., controlling an actuator. In a dormant session, the gateway queues the message with a timeout instead of transmitting it directly. When the timeout is reached, the gateway initiates a dialogue session. However, if the node initiates a dialogue with the gateway before the timeout, then the ongoing dialogue will be extended making the gateway requester and the endpoint responder. The concept of dormant sessions can be employed to avoid using the relatively expensive D7AAdvP mechanism [11].

2.6.4 Weightless

Weightless [41] is an IoT LPWAN technology that operates in both licensed and unlicensed spectrum. This technology is governed by Weightless Special Interest group (SIG), which was formed in 2012 as a nonprofit organization to cater to all the requirements of the weightless standard in the area of IoT. Weightless offers three different standards depending on the application of use, i.e., Weightless-P, Weightless-N, and Weightless-W.

Weightless-P is two-way communications standard that uses Gaussian minimum shift keying (GMSK) and quadrature phase shift keying (QPSK) modulation techniques. Weightless-P is not suitable for wide area networks. The Weightless-W standard operates in the TV white space (TVWS) spectrum. TVWS are the unused licensed frequencies that are made available for unlicensed use, e.g., television broadcast. The regulations for TVWS change with the region of operation making it unfit for an EMS. Weightless-N, like Sigfox, is an ultra-narrow band system. It uses the same modulation technique as Sigfox, but instead of being a closed system, Weightless-N is comprised of network of partners. [31].

2.6.5 Ingenu RPMA

Ingenu is a wireless network provider, whose former name was On-Ramp wireless. Ingenu provides machine to machine (M2M) communication solutions for IoT platforms. In the LPWAN sector, Ingenu holds a proprietary technology which is called Random Phase Multiple Access (RPMA).

RPMA is a cellular type technology that provides 300+ square miles per access point. It achieves this significant coverage through increased transmission power and receiver sensitivity. RPMA operates in 2.4 GHz unlicensed band with a bandwidth of 80 MHz. The most prominent advantage of using 2.4 GHz is its availability in all the countries of the world. RPMA uses the Viterbi algorithm for channel coding; this gives RPMA a Packet Error Rate (PER) of 50%, in other words even if half of the packet containing the message were lost the entire message would still be decoded [17]. Based on RPMA, Ingenu is building a network known as the "Machine network" for M2M communication only. To use the Machine Network users need to subscribe as with any other cellular network. This technology looks very promising in the IoT domain, but the fact that it is proprietary creates a dependency on Ingenue to deploy access points in the region of operation. Their network only covers the U.S. for now. It is expected to take a few years till they extend their service to European countries.

2.6.6 Licensed LPWAN

LPWAN technologies operating in the licensed spectrum are standardized and governed by the 3rd Generation Partnership Project (3GPP). To capture the IoT market in the licensed spectrum 3GPP has introduced three LPWAN standards, i.e., Extended Coverage GSM for the Internet of Things (EC-GSM-IoT), Long Term Evolution Machine Type Communications Category M1 (LTE MTC Cat M1, also referred to as LTE-M) and Narrowband IoT (NB-IoT). 3GPP represents 400 individual members; this broad support is a significant advantage when it comes to standardization and interoperability between different mobile operators and vendors [1].

2.6.7 Extended coverage GSM IoT (EC-GSM-IoT)

EC-GSM-IoT was designed to facilitate time to market by making it backward compatible; it can work with the existing GSM networks. This backward compatibility allows an easy resource sharing between EC-GSM-IoT and legacy network which enables a gradual introduction of the technology, eliminating the need to reserve dedicated resources for IoT [1].

2.6.8 Narrowband IoT

Narrowband IoT (NB-IoT) is a 3GPP release 13 feature. It uses the same principle and building blocks as the LTE physical layer, this allows for rapid standardization and product development. It has been designed inherently to have more coverage and consume less power as compared to conventional GSM networks.

2.6.9 LTE-m

LTE MTC Cat M1 or more commonly known as the LTE-m is the successor of Cat-1 and Cat-0. In 3GPP release 12, a Cat-0 UE (User equipment) was introduced with the aim to reduce complexity as compared to GSM/GPRS mobile devices. The extended battery life is achieved by use of power saving mode (PSM) and extended idle-mode Discontinuous Reception (eDRX) [1].

3 Selection of an LPWAN

One of the tasks of this thesis is to select the most feasible LPWAN solution for the application, i.e., an energy management system. Section 2.4 discusses the available LPWAN technologies in detail. This chapter will focus on the evaluation of previously discussed LPWAN technologies and selection of the most feasible technology for a prototypical implementation of an EMS.

3.1 Selection Criteria

In order for the selection of an LPWAN technology, a selection criteria has to be defined. The technologies will be evaluated on the bases of this criteria. The selection criteria is tailored for our application and should not be used as a general rule for the evaluation of an LPWAN technology. The following are the main selection criterion:

- Modulation technique,
- Data throughput,
- Operating frequency, and
- Range.

The modulation technique (see Section 2.1.5) determines the key characteristic of a communication system. Techniques that provide inherent interference protection are preferred. For instance, spread spectrum techniques are designed to be detected even below the noise level and are preferred over the others. Data throughput should be enough to transmit 100-500 bytes per 5 minutes. Operating frequency of the technology should be in the unlicensed spectrum. Node power consumption should be as minimum as possible with a range of a few kilometers. Low node power consumption is an inherent property of an LPWAN technology therefore, it is not mentioned as a key criteria.

Apart from the aforementioned points, availability, cost, effort and support for the technology are also important when it comes to implementation.

3.2 Comparison

NB-IoT is a desirable solution regarding cost and area coverage, but when it comes to cost per byte and longevity, then it is not viable, especially in applications like EMS. In Germany, only Vodafone has recently started offering an NB-IoT solution, however, due to its high dependency and cost it is not a feasible solution for now. NB-IoT operates in the licensed spectrum making it unfit for an EMS.

Section 3.2 summarizes our findings with some values extracted from the work of Raza, Kulkarni, and Sooriyabandara [32]. A comparison of the technologies can be made with respect to modulation technique, range, data throughput and operating frequency. The majority of the LPWAN technologies use an operating frequency in the SUB-GHz band except for Ingenu using the 2.4 GHz. As mentioned in Chapter 2, SUB-GHz frequencies are less prone to interferences and offer a more significant area coverage.

Sigfox uses UNB, as mentioned in Section 2.6.1. Data transfer rates are in between 100-600 bits per second depending on the region. Sigfox is well suited for low-bandwidth (less than 300 bits per second / up to 12 total bytes per payload), and low transmit frequency (up to 140 messages per day) applications. Sigfox is effective for communications from endpoints to base stations (uploads), but it is not particularly effective from base stations to endpoints (downloads) [8]. Sigfox offers excellent coverage compared to all other LPWAN technologies. It follows a cellular network like business model, forcing users to buy service and hardware. It is not allowed for the users to create custom private networks.

Weightless-N is governed by Nwave, which is an IoT solution provider. The requirement for special hardware, such as temperature compensated crystal oscillator (TCXO) and the relatively unbalanced link budget, puts Nwave at a disadvantage over the LoRa based systems. The Weightless-W standard operates in the TV white space (TVWS) spectrum. TVWS are the unused licensed frequencies that are made available for unlicensed use, e.g., television broadcast. It is an advantage to use the unused VHF and UHF bands, but the regulations for TVWS differ from region to region besides nodes are designed specifically to a certain frequency. Designing nodes for a wider range of frequencies would put a huge constraint on antenna construction and other parameters. RF systems are not flexible to adapt to multiple frequencies with the same antenna. Weightless-P is a two-way communications standard that uses a 12 kHz channel, making it reasonably narrow band. Weightless-P is not suitable for wide area networks because the receiver sensitivity of 12 kHz minimum shift keying channel will not be able to match a narrow band Binary phase shift keying (BPSK). Weightless-P caters to all the cons of Weightless-W/N, but at the cost of less range. Aside from these, there is not much support available for weightless conforming devices; and weightless based sensors are hard to find in the market [31].

Ingenu's RPMA is the most attractive technology that exploits the free ISM 2.4 GHz band for its data throughput, although this frequency band is more susceptible to interference because a massive number of other devices also use this band, such as Wi-Fi devices. This technology requires that the area of operation is covered by Ingenu's RPMA access point, adding a dependency on a third party. RPMA is a proprietary technology, and

Ingenu's business model is that of a Mobile network provider. Apart from these downsides, Ingenu is offering its services only in the U.S. for now, making it unsuitable for application requirements of this thesis.

DASH7 offers an excellent energy-per-bit aspect and is ideal for sensor/actuator data, but DASH7 lacks the range required for the application of EMS. Higher ranges are obtainable at the cost of more energy per bit.

LoRaWAN uses the star topology. To achieve long-range communication, a gateway must be capable of receiving data from a high number of end nodes. LoRaWAN offers "Adaptive data rate" and "Multi-channel multi-modem transceiver" on the gateway, which allows the reception of multiple messages simultaneously on multiple channels. The key factors that affect a gateways capacity are the number of concurrent channels, data rate (time on air), the payload length, and how often nodes transmit. LoRa is a "spread spectrum" based modulation technique, where signals on different spreading factors do not interfere with each other, hence making it possible for the gateway to receive multiple data rates on the same channel simultaneously. If a node is closer to the gateway, it does not always have to use the lowest data rate and occupy the link for a longer time. Instead, it could use the highest possible data rate and keep the link free for a long time for other nodes. The adaptive data rate can optimize the battery life of a node. Adaptive data rate requires symmetrical uplink and downlink with sufficient downlink capacity, causing LoRaWAN to have a high capacity and scaling capability of 6 to 8 times. This scaling capacity is unique to LoRaWAN as other LPWANs have asymmetrical up and downlink. LoRaWAN nodes communicate asynchronously, i.e., they only transmit when the data is ready to send, or an event is triggered, this kind of protocol is called Aloha protocol. In synchronous networks such as cellular networks, the nodes have to frequently synchronize with the network to get messages, this synchronization is power intensive and reduces the battery life significantly. LoRaWAN has shown to have 3 to 5 times the advantage, compared to all other LPWAN technologies in the area of power consumption [22].

Technology/Standard	Modultion	Range	Data throughput	Operating Frequency	Channels
LoRaWAN	CSS	5 km (Urban), 15 km (Rural)	0.3-37.5 kbps (LoRa), 50 kbps (FSK)	SUB-GHz ISM: EU (433 MHz, 868 MHz), US (915 MHz), Asia (433 MHz)	10 in EU
Sigfox	UNB DBPSK (UL), GFSK (DL)	10 km (Urban), 50 km (Rural)	100bps (UL), 600bps (DL)	SUB-GHz ISM: EU (868 MHz), US (902 MHz)	360
Ingenu	RPMA-DSSS (UL), CDMA (DL)	15 km	78 kbps (UL), 19.5 kbps (DL)	ISM 2.4 GHz	40 1-MHz channels, up to 1200 signals per channel
WEIGHTLESS-W	16-QAM, BPSK, QPSK, DBPSK	5 km	1-10 kbps	TV white space 470-790 MHz	16 or 24 channels (UL)
WEIGHTLESS-P	GMSK, offset-QPSK	2 km	200 bps - 100 kbps	SUB-GHz ISM or Licensed	multiple 12.5 kHz channels
WEIGHTLESS-N	UNB DBPSK	3 km	30-100 kbps	SUB-GHz ISM: EU (868 MHz), US (915 MHz)	multiple 200 kHz channels
DASH7	GFSK	0-5 km (Urban)	9.6, 5.6, 66.7 kbps	SUB-GHz ISM: 433 MHz, 868 MHz, 915 MHz	3- different channel types number depends on type and region

Table 3.1: Comparison of various LPWAN technologies and standards extracted from [10, 18, 22, 32, 35].

LoRaWAN based on LoRa modulation has the range, data rate, and an open source mac layer protocol (LoRaWAN) making it an excellent candidate. LoRa and Sigfox were tested in a real-world environment by Nolan, Guibene, and Kelly [25]. They carried out their experiments on the eastern seaboard of Ireland. They were able to cover an area of 1380 square kilometers with 90% coverage using a single LoRa base station. Table 3.2 taken from [25] shows useful field results of the two LPWAN technologies. It is clear that LoRa modulation requires significantly less transmit power, has an antenna sensitivity that is better by a factor of 8, and a bigger payload size while employing open standard. Petajajarvi et al. [26] also carried out field experiments on land and water in Oulu, Finland. Their experiment focused on the coverage of mobile nodes based on LoRa technology. They were able to achieve a packet loss ratio of 15% in the range of 2-5 km on land and 31% in the range of 5-15 km on water.

Features	LoRa (Semtech SX1272)	SigFox (AXSEM)
symmetrical Technology	Y	Y
Uplink	Data + ACK	Data
Payload size	19-250 bytes	12 bytes
Protocol Overhead	12 bytes	26 bytes
TX power	13 dBm	14 dBm
TX consumption	28 mA	45 mA
RX consumption	10.5 mA	10 mA
Encryption	AES-128 E2E	AES-128
Open Standard	Y	N
Technology	CSS/FSK/OOK/GMSK	GFSK/BPSK
Sensitivity (dBm)	-137	-129

Table 3.2: LoRa versus Sigfox comparison (table taken from [25]).

LoRaWAN comes with one drawback, i.e., the dwell time limitation. The time a signal requires to be in the air is known as dwell time, in other words, it is the duration for which the device occupies the channel for active communication. In the EU 863-870 MHz ISM band, LoRaWAN limits the duty cycle to 1% for data, to avoid network congestion.

3.3 Conclusion

Every technology has some perks that others lack. It is always a trade-off between range, data throughput, power consumption, cost and device availability. The selection of technology is highly dependent on the application at hand. For instance Wi-Fi is easily available and has a high data throughput, but cannot be used for wireless sensors because of its limited range and high power consumption, same holds for the conventional technologies like ZigBee, Bluetooth, Z-Wave, etc.

This thesis focuses on an energy management system, where data acquisition through sensors is the essential task. Technologies that are region independent and use unlicensed spectrum are preferred. Technologies that are strictly proprietary e.g., (Sigfox, Ingenu's RPMA) and compel users to buy hardware and services (network) also pose a limitation to the customer base. Enisyst offers its smart energy solution to customers throughout Europe, and cannot afford to deploy technologies that are regional dependent or infrastructure dependent. Using such technologies will add unnecessary dependencies.

Keeping in view the selection criteria LoRaWAN fits this application best. Though it uses a proprietary modulation technique (LoRa); only Semtech produces chips that perform LoRa modulation. It still is in the same category of cost as other LPWAN end devices. Manufacturers, such as Microchip [24], are to produce LoRa based modules in the future, further reducing the cost and eliminating monopoly of the manufacturer.

4 Concept

In this chapter, a standard energy management system will be discussed, which will be used as a template for the implementation.

4.1 Energy Management System

An EMS that is designed specifically for buildings was formerly known as Building Energy Management System (BEMS), today it is referd to as EMS. An EMS is defined as a computer based system that monitors and controls a buildings mechanical and electrical equipment [15]. EMS consists of software and hardware. Its hardware includes a network of sensors and actuators, whereas the software includes algorithms for smart control and buses for intercommunication. The aim of an EMS is to minimize energy waste by using it efficiently to achieve monetary and environmental benefits. Figure 4.1 shows a block diagram of a wired EMS. A standard EMS comprises of the following components:

- Central controller,
- External controller,
- Actuators,
- Sensors, and a
- Graphical User Interface (GUI).

These components are describe as follows.

4.1.1 Central controller

The central controller is where all the algorithms for smart control are implemented. It polls the data from the sensors and controls the actuators accordingly. The central controller can be accessed via a Graphical User Interface (GUI) for setting up various parameters.

4.1.2 External controller

The external controllers serve the purpose of Inputs/Outputs (I/O) extension as well as repeaters or signal amplifiers.

4.1.3 Actuators

An actuator is an electromechanical component that is used for moving and controlling a system. An actuator needs a control signal and a source of energy. In an EMS the actuators are generally mounted on heat pumps, CHP generator, water pumps and valves. The algorithm running on central controller is responsible for controlling the actuators.

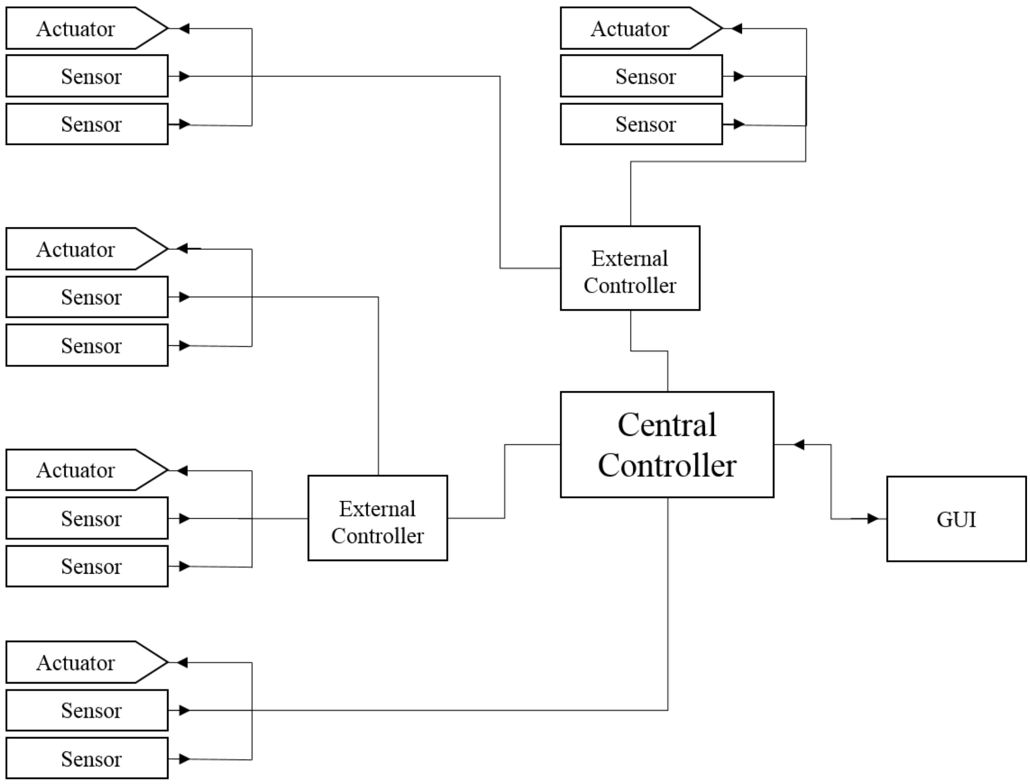

Figure 4.1: Block diagram of an EMS extracted from [13].

4.1.4 Sensors

A sensor is a component that converts non electrical energy into electrical energy so that it can be measured. The sensors generally used in an EMS are: temperature sensors, humidity sensors, smoke detectors, carbon mono-oxide detectors, light sensors, and flow measurement sensors etc., also various types of meters including electricity, gas and water meters.

4.1.5 Graphical User Interface (GUI)

The GUI is used to access the Central controller. An EMS is designed to be flexible and can be configured for different seasons and operating conditions. The GUI of an EMS provides a platform where such changes can be made.

5 Prototypical Implementation of an LPWAN based EMS

In this chapter, a prototypical implementation of an Energy Management System (EMS) will be carried out using LoRa technology. A standard EMS is defined and discussed in Chapter 4. Based on this standard, a prototype will be implemented.

5.1 Hardware Setup

This section will focus on the hardware required to set up a LoRa based EMS. All the hardware for its implementation has to be industrial grade because Enisyst provides industrial grade solutions to its customers. The LoRa based EMS is integrated with the current Enisyst system and to reduce extra hardware, all the implementation is done on the standard hardware used by the eni.os, which is the Enisyst's backend responsible for monitoring and control. The internal workings of eni.os are confidential and are out of scope of this thesis. The transfer of sensor data to the eni.os will be discussed in Section 5.2.2.

5.1.1 Enisyst 1613 module

Enisyst 1613 module uses Phytec's phyCORE-AM3352 [28] System On Module (SOM). This SOM is equipped with Texas Instruments's Sitara [40] processor which is based on the ARM Cortex-A8 [2] processor as shown in Figure 5.1.

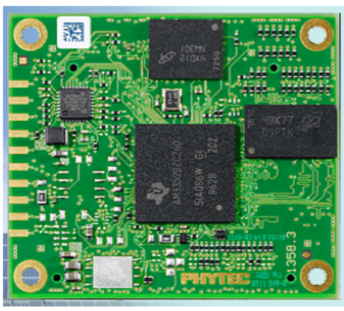

Figure 5.1: phyCore AM3352.

This processor supports Controller Area Network (CAN), Serial Peripheral Interface (SPI), RS232, USB, and Ethernet. It is entirely capable of running embedded Linux on it as well. The distribution of Linux currently running on phyCORE is created by "The Yocto Project" [44], which will be discussed in Section 5.2.2.

5.1.2 phyBOARD

The phyBOARD-Regor is an extension board on which the phyCORE-AM3352 module is mounted. This extension board is developed for use in standard DIN rail housings (e.g. Bopla CombiNorm-Connect). As shown in Figure 5.2 it contains all the ports for

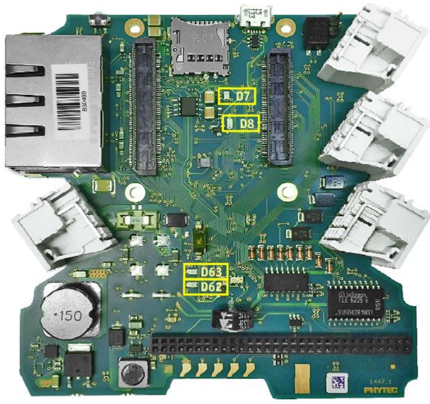

Figure 5.2: phyBOARD Regor.

the common interfaces such as 2x Ethernet, 2x LAN, CAN, RS485 and RS232. Also, the phyBOARD-Regor can be extended via a 60-pin expansion bar.

5.1.3 LoRa Node

RFM95W as shown in Figure 5.4 is used as LoRa transceiver. It supports SPI protocol for communication with other modules.

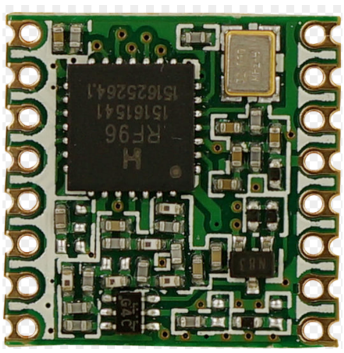

Figure 5.3: RFM95W LoRa transceiver.

It is mounted on the breakout board for ease of use. The RFM95W costs less than 1€ and offers the following key features:

- 168 dB maximum link budget,
- +20 dBm - 100 mW constant RF output vs. V supply,
- +14 dBm high-efficiency PA,
- Programmable bit rate up to 300 kbps, and
- High sensitivity: down to -148 dBm.

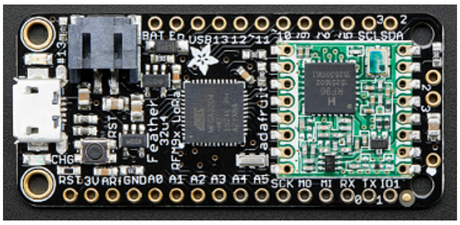

Figure 5.4: RFM95W mounted on the break out board.

It is connected with the 1611 extension board via the SPI to create a LoRa node.

5.1.4 DS18B20

DS18B20 is the standard temperature sensor used by Enisyst systems. Unlike the famous PT1000, it is a digital temperature sensor that uses a 1-wire protocol for transmitting information.

Figure 5.5: DS18B20 digital temperature sensor.

5.1.5 1611 extension module

Enisyst's 1611 is an extension module which is used to extend the I/Os for the Enisyst 1613 module (phyBOARD-Regor). 1611 is equipped with an ATMEL's AVR [3] microcontroller to communicate with the 1613 module via the RS232 interface.

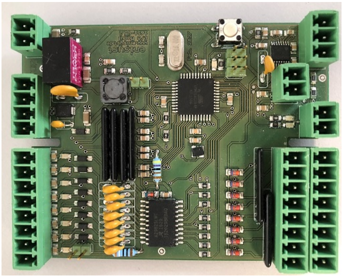

Figure 5.6: 1611 extension module.

Figure 5.6 depicts a 1611 module. For the application of LoRa based EMS, 1611 is used as a node; multiple DS18B20 temperature sensors are connected to the 1611 module. It takes the inputs from the temperature sensors via the 1-wire protocol and sends it to the RFM950W LoRa transceiver via the SPI.

5.1.6 LoRa concentrator board

For setting up a LoRaWAN network, it is required to have a LoRaWAN gateway. This gateway works like any other gateway and receives the LoRa modulated signals from the end nodes. These received packets are then forwarded to the back-end server where the messages are stored and analyzed.

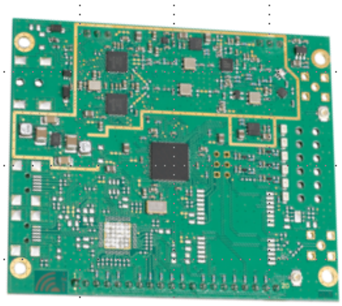

Figure 5.7: LoRa concentrator module ic880a.

LoRa concentrator ic880a, as shown in Figure 5.7, is capable of receiving LoRa modulated signals on eight different channels simultaneously. This module communicates with 1613 module via the SPI protocol, and together they act as a LoRaWAN gateway. There are a few LoRaWAN gateways readily available on the market, but due to specific requirements, a custom LoRaWAN gateway was designed using the 1613 module and ic880a concentrator.

5.2 System Architecture

This section will focus on the whole system architecture of an IoT based EMS. Figure 5.8 shows a top-level view of the entire system. A LoRa node sends temperature sensor values to the gateway via LoRa modulated signals over the air, the signals are received at the gateway-end, and are published to a message broker at the server side.

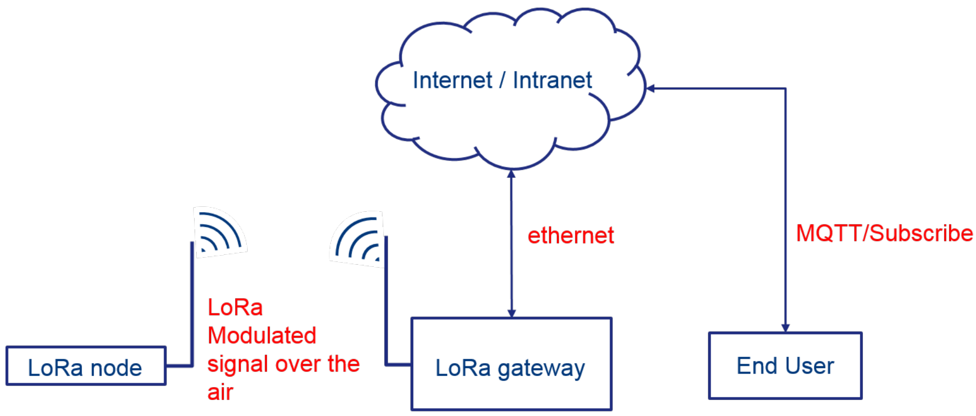

Figure 5.8: Top level view of the whole system.

The end user application can also monitor the values by subscribing to the specific topic. The received values at the gateway-end are decrypted and decoded by a JavaScript (Js) script. The script sends these values to eni.os via Unix domain socket. The values are analyzed by eni.os, and respective actuators are activated. A detailed overview of the whole system architecture is depicted by Figure 5.9. All the internal software modules and their interconnecting communication protocols are also highlighted.

Figure 5.9 can be compared to the standard architecture shown in Figure 4.1. Due to LoRa's dwell time limitation, the wireless part of the EMS will be used just for monitoring, whereas for controlling the actuators standard cable connection is used. The 1613 module in Figure 5.9 is the central controller in our EMS, which receives the temperature sensor data wirelessly via the LoRa modulated signal. The extension board 1611 can be compared to the external controller in the standard architecture. The end user can access the Enisyst EMS to set various parameters, including a timing schedule for heating and cooling.

5.2.1 Node

The node consists of DS18B20 temperature sensors, 1611 module, and the LoRa RFM95W transceiver. As shown in Figure 5.10, the values are read from the sensors and sent to the gateway via the uplink. To comply with the 1% rule of the ISM band and to always send the most up-to-date data, a "scheduler" programme was implemented.

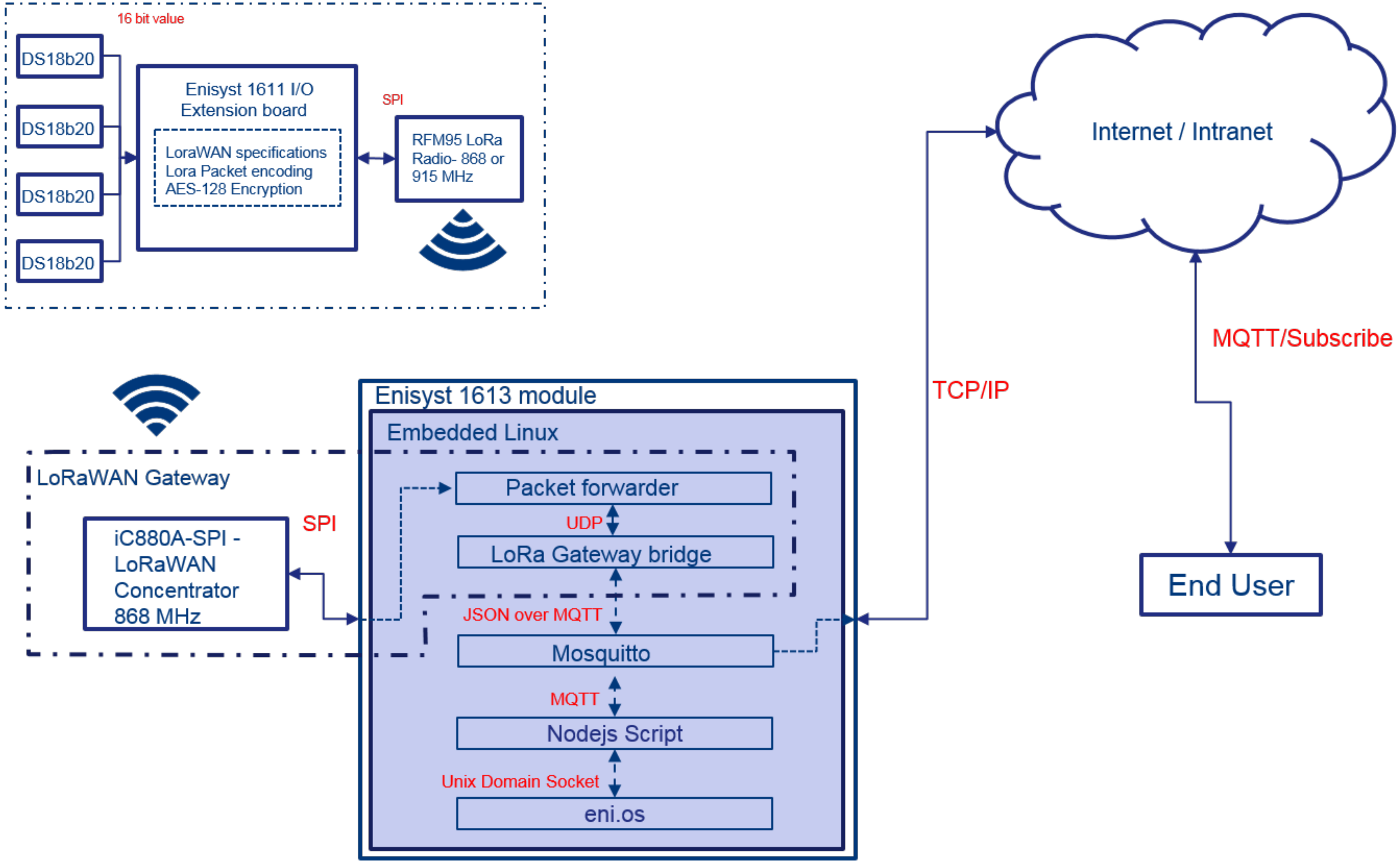

Figure 5.9: Detailed system architecture.

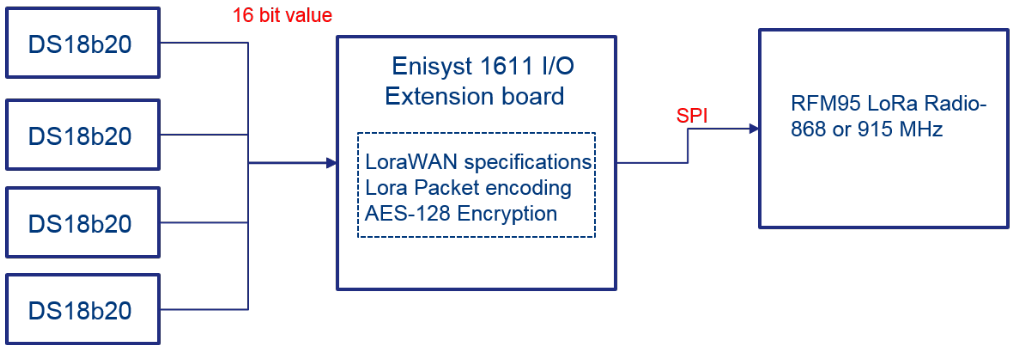

Figure 5.10: LoRa node.

The flow chart shown in Figure 5.11 depicts the sequence flow of a single loop of the scheduler programme. In every loop, the scheduler reads all sensors and inputs, "checkValues()" performs this operation. After that, it checks if the timer for SYNC message has expired. The SYNC message is a flag for the timer that is used for sending the sensor data periodically. An expired SYNC means that the sensor values should be sent right now while resetting the SYNC. This mechanism is useful in case of environmental data acquisition. It is not efficient to store real-time environmental data. Measuring values every 1 to 6 minutes is good enough for efficient heating control. After SYNC, the scheduler checks if LoRa's 1% rule is met, if it is true, the next HEX string for the uplink is assembled. If not, this step is skipped, and the loop ends. At any given time in the loop of the scheduler programme, it is possible that it can be interrupted to set an error code. If this happens, the next uplink is an error message instead of a data message.

Since LoRaWAN is subject to the 1% rule, care must be taken to minimize the amount of data to be transmitted. Therefore it will not use an ASCII-based approach, but a hexadecimal approach. This means, data to be transmitted is in hexadecimal format. For this purpose, a separate format was created, which is optimal for this application. The data format essentially consists of two parts. The first two bytes describe the data type, whether it is a error message or a data message. The bytes after represent the data. This structure is shown in Table 5.1

2 Byte	**X Byte**	...
assignment field	data	...

Table 5.1: Structure of a HEX message of the 1611 node.

The first two bytes of each message is referred to as "assignment field." Here bits 1-15 are used to define the type of data that is present in the message. Bit 0 denotes the mode bit, i.e., when it is set, the message is an error message. For each sensor or input on the 1611 module, its respective bit shows if data is present in the message. For instance, if the bit 0 is set and bit 1 is also set, this means an error message from the temperature sensor T1, and if bit 0 is not set and T1 is set it means data message from T1. An error message is defined to have a length of one byte; which means up to 255 different errors can be transmitted. If the message is a data message, bit 0 is not set. A temperature value has the length of

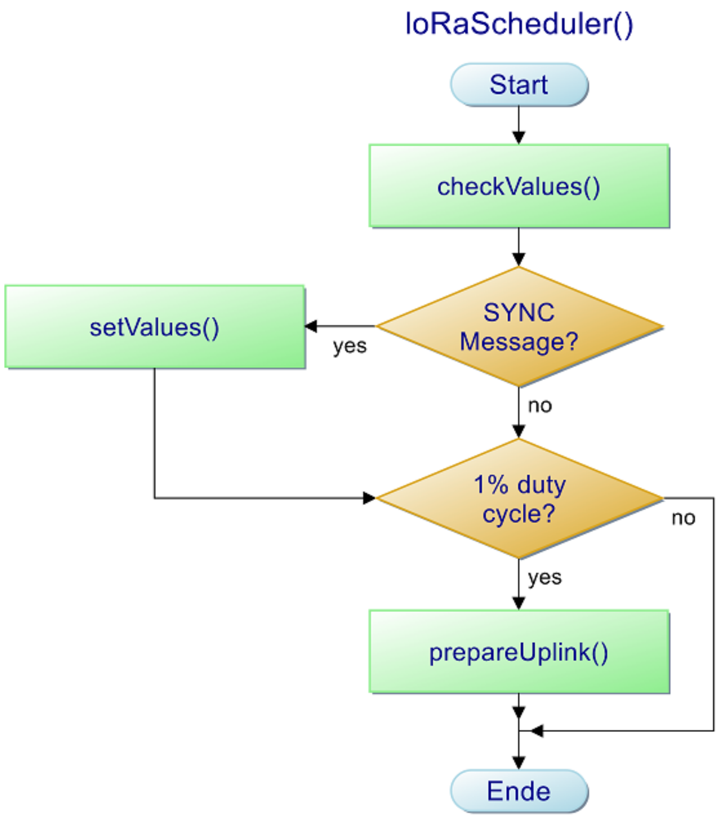

Figure 5.11: Scheduler flow chart.

2 bytes and is transmitted as a 16-bit signed integer. An analog input has the length of 2 bytes and is sent as 16-bit signed integer.

Bit	0	1	2	3	4	5	6	7
Input	M	T1	T2	T3	T4	T5	AE1	AE2

...

8	9	10	11	12	13	14	15
DI1	DI2	DI3	DI4	DI5	DI6	DI7	DI8

Figure 5.12: Structure of the first two bytes of a hex message.

An electricity meter value has a length of 3 bytes. The meter gives two values; the pulse counter and the time between two pulses. The pulse counter value has a length of 1 byte and is transmitted as an 8-bit unsigned integer, whereas the time between two pulses has the length of 2 bytes and is a 16-bit unsigned integer. The detailed structure is shown in

Figure 5.12. The identifier M stands for the mode of the message, data or error message. T1 to T5 stands for the temperature values, AE1 and AE2 for the analog inputs and DI1 to DI8 for the digital inputs.

Public Member Functions

	Uplink (uint8_t size)
void	**reset** (void)
uint8_t	**getSize** (void)
uint8_t *	**getBuffer** (void)
uint8_t	**copy** (uint8_t *buffer)
uint8_t	**addAnalogInput** (uint8_t channel, int value)
uint8_t	**addTemperature** (uint8_t channel, int16_t celsius)
uint8_t	**addPower** (uint8_t channel, uint8_t counter, uint16_t time)
uint8_t	**addError** (uint8_t channel, uint8_t code)

Figure 5.13: Class diagram.

The implementation of the data layout was done on 1611 as a class; the class diagram is shown in Figure 5.13. One complete message can have a maximum length of 51 bytes, and the maximum transferable data at the highest spreading factor is also 51 bytes.

5.2.2 Gateway

A block diagram of the gateway is shown in Figure 5.14. The gateway is formed by several software modules working together. Each of these modules is communicating with the others via communication protocols such UDP, MQTT, and SPI. These software modules are running on a custom distribution of embedded Linux version 4.4. The software modules, i.e., Mosquitto server, nodejs script and LoRaWAN gateway can be run separately on different hardware systems as well.

Enisyst 1613 software setup

The hardware specifications of the 1613 module were mentioned in Section 5.1.1. In this section, the base software setup of 1613 will be discussed. The 1613 module supports embedded Linux. The Linux distribution required for the implementation is custom created via "The Yocto Project."

The Yocto Project is an open source collaboration project that creates custom Linux-based systems for embedded products, regardless of the hardware architecture. The project provides a flexible set of tools and a space where embedded developers worldwide can

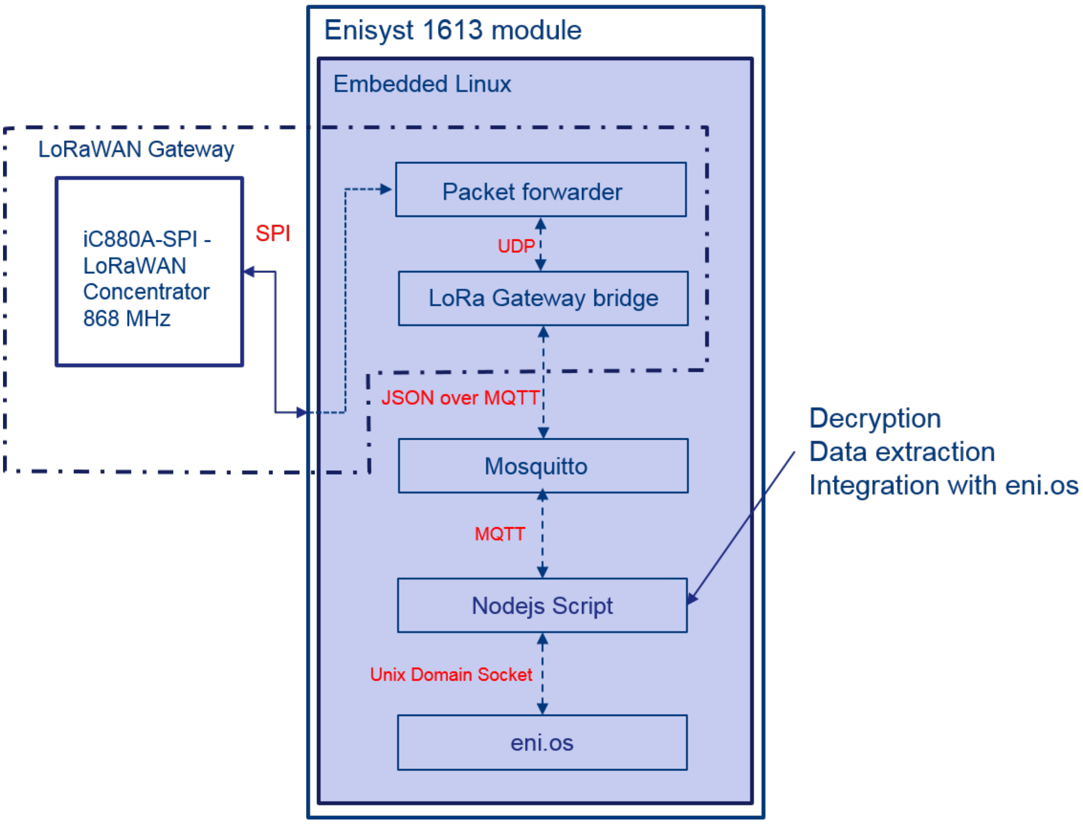

Figure 5.14: Internal software modules at the gateway end.

share technologies, software stacks, configurations and best practices which can be used to create tailored Linux images for embedded devices [44].

Package name	**Required for**
mc, nano, autoamake, git	Debuging, on board compiling
openvpn, apache2	eni.os
stunnel, tunctl, tcpdump	Network managment and security
spitools	1611, 1613, ic880a
nodejs, nodejs-npm	Running Js scripts
mosquitto	Message broker
erlang	LoRa Gateway Bridge
python (pandas, matplotlib)	Data analysis and viusalization

Table 5.2: Package dependencies.

The Yocto Project uses a build system known as "BitBake." It is a scheduler and execution engine which parses instructions (recipes) and configuration data. It then creates a dependency tree to order the compilation, schedules the compilation of the included code, and finally, executes the building of the specified, custom Linux image (distribution). BitBake is a make-like build tool. BitBake recipes define how a particular package is built. They include all the package dependencies, source code locations, configuration, compilation, build, install and remove instructions. Recipes also store the metadata for the package in standard variables. Related recipes are consolidated into a layer. During the build process, dependencies are tracked and native or cross-compilation of the package is performed [44]. To run all the software modules at the gateway end, a Linux distribution with support for the packages shown in Table 5.2 was created.

Packet forwarder

The packet forwarder [9] is an open source program provided by Semtech. It is running on the 1613 module, and it communicates with the concentrator board via the SPI protocol. All the received RF packets are forwarded to LoRa Gateway Bridge via UDP. It uses the following helper programmes:

- util_sink: It is a simplistic program listening on a UDP port for datagrams and displays a notification message when a packet is received. The content of the datagram is not displayed.
- util_ack: This program sends merely the acknowledgment of messages.
- util_tx_test: The network packet sender is a simple helper program used to send packets through the gateway-to-server downlink route.

LoRa Gateway bridge

LoRa Gateway Bridge [5] is an open source service which abstracts the "packet forwarder" UDP protocol into JSON over MQTT. It enables the use of MQTT for receiving data from and sending data to the gateways. LoRa Gateway Bridge is part of the LoRa Server [6]. LoRa Server is an open-source LoRaWAN network-server, part of the LoRa Server Project [7]. LoRa Gateway Bridge makes use of MQTT for publishing and receiving application payloads. It is one of the requirements of LoRa Gateway Bridge to have an MQTT broker to work, for this purpose Mosquitto is used.

As shown in Figure 5.15 taken from [5], the LoRa Gateway Bridge can run on the same host as the packet forwarder or a separate host as well. Keeping in view the Enisyst system the best possible scenario is to have all the software modules running on the same host. Running all the modules on the same host will reduce the hardware cost and effort. The current hardware used by the Enisyst system is fully capable of running all of the modules. Using the modular approach makes the system scalable in case any of the modules need to be deployed on different hardware because of resource management or any other reason. All the modules communicate with each other via standard Internet protocols. The system architecture will remain the same if they are deployed on different hosts.

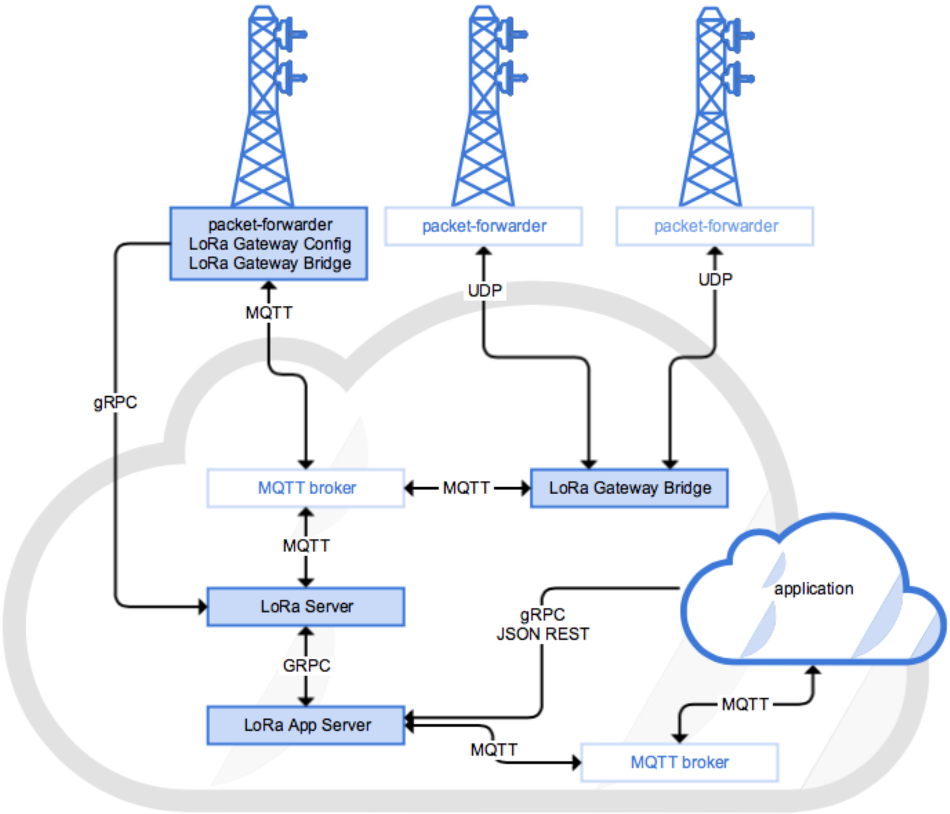

Figure 5.15: Network configuration using LoRa Gateway bridge and packet forwarder.

Mosquitto server

Mosquitto [21] is an open source message broker that uses the Message Queue Telemetry Transport (MQTT) protocol versions 3.1 and 3.1.1. A message broker is a middleware that acts as a mediator between applications. There are a few other open source MQTT message brokers available today such as EMQ (Erlang MQTT Broker) [20], VerneMQ [12] and RabbitMQ [38]. Amongst all these message brokers Mosquitto is the lightest. As described before, the Enisyst system is running on an embedded computer, which makes Mosquitto an ideal candidate for this application.

The publish/subscribe scheme used for machine to machine (m2m) communication has become the defacto in the realm of IoT. The MQTT is a lightweight method of communication between devices that do not have the computing resources to use complex communication protocol.

Nodejs script (Decoder)

The nodejs script creates a connection to the Mosquitto server. It does not make a difference if the Mosquitto server is running on different hardware. In this case, the Mosquitto server is running on the same hardware, so a connection to the local-host is made. In some cases, the Enisyst system is deployed in complete isolation and no or limited internet connectivity is available. For such cases, it is more suitable to run all the software modules on one host. After establishing the connection, the script subscribes to the specific topics. The topics have the same Unique ID as 1611 module. The received messages are decrypted, and the 51-byte long hex string is decoded. The data is extracted from the string and sent to eni.os via Unix domain socket. For the purpose of debugging, the script also establishes a connection with a remote Mosquito server via the internet. It publishes the extracted data to the server, which can be seen by any user who has subscribed to the correct topic.

eni.os

It is a proprietary software module owned by Enisyst. It is responsible for monitoring and control. The internal workings of this module are strictly confidential and can not be discussed in this document. For this thesis, this module will be considered as a black-box that takes sensor values as inputs and transmits signals to actuators.

5.2.3 End user

The end user represents an interface where the data can be visualized. The visualization tool is written in JavaScript and runs in a browser. It uses D3 (Data-Driven Documents) to implement the line chart, bar graphs and scatter plot. D3 is a low-level JavaScript library. Details of this tool are out of scope for this thesis.

6 Range Assessment

This chapter will be focused on our findings after implementing LoRa as a baseline technology for communication between an end node and the central controller. The range tests were performed in the industrial area of Pliezhausen, Baden Würtemburg, Germany. The area is densely populated with various industry with more interference than residential areas.

6.1 Range test

Figure 6.1 shows the paths over which the SNR values were recorded. SNR (see Section 2.1.7) is a measure of the signal quality, the negative SNR shows that LoRa modulated signals can be detected even if they are below the noise level. The orange lines in the map denote the path over which SNR was recorded, every blue mark on the path is the exact point where the value was recorded. The gateway was placed inside the office on the 1st floor like any other Wi-Fi router. The yellow lines in the map show the displacement between the gateway and the peak points on the map.

The reason for the difference between distances amongst different paths is the uneven terrain of the area. Figure 6.2 shows the total area that can be covered by one gateway. The signal reception can be optimized even further by creating line of sight communication. During the range tests, it was observed that, if there was no obstruction between the gateway and the node the signal could reach even further. The empty pocket in Figure 6.2 is because a large metallic structure is obscuring the signals.

Figure 6.1: Paths with SNR values.

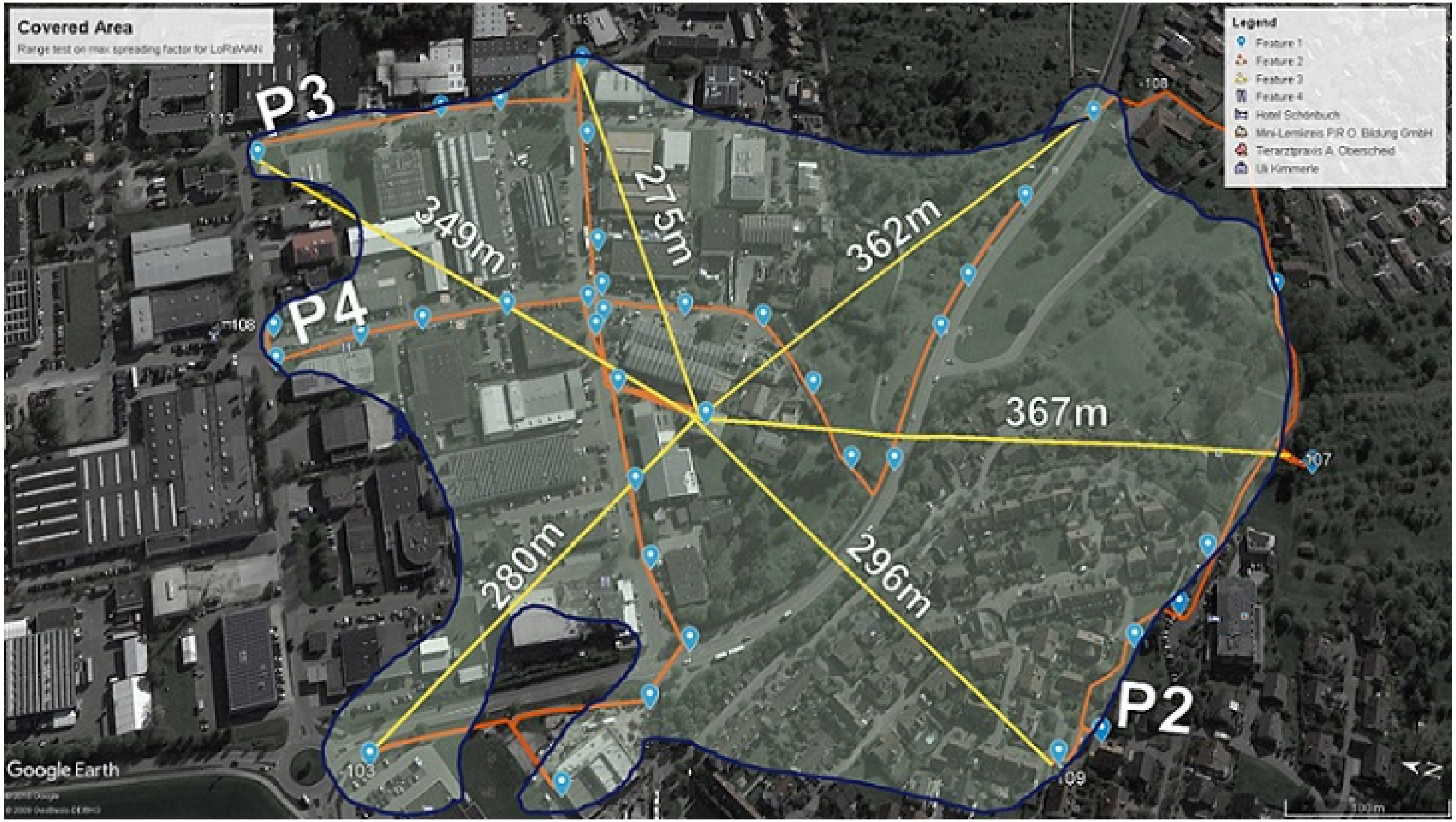

Figure 6.2: Area coverage.

7 Conclusion and Outlook

The ever-growing energy demand of toady's industry and household can be reduced by employing the efficient use of energy. Energy use can be optimized by employing energy management systems. Enisyst offers its customers a reduction of 30% in energy use by employing their EMS. Enisyst uses a wired sensor network for monitoring and a wired network for controlling the actuators. This wired network requires a lot of effort and time to deploy and in most cases, it can only be employed during the construction of the building.

To tackle this problem it was suggested to use a wireless technology. By using a wireless technology, the effort can be drastically reduced and the deployment of the EMS will no longer be dependent on the construction. For this purpose, several technologies were studied and it was decided to use an LPWAN technology for this task. The core concept behind an LPWAN technology is to provide a significant long range with low power consumption at the cost of lower data transfer rates. There are a lot of LPWAN technologies available in the market right now, each offering various advantages and disadvantage. In order to use the right LPWAN technology, a study about the current LPWAN technologies was carried out. The focus of this study was to find an LPWAN technology that is suitable for the task of implementing an EMS.

The study concluded in the selection of LoRa as the LPWAN technology to implement the EMS. The dwell time limitation of LPWAN restricted us to use it only for the collection of sensor data, and not for the controlling of actuators, therefore it was decided to limit the LPWAN use for monitoring only. A prototypical implementation of the LPWAN based EMS was carried out. In the prototype, a customized LoRaWAN gateway and a node were implemented. The node transmitted LoRa modulated signals over the air which were received by the gateway. At the gateway end, there are several software modules running on an embedded computer. An open source message broker is used as a backend for handling packets between software modules. Having a message broker provides the flexibility and scalability required for an EMS. The software modules running at the gateway end, decrypted and decoded the sensor values and passed them to Enisyst's control software. This software controlled the actuators correspondingly.

After the implementation of the system, several range tests were performed in an industrial area which is densely populated with buildings. The gateway was placed inside a building on the first floor. The maximum range at which the signal was transmitted was 360 meters. It was observed that if the line of sight was maintained even more range could be attainable. Due to the uneven mountainous terrain, it was not possible to achieve more in our case.

LoRa modulation is not limited by the distance but the obstructions in the path of the signal. A range of more than 10 km has been achieved using the line of sight communication.

The findings from this thesis will be used to create the next generation Enisyst EMS. Further research is required in order to use LPWAN for the controlling of the actuators as well. Multiple technologies can be used in combination to further optimize the process. As of today, there are not a lot of ready-made LPWAN solutions. We had to create our own sensor node from scratch. Various providers claim to have LPWAN sensor nodes but the availability of such products are said to be at the end of 2018.

Bibliography

[1] 3GPP. “White Paper: 3GPP Low Power Wide Area Technologies.” Tech. rep. 3GPP, 2016 (cit. on pp. 36, 37).

[2] ARM. “ARM Cortex A8.” 2018. URL: https://developer.arm.com/products/processors/cortex-a/cortex-a8 (cit. on p. 47).

[3] Atmel. “AVR atmega32.” 2018. URL: https://www.microchip.com/wwwproducts/en/ATmega32 (cit. on p. 50).

[4] Bluetooth Special Interest Group. “Bluetooth.” 2017. URL: https://www.bluetooth.com/ (cit. on pp. 12, 21).

[5] O. Brocaar. “LoRa gateway bridge.” 2018. URL: https://github.com/brocaar/lora-gateway-bridge (cit. on p. 57).

[6] O. Brocaar. “LoRa Server.” 2018. URL: https://github.com/brocaar/loraserver (cit. on p. 57).

[7] O. Brocaar. “lora server porject.” URL: https://www.loraserver.io/ (cit. on p. 57).

[8] I. Brown. “A Detailed Breakdown of LPWAN Technologies and Providers.” URL: http://web.luxresearchinc.com/hubfs/Insight_Breakdown_of_LPWAN_Technologies.pdf (cit. on p. 40).

[9] M. Coracin. “packet forwarder.” 2017. URL: https://github.com/Lora-net/packet_forwarder (cit. on p. 57).

[10] DASH7 Alliance. “DASH7 Alliance Wireless Sensor and Actuator Network Protocol v1.0.” 2015. URL: http://www.dash7-alliance.org (cit. on pp. 33, 42).

[11] G. Ergeerts, M. Nikodem, D. Subotic, T. Surmacz, B. Wojciechowski, P. De Meulenaere, M. Weyn. “DASH7 alliance protocol in monitoring applications.” In: *P2P, Parallel, Grid, Cloud and Internet Computing (3PGCIC), 2015 10th International Conference on*. IEEE. 2015, pp. 623–628 (cit. on pp. 33, 35).

[12] Erlio GmbH. “VerneMQ.” URL: https://vernemq.com/ (cit. on p. 58).

[13] D. Estates. “Building energy management systems.” In: *Design and Maintenance Guide* 22 (2001) (cit. on p. 46).

[14] Wi-Fi Alliance. “Wi-Fi.” 2017. URL: https://www.wi-fi.org/ (cit. on pp. 12, 21).

[15] D. A. Al-Hammad. “BUILDING MANAGEMENT SYSTEM (BMS).” URL: http://faculty.kfupm.edu.sa/ARE/amhammad/ARE-457-course-web/Building-Management-System.pdf (cit. on p. 45).

[16] Ingenu. “Ingenu.” 2018. URL: https://www.ingenu.com/ (cit. on p. 26).

[17] Ingenu. "White Paper: How RPMA works." Tech. rep. ingenu, 2018 (cit. on p. 36).

[18] Ingenu. "White Paper: RPMA Technology for the Internet of Things." Tech. rep. ingenu, 2018 (cit. on p. 42).

[19] "Information technology – Radio frequency identification for item management – Part 7: Parameters for active air interface communications at 433 MHz." Standard. Geneva, CH: International Organization for Standardization, Sept. 2014 (cit. on p. 33).

[20] F. Lee. "EMQ." 2002. URL: http://emqtt.io/ (cit. on p. 58).

[21] R. A. Light. "Mosquitto: server and client implementation of the MQTT protocol." In: *The Journal of Open Source Software* 2.13 (May 2017), p. 265. ISSN: 2475-9066. DOI: https://doi.org/10.21105/joss.00265 (cit. on p. 58).

[22] LoRa Alliance. "A technical overview of LoRa and LoRaWAN." In: *White paper, Nov* (2015) (cit. on pp. 30–32, 41, 42).

[23] LoRa Alliance. "LoRa Alliance." 2017. URL: https://www.lora-alliance.org/ (cit. on pp. 12, 26).

[24] Microchip. "Microchip." 2018. URL: http://www.microchip.com/ (cit. on p. 44).

[25] K. E. Nolan, W. Guibene, M. Y. Kelly. "An evaluation of low power wide area network technologies for the Internet of Things." In: *2016 International Wireless Communications and Mobile Computing Conference (IWCMC)*. Sept. 2016, pp. 439–444. DOI: 10.1109/IWCMC.2016.7577098 (cit. on p. 43).

[26] J. Petajajarvi, K. Mikhaylov, A. Roivainen, T. Hanninen, M. Pettissalo. "On the coverage of LPWANs: range evaluation and channel attenuation model for LoRa technology." In: *2015 14th International Conference on ITS Telecommunications (ITST)*. Dec. 2015, pp. 55–59. DOI: 10.1109/ITST.2015.7377400 (cit. on p. 43).

[27] J. Petajajarvi, K. Mikhaylov, A. Roivainen, T. Hanninen, M. Pettissalo. "On the coverage of LPWANs: range evaluation and channel attenuation model for LoRa technology." In: *ITS Telecommunications (ITST), 2015 14th International Conference on*. IEEE. 2015, pp. 55–59 (cit. on p. 12).

[28] Phytec. "phyCore AM335x overview." URL: http://www.phytec.de/produkt/system-on-modules/phycoream335x/#uebersicht (cit. on p. 47).

[29] B. Ray. "The Past, Present, and Future of LPWAN." 2017. URL: https://www.link-labs.com/blog/past-present-future-lpwan (cit. on pp. 25, 26).

[30] B. Ray. "What is LoRa?" 2015. URL: https://www.link-labs.com/blog/what-is-lora (cit. on p. 30).

[31] B. Ray. "What is Weightless?" 2015. URL: https://www.link-labs.com/blog/what-is-weightless (cit. on pp. 35, 40).

[32] U. Raza, P. Kulkarni, M. Sooriyabandara. "Low Power Wide Area Networks: An Overview." In: *IEEE Communications Surveys Tutorials* 19.2 (Secondquarter 2017), pp. 855–873. DOI: 10.1109/COMST.2017.2652320 (cit. on pp. 40, 42).

[33] F. Sforza. "Communications system." US Patent 8,406,275. Mar. 2013. URL: https://www.google.com/patents/US8406275 (cit. on p. 30).

[34] Sigfox. "Sigfox." 2018. URL: https://www.sigfox.com/en (cit. on pp. 12, 26).

[35] Sigfox. "Sigfox Technical Overview." 2017. URL: https://www.disk91.com/wp-content/uploads/2017/05/4967675830228422064.pdf (cit. on pp. 28, 29, 42).

[36] Sigfox. "Sigfox Technology Overview." URL: https://www.sigfox.com/en/sigfox-iot-technology-overview (cit. on p. 27).

[37] J. Sliva. "Technologies used in wireless sensor networks." In: *Systems, Signals and Image Processing, 2008. IWSSIP 2008. 15th International Conference on*. IEEE. 2008, pp. 77–80 (cit. on p. 12).

[38] P. Software. "RabbitMQ." 2007. URL: https://www.rabbitmq.com/ (cit. on p. 58).

[39] TEOCO Corporation. "A Short History of LPWAN, and Why the IoT Can't Live Without It." 2017. URL: http://www.teoco.com/latest/news/blog/short-history-lpwan/ (cit. on p. 25).

[40] Texas Instrument. "TI Sitara Overview." 2017. URL: http://www.ti.com/processors/sitara/arm-cortex-a8/am335x/overview.html (cit. on p. 47).

[41] Weightless SIG. "Weightless." 2015. URL: http://www.weightless.org/ (cit. on pp. 12, 35).

[42] M. Weyn, G. Ergeerts, L. Wante, C. Vercauteren, P. Hellinckx. "Survey of the DASH7 alliance protocol for 433 MHz wireless sensor communication." In: *International Journal of Distributed Sensor Networks* 2013 (2013) (cit. on p. 34).

[43] S. Yinbiao, K. Lee, P. Lanctot, F. Jianbin, H. Hao, B. Chow, J.-P. Desbenoit. "Internet of things: wireless sensor networks." In: *White Paper, International Electrotechnical Commission, http://www. iec. ch* (2014) (cit. on p. 11).

[44] Yocto Project. "The yocto project." 2018. URL: https://www.yoctoproject.org/ (cit. on pp. 48, 56, 57).

[45] Zigbee Alliance. "Zigbee." 2017. URL: http://www.zigbee.org/ (cit. on pp. 12, 30).

[46] H. Zimmermann. "OSI Reference Model - The ISO Model of Architecture for Open Systems Interconnection." In: *IEEE Transactions on Communications* 28.4 (Apr. 1980), pp. 425–432. ISSN: 0090-6778. DOI: 10.1109/TCOM.1980.1094702 (cit. on pp. 19, 20).

All links were last followed on April 17, 2018.

Declaration

I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

place, date, signature