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Performance Assessment of LoRa and Sigfox Protocols in Mobility Scenarios

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Performance Assessment of LoRa and Sigfox Protocols in Mobility Scenarios

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No dia 20 de dezembro de 2018, às 10h, no auditório Aureliano Chaves do Inatel, realizou-se a defesa de dissertação de mestrado em Telecomunicações, cuja área de concentração é Engenharia Elétrica, do Engenheiro Luiz Oliveira, intitulada "Performance Assessment of LoRa and Sigfox Protocols in Mobility Scenarios". A banca julgadora foi composta por: Prof. Dr. Joel José Puga Coelho Rodrigues do Inatel, presidente, Prof. Dr. Ricardo de Andrade Lira Rabelo da Universidade Federal do Piauí – UFPI e Prof. Dr. Carlos Nazareth Motta Marins do Inatel. Estiveram presentes, além dos componentes da banca e do mestrando, professores, funcionários, alunos do Inatel e outras pessoas. O presidente deu início aos trabalhos, anunciando ser esta a centésima septuagésima terceira defesa de dissertação do Curso de Mestrado em Telecomunicações do Inatel. Solicitou ao mestrando proceder a sua defesa, o que foi feito no tempo regulamentar. Em seguida, os membros da banca examinadora fizeram perguntas, solicitaram esclarecimentos e teceram comentários sobre o trabalho desenvolvido. Terminada a fase de arguição e debates, os membros da banca reuniram-se em caráter reservado para a deliberação quanto ao resultado da defesa:

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O presidente anunciou o resultado aos presentes e eu Gisele Moreira dos Santos, secretária do Curso de Mestrado em Telecomunicações, lavrei a presente ata que, aprovada, foi assinada pelos membros da banca examinadora. Santa Rita do Sapucaí, 20 de dezembro de 2018.

Joel Rodrigues

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Prof. Dr. Ricardo de Andrade Lira Rabelo

Prof. Dr. Carlos Nazareth Motta Marins

“Our senses enable us to perceive only a minute portion of the outside world.”
Nikola Tesla

Dedication

“To my family that supported me, giving me meaning and strength to go ahead and specially to may Father (in memoriam) that always believed in me and had dedicated his life to our family, to my Mother for love and prayers and to my Brother for his unconditional support.”

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Abbreviations

3GPP	The 3rd Generation Partnership Project Agreement
4G-LTE	Fourth Generation Long Term Evolution
ACK	Scknowledgment
ACL	Asynchronous Connectionless
ADR	Adaptive Data Rate
AES	Advanced Encryption Standard
AMCA	Asynchronous Multi-channel Adaptation
AP	Access Point
API	Application Programming Interface
ARAT	Active Reader Active Tag
ARIB	Association of Radio Industriesand Businesses
ARPT	Active Reader Passive Tag
ARQ	Automatic Repeat Request
ASK	Amplitude Shift Keying
ATT	Attribute Protocol
BB	Baseband
BDT	Bidirectional Transient Capacity
BE	Beacon Enabled
BLE	Bluetooth Low Energy
BPSK	Binary Phase Shift Keying
BPSK	Binary Phase Shift Keying
BR	Basic Rate
BS	Base Stations
BSA	Basic Service Area
BSN	Base Station Networks
BSN	Body Sensor Networks
BSS	Basic Service Set
BTS	Base Transmission Station
BW	Band Width
CA	Contended Access
CCA	Clear Channel Assessment
CID	Channel Identifier
CODEC	Coder and Decoder
CSMA-CA	Carrier Sense Multiple Access With Collision Avoidance
CSS	Chirp Spread Spectrum(
DBPSK	Differential Phase Shift Keying

DL MU-MIMO	Downlink Multi-User MIMO
DS	Distributed System
DSME	Deterministic and Synchronous Multi-channel Extension
DSSS	Direct Sequence Spread Spectrum
EB	Enhanced Beacons
ED	End Devices
ED	Energy Detection
EDR	Enhanced Data Rate
EIRP	Effective Isotropic Radiated Power
EPC	Electronic Product Code
ESS	Extended Service Set
ETSI	European Telecommunications Standards Institute
FastA	Fast Association
FCC	Federal Communications Commission
FFH	Fast Frequency-Hopping
FHMA	Frequency Hopping Multiple Access
FHSS	Frequency Hopping Spread Spectrum
FSK	Frequency Shift Keying
GAP	Generic Access Profile
GATT	Generic Attribute Profile
GFSK	Gaussian Fase Shift Keying
GMSK	Gaussian Minimum Shift Keying
GPS	Global Positioning System
GSM	Global System for Mobile
GTS	Guaranteed Time Slots
H2H	Human to Human
HARQ	Hybrid Automatic Repeat Request
HCI	Host Controller Interface
IE	Information Elements
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IoT	Internet of Things
ISM	Industrial Sientific and Medical
ISO	International Organization for Standardization
ITU	International Telecommunication Union
JSON	JavaScript Object Notation
L2CAP	Logical Link Control and Adaptation Protoco
LACH	Legacy Random Access Channel
LE	Low Energy
LF	Low Frequecies
LL	Link Layer
LLC	Logical Link Control
LLDN	Low Latency Deterministic Network
LM	Link Management

LMP	Link Management Protocol
LoRa	Long Range
LoRaWAN	Long Range Wide Area Network
LoRaWAN	Long RangeWide Area Network
LOS	Line of Sight
LP-WA	Low Power Wide Area
LP-WANs	Low Power Wide Area Networks
LQI	Link Quality Indication
LR-WPAN	Low-Rate Wireless Personal Area Networks
LTE	Long Term Evolution
LTE eMTC	LTE enhanced Machine Type
LTE-A	Long Term Evolution Advanced
M2M	Machine to Machine
MAC	Medium Access Control
MCPS	MAC Common Part Sublayer
MCPS-SAP	MAC Common Part Sublayer Service Access Point
MCS	Modulation and Coding Scheme
MIB	Master Information Block
MIMO	Multiple-Input Multiple Output
MPDCCH	MTC Physical Downlink Control Channel
MTC	Machine Type Communication
MTU	Maximum Transmission Unit
NAS	Non-Access Stratum
NB	Narrow Band
NBE	Non Beacon Enabled
NB-IoT	Narrow Band Internet of Things
NDP	Null Data Packet
NFC	Near Field Connection
NPBCH	Narrowband Physical Broadcast Channel
NPDCCH	Narrowband Physical Downlink Control Channel
NPDSCH	Narrowband Physical Downlink Shared Channel
NPRACH	Narrowband Physical Random Access Channel
NPSS	Narrowband Primary Synchronization Signal
NPUSCH	Narrowband Physical Uplink Shared Channel
NRS	Narrowband Reference Signal
NSSS	Narrowband Secondary Synchronization Signal
NSSS	Narrowband Secondary Synchronization Signal
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OSI	Open Systems Interconnection
PAN	Personal Area Network
PANId	Personal Area Network Identification
PCD	Proximity Coupling Device
PDCP	Packet Data Control Protocol

PDSCH	Physical Downlink Shared Channel
PDU	Packet Data Units
PER	Packet Error Rate
PHY	Physical
PIB	PAN Information Base
PICC	Proximity Integrated Circuit Card
PRACH	Physical Random Access Channel
PRAT	Passive Reader Active Tag
PSK	Phase Shift Keying
PUCCH	Physical Uplink Control Channel
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RAW	Restricted Access Window
REST	Representational State Transfer
RF	Radio Frequency
RFID	Radio Frequency Identification
RFTDMA	Random Frequency and Time Division Multiple Access
RLC	Radio Link Control
RPS	RAW Parameter Set
RRC	Radio Resource Control
RRC	Root Raised Cosine
RRM	Radio Resource Manager
SAP	Service Access Points
SC-FDMA	Single Carrier Frequency Division Multiple Access
SCO	Synchronous Connection-Oriented
SIFS	Short Inter Frame Space
SMP	Security Manager Protocol
SNR	Signal to Noise Ratio
SSCS	Service Specific Convergence Sublayer
STA	Stations
TCXO	Temperature Com-pensated Crystal Oscillator
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TI	Tag Identification
TIM	Traffic Indication Map
TSCH	Time Slotted Channel Hopping
TVWS	Television White Space
TXOP	Transmission Opportunity
UE	User Equipment
UHF	Ultra-High Frequencies
UNB	Ultra Narrow Band
URL	Uniform Resource Locator
WAN	Wide Area Network
WBAN	Wireless Body Area Networks

WBSN	Wireless Body Sensor Networks
Wi-Fi	Wireless Fidelity
WINA	Wireless Industrial Networking Alliance
WirelessHART	Wireless Highway Addressable Remote Transducer Protocol
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Networks
WSN	Wireless Sensor Networks

Resumo

A Internet de Coisas (do Inglês, Internet of Things – IoT) visa oferecer a capacidade de conectar objetos comuns à Internet fornecendo conteúdo e informações ao usuário, independentemente de sua localização. Devido à grande variedade de aplicativos e à diversidade de recursos necessários para atender a um aplicativo, as tecnologias IoT estão impulsionando um forte avanço tecnológico para atender a essa demanda, ao mesmo tempo em que tentam acompanhar a evolução desses aplicativos. As características exigidas pelos aplicativos, como área de cobertura, escalabilidade, taxa de dados de transmissão e aplicabilidade, referem-se às características de camada de Controle de Acesso ao Meio (do Inglês, *Medium Access Control* - MAC) de cada protocolo. É possível comparar as características e requisitos necessários do protocolo para superar as aplicações exigidas. Esta dissertação explora protocolos de camada de controle de acesso ao meio (MAC) que são usados em IoT com uma descrição detalhada de tais protocolos agrupados por curta e longa distância, de acordo com a respetivo raio de cobertura. Para os protocolos de cobertura de curto alcance são considerados os seguintes: Identificação por Radiofreqüência (*Radio Frequency Identification* - RFID), Comunicação de Campo Próximo (*Near Field Communication* NFC), Bluetooth IEEE 802.15.1, Bluetooth de baixa energia (*Bluetooth Low Energy* - BLE), IEEE 802.15.4, Wireless-HART (*Highway Addressable Remote Transducer Protocol*), Z-Wave, Weightless e IEEE 802.11 a/b/g/n/ah. Para o grupo de longa distância, os protocolos NB-IoT (Banda Estreita - IoT), LTE (Long Term Evolution), LoRa - Long Range Protocol e SigFox são estudados. Para cada grupo de protocolos, um estudo comparativo é realizado considerando suas características, limitações e comportamento, a fim de fornecer insumos e um estudo de referência para outras aplicações de IoT. Tópicos de pesquisa em aberto sobre o tema também sao identificados. Dentro os protocolos existentes, o estudo foca-se na avaliação comparativa do desempenho dos protocolos LoRa e Sigfox. O estudo propõe métricas qualitativas e quantitativas para avaliar o desempenho destes protocolos considerando ambientes com suporte à mobiliade. O estudo foi realizado através de uma metodologia de pesquisa baseada em estudos de caso. Para obter os dados necessários para o estudo comparativo, foram construídos dois protótipos reais com uma aplicação utilizando cada tecnologia, isto é, uma aplicação para monitoramento da localização de objectos em tempo real. Cada protótipo possui um sensor GPS (*Global Positioning System*) para informar o ponto de coleta dos dados necessários. Foram desenvolvidos os códigos de programação para o funcionamento dos terminais de cada protocolo bem como as interfaces gráficas compondo a aplicação, para melhor visualização dos dados coletados. Os resultados discutidos apresentam o comportamento dos dois protocolos e o desempenho da transmissão de acordo com as métricas sugeridas. Pelos resultados obtidos pode-se concluir que o comportamento dos dois protocolos estudados não possuem relacionamento direto podendo apresentar diferentes características entre eles, mesmo estando no mesmo ambiente de utilização. Nota-se também que o fato de estarem transmitindo ao mesmo tempo não influenciou em nenhum parâmetro de eficiência. Com isso, percebe-se que a coexistência entre eles não afeta o desempenho de cada um.

Palavras chave

Internet das coisas; Internet of Things; Low-Rate Wireless Personal Area Networks; LR-WPAN; Low Power Wide Area Network; LPWAN; Protolo de controlo de acesso ao meio; MAC; LoRa; LoRaWAN; Long Range Wide Area Network; Sigfox; Mobilidade; Protótipo real; Estudo comparativo; Avaliação do desempenho.

Abstract

Internet of Things (IoT) aims to offer the ability to connect common objects to the Internet providing content and information to the user, regardless of their location. Due to the wide variety of applications and the diversity of resources required to serve an application, IoT technologies are driving strong technological advancement to meet this demand, while trying to keep pace with the evolution of these applications. The characteristics required by applications, such as coverage area, scalability, transmission data rate and applicability, refer to the Medium Access Control (MAC) layer characteristics of each protocol. It is possible to compare the protocol characteristics and requirements necessary to overcome the required applications. This dissertation explores media access control layer (MAC) protocols that are used in IoT with a detailed description of such protocols grouped by short and long distance, according to their coverage radius. For short-range coverage protocols, the following are considered: Radio Frequency Identification (RFID), Near Field Communication (NFC), Bluetooth, IEEE 802.15.1, Bluetooth Low Energy, IEEE 802.15.4, Wireless-HART (Highway Addressable Remote Transducer Protocol), Z-Wave, Weightless, and IEEE 802.11 a/b/g/n/ah. For the long-distance group, Narrow Band IoT (NB-IoT), Long Term Evolution (LTE), LoRa - Long Range Coverage Protocol, and SigFox protocols are studied. For each group of protocols, a comparative study is performed considering its characteristics, limitations and behavior, in order to provide inputs and a reference study for other IoT applications. Open research issues on the topic are also identified. Within the existing protocols, the study focuses on the performance comparison of LoRa and Sigfox protocols. The study proposes qualitative and quantitative metrics to evaluate the performance of these protocols considering environments with mobility support. The study was carried out through a research methodology based on case study. To obtain the results needed for a comparative study, two real prototypes were created with an application using each technology, i.e., an application for objects monitoring location in real time. Each prototype uses a Global Positioning System (GPS) sensor to inform the point of data collection. The software was developed for the terminals operation of each protocol as well as the graphical user interfaces composing the application for better visualization of collected data. The results discussed present the behavior of the two protocols and the transmission performance according to the suggested metrics. From the obtained results it is possible to conclude the behavior of the two studied protocols do not have direct relationship among them and can present different characteristics, even though they are use simultaneously in the same environment. It is also observed the fact that transmitting at the same time did not influenced any efficiency parameter. With this, it is noticed the coexistence between them does not affect the performance of each other.

Keywords

Internet of Things; Low-Rate Wireless Personal Area Networks; LR-WPAN; Low Power Wide Area Network; LPWAN; Medium Access Control protocol; MAC; LoRa; LoRaWAN; Long Range Wide Area Network; Sigfox; Mobility; Real prototype; Comparative study; Performance assessment.

Chapter 1

Introduction

1.1 Motivation

The evolution of technology towards miniaturization and the energy consumption reduction with high operating efficiency has also led to the evolution of new domains and applications with improved performance or enables the development of new types of services and applications. Different requirements can be addressed by IoT applications while the technologies used to provide vertical solutions such communication and some characteristics such as ubiquity, awareness, and big data analysis are the important "horizontals" segments of this panorama. For example, the technology improvement used on health-care brings to patients a plethora of benefits both in the body area technology assistance and increase life quality for certain cases. The concept of mobile health-care applications (using mobile health technologies) strongly contribute to improvements in Ambient Assisted Living (AAL) and clinical environments [1].

In the industry, technological evolution is an obligation in a search for new processes, new tools, techniques, and technologies to a better productivity, reduction of production time and cost, always aiming to increase the quality of its products and offered services. From this environment comes Industry 4.0 that presents a high degree of interactivity between machines and processes working towards the aforementioned objectives [2]. In a constant search for improvement, electric energy sector that involves the networks of transport and distribution of energy (power grids), new technologies have been sought that not only allow the control of their own systems through tele-monitoring, tele-supervision, and tele-control, but also interfaces with the consumer to provide data and power consumption parameters of its users for the purposes of managing their network [3]. Transportation, logistics, and supply chain sectors are examples that follow the development of the automobile industry based on the Industry 4.0 concept which already brings a technology embedded in cars, facilitating the implementation of intelligent transport systems, supply chain, tracking, and security solutions, also contributing to the formation of the technological ecosystem of smart cities. Not less important, agro-industry has a strong demand for technological solutions that bring greater production yield, optimization of the resources used, better quality control and, more important, information collected during these processes over time, thus composing a very important database in the study and sizing of different types of crops.

For the viability of verticals, it is necessary to compose devices, interconnect them, and provide mechanisms to control the communication between these devices and the applications that will make use of the resources provided. These needs are met by the "IoT horizontals" that are responsible for providing the appropriated technology to meet the requirements of emerging applications. To enable this IoT technological ecosystem, it is important to have a smooth compatibility between the devices used by a given application in order to achieve interconnection and interoperability. With a constant arising of new verticals, it is common to have interaction between different verticals. IoT horizontals can provide this interaction in order to optimize or share some kind of resources or data [4].

Among the different requirements imposed by verticals, it is possible to cite the data transmission range of each technology that can define the characteristic of a vertical or even being the prerequisite of a certain application. As an example of verticals that require a short operating distance, health-care topic implies the creation of a sensors network in a human body in order to provide analysis, monitoring, or even prevention of events. For this vertical it is necessary to provide a network of wireless sensors applied to the human body, thus composing the wireless body area network (WBAN) that demands short range coverage and low data transmission. Much has been advanced in technology to improve human sensing such as wireless sensor networks (WSNs) and the use of nanotechnology to contribute to WBANs composition [5]. Still in the context of short distances it is possible to mention technologies that interconnect the human body and its belongings to the external world. For example, watches, wristbands, shoes, and smart clothes as well as other personal belongings like smart-phones, which connect to payment systems, audio systems, internet services, among others [6] [7]. To attend these verticals, there are the low rates wireless personal area networks (LR-WPAN) and their protocols with technology dedicated to verticals that demand low rate of data transmission as well short distance communication.

Leaving aside the proximity of the human body and dealing with the services or verticals that surround the living environment of the human being, there is a need for network technologies that support a demand for higher rates of data transfer and high availability, even with the high energy consumption. Within this category, each type of interconnection considering transport vehicles, elements of an industry, a restaurant, an event environment, a home, among others, requires the characteristics of wireless local area networks (Wireless Local Area Networks - WLANs) [8]. WLANs are designed to serve verticals that have characteristics such as high data communication rates, higher data transmission range (when compared to WBANs or LR-WPANs) and individual delay and latency characteristics. In most cases, solutions that use WLANs take into account the increased availability of systems and power sources required for such solutions as they are generally high energy consumption solutions.

In verticals such as smart agriculture, Smart-grid, and even smart cities, there is a need to transmit data beyond what is offered by WLANs technologies. For example, IEEE 802.11ah works with maximum distance around 700 meters when performing 300 bps data transmission rate and from this point, it is considered like long range coverage protocols [9]. In these cases, some well-established technologies can provide the necessary horizontal needed for long distance solutions or applications. For example, the mobile wireless networks. Strong penetration and high availability make the mobile wireless networks the preferred technologies in applications over long distances. However, there are cases in which there is no coverage of these networks or the cost makes it unfeasible to use them on applications that work with tens or hundreds of monitored elements, devices, or sensors. There are also applications that require a large amount of connected elements to compose a solution, low power consumption, or even the needed transmission rates are low enough to prevent the use of a cellular mobile network terminal. For these types of applications, the Low Power Wide Area Networks (LP-WAN) have arisen with new proposals of protocols aimed at the transmission of low data rate, for long distances coverage and low energy consumption. With these simplifications, LP-WAN terminals present reduced cost and size, simplifying their usage as well.

1.2 Problem Delimitation

The wide variety of emerging IoT applications drives the arising of technologies adapted or developed to meet their different requirements. These requirements change but, in most cases, the communication distance needed by a given technology to compose the application solution is a concern. Applications requiring short-distance coverage use different protocols from those used in long-range coverage applications. Studies of short and long distance coverage protocols characteristics can elucidate many questions about their applications.

Some of long range coverage protocols classified as protocols for LP-WANs are arising to meet the applications demand for solutions with a large coverage area. They are good candidates to support the requirements of IoT wide area applications, being able to surpass the short-range restriction of local area networks [10]. Since these technologies were developed for environments with static terminals having no degree of displacement, new applications are emerging in heterogeneous ecosystems where features such as mobility support and real-time monitoring are demanded. The behavior and performance of long distance protocols with mobility support are increasingly questioned. Then, this study focuses on the study of two protocols for long range coverage (LoRa and Sigfox) for IoT scenarios with mobility support [11].

1.3 Research Objectives

The main objective of this dissertation is to conduct a deep review of the related literature on Medium Access Control (MAC) protocols for IoT and a performance evaluation study of the open-source LoRa LP-WAN protocol in comparison with Sigfox (a proprietary solution) with mobility support using objective metrics. The study will also act as a reference guideline regarding the behavioral expectations of protocols in mobile environments. To attain this main objective, the following partial objectives were defined:

- Deep review of the related literature on MAC layer protocols for IoT;
- Identification of the requirements of long distance communication characteristics applications;
- Proposal of qualitative and quantitative metrics for long range coverage MAC layer protocols considering mobility support;

- Construct the prototypes (hardware and software) that offers a completely solution to meet mobility application requirements as well as a user graphical interface to interact with it;
- Performance evaluation of LoRa and Sigfox MAC layer protocols with mobility support using the proposed metrics in real environments.

The scenario of the experiments was defined as similarly as possible between the two technologies to provide a reference of the two technologies behavior in a mobile environment. Which means that the same experimentation conditions (weather, altitude, traffic, etc.) were the same in both LoRa and Sigfox terminals. So, any other factor to be considered could be compared to this study.

1.4 Main Contributions

This section briefly describes the main scientific contributions resulting from the work and experiments performed in a real environment presented in this dissertation.

The first contribution is a deep review of the state of the art of the medium access control (MAC) layer protocols for Internet of Things presented in chapter 2. This survey brings a classification of the more relevant protocols regarding the covered distance, considering short and long distance. This survey is submitted to an international journal (November 2018).

The second contribution is the identification of communication requirements necessary for IoT applications with mobility support. This contribution presents performance metrics needed for comparison between the studied protocols. It is presented in Chapter 3 and it was published in [12].

The third contribution are the both prototypes (including software and hardware) for objects tracking, in real time, using LoRa and Sigfox to meet the requirements for the experiments. These applications are described in Chapter 3. LoRa protocol prototype and its demonstration and validation is published in [13] and, in a similar way, the Sigfox prototype is published in [12].

The fourth contribution is the performance analysis of LoRa and Sigfox protocols in a mobility scenario. With this contribution, it is possible to observe the characteristics and behavior of the protocols when submitted to applications that demand objects mobility performing an approach to IoT of moving things. These studies are presented in Chapter 4 and they are submitted to an international journal (November 2018).

1.5 Thesis Statement

This dissertation elaborates on the performance analysis of long distance coverage LoRa and Sigfox protocols for Internet of things with mobility support. To attain this goal, a deep review of the state of the art of medium access control layer protocols for IoT was performed. They were classified in short and long distance coverage for study purposes. Despite the lack of references or comparison parameters, this work proposes quantitative and qualitative metrics in order to obtain enough parameters and inputs to perform the study in a practical way. Two prototypes with applications for objects tracking, using LoRa and Sigfox, were created, including all their components, such as transmission system, programming, database storage, and user interfaces. The created prototypes are part of a real environment experimentation scenario with mobility, where is possible to observe the parameters and characteristics profiles. The performance evaluation considered for this study is based on Santa Rita do Sapucaí city, state of Minas Gerais, Brazil, that offers a horizontal urban profile used as reference. This study also presents results of the experiments and their analysis through the proposed metrics. In addition, this study states that in case of mobility, each protocol has its distinct behavior resulting in the behavioral profile observation when used in applications that require mobility support. A performance assessment based on objective metrics can importantly contribute to select the best communication solution for mobility support applications. Improper solutions deployed can compromise the applications expected results.

1.6 Publications

During this research work, several research papers were prepared. They are listed below.

- **Luiz Oliveira**, Joel J. P. C. Rodrigues, Sergei A. Kozlov, Ricardo A. L. Rabêlo, Victor Hugo C. de Albuquerque, ”MAC Layer Protocols for Internet of Things: A Survey”, Future Internet, Special Issue 10th Anniversary Feature Papers, MDPI, Vol. 11, No. 1, Paper Id 16, January 2019, pp. 1-42, DOI: 10.3390/fi11010016.

- **Luiz Oliveira**, Joel J. P. C. Rodrigues, Sergei A. Kozlov, Ricardo A. L. Rabêlo, Vasco Furtado, “Performance Assessment of LoRa and Sigfox Protocols with Mobility Support”, International Journal of Communication Systems, Wiley, ISSN (print): 1074-5351, ISSN (online): 1099-1131 (in press).

- Wesley Silva, **Luiz Oliveira**, Neeraj Kumar, Ricardo A. L. Rabêlo, Carlos N. M. Marins, Joel J. P. C. Rodrigues, "An Internet of Moving Things Tracking System Approach based on LoRa Protocol", IEEE Global Communications Conference (IEEE GLOBECOM 2018), Abu Dhabi, UAE, December 09-13, 2018.

- Guilherme G. L. Ribeiro, Luan F. de Lima, **Luiz Oliveira**, Joel J. P. C. Rodrigues, Carlos N. M. Marins, Guilherme A. B. Marcondes, “An Outdoor Localization System based on SigFox”, 4th International Workshop Research Advancements in Future Internet Architectures (RAFNET 2018), in conjunction with 87th IEEE Vehicular Technology Conference (VTC2018-Spring), Porto, Portugal, June 3-6, 2018.

1.7 Document Organization

The remainder of this dissertation is organized as follows. Chapter 2 provides a survey of IoT MAC layer protocols exploring the main characteristics related to range covered, transmission data rates, and its logical and control characteristics. The architecture model of IoT MAC layer protocols is depicted in order to details the best operation method of each protocol studied in IoT solutions and applications.

Chapter 3 proposes qualitative and quantitative performance metrics to evaluate IoT MAC layer protocols and brings the experimentation scenario considering the environment worked and both protocols platforms used.

Chapter 4 offers the experiment measurements results and its comparison according to performance metrics considered. Signal do Noise Ratio (SNR), packet loss and maximum reachable distance are evaluated.

Chapter 5 concludes the dissertation, sharing invaluable learned lessons, main conclusions, and suggestion for further studies.

Chapter 2

MAC Layer Protocols for Internet of Things

Most of IoT technologies features are defined by the protocols used to design the right technology for the specific requirements of applications. Features such as network topology, power consumption, transmission power efficiency, lost packet rate, error rate, and delays are some of the most important points in the definition or choice for using a certain technology for a particular solution. These are characteristics of Medium Access Control (MAC) layer, which, according to the open systems interconnection (OSI) reference model, is the layer that links the transmission and medium access resources belonging to this element, with the delivery of the useful information, extracted from the received package, to the upper layer. Medium access techniques, data rate, communication mode between devices, transmission range, power consumption, and others are examples of characteristics defined in this layer. Therefore, the study of MAC layer protocols can help to better understand how to compose an application's technological solution according to the design requirements.

2.1 Short Range MAC Layer Protocols

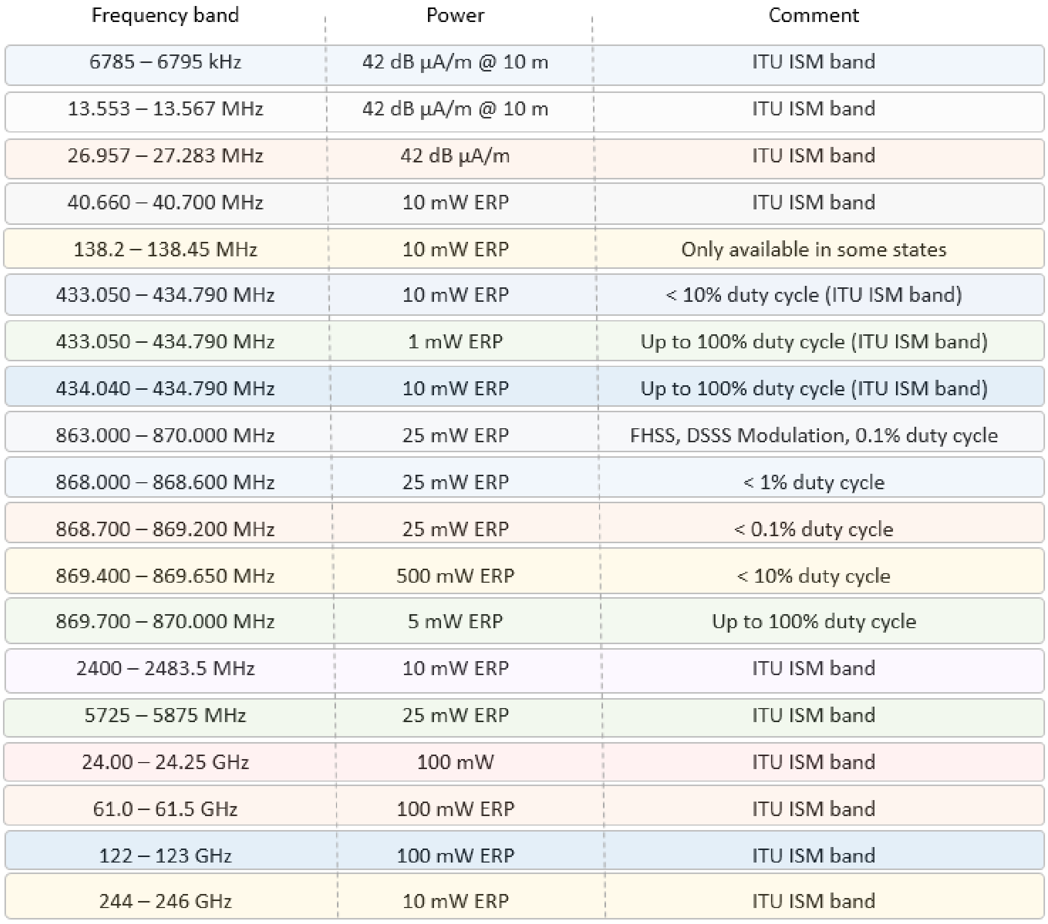
Short range coverage medium access control (MAC) protocols are defined by the Institute of Electrical and Electronics Engineers (IEEE) as Wireless Personal Area Networks (WPAN), which is the network established between elements that surround the human body. WPAN communication technologies differ from other conventional wireless network technologies. These networks call for easy connectivity in order to reach personal wearable or hand-held devices. Moreover, WPAN requires power efficiency, small size, low cost and maybe most importantly easy to use devices [14, 15].

Short-distance technologies such as near field communication (NFC) and radio frequency identification (RFID) are technologies that fit into this study context due to their usage with differentiated mechanisms for the physical and linking layers. Thus, their characteristics are less critical when compared to the IEEE 802.15.6 standard [16], which is dedicated to wireless body area networks (WBAN). Such networks have different scenarios and prerequisites that are very different from those that are supported by the networks of things. Body sensor networks have very critical requirements when compared to the networks of things such as WBANs. These network characteristics should achieve a maximum latency of 125 ms to attend medical applications, they cannot surpass 250 ms to be applied to non-medical applications, and their jitter must be lower than 50 ms. Low power consumption, automatic connection and disconnection of new elements in the network, mixed typologies, low overhead and other characteristics are examples of the high critical parameters in WBANs [17, 18, 19].

There are technologies that use differentiated methods to treat their PHY and MAC layers as Long Term Evolution (LTE) mobile networks. These technologies offer differentiated techniques of connection establishment methods, communication controls, and physical access controls, among others. Thus, it becomes difficult to compare some protocols with the standard offered by the open systems interconnection (OSI) reference model. The physical medium approach and connection establishment methods, communication controls, and other mechanisms are dedicated to systems that cannot be directly compared to the OSI. Another difficulty of establishing a fair comparison with other protocols that follow the OSI reference model is that these protocols are, in the majority of applications, dedicated to the point-to-point communication or large data volumes. These characteristics release them from the need for more elaborate connection establishment methods and data transfer control systems [20].

2.1.1 Radio Frequency Identification (RFID)

Radio Frequency Identification (RFID) refers to a set of technologies that are aimed at identifying and recognizing elements (*tags*). An RFID system is basically composed of two types of devices: the identified devices (tags) and the device identifiers or readers. Tagged devices are triggered by RF (Radio Frequency) waves emitted by the reader devices and reply its identification (ID) tags. Readers handle data exchange between them. When necessary, readers send RF pulses interrogating the tags in the area. Tags reply to this question by submitting their tag IDs. Different classifications of RFID systems can be provided according to operating frequency, radio interface, communication range, tag autonomy (completely passive, semi-passive, active), and different standards have been ratified. Evolution of smart UHF (Ultra High Frequencies) RFID tags with embedded sensors and miniaturization of readers promotes this technology for high pervasive IoT ecosystems [21]. Figure 2.1 presents a brief summary of operation frequencies, transmission power level, and European regulation comments.



Frequency band	Power	Comment
6785 – 6795 kHz	42 dB μA/m @ 10 m	ITU ISM band
13.553 – 13.567 MHz	42 dB μA/m @ 10 m	ITU ISM band
26.957 – 27.283 MHz	42 dB μA/m	ITU ISM band
40.660 – 40.700 MHz	10 mW ERP	ITU ISM band
138.2 – 138.45 MHz	10 mW ERP	Only available in some states
433.050 – 434.790 MHz	10 mW ERP	< 10% duty cycle (ITU ISM band)
433.050 – 434.790 MHz	1 mW ERP	Up to 100% duty cycle (ITU ISM band)
434.040 – 434.790 MHz	10 mW ERP	Up to 100% duty cycle (ITU ISM band)
863.000 – 870.000 MHz	25 mW ERP	FHSS, DSSS Modulation, 0.1% duty cycle
868.000 – 868.600 MHz	25 mW ERP	< 1% duty cycle
868.700 – 869.200 MHz	25 mW ERP	< 0.1% duty cycle
869.400 – 869.650 MHz	500 mW ERP	< 10% duty cycle
869.700 – 870.000 MHz	5 mW ERP	Up to 100% duty cycle
2400 – 2483.5 MHz	10 mW ERP	ITU ISM band
5725 – 5875 MHz	25 mW ERP	ITU ISM band
24.00 – 24.25 GHz	100 mW	ITU ISM band
61.0 – 61.5 GHz	100 mW ERP	ITU ISM band
122 – 123 GHz	100 mW ERP	ITU ISM band
244 – 246 GHz	10 mW ERP	ITU ISM band

FIGURE 2.1: RFID standards for short distance applications.

The various devices identified by radio frequencies (RFIDs) such as wristbands, clothing, footwear, and others are a combination of a small microchip and an antenna integrated into a single casing uniquely identified electronically. When readers send their interrogation radio frequency pulse, tags transmit their identification information to the reader devices using radio frequencies. This transmission takes place depending on the proximity of the tag to the reader device, even though it does not have line of sight (LOS). The transmission range will depend on the class of device used. Transmissions occur from the low frequency (LF) bands at 124–135 KHz to ultra-high frequency band (UHF). There are three classes of RFID devices [22] as follows:

- PRAT—Passive Reader Active Tag. The reader is passive and receives data from a battery-powered tag. The transmission range can reach up to 500 m depending on some characteristics of the system and transmission frequency used.
- ARPT—Active Reader Passive Tag. The reader is active and the identified tags are passive and powered by the energy harvested from the electromagnetic waves present in the air. In general, this power source can be a beacon transmitted by the reader to

feed the tags and it receives back the transmission of the tag data. This is the most commonly used class.

- ARAT—Active Reader Active Tag. This class is where both the reader and the tags are powered by external power sources, but the tags only transmit their data when requested by the readers.

There is a certain variety of standards for RFID systems. ISO (International Organization for Standardization)/IEC (International Electrotechnical Commission) 14443 [23] are the entities responsible for defining the behavior and properties of smart cards [24, 25]. The standard defines the nomenclature of the ’reader device’ as the Proximity Coupling Device (PCD) and the Tag Identified (TI) or, ‘the object to be identified’, is defined as the Proximity Integrated Circuit Card (PICC).

One of the most commonly used identification standards in this case is the electronic product code (EPC) which contains a 96-bit structure in a string data format. This structure consists of eight initial bits that identify the protocol version followed by 28 bits representing the organization entity that produced such a label. The following 24 bits identify the type or class of the element and the remaining 36 bits are the unique serial identification of each particular element. These last two fields are used by vendors to assign identities to their devices [26]. Differentiated information such as Uniform Resource Locators (URLs) or some other more current pattern can also be used as identifiers as long as they meet the standardized format [27, 28].

2.1.2 Near Field Communication (NFC)

For short-range communications, NFC technology is important since its massive adoption by mobile device vendors has popularized its use, making it accessible to the public for applications such as label reading or even peer-to-peer data exchange. The devices involved exchange information between themselves as a machine-to-machine connection mode [29]. Standardization of NFC is assisted by the International Organization for Standardization (ISO) conjoined with the International Electrotechnical Commission (IEC) and NFC Forum.

Near Field Communication is a short range transmission technology that uses low-power transmission links that, differently from Bluetooth, do not require pairing for transmission. Just bringing one device close enough to the other allows communication. This feature forces the user of the device to be handling it during use. As the facility of the device works only with is owner, it is a manner to ensure the safe security of the technology usage. Its operation is comparable to RFID technology because NFC devices can act as both a reader and a tag. The communication is performed in active or passive mode, operating in the 13.56 MHz band. A typical range from another device is about 0.2 m and it is sensitive to near fields or even the touch, its transmission rate can reach 424 Kbps. In the passive mode communication, the active device initiates the connection by transmitting a carrier wave that activates the passive device. Thus, the passive device makes use of this carrier to modulate and transmit its data. In the active mode of communication, both the communication initiating device and the target device communicate by generating their own carrier waves. These devices need to be powered by external power sources.

NFC tags and readers can operate in three different modes: card emulation, reader/writer and peer to peer (or point to point). In NFC Card Emulation mode, usually the active device reads the passive device tag types. Both of them can be active or passive devices. In the NFC Peer to Peer (Point to Point) mode standardized according to the ISO/IEC 18092 [30], two nodes are connected to each other by a peer to peer or ad hoc mode in order to exchange data [31]. The massive deployment of NFC came to join the use of RFID as complementary technology and, as a consequence, are becoming important technological solutions for pay-machines, smart objects, smart wearables, and many other devices. These technologies are commonly used in applications, such as tracking objects and people, to offer personalized information and services such as in e-health applications. This scenario brings a new concept of "thing" or object socialization. In this concept, the link between the ported object and the person who carries it establishes a unique co-ownership and relationship. This relationship is capable of influencing decisions in human environment interactions and raising the level of the consciousness of the object [32, 33].

On the physical layer of NFC, RF communication data rates are 106, 212, 424 as well as 848 Kbps depending on the combination of modulation and code techniques used. The available modulation schemes are ASK (Amplitude Shift Keying) using 10% or 100% modulation depth, Non-Return-to-Zero Level (NRZ-L), Binary Phase Shift Keying (BPSK) and Manchester or Modified Miller coding are used for the data transfer. The International Organization for Standardization (ISO), International Electrotechnical Commission (IEC), and Federal Communications Commission (FCC) regulate the transmission power to be 20 or 23 dBm according to region [34, 35, 36, 37]. The NFC MAC layer is also responsible for connection handling, message exchange, emulation modes, anti-collision bit transmission, activation procedures, data transport, and others. Figures 2.2 and 2.3 illustrates these functionalities [29].

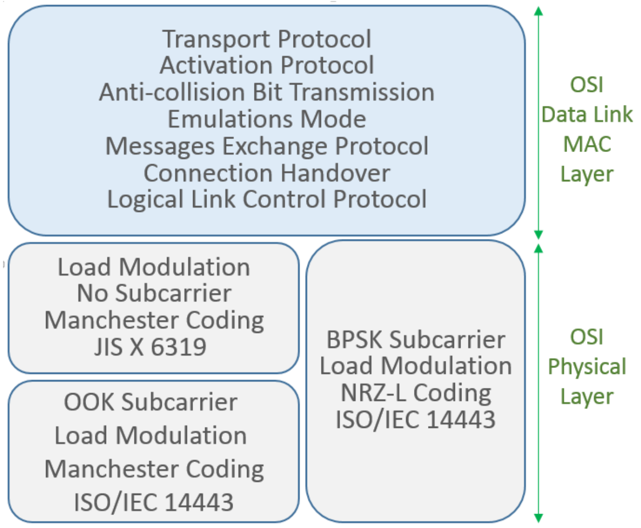


FIGURE 2.2: NFC passive to active device communication protocol stack.

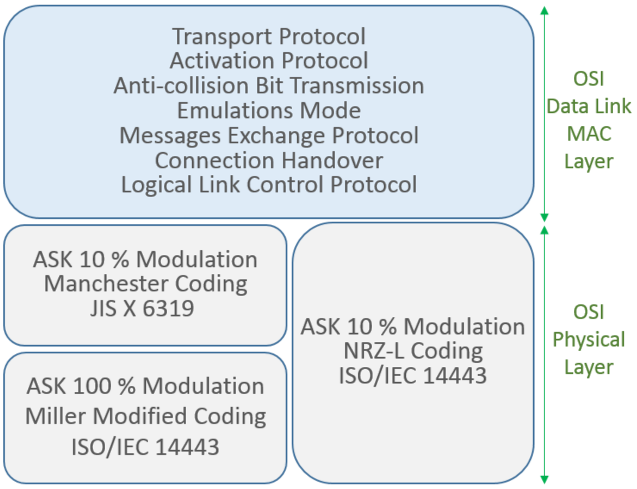


FIGURE 2.3: NFC active to passive device communication protocol stack.

2.1.3 Bluetooth IEEE 802.15.1

WPAN IEEE 802.15.1 also called the Bluetooth Basic Rate (BR) is a global 2.4 GHz specification working with short-range wireless networking. It covers the versions v1.0, 1.0B with voice dialing, call mute, last number redial and a 10 meter range as the main facilities and a v1.2 with adaptive frequency hopping added. Versions v2.0+Enhanced Data Rates (EDR) and v2.1+EDR added more capabilities such as improved resistance to radio frequency interference as well as improving indoor coverage and LOS range to 100 m. Fast transmission speeds and low power consumption mechanisms were also increased on the v2.0+EDR and v2.1+EDR versions. Version v2.1 counts on a sniff subtracting function that results in less transmissions do access the medium and so reducing interference.

The evolution follows with v3.0 receiving enhanced power control to quickly adapt to the changing path loss of the new 5 GHz transmission frequency bands. Version 4.0 increased the modulation index, resulting in less energy used during transmission but still presented a certain medium consumption to complete the receiving process. Version 4.1 shows better alignment on pico-nets timing when the transmission suffers interference. In Version 4.2, the low energy is reinforced with the adoption of longer packet transmissions. This reduces the quantity of packets transmitted for the same information size, using a packet length extension technique. The present version of Bluetooth v5.0 has some improvements regarding transmission and receiving processes. The Bluetooth v5.0 improvements include slot availability mask, which allows the alignment of pico-nets timing with nearby LTE bands, an increased coding gain, increased symbol rate and a better channel selection algorithm.

The IEEE 802.15.1 MAC layer is composed of Logical Link Control, the Adaptation Protocol (L2CAP) layer, the Link Manager Protocol (LMP) layer, and the Base-band or simply the Physical layer. The Bluetooth MAC layer handles the communication types that can be asynchronous connectionless (ACL) or synchronous connection-oriented communication (SCO). Figure 2.4 shows the relationship between the Open Systems Interconnection model (OSI), the seven-layer model and the IEEE 802.15.1 standard.

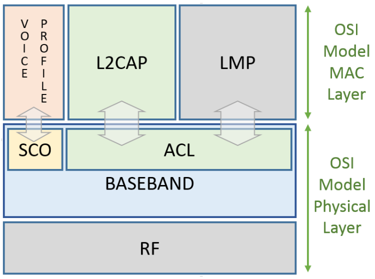
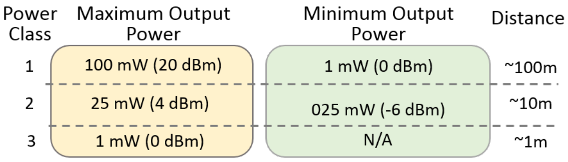


FIGURE 2.4: Mapping of OSI reference model to IEEE 802.15.1 Bluetooth stack.

The Base-band Layer defined by the IEEE 802.15.1 standard operates in the 2.4-GHz Industrial Scientific and Medical (ISM) band using a short-range radio link and a fast frequency-hopping (FFH) transceiver. The Radio and the Base-band sub-layers define the Bluetooth physical layer. The Radio layer provides the physical links among Bluetooth devices with 79 different Radio Frequency (RF) channels spaced of 1 MHz, using a frequency hopping spread spectrum (FHSS) transmission technique. This FHSS technique increases the robustness of the link due to its capability to reduce the interference of nearby systems that may operate in the same frequency range. A Time Division Duplex (TDD) transmission scheme is specified to divide the channel into time slots of 625 μs each, corresponding to a different hop frequency, simulating full-duplex communication in the same transmission channel. The radio link which reaches up to 100 m with LOS is obtained using the nominal power according to its power class and the irradiating system used. Three output power classes divide the Bluetooth Basis Rate protocol devices. Each class is characterized by a maximum power and a minimum output power, and, based on these values, the distance within which the device can communicate is defined according to the list in Figure 2.5.



Power Class	Maximum Output Power	Minimum Output Power	Distance
1	100 mW (20 dBm)	1 mW (0 dBm)	~100m
2	25 mW (4 dBm)	025 mW (-6 dBm)	~10m
3	1 mW (0 dBm)	N/A	~1m

FIGURE 2.5: Bluetooth power class classification.

The main roles of the Bluetooth MAC layer are to set-up the physical connections between the master and slaves; send and receive packets along the physical channels; synchronize the network devices with the master clock and manage the different devices for power saving states [38].

In summary, the base-band functionalities are clock synchronism, management timers, addressing and assessment devices, physical channel handling, channel hop selection, physical link supervision, logical transport management, logical link management, formatting and ordering bits, bit-stream processing, error checking, error correction, definition of ARQ (Automatic Repeat Request) schemes, managing link controller operations, support for general audio recommendations, audio level control, audio paths, frequency mask, and others.

A Link Management Protocol is a control protocol responsible to establish base-band and physical layer links. Functions such as connection establishment and release, among others, are Link Management (LM) features acquired by LMP utilization that handles a Synchronous Connection-Oriented (SCO) link, and an Asynchronous Connectionless Link (ACL). A SCO physical link establishment is a symmetric point-to-point connection between the master and a specific slave. It is used to deliver delay-sensitive traffic, such as voice service, and works as a circuit-switched connection between the master and the slave. The ACL link is a point (master) to multi-point (slaves) in a pico-net domain and works as a packet-switched connection, which considers the Bluetooth devices that support point-to-multi-point connections. To ensure the integrity of the data and to guarantee a reliable delivery of the data, ACL uses a fast Automatic Repeat Request scheme.

The Logical Link Control and Adaptation Protocol (L2CAP) layer is a channel-based abstraction between the base-band and service application layer. The L2CAP layer handles segmentation and reassembly of application data, and multiplexing and de-multiplexing of multiple channels over a shared logical link [39]. The L2CAP layer is responsible for handling the size adjustment of the maximum transmission unit (MTU) when the application layer data is larger than the MTU of the base-band layer. The L2CAP layer can segment the application data in order to seize the maximum MTU transmitted based on the size of the MTUs received by the application This feature reduces the overhead on the information sent thus, improving the efficiency. Endpoint peer devices receive a Channel Identifier (CID) used for signaling purposes associated to its connections, for ACL and SCO data communication between L2CAP devices. Some CIDs are reserved for the L2CAP layer as a logical channel required to meet Bluetooth standards and is reserved for signaling purposes. Connectionless channels support ‘group’ or multi-point communication, while connection-oriented channels are dedicated to peer-to-peer connections only [40]. Figure 2.6 elucidates the data channelization, links and transport structure.

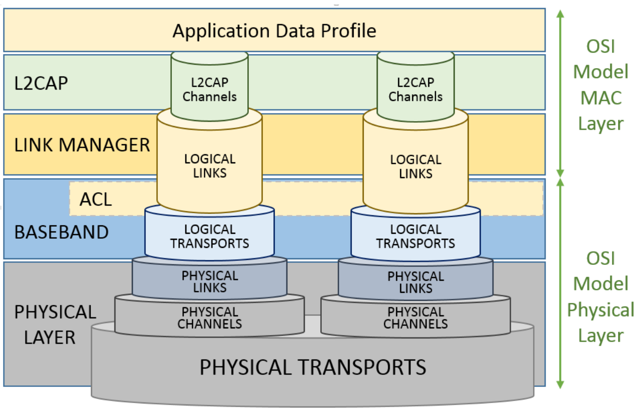


FIGURE 2.6: Bluetooth data link structure.

Bluetooth relies on the contention-free token-based multi-access networks as logical topology. End point devices are mentioned as slaves. A cluster of up to seven slave devices can be attached to a master device, in order to have access to the channel, composing a pico-net cellular topology. The master is responsible to manage the polling process messages to authorize a slave device to access the channel and transmit its data. These features increase the range to more than 100 m with a LOS path in an outdoor environment also increasing its indoor environment range to about 40 m. The utilization of beacons as sense mechanisms and the larger message capacity of 255 bytes improves the communication performance.

Data rates have a theoretical value of 2 Mbps but with a practical recommendation of 1.6 Mbps considering overheads. A pico-net data rate can reach up to 1 Mbps, which represents the channel capacity not considering the overhead introduced by the adopted access control techniques and polling scheme. The coverage areas of the pico-nets can be overlapped forming a scatter-net topology when at least one unit exchanges data with more than one master. This allows a slave to be active in more than one pico-net at the same time but can be managed by only one master element. When using a time-multiplexing mode, a slave can communicate with more than one pico-net but only in different time periods. This is due to the necessity to change its synchronization parameters or in order to listen to different channels. A size of a pico-net is limited to just one master and up to seven active slave stations [38]. The conventional ad hoc topology is also used.

2.1.4 Bluetooth Low Energy

Being part of the Bluetooth v4.0 standard adopted in 2010-06-30, Bluetooth Low Energy (BLE) is also known as Smart Bluetooth. BLE is an IEEE 802.15.1 variation with better and more suitable capacities for low power applications than the classic Bluetooth Basic Rate. Devices that demand communication with both standards of Bluetooth are required to implement and support both protocol stacks due the incompatibilities among them. Star is the only topology accepted by BLE due the standard definition that does not permit physical link connections among slave devices. Any data exchanged between two slave devices shall pass through the unique master and a slave device may not be connected to two master units at the same time. These premises define the formation of a BLE star pico-net [41] .

Using a similar protocol stack as classic Bluetooth, the differences between them starts above the L2CAP layer. Above the L2CAP layer, BLE is the application layer that uses a set of functionalities, which are not present in the classic Bluetooth specifications. These functionalities are the Attribute Protocol (ATT), the Generic Attribute Profile (GATT), the Security Manager Protocol (SMP) and the Generic Access Profile (GAP). Figure 2.7 depicts the BLE protocol stack.

The two main roles of BLE are: controller and host. BLE differs from the classical Bluetooth in the controller stack that defines the association methods of the devices. A slave can belong to only one pico-net during an association lifetime, and is synchronized with only one master element.

A Host Controller Interface (HCI) is a communication standard applied between the slave and controller. In the Bluetooth Basic Rate, 79 channels are used with a 1 MHz bandwidth to reduce interference with adjacent channels. In Bluetooth Low Energy, the channels are defined in the 2.400–2.4835 GHz band with a 2 MHz guard band. To achieve scalability, the master device controls the number of hosts associated with it by adjusting the value of the connection interval (*ConnInterval* parameter) between hosts and controllers.

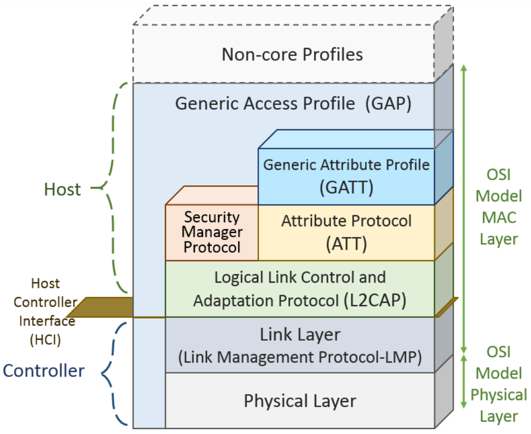


FIGURE 2.7: Bluetooth low energy protocol stack.

Link layer manages events generated by the hosts, at determined time intervals, using the advertising channels. Bidirectional data flow is obtained with a connection between elements, when slaves advertising packets are received by master elements. The energy save handling done at MAC layer can put the slaves in a sleeping mode by default and waking them periodically through a Time Division Multiple Access (TDMA) scheme. In the classic Bluetooth basic protocol, this layer a stop-and-wait flow control mechanism is used to provide error recovery capabilities. At BLE, the L2CAP is an adaption of the classic Bluetooth basic protocol stack but optimized and simplified to receive the application layers designed for low energy platforms. Data exchange between the application layer and link layer are also done by L2CAP using no retransmission techniques or flow control mechanisms as used on the classic Bluetooth. Not using retransmission or flow control mechanisms (present in the classic Bluetooth) and segmentation and reassembly capabilities, the Packet Data Units (PDU) (limited to 23 bytes in BLE) received by the application layer is delivered ready to fit the maximum size of the L2CAP payload.

When two devices are connected under a server and client association architecture, the server needs to maintain a set of attributes. The Attribute Protocol (ATT) handles the attributes of this connection like the definition of data structure used to store the information managed by the Generic Attribute Profile (GATT) that works on top of the ATT. GATT defines the client or server functionalities of a connection and this association is independent of the master or slave roles. The attributes of the server need to be accessed by the client through the requests sent, which trigger the response messages of the server. It is also possible for a server to send to a client, unsolicited messages like notifications that do not need any confirmation message to be sent by the client. A server is also required to send indication messages, which need confirmation messages to be sent by the client. The slave sends requests for responses and indications prior to transactions confirmation following a stop-and-wait scheme. Slaves can either write attributes values at the master.

A framework defined by GATT performs the role of discovery services using the ATT attributes, and allows exchange of characteristics between devices interconnected. An attribute carries a set of characteristics that includes a value and properties of the parameter monitored by the device. For example, a humidity sensor needs humidity characteristics and attributes to describe this sensor, and to store its measurements. Thus, this sensor needs a further attribute to specify the measurement units.

Creating specific profiles with the Low Energy Bluetooth standard takes place in the Generic Attribute Profile (GATT). GATT uses the Attribute Protocol (ATT) protocol in addition to the lower stack protocols, in order to introduce the subdivision of retained server attributes into services and features. Services can contain a set of features, which can include a single value (accessible from the client) and other numerical data that describe such features. Among the assignments of GAP profile specifications are: device role rights, discovery devices and services, as well as establishing connections and security. A new profile based on the existing profile requirements can be created following a profile hierarchy. The interoperability of different devices can be handled through application profiles.

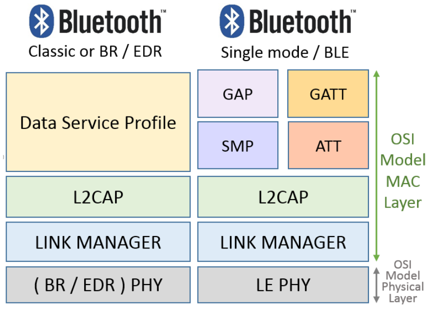


FIGURE 2.8: Classic Bluetooth and single mode Bluetooth Low Energy stacks.

Bluetooth is designed to offer a low-cost alternative to Wi-Fi at the expense of the transmission range. Its transmission range is considerably shorter (up to 100 m LOS) and data rate does not exceed 721.2 Kbps in the classic Bluetooth Basic Rate version and can reach 3 Mbps with the Enhanced Data Rate feature. BLE operates at 1Mbps rate on its physical layer, while its application layer can handle only 236.7 Kbps.

In Bluetooth Low Energy, there are no subdivisions in power classes but only the maximum and minimum output power values of the transmitter are provided. Only an approximate value of the maximum reachable distance can be predicted. The low power required for transmission is the main feature of the Bluetooth Low Energy standard and this result is due to enhancements made on the classic version. These enhancements include reduced frequency band and shorter PDU packets [42].

An energy evaluation is offered at [43] using CC2640 radio chipset consumption reference measurements. The comparison is made when operating on 0 dBm transmission power by gathering the main characteristics of Bluetooth and BLE.

Bluetooth v5.0 has no functional block included in its first and second layers when compared to versions v4.0, v4.1, and v4.2. A representation of the inter-layer communication structure and the relationship with Bluetooth layers of different Bluetooth versions can be seen in Figure 2.8. Device-to-device file transfers, wireless speakers, wireless headsets, and Body Sensor Networks are often enabled with Bluetooth versions.

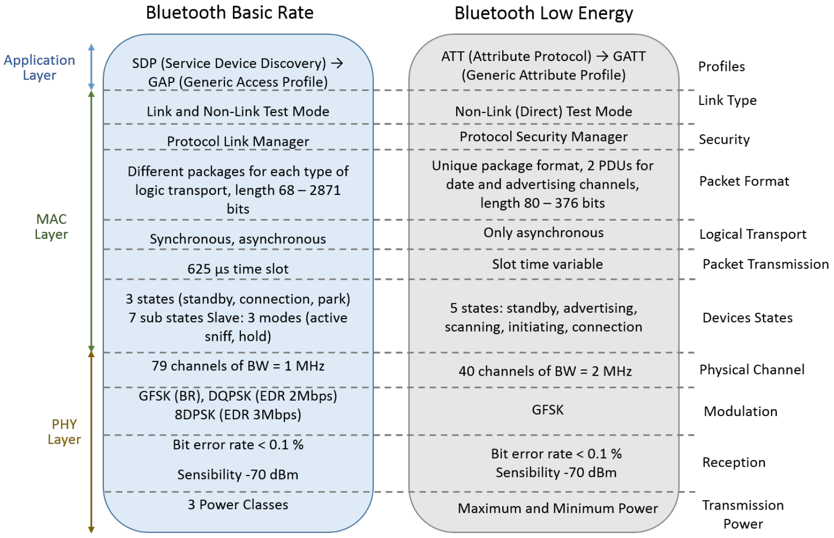


FIGURE 2.9: Bluetooth basic rate versus Bluetooth low energy.

Finally, some characteristics of the Bluetooth BR and BLE technologies are summarized in Figure 2.9. This figure allows the comparison of their differences according to the PHY and MAC layer characteristics.

2.1.5 IEEE 802.15.4

IEEE 802.15.4 is a subgroup of features that refers to physical and medium access control layers that can support ZigBee and 6LoWPAN upper. IEEE 802.15.4 focuses on physical and data link layer specifications while ZigBee Alliance aims to provide the upper characteristics [44]. It is a standard that defines PHY and MAC layers for personal area networks that demand low rate and low cost applications. This also called a LR-WPAN protocol and has some advantages. Among them are a simple and flexible protocol stack, low cost, low energy consumption, short-range operation, reliable data transfer, and ease of operation [45]. These features are more important when operating in the Personal Operating Space (POS) also defined as Personal Area Network (PAN) that involves the human body.

An IEEE 802.15.4 device address can be a short 16-bit or 64-bit address [46]. In addition, IEEE 802.15.4 uses a Direct Sequence Spread Spectrum (DSSS) access mode and operates on 2450 MHz, 915 MHz, and 868 MHz ISM bands working with 16 channels, 10 channels, and one channel, respectively. The main limitations of the radio interfaces working in the ISM frequency band are the small sizes and the narrow bandwidths. Small sizes and narrow bandwidths consequently cause a reduction in output power transmission. With these radio interface characteristics, it is possible to obtain from 20 to 250 Kbps shared among all the nodes using the same channel [47, 48].

The physical layer provides an interface between the physical data service and the PHY management service accessed through service access points (SAPs). This layer is also responsible for activation, and deactivation of the radio transceiver, energy detection (ED) within the current channel, link quality indication (LQI) for received packets, clear channel assessment (CCA) for carrier sense multiple access with collision avoidance (CSMA-CA), channel frequency selection, and data transmission and reception. The energy saving aspects of IEEE 802.15.4 are mainly addressed to this layer by the ED, LQI and CCA functionalities [46]. According to the PHY layer specifications, and following the spectrum utilization of each region, the distances between the nodes based on IEEE 802.15.4 can be up to 100 m. This range depends on propagation environment obstacles and the maximum transmission power levels defined by the IEEE 802.15.4 standard, illustrated in Figure 2.10 [15, 49].

The IEEE 802.15.4 MAC layer provides access to the physical channel for all upper layers, providing two kinds of services: the MAC data service and the MAC management service. MAC data and MAC management are services that are also provided to other layers enabling them to access the PHY layer resources. The standard defines two different methods of channel access that are a beacon enabled (BE) mode and a non-beacon-enabled (NBE) mode. The MAC sub-layer, which is responsible for beacon management, is also responsible for channel access, Guaranteed Time Slots (GTS) management, frame validation, delivered frame acknowledgement, and association/disassociation activities [44].

An IEEE 802.2 Logical Link Control (LLC) can access the IEEE 802.15.4 MAC sub-layer through the Service Specific Convergence Sub-layer (SSCS). The SSCS IEEE 802.2 convergence sub-layer exists in a conceptual perspective, on the top of the MCPS (MAC Common Part Sub-layer). SSCS provides a link between the IEEE 802.2 LLC sub-layer and the IEEE 802.15.4 MCPS in the data service plane through the MCPS-SAP (MCPS-Service Access Point). On the management plane, driving the layer management functions, the MMLE (MAC sub-layer Management Entity) provides the service functions assembling capability through an interface between the SSCS and PHY. MMLE is also responsible for maintaining a PIB (PAN Information Base) which contains the data base of the managed objects belonging to the MAC sub-layer [15].

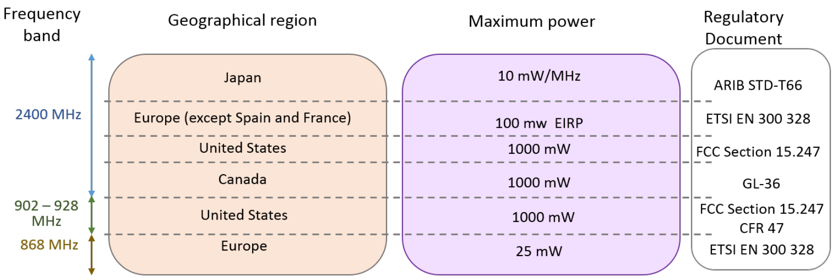


FIGURE 2.10: IEEE 802.15.4 maximum transmission power levels according to regions.

The IEEE 802.15.4 BE and NBE operational modes have being strongly investigated over recent years. Thus, some limitations have been addressed and the most important ones are the unbounded delay, low communication efficiency, low interference robustness, and/or fading and main powered relay nodes [50, 51, 52, 53, 54].

The IEEE 802.15.4 Task Group 4e was chartered to define a MAC amendment to the standard 802.15.4-2006 in order to evolve and add important functions to the 802.15.4-206 MAC protocol to enhance MAC to PHY functionalities interaction [55]. IEEE 802.15.4e supports five new categories of MAC enhancements also called MAC behaviors: Time Slotted Channel Hopping (TSCH), Deterministic and Synchronous Multi-channel Extension (DSME), Low Latency Deterministic Network (LLDN), Asynchronous Multi-channel Adaptation (AMCA), and Radio Frequency Blink (BLINK) [56]. Some general enhancements were also included as follows: Low Energy (LE), Information Elements (IE), Enhanced Beacons (EB), Multipurpose Frame, MAC Performance Metrics, and Fast Association (FastA) mechanism [57]. Figure 2.11 compares IEEE 802.15.4 stack with the OSI reference model.

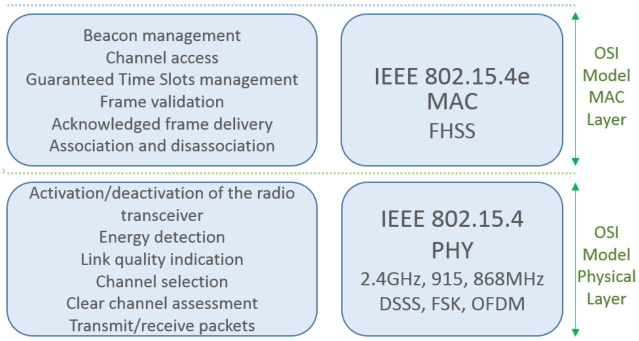


FIGURE 2.11: IEEE 802.15.4 compared with OSI reference model.

The use of multipurpose sensor networks becomes as a natural network environment with a focus on how to reduce the implementation of the operation costs through the reuse of resources. Ordinary traffic generated by regular applications such as environmental monitoring will not require the same treatment as the traffic response required for applications that use information queries time sensitive [5] characteristics. A heterogeneous traffic coexistence, with different QoS (Quality of Service) requirements is not handled well by IEEE 802.15.4. One option to improve QoS is the adoption of multiple transmission queues in both 802.15.4 and 802.15.4e considering the urgency level of the different traffic. This process separates the different QoS traffic in different classes and handles them on four transport queues with differential treatments [47, 58] .

Mobility can be treatable by IEEE 802.15.4 but can hardly degrade the network performance [59] and happens when an orphan device that loses its coordinator association attempts to synchronize with network coordinators. The IEEE 802.15.4 terminal uses the common transmission channel to search for coordinators. On the topology aspect, the coordinators that belong to the same Personal Area Network Identification (PANId) are connected to a Super Coordinator that can handle the device mobility from one coordinator to another. It is important to point out that, during this re-association, the service data are interrupted. Some authors enlarged their visions beyond IEEE 802.15.4 limits suggesting inter-technology mobility. For example, to allow a mobile node to move through the cells in a various cluster tree network. Coordinators have both IEEE 802.15.4 wireless and wired connections” [60] to expand the mobility domain. Energy performance is boosted by channel hopping based on multi-channel support. The development of IEEE 802.15.4 is a joint work between IEEE and ZigBee Alliance. The stack consists of layers one and two of the IEEE 802.15.4 standard as the basis for other protocols such as ZigBee itself, 6LoWPAN, Thread, and ISA100 [61, 62]. Due the fact that these protocols are derived from the IEEE 802.15.4 PHY and MAC layers, they belong to the network layer and are out of context for this comparison.

2.1.6 Wireless-HART

Wireless-HART (Highway Addressable Remote Transducer Protocol) is a variation of IEEE 802.15.4 design to work essentially as a centralized wireless network. IEEE 802.15.4 is designed to meet the requirements of industrial wireless applications with hard timing parameter restrictions, critically security issues, and severity on obstacle interferences. The Wireless-HART protocol has the same specifications as IEEE 802.15.4 PHY, but develops its own MAC layer based on the TDMA technique.

A comparison between the OSI reference model and Wireless-HART protocol layers and its main features is shown in Figure 2.12.

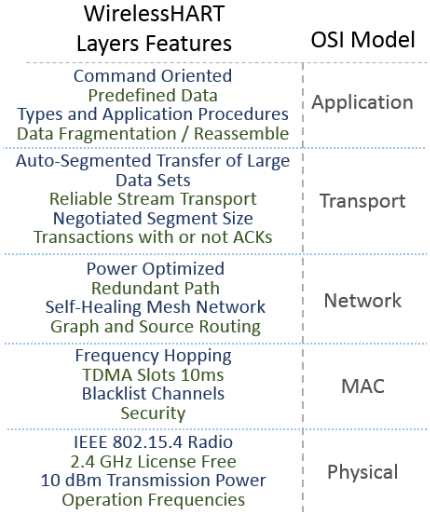


FIGURE 2.12: WirelessHART Protocol Stack.

Using Bluetooth, there is no guarantee to delay values on an end-to-end wireless communication. The absence of a hopping channel technique and a quasi-static star Bluetooth topology works against its scalability. These characteristics make them inappropriate to be used in industrial scenarios. Wireless HART comes as a solution for process control applications through the effort of some industrial organizations such as International Society of Automation 100 (ISA 100) [62], HART [63], Wireless Industrial Networking Alliance (WINA) [64] and ZigBee Alliance [65] to attend their specific requirements ratified by the HART Communication Foundation in 2007.

Using the IEEE 802.15.4 PHY layer, Wireless-HART operates in the license-free ISM of 2.4–2.4835 GHz with 2 MHz bandwidth of each one of the 16 channels. The channels are numbered from 11 to 26 with a gap of 5 MHz between IEEE 802.11b/g adjacent channels, delivering up to 250 Kbps. Wireless-HART uses its own Time Division Multiplex Access (TDMA) on the MAC layer including the 10 ms synchronized time slot features. These characteristics allow the messages routing through a network topology obstacle and interference. This is possible due to the use of self-organizing and self-healing mesh networking techniques supported by the network layer. Even being essentially a centralized wireless network, Wireless-HART uses a network manager in its stack in order to provide routing and communication schedules. This can guarantee network performance and satisfy the wireless industrial applications. The focus of Wireless-HART is communication on a one-hop level and the network layer has its responsibility to the network devices vicinity allocation [15, 66, 67, 68].

Differing from IEEE 802.15.4, Wireless-HART uses time-synchronized the TDMA technique combined with frequency hopping on its MAC layer, thus allowing multiple devices to transmit data at the same time along different channels. During the joining process of the devices onto networks, the network manager distributes the communication links and the channel hop patterns to the devices. It also manages the enabling or disabling of the use of channels that are frequently affected by considerable interference levels, calling this feature *channels blacklist* [69] [61]. The eight types of devices defined on Wireless-HART are: routers, gateways, adapters, network managers, network security devices, access points and field devices on a mesh topology. All of them support the implementation of features to attend network creation, maintenance issues, data and signaling routing capability, and a minimum of reliability.

Another addressable characteristic of Wireless-HART is the information blocks that each network device maintains on its memory. The information of neighbor nodes and the next reachable device is called a neighbor information block. The connection with the network layer is made through the block information, adding data to the network layer routing table. Working with TDMA as a medium access technique, the network devices have very stringent timing requirements to accomplish network synchronization premises. This happens because synchronization occurs both in the joining process and in normal operations [68].

2.1.7 Z-Wave

Z-Wave was developed and is overseen by the company Zensys to provide wireless communication between devices with a focus on residential automation. Monitoring and controlling of lighting, ambient temperature and security through sensors and actuators by tablets, smartphones or computers are some applications in its portfolio. Z-Wave devices are arranged in mesh network topology. They can send and receive messages from any device that is connected to the network [70, 71].

The protocol is a proprietary standard based on the ITU G.9959 specification that operates in the Industrial, Scientific, and Medical (ISM) radio frequency band. Z-Wave transmits on 868.42 MHz (Europe) and 908.42 MHz (United States) frequencies working with FSK and Gaussian Fase Shift Keying (GFSK) modulations. With low transmission rates of

9.6 Kbps, 40 Kbps and 100 Kbps, it employs symmetric AES-128 encryption. The MAC layer uses the CSMA-CA technique for a medium access control technique and, based on ITU G.9959, has the following characteristics: a capacity of 232 unique network identifiers that allows the same quantity of nodes joying the network; collision avoidance mechanism; back-off time when collision occurs; reliability guaranteed by receiving acknowledgments; frame validation and retransmission mechanisms. A power saving mechanism is achieved due to a sleep mode with a dedicated wake-up pattern [72, 73]. Figure 2.13 depicts the Z-Wave protocol stack.

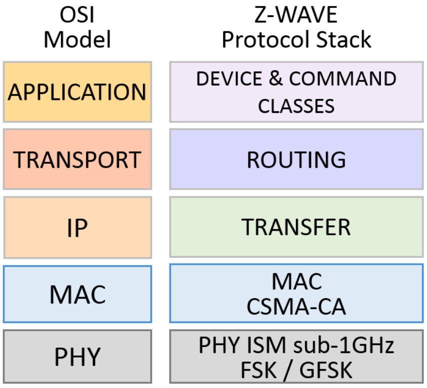


FIGURE 2.13: Z-Wave protocol stack.

The Z-Wave basic device classes are the following: Portable Controller, Static Controller, Slave, and Slave with Routing Capabilities. Different classes provide the device with a certain role in the Z-Wave network. Inside a Basic Class, Generic and Specific device classes are used to achieve the wanted functionality in the control network. In the Z-Wave protocol, the unique identification of the devices is used through a 32-bit ID. This ID value cannot be changed as it is written in the device chipset by the device manufacturer. A Z-Wave network has only one primary controller device at a time. Each of the 232 nodes of this network can also be a repeater for forwarding data to its neighbors, mediating a connection. Battery-powered nodes do not enjoy this facility. In an environment with a certain level of device drift or even when a device is removed from the network for some reason, the network topology may change. Changing network topology can lead to problems in packet forwarding and packet routing in the network. To minimize this effect, routing tables should be kept up-to-date, optimized and any new topology detected; Z-Wave supports the discovery and suitability of the new network topology. This is possible by keeping the routing table up-to-date on each device and showing all neighboring devices [74, 72]. When a node changes its position or is removed from the network, a topology failure can start an automatic topology and healing procedure to detect the new topology and define the best routes to update the routing tables. This mechanism is subjected to unauthorized modification of routing table attacks by rouge nodes [75].

The transfer (or transport) layer management functions are: communication between two neighbor nodes, packet acknowledgment, low power network nodes awake (Beaming), and packet origin authentication. This layer controls the *Beam* frames used to wake-up battery powered Z-Wave devices, as each primary controller device of a cluster can handle up to 232 nodes. All nodes can act as a packet repeater, except those devices that are batteries powered. This is Z-Wave mesh topology formed [76].

Z-Wave data security is based on AES and on the cipher block chaining message authentication code (CBC-MAC). However, standards and rules for command classes, device types and timers are missing. These characteristics are only acquired in the new advanced security framework (S2) determined by the Z-Wave Alliance and developed in conjunction with the cyber security community. For the certification of new products as of 2017, Z-Wave brings devices a higher level of security. The structure of S2 is based on the protection of the devices that is already associated with the network, so they are not hacked while still connected to the network. Once the device has already been associated to the network through its pin-code or Quick Response (QR) code, there is an exchange of security keys through the Elliptic Curve Diffie-Hellman (ECDH) algorithm [74, 77].

2.1.8 Weightless

Weightless is the name of a set of LP-WAN protocols for wireless communication networks with low transmission rates. In this set, Weightless have the variations Weightless-P, Weightless-N and Weightless-W. These technologies are standardized by the Weightless Special Interest Group (Weightless SIG) [78]. The Weightless network is a typical star topology system composed of the end devices (ED) and the base stations (BS). EDs are the sensor nodes or are also called leaf nodes and the base stations (BS) concentrate the communication with EDs. The interconnection with the base stations composes the base station networks (BSN) that, among other things, manages the system facilities such as authentication, roaming and radio resource allocation and scheduling.

The physical layer of the Weightless protocol has one variant for high data rates and another for low data rates. In both cases, the functional blocks that compose the physical layer for downlink are Forward Error Correction (FEC) encoding, interleaving, whitening, Phase Shift Keying (PSK)/Quadrature Amplitude Modulation (QAM) modulation types control, spreading factor used, cyclic prefix insertion, sync insertion and Root Raised Cosine (RRC) pulse shaping. The combination of the modulation type, FEC rates and spreading factor parameters used impacts the final transmission rate. This transmission rate can vary from 125 Kbps to 16 Mbps. The data rate of 125 Kbps is through a modulation of (π/ 2) BPSK with an FEC rate and spectral scattering. In addition, 16 Mbps is achieved when the modulation used is 16-QAM without the use of the FEC mechanism and the scattering factor spectral is reduced. Depending on the availability of FEC encoder module, the interleaving module may be present or not. When present, the interleaving block provides time diversity and increases the robustness of the process adding a processing gain. The whitening module uses a known random sequence to scrambler the bit stream turning it into a pseudo white noise, and increasing the receiver synchronization performance. A spreading module is necessary to spread the modulated data that receives a cyclic prefix insertion, in order to reduce the multi-path transmission effects. This characteristic adjusts the frame conversion from the time domain to frequency domain. The synchronization pattern necessary to receive processes is then inserted by the sync insertion module. The RRC pulse shaping acts as a digital filter to reduce the radiation that surpasses the transmission radio frequency band. On the receiving process, appended modules are necessary to coarsen the time offset estimation and correction. It is necessary to find out the start of the burst, the fine frequency offset estimation and correction, channel estimation and equalization and timing detection to determine payload start position.

Like many other systems, Weightless uses channels to exchange data between the protocol layers. They are classified according to their role as control channels, logical channels transport channels, and physical channels. To allow base-band data exchange, the Physical layer (PHY) has three physical channels. They are named the downlink channel, uplink channel and uplink contended access channel. To transmit data from the base station to one or multiple EDs, the downlink channel is used. To uplink communication, from an ED to the access point, the uplink channel is used. The uplink contended access physical channel is also used to transmit data from the end devices to the base station. This channel is contended by the end devices and several EDs are allowed to transmit at the same time using this channel.

A Base-Band (BB) sublayer is responsible for providing the transport channels to transport the data to or from the Link Layer (LL). This is done by connecting the transport channels to the physical channels of PHY. Among the operations carried out by BB are identification of structured allocations within a frame structure and the transmission of the frames in both uplink and downlink directions, using appropriate physical channels. The Contended Access (CA) procedure is also controlled by BB using the uplink contended access physical channel. The communication between LL and BB is done by a set of transport channels and its channels are defined according to the type of information of addressing that is used. Connecting logical channels to the BB transport channels is the LL. LL is also responsible for retransmission control, reliability of the logical channels and for data fragmentation and reassembly. These processes can be either acknowledged or not. The multiplexing and de-multiplexing processes of the transport channels into logical control or user data channels is done by the LL. Thus, the LL provides such logical channels to allow the data or control traffic between the end devices and the BS or a BSN through an acknowledged and reliable or an unacknowledged and unreliable packet stream.

Radio Resource Manager (RRM) is present to control the traffic between an ED and its BS through Control Channels, using appropriate security provided by LL. The messages that control and maintain the connection between the ED and BS during the communication between them, is handled by RRM through the control channels. RRM also provides a downlink-only control message stream sent by the BSN, in order to maintain the link between the ED and BS. A Weightless protocol stack drawing can be seen in Figure 2.14.

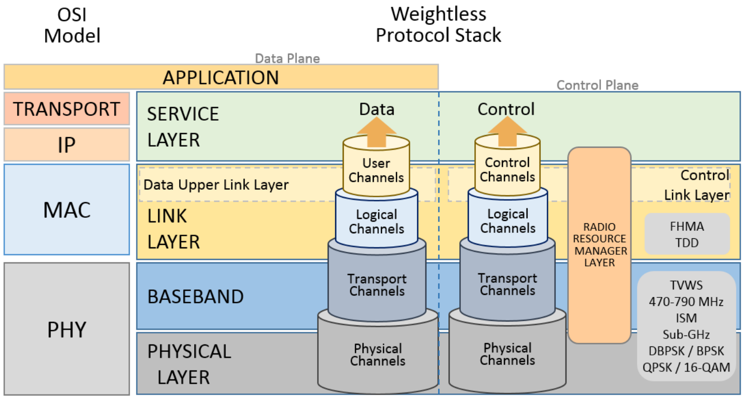


FIGURE 2.14: Weightless protocol stack.

Payload data is conducted from an ED and its BS through user channels that provide specific channels for unicast data, multicast data, interrupt data, and acknowledgement data. While the unicast user data channel is a bidirectional channel between the ED and the BS, the multicast data channel is a downlink-only channel. The multicast user data channel is an uplink-only channel. Weightless-W is a bidirectional communication technology that works on a Television White Space (TVWS) spectrum of 470-790 MHz. Its multiple access mechanism uses frequency hopping (Frequency Hopping Multiple Access—FHMA) with Time Division Duplexing (TDD). This can separate and coordinate the uplink and downlink transmission intervals. The data rates range from 1 Kbps to 10 Mb/s and the battery life is from three up to five years depending on usage. This technology supports star topology and 128-bit AES encryption in its packets. The packets can carry up to 10 bytes of payload, but encryption can be implemented end-to-end depending on other mechanisms, such as the network core. The error correction system is based on a Forward Error Control (FEC) algorithm not specified by the manufacturer. Channeling is done with 16 to 24 channels of 5 MHz bandwidth, depending on the frequency of use. The modulation of the channels is adaptive and can reach high rates at short distances according to the need of the application. The modulation can start with the Differential Phase Shift Keying (DBPSK) and BPSK for greater distances. Lower rates from 1 Kbps use Quadrature Phase Shift Keying (QPSK) or 16-QAM, reaching peaks of 10 Mbps over short distances [79, 80, 81, 82].

Weightless-N is based on the Weightless-W standard and adapted for smaller distances and lower energy consumption (batteries last up to 10 years), sacrificing the transmission rate from 30 up to 100 Kbps. Weightless-N does not reach the data rate peaks that the Weightless-W can reach. Unlike Weightless-W, the Weightless-N is based on an Ultra Narrow Band (UNB) system and operates on the UHF frequency in the 800–900 MHz ISM band, providing only uplink communication. This system supports star topology and applies the UNB DBPSK (Differential Phase Shift Keying) modulation to ultra-narrow 200 Hz wide-band channels. With this simpler modulation, DBPSK, the device can save energy by making the battery last for up to 10 years [79].

Unlike W and N, the Weightless-P standard does not require a Temperature Compensated Crystal Oscillator (TCXO), which makes the system cheaper and less vulnerable to loss of synchronism due to the ambient temperature variation. This characteristic is only possible because it uses Gaussian Minimum Shift Keying (GMSK) modulation and an offset-QPSK modulation.

Weightless-P technology capacity was measured in a comparative way with the capacity of several multiple access technologies. The transmission power is set up serving a defined population of devices. The maximum flow for each multiple access mechanism allows 1404 bps for UNB, 93 bps for spread spectrum, and 4923 for NB (Narrow Band) [79].

2.1.9 IEEE 802.11 a/b/g/n/ah

Certainly, one of the most discussed and exploited standards in its functionalities and applications is IEEE 802.11. Its design has as an impulse the demand for high data transfer rates. Standardized by the IEEE as protocol for WLAN, its technology has evolved to meet the needs of increasingly specific demands. This evolution has initiated a group of IEEE 802.11 standards that have been merged, and named Wireless Fidelity (Wi-Fi). This group is the Wi-Fi Alliance [83] that certifies Wi-Fi products. In order to ensure that the Wi-Fi products meet the standards, this facility was named the WLAN System Toolbox which guarantees the compatibility of the market products in the PHY layer parameters. In addition, it contributes to the exploitation of the various different regional implementations, thus contributing to protocol evolution. The standard defines that communication devices are referred to as Stations (STAs) and can behave independently. Communication is directly between the two devices forming an ad hoc topology. The star topology happens when a certain STA is defined to be the traffic concentration point of other STAs, becoming an Access Point (AP). A STA-AP has a defined coverage area called the Basic Service Area (BSA) that allows it to associate with several STAs, forming a Basic Service Set (BSS). The STA-AP is usually connected to the internet or to a WAN network through a wired connection. It is also possible to have a Distributed System (DS) connecting the various STA-APs of the same LAN by forming a transport backbone infrastructure called the Extended Service Set (ESS) [84].

The IEEE 802.11 protocol stack follows the OSI reference model on its PHY and MAC layers. While the IEEE focuses on defining the PHY and MAC layers of the protocol as a grouped context, the Wi-Fi Alliance aims to work on the physical layer to facilitate peer-to-peer communications. The IEEE 802.11 standard has evolved since its first release in 1997. The PHY layer has evolved to work on the 2.4 GHz and 5 GHz ISM frequency bands with direct sequence spread spectrum (DSSS) and orthogonal frequency division multiplexing (OFDM). The channelization was segmented from 20 MHz for IEEE 802.11 up to 40 MHz for IEEE 802.11 n. The multiple transmission beam-forming technology improves the transmission and reception parameters and, consequently, transmission rates with greater values from 2 Mbps on IEEE 802.11 up to 600 Mbps for IEEE 802.11 n.

The MAC layer also had to adapt to this evolution. The MAC layer of IEEE 802.11 has as its main differential the mechanism of access to carrier sense multiple access with collision avoidance (CSMA/CA) as a medium access method. Features such as MAC level acknowledgments, fragmentation and reassembly, inter frame gaps and exponential backoff algorithm, roaming, synchronism, security and power saving mechanisms are adopted by IEEE 802.11. These techniques guarantee communication in a frequency band with a lot of spectral pollution. The 802.11a operates at the 5 Ghz band, with 52 orthogonal frequency-division multiplexing (OFDM) reaching less than 54 Mbps. Its transmission rate is fragmented on 48, 36, 24, 18, 12, 9 or 6 Mbps. As the 2.4 GHz band is more common and has more spectral pollution, the 5 GHz band offers an advantage over the IEEE 802.11a standard, due its spectrum low interference. Devices using IEEE 802.11a have a low transmission performance compared with IEEE 802.11b when dealing with obstacles. The IEEE 802.11b revision of the original standard was ratified in 1999 with a maximum transmission speed of 11 Mbps and uses the same CSMA/CA access method defined in the original standard. IEEE 802.11b standard uses the same 2.4 GHz, operating at a maximum theoretical speed of 54 Mbps.

With Machine to Machine (M2M) communications emerging, it was necessary to adjust the IEEE 802.11 standard that was primarily designed for computer communication. M2M communication demands distinct characteristics such as transmission range above 1 Km, transmission rates higher than 100 Kbps and low power consumption. There is also a need to have a network that supports a large number of nodes, operating under a policy of lower power consumption.

In an attempt to meet these requirements, the IEEE 802.11ah Task Group (TGah) [85] has guided the necessary improvements in the PHY and MAC layers of the IEEE 802.11 protocol to suit this scenario. The IEEE 802.11ah can be used not only as WSN but as well as back-haul infrastructure to connect the sensors to the data collectors. This is possible due to its large coverage and data rates capability. The IEEE 802.11ah amendment comes to solve some important limitations encountered to use Wi-Fi IEEE 802.11a/b/g/n when used to M2M communications. Its physical layer operates on ISM at 863-868.6 MHz in Europe, 950.8–957.6 MHz in Japan, 314–316 MHz, 430–432 MHz, 433.00–434.79 MHz in China, 917–923.5 MHz in Korea, and 902–928 MHz in USA. It uses an orthogonal frequency division multiplexing (OFDM) modulation scheme to achieve larger areas of coverage and increases the number of simultaneously operable stations. Frequency operations sub 1 GHz depend on local regulations for each region. For this reason, the bandwidth occupation is usually 1 MHz or 2 MHz, but, in some countries, broader configurations using 4, 8 and 16 MHz are also allowed. In the physical layer, the transmission is OFDM-based, working with 32 or 64 sub-carriers with 31.25 KHz spacing. The supported modulation techniques include BPSK, QPSK and 16 to 256 QAM with transmission/reception characteristics. These modulations are enhanced with beam forming by using a multi-input multi-output (MIMO) antenna scheme for single-users, and downlink multi-user MIMO [9]. However, the IEEE 802.11ah physical layer PHY BW channelization can be split into:

- Bandwidth of 1 MHz: Used to extended range of applications especially IoT or M2M applications that work with short burst low data rates. Range extension is obtained when using new Modulation and Coding Scheme index 10 (MCS 10) added to the previous 802.11 MCSs.
- Bandwidths of 2 MHz and more: This mode is oriented to data rates higher than those obtained with the 1 MHz bandwidth, using up to 16 MHz bandwidth with different Modulation and Coding Scheme (MCS) options. MIMO can be used to compose this solution to improve its performance [86].

The PHY layer of IEEE 802.11ah follows the evolution of the IEEE 802.11 standard for IEEE 802.11ac that uses Orthogonal Frequency Division Multiplexing (OFDM) modulation. Its Transmission System now has uplink MIMO antennas and downlink Multi-User MIMO (DL MU-MIMO) antennas. The previous 10, 20, 40, 80 and 160 MHz bandwidths were reduced to a 10 fold scale, resulting in channels with 1, 2, 4, 8, and 16 MHz bandwidths in the IEEE standard 802.11ah. At the same time, keeping the same number of carriers in each channel as previous versions, except for the 1 MHz channel as the guard band value between the sub-carriers cannot be reduced. In this way, the transmission of a symbol lasts 10 times longer than the previous standards. The increase in transmission range is a consequence of the combination of some other improvement factors in the PHY layer.

Due to its operation in the frequency range below 1 GHz, the transmission lost 8.5 dB of its link budget, in the LOS condition. Reducing 10 times the transmission channel bandwidth also reduces the noise level in the transmission. This increases the signal-to-noise ratio (SNR) by 10 dBs. With the adoption of a 1 MHz bandwidth channel, an increment of 3 dBs is achieved in the SNR, when compared to the 2 MHz bandwidth channel. Another 3 dBs of gain is improved on the SNR, with the 1 MHz channel supporting the repetition coding scheme for binary phase shift keying (BPSK) modulation, used with the 1/2 coding rate. The sum of the above gains brings us a total gain in the link budget of 24 dBs when compared to previous standards that operate at 2.4 GHz. When the concern is not the distance but the energy factor, the transmission power of the nodes can also be reduced using its low power mode operation. It reduces the power consumption, the cost of the device and, consequently, its size.

A disadvantage of using a narrower channel is a more sensitive transmission to flat fading that can be deep in indoor environments. This challenge is overcome by using the transmission selection of the best sub-channels for transmission at that time. This technique can increase up to 7 dBs [87] gain for systems working in indoor environments. In cases of node displacement during transmission, the Doppler effect occurs. It is necessary to estimate the channel and the correction of the transmission during transmission. To do this, IEEE 802.11ah changes the pilot carrier of each OFDM symbol [88]. The IEEE 802.11ah MAC layer incorporates the majority of the IEEE 802.11 main characteristics or has improved some of them. This is to optimize M2M communications, to support a large outdoor IoT network and to support energy-efficient communications for sensors [89].

Considering a scenario of a network densely populated by nodes, some factors that imply the containment and the characteristics of access to the medium were implemented, for example, the techniques of restricted access window adjustment, synchronization frame and hierarchical, and traffic indication map (TIM). They are implemented in the MAC layer to mitigate the problems of transmission collisions between hidden nodes [90]. The time window that a group of nodes belonging to the same AP has to access the medium and transmit is called the restricted access window (RAW). RAW is divided into slots that are individually assigned to some transmitting nodes of this group during each RAW. The same group of nodes dispute access to the medium through the same RAW assigned to them and, therefore, is a shared resource. Information such as the number of slots, the duration of each slot and the start time of each RAW is served by the RAW Parameter Set (RPS). The RAW technique prevents transmissions between hidden nodes from overlapping, by limiting the time that a station uses when competing for the transmission medium.

When a station needs to transmit, it must first detect and receive a complete and correct frame. Detection and identification of this frame causes the station to wait for the transmission window in order to avoid transmission collision. When attempting to access the medium, if the station does not receive a frame or is unable to identify the received frame, it must wait for a time interval called *ProbeDelay* to make another attempt to access the medium. The disadvantage of this procedure is to generate a medium access delay, which is reduced with the aid of the AP and its medium access control modes [91]. At the beginning of each RAW slot, the AP transmits a SYNC frame. The AP can detect the availability of the medium and initiate its transmission, after the end of the reception of the SYNC frame, not having to wait for the *ProbeDelay* timeout. Using the SYNC frame can reduce battery consumption by up to 30% [91].

Another improvement brought by IEEE 802.11ah is in regard to the power consumption and latency control. They are caused by the traffic indication map (TIM) based communication process, used in the downlink transmission demand detection mechanism. This method works detecting the demand of downlink communication through to TIM transmitted in the beacon by the AP. Thus, there is also a need for the node to respond to the AP with a PS-Poll frame. This procedure is eliminated by adopting a predefined schedule of the future wake-up time. With the data stored in the buffer, ready to be transmitted, the AP transmits the data to that node in its predefined window, thus saving energy that the node would expend by mapping the TIM, negotiating access to the medium, and receiving data from the AP.

One more characteristic that deserves to be highlighted is the use of PHY preamble fields is to indicate the continuity of the channel utilization. It is used to minimize collisions and to adopt the use of the bidirectional transient capacity (BDT). In addition, the adoption of the short inter frame space (SIFS) between uplink and downlink communications within the same transmission opportunity (TXOP) to improve medium access. These features also contribute to energy saving. Another improvement brought in favor of energy saving is scaling the value of the Max Idle Period field. This field defines the terminal sleep time. In this way, the terminal is able to go into a sleep mode for more than five years.

Reduction of processing, reduction of overhead in addition to reduction and optimization of access to the medium also drives the evolution of IEEE 802.11 PHY and MAC layers. In the PHY layer, the transmission recognition system that uses the acknowledgment (ACK) package has been optimized by reducing the ACK packet itself to the minimum necessary and also by creating the null data packet (NDP) carrying MAC. To keep the QoS parameters, the use of a new frame format dedicated to QoS called the Short QoS Data Frame. Its header was reduced to 12 bytes compared to the 30 bytes of the QoS data frame of IEEE 802.11n. In order to increase the number of stations up to a maximum of 8191, four encoding modes were defined in IEEE 802.11ah. They allow IEEE 802.11ah to compress the traffic indication virtual bitmap, used to signaling the association identifier of a station. A comparison of the IEEE 802.11 standards described is present in Figure 2.15.

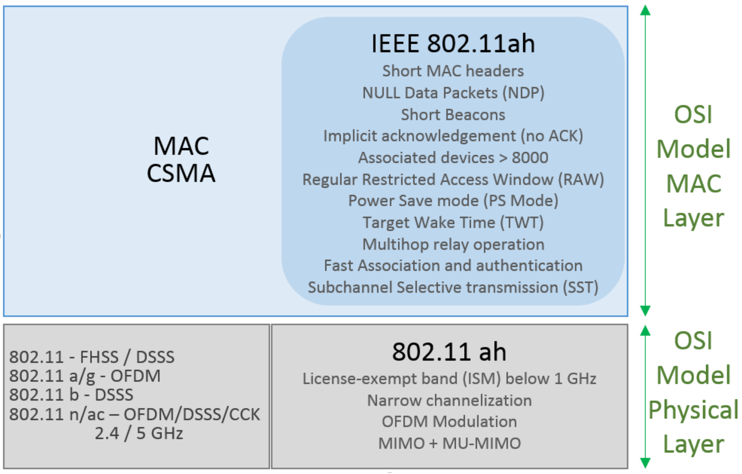


FIGURE 2.15: IEEE 802.11 standards.

Separating the stations in different types, with different procedures, common channel access time periods and other characteristics was added to the MAC protocol. These characteristics permits up to 8191 connected end devices already considering the collision issues among them. Although there is a need to maintain connection and synchronization with the APs, the IEEE 802.11ah terminals are equipped with mechanisms that provide energy saving during the period of inactivity. This ensures that the IEEE 802.11ah features long range and low power consumption when compared to other WLAN technologies, but remaining different from LP-WANs [92]. Using proper antennas and its features, the protocol can also be used in fixed point-to-point arrays typically in ranges of more than 1 km whenever there is line of sight (LOS). IEEE 802.11ah is also used for point-to-point communications or back-haul transport systems.

2.2 Long Range MAC Layer Protocols

Based on their own requirements such as rate, distance coverage, robustness, etc., the existing network protocols need some adaptation to meet the necessary requirements to attend IoT services. In some cases, some protocols were developed to meet IoT applications that demand far-reaching, reliable and robust transmission. Some of the protocols classified as protocols for LP-WANs are able to satisfy the demand for protocols with a large coverage area. LP-WANS protocols can overcome some mobile cellular network failures increasing strong adaptations to meet the IoT requirements.

LP-WAN are presented as good candidates to support several of the previously mentioned requirements of the IoT structure, and are able to surpass the short-range restriction of the LANs [22]. Among the possible solutions are the proprietary and unlicensed ISM band technologies Sigfox, LoRa/LoRaWAN, against mobile cellular network solutions such as Long Term Evolution - Advanced (LTE-A) and Narrow Band IoT (NB-IoT). Mobile cellular network technologies, with licensed spectrum or not, can satisfy energy and latency requirements, and it is better to use existing infrastructure [93, 94, 95].

Communication challenges and the broad set of specifications of M2M communication were added to LTE-based protocols. The development of MTC (Machine Type Communication) resources in the context of LTE (Long Term Evolution) were started in version 10, or Release 10 (R10), of the LTE-A standard [96]. During the development of M2M communication, the 3rd Generation Partnership Project (3GPP) committee defined a new profile, called CAT-0, or Category 0, for the operation of the MTC of low-power WAN (Wide Area Network) networks [97]. In release 13 (R13) from 2016, two special categories CAT-M for MTC and CAT-N for Narrowband-IoT (NB-IoT). These categories was included to support the characteristics of M2M communication and IoT technology, respectively [19]. Such categories will be better addressed in the document. In the literature, it is possible to find references to the CAT-N standard as NB-IoT and the CAT-M standard as LTE eMTC, LTE-M2M, LTE-M and CAT-M1. In this document, the notation LTE eMTC and NB-IoT will be used.

2.2.1 NB-IoT

According to the LTE eMTC regional specifications, it can operate only within the bandwidth of an LTE carrier. NB-IoT systems can be implemented as autonomous systems in the Global System for Mobile Communications (GSM) band, employed in the LTE bandwidth carrier or in the LTE bandwidth guard band. Due to the reduction of the NB-IoT bandwidth to 180 kHz, low data rate devices can have extended coverage, complexity reduction, and low power consumption. For scenarios with coverage problems of cellular network operators, NB-IoT is seen as the future of IoT devices using mobile network infrastructure [98].

With the pressure of the growing IoT connectivity, the 3rd Generation Partnership Project Agreement (3GPP) launched the project called CAT-N. This project presents a set of categories that offer different air interfaces specifically dedicated to low-power systems. These categories also include different characteristics of MIMO radiating system usage and different values of uplink and downlink data rates by exploiting the available GSM spectrum [99].

The NB-IoT covers all important components for communication in the M2M/IoT systems: low complexity, low power consumption, and long range. Some key features of the standard include a 180 kHz bandwidth and uplink and downlink transmission rates of about 250 Kbps with a half-duplex operation. However, even being a new radio interface, NB-IoT implementations can be made in the band of existing LTE carriers. In addition to this mode of operation, the NB-IoT also supports the guard band mode of operation of an LTE carrier. These two modes of operation are shown in Figure 2.16. It is important to differentiate NB-IoT from LTE eMTC, which refers to the use of LTE evolution for use of MTC and IoT [100].

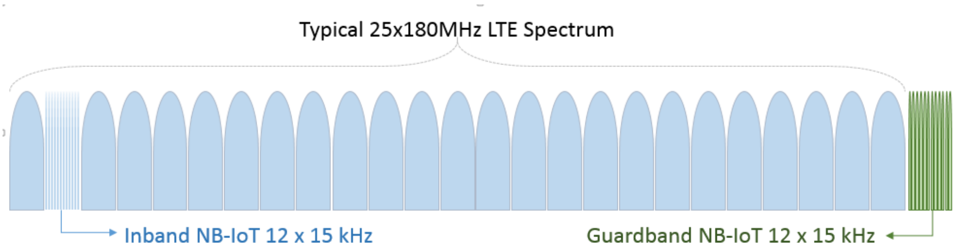


FIGURE 2.16: NB-IoT operation bands.

The third mode of operation of NB-IoT, which can be seen in Figure 2.17, is the deployment of NB-IoT using GSM carrier bands of the spectrum that has been assigned to legacy GSM cellular services [100].

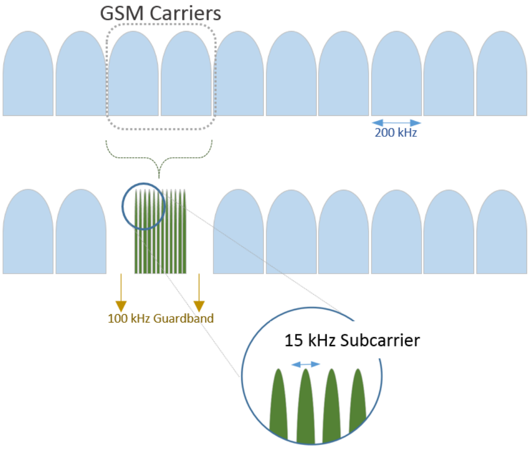


FIGURE 2.17: NB-IoT operation bands.

In the downlink, NB-IoT uses Long Term Evolution Orthogonal Frequency Division Multiple Access (LTE/OFDMA) structures with spacing between sub-carriers of 15 kHz, while the uplink is able to use SC-FDMA with sub-carrier spacing at 3.75 kHz [101].

For the 3.75 kHz spacing between sub-carriers, the frame structure shows little differences from the structure defined for the LTE standard. Each LTE frame slot becomes 2 ms, the frame NB-IoT is then composed of five slots, totaling a period of 10 ms. The NB-IoT technology features a maximum coupling loss extended to 20 dB over the 140 dB LTE. It is achieved through an increase in the number of time repetitions and ($\pi/2$)-BPSK single subcarrier transmission, providing a coverage radius for NB-IoT of about 15 km [100]. The NB-IoT contains the following physical signal and channel resources as shown in Figure 2.18:

- Narrowband Primary Synchronization Signal (NPSS),
- Narrowband Secondary Synchronization Signal (NSSS),
- Narrowband Physical Broadcast Channel (NPBCH),

- Narrowband Reference Signal (NRS),
- Narrowband Physical Downlink Control Channel (NPDCCH),
- Narrowband Physical Downlink Shared Channel (NPDSCH).

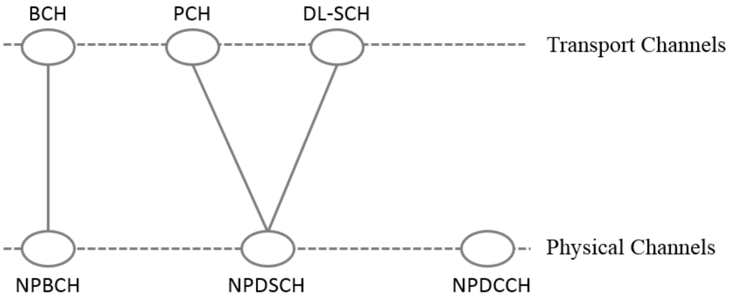
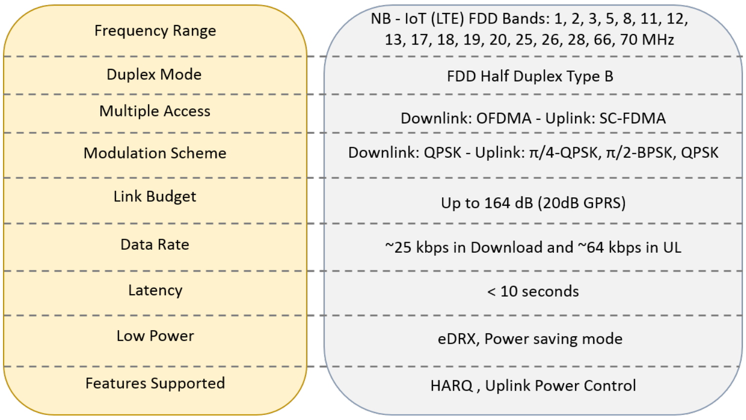


FIGURE 2.18: NB-IoT operation bands.

These channels and physical layer control signals in the NB-IoT are time multiplexed. Sub frames of the frame structure presented for the NB-IoT, are provided for different channels and physical signals. Each NB-IoT sub frame comprises a resource block in the frequency domain and 1ms in the time domain. The NPSS and NSSS signals are used to perform time and frequency synchronization as well as cell detection. An NRS signal is used to provide phase reference in the demodulation of downlink channels. The NB-IoT supports up to two NRS ports [102]. The NPBCH channel, transmitted in each sub frame 0 of the frame, loads the main information block, called the Master Information Block (MIB). The NPDCCH carries scheduling information for downlink and uplink data channels, in addition to the HARQ (Hybrid Automatic Repeat Request) confirmation information for the uplink data channel [103]. The NPDSCH channel carries higher layer data as well as paging message, system information and random access response message.

In uplink, the NB-IoT includes two physical channels that are described as (i) Narrowband Physical Random Access Channel (NPRACH) and (ii) Narrowband Physical Uplink Shared Channel (NPUSCH). NPRACH is a newly designed random access channel substituting the legacy LACH random access channel and uses a bandwidth of 1.08 MHz. It is more than the uplink bandwidth for the NB-IoT. The NPUSCH channel has two formats. The first is used to load uplink data and has a maximum block size of 1000 bits [104], which is much smaller than the LTE legacy. The second format is used to signal Hybrid Automatic Repeat reQuest (HARQ) recognition for the NPDSCH, and uses a repeat code for error correction.

NB-IoT reduces extreme simplicity for delay-tolerant applications such as meters, devices and sensors, providing wider coverage [105]. Common IoT solutions require low cost, high network device density and low data transfer. The NB-IoT technology aims, through LTE optimization, to meet this demand (more than 50 thousand devices) with low data rates in delay-tolerant applications. Figure 2.19 consolidate key parameters of NB-IoT.



Frequency Range	NB - IoT (LTE) FDD Bands: 1, 2, 3, 5, 8, 11, 12, 13, 17, 18, 19, 20, 25, 26, 28, 66, 70 MHz
Duplex Mode	FDD Half Duplex Type B
Multiple Access	Downlink: OFDMA - Uplink: SC-FDMA
Modulation Scheme	Downlink: QPSK - Uplink: π/4-QPSK, π/2-BPSK, QPSK
Link Budget	Up to 164 dB (20dB GPRS)
Data Rate	~25 kbps in Download and ~64 kbps in UL
Latency	< 10 seconds
Low Power	eDRX, Power saving mode
Features Supported	HARQ , Uplink Power Control

FIGURE 2.19: NB-IoT key parameters.

2.2.2 LTE - Long Term Evolution

Long Term Evolution enhanced Machine-Type Communication (LTE eMTC) standards-based technologies support CAT-0 and CAT-M modes. While LPWAN LTE CAT-0 is commonly used to implement M2M/IoT, CAT-M reduces complexity keeping the coverage aspect using existing mobile cellular network infrastructure [106, 107]. LTE eMTC counts on the same mobile technology benefits as security, privacy, data reliability and device identification [108].

With the applications involving the communication information generated by the human-to-human (H2H) services, the transmission data rate in the cellular networks increased considerably in the last decade. However, the traffic generated by M2M communication has different characteristics from those generated by H2H services in actual mobile technologies. M2M devices send more traffic than receive traffic when compared to H2H devices. For example, (H2H) service traffic has specific concentration characteristics at certain times of the day, while M2M traffic may present a uniform characteristic. In applications, such as measuring, M2M traffic tends to be periodic and mobility is short when compared to (H2H) communication devices. Thus, service quality requirements between M2M and H2M may be very different [109, 110].

3GPP offered the appropriateness of LTE to permit MAC connection and PHY links through LTE networks and to optimize the technologies and mechanisms related to radio access. It provides LTE networks updates do deal with MTC and IoT requirements as follows:

- CAT-0, version 12 (R12): Since Category 1 (CAT-1) has low transmission capacity, a new category has become necessary to support the new challenges of MTC and IoT. The Category 0, or CAT-0 of R12 have lower hardware complexity when compared to CAT-1 [111].
- CAT-M, version 13 (R13): With the objective of new complexity reduction techniques, CAT-M was proposed in R13[20].

- CAT-N, version 13 (R13): As major IoT devices, or MTCs, typically deal with long distance coverage to transmit few data bytes, CAT-N has been incorporated into the LTE specifications to support the required functionality. The main objectives of CAT-N is to improve distance coverage reducing its complexity and, as a consequence, a greater battery life cycle [99].

In order to fulfill the prerequisites necessary for LTE networks to be able to attend MTC services, 3GPP worked on the R12 to minimize power consumption and cost with new data traffic profile, hardware simplification and spectrum adjustments. LTE OFDMA modulation and SC-FDMA coding is maintained. 3GPP LTE Release 13 is being studied for IoT applications due to the fact that it uses a lower transmission bandwidth than the LTE terminals of previous releases. Release 13 works with freedom of spectrum occupancy within the LTE carrier using only 1.4 MHz of the 20 MHz available LTE carriers. A 15 dB link budget enhancement can guarantee longer distance coverage and better obstacle penetration factor [20, 99, 112, 113, 114]. LTE eMTC technology presents the same layers observed in the LTE protocol stack, shown in Figure 2.20. Briefly, the layers can be described as follows [100]:

- Non-Access Stratum (NAS): Works between Device and Network Core and is used for control, authentication and mobility management purposes.
- Radio Resource Control (RRC): In an eNodeB base station, this layer takes handover decisions, sends broadcast messages containing system information and controls the measurements of the device (UE) parameters.
- Packet Data Control Protocol (PDCP): Responsible for the compression and decompression of the user IP packet headers. It also performs data encryption, both on the user data plane and on the control plane data plane.
- Radio Link Control (RLC): Used to format and transport data between the Device and eNodeB base station, transfer upper layer Protocol Data Units (PDUs), error correction, concatenation, segmentation, and reassembly of Service Data Unit (SDUs).
- MAC: It performs physical transport channel mapping.
- Physical Layer: This layer carries all the information from the transport channels through the air interface.

With LTE-RACH fixed on the 1.08 MHz bandwidth, it is convenient to use LTE-eMTC channelization in multiples of its value, allowing compatibility with previous versions. The sub-frame structure of the LTE eMTC is the same as the LTE standard. From a frequency plane perspective, the 180 kHz bandwidth of a resource block is divided into 12 sub-carriers, each of them with 15 kHz bandwidth [115, 116].

In terms of coverage, the LTE eMTC's have a 155 dB link budget is achieved with the addition of 15 dB in channel prediction and resource tuning processes, enabling coverage of up to 11 km. These characteristics allow the LTE eMTC to have satisfactory communication even in conditions of excessive losses but transmission rates are affected [117].

In the downlink, the sub-frame structure of the LTE eMTC uses only a part of the LTE framework legacy. As LTE eMTC devices can be implemented with a narrow bandwidth, it is not possible to use the LTE control channels. Thus, it is necessary to create a MTC Physical Downlink Control Channel (MTC-PDSCH) and Physical Downlink Shared Channel (PDSCH) using LTE data channels. PDSCH transports higher data layers, segmented according to the transmission resources available.

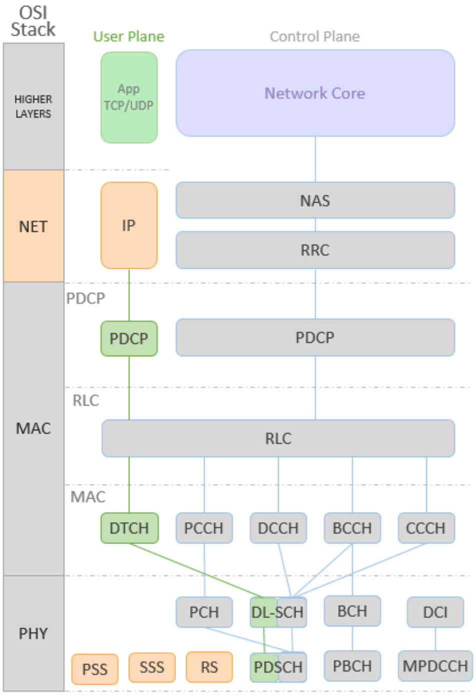


FIGURE 2.20: LTE-eMTC downlink layers.

The LTE eMTC devices depend on the NPSS and NSSS of the LTE standard for the acquisition of the carrier frequency of a cell and frame time usage. LTE signals can be used unchanged by LTE eMTC devices even under challenging coverage conditions. To improve reception performance, LTE eMTC devices can accumulate data received in buffer. This happens because the NPSS and NSSS signals are transmitted periodically. In order to discover the communication channel characteristics, the NRS signal is used to give estimates of channel behavior. This signal, which has a known pattern, is transmitted by the base station and performs downlink quality measurements [118, 102] .

For uplink data transmission, there is only one Physical Uplink Control Channel (PUCCH) that carries information such as scheduling requests, channel quality information, and transmission confirmations. The channel used by the user equipment to transmit data in uplink is the Physical Uplink Shared Channel (PUSH). Some sub-carriers can be used to assign resources to the user and are not used by the PUCCH or Physical Random Access Channel (PRACH) signals. To initiate the connection between the terminal and the base station and estimate the arrival time of the uplink message, the PRACH channel is used [116]. Figure 2.21 illustrates the LTE eMTC uplink channels.

Power consumption on IoT devices consists of standby and active power consumption (Idle and Connected modes, respectively). The power consumption of standby mode depends on the design and technology used, and essentially should not differ between LTE MTC and NB-IoT (both technologies have a battery life of approximately 10 years). Active energy consumption differs between these two technologies. Operating on active power consumption for downlink transmission, LTE eMTC has substantially higher throughput (both bandwidth and higher order modulation) than NB-IoT. As a result, it is possible to obtain an estimated active energy consumption 50% lower than the NB-IoT [101].

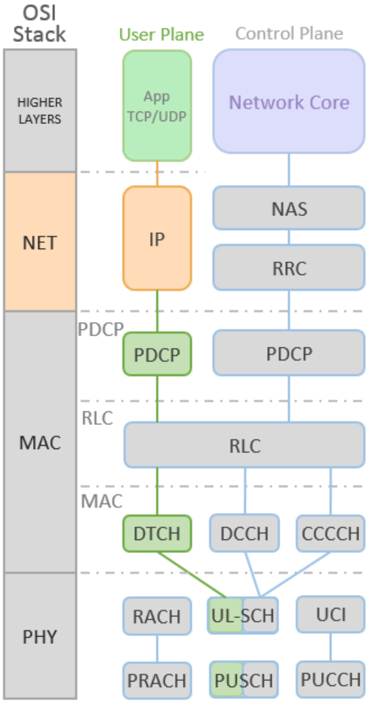


FIGURE 2.21: LTE eMTC uplink channels.

2.2.3 LoRa - Long Range Protocol

LoRa defines a physical layer technology developed by Cycleo in 2010, a company that was acquired by Semtech from Camarillo, United States of America. The LoRa module manufacturer offers the user a programmed library that allows communication between LoRa nodes, providing a simple link protocol [119]. Libelium, a company based in Zaragoza, Spain provides the tools and libraries needed to operate with LoRa [120]. The LoRa protocol is an open standard defining physical layer to use direct sequence spread spectrum (DSSS) with multiple spreading factors that range from 7 to 12. This combination allows the establishment of a relationship between distance coverage and the desired data rate. This technique in sub-GHz ISM band enables robust communication with a low power consumption for long distances. By using Frequency Shift Key (FSK) modulation with the optional use of forward error correction (FEC), LoRa allows demodulation of the signal even when the signal level is below the noise level. LoRa also counts on use of a frequency modulated (FM) chirp, based on a spread spectrum modulation with a chirp spread spectrum (CSS) variation. Thus, LoRa modulates data in different channels and speeds them, with a forward integrated error correction (FEC). Thus, it is possible to increase the coverage range while maintaining the low energy consumption characteristics offered by the FSK modulation. The usage of coding gain significantly improves receiver sensitivity and uses the full bandwidth spectra to transmit a signal. Then, it is more robust to channel noise and independent from the frequency compensations caused by low cost crystals. LoRa techniques assure signal demodulation lower than -50 dB SNR against 8 to 10 dB necessary for FSK demodulation of signals in different ISM bands. The frequency band used in Europe is the ISM band of 863–870 MHz regulated by European Telecommunications Standards Institute (ETSI). It uses 8 arbitrarily chosen channels, according to the current UN-111 in Spanish BOE-A-2013-4845 [121], with a bandwidth of 0.3 MHz per channel. For the ISM 902-928 MHz FCC regulation, LoRa works with 2.16 MHz per each one of the 13 channels.

To address the low-cost, low-power and robustness issues, LoRa Modulation counts on some key properties. Easy scalability of the LoRa modulation involves frequency and bandwidth domains, thus allowing its use in wide band direct sequence and narrow-band frequency hopping systems. This adaption can be done by programming the device to work according to its needs. The low-cost and low-power high efficiency can be achieved with a constant modulation scheme and the great link budget obtained using the processing gain, thus reducing the transmitted power. The asynchronous nature and high bandwidth used makes the LoRa signal more resistant to interference mechanisms, whether they are in-band or out-of-band inferences.

LoRa modulation presents better immunity, mainly to pulsed AM (Amplitude Modulated) interference, compared with FSK modulation systems. This is due to the period duration of the LoRa modulation is longer than the short duration typical bursts of FHSS systems. The effects of fading and multipath, common in urban and suburban areas, are faced with wide spreading of the chirps in the spectrum. The usage of Chirp Spread Spectrum (CSS) modulation, allows the system to be more resistant to these effects. The Doppler effect, when present, influences the quality of demodulated signals in applications. However, the CSS modulation shows small sensitivity to the Doppler effect due to the low frequency variation generated by it. This characteristic can be suitable for applications where the monitored targets have mobility support. With robustness against spectrum interference and unaware of fading and multipath effects, LoRa exceeds the link budget of conventional FSK systems and can increase up to four times the range, when compared to FSK systems. This is considering fixed transmission power and throughput. Like in reception, the transmission counts on the LoRa modulation characteristic to transmit or receive multiple signals, along the same channel. This is due to the advantage of the orthogonal spreading factor, with a low level of degradation. Localization services or other real-time applications such as ranging are easily handled by LoRa Modulation due to the capacity to discriminate linearly errors due to frequency or time shift effects [122].

The applications can make use of many possible data rates, payload sizes, and bandwidths according to its needs. Another level of diversity is obtained with the use of 125 kHz or 250 kHz according to the spreading factor used. The spectral scattering factor used influences both the final range obtained and the final acquired data rate. The higher the spectral scattering, the greater the maximum range obtained. In contrast, the data rate obtained will be lower. One base station can handle more than 700 end devices (EDs) depending on the conditions. To satisfy the network responsiveness capability, LoRa scheduling methods, and the frequency hopping method used have to assume that the RF channel conditions will not vary during a certain period of time. LoRaWAN is a network specification proposed by the LoRa Alliance that offers a MAC layer based on the LoRa modulation PHY layer. In order to meet the optimization characteristics of the data transmission rate, transmission resource utilization and energy usage, LoRaWAN MAC technology controls the transmission resources. These resources are the bandwidth to be occupied, the spread spectrum factor to be used, and which the transmission power of each node. This combination of features results in the Adaptive Data Rate (ADR) feature [123, 124]. The three classes of devices specified are the following:

- Class A: The node can initiate the communication and only transmits to the gateway when necessary. To receive messages from the gateway, the node opens a receive window after each transmission.
- Class B: Beacons are used to synchronize nodes with the gateway through the insertions of received windows after its transmission.
- Class C: except when transmitting, the node stays in the listening mode ready for reception [125, 126]. This class is a limitation for battery powered systems [127].

The communication distance and the message transmission duration time define the data transmission rate reached. Thus, different rates of data transmission are due to the spreading the nodes transmission through different channels. ISM 863–870 MHz and 902-928 MHz bands typically operate with 125, 250, and 500 bandwidths (BW). The final data rate is obtained according to the SF and BW chosen. For BW = 7.8 kHz and SF = 12 it is possible to transmit at 22 bps and for BW = 500 kHz and SF = 7, it is possible to transmit up to 27 Kbps. Frequency hopping is also combined to improve external interference mitigation [79]. Figure 2.22 presents a representation of LoRa and LoRaWAN protocol stacks.

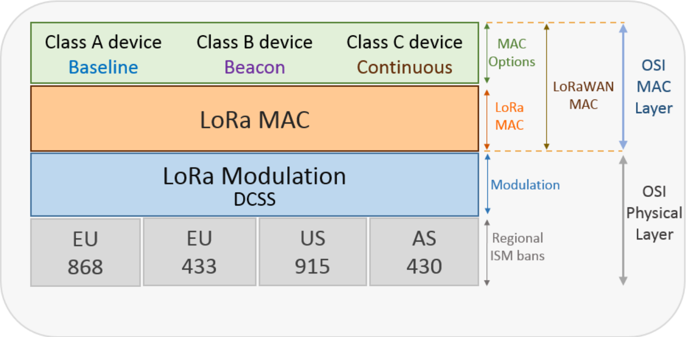


FIGURE 2.22: LoRa and LoRaWAN protocol stack.

The LoRaWAN scalability is a major advantage since it can reach up to millions of devices depending on some factors. Among these factors are: the scenario, the average message transaction rate, the average size of the transmitted message, the number of LoRa channels used, and the number of GFSK channels used [124].

2.2.4 SigFox

SigFox is a technology that brings a new network and information strategy to IoT. Named by its developer, a group from Labège, France with the same name, SigFox is an IoT player with a network operator business model. Used by applications that require low data rates, SigFox is also classified as a Low Throughput Network (LTN) protocol, as defined by ETSI ERM TG28. Based on an Ultra Narrow Band (UNB) technology, Sigfox uses a 100 Hz transmission band in ETSI and ARIB (Japanese regulatory body Association of Radio Industries and Businesses) regions and a 600 Hz transmission band in FCC (Americas and Oceania) regions. This characteristic allows a data rate of 100 bps and 600 bps at ETSI and FCC regions, respectively [128, 129].

SigFox protocol stack is composed of three main layers: Frame, MAC and Physical layers. Figure 2.23 depicts the comparison between SigFox and the OSI reference model. Sigfox operates on the Sub-GHz ISM band carrier using 863–870 MHz in ETSI and ARIB (Europe and Japan) and 902–928 MHz in FCC (Americas and Oceania). The bit rate depends on the bandwidth of each region. In ETSI and ARIB, the bandwidth used for the transmission is 100 Hz so, in this case, the bit rate is 100 bps. In the FCC regions, the 600 Hz transmission bandwidth occupancy permits a 600 bps transmission data rate [125].

The regulations in the FCC, ETSI, and ARIB regions determine the permitted transmission power in each case. In the ETSI regions, the maximum power transmission is 14 dBm per device for a maximum of two seconds of emission time, and a total of 140 messages per day. Sigfox Base Transmission Station (BTS) can transmit up to 26 dBm at a maximum. The regulations in the FCC region (Latin and Americas, United States of America and Asia) defines that each device can transmit up to 22 dBm with a maximum time transmission of 0.346 seconds, and a total of 140 messages per day. The FCC regulated BTSs can transmit up to 30 dbm. To overcome challenges with interference from the transmission medium, as well as transmission collisions that are inherent in the process, diversity comes as an efficient tool. Since there is no need to synchronize the network elements, devices can use an initial random frequency for transmission and then send two replicas randomly at different frequencies and at random time-slots. This simultaneous time and frequency diversity mechanism increases the robustness against interferences while increasing reception efficiency.

Different from mobile cellular systems, a Sigfox terminal is not attached to a single base station. With proper deployment, the message sent by a Sigfox terminal can be received by several base stations. This feature is called spatial diversity that, coupled with the time and frequency diversity of repetitions, are strong points in Sigfox protocol conception technology.

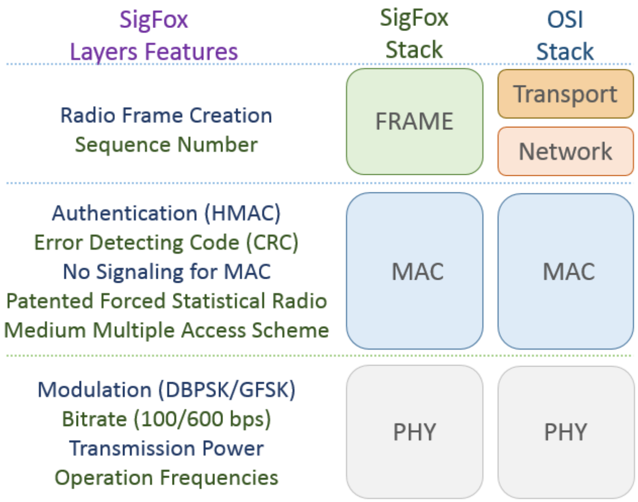


FIGURE 2.23: Sigfox protocol stack.

SigFox systems use D-BPSK (Differential Binary Phase Shift Keying) modulation to uplink and GFSK (Gaussian frequency shift keying) modulation to downlink. D-BPSK transmits at 1 bps using only 1 Hz of the operational band, which means that one single signal uses only a small part of the operational band, and therefoe brings higher efficiency in the spectrum medium access. Applications that demand low transmission data rates, with lower cost devices, high availability, and easy implementation coupled with the advantages of high link-budget, drive the use of D-BPSK modulation. Its physical layer employs a proprietary frequency hopping and frame repetition pattern to avoid interference of signals and it is responsible to determine how SigFox signals will be transmitted. The physical layer handles the modulation used, the bit rate and transmission power control, as well as the radio resource occupation.

UNB technology is identified by using a legacy Aloha protocol-based medium access technique called Random Frequency and Time Division Multiple Access (RFTDMA). This medium access technique has no medium access collision control method, thus allowing the terminals to access the medium at any instant of time, at any frequency (within the operating band), without any prior perception of medium occupancy [123]. The RFTDMA technique favors the low power consumption because it does not use energy to sense the medium before transmitting. It does not use any type of synchronization package or beacon technique, which also favors the cost of the terminals due to no need for expensive oscillator circuits. Another feature is that in RFTDMA the transmission frequencies are chosen randomly but within a continuous interval. A disadvantage that can be cited is the probability of colliding terminal packets that are transmitted simultaneously.

The Medium Access Control layer header adds field for device identification and error detecting codes. Sigfox devices are not synchronized with the network and can transmit anytime because Sigfox removed medium access control from its conception. The purpose of the frame layer is to receive the payload coming from the application layer; then, do the segmentation and deliver the fragments to the MAC layer. The MAC layer can identify and order the generation of the radio frames with a sequence number included. As usual on UNB systems, each transmission occupies a simple 100 Hz or 200 Hz bandwidth of available spectrum permitting high capacity for the SigFox network. High resilience is obtained as the SigFox signal power is squeezed into a narrow bandwidth supporting better behavior regarding interference. The energy concentration of the SigFox signal enables base stations to demodulate it easily, even if more powerful and spread interference signals are received simultaneously [93].

Depending on global regions, the transmission power varies from 14 dBm (ETSI) up to 22 dBm (FCC). UNB brings long range features thanks to D-BPSK modulation plus the low bit rate transmission performed by SigFox. This results in a highly sensitive base station receiver. The sensitivity of the base station receiver changes depending on the transmission bit rates of the devices. Sensitivity operates around -142 dBm for 100 bps and -134 dBm for 600 bps transmission rates. Such sensitivity offers a very large link budget. The transmission range achieved is defined by the channel conditions, interference, and the received noise level. With a high coupled irradiating system, the device can transmit up to 16.15 dBm EIRP (Effective Isotropic Radiated Power) with a 5.15 dBi antenna gain at the base station. With this combination, the receiver sensitivity has a link budget from -142 dBm up to 163.3 dBm. For transmission at 600 bps, the base station receiver sensitivity is 8 dB lower due the high transmission rate. However, it is compensated with 24.15 dBm EIRP devices transmission power. The typical sensitivity of the device considered as a receiver is -126 dBm. Devices are free to transmit on any operational band carrier and the base stations are ready to receive from all carriers anytime, permitting devices to work with low frequency accuracy [130].

SigFox has tailored a lightweight protocol to handle small messages. When dealing with short message transmissions, conventional protocols are not suitable due the overhead imposed by their design. Sigfox works with 26-byte packets carrying 12-byte data payloads. This gives Sigfox high transmission efficiency when compared to its useful data transmitted, against 20 bytes of ethernet header to carry the same 12 bytes plus 52 complementing bits. The payload data that can be put in a SigFox message rages from zero bits to 12 bytes composing a maximum packet size of 26 bytes. With a light protocol frame size, each transmission has less data to send, less energy is used and so the battery life increases. The uplink modulation is D-BPSK, the bit rate can be 100 bps or 600 bps according to the regional rules and the transmission power can go up to 22 dBm EIRP at radio configuration zone number two (RCZ2).

The topology followed by Sigfox is simple. It follows a star topology approach around the world. Objects transmit their messages to a SigFox base station. Point to point links connect a Sigfox base station to its Internet database and so, after receiving and decoding the message, data are sent to its internet database. Finally, SigFox cloud backend pushes the messages to the customer servers and IT platforms through APIs (Application Programming Interface).

Downlink communication procedure is triggered by the network node and therefore cannot be transmitted to the device at any time. Devices open their reception widow after a transmission, in order to receive the downlink packets. When the device needs to receive a downlink message, a flag is set in the uplink message requesting the sending of a downlink message. Only after this flag is sent will the device be ready to receive its downlink message during the interval of a time window that is set for receiving downlink messages. This procedure characterizes the sending of a downlink message to a specific device. To receive the broadcast messages, the nodes have a default time window for waiting to receive broadcast messages. This receiving window opens after the transmission of every uplink message. This procedure reduces the power consumption without communication requests, which exempts the use of network communication control. This makes the protocol simpler and allows greater network capacity. Without the need for traffic signaling and control in the MAC layer, the nodes are free to transmit at any time by simply going out of the sleep mode, transmitting and returning to the sleep mode. The transmission is then repeated two more consecutive times in random carriers in order to avoid collisions increasing capacity and scalability. Other aspects that contribute to the low power consumption are the fact that the message payload has only 12 bytes prolonging the life of the batteries of the element, reducing the cost of the nodes, and the low number of transmission per day. The modulation technique combined with a few hundred Hertz occupying its operational frequency band leads to high spectral efficiency. The small bandwidth used in the frequency spectrum available also contributes to the high capacity of the system. Due to its high reception sensitivity at the gateway and ability to transmit with a considerable level of power, Sigfox technology reaches a high link-budget. It is also possible to improve its performance adjusting its irradiating system [126, 93].

2.3 Discussion and Open Issues

A comparison of the performance of the available MAC layer protocols is made here considering both groups, defined according to their range coverage (short and long range). Then, based on this discussion, open research issues are identified.

2.3.1 Comparison Analysis of Short Range Coverage Protocols

This study demonstrated the diversity of patterns in the MAC layer of short range protocols, regarding their application characteristics. RFID and NFC technologies do not have many features in common although both were developed for short-range communications. For example, applications for identification and tracking uses RFID more commonly while NFC has been popularized among smartphones for exchanging media content and e-business devices for payment machines. There is a constant evolution of these technologies, adapting to new demands. Retaining miniaturization, energy consumption, and transmission efficiency characteristics.

Different features sometimes prevent a direct protocol comparison due to strong differences in the design and construction of their PHY and MAC layers. However, the PHY layer of the standard IEEE 802.15.4 is used as a base for many other short range protocols. In addition, protocols that present different solutions do not compensate the drawbacks of the IEEE 802.15.4, but rather they meet the requirements of the different applications. The comparison between BLE and IEEE 802.15.4 elucidates the lower power consumption of BLE against IEEE 802.15.4. Regarding throughput and energy efficiency, IEEE 802.11a indicates some advantages over IEEE 802.15.4. Using the PHY layer of IEEE 802.15.4

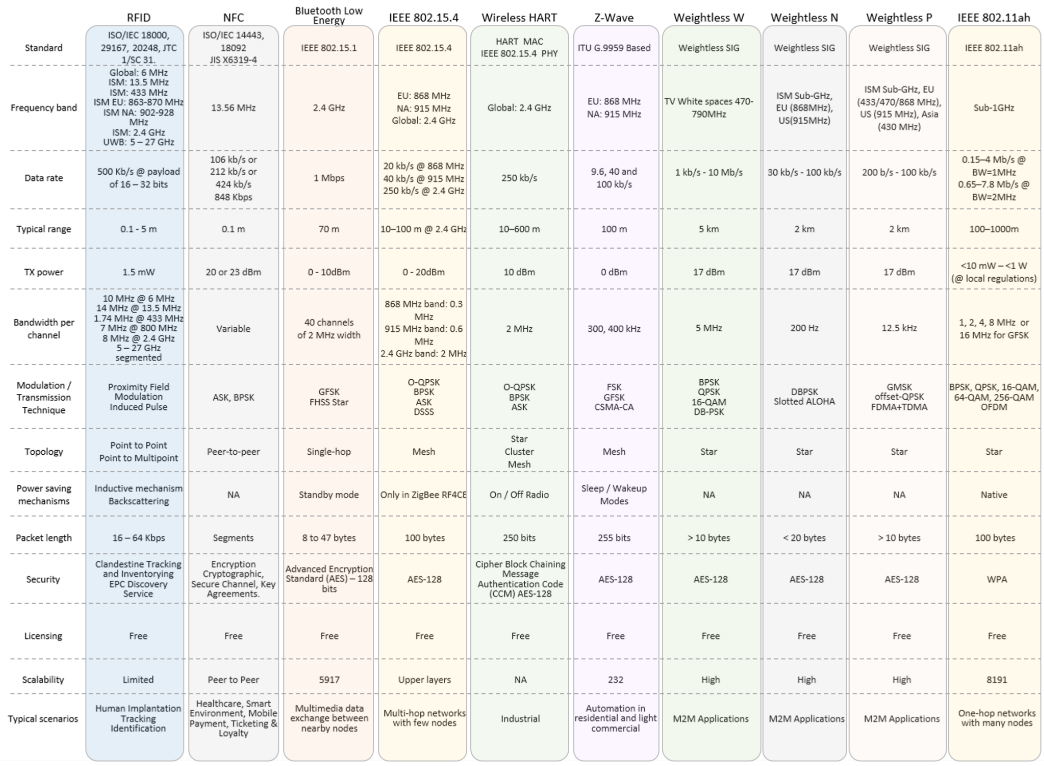
protocol, the Wireless-HART protocol implements different facilities in its MAC layer such as TDMA as the medium access technique and frequency hopping that increases its capacity [131, 132].

The Z-Wave protocol presents the PHY and MAC layers with a different combination. Its MAC layer, standardized by ITU G.9959, presents the CSMA-CA inheritance middle access technique, security mechanisms, medium access optimization (such as backoff time, frame validation, and topology flexibility). These features allow high data rate performance with the range that the sub-GHz ISM band can provide.

Operating in the range of TVWS (470–790 MHz), the Weightless protocol needs to compensate the transmission bandwidth affected by spectral pollution. It does this by using complex modulation techniques such as Phase Shift Keying derivations and quadrature amplitude modulation options. Its transmission performance is also reinforced by the joint use of multiple access mechanisms such as the FHMA and TDD medium.

The different variations of the IEEE 802.11 protocol have been following the demands for wireless communications. The massive use of its variations that have evolved is a consequence of the demand for H2H services that require high transmission rates, with very dense networks. The IEEE 802.11ah variant has come to improve the performance and robustness of data communication. It is due to various mechanisms implemented in the MAC layer, such as Short MAC headers, short beacons, power saving mode, regular restricted access window, among others. In addition, it contributes to good transmission range performance, a reduction of channel usage compared to the previous IEEE 802.11 standards and new techniques for multiple antenna features.

The differences between applications and technical characteristics makes it difficult to compare short distance coverage protocols (Bluetooth, Bluetooth Low Energy, IEEE 802.11ah and IEEE 802.15.4) with long distance coverage protocols. Then, the next subsection discusses the IoT long range protocols. Figure 2.24 presents a comparison of short range protocols studied in this survey.



	RFID	NFC	Bluetooth Low Energy	IEEE 802.15.4	Wireless HART	Z-Wave	Weightless W	Weightless N	Weightless P	IEEE 802.11ah
Standard	ISO/IEC 18000, 29167, 20248, JTC 1/SC 31.	ISO/IEC 14443, 18092 JIS X6319-4	IEEE 802.15.1	IEEE 802.15.4	HART MAC IEEE 802.15.4 PHY	ITU G.9959 Based	Weightless SIG	Weightless SIG	Weightless SIG	IEEE 802.11ah
Frequency band	Global: 6 MHz ISM: 13.5 MHz ISM: 433 MHz ISM EU: 863-870 MHz ISM NA: 902-928 MHz ISM: 2.4 GHz UWB: 5 – 27 GHz	13.56 MHz	2.4 GHz	EU: 868 MHz NA: 915 MHz Global: 2.4 GHz	Global: 2.4 GHz	EU: 868 MHz NA: 915 MHz	TV White spaces 470-790MHz	ISM Sub-GHz, EU (868MHz), US(915MHz)	ISM Sub-GHz, EU (433/470/868 MHz), US (915 MHz), Asia (430 MHz)	Sub-1GHz
Data rate	500 Kb/s @ payload of 16 – 32 bits	106 kb/s or 212 kb/s or 424 kb/s 848 Kbps	1 Mbps	20 kb/s @ 868 MHz 40 kb/s @ 915 MHz 250 kb/s @ 2.4 GHz	250 kb/s	9.6, 40 and 100 kb/s	1 kb/s - 10 Mb/s	30 kb/s - 100 kb/s	200 b/s - 100 kb/s	0.15–4 Mb/s @ BW=1MHz 0.65–7.8 Mb/s @ BW=2MHz
Typical range	0.1 - 5 m	0.1 m	70 m	10–100 m @ 2.4 GHz	10–600 m	100 m	5 km	2 km	2 km	100–1000m
TX power	1.5 mW	20 or 23 dBm	0 - 10dBm	0 - 20dBm	10 dBm	0 dBm	17 dBm	17 dBm	17 dBm	<10 mW – <1 W (@ local regulations)
Bandwidth per channel	10 MHz @ 6 MHz 14 MHz @ 13.5 MHz 1.74 MHz @ 433 MHz 7 MHz @ 800 MHz 8 MHz @ 2.4 GHz 5 – 27 GHz segmented	Variable	40 channels of 2 MHz width	868 MHz band: 0.3 MHz 915 MHz band: 0.6 MHz 2.4 GHz band: 2 MHz	2 MHz	300, 400 kHz	5 MHz	200 Hz	12.5 kHz	1, 2, 4, 8 MHz or 16 MHz for GFSK
Modulation / Transmission Technique	Proximity Field Modulation Induced Pulse	ASK, BPSK	GFSK FHSS Star	O-QPSK BPSK ASK DSSS	O-QPSK BPSK ASK	FSK GFSK CSMA-CA	BPSK QPSK 16-QAM DB-PSK	DBPSK Slotted ALOHA	GMSK offset-QPSK FDMA+TDMA	BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM OFDM
Topology	Point to Point Point to Multipoint	Peer-to-peer	Single-hop	Mesh	Star Cluster Mesh	Mesh	Star	Star	Star	Star
Power saving mechanisms	Inductive mechanism Backscattering	NA	Standby mode	Only in ZigBee RF4CE	On / Off Radio	Sleep / Wakeup Modes	NA	NA	NA	Native
Packet length	16 – 64 Kbps	Segments	8 to 47 bytes	100 bytes	250 bits	255 bits	> 10 bytes	< 20 bytes	> 10 bytes	100 bytes
Security	Clandestine Tracking and Inventorying EPC Discovery Service	Encryption Cryptographic, Secure Channel, Key Agreements.	Advanced Encryption Standard (AES) – 128 bits	AES-128	Cipher Block Chaining Message Authentication Code (CCM) AES-128	AES-128	AES-128	AES-128	AES-128	WPA
Licensing	Free	Free	Free	Free	Free	Free	Free	Free	Free	Free
Scalability	Limited	Peer to Peer	5917	Upper layers	NA	232	High	High	High	8191
Typical scenarios	Human Implantation Tracking Identification	Healthcare, Smart Environment, Mobile Payment, Ticketing & Loyalty	Multimedia data exchange between nearby nodes	Multi-hop networks with few nodes	Industrial	Automation in residential and light commercial	M2M Applications	M2M Applications	M2M Applications	One-hop networks with many nodes

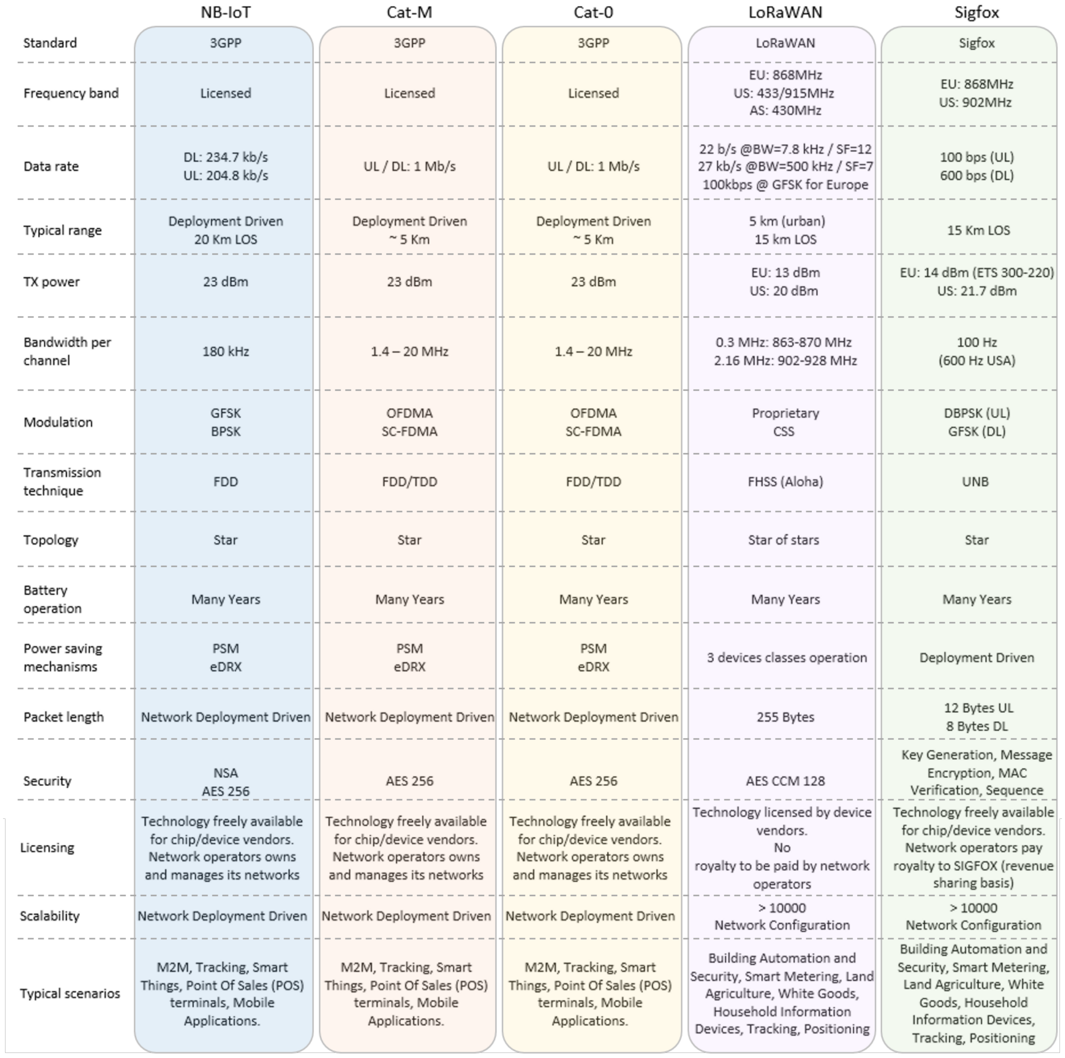
FIGURE 2.24: Comparison of the short range protocols.

2.3.2 Comparison Analysis of Long Range Coverage Protocols

In the case of the LPWANs presented, the main parameters that differ are the distance range of the protocols discussed. Improvements, adaptations, and innovations have occurred mostly at the PHY layer while the MAC layer was adjusted as needed. Figure 2.25 presents a comparison of the long-range protocols studied in this survey.

With no power control and baud rate adjustment mechanisms, the LoRa modulation itself becomes inefficient for applications that demand frequent transmissions and high transmission rates (tens of kilobits or more). Due to these characteristics, LoRa is automatically surpassed by its evolution, the LoRaWAN. LoRaWAN improves the MAC layer with the power control mechanism by dividing the operational mode of the devices into classes and using adaptive data rates (ADR).

SigFox comes as a great choice for applications that do not require high data rates and require low power consumption. The transmission efficiency presented is due to the high robustness of the link, with a link budget greater than 150 dBm in some regions. This ensures robustness against interference, thanks to the narrow band occupied in the transmission. Its disadvantage is the low transmission rate as Sigfox takes a long time to transmit a message. This characteristic imposes hard operational conditions for a mobile supported application. In SigFox, LoRa, and LoRaWAN, the uplink capacity depends on spectrum occupation and quantity of messages transmitted simultaneously to uplink. These systems capacity is not limited by data traffic load. Figure 2.25 illustrates long range protocols characteristics.



	NB-IoT	Cat-M	Cat-0	LoRaWAN	Sigfox
Standard	3GPP	3GPP	3GPP	LoRaWAN	Sigfox
Frequency band	Licensed	Licensed	Licensed	EU: 868MHz US: 433/915MHz AS: 430MHz	EU: 868MHz US: 902MHz
Data rate	DL: 234.7 kb/s UL: 204.8 kb/s	UL / DL: 1 Mb/s	UL / DL: 1 Mb/s	22 b/s @BW=7.8 kHz / SF=12 27 kb/s @BW=500 kHz / SF=7 100kbps @ GFSK for Europe	100 bps (UL) 600 bps (DL)
Typical range	Deployment Driven 20 Km LOS	Deployment Driven ~ 5 Km	Deployment Driven ~ 5 Km	5 km (urban) 15 km LOS	15 Km LOS
TX power	23 dBm	23 dBm	23 dBm	EU: 13 dBm US: 20 dBm	EU: 14 dBm (ETS 300-220) US: 21.7 dBm
Bandwidth per channel	180 kHz	1.4 – 20 MHz	1.4 – 20 MHz	0.3 MHz: 863-870 MHz 2.16 MHz: 902-928 MHz	100 Hz (600 Hz USA)
Modulation	GFSK BPSK	OFDMA SC-FDMA	OFDMA SC-FDMA	Proprietary CSS	DBPSK (UL) GFSK (DL)
Transmission technique	FDD	FDD/TDD	FDD/TDD	FHSS (Aloha)	UNB
Topology	Star	Star	Star	Star of stars	Star
Battery operation	Many Years	Many Years	Many Years	Many Years	Many Years
Power saving mechanisms	PSM eDRX	PSM eDRX	PSM eDRX	3 devices classes operation	Deployment Driven
Packet length	Network Deployment Driven	Network Deployment Driven	Network Deployment Driven	255 Bytes	12 Bytes UL 8 Bytes DL
Security	NSA AES 256	AES 256	AES 256	AES CCM 128	Key Generation, Message Encryption, MAC Verification, Sequence
Licensing	Technology freely available for chip/device vendors. Network operators owns and manages its networks	Technology freely available for chip/device vendors. Network operators owns and manages its networks	Technology freely available for chip/device vendors. Network operators owns and manages its networks	Technology licensed by device vendors. No royalty to be paid by network operators	Technology freely available for chip/device vendors. Network operators pay royalty to SIGFOX (revenue sharing basis)
Scalability	Network Deployment Driven	Network Deployment Driven	Network Deployment Driven	> 10000 Network Configuration	> 10000 Network Configuration
Typical scenarios	M2M, Tracking, Smart Things, Point Of Sales (POS) terminals, Mobile Applications.	M2M, Tracking, Smart Things, Point Of Sales (POS) terminals, Mobile Applications.	M2M, Tracking, Smart Things, Point Of Sales (POS) terminals, Mobile Applications.	Building Automation and Security, Smart Metering, Land Agriculture, White Goods, Household Information Devices, Tracking, Positioning	Building Automation and Security, Smart Metering, Land Agriculture, White Goods, Household Information Devices, Tracking, Positioning

FIGURE 2.25: Long-range protocol characteristics.

Existing cellular network technologies are now heavily challenged by new IoT applications incoming their technological eco-system. Cellular networks are designed to operate with the human voice traffic profile that has a known and predictable pattern. With the advent of Internet traffic, mobile networks have had to adapt to meet an instant and floating demand for this service.

Based on the adaptations made from LTE network, NB-IoT networks are eminent solutions for harnessing the existing mobile cellular network infrastructure. NB-IoT emerges as a strong alternative given the available and well consolidated mobile network infrastructure. The adaptations made in LTE to support NB-IoTIoT services offer a new data traffic profile, different from the user services that demand for high transmission data rates. As data traffic from H2H applications such as audio, video, and voice tends to migrate to higher capacity systems such as 5G, NB-IoT capabilities become more widely available. This is an excellent alternative to the telecommunication operators since they have a 4G infrastructure and it is not compatible with the upcoming 5G. Then, telecommunication operators can re-use the available network infrastructure for IoT, based on NB-IoT, and perform its investments for 5G.

Challenged by IoT applications, it is not enough to adapt. Now, it is necessary to re-invent in order to support a new data traffic profile coming from objects which have completely different traffic, range, and time-based characteristics. Without the predefined parameter definitions regarding data transfer delay, NB-IoT has its limitations when used by systems that require some time dependency parameter. To meet this demand, LTE CAT-M technology, has brought to this new service profile an immediate deployed solution. Although they seem to be competitors, LTE CAT-M and NB-IoT protocols support services with different requirements for data transfer time requisites. They can become a complementary solution. Even though they are treated as networks for long distances, the differences between LP-WAN technologies and cellular mobile network technologies are very clear. The strong differences between the architectures of the PHY and MAC layers of these two types of networks make it difficult to have a fair comparison between them. Better comparison bases could be provided considering the same application (or solution), deployed using both technologies.

2.3.3 Open Issues

In this rapidly evolving scenario, the emergence of new features, interoperability and performance aspects to be studied or validated is constant. Considering the discussion presented here and the characteristics of the protocols, the following open research topics are identified:

- Regardless of the technology used in any solution or application, the information exposure always raises questions regarding each protocol security requirements, emphasizing that each solution requires different aspects of security. Beyond the scope of fixed or mobile WSNs security [133], from this study, the use of AES encryption by most protocols is clear. Some protocols that do not use it have some other methods to ensure data privacy at the MAC layer level such as proprietary coding or the vendor specific modulation type. Proprietary technologies like Sigfox and Wireless-Hart ensure this security by keeping their development features closed, limiting access to their techniques. Based on the information presented, it is clear that, in terms of security, there is a need to treat data at upper layers and have security embedded in the solution code, aspects that deserve more attention.

- The ability of terminals to roam between technologies is also an untreated topic. The design of hybrid systems such as multi-protocol gateways seems to be an unavoidable consequence of these protocol heterogeneities [134]. The rapid evolution of hardware solutions induces the development of multi-protocol platforms and systems [8], multi-band radio interfaces with adaptive and opportunistic techniques such as 5G. These protocols are required to be inter-operable in different layers, allowing performance comparisons. For example, in areas of roaming between different protocol technologies, systems and network operators, technical alliances necessary to obtain a good cross-border roaming, including the security aspect.

- With the current evolution, devices need several connectivity technologies. The same application can use more than one connectivity technology and terminal roaming between technologies can happen abruptly. Once the technology roaming aspect has become part of the scenario, the need for a verification of existing tools or solutions will arise to bring the interconnectivity standardization to the MAC layer. Thus, leaving the application layer and its applications, operating transparently and inherently to the protocol technology being used.

- Since there are such heterogeneity, connectivity, and interconnection, there are coexistence, dispute for resources, and interference. Although numerous works have been done on the performance of these protocols, little has been published on practical comparisons in identical scenarios. This comparison can point out the capabilities offered by each protocol and investigate their characteristics in a co-existent environment. As ISM bands are preferred by LP-WAN protocols, their coexistence in the same scenario calls for more studies so that more can be learned about the inter-technology interferences that can degrade their qualities.

- For more critical environments and applications, such as healthcare and some industrial environments, reliability may be more important than other features. Highly reliable services may sacrifice other characteristics such as latency. Studies of data "acknowledgment" mechanisms demand flexibility in the packet sizes used and network responsiveness to these characteristics.

- Some techniques or applications, primarily for management platform purposes, are still dependent on broadcast and multicast functions inherited from IP networks that still need to be adapted or evolved. Broadcast, multicast, and control channels are also emerging aspects that are having their applications questioned without many specific studies.

2.4 Summary

In this chapter long and short distance MAC layer protocols for Internet of things were studied. The analysis delves into the characteristics of the MAC layer protocols because this layer defines the main behavior characteristics of the protocols regarding the coverage distance, type of network topography, data transmission rate, mode of communication between end devices and their platforms, among others. It was also presented a comparison analysis of the short distance and long distance protocols studied on this work in order to allow a comparison among them and identify the most promising for a given application.

The exposed features and presented discussion leads to choose the most appropriate protocol for a given application. It is also possible to understand the limits of the technological solution used as well as point out the protocols evolution or updates necessary to follow the demands evolution.

Chapter 3

Experimental Environment and Performance Metrics

Considering the open issues identified in Chapter 2, this study focuses on long range coverage protocols (LP-WAN), in particular, performing a comparison analysis among LoRa and Sigfox. This choice is based on their characteristics as promising alternatives for IoT scenarios where applications need mobility support. These emerging LP-WAN protocols are considered very promising for different vertical applications like smart agriculture, smart-cities, or mobility.

3.1 Experimentation Scenarios

In order to provide a reference behavior of the two protocols in a mobile environment, experiments scenarios were defined as similar as possible for the two protocols. Then, there is an experiment with a simultaneous and alternated transmission modes for urban scenario in order to evaluate SNR and packet loss indices. For a road scenario, maximum reached distance is the goal. For simplicity and, at the same time to maintain soft conditions variations, this basic scenario was chosen as a reference. Any other factor to be considered in other analysis can complement this study.

Sigfox communication system is provided by the local operator and a temporary free license to use its solution was supported by the operator. Regardless the involved protocols, for any comparison to be fair, the radiating system is of fundamental importance. There is a great difficulty to build two systems with identical irradiation characteristics when they are built by independent projects. Especially when dealing with the Sigfox system that works as a private wireless communication operator profile, protecting technical design details. The difficulty of obtaining two antennas from different manufacturers with the same irradiation pattern forced the search for the highest possible similarity. Not only the type and model of the antennas but the positioning of them should also be as similar as possible. Therefore, the same mast was used for the installation of the two antennas, thus maintaining the equality of the systems in position and altitude. As the studied scenario considers only the transmission characteristics in the uplink direction, it can be affirmed that there will be no interference generated between the reception antennas since the antennas will only receive and not transmit. The vertical and horizontal distance between antennas is three times the wavelength of 915 MHz (0.98 meters) in order to minimize the harmful interference.

The used antennas are the following (shown in the Figure 3.1):

i Antenna model CXL 900-3LW/H from Procom manufacturer used by Sigfox.

ii Antenna model AU09G6-NF from Altelix manufacturer used at the LoRa created solution.

Considering that Sigfox platform is from the exclusive property of the operator, it does not allow any changes in it, not even in its radiating system. Therefore, based on the pattern of the irradiation diagram provided by the antenna's manual used in the Sigfox platform, an antenna with specifications as close as possible to the specifications of the antenna used in the Sigfox was chosen for LoRa solution.

(i) Antenna model CXL 900-3LW-4 used by Sigfox operator solution.

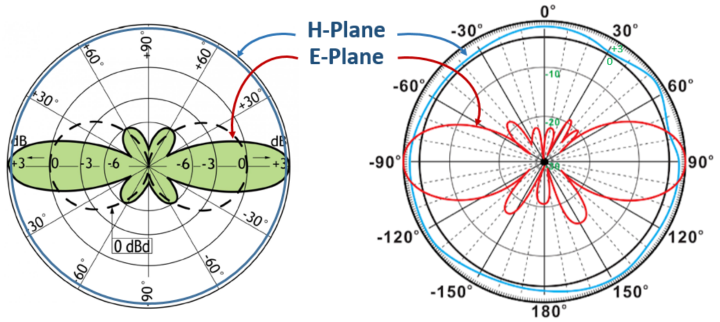
(ii) Antenna model AU09G6-NF used on LoRa developed solution.

FIGURE 3.1: Photo of the Antennas Models Used for LoRa and SigFox Prototypes.

The irradiation diagram was the main factor to be considered when choosing the antenna. The operating frequency range parameters and LoRa antenna gain were also observed and obtained more easily. The two irradiating systems have the same gain value as 3 dBi, the same horizontal plane (H-Plane) irradiation diagram and similar irradiation vertical plane (E-Plane) aperture patterns. The same vertical aperture pattern and identities of the horizontal openings of the irradiation diagrams, together with the same irradiation gain value for them, characterize the similarity of the two irradiating systems. The irradiation diagrams of the antennas are shown in Figure 3.2.

The equipment installation is in the same room, which made it easy to maintain the same cable size for the connections between gateways and antennas. Once the same operating frequency range, similarity in the radiating system, and the maximum transmission power standardized, is possible to consider the close similarity of the systems in this regard, making it fair and suitable to compare the two systems.

According to the objective of the study, the experiments were performed with the respective terminals in displacement throughout the course. Experiments were performed under the following conditions:



i) Antenna Model CXL 900-3LW-4 Used on Sigfox Solution.

ii) Antenna Model AU09G6-NF Used on LoRa Solution.

FIGURE 3.2: Irradiation Patterns of the Used Antennas for LoRa and Sigfox Prototypes.

- Scenario with only the LoRa terminal in displacement, in an urban scenario.
- Scenario with only moving the Sigfox terminal, in an urban scenario.
- Scenario with displacement in an urban scenario with the two terminals LoRa and Sigfox simultaneously transmitting along the same route.
- Scenario with displacement in an urban scenario with the two terminals LoRa and Sigfox transmitting alternately during the same route.
- Coverage range test scenario in road environment.

The experiments carried out in the urban environment goals not only verifying the possible interference due to the simultaneous transmission of the two devices, but also the efficiency of messages received with success. The comparison of the Signal to Noise Ratio (SNR) levels will inform the degree of interference between the two systems during the simultaneous transmissions, compared to the SNR value obtained during the experiments with the alternating transmissions between terminals.

The experiments were performed with the two devices within the same housing, being transported by a vehicle through the selected route. The urban route was defined in such a way as to present the best possible conditions for the experiment, taking into account the variation degree of the urban density and the obstacles density and height, imposed by the civil constructions. The geographic conditions of altitude variation and possible shadow areas and signal coverage in line of sight (LOS) or not, were also considered. Therefore, the urban route has been chosen to endure slight obstructions but in general, a route in a line as straight as possible It was avoided to take paths that offer total obstruction of the line of sight due to the local relief, since it becomes a behavior peculiarity of the studied systems. It is important to emphasize the concern to provide experiments conditions in a non-particularized way is the basis of this work objective. Thus, in order to provide a study that will serve as a basis for these two protocols performance evaluation in a mobile environment, care has been taken to work in a scenario with a basic urban environment.

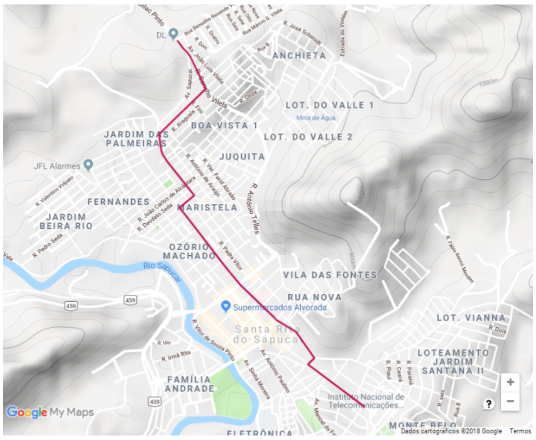


FIGURE 3.3: Illustration of the Urban Drive Test Path Relief.

The route definition also took into account the need to repeat the experiments for several times under different conditions. The fluidity regarding the urban traffic was considered as a normal situation when tracking any element. As emphasized in the Figure 3.3, considering the conditions of relief where it does not impose complete obstruction of the signal, it was a premise in the route definition. This occurs because the main objective is to analyze the systems behavior in feasibility conditions of transmissions and measurements. Choosing a path with total signal obstruction can lead to the error of not knowing if a message did not reach its gateway due to the total transmission obstruction or if it was due to other impacting element in the measurement or transmission, compromising the results of the experiment.

It was considered to perform the experiments with the two prototypes transmitting simultaneously and alternately at same path. This condition exposes the two protocols to the same environment and experimental conditions, making the experiment more fair and balanced.

During twenty days of experiments, 6 measurements were performed per day, resulting in a total of sixty measurements during the twenty days. Due to urban traffic conditions and events in the city, some measurements were compromised by the interruption of the measurement or involuntarily route changes. Thus, the fifty most consistent experiments were used for the proposed analysis. These fifty experiments were separated into groups of 5 experiments totaling 10 groups of measurements and, for each of these groups of measurements, the averages of each group were calculated and are presented in the following analyzes.

The urban density is basically a horizontal density because it has very few building constructions with more than three floors. In spite of this, the constructions are generally made by clay or cement bricks. Unlike dry-wall partitions, this type of construction offers strong obstruction to the Radio Frequency signals transmitted by the terminals. In a horizontal urbanization profile scenario, where the types of dense materials used in urban constructions are considered, this presents itself as a good reference profile. Taking into account the variations of obstruction conditions imposed by this urban profile there was a need to take several measurements on the same day.

In order to analyze the protocols maximum coverage reached, an experimental scenario was carried out along the road MG-459 in the Itajubá-MG direction (Minas Gerais state, Brazil). The road was chosen based on the geographic conditions of altitude variation, possible shadow areas, and LOS signal coverage. Due to region relief, this road is the only one that can experiment the maximum range of the system transmission, within the offered conditions and without total obstruction to the transmission. The urban and road scenarios are two very adverse condition scenarios. Different from urban experiment scenario, road experiment scenario was done only to measure maximum reached distance. There are no comparison between road and urban scenarios.

Given the relief of the region, the most distant point from which a terminal measurements was collected was at 13.7 km far from the bases, close to Olegário Maciel - MG city, as illustrated in Figure 3.4. From this point, the road enters an area where there is a total transmission obstruction due to the region relief. With the level of obstruction, it becomes impossible that a transmission in this frequency band transposes such obstacles.

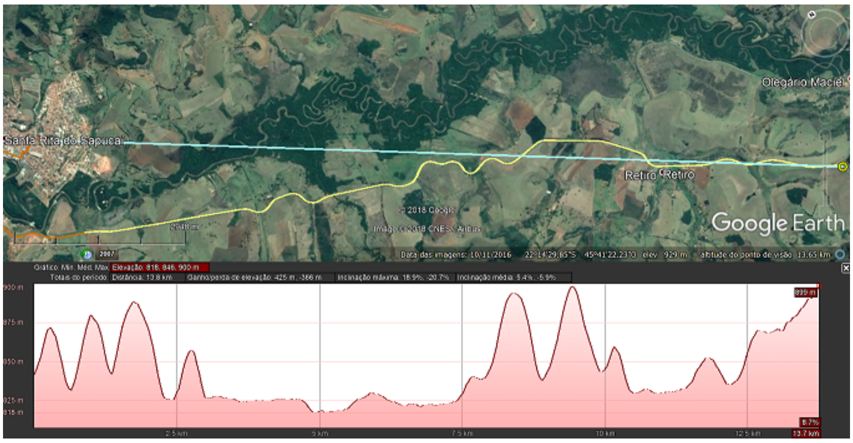


FIGURE 3.4: Road Test-Drive Altitude and Distance Profiles.

Figure 3.4 shows the section of road chosen for this experiment, highlighted in yellow color. It is inside a valley where there is favorable transmission and reception under low influence of obstacles. The direct line of sight between the transmitter terminal and the gateway is represented by the light blue line that has its red highlighted altitude profile shown in the graph below the map image.

The path projected follows the BR459 road for 40km towards the South-East (SE) direction, being a well-known geographic relief and also due to this path is already used and well known by other concurrent protocols. Given this road environment setup, the analysis performed was a road tracking and transmission propagation performance experiment on a higher speed than the urban paths. However, the relief conditions are more critical considering the coverage shadow areas.

Figure 3.5 shows the route information to be traversed for the test-drives on roads, made for the experiments. The orange line indicates the experiment path to the farthest reached point. The green line indicates the radius of 10 km of the urban city center and the red line indicates the radius of 15 km of distance to the city center. The red thin line represents the 15 km (10 miles) approximately radius reference point and the green line represents 10 km (6.21 miles) approximately. The orange line indicates the path driven during the experiments.

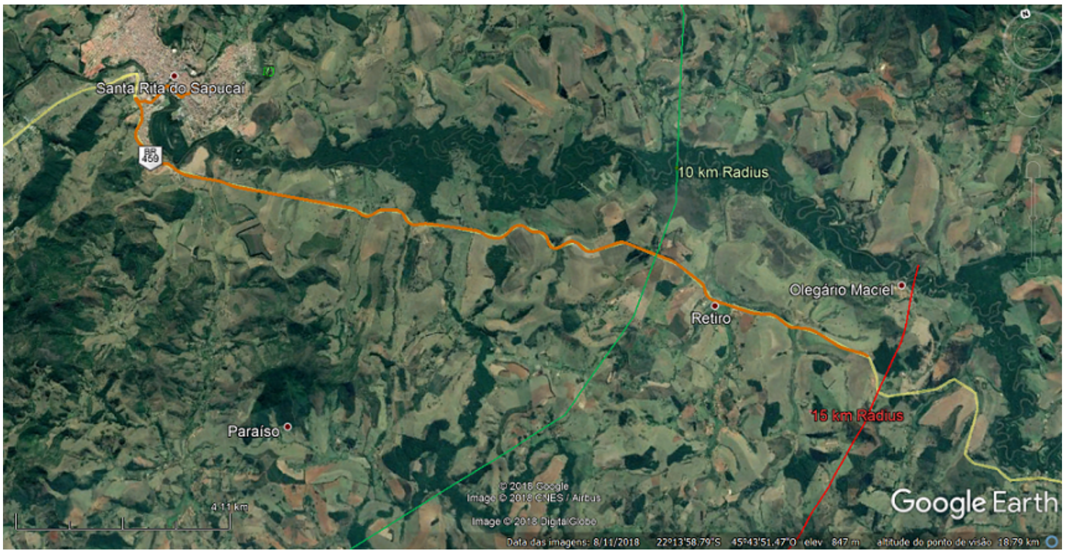


FIGURE 3.5: LoRa Road Experimentation Path.

3.2 Construction of the Hardware Prototype

In terms designing the platform devices, it was easy to develop the LoRa platform design due to the high availability of transceivers in the market and due to the fact the protocol work frame is open, which allows easy access to the transceivers and the codes necessary to build the solution for the LoRa system. Thus, it was possible to adjust the transmission parameters of LoRa to fit the bandwidth used by Sigfox protocol.

Regarding Sigfox protocol, it was difficult to build Sigfox terminals due to the lack of transceivers available in the market and also due to the fact that this protocol is proprietary. Despite being a proprietary protocol, sample codes are available to work as well as some transceivers modules for experimentation purposes. As it owns the techniques of the layers PHY and MAC, it is not possible to work with the characteristics of transmission of the protocol, nor to change them.

3.2.1 LoRa Hardware Platform

The LoRa platform used is an open platform composed by a gateway and an application that links the gateway to the Docker-based database, which runs on a linux virtual machine over a Windows 10 operating system.

The Microchip vendor gateway receiving station model DV164140-2 is illustrated on Figure 3.6. It receives the geographic coordinates provided by a U-blox vendor, NEO6 model type GPS device illustrated on figure 3.7, being transmitted by a P-NUCLEO-LRWAN1 model kit from STMicroelectronics manufacturer.

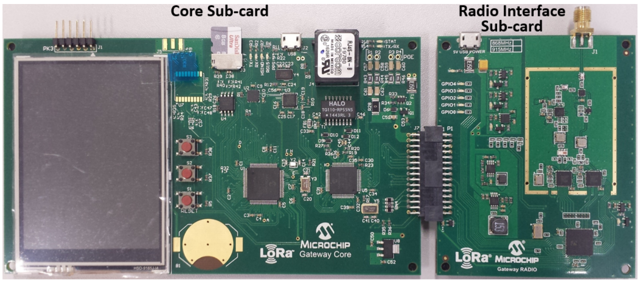


FIGURE 3.6: LoRa Gateway.

FIGURE 3.7: GPS Ublox Neo 6MV2.

Equipped with a model L073RZ Micro Controlled Unit (MCU), this kit illustrated on Figure 3.8 is mounted with a radio frequency (RF) expansion board (SX1272MB2DAS), designed with the SX1272 low power transceiver from the STMicroelectronics manufacturer. The SCX1272 transceiver is responsible for the treatment of LoRa modulation as well as the On-Off Keying (OOK) and Frequency-Shift Keying (FSK) modulations present in the LoRa transmission system standard support.

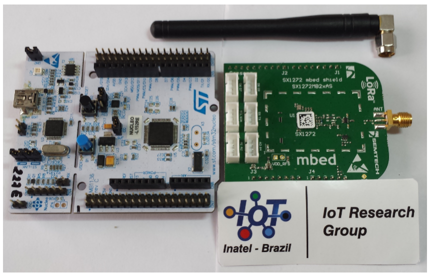


FIGURE 3.8: STMicroelectronics P-NUCLEO-LRWAN1 Model LoRa Terminal.

LoRa module MCU is programmed in C++ programming language, a code specifically designed for this application in order to control the simultaneity between the terminals, define spread spectrum factor, channel, bandwidth used and defining the terminal transmission. The code developed is also responsible to receive the coordinates data supplied by GPS module, extract its payload data, interpret it, separate necessary data, and concatenate them into 12 bytes payload to be transmitted.

Microchip DV164140-2 gateway is composed by a radio module based on Semtech's SX1257 model transceivers chipsets that demodulate the received signal and send them to the core board via a Serial Peripheral Interface (SPI) standard interface to be interpreted and adapted according to chosen transport protocol and interface that connects the gateway core module to its server application.

The gateway core module is responsible for handling the data sent and received from the radio module and adapting them in IP packets that are handled by a server. On this server, a Structured Query Language (SQL) database provides storage and a graphical Application Programmed Interface (API) to the system operator. Stored and processed, the data is pointed to an User Datagram Protocol (UDP) port, added an IP (Internet Protocol) header, and encapsulated in an Ethernet frame to be transmitted through an IEEE 802.3 interface.

3.2.2 Sigfox Hardware Platform

A Sigfox base station, SBS-T902 presented on Figure 3.9 was provided by the company WND, a representative of Sigfox in Brazil, which is installed at the Inatel campus highest building, with its antenna operating at an altitude of 885 meters.

FIGURE 3.9: Sigfox Gateway.

As a proprietary protocol, access to the Sigfox gateway is neither possible nor necessary, since Sigfox solution data is made available directly on its Web back-end interface, which is available on the Internet.

The used Sigfox terminal includes a STMicroelectronic STEVAL-FKI915V1 kit composed by a Nucleo-L152RE card, which is a low power MCU (Micro Controller Unit) that has interface with a S2-LP Sigfox transmission module, responsible to receive the data to be transmitted and treat them according to Sigfox standards and transmit them on a controlled radio interface. Sigfox module MCU is also programmed in C++ programming language specifically designed for this application but different from LoRa's transmission shield, at Sigfox, the transmission parameters are not accessible and cannot be changed.

In order to activate and register the kit to be used on Sigfox operator platform, the S2-LP software tool Sigfox Demo GUI v.1.0.0 was used which, besides the registration, also allows making experiments of transmission with the S2-LP transceiver separately, to test it. Integrated Development Environment (IDE) Keil μVision 5 for ARM processors was then used to develop and implement the kit programming code for both LoRa and Sigfox deployment. Figure 3.10 shows STMicroelectronic STEVAL-FKI915V1 kit.

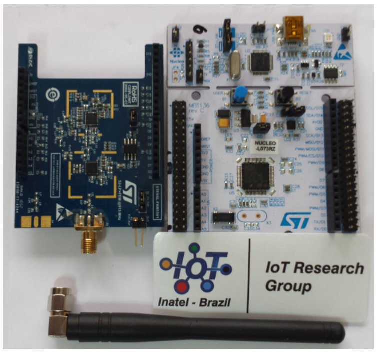


FIGURE 3.10: Sigfox STEVAL-FKI915V1 Terminal.

Another identical LoRa's GPS module is integrated to Sigfox kit to provide the coordinates and other data demanded by the experiment.

3.2.3 Assembly of the Mobile Prototypes in a Single Equipment

A mobile experimental device was constructed by joining the two terminals in the same shell, allowing the displacement with both at the same time. In this way, it would be easier to perform the experiment in any vehicle. The LoRa P-NUCLEO-LRWAN1 and Sigfox STEVAL-FKI915V terminals were fitted with a GPS sensor (each one) in a properly fixed enclosure, protecting the weather terminals from outdoor test-drives such as sun, dust, and rain. It was also convenient to install Light Emitting Diodes (LEDs) to visualize and monitor the system's operating state visually, from the outside of the enclosure. Power was supplied through the Universal Serial Bus (USB) ports of the used terminals. The power supply input connection uses a standard USB port as well.

In order to change the modes of transmission between simultaneous and alternated, a key has been installed outside the enclosure where, in addition to the two transmission modes, it is also possible to leave the two terminals powered, but not transmitting, in standby mode. This means that it is possible to change the mode of transmission between simultaneous or alternating, without having to change the programming code, being able to select the mode of transmission according to the type of transmission to be used at that moment. An illustration of the constructed prototype is shown in the Figure 3.11.

Two buttons have been installed for reset control and start transmission. The reset button is responsible for initial charge of the terminal code, preparing them to start transmission in the selected mode through the key. The other button is used to start the process of transmitting the coordinates acquired by GPS. Thus, it is possible to start the transmission and stop it, when desired, bringing its functionality to a real usage as close as possible.

FIGURE 3.11: Assembled Equipment with LoRa and Sigfox Terminal Devices.

3.3 Data Collection, Storage, and Treatment

It is known that receiving a message does not mean being able to understand it. Only the comparison of the messages indexes received successfully cannot guarantee that information is complete. It is necessary to process the content of the messages to ensure that, in addition to the package being successfully received, the message has been received without errors, so its payload is readable.

The processing of the received packet was done first, comparing the sequential number transmitted in the messages payload to the sequential number of messages received and made available at the back-end of each prototype. This technique allows to identify the number of packets that were not received by the gateways or were received, but could not be interpreted because of error presented in the packet. Payload standard format adopted is presented in Figure 3.12.

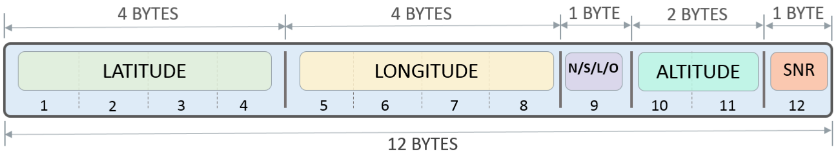


FIGURE 3.12: Payload Structure.

Apart from that, the package data is processed and its contents interpreted. The positive result is indicated by the correct reading of the geographical coordinates. The standard defined and adopted for the format of the coordinates in the payload of the package is such that it is possible to identify when data present in its payload represents or not a pair of geographic coordinates.

3.3.1 Data Storage

The Sigfox platform database is exclusively owned by the system operators, being available for consultation only at its back-end, through an Web user interface available through the Internet.

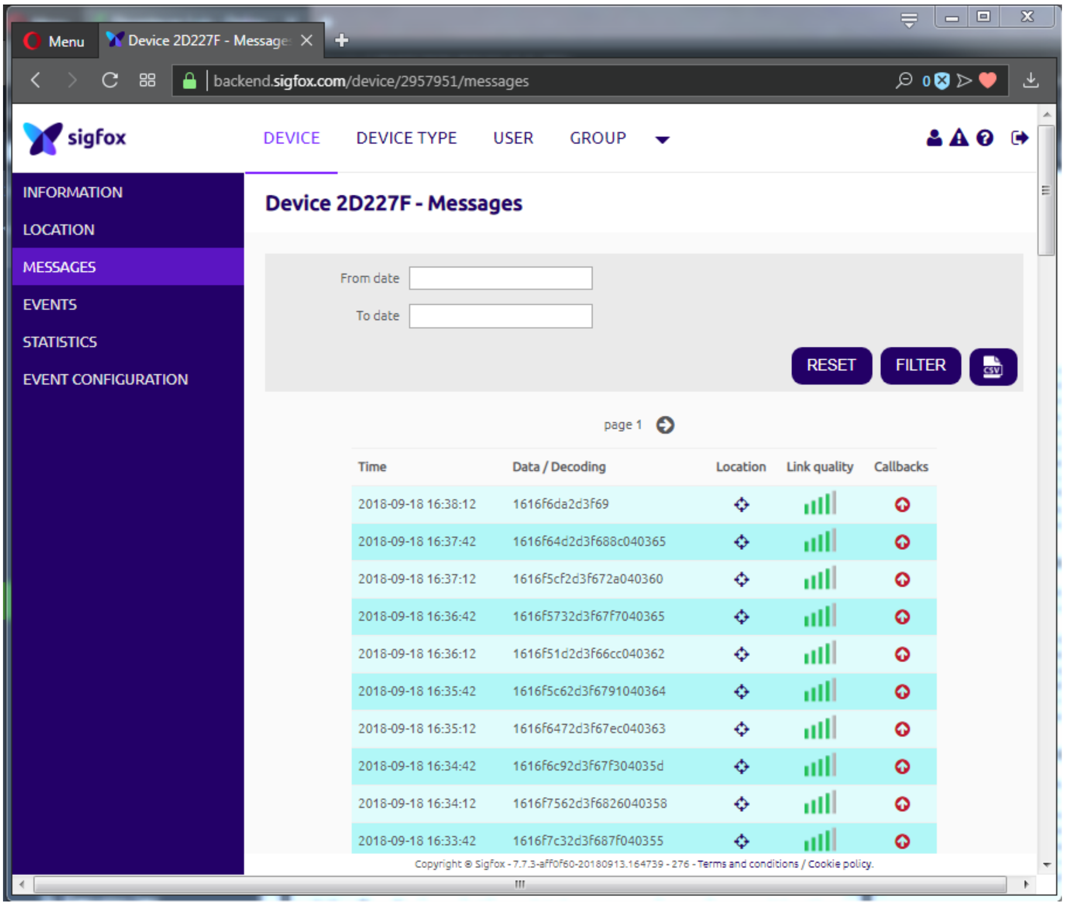
The database of the LoRa platform is supplied through a Docker data structure and easily adaptable to other structures due to the commercial opening of the platform. Therefore, for this application, in addition to the local database present on the computer where LoRa application is installed, it is also made the replication of this database in the cloud, so this data is forwarded and worked on the same front-end where they are also available the information received by the Sigfox platform.

3.3.2 Data Storage on LoRa and Sigfox Platforms

The information generated by this process will be obtained through cloud interfaces called *back-end*, provided by each platform and used to study the performance metrics defined in this work. For the Sigfox solution, the operator itself makes available a back-end through the Internet with a graphical user interface where it is possible to read the information received in each message, being presented in hexadecimal. Sigfox back-end user interface is shown in Figure 3.13. The user interface with all data treated according this specific application (front-end) that will be detailed ahead in this work, necessary to give graphical visualization of the obtained information, uses the back-end of Sigfox in the cloud, that allows the creation of APIs (Application Programming Interfaces). These APIs send data in hexadecimal to be interpreted, converted into coordinates, and presented in a graphical interface in a smart map format.

The LoRa platform back-end was developed specifically for this study and it is stored locally, along with the database required to compose it. With greater freedom of the database manipulation of this platform, is possible to customize the database and the API that connects with the graphical user interface more assertively. From there, the APIs follow the same functions already described. Detailing, LoRa platform does not have an integrated back-end, ready to be accessed and easily available. The LoRa platform back-end includes an application that communicates with the gateway. The application manages the gateway, handles its settings, and sends the received packet data to a virtual machine based on the Linux operating system where the Docker database is installed.

This solution is composed by modular and interdependent systems that need to be handled together during platform operation. Through local storage and the opening of the platform domain, it is possible to easily access the database composed by the messages data transmitted by the terminals and collected by the LoRa gateway. In addition to provide the payload of the terminal transmissions, this interface also provides, among others, packet count sequence values, time stamp, SNR, received signal strength indicator (RSSI), and in



Device 2D227F - Messages

Time	Data / Decoding	Location	Link quality	Callbacks
2018-09-18 16:38:12	1616f6da2d3f69	⌖	📶	⬆
2018-09-18 16:37:42	1616f64d2d3f688c040365	⌖	📶	⬆
2018-09-18 16:37:12	1616f5cf2d3f672a040360	⌖	📶	⬆
2018-09-18 16:36:42	1616f5732d3f67f7040365	⌖	📶	⬆
2018-09-18 16:36:12	1616f51d2d3f66cc040362	⌖	📶	⬆
2018-09-18 16:35:42	1616f5c62d3f6791040364	⌖	📶	⬆
2018-09-18 16:35:12	1616f6472d3f67ec040363	⌖	📶	⬆
2018-09-18 16:34:42	1616f6c92d3f67f304035d	⌖	📶	⬆
2018-09-18 16:34:12	1616f7562d3f6826040358	⌖	📶	⬆
2018-09-18 16:33:42	1616f7c32d3f687f040355	⌖	📶	⬆

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FIGURE 3.13: Sigfox Cloud User Interface.

the case of terminals triangulation through the reception of the same message by multiple gateways, information is also available from the geographic coordinates of such a terminal.

It was necessary to develop APIs to extract information from the message payloads as well as the SNR data that are generated, transmitted, and stored by the platform itself from the LoRa prototype database and the Sigfox platform back-end. In addition to fetching and extracting, the APIs also validate message payloads to confirm whether the extracted payloads are with the correct information or whether payload data changes due to the characteristics of wireless transmissions.

After validating the data, this API sends data to the front-end that decodes, interprets, and classifies data making them into information in a way the front-end can understand according to the needs of the programming codes.

3.3.3 Front-end Application User Interface

The front-end application user interface was developed in Java programming language. It was specifically developed for these prototypes to perform the experiments, from the basic tools offered by each system. With the freedom of access to this database through the APIs dedicated to extract data from the LoRa database, validate the 12-byte payload according to the pattern used, and, finally, send this processed data to the front-end. The front-end is then provided with a graphical user interface for the manipulation and visualization of the obtained information and shows the position of the terminal in a map through the coordinates obtained by the terminals and transmitted to the platforms.

In another approach, the Sigfox operator offers access to its back-end user interface where it is also possible to extract the data obtained from the terminals through the mechanisms of post or push data, such as Hyper Text Transfer Protocol (HTTP) that was used in this solution. The API developed for Sigfox prototype performs the same procedure already described but for the data provided by the Sigfox platform.

The front-end receives the API posts sent over the Internet and differentiates the information of each platform providing visual access to this data through the offered screen options. The differentiation of the information obtained from each platform is in their presentation mode, in different sections or windows with the plot of the obtained coordinates over a map layer.

Tracking information for each platform is shown in different screens of the developed interfaces. It is possible viewing the tracking maps obtained by the Sigfox prototype in an window and the tracking maps of the LoRa platform in another application window as presented in Figure 3.14. The same is done for the tracking data as shown in Figure 3.15. The Tracking mode allows the visualization of a point that represents the coordinates received by the moving terminal and it is possible to follow the displacement of the terminal through a point on the screen. In tracking mode, it is possible to track the route traveled by the monitored element leaving a trace left along the path through the moving terminal.

FIGURE 3.14: Tracking Map User Interface.

FIGURE 3.15: Tracing Map User Interface.

In this user interface it is also possible to customize the format of presentation and information visualization according to the need of the user and its application. For devices and smartphones based on Android operating system, an application has been developed and it shows the same options offered in the front-end user interface of the mobile device.

3.3.4 Integration with an Iot Middleware

At the application layer it is used an open source middleware platform for IoT, called In.IoT, that includes a data analysis module. It was created at the IoT Research Group, from INATEL. Middleware collects data and exposes them to users as well as third party applications [135]. Moreover, they are responsible for a significant "part" of the intelligence in IoT. Therefore, the middleware platforms are responsible for part of the intelligence in IoT. The obtained data are extracted from the database of each prototype and are sent to In.IoT through a message formatted in JSON (JavaScript Object Notation) using its REST (Representational State Transfer) API. Middleware presents data collected from front-ends into graphics, tables, or other graphic tool according the need to allow a better data analysis [136] [137]. Different types of graphic interfaces can be applied or constructed as demanded. A graphical user interface of the In.IoT middleware is displayed on Figure 3.16.

3.4 Performance Metrics

For a fair comparison between the two protocols under study, it is important to define the metrics used and make clear how data was obtained, so as to allow a fair comparison. Metrics are needed to evaluate the quality of the systems analyzed regarding their capabilities and behavior in a given scenario. They are used to identify the limitations of each protocol

FIGURE 3.16: In.IoT Middleware User Interface.

involved in the performed experiments. It is necessary to establish metrics that allow the comparison between the two protocols. These metrics must take into account the characteristics of long distance coverage and the communication efficiency of each protocol. In this way, it will be possible to identify, classify, and obtain reference values to evaluate the performance and limitation of each protocol. The considered qualitative and quantitative metrics are described below.

3.4.1 Qualitative metrics

Qualitative metrics are difficult to translate into numbers because the way they are observed depends on the a subjective measures analysis. The qualitative metrics in this dissertation are proposed with the objective of reducing subjectivity, and it supports the user who is trying to select a LP-WAN protocol.

The considered qualitative metrics used in this study are the following: packet size, operation frequencies, and modulation robustness. These metrics are directly associated to the characteristics inherent to each protocol and allow the analysis of each protocol behavior over the scenario used in the experiments.

Packet Size

Package size is an important parameter in this comparison. As the protocols presents different size of Packets Data Units (PDU) it is necessary to conform the payload size to be sent so that, when considering the power consumption, the transmission time and the maximum PDU capacity, is possible to have a fair comparison. In this way others differences regarding this aspect, will be referring to the inherent differences in each protocol such as header size, coding types and modulation of each protocol.

Since the Sigfox protocol has a payload limited to 12 bytes, it was necessary to concatenate the GPS data to fit all the necessary information. Due to this fact, it was also used the same payload size and format for the LoRa protocol to become a fair experiment.

Operation Frequencies

The operating frequencies are also very important in the definition of parameters comparison. The fact that both prototypes work in the same band (ISM - 800 to 930 MHz) provides the same transmission and propagation characteristics that are relevant to the characteristics of the transmission channel at the same time.

The simultaneous transmission of the two terminals, generating interference between them, will allow the measurement and analysis of the behavior and performance of each system in a coexistence environment. These experiments aims to provide information and inputs to be considered in future projects or applications.

Modulation Robustness

In an indirect way, the behavior of the two protocols regarding the reception sensitivity of each proposed system will also be measured. The transmission technique of Sigfox that bets on the good transmission quality making three consecutive transmissions of the same information is put to the test when analyzing the interference suffered during the transmission of the LoRa terminal. In turn, using a spectral scattering-based modulation technique that distributes the transmitted energy over a wider bandwidth, it can also suffer strong interference during Sigfox signal transmission that uses a lot of energy over a much narrower bandwidth.

The robustness of each modulation is indirectly measured when the percentage metrics of received messages are successfully obtained and, within these measures, the percentage of messages with integral and readable payload is analyzed. Indoor and outdoor environments will also be obstacles to overcome by both systems. In this way, it may be possible to identify which system performs better in a given environment.

3.4.2 Quantitative metrics

Qualitative metrics are also needed to offer numerical dimensions and references from obtained information that can be analyzed. It gives inputs for a better analysis of the obtained results. Following, there are presented the metrics that will be used in this study.

Packets Lost

Packet loss is always a challenge to be overcome by wireless networks. Many techniques are adopted to minimize this loss, such as the use of Multiple Input and Multiple Output (MIMO) antenna systems, directional antennas, mathematical corrections in the signal, hybrid systems where the use of antenna resources is controlled by the characteristics of the antennas. signals received, etc. In the context of IoT, packets loss has low significance for the service quality of some applications that accepts a lower packet rate loss to ensure a certain level of reliability or data convergence analysis.

Having been designed for use in applications that require fixed points, that is, without mobility, the packet loss parameter can have a fixed value, known or possible to be estimated. For the proposed objective, the scenario is a mobile environment. Therefore, it is expected a certain amount of lost packets that can indicate how susceptible to mobility are these protocols. The count of the lost packet index is done by checking the sequential number of each transmitted message. Both systems have this enumeration feature of the transmitted packets and make this information available in their corresponding back-ends. This information will be worked out to identify, within a numerical sequence, those packets that were not received by the system.

Signal to Noise Ratio

Because they work in the same frequency range, there may be interference from one system to another. This co-interference is measured and compared during the simultaneous and alternated terminals transmission. As it is a real experiment environment, there are many interference in the spectrum, generated by primary systems, irregular transmissions, spurious in the spectrum, among others.

The individual test-drive gives the performance reference in the co-interference condition. In an attempt to understand the level of this variation, the comparison reference is the Signal-to-Noise Ratio (SNR) values presented by the two systems, during separate individual transmission and during the simultaneous transmission of the two terminals.

The SNR value of each protocol is acquired through the back-end of each system. In the case of the LoRa prototype, the local application has a database also from where, among others, it is possible to read the SNR value. In the case of Sigfox protocol, the carrier back-end platform does not directly provide the SNR value. However, with the use of specific APIs enabled by the Sigfox back-end operator interface, it is possible to acquire the desired SNR value.

Chapter 4

Performance Evaluation of LoRa and Sigfox Protocols in Mobility Scenarios

This chapter presents the results obtained with the experiments performed in a real scenario using the created prototypes presented in Chapter 3. The parameters signal to noise ratio (SNR), packet loss, and maximum distance reachable will be analyzed. The SNR parameter will aid in the protocols performance analysis along the path traveled providing data of the signal level received by the gateway and the received noise level value at the same time. Monitoring the variation of these parameters is important to support the comparison with other performance parameters such as packet loss. Packet loss is used as the quality index to compare the reception efficiency during the transmission process with mobility support and can be associated with SNR variation patterns. The results of the experiments performed on the road with the objective of measuring the maximum distance reached are also discussed.

4.1 Results Analysis of the Signal to Noise Ratio

For 20 days, the chosen route was traveled 6 times a day, resulting in a total of 120 experiments made. For each day, an average value was calculated. Better 10 experiments were selected due its similarity conditions according to city traffic, displacement speed, weather conditions, or an unexpected interruption. The 10 better experiments were chosen based on the maximum similarity between them. One characteristic that has been taken into account is the displacement speed profile during the course. Were also discarded the paths that had their speed profile with very abrupt variations or interruptions. Often, street traffic obstructed, paralyzed or forced the experiments detour through alternative routes, which compromise the experiments performed, due to the alteration of path and elevation profile. The experiments where the weather conditions variations forced an abrupt speed variation or even interrupting, were also discharged

The average SNR values of each protocol collected during the experiments are presented and then compared. A comparison profile will be based on the SNR averages values collected in the simultaneous transmission mode and another comparison profile will be with the alternated transmission mode. The SNR values are plotted according to the distance traveled from the gateway position, as a reference. Due to urban obstruction profile, an interference effects comparisons can be made between the SNR values and the type of urban density presented at that point of the SNR curve.

4.1.1 SNR Values for LoRa Transmission in Alternated Mode

Figure 4.1 describes the SNR curve behavior for experiments with LoRa terminal along the total distance traveled, which is about 2.7 km. This distance is limited due to the urban relief and its large transmission signal shadow areas. In this figure, it is possible to note that, despite its abrupt variations, there is a certain level of predictability. As expected, so far the terminal is from gateway, lower shall be its SNR value. This effect can be noted when terminal moves a mile away from the gateway.

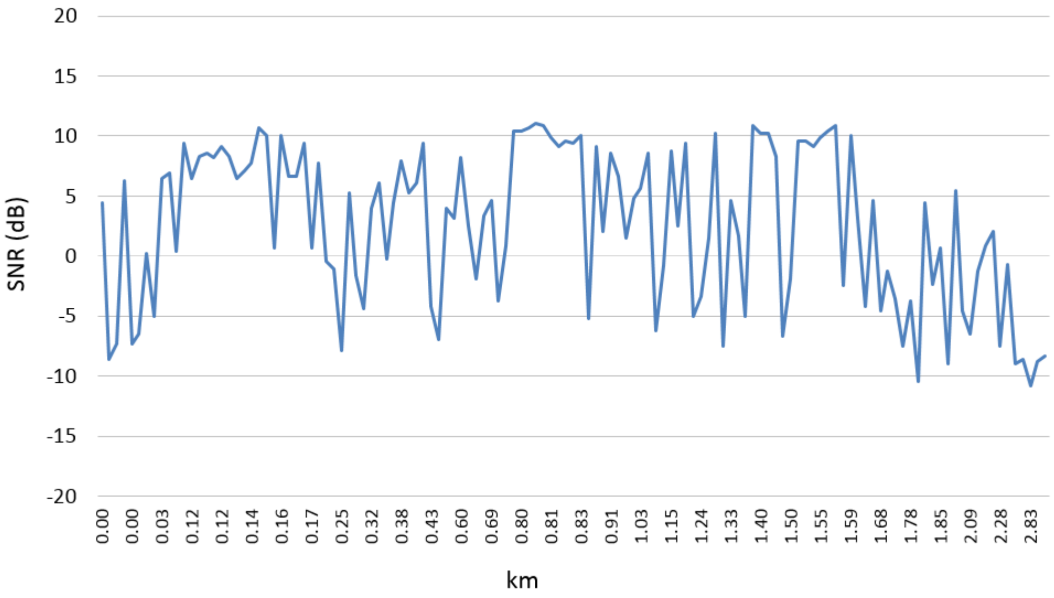

FIGURE 4.1: SNR Values for LoRa Transmission in Alternated Mode.

It is possible to observe that strong variation of the SNR in few distances can indicate how susceptible the protocol is regarding the variations imposed by the urban obstacles along the path. However, the system ability to receive transmissions with an SNR lower than -10 dB is noticeable. The system sensitivity level obtained during the experiments indicates that even with a certain variation of the urban density, it is possible to achieve good performance with LoRa protocol received packets.

It is also worth noting the 25 kbps LoRa transmission rate used, guarantees the rapid transmission of the entire packet within the same blocking condition window. This feature is advantageous in attempting to predict the characteristics for a given geographic location or defined obstruction level. Using the same blocking condition window, LoRa transmission can surpass the mobile transmission effects as Doppler and multi-path. Due to these effects, simulations or alternated experiments are necessary to estimate the transmission performance of a protocol.

4.1.2 SNR Values for Sigfox Transmission in Alternated Mode

For the same experimentation path with the simultaneous transmissions, the Sigfox protocol presented a different behavior when compared to LoRa protocol. From the analysis of Figure 4.2, a strong limitation of the SNR values acceptable by the Sigfox protocol is noted. This limitation is in the range of 6 to 16 dBs. Also clear is the floor of SNR in the value of 6 dBs indicating that Sigfox protocol requires the received signal level must be least 6 dBs above the noise level. This also means that packets that were received with SNR less than 6dB were discarded or were neither recognized. This 6 dBs window does not leave much margins for noise level variation. The reached value of 16dBs indicates that this is the maximum SNR value for a packet received under better propagation conditions during the experiments. It is evident the constant overlap of 10 dBs to the floor of noise. This is a very important information that can be used as maximum and minimum SNR reference values and can be considered to compose a technological solution.

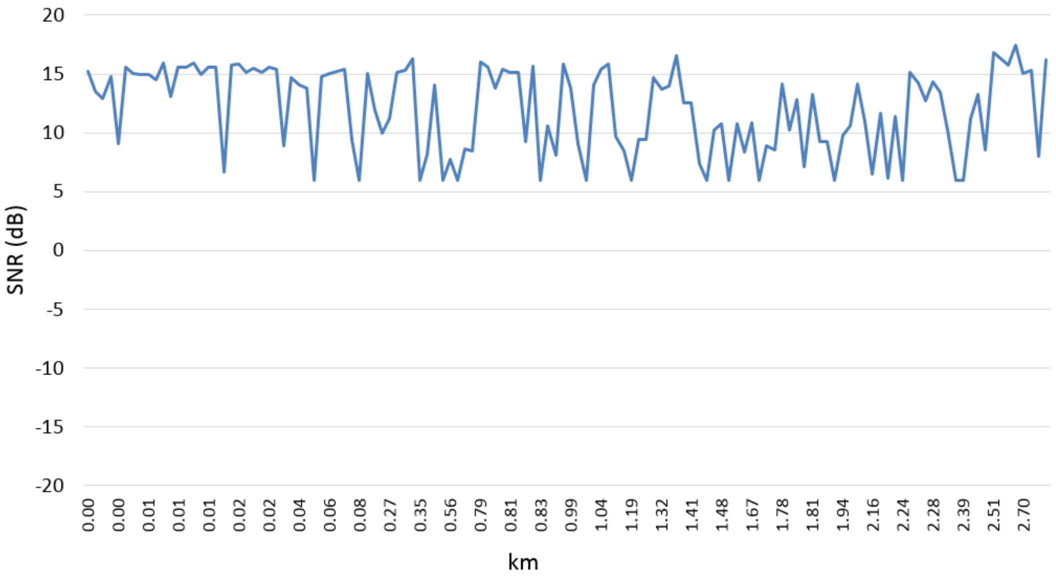

FIGURE 4.2: SNR Values for Sigfox Transmission in Alternated Mode

In a certain part of the route, from approximately 1.3 km from the base, the characteristics of the SNR for both protocols becomes inversely proportional. At the end of the path, Sigfox presents a noticeable increase in the SNR values against decreasing SNR values presented for LoRa alternated transmission mode.

The horizontal axis of Figure 4.2 indicates the distance from the terminal to the base at the transmission moment, in kilometers. Compared to the LoRa transmitting in alternate mode, it is possible to note a lower granularity of points observed on distance axis of Figure

4.2. This indicates a smaller amount of received packets when compared to LoRa protocol alternated transmission, at the same period of time, under the same environmental conditions. Even with high sensitivity achieved by the protocol development, Sigfox protocol supports limited SNR values, in this case, presenting a poor performance when compared to LoRa SNR variation.

As Sigfox transmission happens at 600 bps, environmental conditions can change strongly during transmission of a single package, since it takes a long time to be transmitted. It is also convenient to taki into account that, malicious degradation effects of a wireless transmission that takes a long time to be transmitted, can be much greater when compared to other protocol with the same characteristics. A higher transmission rate would take less time to transmit the same data size when compared to Sigfox, enjoying almost the same environmental conditions.

4.1.3 SNR Values for LoRa Transmission in Simultaneous Mode

It is also important to verify the behavior of the SNR between the two transmission modes of LoRa protocol. For LoRa transmission in simultaneous Mode, Figure 4.3 shows the behavior of the SNR curve variation as a function of the distance traveled from the gateway. For simultaneous transmission, the decrease of the SNR shown in the Figure 4.3 is evident as the terminals move away from the gateway. Then, it is possible to associate this increase of the noise factor to the simultaneous transmission of the two terminals.

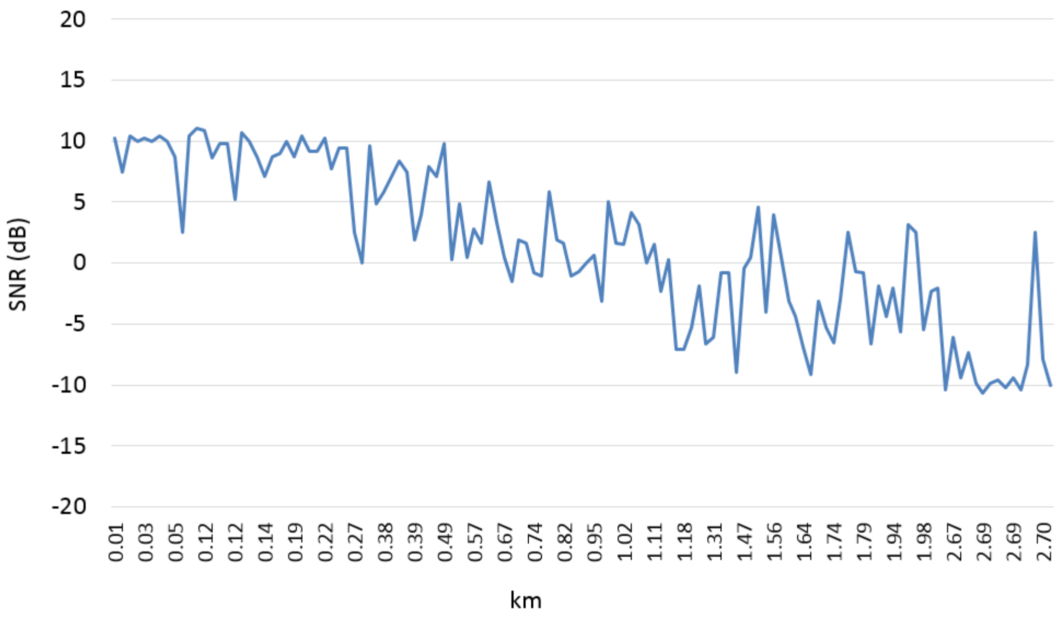

FIGURE 4.3: SNR Values for LoRa Transmission in Simultaneous Mode.

Initially, it is noticeable a differentiated characteristic at the beginning of the route where the protocol presented a positive and smaller SNR variation when compared to alternated transmission. In fact, it was expected the opposite happens with the simultaneous transmission because Sigfox generates a strong interference on LoRa transmission. It is possible to perceive the high efficiency of the signal coding and the CSS modulation used by LoRa. As the transmitted signal is scattered along the channel, only a small part of LoRa transmission spectrum is affected by the Sigfox transmission. Transmitting in narrow band, the strong and concentrated interference from the Sigfox transmission is overcome by the coding and spectral scaling used by the LoRa protocol. Some points with negative SNR values were already expected at the end of the path due to the presence of the Sigfox signal transmission simultaneously.

From 0.62 km away from the gateway, the protocol works with negative SNR regimes and tends to work with negative values from that. In this aspect, it must be considered the fact that, with a transmission rate of 600 bps and this is repeated three times, Sigfox directly influences the adjacent transmission systems because it has strong spectral energy.

LoRa protocol works with a spectral spreading technique and presents strong robustness. It is proven with the SNR operation demonstration up to 10 dB. This robustness can be justified with the presence of measurements with SNR values lower than -10 dB in the final region of the path.

4.1.4 SNR Values for Sigfox in Simultaneous Transmission Mode

The experiments results presented offers data to perform the analysis for LoRa and Sigfox terminals transmitting simultaneously. From Figure 4.4, it is noticeable that, for Sigfox, the SNR ranges for simultaneous transmission mode has an amplitude of 12 dB. Its maximum value is observed at 18 dB and its minimum at 6 dB. From this observation, it is now possible to visualize the Sigfox SNR operation limits. This information, itself, indicates that Sigfox operating SNR amplitude can be constant, regardless of the interference level offered by the environment. It is up to Sigfox terminal to fit or adapt to these characteristics and conditions. As transmission power is limited by standards, the only possibility of system tuning is working on the terminal antennas characteristics.

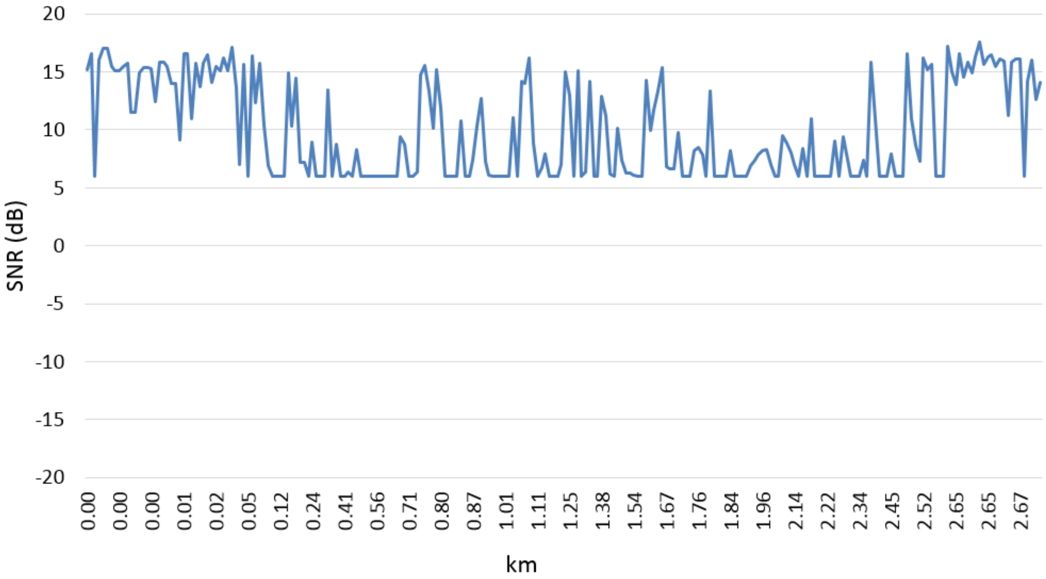

FIGURE 4.4: SNR Values for Sigfox Transmission in Simultaneous Mode.

It can be also observed that Sigfox shows remarkable robustness due to two reasons. First, Sigfox works with a narrow band modulation presenting transmission energy concentration in a small part of the used spectrum. Second, Sigfox re-transmits the same packet three consecutive times to guarantee the packet receiving and best SNR obtained. On receiving, Sigfox platform chooses the best SNR packet to process. Repetitive transmission coupled with the construction of an appropriate radiating system suitable for an application can present significant improvements. On the other hand, this technique of sequential re-transmission leads to an energy consumption and spectrum occupation that could be better used. It is important to highlight the Sigfox SNR curve profile since it presents a linear behaviour from the beginning to the end of the route. This linear variation limited from 6 db up to 18 dBs. Even with the fall of the received packet index Sigfox presents an optimal SNR performance.

4.2 Results Analysis of Packet Lost Indices

The data collected and results analysis of the experiments considering transmission at the simultaneous mode are presented. The packet loss characteristic of each protocol is evaluated with the protocols transmitting in simultaneous and alternated modes. Then, it is also possible to compare the performance of the same protocol when presenting the results of the two transmission modes. The curve and values shown in the figures are based on the numeric results average obtained on each experiment.

4.2.1 Percentage of Packet Loss for LoRa and Sigfox Transmitting in Simultaneous Mode

In the results shown in Figure 4.5 it is possible to observe that, for simultaneous transmission mode, Sigfox protocol unexpectedly undergoes strong values variation throughout the experiment.

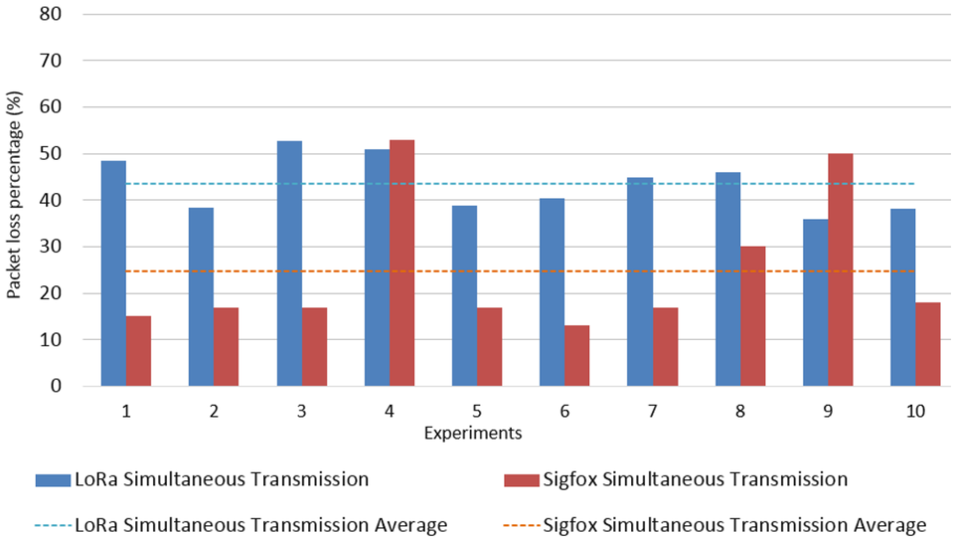

FIGURE 4.5: Packet Loss Percentage for LoRa and Sigfox Transmitting in Simultaneous Mode.

In Sigfox case, for the first experiment, the packet loss indices have its lowest points of the curve indicating low packet loss value. In the fourth experiments both protocols packet loss values reached 50% of the total messages transmitted. Next, the curve shows values less than 20% and following this alternation. Despite the inconsistencies, Sigfox protocol packet loss average value is less than 30%. Lora protocol presents a worst performance with packet loss average value with more than 40%. As the average is slightly more than 20%, this value can be taken as the minimum reference for any expectation within a similar scenario. These results affirm that performance of LoRa is worse for the simultaneous transmission condition. This demonstrates the strong interference that Sigfox protocol generates during its transmission. The fact that Sigfox protocol transmits 3 identical and simultaneous messages demonstrates the strong interference that the Sigfox protocol imposes during its transmission. Looking at the results for LoRa protocol, considering the curve and average values, LoRa presents low performance when compared with Sigfox.

For Lora, the variation of packet loss values between experiments is lower when compared to Sigfox variation curve. That is, the values present smoother variations with the best case happening with Sigfox packages loss about 10%, and to the worst case that presents packet loss greater than 50%. Although LoRa protocol has a high rate of packet loss, experiments indicate the variation around its average curve is smooth. The low variation of LoRa packet loss curve may indicate a greater level of accuracy in attempting predictability of packet loss for LoRa protocol. On the other hand, following the variation of the packet loss curve for Sigfox protocol and its average, it is possible to observe the result of average packet loss is around 25%. Thus, the average packet loss of Sigfox is considerably lower than the average packet loss variation for LoRa. However, the instability of the values obtained for the simultaneous transmission of Sigfox does not inspire reliability in the predictability of its performance.

In LoRa results, the main cause of packet loss would be the high interference level between the two protocols transmission. With smooth variation between the experiments, the average packet loss can be used to attempt to predict loss of packets, thus favoring the specification of some application that can use LoRa protocol. The lack of convergence in the presented results does not inspire strong expectations for applications that demand a certain predictability of packet loss.

4.2.2 Percentage of Packet Loss for LoRa and Sigfox Transmitting in Alternate Mode

After analyzing the scenario where experiments were taken with the two protocols simultaneously transmitting, it is expected now a scenario with low interference level between the protocols.

Figure 4.6 presents the results of the packet loss index variation for LoRa and Sigfox protocols for the alternated transmission scenario.

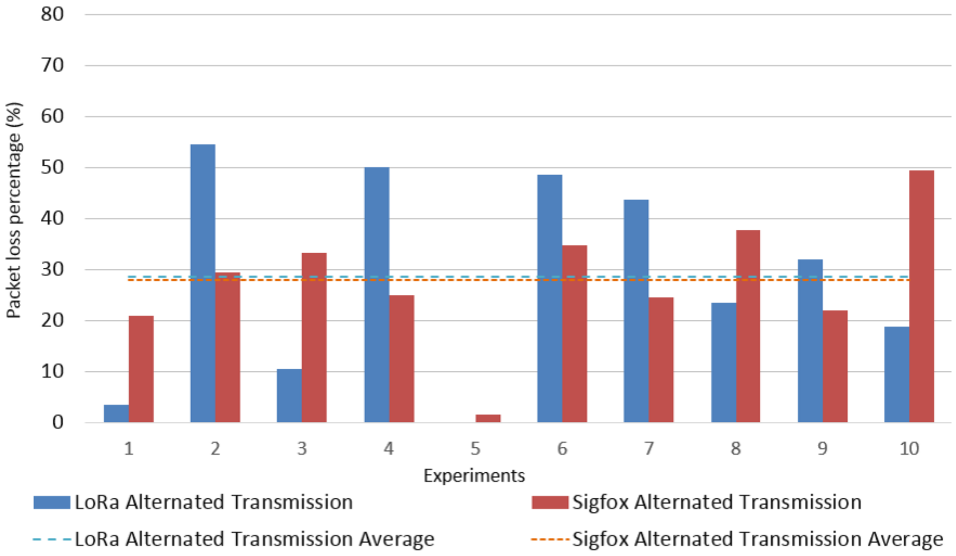

FIGURE 4.6: Percentage of Packet Loss for LoRa and Sigfox Transmitting in Alternate Mode.

Operating alternately, it is believed that transmissions of the two protocols now have no interference between them. However, because the experiments are made in a real environment, it is not possible to guarantee the absence of interference inherent to the environment of the experiments scenario. Observing the results of the experiments in this scenario, it is able to perceive a strong fall in the average of lost packets for both protocols. The fact that the average value has reduced does not necessarily indicates an improvement in terms of performance, since the points dispersion are bigger. Increasing dispersion reduces reliability in the LoRa protocol behavior predictability. A less aggressive characteristic was expected because the results obtained in the SNR study for the alternated transmission between the protocols. LoRa simultaneous transmission SNR curve presents better results than those obtained during the simultaneous transmission, as observed in Figures 4.6 and 4.5. Although both protocols presents a low average percentage of packet loss around 30%, the variation of the values obtained in the different experiments have a large variation range. This curve behaviour does not provide enough information to guarantee reliability resulting from this scenario.

For this experimental scenario, there is no relationship between the variation of the SNR curves behaviour and the packet loss indexes. Even though, it has a lower index of variation than the previous scenario, Sigfox protocol has an average packet loss similar to the previous scenario. For LoRa protocol, a lower level of variation in the packet loss index curve is observed when compared with LoRa protocol transmitting simultaneously.

For Sigfox, dispersion of the values obtained by the experiments is smaller than the dispersion obtained for LoRa. This lower dispersion indicates a more stable behavior of the Sigfox performance. In this case, the expectation was a significant improvement in the index of packages lost by Sigfox. But, its performance was also worse when compared to its own performance for the simultaneous transmission.

4.2.3 Percentage of Packet Loss for LoRa Transmitting in Simultaneous and Alternated Modes

The LoRa protocol alternated transmission results showed greater values of dispersion, obtained in the experiments. In spite of this, the LoRa alternated transmission presented an average value of lost packets, better than the average value of lost packets, for simultaneous transmission mode.

Even with this strong variation in the lost packet index curve, LoRa protocol presents a strong improvement in terms of performance when compared to the scenario of simultaneous transmission of the two protocols as illustrated in Figure 4.7. This performance improvement is expected due to the reduction of interference between the protocols, that occurs during the simultaneous transmission.

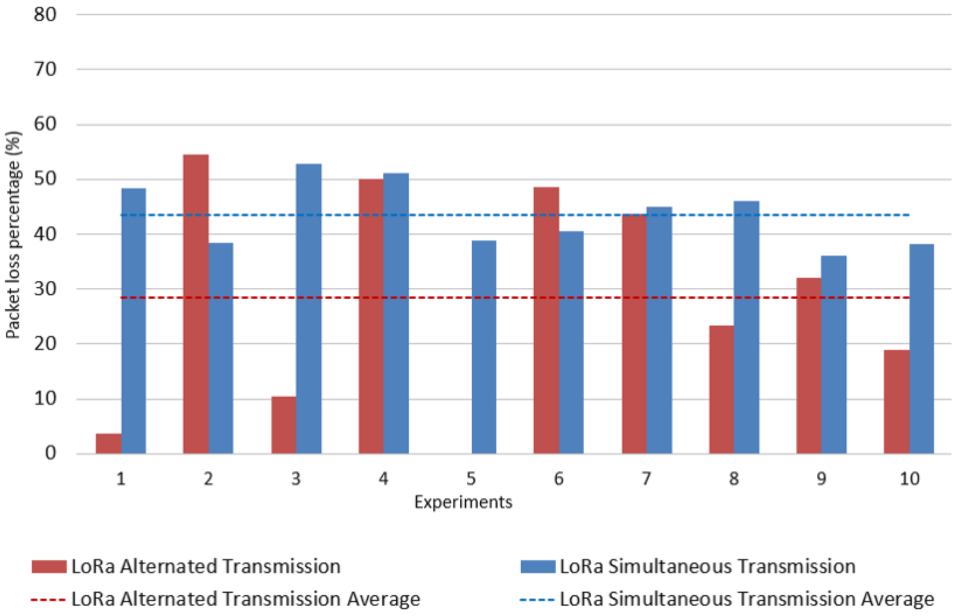

FIGURE 4.7: Percentage of Packet Loss for LoRa Transmitting Both Modes.

For the simultaneous transmission mode, LoRa presents a higher average value of packet loss when compared to the alternate transmission mode. This behavior was already expected. However, the variation around the average value is small. This can be noticed by the smooth variation of the values obtained in the experiments around the average value.

Despite the notable increment in the average packet loss index, the smooth variation of LoRa packet loss index curve still offers some degree of uncertainty in order to take this value as a reference for a given situation, even if it is in a similar scenario. This comparison becomes more interesting since it is comparing the performance of LoRa with itself, in situations of different levels of interference in the Radio Frequency (RF) spectrum.

4.2.4 Percentage of Packet Loss for Sigfox Transmitting Both Modes

Similar to the comparison done for the LoRA protocol, it is now possible to compare the packet loss indexes between the two transmission modes of Sigfox. This comparison will allow to observe the packet loss index behavior when Sigfox is transmitting with or without interference of LoRa protocol transmission. The lost packet indexes for Sigfox are presented in Figure 4.8. Experiments 4, 5, and 9 presented a higher number of packets lost by Sigfox with simultaneous transmission when compared to packet loss observed for Sigfox with alternating transmission. Although these experiments strongly contribute to the increase of the mean packet loss value for Sigfox transmitting in the simultaneous mode, it stills remained lower in comparison with transmission in the alternate mode.

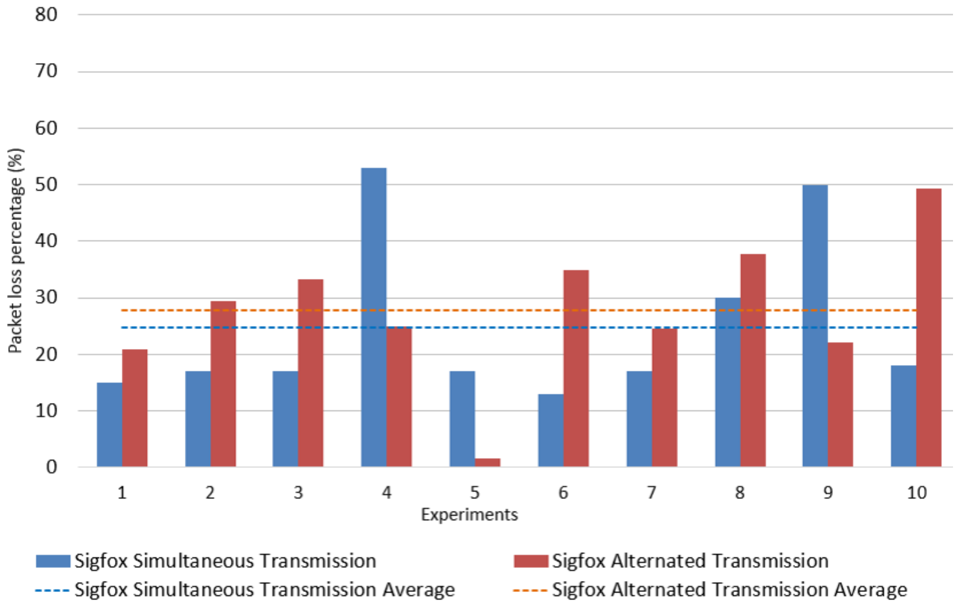

FIGURE 4.8: Percentage of Packet Loss for Sigfox Transmitting Both Modes.

Sigfox transmits at low data rate in a narrow bandwidth resulting in a longer transmission time. Longer transmission time may be more susceptible to noise peaks or short-time interference, and transmission power peaks incoming from external systems carriers in same frequency band. However, when comparing the packet loss performance index in the two transmission modes, it is noticeable a small but significant increment in the average packet loss index value for Sigfox transmitting in alternated mode. But when analyzing the packet loss index curve, it is possible to note that the packet loss index in the alternate transmission mode follows the variation of the packet loss ratio in the simultaneous transmission mode.

4.2.5 Percentage of Packet Loss

Based on the results and analyzes using the previous metrics, it is now possible to observe the results of the packet loss indexes and comparing the performance of the two protocols, in both transmission modes. Figure 4.9 shows the comparison of the packet loss obtained through the experiments.

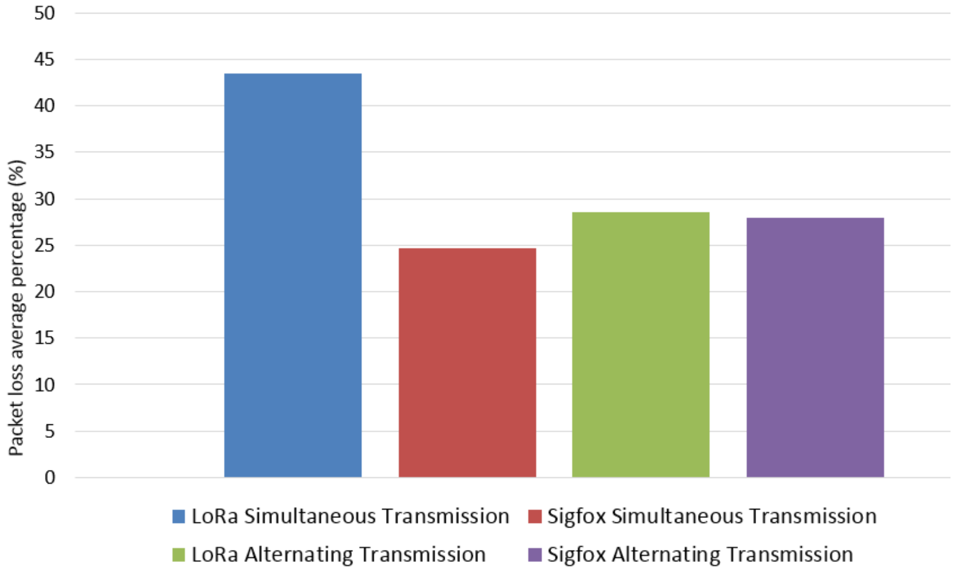

FIGURE 4.9: Packet Loss Percentage for LoRa and Sigfox Protocols using Simultaneous and Alternating Data Transmission.

LoRa protocol presents most discrepant situations in the scenario of simultaneous transmission between them. For simultaneous transmissions, it was expected that the LoRa protocol would present a higher level of interference, and thus, a worse performance, confirmed by the graph. In alternating transmission condition, LoRa protocol behavior was more consistent and presented better performance. LoRa protocol chirped spread spectrum (CSS) modulation technique offers strong robustness upon low or negative SNR even with great mobile radio channel characteristics variation. But under simultaneous transmission, LoRa protocol presented the highest packet lost ratio indicating that Sigfox transmission has a great impact on LoRa protocol performance regarding packet lost index. On Sigfox packet loss average indices, it is possible to observe throughout the experiments that Sigfox protocol average values of packet lost indexes remains around 30%. This results indicates that Sigfox protocol RFTDMA technique associated with three times re-transmission of same packet has a better performance than LoRa when compared packet lost index.

Comparing the simultaneous and alternated transmissions using Sigfox, a low variation of the results is observed among them with a variation below 10%. This low variation may indicate an indifference between the two transmission modes. For the both transmission modes using LoRa, this difference is around 25%. This high variation can be associated to the interference presented by the Sigfox terminal during simultaneous transmission mode. When compared the simultaneous transmission mode presented by the two protocols, it is noticeable that LoRa presents a packet loss percentage much higher than Sigfox. This difference can be associated to the interference generated by Sigfox transmission on LoRa during simultaneous transmission. In the case of the alternating transmission between the protocols it is possible to observe that the variation between packet loss is smaller than all the previous conditions as expected due the absence of the generated interference. This low values may indicate that, for alternate transmissions and under the same experimental conditions, the performance of the two protocols is similar. The objective of mobile communication systems is to offer services over mobile radio channels. Different from static networks, point-to-point or dedicated communications channels, wireless communications systems with mobility support have its performance drastically affected by the mobile radio channel random variation conditions that do not offer easy analysis. During a mobile transmission, obstructions like buildings, mountains and urban density generates characteristics changes on the path between the transmitter and receiver. For a mobile terminal moving in space, its speed of motion affects its signal level fades. Characteristics that affects mobile radio channel performance are generally attribute to obstacles reflection, ground reflection, diffraction, scattering, Doppler effect, time dispersion parameters, among others. One of the most difficult part of mobile radio design is modelling the radio channel characteristics. It is usually done in a statistical perspective based on measurements made specifically for an intended communication system or spectrum allocation [138] [139]. The effects of the random variation of the radio channel are reflected in the results of packet loss where it is possible to perceive the inconsistency and the absence of convergence of the packet loss indexes of the LoRa and Sigfox protocols.

LoRa protocol presents most discrepant situations in the scenario of simultaneous transmission between them. However, in alternating transmission condition, LoRa protocol behavior was more consistent. LoRa protocol chirped spread spectrum (CSS) modulation technique offers strong robustness upon low or negative signal to noise ratio even with great mobile radio channel characteristics variation. But under simultaneous transmission, LoRa protocol presented the highest packet lost ratio indicating that Sigfox transmission has a great impact on LoRa protocol performance regarding packet lost index.

Regarding the values presented by Sigfox, is possible to observe throughout the experiments that Sigfox protocol average values of packet lost indexes remains around 30%. This results indicates that Sigfox protocol random frequency and time division multiple access (RFTDMA) multiple access technique associated with three times re-transmission of same packet has a better performance than LoRa when compared packet lost index.

4.2.6 Road Experiments Results Analysis for LoRa Protocol

The results of the experiments are printed on Figure 4.10 with the path route and acquired points over a relief terrain map layer. The red thin line represents the 15 km (10 miles) radius reference point and the green line represents 10 km (6.21 miles) one. The orange line indicates the path driven during the experiments. The blue points indicate the coordinates transmission points of the projected terminal during the road drive-test that were transmitted and successfully received by LoRa gateway.

Figure 4.11 shows the results of the road outside the urban perimeter of the city. The red icon at left upper corner inside of Figure 4.11 represents the altitude of the obtained points, as well as the altitude profile of the terrain profile represented by the shaded gray curve. On the right y-axis, the reading of the blue curve values represents the speed variation. On the x-axis, the distance traveled along the road is scaled. At road, the developed speed reached the maximum of 97.2 km per hour with an average value of 53.4 km per hour. It is possible to notice two zero points at the speed curve due to two stops necessary due to the traffic.

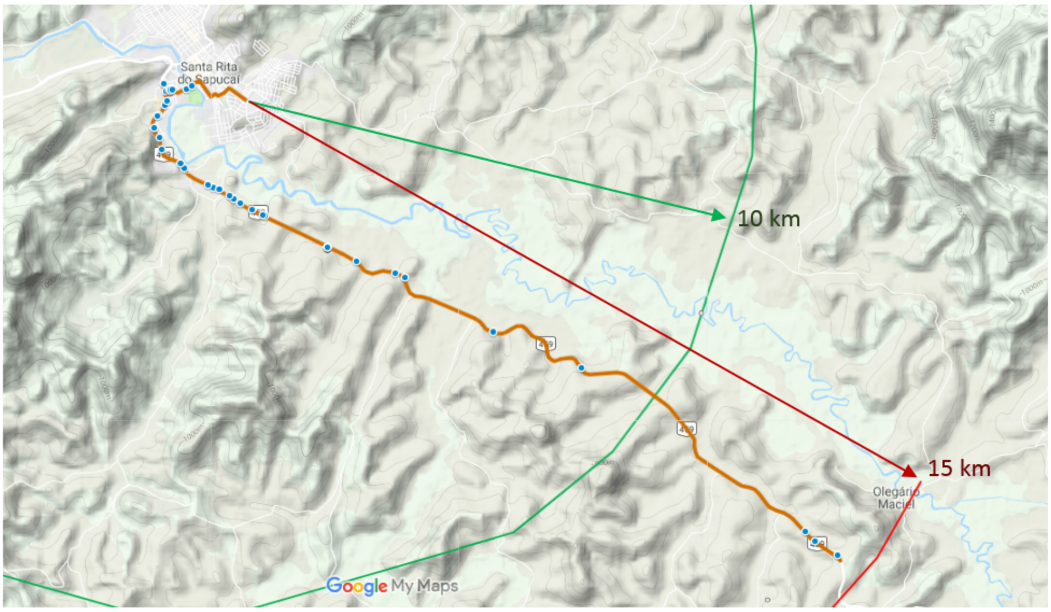

FIGURE 4.10: LoRa Protocol Road Experimentation.

The dark points over the altitude curve are the acquired coordinates points transmitted by the terminal. The antenna height is represented by its red symbol on the left y-axis.

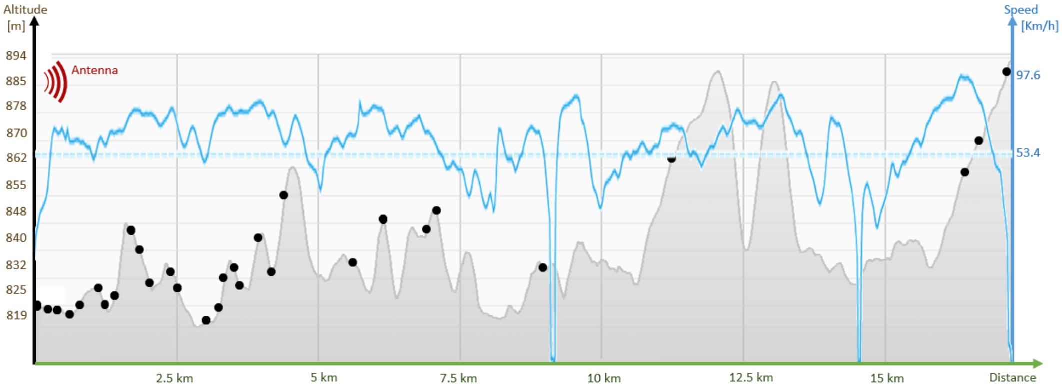

FIGURE 4.11: LoRa Protocol Road Experimentation Results.

In road drive-test, it is noticeable the lack of received packets during significant part of the journey, mainly after 7.5 km traveled. It is expected that two main reasons can affect this result, the increase in the speed of journey and the distance between the terminal and the gateway antennas. The maximum distance reached was 13.6 km (8.6 miles).

4.2.7 Road Experiments Results Analysis for Sigfox Protocol

As same as LoRa road experimentation, the experiments results are printed in Figure 4.12, with the path route and acquired points over a map layer.

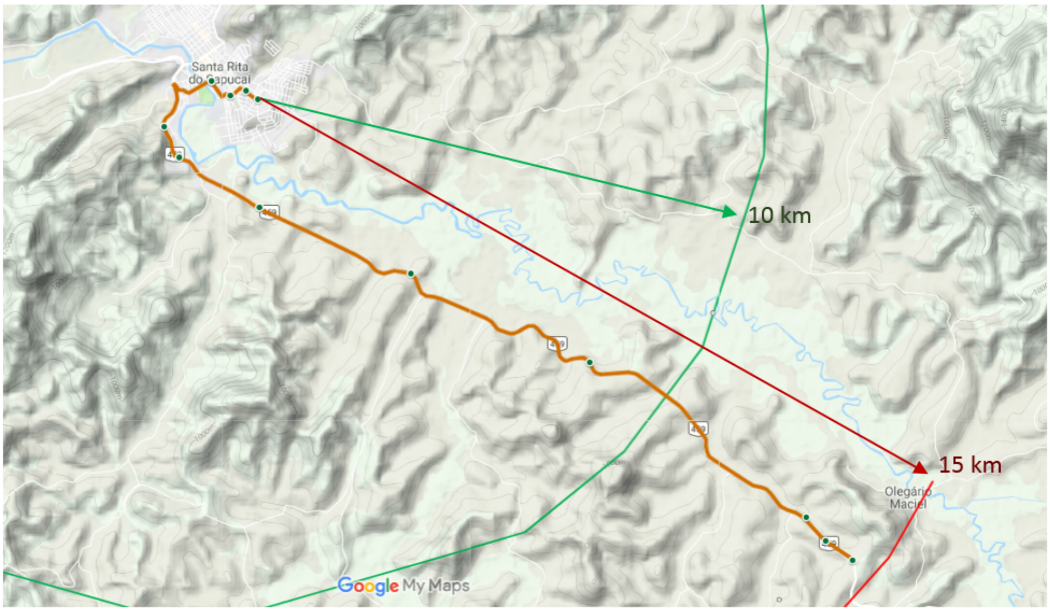

FIGURE 4.12: Sigfox Protocol Road Experimentation.

On Figure 4.12, the orange line represents the path traveled during the experiments and the green points represent the points of the coordinates received by the Sigfox network. Overlapped on the terrain relief, there is the path where the drive-test was done and the points indicating the coordinates sent to the back-end of the Sigfox network.

With the drive-test for this scenario, Sigfox network received the transmission of the points indicated on the map during the traversed trajectories. At the beginning of the route, in an urban area, the collection of coordinates had a greater index of success because, at this region, the relief was favorable. These data are exposed in Figure 4.13.

On Figure 4.13 the altitude parameters can be compared in the main vertical axis. The altitude profile highlighted in the image background with the gray shadows and the speed profile presented by the blue line with its measurements in the secondary vertical axis. The orange dots represent the coordinates received at the back-end of Sigfox platform, the background on the gray shadows represents the altitude of the point at the time of transmission and its value can be read on the main vertical axis. Orange points numbered from 750 to 778 represents the sequence number of received packets.

The last received point, number 778, was received at an altitude of approximately 900 m. Reflecting this point in the blue curve, it is possible to read that the object was moving at a speed of approximately 70.6 km/h at the time of transmission. On the horizontal axis, it is possible to observe that packet 778 was transmitted at a maximum distance of 13.66 km from the base station reception antenna. All these records are stored at Sigfox back-end.

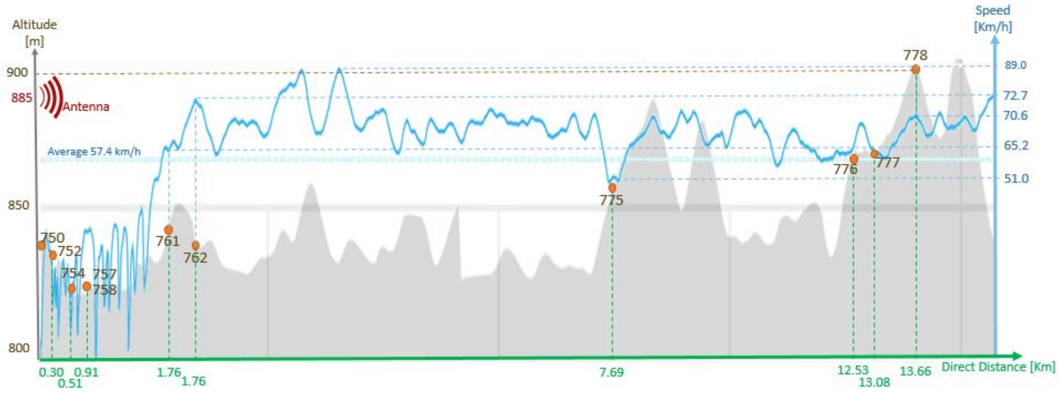

FIGURE 4.13: Sigfox Protocol Road Experimentation Results.

According to the results shown in Figure 4.13, it is possible to conclude that, although relative, the high speed was not such a significant obstacle since it was possible to perceive the reception of a valid sequence between points 775 and 778. The absence of readings in the interval between points 762 and 775 was impacted by the shadow area because this part of the route is located behind a hill whose altitude exceeds in approximately 20 meters the altitude of the system antenna. In these experiments, altitude and lack of coverage had a greater impact in the absence of readings, more than the mobility characteristics.

4.3 Summary

This chapter presented the results obtained through the experiments carried out in the comparison of MAC protocols LoRa and Sigfox with mobility support and the corresponding analysis. The values of SNR and percentage of packet loss were taken as reference parameters to be exploited. A result analysis of a coverage distance case study were also presented.

Chapter 5

Conclusion and Future Works

This chapter presents the lessons learned, main conclusions, and future works of this study. Along the study, including experimental scenario design and experiences, it is possible to point out the difficulties faced, the needs for project readjustments, and surpassed interference. The final conclusions of the work are presented bringing relevant considerations about the studied protocols. They are also highlighted some relevant points that stand out during the research and through the experiments that may be considered in future works.

5.1 Lessons Learned

Throughout this study, several lessons were learned that may contribute to future studies and research on MAC layer protocols for IoT, especially in scenarios with mobility support. They can also contribute to developers and designers to improve or create their solutions.

During the design of the case-studies to perform the experiments, it was necessary to know in depth the parameters of Lora protocol because adjustments in the gateway were very important for the construction of the prototype. The ease of adjustments in Lora transmission parameters, such as spread factor (SF) and bandwidth (BW), allowed a fair spectral similarity with Sigfox protocol. For test-drives, it was needed to adjust the system parameters before starting the experiments.

During the experimental scenario construction, it was necessary to look for LoRa antennas that presented similar irradiation characteristics to those of Sigfox. It is a proprietary protocol and it is not possible to access its system so, it is not allowed to change the characteristics of its antennas. As the used antennas were not the same, it was necessary to verify the entire path within the beam of vertical irradiation for each antenna. Therefore, there may be a need for definition and adjustment of the irradiating system depending on the application.

In the description of LoRa protocol there is strong emphasis that LoRa protocol does not present index of packages received with errors in its payload. During the experiments, it was possible to confirm this characteristic since LoRa did not present any package received with an invalid payload. In the case of the Sigfox protocol, there is no mechanism for packet integrity checking when receiving the packet. Therefore, in order to have reliability of the received data, a packet payload verification mechanism is required upon receipt.

In Sigfox, it was observed that due to three times re-transmission of same packet but its back-end only turns available the best package received among these three. By this way there is already a pre-selection of the best SNR index received by the Sigfox platform, processed, and made available for reading.

Initially, the construction of the modules programming software was done to meet only the characteristics of simultaneous and alternating transmissions. However, during the experiments, it was necessary to adapt the software not only to the measured parameters but also from an accidental hardware or measurements interruption by the vibrations and sudden movements during the experiments.

5.2 Concluding Remarks

In this dissertation a performance study of medium access control (MAC) layer protocols LoRa and Sigfox with mobility support was presented. To achieve this, a deep study of IoT-based MAC layer protocols was done. Within this study, the protocols were identified and classified according to distance coverage in short and long-range coverage protocols. The comparison scenario is offered through the qualitative and quantitative metrics suggested for the protocols performance analysis. The experiments scenario is exposed with the detailing of software and hardware elements used to compose the application developed to realize the experiments. In order to evaluate the performance of LoRa and Sigfox protocols with mobility support, a real experiment prototypes were constructed to obtain the necessary data for the performance analysis through measurements. With the measurements obtained during the experiments, the quantitative and qualitative performance analyzes of two protocols could be made. After completing the qualitative and quantitative comparisons, is observe that some points deserve attention. To conclude this study, the more relevant findings of this study concerning the performed experiments are summarized as follows.

In a mobility environment aspect, a strong and abrupt propagation conditions variation of the RF signal is expected in the scenario due mobile radio channel random variation characteristics. Observing the coverage range of LoRa protocol, signal do noise ratio (SNR) values obtained during the experiments ranges from -100 dB to 100 dB and the profile of the SNR curve is expected to have a better reliability in more adverse situations. It is evident the well defined limits of Sigfox SNR values variation. For this case, its limits are now well known. This makes the specifications of the platform design favourable for an application that requires these well-known characteristics in order to have a good predictability of the results obtained.

With just 12 bytes in its payload to accommodate data, reaching large scope and easy to deploy due to the business model adopted as platform solution, Sigfox becomes a fast and practical solution that has a strong demand when considering applications that demands for a few information bytes at low frequency of data transmission. Sigfox is designed for measurements, telemetry, and long range coverage scenarios. It has a well defined application demand.

For applications that demand mobility, Sigfox presents less performance when compared to the same solution in LoRa considering the SNR parameters associated to a simultaneous transmission. The large SNR tolerance range presented favors LoRa protocol reliability perception.

The main perceived characteristic that affects Sigfox deployment in mobile environments is the large transmission time of its package due to the low transmission rate conceived by the protocol, which cannot be changed. The Sigfox characteristic of the consecutive and non-intelligent transmission of three identical messages to ensure the robustness may be unnecessary, thus causing unneeded power consumption and spectrum occupancy depending on the use case. However, in displacement situations, this feature of Sigfox can be favorable because each of these three transmissions will enjoy different conditions of the mobile radio channel.

LoRa protocol can carry up to 255 bytes in its payload thus allowing greater flexibility in a wider range of applications. Even using modulation and transmission techniques, LoRa protocol also has its limitations when considering parameters such as penetration in indoor environments. Results obtained may assist in the definition, development, and configuration of new protocols in a similar environment, such as the need for its irradiating system optimization using MIMO or directional antennas.

Being a local and independent system, LoRa protocol platform offers an easy customization and optimization of used resources. This solution profile requires human resources with a certain expertise to keep the technological environment under operation. It is possible to note that the application and the used environment will determine the type of the platform architecture to be used.

5.3 Future Works

As future works it is important to cite the properties of other protocols that can be adapted or used by LoRa and Sigfox to improve their performance.

The available auxiliary technologies can be employed to enhance the protocols' functionality and also be used as enrichment techniques. With the advent of the fifth generation of mobile communications (5G), beamforming and MIMO techniques are becoming accessible and incorporated by other PHY-MAC protocols. Depending on the terminal nodes geographical distribution, antenna sectorization feature can be considered. These features are more practical and easy to apply in both studied protocols. The narrow band IoT (NB-IoT) protocol arises bringing improvements in technologies of the current mobile networks regarding the techniques of channels allocation and frequency spectrum usage adjustments that demands a future comparison study with the results of this work as well as raising new parameters and references.

The use of MIMO and beamforming techniques is limited when the protocol is proprietary and difficult to adjust its characteristics like Sigfox. This limitation imposed by the use of these techniques is based on signal processing required in both the physical and MAC layers. Being an open framework protocol, LoRa accepts adjustments techniques, as well as easy interaction deployments with other protocols. Therefore, there is space for the study and experiments of these techniques feasibility and implementation, which are very powerful and efficient.

The availability of a platform with multiple gateways can bring the perspective of spatial diversity into this mobility solution. The ability to receive the same packet by more than one gateway can make even more robust the systems performance against packets loss due to Doppler effect and low signal level in environments with obstacles. It may be another way to evaluate the accuracy of the coordinates acquired by the terminal signal triangulation comparing information of each gateway against the geographical coordinates provided by GPS (GLobal Positioning System).

Another important feature that a multi-gateway solution can bring is the use of Fog and/or CLoud solutions for storage and treatment of incoming data. Depending on the information obtained, this information base can be useful as a database for future projects, information integration, and networks intelligence. Working on Fog or Cloud consolidated solutions, the handover process can be brought to the application level and deserves study.

Although the quantitative measurements of messages received correctly and with full integrity of its package, can give dimensions of these two physical layer protocols as spectral efficiency. Spectral efficiency, when measured, can bring another perspective of energy consumption and transmission characteristics such as spectrum usage improvements.

The ability of terminals to roam between different protocols is also an untreated topic. The design of hybrid systems such as multi-protocol gateways and terminals seems to be an unavoidable consequence of IoT protocols heterogeneity [134]. The rapid evolution of hardware induces the development of multi-protocols, multi-band radio interfaces with adaptive, and opportunistic techniques such as 5G. These protocols are required to be inter-operable in different layers so their performance can be compared. For example, in areas of roaming between the systems and operators, technical alliances are necessary to obtain a good cross-border roaming, including security issues.

Finally, but not limited to this, it is possible to complement this study with an experiment to investigate the performance of LP-WANs based on transmission characteristics under high speed displacement and compare with mobile networks protocols like NB-IoT, LTE's standards, and the coming 5G mobile protocol.

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