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GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

A Comparison of Long-Range Licensed and Unlicensed LPWAN Technologies

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ACCEPTANCE AND APPROVAL PAGE

On 27/06/2019, **Ylli RAMA** successfully defended the thesis, entitled **"A comparison of Long-Range Licensed and Unlicensed LPWAN Technologies",** which he prepared after fulfilling the requirements specified in the associated legislation, before the jury members whose signatures are listed below. This thesis is accepted as a **Master's Thesis** by Istanbul Commerce University, Graduate School of Natural and Applied Sciences **Mechatronics Engineering Department.**

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ABSTRACT

M.Sc. Thesis

A comparison of Long-Range Licensed and Unlicensed LPWAN Technologies

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Supervisor: Assist. Prof. Dr. Mustafa Alper ÖZPINAR

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Internet of Things have already started to be a part of our daily lives. During years, the limited connection ranges and energy are the biggest barrier on the IoT solutions. The key solution for these issues are Low Power Wide Area Networks (LPWAN), as they have the ability to operate on e very low power and they can communicate in very long distances. These features have made the LPWAN technologies become widely useful in different fields of various applications.

In this paper, the currently available LP-WAN technologies are categorized in two groups, those unlicensed and licensed. Being explored from both technical and non-technical requirements for applications, they are also compared to each other regarding their technological and commercial aspects, and a roadmap for Turkey takes place. This would help MNOs (Mobile Network Operators) and also LPWAN customers to decide which technology is more feasible for their use-cases.

Keywords: Internet of things, long-range, LPWAN, LoRa, NB-IoT, Sigfox, IoT

ÖZET

Yüksek Lisans Tezi

A Comparison of Long-Range Licensed and Unlicensed LPWAN Technologies

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IoT teknolojilerindeki son gelişmeler, mobil şebeke operatörleri (MŞO'lar) ve diğer nesnelerin bağlantısını sağlayan operatörleri tarafından oldukça fazla ilgi çekmektedir. Bu operatörler için en büyük endişeler: batarya dostu, uzun menzilli, yüksek kapasiteli ve güvenli bağlantılar sağlamakla ilgilidir. Düşük Güç Geniş Alan Ağları (LPWAN), çok büyük alanlarda dağıtılan çok düşük güç aygıtlarını bağlayabilmesi nedeniyle bu iki ana konu için en önemli çözümlerden biridir. Bu ihtiyaç, LP-WAN teknolojilerinin akıllı şehirlerin çeşitli uygulamalarının farklı alanlarında yaygın olarak kullanılmasını sağlar.

Bu yazıda, LP-WAN teknolojilerinin karşılaştırmaları incelenmektedir. Mevcut olan LP-WAN teknolojileri iki gruba ayrılmıştır. Teknik ve teknik olmayan gerekliliklerden araştırıldı ve analizler sunuldu. Aynı zamanda Türkiye için bir LPWAN yol haritası yer almaktadır. Bu, MNO'lara (Mobil Şebeke Operatörleri) ve ayrıca LPWAN müşterilerine yardımcı olacaktır.

Anahtar kelimeler: Hücresel ağlar, lisanslı, lisanssız, LPWAN, LoRa, Nb-IoT, nesnelerin interneti.

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Finally, I must express my very profound gratitude to my family and to my friends in Turkey, for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

Ylli RAMA
Istanbul, 2019

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SYMBOLS AND ABBREVIATIONS

3GPP	3rd Generation Partnership Project
ABP	Activation By Personalization
ABP	Activation By Personalization
ADR	Adaptive Data Rate
CDMA	Code DivisionMultiple Access
CSS	Chirp Spread Spectrum
D7A	DASH7 Alliance
EC-GSM-IoT	Extended Coverage GSM-IoT
EDGE	Enhanced Data rates for GSM Evolution (Also known as EGPRS)
eDRX	Extended Idle-Mode Discontinuous Reception
EGPRS	Enhanced GPRS
eMTC	Enhanced Machine Type Communication
ETSI	European Telecommunications Standards Institute
FCC	(United States of America) Federal Communications Commission
FCS	Frame Check Sequence
FEC	Forward Error Correction
FSK	Frequency Shift Key
FSPL	Free Space Path Loss
FUOTA	Firmware Update Over The Air
GFSK	Gaussian Frequency Shift Keying
GPRS	General Packet Radio Service
GSM	Global System forMobile Communications
GSMA	GSM Association
IoT	Internet of Things
ISM	Industrial, Scientific, andMedical bands
LoRaWAN	Long Range Wide Area Network
LPWAN	Low Power Wide Area Networks
LTE	Long Term Evolution (4G)
M2M	Machine-2-Machine
MAC	Media Access Control
NB-FI	Narrowband Fidelity
NB-IoT	Narrow Band IoT
OFDM	Orthogonal Frequency-Division Multiplexing
OSSS	Orthoganol Sequence Spread Spectrum
OTAA	Over-The-Air Activation
PRB	Physical Resource Block
PSM	Power Saving Mode
QoS	Quality of Service
RFTDMA	Random Frequency and Time Division Multiple Access
RPMA	Random Phase Multiple Access
SC-FDMA	Single Carrier Frequency Division Multiple Access
SDO	Standart Development Organization

SF	Spreading Factor
SIG	Special Interest Group
TTN	The Things Network
UNB	Ultra Narrowband
VPN	Virtual Private Network
WLAN	Wireless Local Area Network

1. INTRODUCTION

Nowadays, the term Internet of Things (IoT) is constituted by a large number of connected devices and sensors worldwide (El Khodr, S. Shahrestani, H. Cheung, 2016; U. Raza, P. Kulkarni, M. Sooriyabandara, 2017; W. Guibene, K. E. Nolan, M. Y. Kelly, 2015), and year by year it is increasing more (Ericsson, 2009). The main key for continuing the growth is the fact that these devices can be connected wirelessly (A. Wood, 2015; S. Andreev, O. Galinina, A. Pyattaev, M. Gerasimenko, T. Tirronen, J. Torsner, J. Sachs, M. Dohler, Y. Koucheryavy, 2015; F. Samie, L. Bauer, J. Henkel, 2016; G. Margelis, R. J. Piechocki, Dritan Kaleshi, P. Thomas, 2015). Also, being useful in different applications regarding smart city applications, such as smart grid, smart metering, smart buildings, security alarm, geolocation, access control, contactless access, remote motor control, industrial and environment monitoring and a lot of other smart city applications (J. G. S. Filho, J. P. Filho, V. L. Moreli, 2016; M. Bor, J. Vidler, U. Roedig, 2016; J. Petajajarvi, K. Mikhaylov, A. Roivainen, T. Hannien, M. Pettissalo, 2015), it creates the digital twins in manufacturing, as shown in Figure 1.1. These are some of the reasons that it is becoming an inseparable part of our lives.

In such typical applications, the data gets periodically stored by an IoT device and then this data is transmitted to a gateway, and makes possible the communication between the sensor devices and computing clouds for big data applications. The gateway devices could be either regular broadband WAN connected Edge Servers, cellular networks, smartphones or Wi-Fi access points. Depending on their transmission range, the wireless IoT world is categorized in several groups. In the first category there is NFC and RFID, which are technologies operating at a very shortest range. For LF and HF applicationstha range is limited up to one meter, while for UHF four to ten meters. Depending on the size of the antenna, transmission power and environmental conditions, home wireless technologies such as Wi-Fi, Bluetooth, ZigBee and others, can reach a range up to 100 meters. Later, these ranges were somehow increased by other IEEE 802.11x standard technologies reaching a distance of 1 km, known as Wireless Local Area Networks (WLAN). To achieve more transmission range technologies such as cellular technologies, ZigBee NAN and Wi-SUN can be implemented and used.

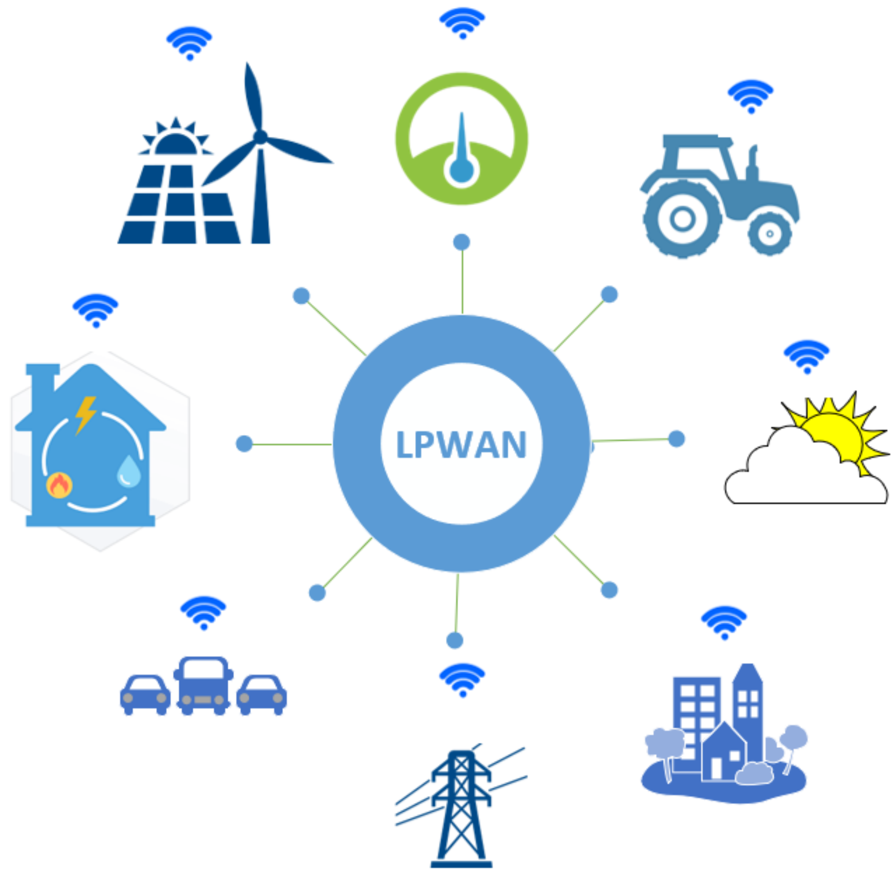

Figure 1.1. Current applications of LPWAN Technologies

In the previous years, the cellular technologies were the only option designed to provide the long-range services for various applications (B. Reynders, W. Meert, S. Pollin, 2016; C. Goursaud, J-M. Gorce, 2015) and GPRS. However, these Technologies are energy consuming and very expenisve solutions, features making them not widely supported by different vendors and applications. To overcome these problems, long range Low Power Wide Area Network technologies such as LoRa (M. Centenaro, L. Vangelista, A. Zanella, M. Zorzi, 2016), Sigfox (Sigfox, 2016), NB-IoT (P. Reininger, 2016; Nokia, 2017; Sequans, 2016), RPMA (Ingenu, 2016), NB-FI (WAVIoT, 2016), etc., have been developed, merging into successful solutions. Factors such as long range, low cost, and low energy consumption are the key why there is shown a high interest in these technologies, as they provide "install and forget the device" for a long time with a low project budget. In Figure 1.2. technologies with different ranges are shown.

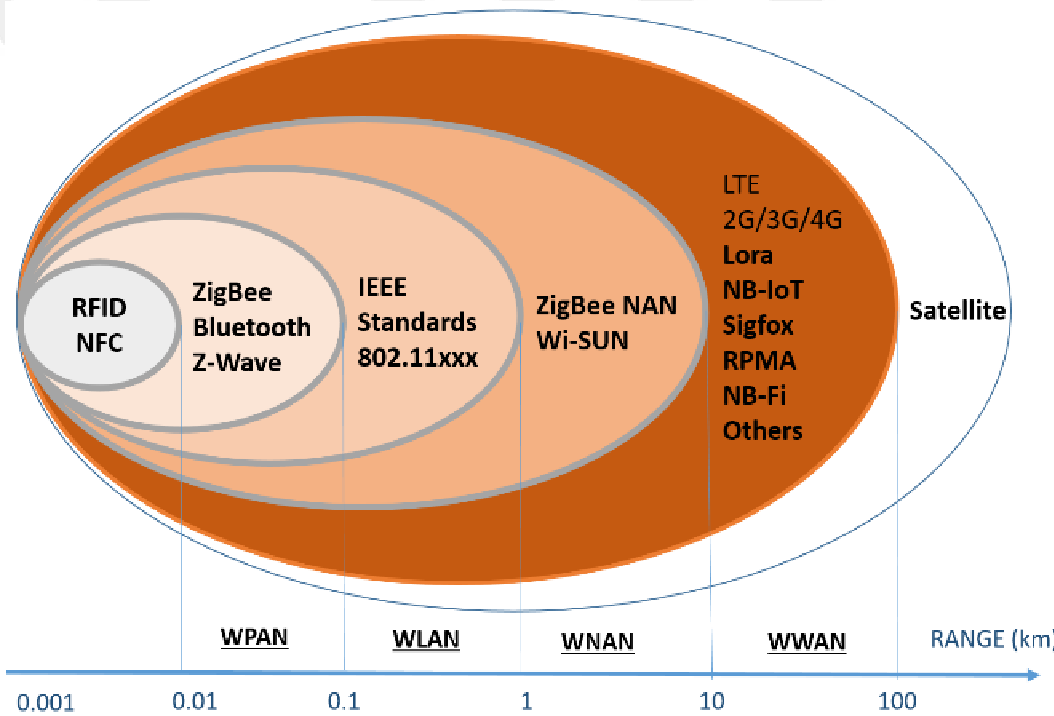

Fig. 1.2. Various IoT wireless technologies' ranges

1.1 LPWAN History

In the late 1980s and early 1990s, there were similar topologies and network architectures not being called LPWAN. ADEMCO (Alarm Device Manufacturing Company), was a major manufacturer of alarm panels and systems. To monitor alarm panels, ADEMCO built a 900 mHz network called AlarmNet. The system operated at 928 MHz band. Being designed with a low data rate, there were transmitted a very small amounts of data. Nowdays, owned by Honewell company, AlarmNet networks operate in 18 major areas around the U.S. It covers around 65% of the urban population. The cellular networks recognized that it could move voice as well as the data. That is where 2G was born. Availability of 2G made many similar systems such as alarm panels migrate to a cellular network. Its biggest advantages were the wide coverage and the very low hardware costs.

ARDIS has a similar story to AlarmNet. It is a wireless wide-area network built specifically for data-only applications. Owned by Motorola, it had a relatively low-speed network used primarily for fleet tracking, sales automation, e-mail, and other online transaction processing and messaging. Then, American Mobile migrated them to later technology.

Figure 1.3. Evolution of LPWAN Technologies (Link Labs, 2017)

The more the things are getting connected to the internet, the more people are concentrating at low-cost and low-data devices. Much of this reinvigorated interest was led by Sigfox. Sigfox, which started in 2009. In 2009, Sigfox was the first to built a modern LPWA network in France and their €100 million got everyone excited about using LPWAN devices in the industry (in Europe). Then, other LPWAN technologies were developed and the market became wider, as shown in Figure 1.3. This came at a time when the tools for integrating applications were becoming easier for use, and when radio technology was becoming less expensive.

1.2 Problem Definiton

With the development of several LPWAN technologies, some of them being licensed and some other unlicensed, MNOs and other players such as consumers, have to decide on which LPWAN technology/technologies to include in their portfolio or application. In order to decide, firstly a brief analysis and comparison have to be done to the current LPWANs.

Some MNOs are quite clear about their choices regarding LPWANs. According to Vodafone, the cellular LPWAN technology called NB-IoT will "crush" proprietary LPWAN technologies such as LoRa and Sigfox (Morris, 2016). In Turkey, MNOs, to some extent, have already started to explore their options. Turkcell has started its plans for NB-IoT and LTE-M deployment, while Vodafone has been concentrated on a single cellular technology, NB-IoT. Apat MNOs, there are several companies that have integrated LoRa in their commercial smart city solutions.

1.3 Purpose and Goals

The purpose of this thesis is comparing the LPWAN technologies according to their technical and commercial aspects, so that the MNOs and other players such as companies integrating LPWANs would know which technology fits best with their commercial applications.

1.4 Structure

In this paper, the Low Power Wide Area Network current technologies will each be reviewed in detail, compared and analyzed. The paper is organised as follows: In section II, there is a detailed review of the all LPWAN technologies developed and commercially available nowadays. The main technical and non-technical essentials of the technologies are mentioned. Separated in unlicensed and licensed categories, each of the technologies is generally described. In section III, the Technologies are compared to each other due to their technical and commerial characteristics. Section IV includes an interview regarding one of the leading LPWAN technologies. And finally, a summary conclusion and future work has been made in Section V.

2. LITERATURE: A DETAILED REVIEW

LPWAN is often used when other wireless networks such as WiFi, BLE, Bluetooth, etc., are not suitable for such long-range connectivity, while current cellular M2M networksa are energy consuming and expensive (including their hardwares). LPWAN Technologies do perfectly suit for connectivity where small amount of data needs to be sent over a long range, while maintaining a long battery life. These technologies are separated in two main groups: the one operating in the unlicensed bands (ISM bands) and the other one in the licenced (cellular) bands (Figure 2.1).

LPWANs	
Cellular	**Non-Cellular**

• LTE-M (aka Cat-M / Cat-M1 / LTE Cat-M1 / eMTC)
• NB-IoT (aka Cat-M2)
• EC-GSM-IoT
	• LoRa
	  ◦ LoRaWAN
	  ◦ Symphony Link
	• Sigfox
	• Ingenu (RPMA)
	• Weightless
	  ◦ Weightless-P
	  ◦ Nwave

Figure 2.1. Categories of LPWAN Technologies: Licensed (Cellular) and Unlicensed

2.1 Unlicensed LPWAN Technologies

In this section, the technical and non-technical features of LPWAN technologies will be described in detail.

2.1.1 LoRaWAN

LoRaWAN means Long Range Wide Area Network. It is actually two Technologies combined. There is LoRa, its physical layer including modulation. And in the other hand there is its MAC layer, both implementing the LPWAN network. The MAC Layer of LoRaWAN is open-standart.

2.1.1.1 Architecture

Most of the existing LPWAN technologies are based on MESH network topology. In mesh, the nodes are connected to each other and cooperate. They receive and transmit the data that might be irrelevant for them. In this network type the range might increase, but the networks becomes more complex and the batery lifetime decreases since it consumes more energy. In the other hand, we have the star topology (T 2.2.). In the the star topolgy all the nodes are connected directly to the "master" or gateway, this decreasing energy consmuption to a great extend while compared to other mesh networks. LoRa is based in star topology (Figure 2.2), and its network consist of gateway, nodes, network server and application server, which will be discussed below.

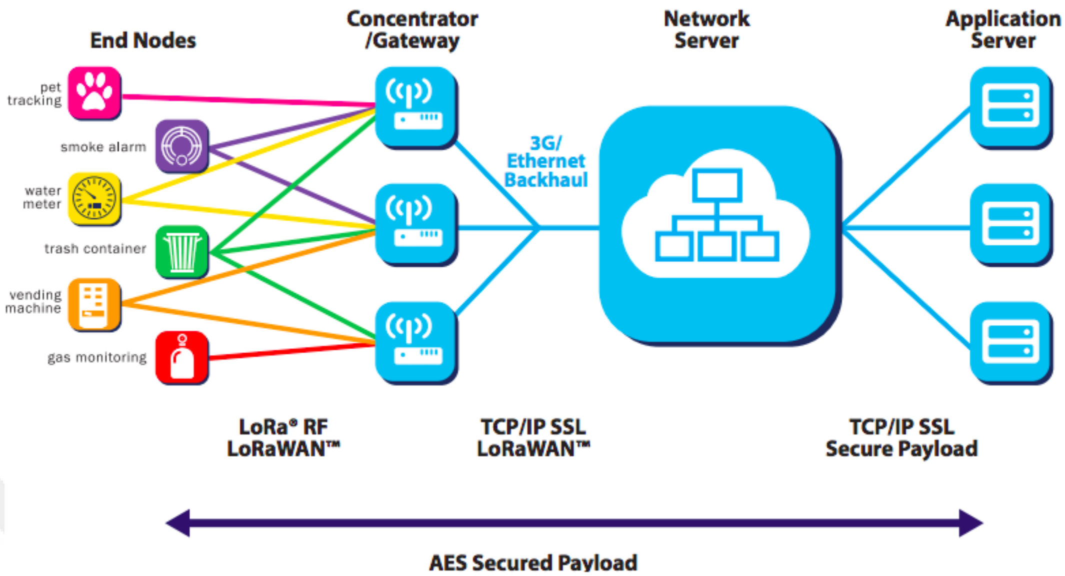

Figure 2.2. LoRaWAN network architecture (LoRa Alliance).

The gateway is the main element in the star topology. It is connected to every node in the LoRa network. There would be several gateways, which communicate directy to the nodes and collect the data transmitted by the nodes (Orange, 2016; Semtech, 2015; Rashmi Sharan Sinha, Yiqiao Wei, Seung-Hoon Hwang, 2017; Lra Alliance, 2015). Then, the data collected is sent to the server via Wi-Fi, Ethernet, celllular, etc. Using omni-directional and multi-sector antennas, there are two types of gateway: pico and macro. In the dense mediums where the Quality of Service (QoS) needs improvement, pico gateways are used, as they increase the network capacity and by reaching dense areas. And in the other hand, micro gateways are used in public. The give high coverage.

- *The nodes* are the end-devices. Here is where sensing and control takes place. Generally, they gather the data by the sensor/sensor sor application and transmit it to the gateways, but the could be also used as “actuators” too, as they would get commands from gateway and transmit it to the application.

- *The network serv*er is the brain of the network, because all the information is processed in it, such as data rate, security checks, etc.
- *The application server* receives all the data from the application server and makes possible the connection between end-user and the end-nodes.

2.1.1.2 Physical layer and modulation/demodulation

The physical layer uses robust CSS modulation. CSS stands for Chirp Spread Spectrum (Semtech, 2015). LoRa modulation is a PHY layer implementation that provides link budget improvement over conventional narrowband modulation. This delivers orthogonal transmissions at different data rates. Moreover, it provides processing gain and hence transmitter output power can be reduced with same RF link budget. In addition, the enhanced robustness and selectivity provided by the spread spectrum modulation enables greater transmission distance to be obtained. CSS technique spreads the signal around the noise floor, meaning that it is very difficult for an intruder to differentiate the signal because of the random noise.

Semtech (2015), LoRa modulation multplies the data signal with the chirp singal (Figure 2.3). LoRa modulates the signal into chirps which has a varying frequency over time. The chirp modulated uses the entire bandwidth of the channel (Mat, 2018). The increasing chirps are called upchirps and the decreasing ones are called downchirps.

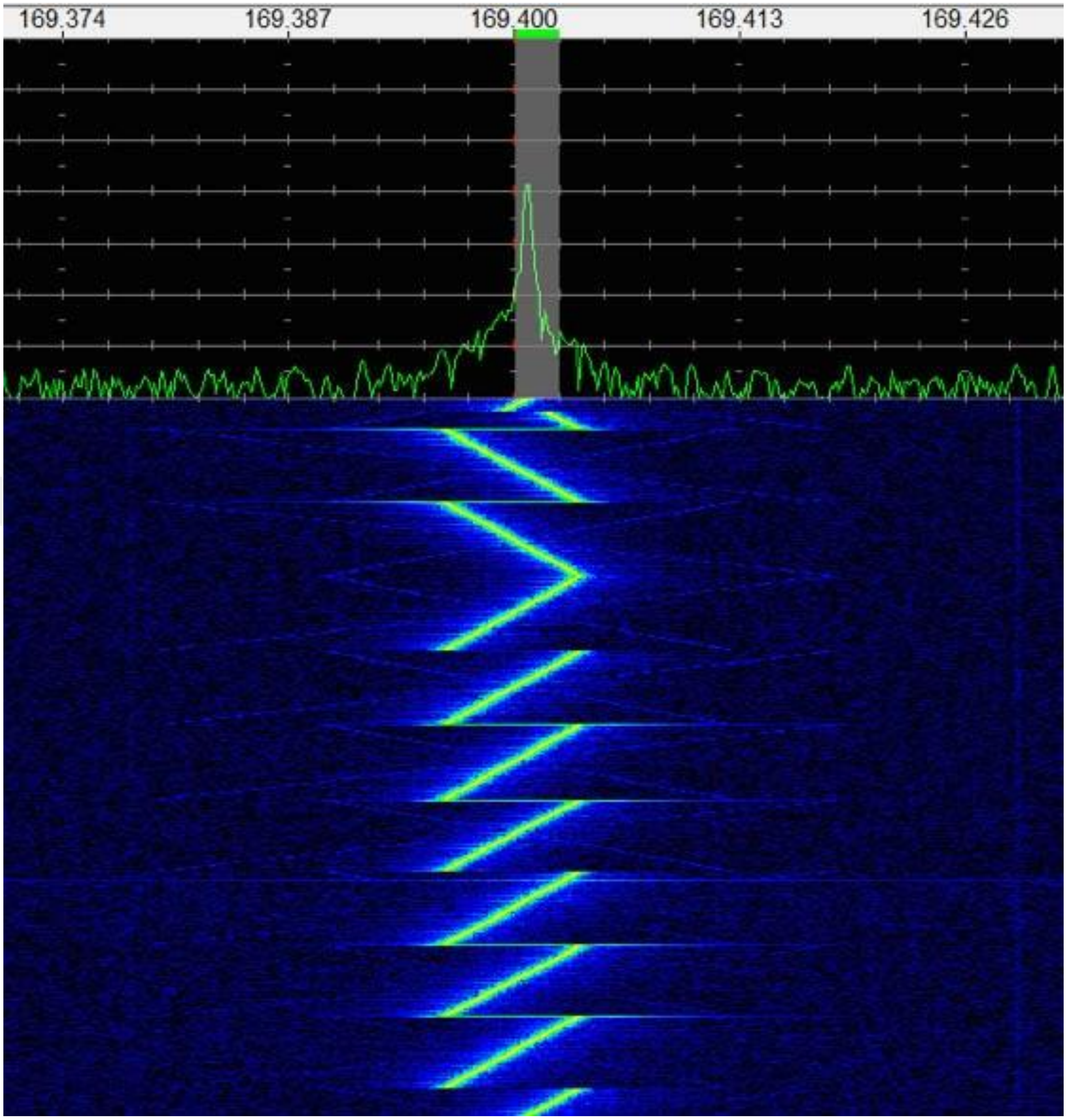

Figure 2.3. CCS Modulation (LoRa Modulation): The chirps shown (Link Labs, 2018)

LoRa modulation has constant envelope modulation similar to Frquency Shift Key (FSK) modulation type and hence available PA (power amplifier) stages having low cost and low power with high efficiency can be used. Compared to FSK, LoRa Modulation has a much higher sensitivity.

LoRa Alliance (2017), it uses Adaptive Data Rate (ADR) technique to vary output data rate/RF output of end devices. Having a robust nature and long-range feature, it has been used in military applications for decades, and now it is used commercially in LoRa. ADR helps in maximizing battery life as well as overall capacity of the LoRaWAN (Long Range Wide Area Network) network. It provides immunity to fading and multipath. For the receiver, to demodulate a signal, information about the modulation is required. In chirp spread spectrum demodulation, the receiver generates chirps and multiplies these paterns by the received signal in order to extrat the meaningful data. Having the ability to extract a signal below the niose floor is the main advantage of LoRa. It provides long-range communcation and good penetration.

2.1.1.2.1 Range

LoRa Alliance advertises LoRaWAN as a long range radio technology. A LoRa gateway can cover hundred-kilometer square of area. The range can be theoritically calculated with several equations and models. According to calculations LoRa singals can be demodulated up to 15 Km far from the transmitter, but the test result generally do not match the calculated values. The medium where its transmitted, data rate, spreading factor, link budget, etc are some of the factors affecting the range of LoRa (LoRa Alliance, 2018).

2.1.1.2.2 Spreading factor:

Spreading factor is one of the most important parameters of LoRa. It represents the duration of the chirp. Each symbol is spread through a chirp code whose length is 2^{SF} uses 6 SF (spreading factors) from SF 7 to 12 (Table 2.1) (Semtech, 2015). The higher the spreading factor is, the biggest will be the chirp code length.

Table 2.1. Spreading Factor and Chirp Length

Spreading Factor (SF)	Chirp Length (Bits)
7	128
8	256
9	512
10	1024
11	2048
12	4096

In other words, SF = 7 means the shortest transmission time on air, while SF = 12 means it will last more (Figure 2.4). One step higher in the spreading factor doubles the transmission time for the same amount of data to be transmitted.

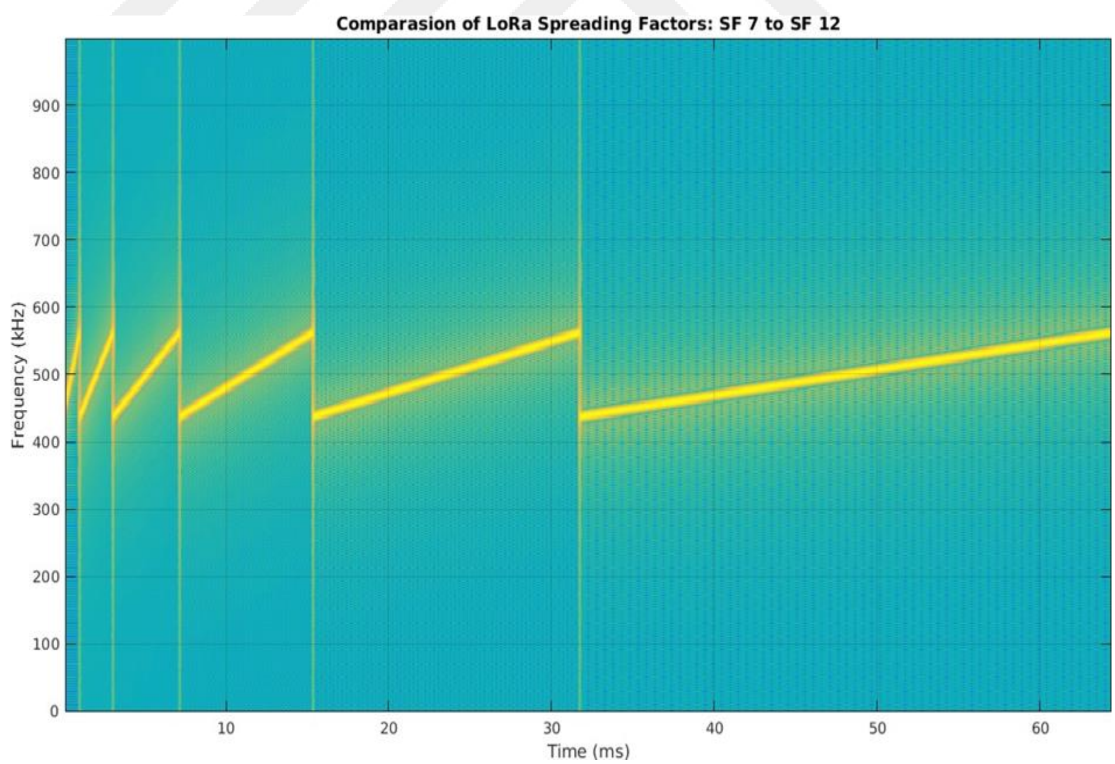

Figure 2.4. Comparison of LoRa Spreading Factors: SF = 7, to SF = 12 (LoRa Alliance, 2018).

Apart spreading factor, the CSS modulation has two other parameters such as modulation Bandwidth, Forward Correction Code and Code Rate.

2.1.1.2.3 Bandwidth

LoRa Modulation operates in 125KHz, 250 KHz and 500 KHz ranges of bandwidth, with a data rate varying from 0.29 Kbps to 27 Kbps (LoRa Alliance, 2018). The higher the bandwidth is, the higher dhe data transfer rate will be. Having not fixed bandwith, it can operate in different bandwidths ranges set by the user.

2.1.1.2.4 Forward error correction

Forward Correction Code is (FEC) is called the process where error correction bits are added to the transmitted data. When the transmitted data is corrupted by the interference, the error correction bits will help restore the data. The more bits added means the easier dhe data will be corrected. This, in the cost of battery lifetime lifetime because more data transmitted means more energy consumed.

2.1.1.2.5 Code rate

Code Rate refers to the proportion of the transmitted bits that actually carries the information (Table 2.2). The Coding Rates values used by LoRa are CR = 4/5, 4/6, 4/7, 4/8. The most frequently used one is CR = 4/5. Another notation of Coding Rate is:

CR = 4 / (4 + CR), where CR = 1,2,3,4.

In the case where SF = 8 and CR = 4/8, then the number of that carries data are only SF*CR = 8*4/8 = 4 bits. The rest 4 bits are used for error correction. The Code Rate is expressed as k/n, meaning that for every k bit, n bits of data will be generated by the coder.

Table 2.2. Code Rate in LoRa

Coding Rate (CR)	CR = 4 / (4 + CR)
1	4/5
2	4/6
3	4/7
4	4/8

2.1.1.2.6 Link budget

The Link budget defines the quality of a radio transmission channel. It can be calculated by adding the Receiver sensitivity (Receiver Power, RX), the transmit power (transmitter power, TX), Antenna gain, and Free Space Path Loss (FSPL).

The FPPL is represented below:

$$FSPL = 2(44\pi d/\lambda)2 = 2(44\pi df/c) \quad (1)$$

Where,

FSPL = Free Space Path Loss

d = distance between TX and RX (m)

f = Frequency (Hz)

For FSPL calculation there is another widely used algroithmic formula, represented as:

$$FSPL\ (dB) = 20\log10(d) + 20\log10(f) - 147.55 \quad (2)$$

Receiver's side sensitivity is one the main indicators on calculating the link budget. It describes the minimum possible perception power, and is calculated as follows:

$$\text{Rx-Sensitivity} = -174 + 10\log10(BW) + SNR + NF \tag{3}$$

BW = bandwidth (Hz),

SNR = Signal to Noise Ratio

NF = noise factor (dB),

Without including the antenna gain link budget fomula is:

$$\text{Link Budget} = \text{max. RX Sensitivity (dB)} - \text{Max. Tx power (dB)} \tag{4}$$

In the case where the data rate of LoRa modulation signal is four times equivalent to the data rate of FSK Modulation signal, they have equal or similar sensitivity. Thus, as the most of the technologies use FSK modulation, LoRa covers more distanances than any other technique (Figure 2.5).

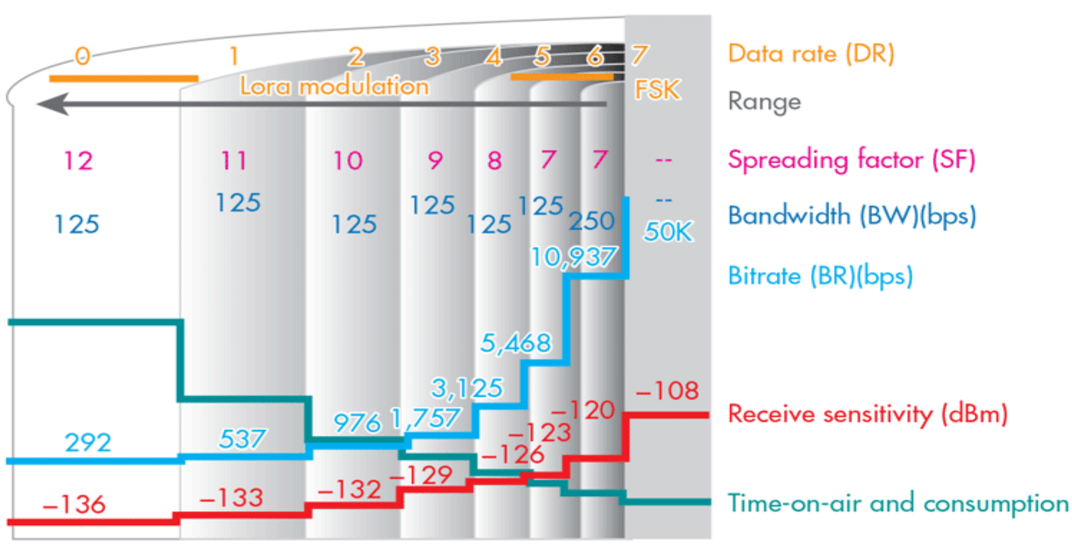

Figure 2.5. Technical details of LoRa.

2.1.1.3 MAC layer

LoRaWAN is the Media Access Layer protocol of LoRa. Initially, the MAC layer of LoRa was called LoRaMAC by the Semtech. It is mapped in the second and third layers of OSI model (Figure 2.6). Then, it became LoRaWAN after LoRa Allicance was created. In this layer the frequency, spreading factor, code rating, data rate etc, is defined. Other functions are eliminating duplicate receptions, scheduling, acknowledgements, etc.

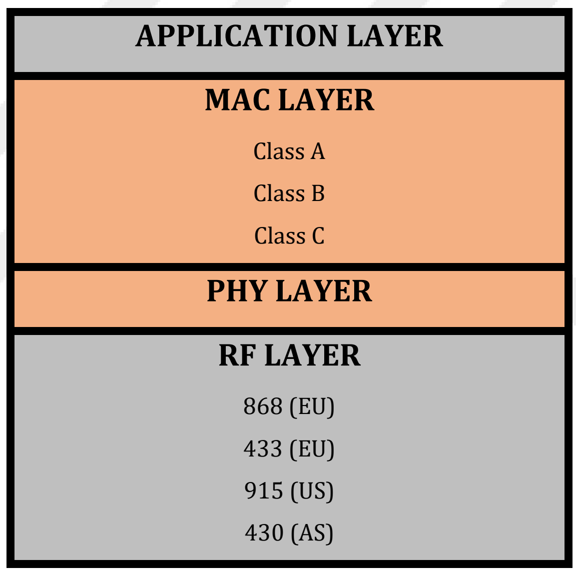

Figure 2.6. LoRaWAN according to OSI Model

2.1.1.3.1 Classes

Class A: It requires the lowest power. In this class, the device is always on sleep mode. It wakes up when it is triggered from the connected sensors which have some data to transmit. In other words, we can call it a pure ALOHA system because it sends data whenever it has to send. The LoRa server is able to schedule a downlink to the device only if it has received an uplink from the end-device. Compared to the other classes, these IoT devices have the longest battery lives with the same size of battery and sensors. Early earthquake detections and fire detection are some well-known applications where A Class devices can be applied.

Class B: It operates over beacons emitted by the gateway. The inform the end device with a time interval so that they would know when to send the uplink. After transmits the required message, it sleeps again for the rest of time.

Class C: It works continuously. The end device listens all the time, excepting the time when it has to transmit. These devices are good for applications dealing continuous data collecting (Table 2.3).

Table 2.3. LoRaWAN Classes

Class A	Class B	Class C
Communication initiated by an uplink	There is an extra window especially open for receiving	Server owns the right to initiate anytime the end-device
Small payloads and long intervals	Scheduled beacons from gateway	Small payloads
Bi-directional communication	Bi-directional communications with receive slots	Bidirectional Communications
Battery powered	Low latency	No latency
Gateway sends downlink during predetermined response windows	Gateway periodically transmits downlinks	End-device receives any time

2.1.1.3.2 Message types: uplink and downlink messages

The messages sent by gateway to the end-node are called downlinks (Figure 2.6), while the messages sent from the end-node to the gateway are called uplinks (Figure 2.7). LoRaWAN supports both messaging types. The most widely used messaging type is uplink, as most of the applications intend to collect and report sensor values to the Application Server. Under certain conditions, when an acknowledgement is needed, it might be useful to use a downlink message. Downlink messages can also be used for several purposes such as controlling the settings of a sensor, adjusting its update frequency, or it can command an actuator that can be a relay, a lock, or a valve. One important issue in messages is their confirmation. To be confirmed, an uplink must be send from the gateway in order to be sure whether the downlink has been sent to the node, or instead it has gone lost on the radio path. The downlink message queue acts on a First In-First Out mechanism, meaning that, in a full queue (5 messages) when a new one is queued, the oldest message is removed. The queue cannot be adjusted. While the uplinks are received by only the gateways around, the downlinks are shared across all end-nodes covered by the gateway range. This makes the downlink number limited.

Preamble	PHDR	PHDR_CRC	PHYPayload

Figure 2.6. LoRa Downlink PHY Structure.

Because downlink capacity is shared across all talking end-devices this is more limited than upload messaging; gateways are also seen as one device, so duty cycle applies to the gateways as well. For receiving uplink messages from devices, no regulatory limit applies, but for downlink messages the gateway has to obey the Duty Cycle.

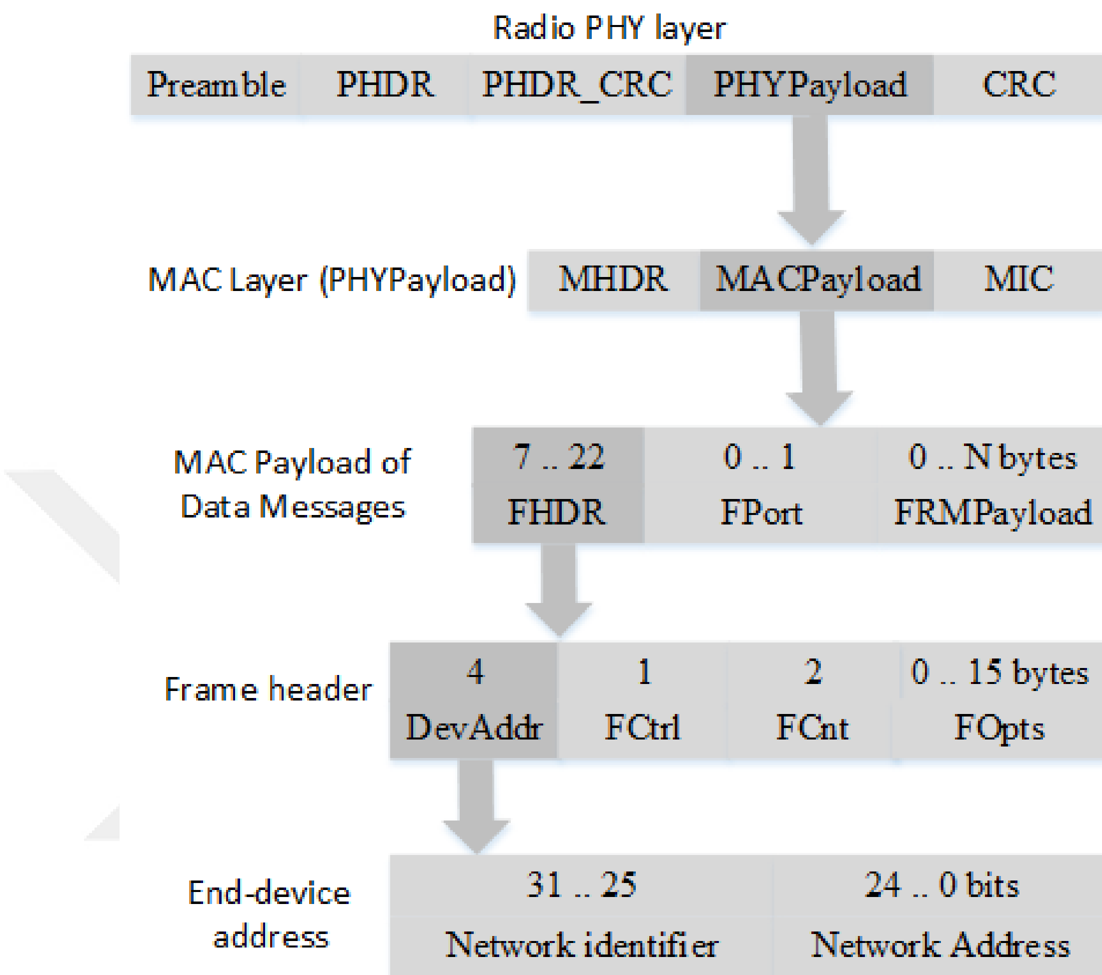

Figure 2.7. LoRa Uplink PHY structure and Frame

2.1.1.4 Limitations: frequency band and duty-cycle

LoRa operates Industrial, Scientific and Medical (ISM) bands, a.k.a unlicensed radio spectrum (Figure 2.8). Different regulations are applied depending on the region where it operates. The uplink and downlink number is limited due to the duty cycle and payload in combination with the quality offered by the network. The ISM band limits the use of a device to 1% (up to 0.1%) of the time on air. LoRaWAN regulation specifies that each time the user send a message in one ISM sub-band, the device has to wait the remaining time of the duty cycle in that band before resending. Meaning that, a sensor sending a message which takes 1 second should wait 99 seconds for resending another message. Every Every device must obey these limitations. The message size and the distance to the gateway defines the time on air. Being very close to the gateway provides more messages to be sent, because the time on air will be minimum.

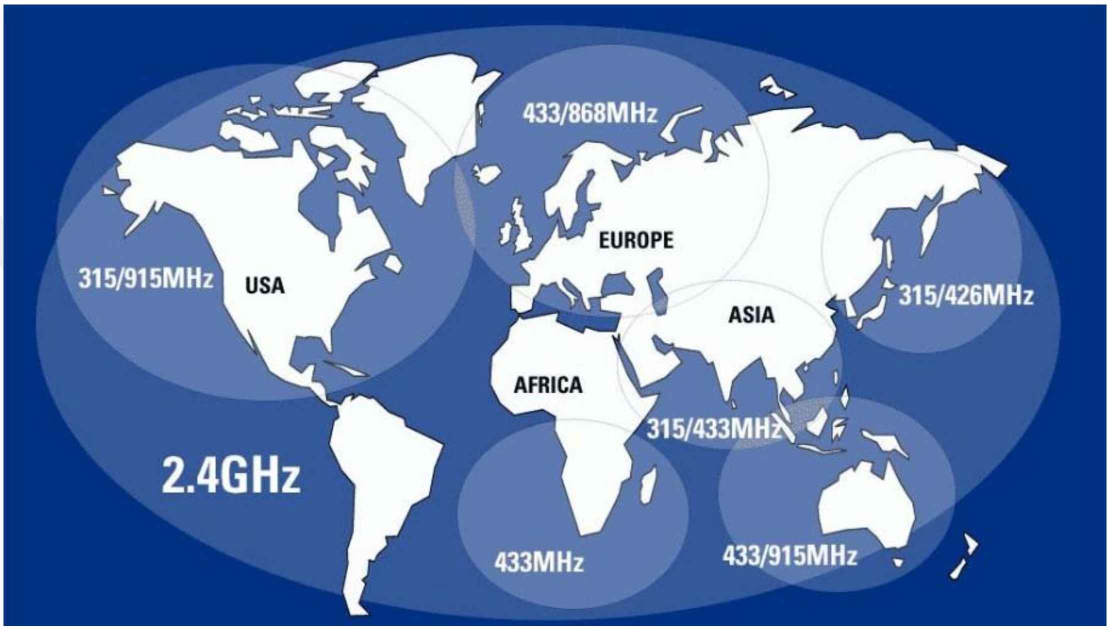

Figure 2.8. Global ISM bands.

Semtech, IBM and Actility (2015), based on LoRa MAC layer, it operates in 433 MHz, 868 MHz and 915 MHz for Asia, Europe and USA, respectively (LoRa Alliance, 2017).

2.1.1.4.1 Europe

In Europe, LoRaWAN operates in the 863-870 MHz frequency band, defining 10 channels at total. 8 of these channels are multi data-rate channels (250 bps to 5.5kbps), one channel operates at a higher data-rate, reaching a speed of 11 kbps. And the last channe, the tenth one, is FSK channel and operates at a speed of 50 kbps. The maximum allowed power is +14 dB.

There are imposed specific duty-cycles on devices for each sub-band. All the gateways and devices of LoRa have te respect the these duty-cycles. These apply to each device that transmits on a certain frequency, so both gateways and devices have to respect these duty-cycles. Most channels of LoRaWAN having a duty-cycle as low as 1% or even 0.1%, leads in a need for smart scheduling messages on gateways. It is good to keep the payloads small, not transmit too often and avoid downlink messages as much as possible.

2.1.1.4.2 North America

LoRaWAN operates in the 902-928 MHz frequency band in the United States. Unlike the European band, the US band has dedicated uplink and downlink channels. Divided into 8 sub-bands, each have 1x500 kHz uplink channel, 1x500 kHz downlink channel and 8x125 kHz uplink channels. The maximum power allowed in North America is +30 dB. The second sub-band of the band in the United States is used by The Things Network (if start counting from 0).

2.1.1.4.3 Australia

The specification of the Australian 915-928 MHz band is practically to that of the United States. The only difference is that its uplink frequencies are on higher frequencies than in the US band. The downlink channels remain the same as in the US band. The Things Network uses the same band as in the US.

2.1.1.4.3 China

Similar to European sub-bands the Chinesse 779-787 MHz band has three common 125 kHz channels (779.5, 779.7 and 779.9 MHz). The Chinese 470-510 MHz band behaves similar to the US bands. There are 96 uplink channels and 48 downlink channels. In some regions, a subset of these LoRaWAN channels cannot be used for LoRaWAN. Here, the eleventh sub-band is used by The Things Network.

2.1.1.5 Security

IEEE 802.15.4/2006 Annex B and AES-128 encryption methods are used in this LPWAN technology for authentication and security. Before forwarding the data to the appropriate Application Server for processing, every LoRa device should be activated. There are two popular schemes used to authenticate and activate a LoRa device in the network: Over the air activation (OTA) and Activation by personalisation (ABP).

2.1.1.5.1 OTAA

Over The Air Activaiton (OTAA) is the most frequently used activation method. In OTAA, a DevEUI (unique ID of the device), AppEUI (unique ID of LoRaWAN network) and an AppKey is generated. In order te become active, a LoRa device sends a join request to the gateway and then uses the join response to derive two session keys: NwkSKey (Network Session Key) and AppSKey (Application Session Key). When OTAA is used, the derivation of the network session is done automatically. Similarly to other assymetric encryption methods, we can call the AppSKey a private key because it is kept private, and the NwkSKey can be called a public key as it is shared with the network, The AppSKey will only be known by the device and the application. It encrypts the application payload. The device can continuously communicate with the gateway by saving the both session keys, or can re-join to connect again to the gateway by generating new session keys. No re-programming is required in this method to generate new keys.

2.1.1.5.2 ABP

Activation by Personalization (ABP) is used in specific cases. There is no DevEUI, AppEUI and AppKe is generated. The session keys AppSKey and NwtSKey are preprogrammed in the device (Figure 2.9). When started, the device uses the information predefined in it to directly connect to the gateway. A join procedure is not required. LoRa Alliance does not strongly recommend ABP in several applications as it may be a security risk. Cracking the devices and stealing the keys, those leading to the application access of the user, are the biggest weaknesses of ABP.

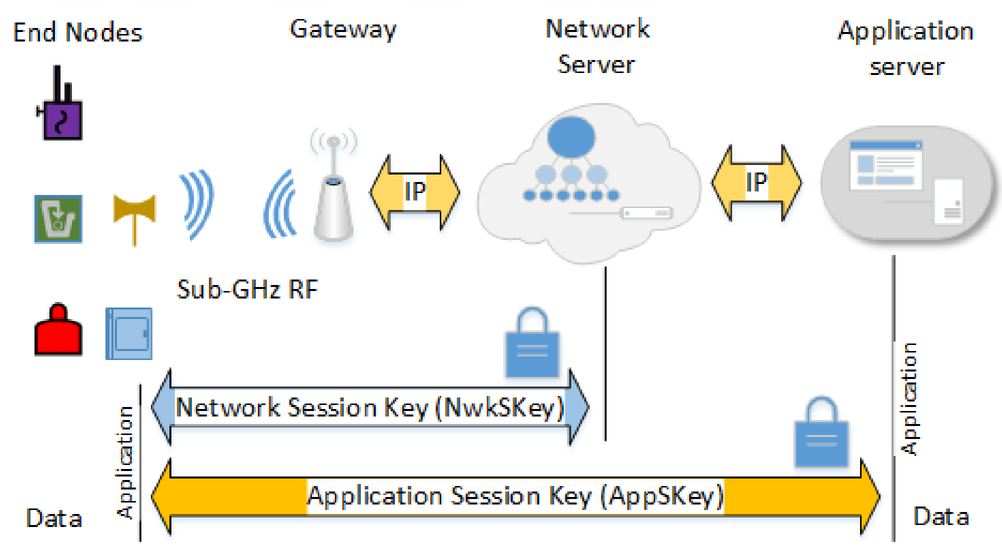

Figure 2.9. Communication Exchanging and Security of LoRaWAN

2.1.1.6 Commercial aspects

The LoRa Alliance is an open, nonprofit organization. It became the largest and fastest-growing alliance in the technology sector by counting more than 500 industrial and commercial members since its inception in March 2015. Its objective is making LoRaWAN an open global standart.

2.1.1.6.1 Founders and business model

LoRa Alliance, LoRa and LoRaWAN are exclusive trademarks of Semtech. Currently it is the only company providing LoRa chips. LoRa Alliance is divided into five categories: sponsor, contributor, institutional, adopter, and public member. The cost of becoming a LoRa Alliance member varies from Free to US$50,000, depending on the membership category. Some of the technological, product oriented, telecommunication network operator companies that have joined LoRa Alliance are Actility, Alibaba, Google Cloud, IBM, Bosch, Schneider, Kerlink, Orange, Swisscom, etc; and also, small/medium sized enterprises and startups (Lora Alliance).

2.1.1.6.2 Deployment

LoRa Alliance says that LoRaWAN has more than 100 publicly announced operators and more than 100 countries that are known with LoRaWAN deployment, where in some of the countries there is a full deployment, and in some other there is on-going deployment (Figure 2.10). There are both, public and private deplyments. The Figure illustrated below is lastly updated in December, 2018.

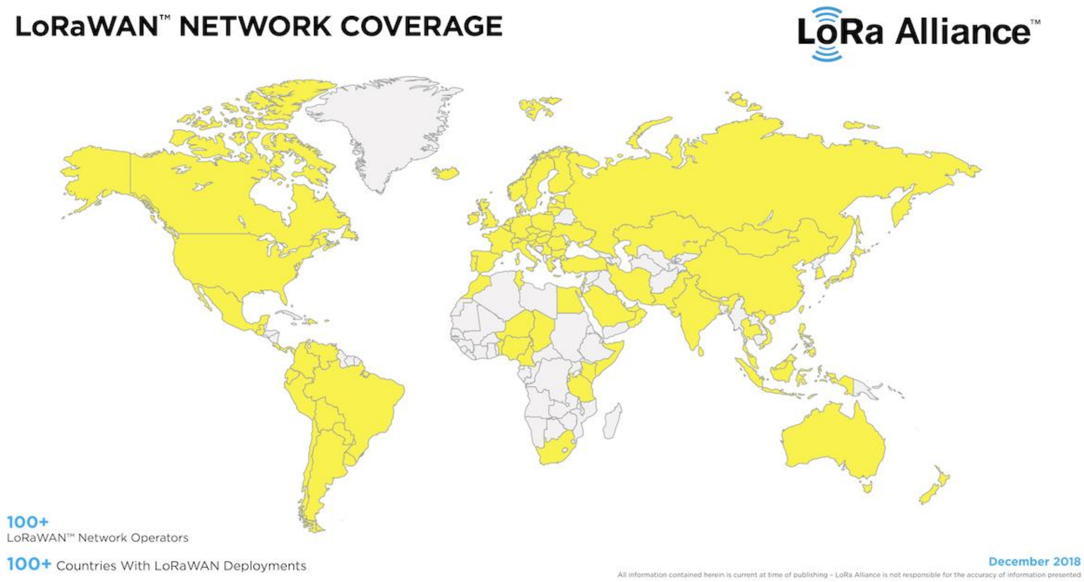

Figure 2.10 LoRaWAN deployments (LoRa Alliance, 2019).

Semtech claims that by the end of 2020 there are predicted to be 500,000 LoRa-based gateways and 140 million LoRa-based end-nodes deployed, these being both private and public. According to IHS Marketinsider, Sep 17, 40% of all LPWANs are predicted to run on LoRa by the end of 2019.

2.1.1.6.3 Cost

For a LoRaWAN operator, the pricing depends on the infrastructure it is implemented. The price of a LoRaWAN Gateway varies from €500 to €1750, while the prices of several transmitter are shown in Table 2.4. One can implement his own infrasturcture, or pay another operator to use the service of the LoRaWAN gateway. Several companies has made investments on deploying LoRaWAN infrastructure, such as ATA communications in India, that expect to reach at least 400 million people (TeleGeography, 2017), or SK Telecom, which planned to invest US$84 million to deply LoRaWAN nationwide in South Korea (SK Telecom, 2016).

Table 2.4. LoRaWAN Transcievers provided by Semtech (Semtech, 2015-2016; Digi-Key, 2016-2017).

Model	Power (dBm)	Max. Link Budget (dB)	Price (unit)
SX1261	15	170	1 → US $7.53 1000+ → US $5.24
SX1262	22	170	1 → US $7.94 1000+ → US $4.46
SX1268	22	170	1 → US $7.86 1000+ → US $4.92
SX1272	20	157	1 → US $7.56 1000+ → US $4.25
SX1276	20	168	1 → US $7.53 1000+ → US $5.24
SX1278	20	168	1 → US $8.06 1000+ → US $4.54

2.1.1.6.4 Roaming

In 2018, LoRa Alliance announced released a new version of LoRaWAN where the enabled roaming in LoRaWAN. A major contribution in this field was given by Actility. Olivier Hersent, CTO of Actility says:

"*This first successful LoRaWAN compliant roaming communication in the field is a critical milestone to unlock several key segments of the IoT market by removing the barrier of national borders,"* says Bertrand Waels, head of Alternative Radio Access at Orange. *"Our tests in an open collaboration with KPN in the Netherlands and with the support of Actility show that the specifications published by the LoRa Alliance do work reliably in the field*."

"Ultimately the LoRaWAN ecosystem can seamlessly cluster thousands of networks. We believe an open and multi-vendor system can scale up to the requirements of the Internet of Things."

2.1.2 Sigfox

Sigfox is an unlicensed narrowband LPWAN protocol developed in 2009, in France. Its founder company carries the same name. Firstly, Sigfox was unidirectional. It only intended to collect information from sensors. Later on, it become bi-directional by making available the downlink channel. It has a lightweight protocol and using the Cloud for the network and complexity, it drastically reduces cost of devices and the energy consumption.

Sigfox protocol is a closed, patented technology. Even its hardware is open, the network is closed. Some of the Sigfox partners include TI, Atmel, Silicon Labs, etc. Its infrastructure is similar to the LTE Carriers infrastructure. Differently from LoRaWAN, Sigfox model does not require a proprietary PHY to be used in their network. It uses a single managed network and several hardware vendors.

2.1.2.1 Architecture

Sigfox has built its simplicity in network architecture and objects. It uses star topology (Figure 2.11). The devices (ex: sensors) transmit their messages to the Sigfox network using Sigfox base stations. Unlike cellular protocols, a device is not attached to any specific base station, but its message is received by any base station. Every single base station deployed around the world by Sigfox network operators is directly connected to the Sigfox Cloud, through a point-to-point link. These base stations detect, demodulate and report the messages to the one and only Sigfox Cloud. The Sigfox Cloud then pushes the messages to the customer servers and IT platforms. (U. Raza, P. Kulkarni, M. Sooriyabandara, 2017).

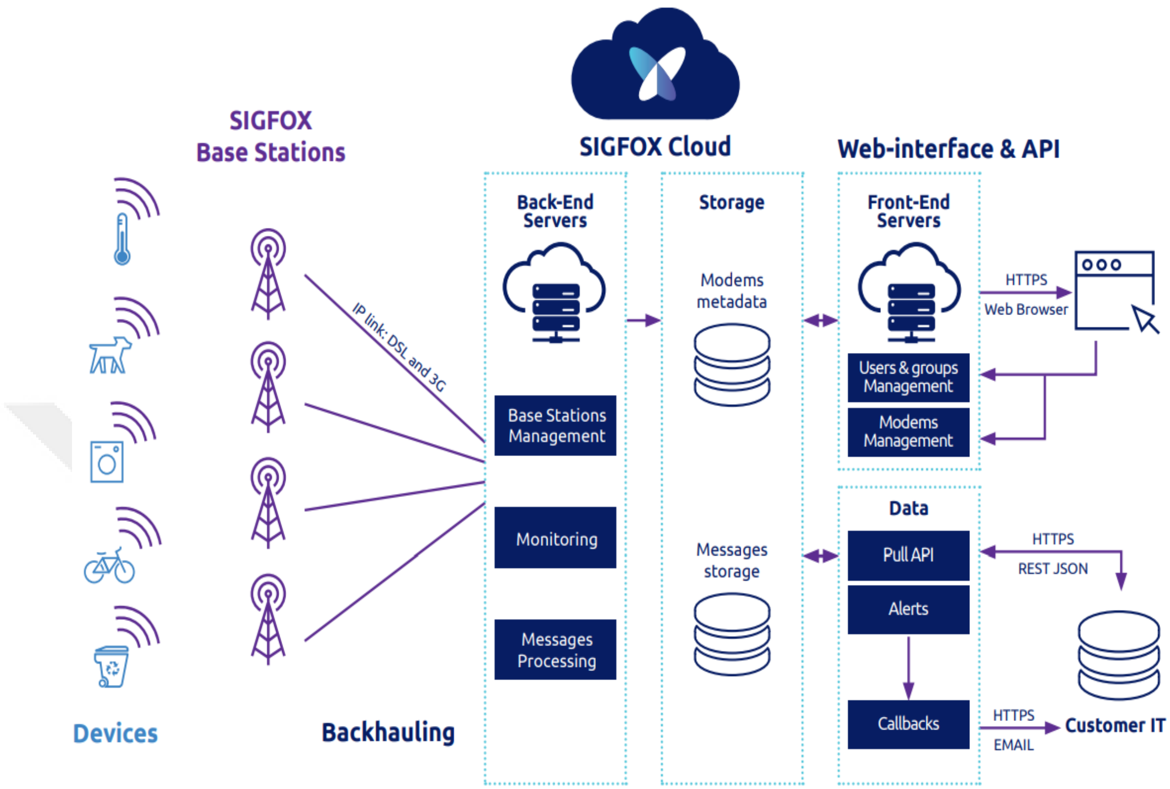

Figure 2.11. Sigfox Architecture (Sigfox, 2016)

2.1.2.2 Physical layer

Sigfox technology is an Ultra Narrow-Band (UNB) technology (Figure 2.12). It implies that it does not spread the energy across a wide channel, but instead a very narrow channel is used for the transmission of the messages, requiring less energy. Rather than spreading the energy across a wide channel, a narrow slice of that energy is confined.

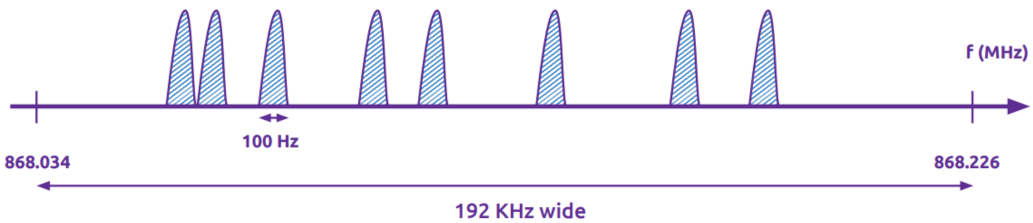

Figure 2.12 Sigfox Technology (Sigox, 2016)

Sigfox includes two types of modulations, one for the uplinks and other one for the downlinks. In uplinks, Orthoganol Sequence Spread Spectrum (OSSS) modulation is used in a band of 100 Hz, while in the downlinks Gaussian Frequency Shift Keying (GFSK) is used in a band of 600 Hz (Table 2.5).

Table 2.5. Basic parameters of Sigfox

	Uplink	**Downlink**
Modulation Scheme	OSSS	GFSK
Data Rate (bps)	100	600 Hz
Payload max length (B)	12	8
Max Sensitivity (dBm)	14	27
Maximum Messages / Day	140	4

The bandwidth in the Sigfox channels is 100 Hz, and it has a total of 333 channels. There are three copies of the payload being transmitted in random frequencies and channels with a delay varying from 500ms to 525ms (Figure 2.13). This is called Random Frequency and Time Division Multiple Access (RFTDMA). The sensitivity of the receiver reaches up to -142 dBm, and transmission power is defined +14 dBm in Europe and + 22dBm in North America.

Sigfox a range of 3-10 km in urban medium, and 30-50 km in rural mediums (U. Raza, P. Kulkarni, M. Sooriyabandara, 2017; M. Centenaro, L. Vangelista, A. Zanella, and M. Zorzi, 2016).

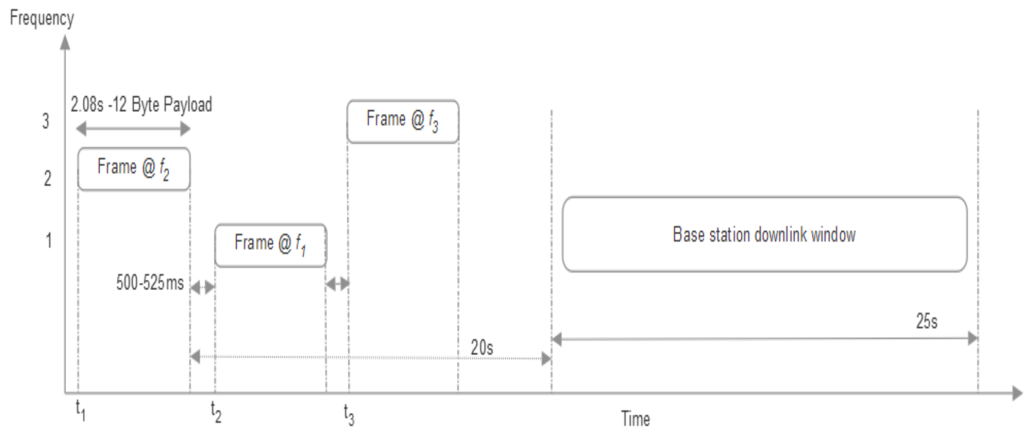

Figure 2.13. Transmission of the uplink.

2.1.2.3 MAC layer

Every device in Sigfox is assigned with a unique ID (regarding the Sigfox Network) that is used for routing ans signing of the messages. Sigfox uses "fire and forget" model, meaning that there is no way of ensuring if the message was transmitted or lost in the medium.

2.1.2.3.1 Message types: uplink and downlink connectivity

Uplink Connectivity: In the case of uplink communication, the connected devices emit the Sigfox radio messages, which are then harvested by the Sigfox base stations in the range. Then, every base station that received the message will transmit it to the Cloud. Finally, the Cloud verifies there are no duplicated messages and sends the message to the customer. The payload data that can be put in a Sigfox message ranges between 0 bits to 12 bytes (Figure 2.14). The data rate varies from 100 bps to 600 bps, depending on the operation region. The maximum number of uplink messages that would be sent in a day is 140.

32 bits	16 bits	32 bits	0 to 96 bits	variable bits	16 bits
Preamble	Frame Sync	End-Device ID	Payload	Authentication	FCS

Figure 2.14. Sigfox Uplink Frame.

A preamble is used to synchronise the transmission, while the Frame Sync specifies the type of the frame being transmitted. Here, for error detection there is Frame Check Sequence (FCS) used.

Downlink Connectivity: In Sigfox, a downlink message cannot be transmitted to the devices anytime. It is up to the device whether it requests from the network a downlink message. The device transmit an uplink message containing an uplink request flag. This request is received by the base stations in the range, and they relay it to the Cloud. Then, the cloud delivers it to the customers, who realizes that it is not a simple uplink message, but in addition the devices are requesting for a downlink message. They decide whether to transmit the downlink data or not. In case they decide to accept the request, the provide the payload message to the cloud, which then transmit it to the device via a base station. The length of the payload in a downlink sequence can be 8 bytes long (Figure 2.15). A 8 Byte payload would be anough to change the parameters of a device, but it would not be enough to upgrade a device. The maximum number of downlink messages that would be sent in a day is 4.

32 bits	13 bits	2 bits	8 bits	16 bits	variable bits	0 to 64 bits
Preamble	Frame Sync	Flags	FCS	Auth	Error Codes	Payload

Figure 2.15. Sigfox Downlink Frame

2.1.2.4 Limitations: frequency band and duty-cycle

Sigfox (2016), it transmits in ISM band, using the 868 MHz in Europe and the 900 MHz band in North America. Being approximately 200 bits sent, with a data rate of 100 bps it means that it lasts 2 seconds to send an uplink message. As the Euroepan Regulations (ETSI) limit the transmission to 1% duty cycle, then:

3600 Seconds @ 1% duty cycle → 36 seconds / hour

As mentioned above, the Sigfox uses RFTDMA method. This means each message will be sent 3 times. So,

3 x 2 seconds (time per message) = 6 seconds

→ 36 seconds / 6 seconds = 6 messages / hour

A total of 144 messages can be sent during a day in the Sigfox network. Depending on the location of the customer, the results above might change.

2.1.2.5 Security

There is an end-to-end authentication method between the connected devices and the Sigfox Cloud, based on a secret key that is pre-programmed in a non-accessible read-only memory of the end-device during manufacturing (TD next RF modules, 2017; Sigfox, 2016). The secret key is unique for each message sent, and it is used to authenticate the sender. As mentioned before, as every message is sent three times and randomly on three different frequencies, it protects the radio frames against missing because within the operation band it is not possible to know where the device is going to transmit (Sigfox, 2015). The Sigfox base stations are connected with the Sigfox Cloud through a point-to-point link, using an encrypted Virtual Private Network (VPN).

2.1.2.6 Commercial aspects

2.1.2.6.1 Business models and deployment

Sigfox network was founded by Sigfox, in 2009. In the last ten years it has been growing rapidly since its partner number has reached more than 650 and has investments from more global silicon-product, utility and service providers such as Intel, Samsung, Eutelsat, Telefonica, etc. According to Sigfox, there are more than 715 end products avaliable in the IoT market of Sigox (Sigfox, 2015).

In 2016, Sigfox launched Sigfox Partner Network, in which intended to bring together key partner companies regarding different fields. In 2019, Sigox Partner Networks has reached a number of 203 companies. The network includes sectors such as smart industry, smart agriculture/environment, utilities, smart automotive and fleet, public sector, smart home and lifestyle, smart retail and health (Table 2.6). These companies provide a total number 715 devices compatible to Sigfox Network, where 421 are certificed devices, 101 of them are in pending position, and 193 are not certified.

Table 2.6. The company number according to the use case of the products the provide (Sigfox, 2015).

Use Cases	Company Number
Smart Tracking – Assets and People	131
Temperature Monitoring	91
Monitor Environmental Conditions	85
Universal Acquisition Transmitter	62

Buttons	57
Building Office Monitoring	55
Secure Beter	50
Consumption Meters	49
Monitor Asset Usage	49
Water Infrastructure Operation	37
Smart Parking	23
Waste Management	18

Link Labs (2016), there are two business model approaches in Sigfox. In the first model, Sigfox itself deploys the network and acts as an operator. Examples of this model are deployments in France and the United States. The second model in the other hand allows other operators to deploy and commercialize the their network, in exhange for royalties. Currently, in the Sigox's web site there are 42 service providers of the Sigfox network, located in 47 different countries (Figure 2.16) (Sigfox, 2016).

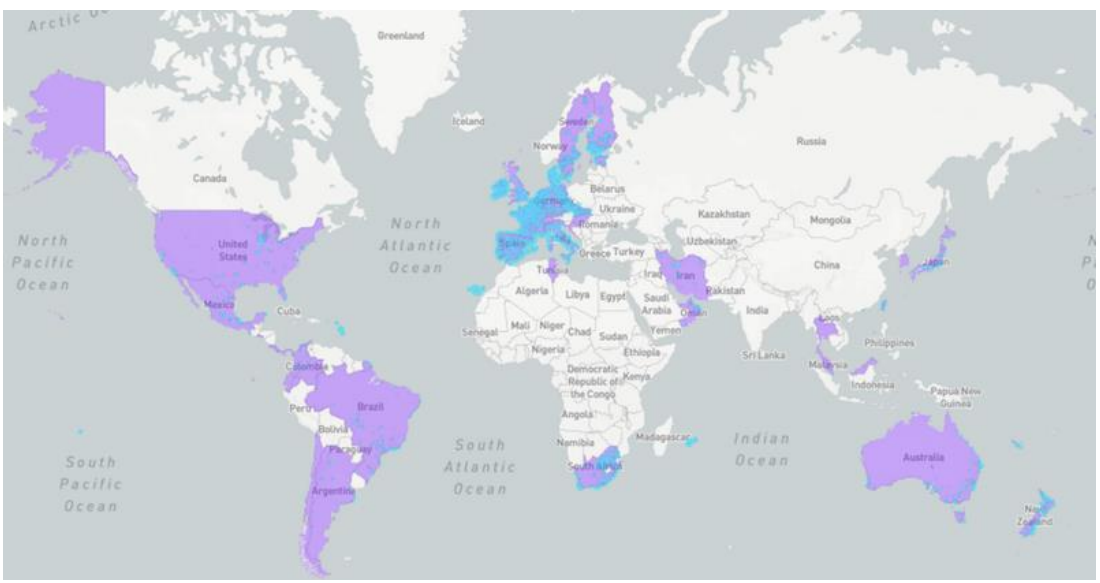

Figure 2.16. Countries known with Sigfox deployment (Sigfox, 2017).

2.1.2.6.2 Cost

Sigfox is designed to be a cost-effective network. There are several hardware companies that provide Sigfox devices, where some of them manufacture specific Sigfox devices, and some of them manufacture devices that would be compatible to Sigfox network. To be compatible to Sigfox, the device must accomplish some technical requirements such as having a flash memory space of 5 to 10 KB in its MCU, in order to receive the Sigfox stack. Some examples of the manufacturing companies are Texas Instruments, Silicon Labs, OnSemi, STMicro, Microchip, NXP, M2COM, Semtech, etc (D. Sjöström, 2017).

There is no public information about the cost of the base stations and insfrastructure or service. They are manufactured and can be provided by only Sigfox. A module has been taken as an example to derive the details of its cost according to its parameters (Table 2.7).

Table 2.7. Pricing of ATA8520E module (Atmel, 2016; Avnet, 2017; (D. Sjöström, 2017))

Model	ATA8520E (Microchip)
Cost per device	+1500 units: US$2.276 +6000 units: US$2.15 +15000 units: US$2.065
Operating Band	Europe: 868.0 – 868.6 MHz (uplink) Europe: 869.4 - 869.65 MHz. (downlink) US: 902 - 906 MHz (uplink and downlink)
Power and Current Consumption	EU: 13.8 dBm (TX: 32.7 mA, RX: 10.4 mA) US: 9.5 dBm (TX: 16.7 mA, RX: 10.5 mA)

Being a private company that offers access to its service, Sigfox arranges different prices for different places regarding the subscription of the clients. Apart location, it also depends on the number of connecting devices. Another issue that indicates the prcising of Sigfox subscriptions are the data packed and packet rate limitations.

2.1.2.6.3 Roaming

Sigfox is a global network, therefore there is not any requirement for roaming. In order to roam internationally across the global Sigfox network, the devices must support ETSI and FCC compliance.

2.1.3 RPMA

Formerly known as On-Ramp Wireless, RPMA (Random Phase Multiple Access) is an unlicensed LPWAN technology developed by INGENU. RPMA includes all the stack, from Physical layer to the Network Layer. Machine Network, also built by INGENU, is the public network for using of RPMA technology, dedicated to M2M communcation. Similar to other LPWAN unlicense Technologies, also RPMA uses star network topology in its architecutre, but it differentiates itself from the market with the flexible network system. For modulation and demodulation, Direct Sequence Spread Spectrum (DSSS) modulation type is used. AES-128 Ecnryption algorithm is implement in the network for secure communication (Ingenu, 2016).

2.1.3.1 Spectrum

RPMA uses the 2.4 GHz ISM band, which is available globally. Compared to other ISM bands, there are no limitations on it. RPMA has 80 channels worldwide, because the 2.4 GHz band has 80 MHz of spectrum and a single RPMA channel takes up 1 MHz. This is a much larger bandwidth compared to other unlicensed technologies. It is feasible to use antenna diversity due to smaller wavelength in 2.4 GHz band.

2.1.3.2 Coverage

RPMA supports a -145 dBm receiver sensitivity worldwide with no restrictions based on the regulations of the 2.4 GHz band. According to INGENU, an RPMA access point can cover 456 square kilometers in America and Australia, and 85 square kilometers in Europe, Middle East, and Africa (EMEA). Detailed features of RPMA are shown in Table 2.8.

Best-in-class coverage for Access point and 100% acknowledgement of the messages combined together, makes a reliable coverage for RPMA.

Table 2.8. Technical features of RPMA

Features	**RPMA**
Deployments at scale	Yes; more than 30 commercial deployments. More than 4.5 million messages sent each day.
Acknowledged Delivery	Yes; 100%: all messages acknowledged.
Packet Size Flexibility	Yes, 6 bytes to 10,000 bytes.
Congestion Management	Yes; handling peak tra-ffic periods and crises designed into protocol.
Interference Robustness	Yes; Has advanced channel coding, intelligent retransmission scheme, very fast data rate adaptation.
Firmware Downloads	Yes, without disrupting normal communications.

2.1.3.3 Commercial aspects

Due to a lack of first mover advantage, RPMA's ecosystem is less mature than competing technologies. Also, as Ingenu is the only provider of an RPMA access point. Meaning, if the goal is to build a custom module or gateway, it would be more appropriate joining the LoRa Alliance. Operating at 2.4GHz band, it is an advantage for the partners of Ingenu and customers of RPMA, because they will deal with any duty-cyle or limitation in the band. RPMA global coverage is shown in Figure 2.17.

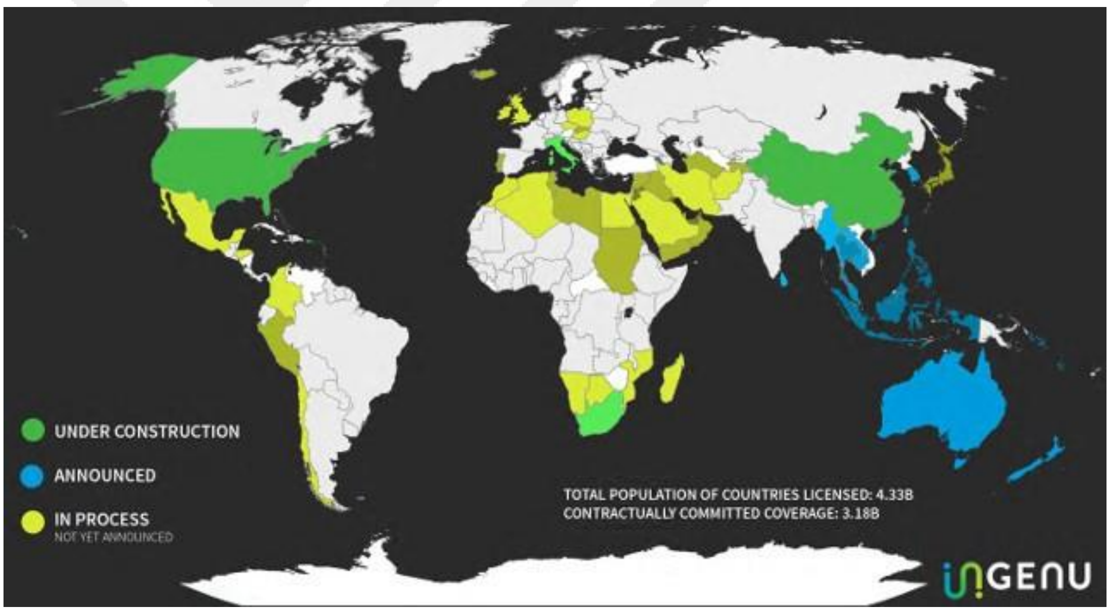

Figure 2.17. RPMA global coverage map (Ingenu, 2019)

2.2.3.3.1 Cost

U-Blox America Inc. is the leading company that manufactures devices compatible to RPMA. One of the examples is SARA-S200 (Table 2.9), the transciever released by U-Blox, which also Works with Machine Network. It is an update to the first RPMA module (NANO-S100), with cost and size optimization, that makes it suitable for different applicaitons. The module supports FOTA (FW updated over the air) with the ability to also update the application firmware. There are development kits available for this module. Specifications of SARA-S200 RPMA transciever are shown in Table 2.10.

Table 2.9. Price of SARA-S200 RPMA Transciever (Digi-Key, 2016)

Price Break	**Unit Price**	**Cost**
1	30.71000	$30.71
10	28.35000	$283.50
50	25.98760	$1,299.38

Table 2.10. Specifications of SARA-S200 RPMA transciever (U-Blox, 2017)

Feature	
Radio Spectrum (MHz)	80
Frequency Band (GHz)	2.4
Bandwidth (MHz)	1
Modulation	DSSS
Receive Sensitivity (dBm)	-133
Transmit Power (dBm)	+22
Link Budget (dBm)	-176

2.1.4 NB-FI

NB-FI means Narrowband Fidelity. It is a ground-up LPWAN technology designed in Russia, in 2010. Similar to LoRaWAN, it is an open protocol, making it suitable for worldwide deployment. Being full stack, it covers all the OSI model layers from PHY layer to Application Layer (Figure 2.18) (WAVIoT, 2016).

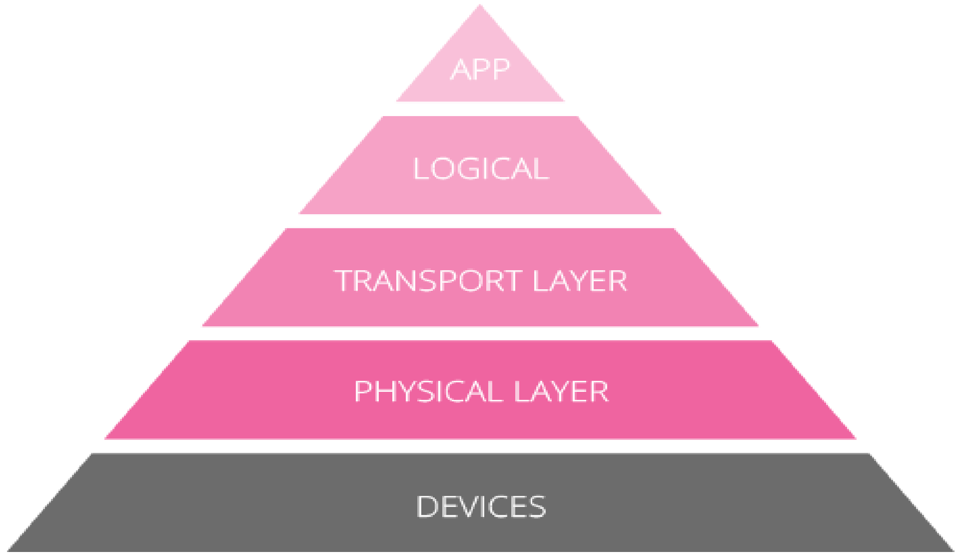

Figure 2.18 NB-FI OSI Model (WAVIoT, 2016)

2.1.4.1 Network

NB-FI is architected as a star topology network (Figure 2.19). The end-devices communiate directly to gateways. Then, the data collected is processed in the client's IoT Cloud Platform, called WAVIoT Cloud. It is used to display and visualise end user's data, to manage the end-device, give full reports, export data to different formats, and also it is an API for integration with other external systems.

There are two approaches of network in NB-FI, the public and the private one. The public network, which suits best for massive IoT applications. WAVI-IoT pretends that their powerful base stations provide a range of 30 km, and more than 2 million devices can be managed by a single base station. The private network is implemented in country scale, and is managed by a Network Operator under a license provided by WAVIoT. In the other hand, the private network is implemented in city scale. It also supports 2 million end-devices, but is managed by WAVIoT, including the Cloud Server of WAVIoT which is available worldwide.

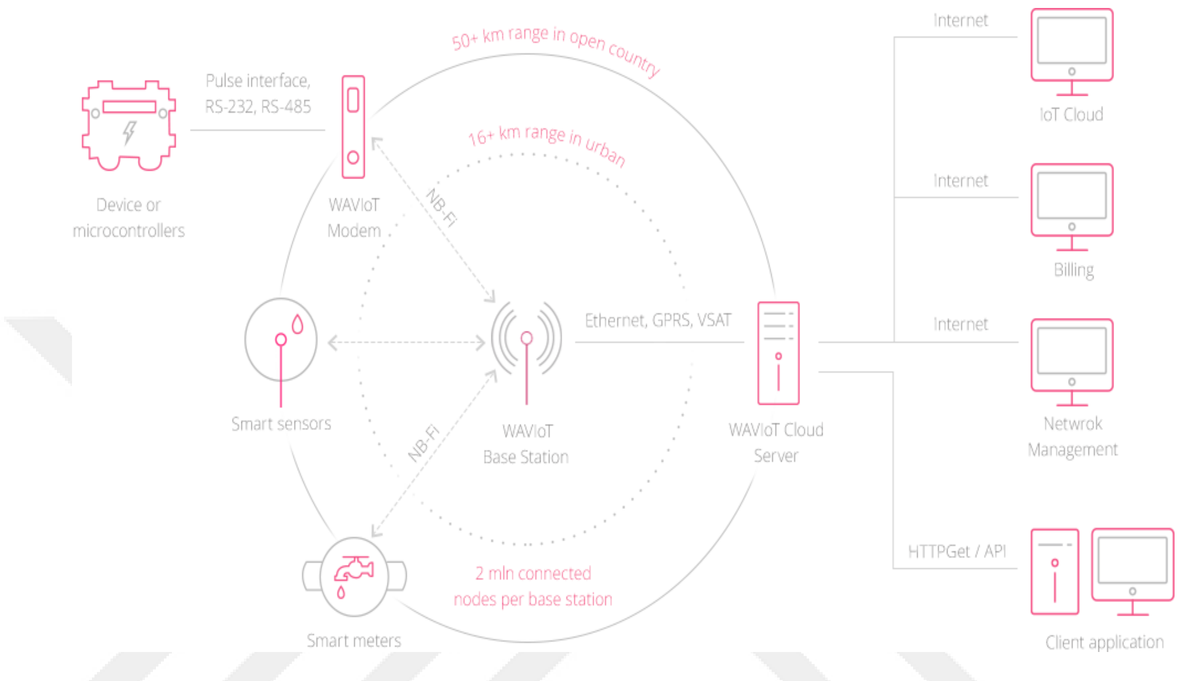

Figure 2.19. Architecture of NB-FI

2.1.4.2 Base stations and transcievers

WAVIoT NB-300 is taken as a base station example of NB-FI. The use of FPGA processing technology, allows it to process up to 1024 channels simultaneously. For installation of this base station there are no special requirementes needed. An AC power and an internet connection would be enough.

WAVIoT NB-FI is a low power transciever. The modulation type used to communicate with the base stations is DBPSK. It is half-dublex and has a sensitivity of -148 dBm, and an output power of 15 dBm (Table 2.15).

Table 2.11. NB-FI Transciever Specifications

Wireless Protocol	WAVIoT NB-FI
Modulation Type	DBPSK
Frequency Band (MHz)	430-500, 860 – 925
RX Sensitivity (dBm)	-148
Max TX Power (dBm)	15
Supply Range (V)	1.8 – 3.7
Weight (g)	20
Compliance	FCC / ETSI

2.1.4.3 Frequency and range

The protocol of NB-FI is built in such way that it would use the 915 MHz, 868 Mhz, 500 MHz, and 433 MHz ISM bands. It has a bandwidth of 500 KHz, and provides high efficiency utilizing 5000 channels in their full capacity. It has a link budget of 168 dBm, providing a good penetration, as shown in the Figure 2.20:

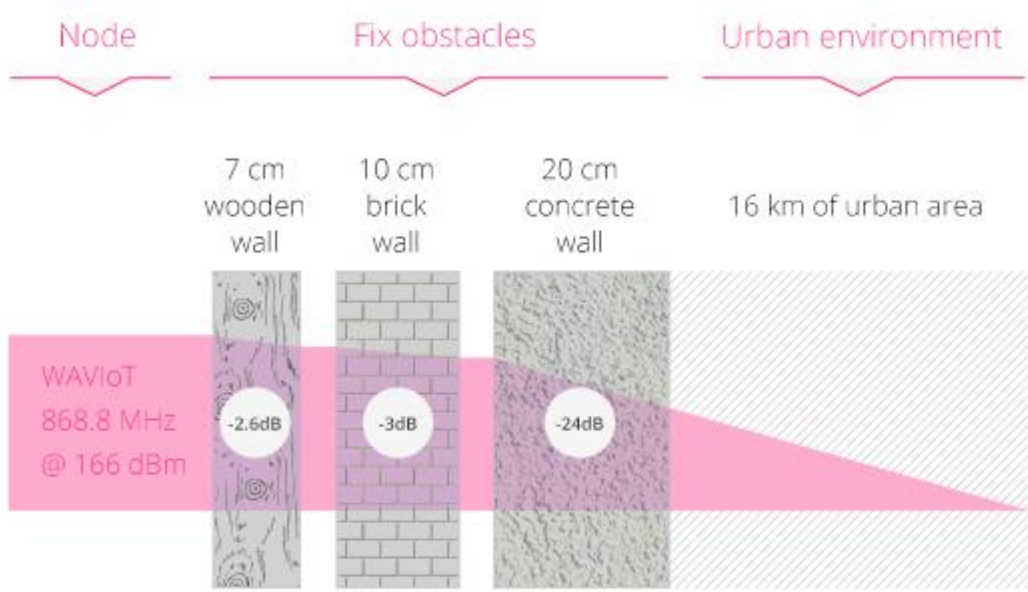

Figure 2.20. WAVIoT Penetration (WAVIoT, 2017)

In urban areas, WAVIoT pretend that their protocol reaches a range of 10 km, and in the rural areas it could reach 50+ km.

2.1.4.4 Commercial aspects

WAVIoT, HoloNet Networks, NERO Electronic, EyeWatt, Metering Ltd and EyeWatt are a gorup of companies united to announce the launch of NB-FI Alliance. Their commons mission is to develop the NB-FI protocol. There are three membership classes to become an Alliance Member: Free (with no fee), Gold (haveing a fee of US$1000, and Platinum (having a fee of US$4000) memberships. There are different services provided in the membership classes. The membership companies are focues on “working together to advance IoT”. NB-FI Alliance pretends that different commercial NB-FI networks have been deplyed around the globe, and some of the companies are developing and have began dhe production of the devices compatible to NB-FI, but there is not any public information related to locations of these deplyoments. They say that the number of NB-FI devices installed currently has exceeded 100.000 pieces.

2.1.4.4.1 Cost

According to NB-FI Alliance official website, the fee of becoming a Gold membership and Platinum membership, is US$1000 and US$4000, respectively. In Gold membership, there are 250 device licenses included. While in Platinum membership there are 1000 device licenses included. The cost of device licenses varies from the total number of the devices to be installed (Table 2.12).

Table 2.12. NB-FI device license fees

Number of devices	Fee
1-3000	US$5.6

3000-10.000	US$4.8
10.000 +	US$4.1

According to NB-FI Alliance, the NB-Fi transceiver cost starts from US$4.99, and the firmware for the NB-Fi compatible transceiver costs US$3.0. There is no public information available related to the base stations' cost.

2.1.5 DASH7

The DASH7 Alliance Protocol (D7A) is an open source LPWAN protocol. D7A implies with ISO 18000-7 for Active RFID and operates in the 433 MHz sub-GHz ISM band. A ful stack OSI stack is specified in the D7A protocol (DASH7 Alliance, 2017). The protocol is free to use without any requirement such as patent or license.

Features like smart adressing and local synchronisation allow the upgrade of thousand end-module simultaneously. The latency of a message is 1 second, with a communication range up to 2 km. Compared to other LPWA networks, D7A has a shorter range, filling the gap between short and long range technologies.

2.1.5.1 Architecture

The architecture of D7A is very similar to LoRaWAN's architecture due to some basic elements: the end-devices send the information gathered by the sensor to the gateways in a asynchronous mode, than the gateways receive the messages and remove the unnecessary duplicates and send them to the network server. The difference is that in D7P there is a blinker in the end-device side, which does not receive but only transmits.

2.1.5.2 Physical and MAC layer

M. Weyn, G. Ergeerts, R. Berkvens, B. Wojciechowski, Y. Tabakov (2015), D7A's physical layer, having a small data to be trnasmitted and authenticated, carries very efficient energy-per-bit characteristics. The modulation, spectrum and channel encoding are handled by this layer (DASH7 Alliance, 2017). It allows FUOTA and reactive downlink access and over-the-air (OTA) code upgrade. D7A uses 2-GFSK modulation scheme.

D7A operates using the "blast" concept: bursty (the transfer is abrupt, there is no continuous transmission), light-data (packet-size limitation to 256 bytes), asynchronous (there is no synchronous "hand-shake" communication, it is realized by command-response), and transitive (the devices do not have to be managed by fixed base stations (it is upload centric).

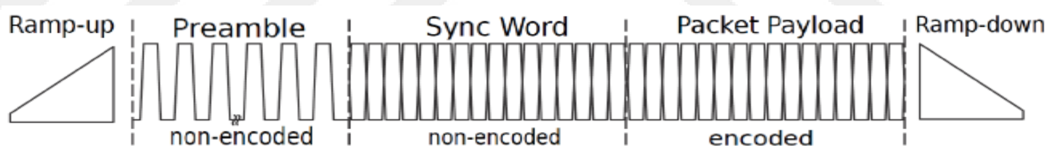

Figure 2.21. The Frame of DASH7 (DASH7 Alliance, 2017)

For meeting the channel requirements, the power ramp-up and ramp-down that are incorporated. The preamble consists of 32 bits for base and 48 bits for high rate, while the sync word consists of 16 binary symbols (Figure 2.21). There are three different channel classes defined in the protocol: low-rate, normal and high-rate. The classes are shown in the Table 2.13.

Table 2.13. GFSK Modulation Schemes in D7P (M. Weyn, G. Ergeerts, R. Berkvens, B. Wojciechowski, and Y. Tabakov (2015)

	Low Rate	Normal	High Rate
Channel Spacing (MHz)	0.025	0.2	0.2
Symbol Rate (kbps)	9.6	55.55	166.67
Modulation Index	1	1.8	0.5
Frequency Deviation	4.8	50	41.667

There are two types of frames defined in D7P, which are shown in the Figure 2.22 and Figure 2.23. below: foreground frame which has a length that varies up to 256 bytes, and background frame which has a fixed length of 6 bytes.

PHY Header	Length	Subnet	CTRL	TADR	Payload	CRC16	PHY Footer
	1 Byte	1 byte	1 byte	0/1/2/8 bytes	0-251 Bytes	2 Bytes	

Figure 2.22. D7A Foreground Frame

PHY Header	Subnet	CTRL	Payload	CRC16	PHY Footer
	1 byte	1 byte	2 Bytes	2 Bytes	

Figure 2.23. D7A Bacground Frame

2.1.5.3 Commercial aspects

Among the proponents of DASH7, there are several semiconductor manufacturers that provide silicon solutions and development tools, such as Texas Instruments, ST Microelectronics, Melexys, and Semtech. The exact price depends on the requiremets of the Project. Being an open-standard, makes the protocol competitive to other wireless technologies as the customer is not “locked” into a single company. Due to the fact that DASH7 would incorporate with active and passive RFID tags, it becomes suitable for a large number of applications.

2.1.6 WIGHTLESS – P

2.1.6.1 Technical aspects

Weightless SIG (2016), Weightless-P is an open-standard LPWAN technology designed by the Weightless – Special Interest Group, in 2017. There are three different types designed by the group: Weightless-W, Weightless-N and Weightless-P. Since Weightless-W and Weightless-N are focused on ultra-low cost and TV whitespace, respectively, there is Weightless-P more similar to other LPWAN technologies.

Weightles-P operates in sub-GHz ISM bands. In this technology, an optimal capacity for uplink-dominated traffic is offered by combining FDMA and TDMA modulation, in 100kHz and 12.5 kHz narrowband channels (Table 2.14).

Table 2.14. Wightless-P Features

Features	
Data Rate	625 bps to 100 kpbs
FEC	Yes
Operating Band	ISM (sub-GHz)
Security	AES 128
Channel Bandwidth	12.5 kHz and 100 kHz
FOTA	Yes
Acknowledgement	Yes (Full)

2.1.6.2 Commercial aspects

The Weightless SIG is a global, non-profit, member based organisation that develops open standard IoT connectivity technology. It is launched to support the interests of the members and to provide IoT solutions to the community. To provide full access to Weightless technology free, Weightless developers sign an agreement. Weightless Developers also benefit from a number of very significant offers exclusive to members. Countries including Weightless-SIG Membership are shown in Figure 2.24

Figure 2.24. Countries including Weightless-SIG Membership (Weightless SIG, 2019)

2.1.7 Symphony Link

Symphony Link is a LPWAN technology developed by Link Labs. It is primarily used by industrial and enterprise customers who apart the range of LoRa, they also need high reliability and advanced features in their application. Built in LoRa's CSS phyical layer technology, Symphony Link is as an alternative to LoRaWAN. Symphony Link is independent to LoRaWAN, and vice versa. A comparison of Symphony Link and LoRaWAN is conducted in Table 2.15.

There are some Symphony Link modules and gateways available in the market. RLP-20 and RXR-27 are two end-modules lanched by Link Labs. As gateways, they have launched Inoodr Gateway (LL-BST-8) and Outdoor gateways.

Table 2.15. Advantages of Symphony Link vs. LoRaWAN

Feature	Symphony Link	LoRaWAN
Acknowledgement	Full	Too limited
Duty-Cycle	No limits	1%
Security	+++++	++++
Real Time Power and Data-Rate Control	Yes	No
Capaciy	4X	X

2.1.8 Telensa

Telensa UNB (Ultra Narrowband) is Low Power Wide Area wireless network designed in 2005, in United Kingdom. For more than a decade it has proven itself in Street lighting control systems in several implementations all over the world. Its first major city deployment was in 2010, where Telensa was implement in 100.000 street lights in Birmingham. In 2012, it owned 50% of the market share in UK, controlling 10% of the Street lights in UK. Later on, in 2014, another large deployment was realized in Georgia, United States. Now, it is world's largest deployment. In 2015, Telensa controls 1 million lights globally. Nowdays several implementations of the Telensa Tech are found around the world.

2.2 Licensed LPWAN Technologies

In this section, the cellular LPWA will be described in detail according to their technical and non-technical aspects.

2.2.1 3GPP Technologies

2.2.1.1 Technical overview

3GPP (Third Generation Partnership Project) was formed in 1998 when the ETSI with collaborated with other SDO (standard development organizations) from around the world in order to develop new technology specifications for the 3G cellular networks. Dute to the diversity and the need to support development of IoT applications, the mobile industry together with 3GPP standardised a new class of GSM technologies that support devices with requirements such as: low power consumption, long range, low cost and security, etc.

There are three complementary licensed 3GPP standards merged to address the reqirement of the IoT applicaitons: Narrowband IoT (NB-IoT), Long Term Evolution Machine Type Communications Category M1 (LTE MTC Cat M1/ LTE-M) and Extended Coverage GSM for Internet of Things (EC-GSM-IoT). These three technologies were launched in Release 13 of 3GPP (3GPP, 2016). During the years these 3GPP standardised technologies have been imlemented by MNOs around the world, bringing to the market a very wide range of different benefits.

Cellular LPWANs run on public GSM and 3GPP standardised cellular networks which use the licensed radio spectrum. Having a global coverage, the collaboration among the operators provides mobility, as the are over 900 mobile operators around the world. Also, the fact that a certain portion of the radio spectrum is reserved by an induvidual mobile operator, provides security and reliability. The objectives of cellular LPWAN technologies are:

- Extended range
- Lower cost
- Support massive IoT devices
- Longer battery life

2.2.1.1.1 NB-IoT (LTE Cat-NB1)

Narrow Band Internet of Things (NB-IoT) is a part of Release 13. It defines a new low power IoT technology that can be integrated into the LTE standard, also it operates in the licensed frequencies of LTE. Actually, it is the non-complex version of LTE technology, because it is built by removing many features of LTE, suh as: carrier agreegation, channel quality, dual connecitivity, handover, etc. To support NB-IoT, there is only a software upgrade required in the base stations.

2.2.1.1.1.1 Architecture

NB-IoT operates in star topology. It has the same architecture as LTE, but with some optimizations in order to meet the requiremets of LPWAN. There are four main components in NB-IoT architecture: end-devices, cellular base stations, cloud platfrom and and application server. The sensors carrying the information are connected to the end-devices, which transmit the information to the cellular base stations. Then, the data received from the end-devices is relayed to the Narrowband Cloud platform, which forwards the data to the application servers.

2.2.1.1.1.2 Physical layer and communication protocol

NB-IoT has a bandwidth of 200 kHz (Qualcomm, 2016), corresponding to one resource block in the LTE transmission. There are three modes of operation for NB-IoT (Figure 2.25): Stand Alone, In-Band, Guard-Band. In the stand alone mode, an entire 200kHz GSM carrier signal range is occupied by the signal. While in both, the in-band and guard-band mode, NB-IoT is implemented as a 180kHz Physical Resource Block (PRB) inside the LTE carrier signal. LTE protocol functionalities are reduced to minimum and modified by NB-IoT to meet the requirements of IoT case. This modification has to do with the backend system that is used to send information to end devices, since broadcasting consumes energy which is critical in IoT devices. The frequency and data size is reduced to the minimum.

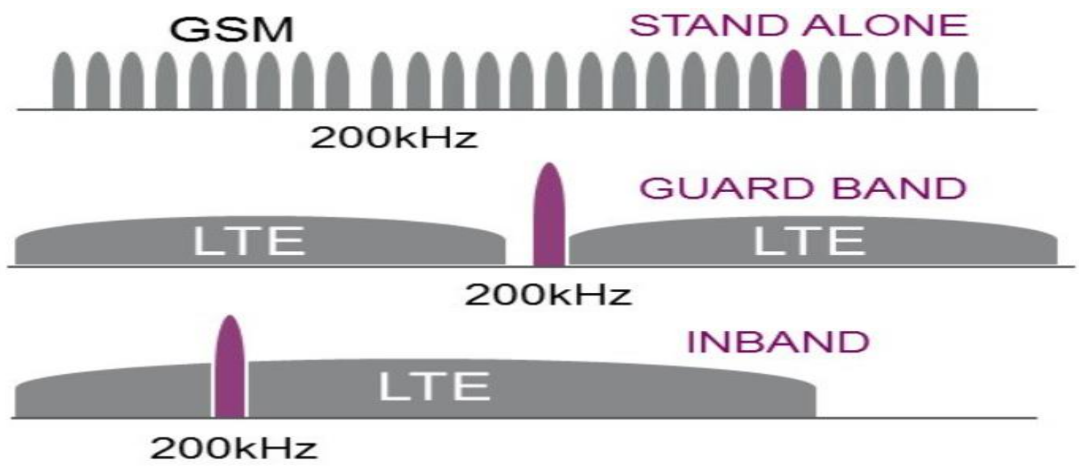

Figure 2.25. Operation modes of NB-IoT: Stand-Alone, Guard-Band and In-Band.

NB-IoT uses Quadrature Phase Shift Keying (QPSK) modulation. For downlink transmission Orthogonal Frequency Division Multiple Access (OFDMA) is used, while for the uplink transmission Single Carrier Frequency Division Multiple Access (SC-FDMA) is used. SC-FDMA requires less power compared to OFDMA, thereby the end-devices' battery lifetime increases. The packet-size of NB-IoT data reaches a maximum of 1600 bytes. The data rate for uplink and downlink is 20 kbps and 200 kbps, respectively. The battery of the devie would last 10 years if only 200 bytes were send per day. A single base station can support up to 100,000 end-devices, and the number can increase by exploiting multiple carriers (K. E. Nolan, W. Guibene, M. Y. Kelly, 2016). Currently, the improvement of NB-IoT is continuing with the Release 15 of 3GPP.

2.2.1.1.2 EC-GSM-IoT

Extended Coverage Global System for Mobile IoT (EC-GSM-IoT) is one of the third 3GPP LPWAN standard operating within the licensed spectrum. Formerly it was known as EC-EGPRS, but for marketing purposes its brand name was edited (H. Welte, 2016). This is also confirmed by a press conference held by Ericsson. Unlike LTE-M and NB-IoT, which respectively operate on the LTE band and 3G bands, EC-GSM operates on General Packet Radio Service (GPRS) spectrum. According to GSMA, EC-GSM-IoT is based on EGPRS, so that it operates on existing core of GPRS network. Similarly to other cellular IoT technologies, in order to use EC-GSM-IoT on GSM networks this protocol simply requires a software upgrade of GSM networks, since most mobile hardware companies already support it. Of the three cellular options, EC-GSM-IoT seems to have the least momentum.

2.2.1.1.2.1 Physical layer and communication protocol

In EC-GSM-IoT, there is multiple access accomplished by TDMA (Time-Division Multiple Access) and FDMA (Frequency-Division Multiple Access), as in 2G. There is 200 kHz of bandwidth occupied by each channel (3GPP, 2016). In TDMA modulation, the transmissions are divided into different time slots, so that a user is allowed to use a single frequency band. There are 8 time slots in GSM, and 4 of them are utilized by EC-GSM-IoT (L. Nielsen, 2017). In the other hand, in FDMA the the communication is divided in different frequency bands, thereby multiple simultaneous transfers can occur by multiplexing information in different time slots (M. Sauter, 2010).

GSMA claims that all the three cellular LPWANs (NB-IoT, EC-GSM and LTE-M) support Power Saving Mode (PSM) and Extended Idle-Mode Discontinuous Reception (eDRX) (Figure 2.26) (GSMA, 2016). According to GSMA, PSM reduces power consumption by enabling devices to enter a new deep sleep mode. In the other hand, according to Qualcomm the device is unreachable when PSM is active (PCMAG, 2017). It also states that the power consumption is reduced by eDRX by extending the maximum time between data reception from the network in connected mode (Qualcomm, 2016).

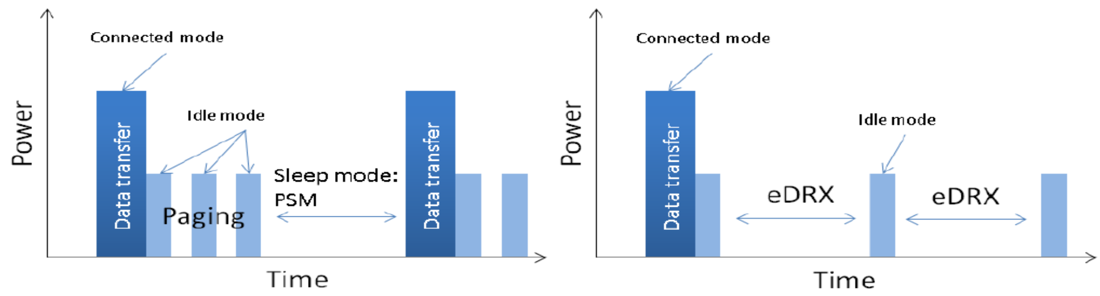

Figure 2.26. PSM and eDRX optimization (Qualcomm, 2016)

2.2.1.1.3 LTE-M (LTE Cat-M1)

2.2.1.1.3.1 Technical apects

LTE-M, also known as CAT-M1, use the LTE installed bases and is optimized for higher bandwidth and mobile connections, including voice. It is part of the Release 13 of 3GPP. It provides real time communication with a bandwidth varying from 350kb/s in half duplex up to 1Mb/s in full-duplex. Its objectives are:

- Higher Speed
- Voice Support
- Mobility

Similar to NB-IoT, one of the biggest advantages of LTE-M is that it's completely compatible with existing cellular networks. MNOs do not need to install any new hardware to use it—they just need to upgrade the software of the base stations. Being half-duplex and have a narrow bandwidth, the devices can connect to LTE networks with simpler modems that only require 1 antenna. Devices would leverage the new Power Savings Mode (PSM) and extended discontinuous reception (eDRX) to achieve up to 10 years of battery life. According to Qualcomm, a LTE-M device occupies a bandwidth of 1.4 MHz. Nokia claims that LTE-M can be allocated on a legacy LTE carrier, and in the other side GSMA states that this carrier can be shared by several LTE-M devices (Nokia, 2017; GSMA, 2017). For uplink and downlink modulation, LTE-M uses QPSK and 16 QAM modulation, respectively (E. Dahlman, S. Parkvall, J. Skold, 2016) The latency of LTE-M is said to be between 10-15 ms (Sequans, 2016).

2.2.1.2 Commercial aspects of licensed technologies

The biggest advantage of cellular LPWAN solutions is the globally wide ecosystem made of more than 400 individual members. According to GSMA, more than 750 MNOs are currently operating worldwide, but only 52 of them have deployed commercial LPWAN networks. This makes only 7% of the total number of the MNOs included in deployments of cellular solutions. During the last two years, several MNOs announced significant progress in development of cellular coverage in their networks. Some European MNOs already provide country-wide availability.

2.2.1.2.1 Deployment

GSMA has been establishing an LTE-M task force for the purpose of accelerating the adoption of LTE-M, as it also benefits from 3GPP large ecosystem (GSMA, 2017). The first test results of LTE-M were first published by Verizon and Link Labs, in 2017 (Link Labs, 2017). Similarly to LTE-M force, also a forum of NB-IoT established by GSMA has been accelerating the deployment progress of NB-IoT, where some big players such as Huawei, Ericsson, Telit, T-Mobile, Nokia, and a lot more are included. In the other hand, a group formed specifically regarding EC-GSM- IoT Group has an aim to provide a wider ecosystem in order to accelerate the global adaption of EC-GSM-IoT technology. Its first commercial solutions were launched in 2017. Samsung Electronics, Intel Coorporation, Brandcom, Cisco, Nokia, Ericsson, Sierra Wireless, etc; are some of the members of EC-GSM-IoT Group. LTE-M and NB-IoT deployment map is shown in Figure 2.27. In the Table 2.16 there are shown the number of the MNOs included or planning to be included in the cellular LPWAN networks.

Table 2.16. Operators identified by GSA (No available information for EC-GSM-IoT)

	LTE-M	NB-IoT
MNO number to deploy or commercially launch the network:	13	44
MNO number investing on the network:	37	107
MNO number planning or deploying the network:	12	29
MNO number to trail the technology	13	34

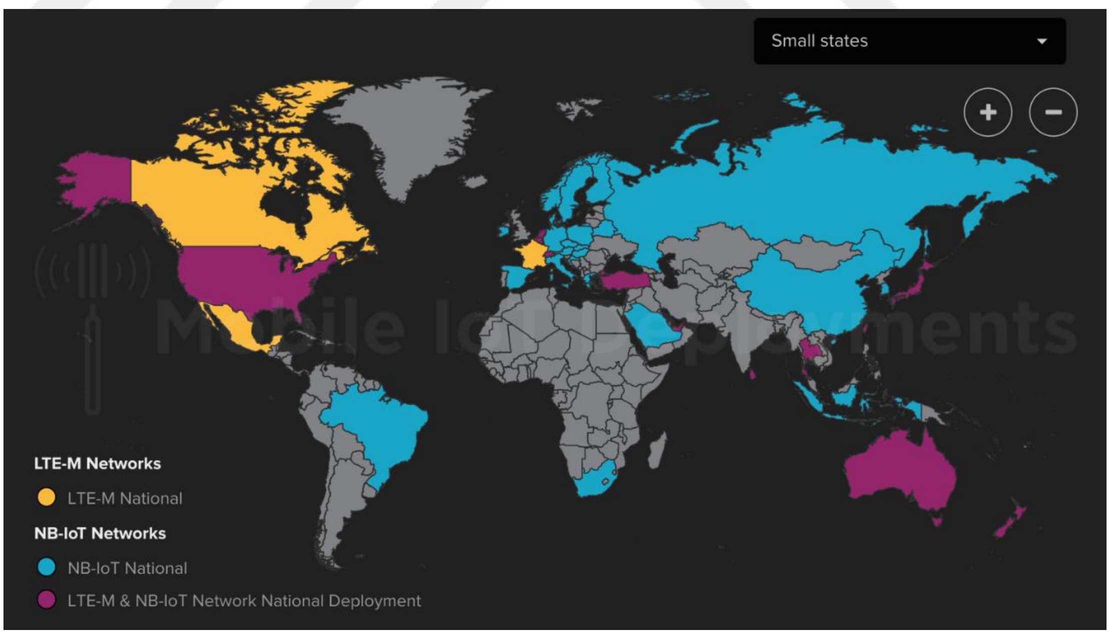

Figure 2.27. LTE-M and NB-IoT deployment map (3GPP, 2019)

2.2.1.2.2 Cost

In order to benefit from the cellular IoT services, the customers should subscribe to MNOs. Generally, a certain fee per device is required due to the data amount to be sent and the frequency of uplinks and downlinks. In the beggining of 2018, communications company T-Mobile, being the third largest carrier in United States (after AT&T and Verizon), has outlined a pricing model for the NB-IoT service it provides. Magneta, the so-called pricing plan, defined that it costs US$6 a year per device, will a limitation of 12 MB data. This, being only 10% of Compared to the Verizon's charge of its LTE-M service, it is only 10% of price. This, because ot their technical differences. Apart MNO subscription, the users must also take into account the cost per end-module, which, as more and more manufacturers are included in market, the price is decreasing. The details for some of NB-IoT and LTE-M modules available in the market are shown in the Table 2.17, and the module number supporting each technology are shown in Table 2.18.

Table 2.17. Some module details of LTE-M and NB-IoT (Ublox, 2017; Telit, 2017; Quectel, 2017)

	NB-IoT		**LTE-M**
Manufaturer	Telit	Quectel	Ublox
Model Name	NE866B1	BC95	SARA-R404M
Data Rate	uplink: >20 kbps downlink: >250 kbps	100 kbps	Uplink and downlink: 375 kb/s
Power Details	Supply voltage: 3.8 V. Output power: 23 dBm	Supply voltage: 3.8 V. Output power: 23 dBm.	Supply voltage: 3.8 V. Tx current (max power): 125 mA
SIM	1.8 V SIM interface	SIM/USIM interface	(u)SIM interface (1.8 V / 3 V)

Cost	1 unit: US$35.	Unknown.	Unknown.

Table 2.18. Module number supporting the Technologies

Function	**Number of modules**
Modules only supporting NB-IoT	50
Modules only supporting LTE-M	39
Modules supporting both technologies	26

2.2.1.2.3 Roaming

There are first international roaming agreements in place, putting customers into position to take advantage of this service not only in their home country, but also to access networks while acting abroad. The first international roaming between cellular technologies were announced by GSMA in June 2018. GSMA claims that these agreements will be compatible will all cellular LPWANs, no matter which network operator they correspond to.

3 COMPARISON OF TECHNOLOGIES

This thesis is a theoretical study due to the fact of not having systems available to in order to provide novel information using simulations or experiments. However, a comparison is performed by gathering data from different dimensions. The thesis compares the technologies according to their technical and commercial characteristics. It is focused on MNOs, since their role in IoT connecitivity world still remains unrivalled. It is also focused the challenge between MNOs and the new players being operators of unlicensed technologies. As far as there are no real deployed networks for each technology, the analysis and results of the thesis are based on a large filtered public data and interviews from players of the main technologies.

3.1 Unlicensed Technologies

3.1.1 Technical comparison

This section compares the unlicensed technologies according to their technical characteristics. The results of the technical comparison are shown in the Table 3.1 and Table 3.2.

Table 3.1. Technical specifications of leading unlicensed LPWAN technologies

	LORAWAN	**SIGFOX**	**RPMA**
Spectrum	ISM Band EU: 868 MHz US: 915 MHz	ISM Band EU: 868 MHz US: 900 MHz	ISM Band 2.4 GHz
Proprietary / Open	LoRa - Proprietary LoRaWAN - Open	Network- Proprietary	Proprietary

		Hardware-Open	
Bandwidth	125-250-500 kHz	200 kHz	1 MHz (40 channels available)
Range	Urban: 5 Km Rural: 15 Km	Urban: up to 10Km Rural: up to 50Km	Urban: up to 10Km Rural: up to 30Km
Link Budget	157 dB	146 dB	176 dB
Sensitivity	-137 dB	-129 dB	-137 dB
Modulation Type	LoRa (CSS), FSK	Uplink: DBPSK Downlink: GFSK	D-DSSS
Output Power	14 dBm (depends on regional regulations) EU: 14 dBm US: 22 dBm	14 dBm	20 dBm
TX Current Cons.	22mA @14dB	45 mA @14 dBm	245 mA @ 23dBm
RX Current Cons.	10mA	20 mA	20 mA
Data Rate	EU: 0.29 – 50 kbps US: Up to 100 kbps	Uplink: 100 bps Downlink: 600 bps (US: Up to 100kbps)	Uplink: 624 kbps Downlink: 156 kbps

Payload Length	Up to 250 Bytes	Uplink: 12 Bytes Downlink: 8 Bytes	Up to 10 KB
Messages/Day	Payload dependent	Uplink: 140 Downlik: 4	Uplink: 140 Downlik: 4
QoS	Acknowledgement available	Unslotted ALOHA (transmits 3 times and hopes for the best)	Full Acknowldgement
Bidirectionality	Yes	Yes	Yes
Battery Lifetime	More than 10 years	Max 10 years (one message per day)	More than 10 years
Node Capacity	Up to 60.000; Depends on uplink frequency	Max. one million nodes	500.000 nodes
FEC	Yes	No	No
FUOTA	Yes	No	No
Roaming	Yes	Yes	No
Location Support	Yes	No	Needs GPS
Security	AES-128	AES-128	AES-128
Spectrum License	Not required	Not required	Not required
Topology	Star on Star	Star	Star, Tree

			(supported with an RPMA extender)

Table 3.2. Technical specifications of following unlicensed LPWAN technologiesb

	NB-FI	**WIGHTLESS-P**	**DASH7**
Spectrum	ISM Sub-GHz EU: 868 MHz US: 900 MHz	ISM Sub-GHz	ISM Sub-GHz 433 MHz 868 MHz 915 MHz
Proprietary / Open	Open	Open	Open
Bandwidth	100 Hz (5000 channels in 500 kHz band)	12.5 kHz	236/432/648 kHz
Range	Urban: up to10 Km Rural: up to 30Km	Urban: up to2 Km Rural: -	Urban: 1 Km Rural: -
Link Budget	166 dB	146 dB	176 dB
Sensitivity	-154 dB	-129 dB	-137 dB
Modulation Type	DBP SK	Uplink: DBPSK Downlink: GFSK	FSK, GFSK
Output Power	14 dBm (depends on regional regulations)	14 dBm	-
TX Current Cons.	44 mA @14dB	45 mA @14 dBm	-

RX Current Cons.	16 mA	20 mA	-
Data Rate	Up to 100 bps	Uplink: up to 100 kbps Downlink: up to 100 kbps	Up to 166 kbps
Payload Length	-	-	-
Messages/Day	-	-	-
QoS	Full Acknowldgement	-	Full Acknowldgement
Bidirectionality	Yes	Yes	Yes
Battery Lifetime	More than 10 years	More than 10 years	More than 10 years
Node Capacity	Up to 2 million nodes supported	Unlimited	More than one 1 million nodes
FEC	-	-	Yes
FUOTA	Yes	-	Yes
Roaming	No	-	-
Location Support	No	-	Yes (Real-Time)
Security	XTEA-256	AES-128	AES-128
Spectrum License	Not required	Not required	Not required
Topology	Star	Star	Node-to-Node, Star, Tree

3.1.2 Commercial analysis

LoRaWAN counts 83 operators globally by October 2018, according to the LoRa Alliance. These 83 operators provide coverage in 49 countries. If other entities such as The Things Network open-source community's deployments are counted too, then the number of countries providing LoRaWAN reaches 95 globally. Most of the LoRaWAN publick networks are deployed by medium or small non-cellular companies. These networks are not built in a very large scale, but in regional-scale or city-scale. Some of the deployer companies were formed specially to be an operator of LoRaWAN, and some others come from telecommunications or IoT related businesses which provide end-to-end communication services. Compared to other LPWAN companies, LoRaWAN is the most heterogeneous one.

Sigfox counts 57 operators globally by October 2018, according to Sigfox. Sigfox also claims that these operators provide coverage in 45 countries, a doubled number of countries compared to 2016. When analyzing the Sigfox global coverage map, we see that countries providing coverage are mostly western countries, and in the other geographical locations the coverage is very limited. Currently, Sigfox is providing exclusive rights to only one operator in each country. Until now, in the list of Sigfox operators is not included any MNO. Most of the operators are you players in the field. In countries such as USA, France, Germany, Spain, etc., Sigfox is acting itself as an operator.

3.2 Cellular Technologies

3.2.1 Technical comparison

In this section, the emerging proprietary licensed technologies and the technical aspect of NB-IoT, LTE-M, EC-GSM-IoT are highlighted and summarized in Table 3.3.

Table 3.3. Technical specifications of cellular LPWAN technologies

	NB-IoT	LTE-M	EC-GSM-IoT
Spectrum	LTE: 0.4 -3.5 GHz	LTE: 0.4 -3.5 GHz	GSM bands: 850-900 MHz 1800-1900 MHz
Proprietary / Open	Open	Open	Open
Bandwidth	200 kHz	1.4 MHz	200 kHz (both uplink and downlink)
Range	Urban: 5 Km Rural: 15 Km	Urban: 5 Km	
Link Budget	164 dB	156 dB	154 dB (@23 dBm) 164 dB (@33 dBm)
Sensitivity	-142 dB	-123 dB	-
Modulation Type	Uplink: BPSK, QPSK, 8PSK, 16 QAM Downlink: BPSK, QPSK, 16QAM	Uplink: QPSK, 16 QAM Downlink: QPSK, 8PSK, 16 QAM	GMSK and 8PSK
Output Power	20/23 dBm	20-23 dBm	23/33 dBm
TX Current Cons.	220mA @23dB	100-490 mA	-
RX Current Cons.	20mA	-	20 mA

Data Rate	Uplink: < 250kbps Downl.: < 250 kbps	Up to 1 Mbps	Up to 70 kbps for GMSK; Up to 240 kbps for 8-PSK;
Payload	Unknown	Uknown	Up to 150 Bytes
Messages/Day	Private Spectrum; No restrictions	Private Spectrum; No restrictions	Private Spectrum; No restrictions
QoS	Acknowledgement available	Acknowledgement available	Full Acknowldgement
Bidirectionality	Yes	Yes	Yes
Battery Lifetime	10 years	10 years	10 years
Node Capacity	More than 20.000 (Depends on uplink frequency)	More than 20.000 (Depends on uplink frequency)	Up to 50.000 nodes (Depends on uplink frequency)
FEC	Yes	Yes	No
FUOTA	Yes	Yes	No
Roaming	Yes	Yes	No
Location Support	Yes	Yes	Needs GPS
Security	Based on LTE Security Features	Based on LTE Security Features	Based on GSM/EDGE Security Features
Spectrum License	Required	Required	Required
Topology	LTE Based	LTE Based	GSM/EDGE

3.2.2 Commercial analysis

A research from IoT Analytics states that MNOs such as Vodafone, AT&T or China Telecom have realized a potential on LPWANs, but also a threat that this technology is posing. However, their strategies related to LPWANs varies. In the Figure 3.1, the mobiles, tablets, computers and other similar devices are not included in the graph. The number corresponds to only the active end-devices and gateways.

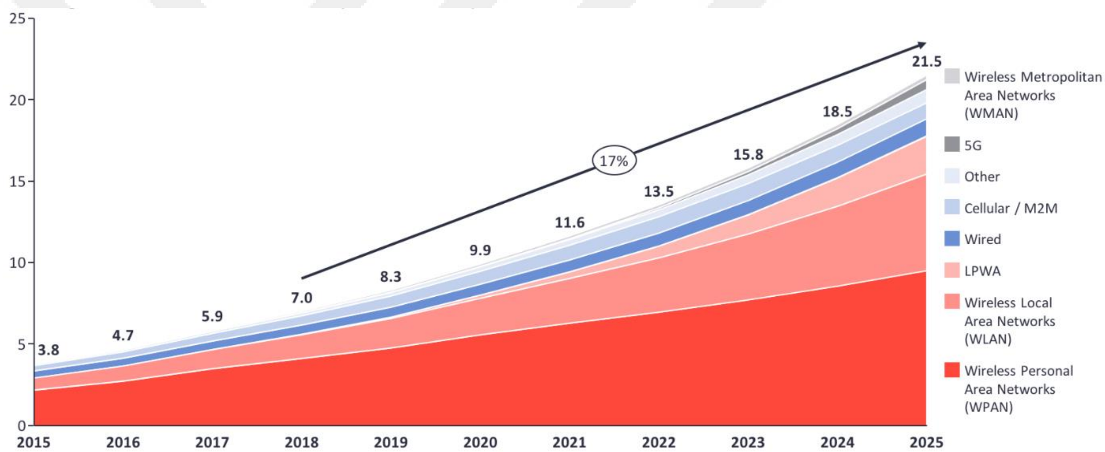

Figure 3.1. Number of global installed (active) IoT devices in Bn.

Being predicted that LPWANs will be the fastest growing IoT connectivity technology in the next decade, it is expected that the number of LPWAN connections will grow 110% per year and in 2023 it should exceed the 1B connections. Currently, the market is still at an early phase and characterized by a high degree of technological fragmentation. Investigated a considerable number of LPWAN technologies, we can say that their network footprint might be far from being globally wide. However, for several LPWAN technologies such as LoRa, NB-IoT, LTE-M and Sigox, the market seems to consolidating quickly. It is unprecedented how fast a large amount of public networks have been launched by MNOs over the last few years.

NB-IoT counts 46 operators globally by October 2018, according to GSMA. All the networks are launched in over 28 countries. In Europe there are counted to be 17 countries, 8 in APAc and in the Middle East there are 3 countries. Vodafone, Orange, T-Mobile, and three Chinese MNOs are some of the deployers of NB-IoT networks. For deployment only an upgrade of existing LTE base stations was required.

LTE-M counts 13 operators globally by October 2018, according to GSMA. Being deployed in 12 different countries, 6 of the countries are placed in Asia Pacific, 2 of them in Europe, 2 countries in Middle East, 1 country in North America and 1 country in Latin America. Verizon, AT&T and KPN are some of the MNO examples having deployed LTE-M netowrks.

4 LPWAN ANALYSIS AND A ROADMAP FOR TURKEY

4.1 Current LPWAN state

By October 2018, there are counted to be 200 public LPWA networks commercially deployed globally, while in Turkey the number counts to be less than 10. These networks operate on one of the 4 technologies mentioned in the paragraph above. There is at least one technology deployed in a major city. For example, in Turkey Turkcell that provides both cellular networks NB-IoT and LTE-M, and also Vodafone and Turk Telekom providing NB-IoT. These MNOs have deployed their corresponding network on minor and major projects regarding Smart City applications. Turk Telekom invested in digital traffic and energy efficieny applications in Kars, Karaman and Antalya. Lastly, the Water Services of Bursa have been eqquiped with NB-IoT, provided by Turk Telekom. In the other hand, there are a couple of private and public LoRaWAN gateways deployed in Turkey (Figure 4.1). An example would be the deployment of LoRaWAN in Istanbul Airport.

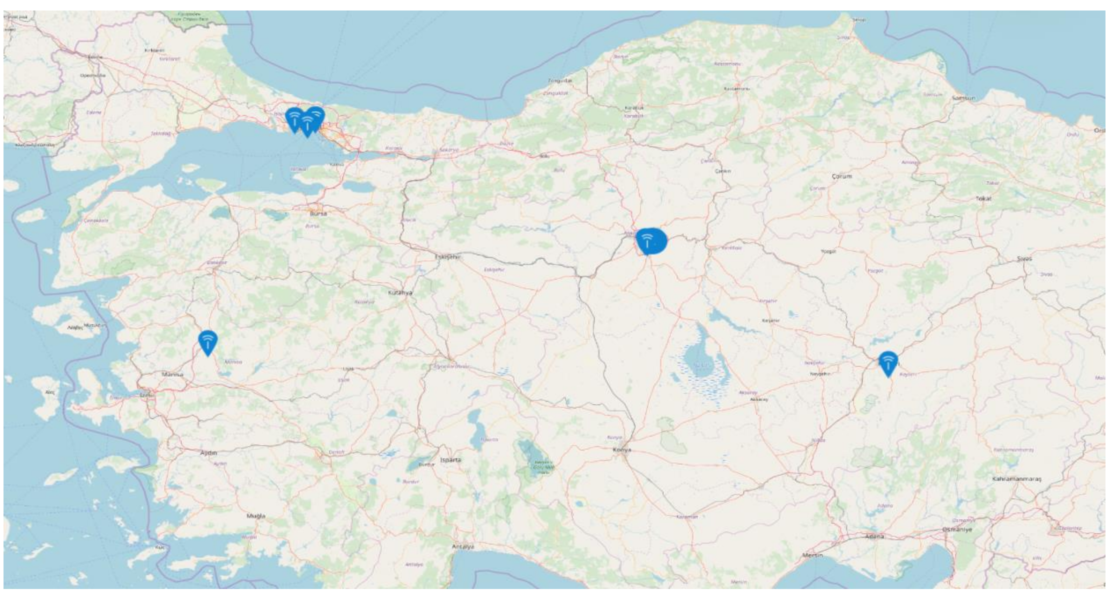

Figure 4.1. LoRaWAN public networks in Turkey

The fact that Sigfox is a non open standard and it's ecosystem is closed, currently there is no coverage in Turkey. SigFox, being the only vendor for the required hardware (SigFox base stations) and also the only provider of the server, makes the main two reasons that have made many companies in Turkey decide not to deploy SigFox. In case the applications concern essentail information regarding high privacy, that would still be an disadvantage on deplying SigFox as the data will be dependent on third parties. In the other hand, LoRa and NB-IoT could offer more privacy since everything would be processed inside the country (with LoRa being an open standar and so giving the possibility to deploy a private network with your own designed network ans server layer). Having multi-vendors, the operators of LoRaWAN and NB-IoT/EC-GSM give to the operators other options to replace the hardware.

4.2 Strategies

The emerging of LPWAN Technologies by MNOs and other IoT companies are categorized in four different groups:

Group 1: Until 2016, LPWAN technologies were still ignored in Turkey. There were not clear strategies on LPWAN networks. Many mid-sized and small companies still do not see LPWANs relevant for their bussinesses, so that adopting one of the technologies is not part of their near future plans. There are also companies and MNOs in less developed countries which have not yet deployed any LPWAN network, for reasons such as: lack of the lack of LTE infrastructure, their concentraiton on only GSM networks, not enough funds to invest on LPWAN networks, or their investment priority would be 5G technology.

Group 2: Being focused on only one LPWAN technology. Globally, approximately 80% of the MNOs having deployed an LPWAN technology are focused on only one cellular technology that they think would have a brighter future by having a higher market traction regarding IoT connecitivity in their local market. In the near future other more MNOs are planning to get involved in LPWAN market by commercializing only one LPWAN technology.

Group 3: Being focused on two LPWAN technologies. There are only 8 MNOs that have launched both LTE-M and NB-IoT, according to GSMA. Both technologies are available in the same country. In the Table 4.1 there are shown the MNO companies and corresponing countries where they have launched the technologies:

Table 4.1. MNOs having launched more than two LPWAN Technologies

MNO	**Country**
AIS	Thailand
APTG	Taiwan
Dialog Axiat	Sri Lanka
Etisala	UAE
Orange	Belgium
SingTel	Singapore
Telstra	Australia
Turkcell	Turkey

Group 4: Getting involved in both cellular and unlicensed technologies. According to IoT Analytics, currently there are two operators that have launched both technologies: KPN and SK Telekom, located in The Netherlands and South Korea, respectively. The preferred unlicensed LPWAN technology for both operators has been LoRaWAN, while Orange has deployed two cellular Technologies (NB-IoT and LTE-M) in Belgium one unlicensed technology (LoRaWAN) in France. Many other MNOs which have not made any announcements relating cellular technologies, have already joined LoRa Alliance. In Turkey the MNOs have been concentrated on only cellular technologies, mostly NB-IoT. Currently none of the major MNOs have deplyed LoRra or SigFox. There are mid-sized and startup companies that have deplyed LoRa for their commercial purpose applications.

4.3 Regulation

One of the main advantage of the licensed LPWAN Technologies is their ability to operate at ISM bands, a property that directly decreases the cost to deploy a one of the technologies. That would also give the opportunity to anyone to deploy their own network by simply purchasing a gateway and several modules. The actual rapid growth of LPWAN Technologies and their future expectations have attracted the attention of Information and Communication Technologies Authority (ICTA/BTK) in Turkey. Even they are encouraging the LPWAN technologies' operators in their annual report, the medium density that would appear in the future years by the use of the technologies in ISM bands would lead into regulations that would price the modules operating at the band, or changes would occur in the regulations regarding their output power. This currently would be a "nightmare" for the operators of unlicensed LPWAN technologies, because there is not a certain decision yet regarding the topic.

The scenario where a price is applied to each of the unlicensed technologies or a change in the regulations ocur, would lead the operators to mostly concentrate on the licenced technologies for reasons such as QoS and other advantages of those technologies. Another scenario would also be a decrease in the duty cycle so that there would be a balance with the increasing number of the devices transmitting. The examples of regulatory changes in other countries not always have been negative to unlicenced Technologies, since in South Korea occured a change that increased the output power of the technolgies operating at ISM band (900 MHz) from 10 mW to 200 mW.

4.4 Discussion on Turkey's Business Plan on LPWANs

Currently, there is not any national-wide or a grand plan for adapting, or more importantly, for contributing on LPWAN technologies in Turkey. Usually mid-size or large companies try to adapt IoT technologies coming from international players to gain advantage in their own businesses, whereas the startup companies see this as an opportunity to destruct or enter the market with new technologies or new products. That is what is going to happen in the absence of a coordinated afford.

Turkey becoming competitive in this area would be pretty challenging. That is exactly what will try to change IOTXTR (Internet of Things for Turkey) committee in Turkey: try to create awareness and try to create an environment where companies become more aware of the need of creating value-added solutions, contributing to technology and driving forward to become more competitive in the global arena.

In terms of the place of LPWAN Technologies in the market, they will initially enter the market for enterprise and private deployment. Over time, they will also attract the commercial attention of public operators. Now, this order is the oppose of what happened elsewhere in the world. Several countries entered with public operators and later they kicked in the enterprise private market. Turkey will mostly end up doing the other way around. The most concrete example at the moment is the third airport of Istanbul, Istanbul Airport, which will deploy LoRaWAN on it. It is not going to deploy it for public access, but for its own use. That qualifies as an enterprise/private deployment. Starting with that example, more is to appear in the upcoming years regarding LPWAN deployments.

5 CONCLUSION AND FUTURE WORK

This thesis provided a brief overview of the current low power wide area networks Technologies. A technical and non-technical characteristics comparative study was presented, showing all the essentials regarding the LPWAN technologies. The results show that the unlicensed and licensed LPWANs generally speaking are technically comparable to each other. If there are no strict requirements such as latency, payload size or downlink and uplink limitation, then all of the Technologies would support any application. Examples of these applications not demanding these specific characteristics would be smart metering, agriculture, different sensors, etc. In such cases where these applications fulfill the technical requirements, than the choice will be determined according to their non-technical characteristics: hardware cost, subscription cost, roaming service, flexibility, etc., where the unlicensed technologies seem to be cheaper.

To benefit from features such as independence, having full control and no subscription cost, deploying a LoRaWAN network would be an optimized IoT solution. While in the other hand, for a “out of the box solution”, Sigfox would be appropriate. For real-time solutions with high data-rate transfer, NB—IoT/LTE-M would fit more the application.

However, putting all the bets on a single technology would be the best choice. Having trade-offs between their characteristics such as spectrum, bandwidth, coverage, and QoS, means that a single technology would not serve all the IoT applications. The right formula would be “pick and mix”, depending on the case.

In Turkey, the future of LPWANs would be a mix of licensed and unlicensed technologies being used in overlapping situations. The two categories, or more specifically, the Narrowband IoT and LoRaWAN will co-exist. There would be use cases that can only be handled by Narrowband IoT, such as the ones that require QoS (ex: real-time applications) or the ones that require bandwidth such as 250 kbps and above. That is where Narrowband IoT becomes the preferred a solution. And then, whenever there is a need for a low-cost solution and we are not dealing with a real-time application, LoRa fills the gap. Also, there are a bunch of applications that can be handled by either Narrowband IoT or LoRaWAN. A lot of applications using one or another, or both, will be seen in the future. The picture is pretty much the same as what we have seen with 3G and Wi-Fi back in year 2000, where the same conversation was happening around these two technologies. Neither 3G killed Wi-Fi nor Wi-Fi killed 3G, but they co-exist. They have their own use cases or they have overlapped use cases. We expect the same thing will happen between LoRaWAN and Narrowband IoT. Regulation will play i big role in these technologies.

5.1 Future work

For further steps, once all of these different licenced and unlicenced technologies have been fully developed and commercially or publicly deployed, real-life measurements may be performed for a Proof of Concept (PoC), such as real range, true power consumption, scalability and mobility, dense medium penetration, etc. measurements in different situations would conduct.

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