Sudan University of Science and Technology

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Modeling and Evaluation of LoRa and Sigfox Low Power Wide Area Networks for Internet of Things

نمذجة وتقييم شبكات لورا وسيق فوكس الواسعة متدنية القدرة لأنترنت الأشياء

A Thesis Submitted in Partial fulfillment for the Requirements of the Degree of M.Sc. in Electronics Engineering (Communication Engineering)

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استهلال

"يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنكُمْ
وَالَّذِينَ أُوتُوا الْعِلْمَ دَرَجَاتٍ وَاللَّهُ
بِمَا تَعْمَلُونَ خَبِيرٌ "

سورة المجادلة الآية رقْم (١١)

DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

ACKNOWLEDGEMENT

I would like to express my thanks to Dr. Niemah Izzeldin Mohamed Osman; she has been the ideal thesis supervisor. Her sage advice, insightful criticisms, and patient encouragement aided the writing of this thesis in innumerable ways. I would also like to thank the department of Electronics Engineering whose steadfast support of this thesis was deeply appreciated.

Not least of all, I owe so much to my whole family for their undying support, their unwavering belief that I can achieve so much.

Abstract

During this decade, there is a huge expansion in the number of low-power Internet connected devices. The Low Power Wide Area Network (LPWAN); because of its low-cost communication ability and long-range, is considered as the future wireless communication standard for Internet of Things (IoT). Although IoT is gaining more popularity, it is hard to identify the suitability of LPWAN technologies for those IoT devices. In this thesis a simulation modeling had been developed focusing on LoRa and Sigfox to evaluate each individual LPWAN technology.

The influence of the number of devices on LoRa and Sigfox performance had been evaluated by measuring collision, packet error rate and spectrum under 500 and 1000 number of IoT devices and bandwidths (125,250 and 500KHz)for LoRa and 200 KHz for Sigfox. The results show that Sigfox has less collisions and packet error rate compared to LoRa. Also in general, by increasing the number of devices leads to increasing collision and packet error rate, the higher the bandwidth the less collision and more available slots.

المستخلص

خلال هذا العقد ، هنالك توسع كبير في عدد الاجهزة منخفضة الطاقة المتصلة بالانترنت.والشبكة ذات النطاق الواسع و منخفضة الطاقة نظرا لقدرتها علي الاتصال طويل المدى و منخفض التكلفة تعتبر معيار الاتصال اللاسلكي المستقبلي لانترنت الاشياء. وعلي الرغم من أن انترنت الاشياء يكتسب شعبية اكتر،الا أنه لازال من الصعب تحديد مدى ملائمة تكنولوجيات هذه الشبكة لاجهزة انترنت الاشياء.

في هذا البحث تم تطوير محاكاة تركز علي تكنلوجيتي (لورا و سيق فوكس) لتقييم كل تقنية بصورة فردية ويتم ذلك بتقييم تأثير عدد الاجهزه علي اداء التكنلوجيتين. تم هذا التقييم عن طريق قياس تصادم الحزم و معدل الخطأ في الحزم و شكل الطيف تحت قيم مختلفه لعدد اجهزه انترنت الاشياء (٥٠٠ و ١٠٠٠جهاز) تحت عدد من الحزم الترردديه (١٢٥ ،٢٥٠و٥٠٠ كيلوهيرتز) بالنسبه ل(لورا) و ٢٠٠ كيلوهيرتز بالنسبه ل(سيق فوكس) . تظهر نتائج المحاكاة أن (سيق فوكس) لديها تصادمات و معدل خطأ في الحزم اقل من (لورا) وأيضا بشكل عام ، زيادة عدد الأجهزة يؤدي إلى زيادة تصادم الحزم و معدل خطأ التصادم ، بالإضافة إلي أنه كلما ازداد عرض النطاق كلما قل تصادم الحزم.

LIST OF CONENTS

5 Conclusion & Recommendations

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

LPWAN	Low Power Wide Area Network
IoT	Internet of Things
M2M	Machine to Machine
LoRa	Long Range
GUI	Graphical User Interface
GIS	Geographic Information System
WSN	Wireless Sensor Networks
UNB	Ultra Narrow Band
SSM	Spread Spectrum Modulation
CSS	Chirp Spread Spectrum
ADR	Adaptive Data Rate
SF	Spreading Factor
BPSK	Binary Phase Shift Keying
VPN	Virtual Private Network
HTTP	Hypertext Transfer Protocol
RF	Radio Frequency
ESTI	European Telecommunications Standards Institute
SDOs	Several Standard Developing Organizations
SIGs	Special Interest Groups
LTE-M	Long Term Evolution for Machines
NB-IoT	Narrow Band IoT
GPRS	General Packet Radio Service
QoS	Quality of Service
PER	Packet Error Rate
RSSI	Received Signal Strength Indicator
SNR	Signal to Noise Ratio

Chapter One

Introduction

1.1 Overview

Low Power Wide Area (LPWA) networks are attracting a lot of attention primarily because of their ability to offer affordable connectivity to the low-power devices distributed over very large geographical areas. In realizing the vision of the Internet of Things (IoT), LPWA technologies complement and sometimes supersede the conventional cellular and short range wireless technologies in performance for various emerging smart city and machine-to-machine (M2M) applications. By 2020, more than twenty five billion devices would be connected through wireless communications [1].

In accordance with the rapid growth of (IoT) market, low power wide area (LPWA) technologies have become popular. In various LPWA technologies, Sigfox and Long Range (LoRa) are two leading technologies.

1.2 Problem Statement

The majority of previous studies were built on experiments and statistics. To the best of our knowledge, only limited work has provided simulation based models for LPWA technologies. Therefore, extensive simulation models are required to fully evaluate the expected performance of the network and its impact on the IoT devices without the need for experimental setup.

1.3 Proposed Solution

We develop a simulation tool to evaluate each individual LPWAN technology on the network performance in order to facilitate the applying of real data in experiments. We consider LoRa and Sigfox as the most promising LPWA technologies. We initially investigate the influence of number of devices on LoRa and Sigfox performance. The performance of the network is evaluated by calculating collision, packet error rate and spectrum under different number of IoT devices.

1.4 Research Aims and Objectives

The aims and objectives of this research are:

1. To study the influence of performance parameters (Number of slots, number of devices, bandwidth) on LoRa and Sigfox performance metrics (Collisions, Packet error rate and Spectrum).
2. To develop a simulation model that enables evaluating LPWA without the need for experimental setup.

1.5 Methodology

The research uses Monte Carlo simulation method which is used to solve various problems by generating suitable random numbers and observing that fraction of numbers that obeys some property .The main method of this research is to create a GUI to verify LoRa and Sigfox technologies performance for different parameters according to specific performance metrics and observe the impact of these parameters for each technology.

The general methodology will be implemented using GUI MATLAB simulation to generate specific packet duration values according to each technology specifications. The simulation sets the LPWA technology and the number of devices. It continues to transmit packets for the simulation duration. The simulation outputs collision, packet error rate and spectrum.

1.6 Organization of the Thesis

There are five chapters in this thesis. The second chapter gives an overview of Low Power Wide Area Networks; surveys several emerging LPWA technologies and the standardization activities carried out by different standards development organizations and the literature Review. Chapter three describes the methods and tools that were used to simulate the LPWAN technologies. The forth chapter shows the results and discussion, the fifth chapter is conclusions and recommendations.

1.7 Publication

The work in this thesis has provided a simulation to evaluate LoRa and Sigfox. The research outcomes have been published in the Institute of Electrical and Electronics Engineers (IEEE) International Conference on Computer, Control, Electrical, and Electronics Engineering (ICCCEEE).

- N. I. Osman and E. B. Abbas, "Simulation Modelling of LoRa and Sigfox Low Power Wide Area Network Technologies" *Proceedings of* IEEE 4rd 2018 International Conference on Computer, Control, Electrical, and Electronics Engineering (ICCCEEE), August 2018, Khartoum, Sudan.

Chapter Two

Background & Literature Review

2.1 Introduction

This chapter gives brief information about the Internet of Things (IoT) and the Low Power Wide Area Network (LPWAN) as a new research area in IoT; it also reviews related work in literature

2.2 Internet of things (IoT)

The Internet of Things [2] represents a vision in which the Internet extends into the real world embracing everyday objects. Physical items are no longer disconnected from the virtual world, but can be controlled remotely and can act as physical access points to Internet services. An Internet of Things makes computing truly ubiquitous – a concept initially put forward by Mark Weiser in the early 1990s. This development is opening up huge opportunities for both the economy and individuals.

However, it also involves risks and undoubtedly represents an immense technical and social challenge. The Internet of Things vision is grounded in the belief that the steady advances in microelectronics, communications and information technology we have witnessed in recent years will continue into the foreseeable future. In fact – due to their diminishing size, constantly falling price and declining energy consumption – processors, communications modules and other electronic components are being increasingly integrated into everyday objects today. “Smart” objects play a key role in the Internet of Things vision, since embedded communication and information technology would have the potential to revolutionize the utility of these objects. Using sensors, they are able to perceive their context, and via built-in networking capabilities they would be able to communicate with each other, access Internet services and interact with people. “Digitally upgrading” conventional object in this way enhances their physical function by adding the capabilities of digital objects, thus generating substantial added value. Forerunners of this development are already apparent today – more and more devices such as sewing machines, exercise bikes, electric toothbrushes, washing machines, electricity meters and photocopiers are being “computerized” and equipped with network interfaces.

2.2.1 IoT Infrastructure

The Internet of Things will become part of the fabric of everyday life. It will become part of our overall infrastructure just like water, electricity, telephone, TV and most recently the Internet. Whereas the current Internet typically connects full-scale computers, the Internet of Things (as part of the Future Internet) will connect everyday objects with a strong integration into the physical world [3].

2.2.2 IoT Applications

It is impossible to envisage all potential IoT applications having in mind the development of technology and the diverse needs of potential users. In the following sections, we present three applications, which are: monitoring and control, big data and business analytics, and information sharing & collaboration [3]. These applications are described, and the research challenges are identified as follows [4]:

1. Monitoring and control

Monitoring and control systems collect data on equipment performance, energy usage, and environmental conditions, and allow managers and automated controllers to constantly track performance in real time anywhere, anytime. Advanced monitoring and control technologies such as smart grid and smart metering reveal operational patterns, spot areas of potential improvement, or predict future outcomes and optimize operations, leading to lower costs and higher productivity.

2. Big data and business analytics

IoT devices and machines with embedded sensors and actuators generate enormous amounts of data and transmit it to business intelligence and analytics tools for humans to make decisions. These data are used to discover and resolve business issues such as changes in customer behaviors and market conditions to increase customer satisfaction, and to provide value-added services to customers. Business analytics tools may be embedded into IoT devices, such as wearable health monitoring sensors, so that real-time decision making can take place at the source of data.

3. Information sharing and collaboration

Information sharing and collaboration in the IoT can occur between people, between people and things, and between things. Sensing a predefined event is usually the first step for information sharing and collaboration. In the supply chain area, information sharing and collaboration enhance situational awareness and avoid information delay and distortion. For example, if sensors are placed throughout a retail store where refrigeration is necessary, alerts can be sent to the store manager's mobile device whenever the refrigerators malfunction. The manager can then check the employee status report to see who is available and send task assignments to that employee via his or her IoT-enabled mobile device.

2.2.3 Open Challenges and Future Directions

The challenges include IoT specific challenges such as privacy, participatory sensing, data analytics, Geographic information system(GIS) based visualization and Cloud computing apart from the standard of wireless sensor network (WSN) challenges including architecture, energy efficiency, security, protocols, and Quality of Service. The end goal is to have Plug n'Play smart objects which can be deployed in any environment with an interoperable backbone allowing them to blend with other smart objects around them. Standardization of frequency bands and protocols plays a pivotal role in accomplishing this goal [5].

IoT applications have specific requirements such as long range, low data rate, low energy consumption, and cost effectiveness. The widely used short-range radio technologies (e.g., Zigbee, Bluetooth) are not adapted for scenarios that require long range transmission. Solutions based on cellular communications (e.g., 2G, 3G, and 4G) can provide larger coverage, but they consume excessive device energy. Therefore, IoT applications' requirements have driven the emergence of a new wireless communication technology which is low power wide area network (LPWAN).

2.3 Low power wide area network (LPWAN)

Low Power Wide Area Network (LPWAN) is drawing in significant attention due to their capability to provide reasonable connectivity to the low-power devices scattered over large areas. LPWA technologies are replacing conventional short range wireless technologies including cellular, Wi-Fi, etc. As the era of Internet of Things (IoT) calls for more suitable technologies to support its applications such as smart city and machine-to-machine (M2M) applications. As over twenty five billion devices are expected to be connected through wireless communications by 2020, LPWA technologies are expected to follow in widespread deployment and popularity [6].

LPWAN is increasingly gaining popularity from industrial and research communities because of its low power, long-range and low-cost communication characteristics. More specifically, it provides long-range communication of up to 10-15 km in rural areas and 2-5 km in urban areas, and it is highly energy-efficient and inexpensive. The industry is targeting 10+ year battery life with a radio chipset cost of less than $2 and the operating cost of $1 per device per year [7].

2.3.1 LPWA Technologies

LPWA technologies [1] offer unique sets of features including wide-area connectivity for low power and low data rate devices, not provided by legacy wireless technologies. Their market is expected to be huge. Approximately one fourth of overall 30 billion IoT/M2M devices are to be connected to the Internet using LPWA networks using either proprietary or cellular technologies.

LPWA technologies are expected to follow in widespread deployment and popularity. Among different LPWA technologies (Sigfox, LoRa, INGENU and TELENSA), Sigfox and long range (LoRa) are the two leading technologies.

2.3.1.1 LoRa Technology

Long range (LoRa) is a physical layer technology [6] which adjusts and modulates the signals in sub GHZ ISM band utilizing an exclusive spread spectrum technique. LoRa utilizes unlicensed ISM groups, i.e., in Europe: 868 MHz, in North America: 915 MHz, and 433 MHz in Asia.

This section includes the assumption of LoRaWAN network topology, terminals, and mechanism that specified by LoRaWAN TS [8]. LoRa™ is a wireless modulation for long-range low-power low-data-rate applications developed by Semtech.

2.3.1.1.1 LoRaWAN Topology

LoRa network distinguishes between a basic LoRaWAN (named Class A) and optional features (Class B, Class C) as shown in figure 2.1 below.

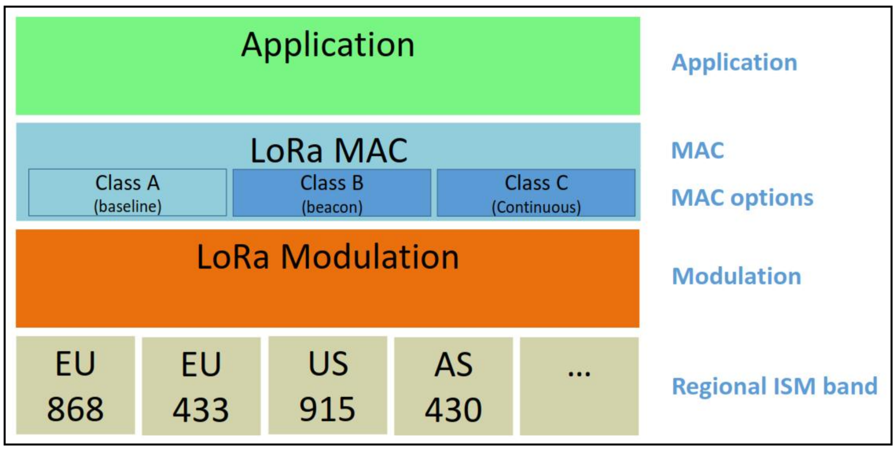

Figure 2.1: LoRaWAN Classes and layers

- Class-A (Bi-directional end-devices)

End-devices of Class A allow for bidirectional communications whereby each end-device's uplink transmission is followed by two short downlink receive windows. The transmission slot scheduled by the end-device is based on its own communication needs with a small variation based on a random time basis (ALOHA-type of protocol). This Class A operation is the lowest power end-device system for applications that only require downlink communication from the server shortly after the end-device has sent an uplink transmission. Downlink communications from the server at any other time will have to wait until the next scheduled uplink. And it's also necessary to mention that "All LoRaWAN end-devices MUST implement Class A features".

- Class-B (Bi-directional end-devices with scheduled receive slots):

End-devices of Class B allow for more receive slots. In addition to the Class A random receive windows, Class B devices open extra receive windows at scheduled times. In order for the End-device to open its receive window at the scheduled time, it receives a time synchronized Beacon from the gateway.

- Class-C (Bi-directional end-devices with maximal receive slots):

End-devices of Class C have nearly continuously open receive windows, only closed when transmitting. Class C end-device will use more power to operate than Class A and Class B but they offer the lowest latency for server to end-device communication.

2.3.1.1.2 LoRa Modulation

Modulation is a process where a periodic waveform, called a carrier signal or carrier wave, is combined with a modulation signal containing the information to be transmitted.

There are two different branches of LPWAN modulation standards – the Ultra Narrow Band (UNB) and the Spread Spectrum Modulation (SSM). In short, UNB can provide a slightly longer range of communication while SSM has a higher robustness to interference [9, 10]. Figure 2.2 visualizes the waveforms of UNB and SSM.

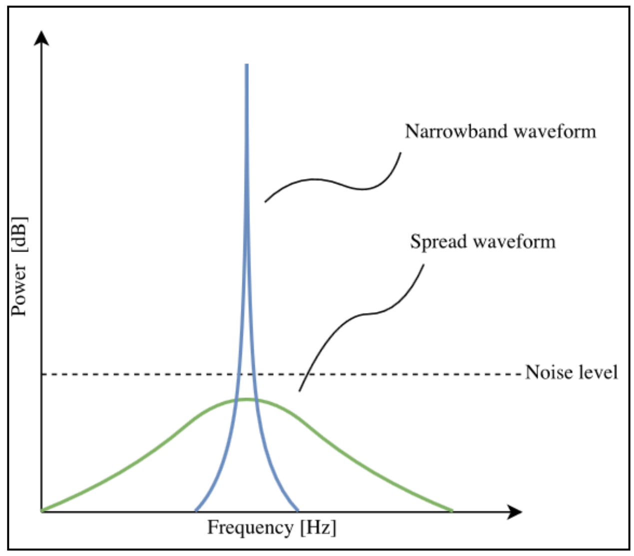

Figure 2.2: Waveforms for UNB and SSM

LoRa is a physical communication layer, using the proprietary modulation technique that operates in the Sub-GHz bands and is developed and distributed by Semtech. The LoRa Modulation is a derivative of the Chirp Spread Spectrum (CSS)[11].

LoRa uses SSM scheme which spreads the signal according to a spreading sequence over the whole channel bandwidth creating a signal typically below the noise floor, as seen in Figure 2.2. The signal can then be decoded by the receiver by using the inverse of the same spreading sequence. SSM improves the receiver sensitivity and makes a signal more robust to channel noise [1]. A SSM modulation technique used in wireless communication is the Chirp Spread Spectrum (CSS). A chirp is a sinusoidal signal that cyclically increases and decreases the signal frequency at a set chirp rate. Figure 2.3 shows how the frequency of the signal varies over time.

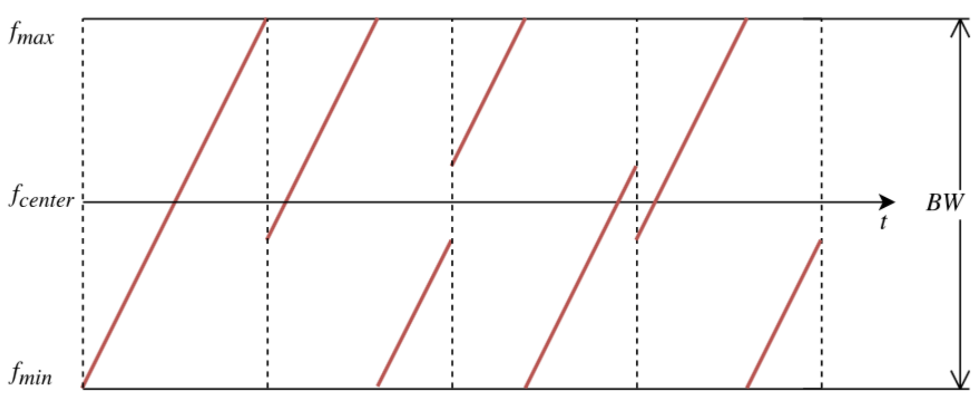

Figure2.3: CSS signal

In the figure above the signal starts at a stochastic start frequency F_{start} somewhere within allowed bandwidth BW. During a set time cycle, the signal frequency is increased from F_{start} until reaching F_{max}, then drops to F_{min} and then increases again until the frequency reaches the initial value F_{start} [12].

The Chirp Rate, which is the rate at which the frequency of the signal changes, will always be equal to the BW and the Spreading Factor (SF) sets the number of possible F_{start} to 2^{SF} [13].

2.3.1.1.3 LoRa Network Characteristics

Gateways are connected to the Network Server via secured standard IP connections while end-devices use single-hop LoRa™ or FSK communication to one or many gateways.

All communication is generally bi-directional, although uplink communication from an end-device to the network server is expected to be the predominant traffic. Gateways are also known as concentrators or base stations.

Communication between end-devices and gateways is spread out on different frequency channels and data rates. The selection of the data rate is a trade-off between communication range and message duration, communications with different data rates do not interfere with each other. LoRa data rates range from 0.3 kbps to 50 kbps. To maximize both battery life of the end-devices and overall network capacity, the LoRa network infrastructure can manage the data rate and RF output for each end-device individually by means of an adaptive data rate (ADR) scheme.

End-devices may transmit on any channel available at any time, using any available data rate, as long as the following rules are respected:

- The end-device changes channel in a pseudo-random fashion for every transmission. The resulting frequency diversity makes the system more robust to interferences.
- The end-device respects the maximum transmit duty cycle relative to the sub-band used and local regulations.
- The end-device respects the maximum transmit duration (or dwell time) relative to the sub-band used and local regulations.

The narrowband signal is spread into a broadband signal by representing each bit of information with a number of chips of information. The spreading factor is related to the number of chips per bit of information. It is given as $\log_2 (N)$, where N is the number of chips per symbol. LoRa uses seven different spreading factors ranging from 6 to 12. The nominal bit rate is decreased by increasing the spreading factor, but the receiver sensitivity and packet duration increases. The relation between data rates, spreading factor and receiver sensitivity are given in Table 2.1. The FEC codes use a coding rate of 4/5 up to 4/8. The physical frame structure is composed of a preamble, an optional header and the LoRaWAN packet itself.

Table2.1: LoRa characteristics for different SF values for 25 byte payload [1,7]

Spreading Factor	**Bit rate (bps)**	**Packet Duration (ms)**	**Receiver Sensitivity[dBm]**
12	293	682	-137
11	547	365	-135
10	976	204	-133
9	1757	113	-130
8	3125	64	-129
7	5478	36	-124
6	9275	21	-120

2.3.1.2 Sigfox Technology

Sigfox [6] is an LPWAN technology that offers connectivity solutions for end-to-end IoT devices based on patented technologies. By using an IP-based network, Sigfox sends its proprietary base stations outfitted with cognitive software-defined radios and interface them to the back end servers. Using binary phase-shift keying (BPSK) modulation and in an ultra-narrow band (100 Hz) sub-GHZ ISM band carrier, the end devices will be connected to these base stations. Sigfox technology utilizes unlicensed ISM bands similar to LoRa. By utilizing the ultra-limited band, Sigfox efficiently uses the frequency bandwidth with very low noise levels prompting low power consumption, higher receiver sensitivity, and low-cost antenna design and maximum 100 bps throughput.

2.3.1.2.1 Sigfox communication

Initially, Sigfox upheld just uplink communication; however it later evolved to bidirectional technology with a significant link asymmetry. The downlink communication, i.e., data from the base stations to the end devices, can just happen following an uplink communication. The number of messages over the uplink is constrained to 140 messages per day, and the maximum payload length for every uplink message is 12 bytes. In any case, the number of messages over the downlink is constrained to four messages per day, which implies that the acknowledgment of each uplink message isn't supported. Also, the maximum payload length for each downlink message is eight bytes.

Without the satisfactory help of acknowledgments, the uplink communication reliability is guaranteed by utilizing time and frequency diversity and additionally transmission duplication. Each device's message is transmitted multiple times (three by default) over different frequency channels.

2.3.1.2.2 Key features of the network

This section addresses the main characteristics of the Sigfox network itself in terms of architecture & performances [14]

1. **Sigfox architecture:**

The communication between the Sigfox base stations and the Sigfox Cloud is protected by a Virtual Private Network (VPN) tunnel, while the communication between the Sigfox Cloud and a generic IoT platform is secured by Hypertext Transfer Protocol (HTTP) over Transport Layer Security [15] .Sigfox Network Architecture is depicted in Figure 2.4.

Figure 2.4: High level description of the Sigfox network architecture

2. **High network capacity**

The capacity of the network is high, enabling Sigfox to scale for the billions of objects. The massive capacity of the infrastructure of the Sigfox network is the result of:

- ultra-narrow band modulation has the benefit of being spectrum efficient and resistant to interferers as all of the energy is concentrated into a very small bandwidth;
- frequency and time diversity introduced by the random access;
- Spatial diversity due to the overlapping network cells.

3. **High energy efficiency**

The high energy efficiency enabled by Sigfox technology also relies on the Sigfox semiconductor partners as their chips consume from 10mA to 50mA in transmission – depending on the partner and chip used. These values are applicable in Europe where the output power is 14dBm but the current is higher in the US where 22dBm are required. However, the time on air is six times inferior therefore the battery life is about the same. There are two more factors explaining the long battery life with Sigfox.

- No pairing is required, which means that no synchronization messages are exchanged between the object and the base station before transmitting the data. This is a big advantage compared to other technologies which all include those additional steps.
- Also the idle consumption is very low, often a few nanoamperes, which makes it almost negligible.

4. **Long range**

The main competitive advantage of the Sigfox technology is on the deployment with large coverage and a limited number of base stations:

- For a given output power, the range of the radio frequency (RF) link is determined by the data rate, i.e. a lower rate provides a longer range;
- The second factor is the link budget, sum of the base station sensitivity and the output power of the object;
- Highly depends on the topography;
- Good indoor coverage due to the use of sub GHz band. The long range of the base stations enables Sigfox to deploy a nationwide network at a minimum cost.

In terms of radio frequency range, Sigfox uses a metric called the link budget, the link budget is the sum of the sensitivity of the base station, the antenna gains and the output power on the object's side; It ends up with a slightly higher budget link in the European Telecommunications Standards Institute (**ETSI**) zone, resulting in larger cells.

The good indoor coverage of Sigfox is due to the use of the sub GHz band. Other technologies claiming a higher budget link and using 2.4 GHz, will suffer for indoor use cases.

5. **Security**

On the device side, Sigfox defines three different levels of security. Depending on the use case and its sensitivity, the device maker or the application provider will decide which level to implement:

- Medium level – the security credentials are stored in the device;

- High level – the security credentials are stored in a S/W based protected area;
- Very high level – the security credentials are stored in a secure element.

The secure element also helps to encrypt the data that is transferred over the network. Only the device and the end-customer know the secret key. The algorithm does not impact the size of the payload. While the message is encrypted, the payload is still 12-bytes long.
Throughout the path of the message, the Sigfox network makes sure that the device ID has not been duplicated. In the case of a corrupted device, a blacklist list mechanism will prevent the communication of this device.
From the start, Sigfox has designed the network with security in mind, separating functions onto several servers. For instance, the server generating IDs has a reinforced security.
As sum, the next table illustrates the technical specifications of LoRa and Sigfox LPWAN technologies [1].

Table 2.2: Sigfox and LoRa specifications

	Sigfox	**LoRa**
Modulation	UNB DBPSK(UL), GFSK(DL)	CSS
Band	SUB-GHZ ISM:EU (868MHz), US(902MHz)	SUB-GHZ ISM:EU (433MHz 868MHz), US (915MHz), Asia (430MHz)
Data rate	100 bps(UL), 600 bps(DL)	0.3-37.5 kbps (LORa), 50 kbps (FSK)
Range	10 km (URBAN), 50 km (RURAL)	5 km(URBAN), 15 km (RURAL)
No. of channels/orthogonal Signals	360 channels	10 in EU, 64+8(UL) and 8(DL) in US plus multiple SFs
Link symmetry	No	Yes
Forward error correction	No	Yes
MAC	unslotted ALOHA	unslotted ALOHA
Topology	star	star of stars
Adaptive Data Rate	No	Yes
Payload length	12B(UL), 8B(DL)	up to 250B (depends on SF & region)
Handover	end devices do not join a single base station	end devices do not join a single base station
Authentication & encryption	encryption not supported	AES 128b
Over the air Update	No	Yes
Localization	No	No

2.4 Literature review

In [1] a comprehensive overview of many such standardization efforts led by several standard developing organizations (SDOs) and special interest groups (SIGs) is provided. It had been observed that most standards focus on physical and MAC layers. A gap at the upper layers (application, transport, network etc.) is to be bridged. Further, important challenges that LPWA technologies face today and possible directions to overcome them are pointed out. Further developments in LPWA technologies to push the envelope of connecting massive number of devices in future had been encouraged.

The next study provided an analysis of LPWA underlying technology in licensed and unlicensed spectrum by means of literature review and comparative assessment of Sigfox, LoRa, Narrow band IoT(NB-IoT) and Long Term Evolution for Machines LTE-M [16]. The authors reviewed their technical aspect and discussed the pros and cons in terms of their technical and other deployment features. General IoT application requirements is also presented and linked to the deployment factors to give an insight of how different applications profiles is associated to the right technology platform, thus provide a simple guideline on how to match a specific application profile with the best fit connectivity features.

The study compared the differences of Sigfox, LoRa, NB-IoT and LTE-M in terms of their technical features and shortly discussed the pros and cons of their deployment factors. General IoT application requirements are also presented and associated to the deployment factors to give an insight of different applications profiles against the right technology platform, thus provide a simple guideline on how to fit the right connectivity features for different applications profiles. It might be a stern competition between the licensed and unlicensed spectrum, but both actually can co-exist as each of them has a different business model and serve a different IoT market segments and application profiles. How all the technologies will co-exist or compete with each other after the arrival of cellular technology are much depend on how they are regulated to fit business requirements and demands, technically and economically.

In [7] an experimental study had been conducted to analyze, and characterize LPWAN in both indoor and outdoor mobile environments. The experimental results indicate that the performance of LPWAN is surprisingly susceptible to mobility, even to minor human mobility, and the effect of mobility significantly escalates as the distance to the gateway increases. These results call for development of new mobility-aware LPWAN had presented a real-world experimental study that revealed the relationship between the mobility and the performance of LPWAN to understand the suitability of LPWAN for mobile IoT. Consequently, they provided rather negative results: LPWAN is easily impacted by mobility, even by minor ones such as human mobility. The impact of mobility dramatically increased depending on the distance to the gateway, the vehicle speed, and whether the end node was placed in an indoor environment. As future work, based on these results, they will develop mobility-aware LPWAN protocols that address this mobility issue to support mobile IoT.

This study in [17] summarized the technical differences of Sigfox, LoRa, and NB-IoT, and discussed their advantages in terms of IoT factors and major issues. Each technology will have its place in the IoT market. Sigfox and LoRa will serve as the lower-cost device, with very long range (high coverage), infrequent communication rate, and very long battery lifetime. Unlike Sigfox, LoRa will also serve the local network deployment and the reliable communication when devices move at high speeds. By contrast, NB-IoT will serve the higher-value IoT markets that are willing to pay for very low latency and high quality of service. Finally, it is expected that 5th Generation (5G) wireless mobile communication will provide the means to allow an all-connected world of humans and devices by the year 2020, which would lead to a global LPWAN solution for IoT applications.

The study [18] analyzed the coverage and capacity for SigFox, LoRa, General Packet Radio Service (GPRS), and NB-IoT in a real deployment scenario covering 8000 km2 in North Jutland, Denmark. The four technologies provide better than 99% outdoor coverage, based on Telenor's existing site locations. GPRS is unable to provide indoor coverage for 40% of the users, while Sigfox, LoRa, and NB-IoT cover more than 95% of the indoor users experiencing 20 dB penetration losses. Sigfox provides very good outdoor and indoor uplink performance with a 95%-tile failure probability of maximum 12%. However, Sigfox is limited in downlink due to blocking and duty cycle violations of the 868 MHz ISM band. LoRa can be operated in an unacknowledged mode, but since all devices will utilize the most robust communication settings the uplink collision probability is significant. When using acknowledged mode in downlink the uplink transmission settings can be adjusted and the performance improves. Nevertheless, LoRa does not match Sigfox in uplink performance, but it provides lower blocking probability and duty cycle violations in downlink, however also with worse coverage. NB-IoT outperforms the other technologies, having a 95%-tile uplink failure probability of less than 4% even for ten devices. The reasons include the best coverage and the use of link adaptation, while a drawback is the longest time on air.

It remains to be studied how the technologies compare in terms of device cost and energy consumption, which are also key performance indicators for the Internet of Things.

In [19], a comprehensive survey on NB-IoT and LoRa as efficient solutions connecting the devices has been provided. It is shown that unlicensed LoRa has advantages in terms of battery lifetime, capacity, and cost. Meanwhile, licensed NB-IoT offers benefits in terms of QoS, latency, reliability, and range. In this survey study, it is shown that both LoRa and NB-IoT have their own advantages and disadvantages according to their different technological principles. In general, there is not a unique LPWA technology, but the most appropriate technology for the specific application. Each application has its specific requirements, which lead to a specific technology choice. Both LoRa and NB-IoT have their place in the IoT market. LoRa focuses on the low cost applications. Meanwhile, NB-IoT is directed to applications that require high QoS and low latency.

In [20], the authors evaluated the performance of LoRaWAN unconfirmed uplink data frames in an indoor environment. They firstly showed the limitations in terms of periodicity and size of data because of the ISM band regulation in a default channel configuration. Such regulation also limits the maximum amount of data that can be sent per day. Then, they evaluated the signal quality received from different locations, in order to verify the feasibility to cover an entire building with the LoRaWAN technology. The difference in the composition of walls between the rooms and the lab floors had not much impact on the quality of the transmission and packet loss. Only communications with the basement experienced degradations. In these experiments, a part of the basement is used as a parking space. Thus parking monitoring applications may take this kind of configuration into consideration. They also had shown that the data rate can be a factor of loss and should be selected appropriately when configuring end-device. Finally, they had shown the average current consumption of a LoRa mote and how the used data rate can impact the global energy consumption. Depending on the network configuration, several data rates will not be able to fit specific application requirements such as the amount of data exchanged per a certain period of time. If an end-device is too far from the gateway, it will be constrained to lower data rate to maintain a satisfactory quality of transmission. Encouraged by the results presented in this study, they planned to extend their performance evaluation. They will first focus on increasing the density of gateways to measure their impact on the network performance, especially the overall coverage and frame duplications and also increase the number of end-devices to evaluate the maximum capacity per gateway.

The recently proposed LoRa low power wide area network (LoRaWAN) technology has been discussed and analyzed in [21] when used under European frequency regulations. First of all, they derived the performance metrics of a single LoRaWAN end device, namely uplink throughput and data transmission times. Then they were analyzing for several illustrative application scenarios the maximum number of end devices which can be served by a single LoRaWAN base station and discussed the spatial distribution of these devices. It is shown that subject to the used channels and application requirements, a single cell may include several millions of devices. Also they showed that the capacity of the uplink channel available to a LoRaWAN node strongly depends on the distance from the base station and does not exceed 2 kbit/s.

In terms of scalability, they presented results showing that a single LoRaWAN cell can potentially serve several millions of devices sending few bytes of data per day. Nonetheless, they have shown that only a small portion of these devices can be located sufficiently far away from the base station. Most of the devices, and especially the ones with higher upload traffic needs, should be located in the vicinity of the base station. Furthermore, this call for more effective management of the data rates used by the end nodes since only few nodes operating with low data rates can be supported. Another factor which somewhat limits the scalability of the LoRaWAN cell is the use of acknowledgements. Given that the base station is subject to the very same duty cycle restrictions imposed by the frequency regulations, in a dense network it cannot acknowledge each and every packet. Moreover, the base station’s duty cycle restrictions also need to be carefully pondered when planning the downlink traffic.

In this measurement study [22] the signal activity and power levels are measured in the European Industrial, Scientific and Medical band 863-870 MHz in the city of Aalborg, Denmark . The target is to determine if there is any interference, which may impact deployment of Internet of Things devices. The focus is on the Low Power Wide Area technologies LoRa and SigFox. The measurements show that there is a 22-33% probability of interfering signals above -105 dBm within the mandatory LoRa and SigFox 868.0-868.6 MHz band in a shopping area and a business park in downtown

Aalborg, which thus limits the potential coverage and capacity of LoRa and SigFox. However, the probability of interference is less than 3% in the three other measurement locations in Aalborg. Finally, a hospital and an industrial area are shown to experience high activity in the RFID sub and 865-868 MHz, while the wireless audio band 863-865 MHz has less activity.

The authors of [23] did a performance testing on one such star-topology network, based on Semtech's LoRaTM technology, and deployed in the city of Rennes – LoRa FABIAN. In order to check the quality of service (QoS) that this network can provide, generally and in given conditions, they conducted a set of performance measurements. They performed their tests by generating and then observing the traffic between IoT nodes and LoRaTM IoT stations using the LoRa FABIAN protocol stack. With their experimental setup, they were able to generate traffic very similar to the one that can be used by real applications such as sensor monitoring. This allowed them to extract basic performance metrics, such as packet error rate (PER), but also metrics related specifically to the LoRa physical layer, such as the Received Signal Strength Indicator (RSSI) and Signal to Noise ratio (SNR), within various conditions. Their findings provide insight about the performance of LoRa networks, but also about evaluation methods for these types of networks.

Even though the authors proposed a plot of the PER as a function of the SNR, for some system conditions, there are many measurements that can still be done to further improve characterization of LoRa networks. Besides trying to find the correlation between elevation and performance, many other factors, such as influence of small-scale fading should be validated before proposing a channel model for LoRa and more generally for LPWANs. Measurement for other LPWAN devices (using other physical layer technology) also should be done. Some parameters have still to be varied and analyzed, for example: packet size, bandwidth and coding rate.

Chapter Three

Network Modelling Approach

3.1 Introduction

This chapter illustrates the simulation models of the two considered LPWA technologies. It explains the input and output parameters, and also describes the simulation.

3.2 Simulation methodology

The general method for simulation is to use Monte Carlo simulation method which is used to solve various problems by generating suitable random numbers and observing that fraction of numbers that obeys some property and one of this method interfaces is the MATLAB Graphical User Interface (GUI). The main method of this research is to create a GUI to verify LoRa and Sigfox technology performance for different parameters according to specific performance metrics. And observe the impact of these metrics in the number of devices for each technology.

3.3 Model inputs

The inputs of the model are:

- **LPWAN technology**

There are two LPWA technologies that have been considered in the model which are: (LoRa and Sigfox).

- **Bandwidth**

There are three bandwidths specified for LoRa (125, 250, and 500 KHz). Sigfox uses 200 KHz for which is defined for 868.7 - 869.2 MHZ frequency band.

- **Maximum number of devices**

The chosen number of devices to evaluate the network operation according to the performance metrics Here we compare between two different number of devices (500 and 1000) for each technology.

3.4 Model outputs

The outputs of the model are:

- **Collisions**

  When two or more devices attempt to transmit a packet across the network at the same time, a packet collision will take place. And the output here is the number of collisions that occurs during the simulation process.

- **Packet Error Rate (PER)**

  PER is the ratio, in percent, of the number of packets not successfully received to the number of packets sent by the test set.

- **Spectrum representation**

The spectrum is a mapping operation (i.e. visualizing)of the packets performance. It is expressed in the form of a matrix; the rows represent the number of slots, and the columns represent the number of channels, the colors express the slots status as shown in Table.3.1.

Table 3.1 spectrum representation

Status	Representation
Available slots	Black
Used slots	Green
Collision	Red

3.5 Simulation description

In this thesis, the two technologies are considered for practical evaluation using MATLAB by an intermediate simulator that is developed with a GUI for different characterization evaluation.

The simulation works with the principle of Monte Carlo simulation which is an iterative simulation methodology. The Simulation is first initialized with constant parameters and the declarations of other parameters used for performance evaluation. Performance evaluation metrics used are the number of collisions, packet error rate, and spectrum analyzer graph.

The general methodology that is applied in the simulation is described in the flowchart shown in Figure 3.1.

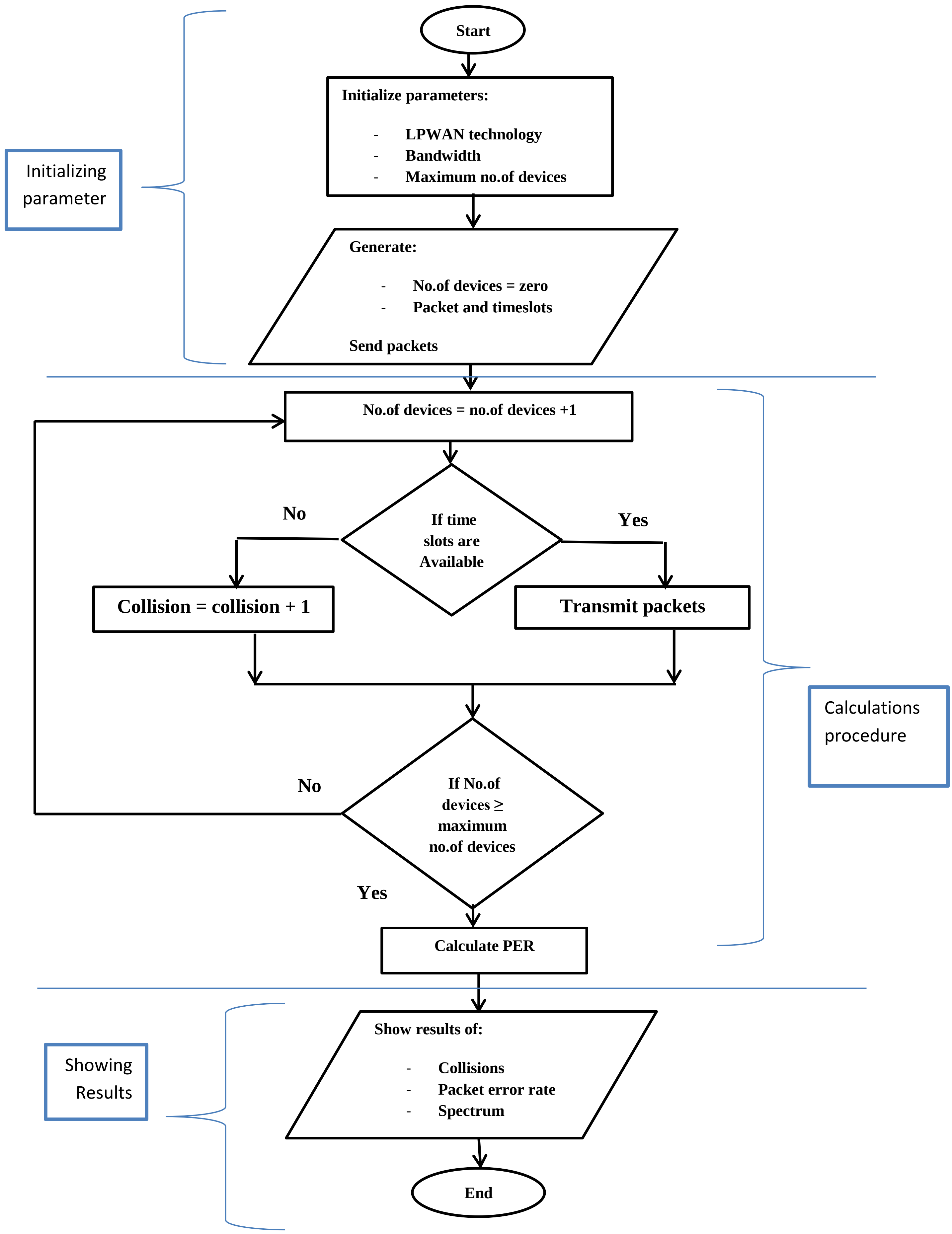

Figure 3.1: Simulation Flowchart.

Figure 3.1 shows the flowchart diagram for the simulation. The simulation starts by selecting the desired LPWA technology (LoRa or Sigfox), bandwidth and maximum number of devices. It sets the current number of devices to zero and for LoRa it randomly generates the spreading factor according to the number of channels. The simulation generates specific packet duration values according to each technology specifications. For each number of devices the time offset is calculated.

The simulation generates specific packet duration values according to each technology specifications. The first step in the simulation is calculating the number of time slots which is found by equation (1):

$$Number\ of\ slots = \frac{Simulation\ time\ (ms)}{time\ interval\ (ms)} \qquad (1)$$

Then time offset values are randomly generated as shown in equation (2). The time offset is generated for all simulated devices which represents offset between each device packet transmission, each device considered to send one message or packet.

$$Time\ offset = No.of\ slots - \frac{(Packet\ duration * no.of\ packets)}{time\ interval} \qquad (2)$$

While the time offset is more than the number of slots, the simulation will check if there is an available slot in the current channel in order to continue. In this case the number of devices is increased and continues transferring packets. Otherwise, a collision occurs and the packet transmission fails.

The simulation terminates when the maximum number of devices is reached, the PER is calculated using equation (3):

$$PER = \frac{Number\ of\ Collisions}{Total\ number\ of\ packets} * 100\ \% \qquad (3)$$

Finally the PER, collisions and spectrum representation are displayed.

Appendix A and Appendix B explain selected lines of code from the LoRa and Sigfox simulation, respectively.

Chapter Four

Simulation Results & Discussion

4.1 Introduction

This chapter demonstrates by results the outcomes of the comparison between LoRa and Sigfox LPWA technologies in terms of PER, collisions and spectrum representation.

4.2 Implementation

4.2.1 Input values

Table 4.1 shows the input values of considered simulation parameters. The simulation assumes random access to six channels specified inside the bandwidth so random spreading factors are generated in the range from 6-12 inside the specified bandwidth, it randomly generates the spreading factor according to the number of channels.

Table 4.1 simulation parameters

Parameter	Value
Spreading Factor	6-12
Frequency band	868.7 - 869.2 MHZ
LoRa Channel bandwidth	125, 250, and 500 KHz
SigFox Channel bandwidth	200 KHz
Payload size	25 bytes
Number of devices	500/1000
Frequency interval	100 Hz
Time Interval	10 ms
Simulation time	60 seconds

4.2.2 Running the simulation

The system evaluates each individual technology with different number of devices . Figure 4.1 illustrates the main interface; the simulation runs after entering the inputs. The results are mathematically calculated and displayed on the interface. Simulation results are displayed in figures which are shown in the following sections.

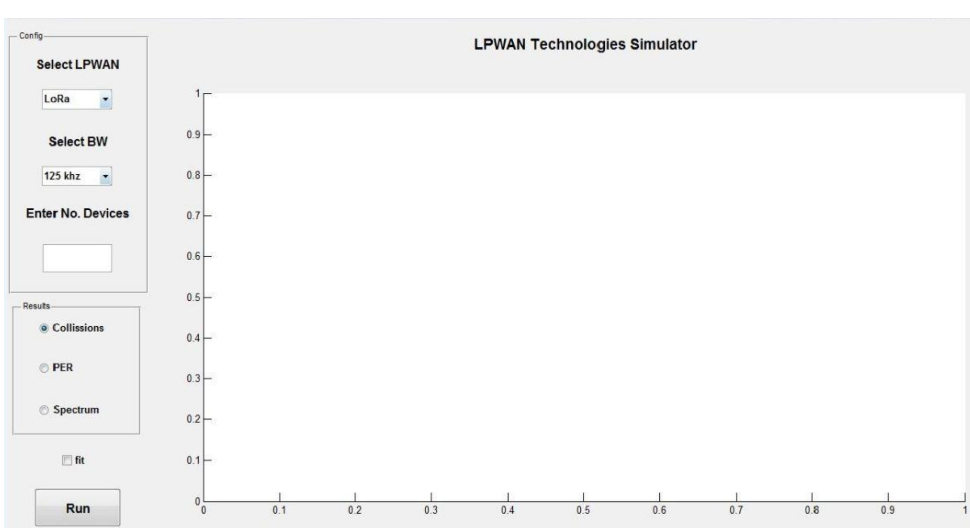

Figure 4.1: Main interface

4.3 First scenario: LoRa Technology

This section discusses the simulation results of LoRa technology according to the performance metrics (Collisions, packet error rate and Spectrum).

4.3.1 Collision

The upcoming figures (Figure 4.2 throughout figure 4.7) illustrate the packets collision of LoRa technology for a total number of devices 500 and 1000, in this evaluation we choose a bandwidths of 125, 250 and 500 kHz.

A. Number of devices = 500

In the case of 500 numbers of devices the collision of packets will be discussed considering the three bandwidths of LoRa Technology.

- Bandwidth of 125 KHz:

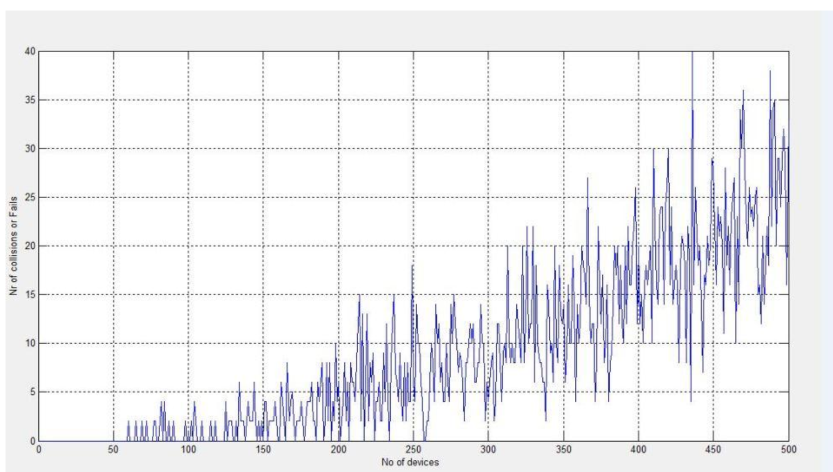

Figure 4.2 collisions of packets in 125 KHz bandwidth (500 devices)

- Bandwidth of 250 KHz

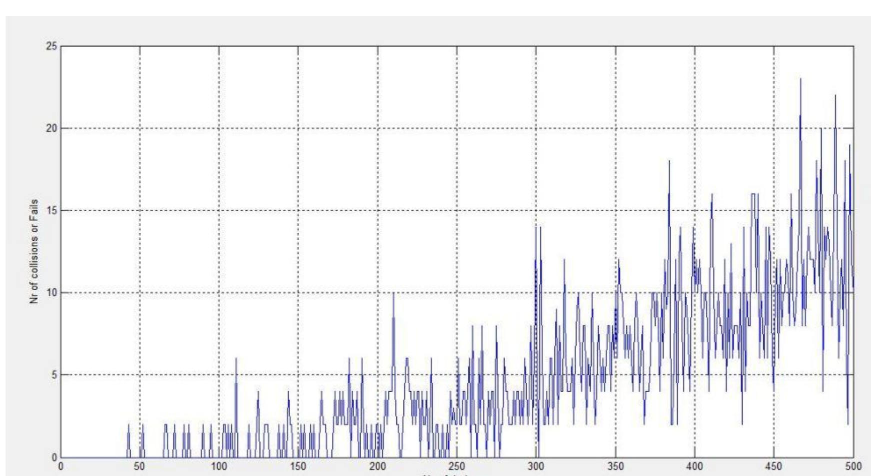

Figure 4.3: collisions of packets in 250 KHz bandwidth (500 devices)

- Bandwidth of 500 KHz

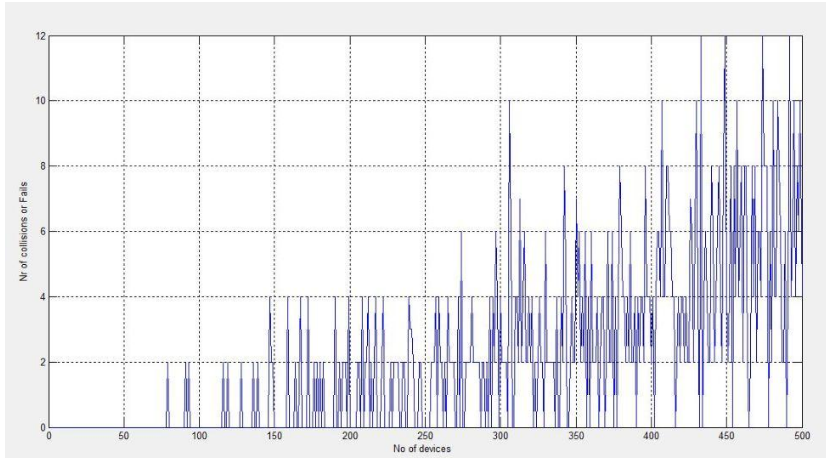

Figure 4.4: collisions of packets in 500 KHz bandwidth (500 devices)

From the previous three figures the collision increases when the bandwidth is increased.

B. Number of devices = 1000

Following, we evaluate collision of packets under 1000 devices considering the three bandwidths of LoRa technology.

- Bandwidth of 125 KHz

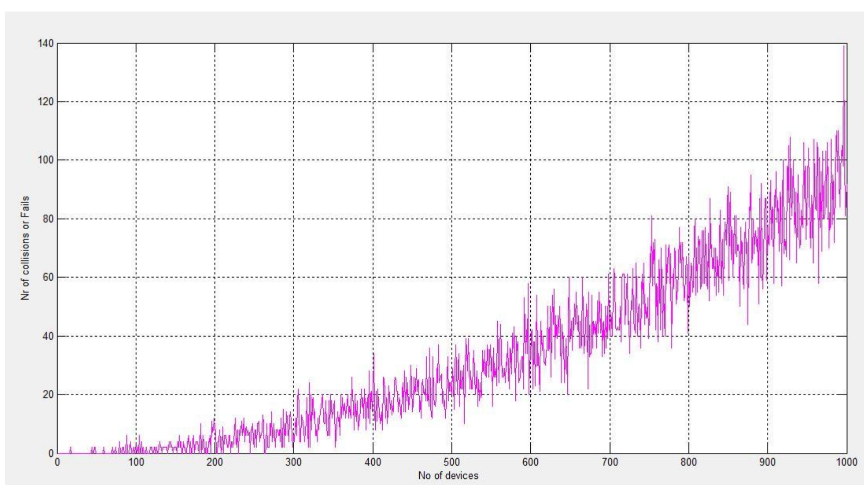

Figure 4.5: collisions of packets in 125 KHz bandwidth (1000 devices)

- Bandwidth of 250 KHz

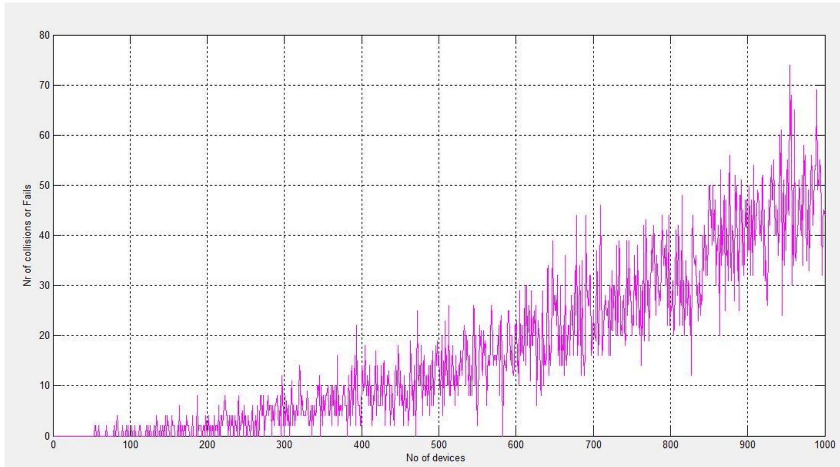

Figure 4.6: collisions of packets in 250 KHz bandwidth (1000 devices)

- Bandwidth of 500 KHz

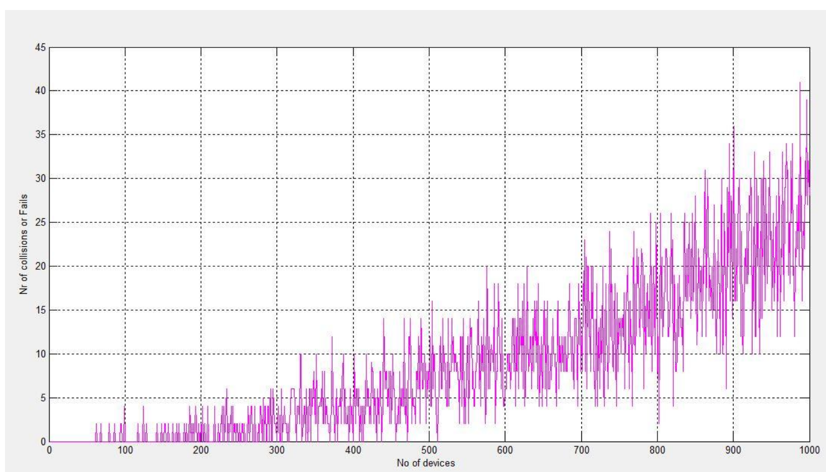

Figure 4.7: collisions of packets in 500 KHz bandwidth (1000 devices)

From the previous three figures (figure 4.5 to figure 4.7) the collision increases when the bandwidth is increased. The packet collision is higher compared to having 500 devices; which means that collision increases when increasing the number of devices.

5.3.2 Packet Error Rate

The upcoming figures (figure 4.8 throughout figure 4.13) illustrate the packet error rate (PER) of LoRa technology for a total number of devices 500 and 1000. In this evaluation we choose bandwidths of 125, 250 and 500 kHz.

A. Number of devices = 500

In the case of 500 devices the packet error rate (PER) is discussed considering the three bandwidths of LoRa technology.

- Bandwidth of 125 KHz

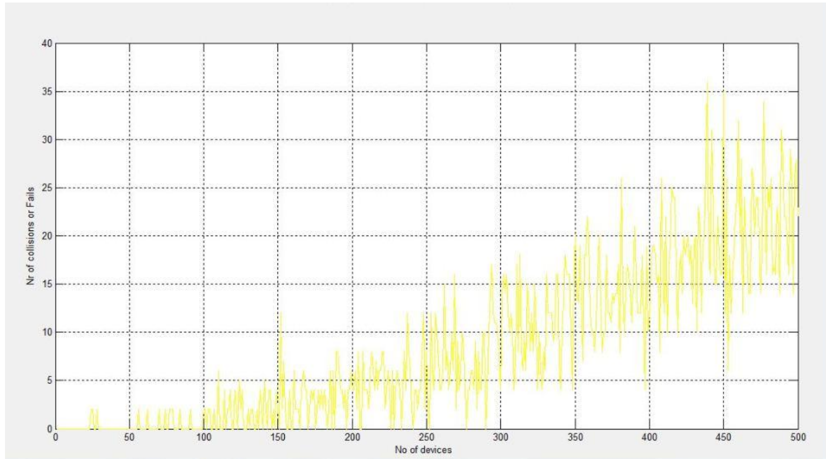

Figure 4.8: PER in 125 KHz bandwidth (500 devices)

- Bandwidth of 250 KHz

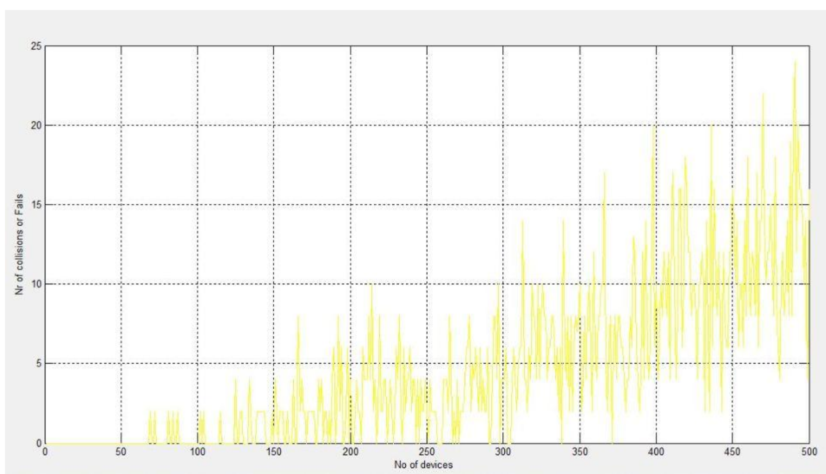

Figure 4.9: PER in 250 KHz bandwidth (500 devices)

- Bandwidth of 500 KHz

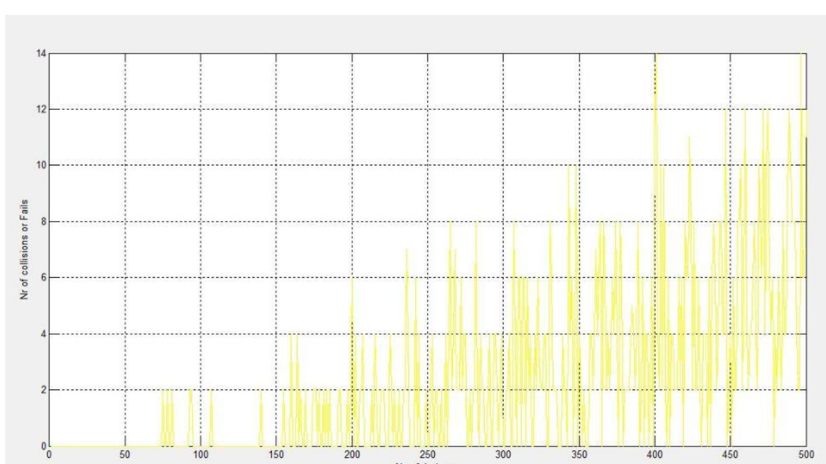

Figure 4.10: PER in 500 KHz bandwidth (500 devices)

It is observed that when the bandwidth is increased the PER will be increases.

B. Number of devices = 1000

Here, the packet error rate (PER) is evaluated under 1000 devices considering the three bandwidths of LoRa technology.

- Bandwidth of 125 KHz

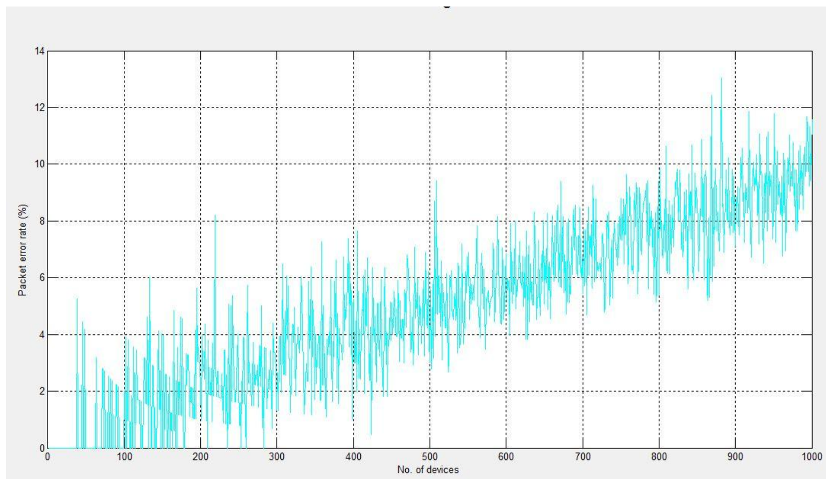

Figure 4.11: PER in 125 KHz bandwidth (1000 devices)

- Bandwidth of 250 KHz

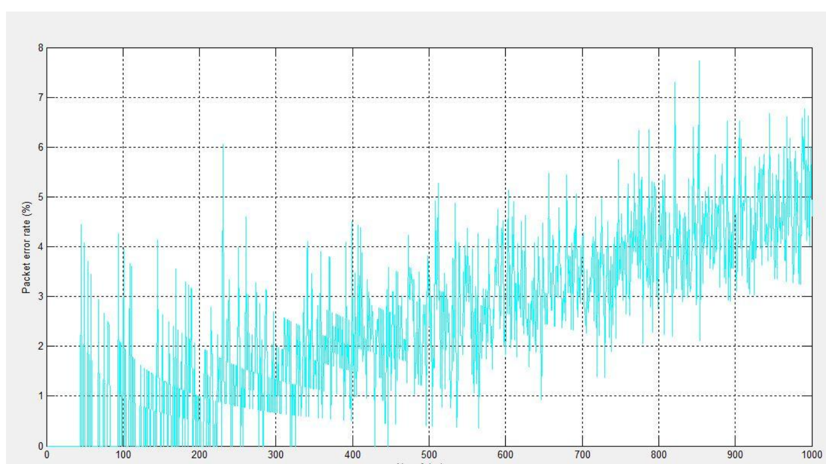

Figure 4.12: PER in 250 KHz bandwidth (1000 devices)

- Bandwidth of 500 KHz

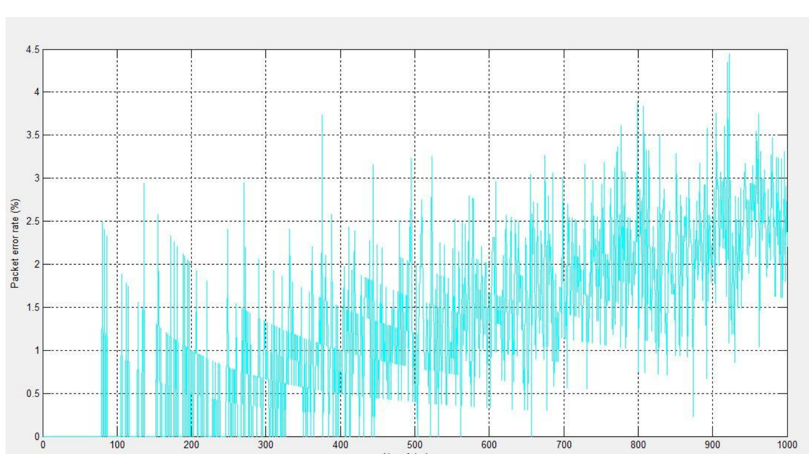

Figure 4.13: PER in 500 KHz bandwidth (1000 devices)

From the previous three figures (figure 4.11 to figure 4.13) the PER increases when the bandwidth is increased. But the PER is higher compared to having 500 devices; which means that in general PER increases when increasing the number of devices.

5.3.3 Spectrum

Figure 4.14 throughout figure 4.14 illustrate the spectrum representation of LoRa technology for a total of 500 and 1000 devices. In this evaluation the green lines represent the used slots, the black lines are the available slots and the red line is the collisions.

A. Number of devices = 500

In the case of 500 devices the spectrum visualization is discussed considering the three bandwidths of LoRa technology.

- Bandwidth of 125 KHz

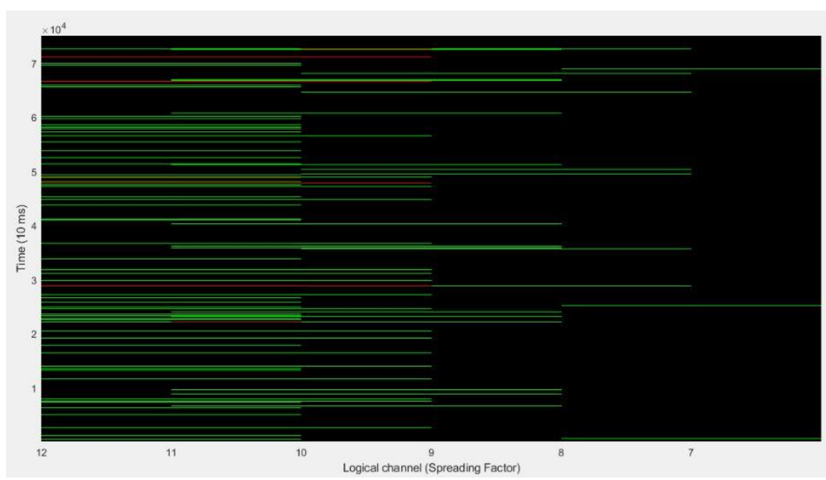

Figure 4.14: Spectrum in 125 KHz (500 devices)

- Bandwidth of 250 KHz

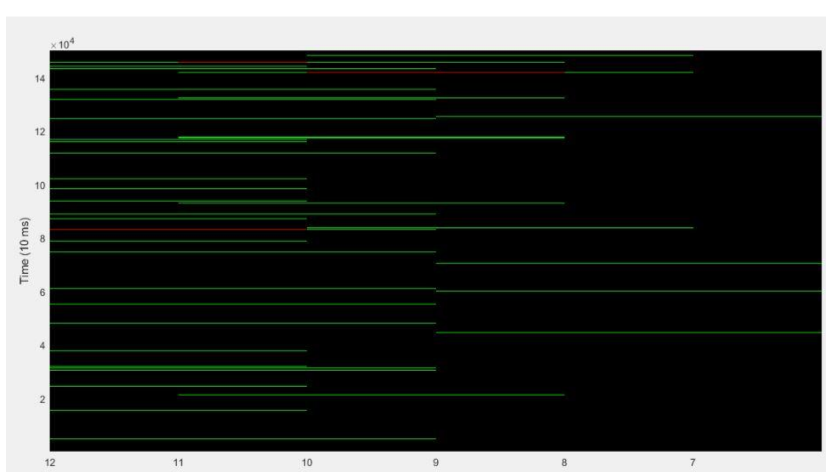

Figure 4.15: Spectrum in 250 KHz (500 devices)

- Bandwidth of 500 KHz

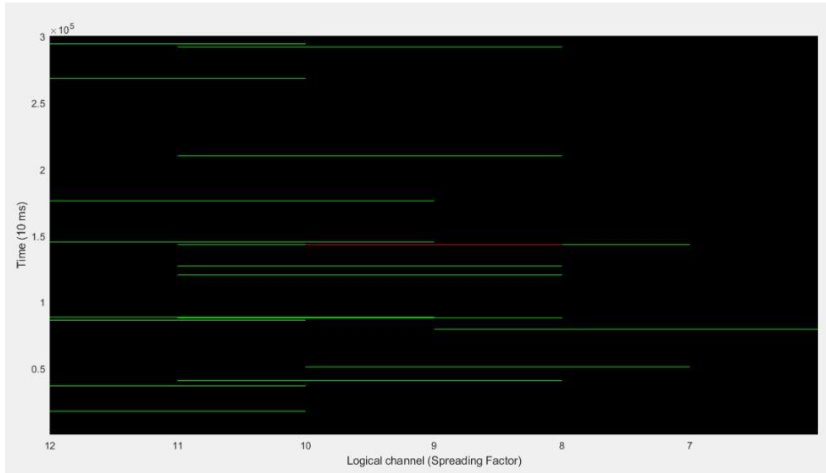

Figure 4.16: Spectrum in 500 KHz (500 devices)

From the previous three figures (figure 4.14 to figure 4.18) it can be observed that when the bandwidth is increased the available slots are increased and at the same time collision decreases.

B. Number of devices = 1000

In the case of 1000 numbers of devices the spectrum visualization is discussed considering the three bandwidths of LoRa technology.

- Bandwidth of 125 KHz

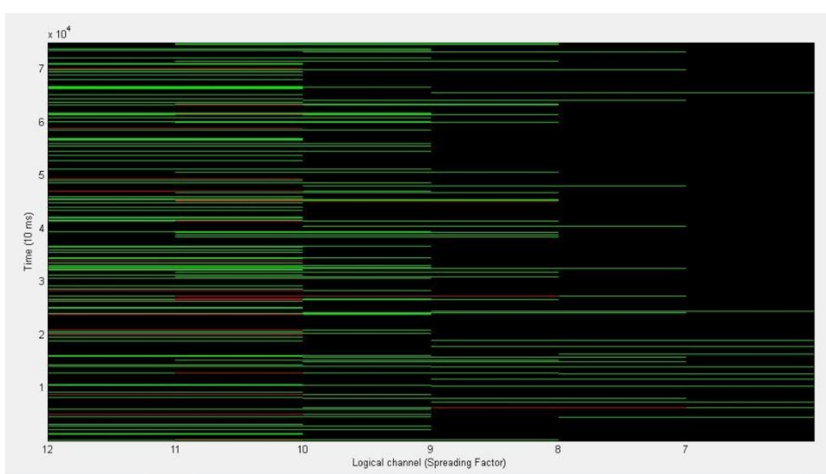

Figure 4.17: Spectrum in 125 KHz (1000 devices)

- Bandwidth of 250 KHz

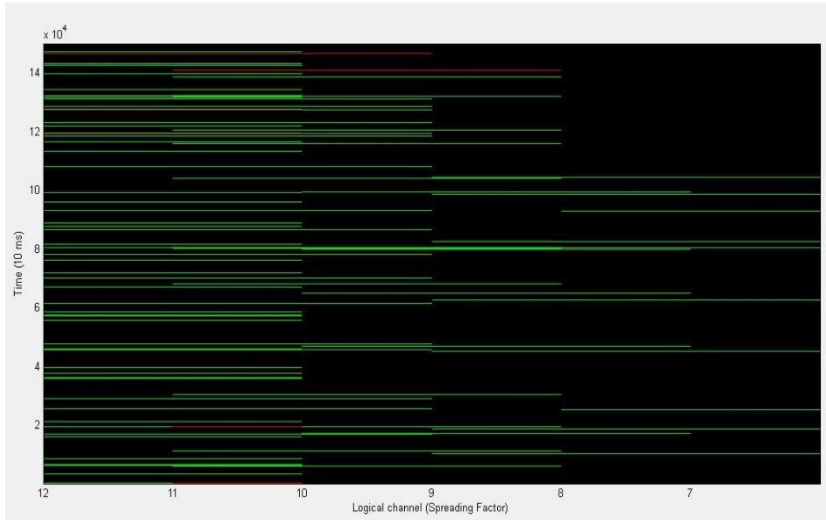

Figure 4.18: Spectrum in 250 KHz (1000 devices)

- Bandwidth of 500 KHz

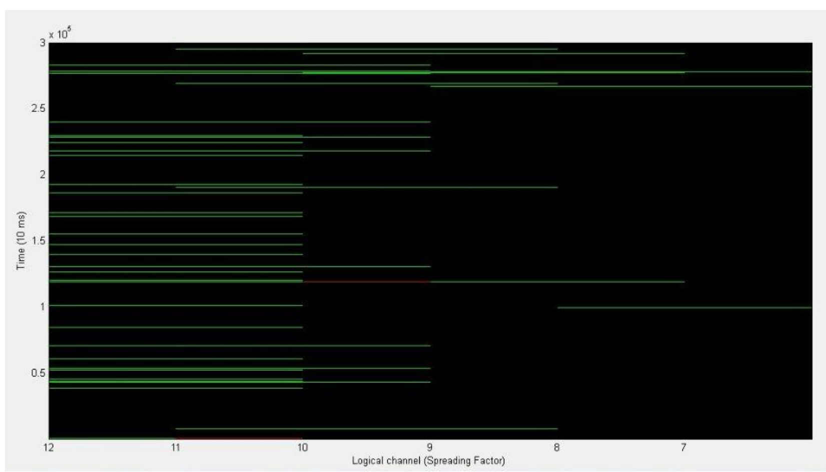

Figure 4.19: Spectrum in 500 KHz (1000 devices)

From the previous three figures (figure 4.17 to figure 4.19), it can be observed that when the bandwidth is increased the available slots also increased. Also the used slots increase and packet collision is higher compared to having 500 devices.

5.4 Second Scenario: Sigfox Technology

Similar to LoRa, the second scenario we simulate Sigfox technology according to the performance metrics (Collisions, packet error rate and Spectrum).

5.4.1 Collision

Figure 4.20 and figure 4.21 illustrate the packets collision of Sigfox technology for a total number of 500 and 1000 devices. In this evaluation we choose a bandwidth of 200 kHz.

A. Number of devices = 500

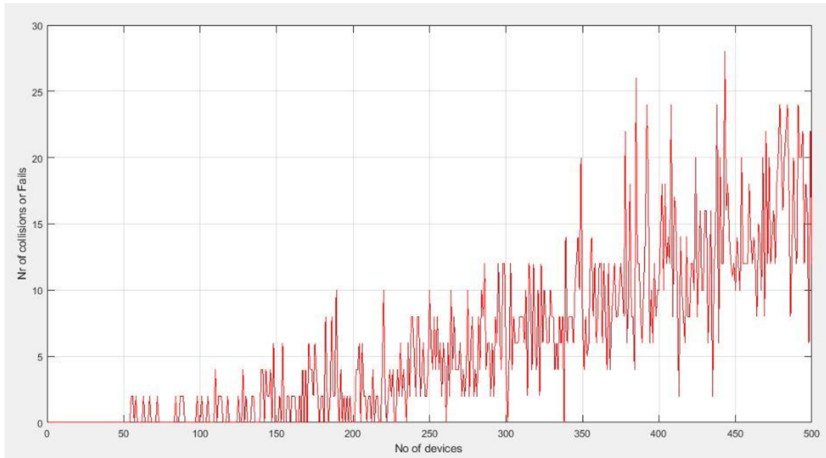

Figure 4.20: collisions of packets in 200 KHz bandwidth (500 devices)

As can be seen in figure 4.20 the collision increases when the bandwidth is increased.

B. Number of devices = 1000

Also in the case of 1000 devices the collision of packets is evaluated considering the bandwidth of 200 KHz.

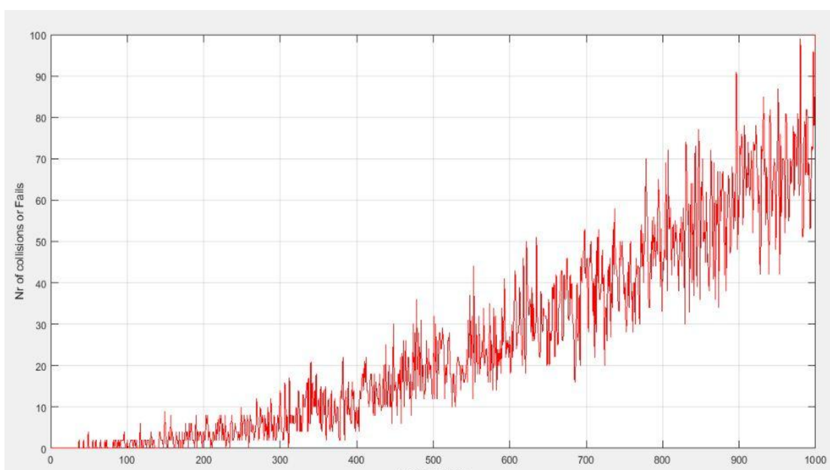

Figure 4.21: collisions of packets in 200 KHz bandwidth (1000 devices)

packet collision is higher compared to having 500 devices; which means that collision increases when increasing the number of devices.

5.4.2 Packet Error Rate

Figure 4.22 and figure 4.23 illustrate the packet error rate (PER) of Sigfox technology for a total number of 500 and 1000 devices. In this evaluation we choose a bandwidth of 200 kHz.

A. Number of devices = 500

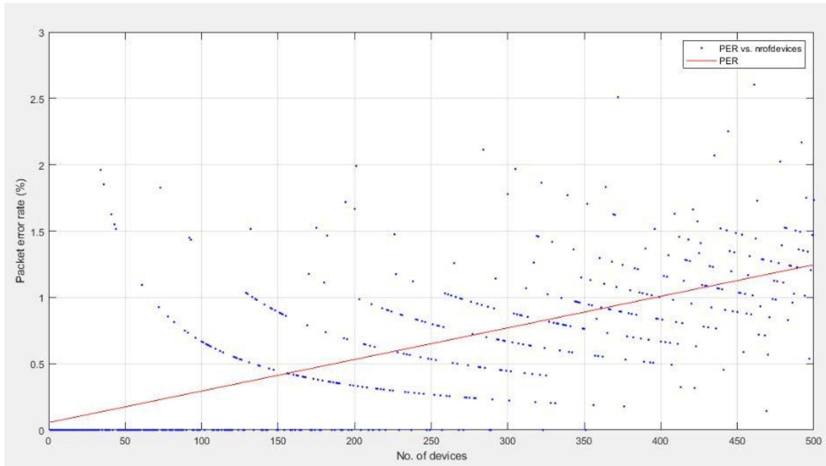

Figure 4.22: PER in 200 KHz bandwidth (500 devices)

B. Number of devices = 1000

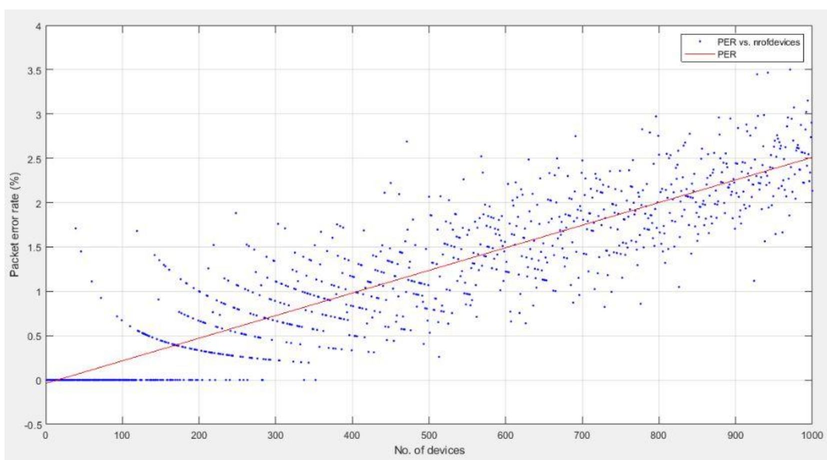

Figure 4.23: PER in 200 KHz bandwidth (1000 devices)

Observing figure 4.22 and figure 4.23 the PER is higher compared to having 500 devices; which means that in general PER increases when increasing the number of devices.

5.4.3 Spectrum

Figure 4.24 and figure 4.25 illustrate the spectrum representation of Sigfox technology for total number of (500 and 1000) devices. In this evaluation the green lines represent the used slots, the black lines are the available slots and the red line is the collisions. Similarly, a bandwidth of 200 KHz is chosen.

A. Number of devices = 500

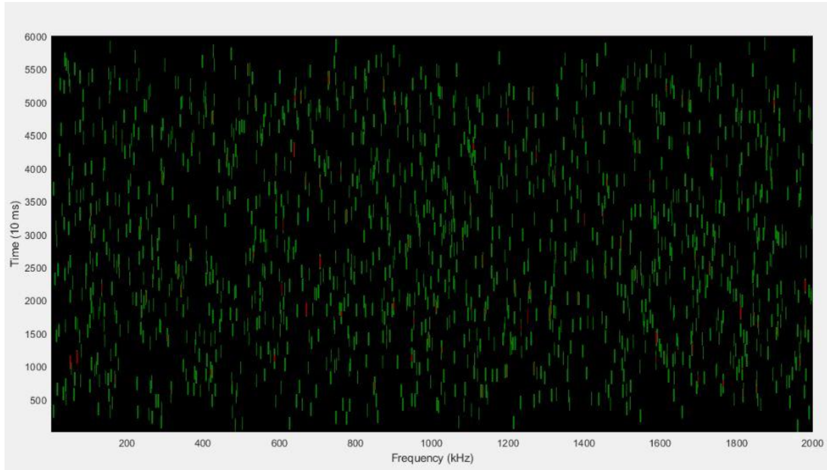

Figure 4.24: Spectrum in 200 KHz (500 devices)

B. Number of devices = 1000

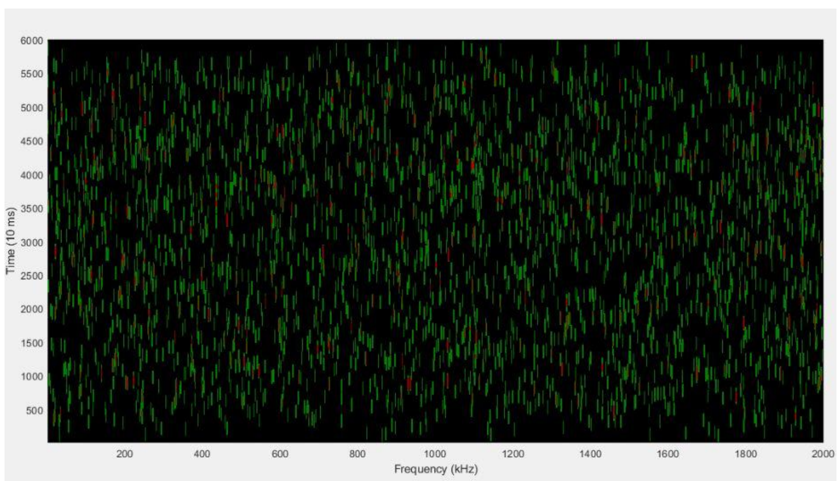

Figure 4.25: Spectrum in 200 KHz (1000 devices)

From figure 4.24 and figure 4.25 it can be observed that when the bandwidth is increased the available slots increase .In addition the used slots are increased and packet collision is higher compared to having 500 devices.

5.5 Discussion

The findings can be summarized as following:

- Packet collision increases with the increase in the number of packets under both LoRa and Sigfox.
- Increasing the number of devices leads to increasing PER using both technologies.
- Sigfox experiences less collisions compared to LoRa.
- Compared to LoRa, Sigfox has less PER.
- Spectrum representation is slightly different between the two technologies (when the bandwidth is increased the available slots also increased).

Chapter Five

Conclusions and Recommendations

5.1 Introduction

This chapter presents the conclusions of the research and recommendations for future work.

5.2 Conclusions

This thesis has evaluated LoRa and Sigfox as promising LPWA technologies. A simulation model is designed and implemented using MATLAB environment, which allows multiple features and comprehensive platform for such studies. The system is constructed by using Graphical User Interface (GUI), which allows the users to enter multiple input values to get different evaluation results. The simulation evaluates the influence of the number of devices on collision, packet error rate and spectrum.

Our results show that Sigfox has less collision and packet error rate with a slightly better spectrum representation compared to LoRa. Also that increasing the number of devices leads to increasing collision and packet error rate, and more bandwidth means more available slots.

5.3 Recommendations

For future work we recommend to:

- Eextend the evaluation by considering different parameter values including the number of channels and device mobility.
- Evaluate other LPWA technologies.

References

1. U. Raza, P. Kulkarni, M. Sooriyabandara, "Low power wide area networks: An overview", IEEE Communications Surveys & Tutorials, Volume: 19, no.2, January 2017.
2. F. Mattern , C. Floerkemeier, "From the Internet of Computers to the Internet of Things", *Springer,* vol 6462, 2010, Berlin, Heidelberg.
3. O. Vermesan, and P.Friess, (2014). Internet of things. *River Publishers.*
4. L. Kyoochun ,"The Internet of Things (IoT): Applications, investments, and challenges for enterprises ", *Business Horizon*s ,Volume 58, Issue 4, August 2015.
5. J. Gubbi, R.Marusic, M. Palaniswamia, "Internet of Things (IoT): A Vision, Architectural Elements, and Future Directions ", *Future Generation Computer System*s, Volume 29, Issue 7, September 2013.
6. N. I. Osman and E. B. Abbas, "Simulation Modelling of LoRa and Sigfox Low Power Wide Area Network Technologies" *Proceedings of IEEE 4rd 2018 International Conference on Computer, Control, Electrical, and Electronics Engineering (ICCCEEE),* August 2018, Khartuom, Sudan.
7. D. Patel, M. Won, "Experimental study on low power wide area networks for mobile internet of things*", Proceedings of the IEEE 85th Vehicular Technology Conference: VTC'17*, May 2017 ,Sydney, Australia.
8. LoRa Alliance Technical Committee, "LoRaWAN™ 1.1 Specification," vol. Final Release., LoRa Alliance, Inc., October, 2017.
9. B. Reynders and S. Pollin, "Chirp spread spectrum as a modulation technique for long range communication," *Symposium on Communications and Vehicular Technologies (SCVT),* pp. 1–5, 2016.
10. B. Reynders, W. Meert, and S. Pollin, "Range and coexistence analysis of long range unlicensed communication," *23rd International Conference on Telecommunications (ICT),* pp. 1–6, 2016.
11. Semtech Corporation, "LoRaTM Modulation Basics," ed, http://www.semtech.com/images/datasheet/an1200.22.pdf, [Online; accessed 25-jun-2018], 2015.
12. D. Bankov, E. Khorov, and A. Lyakhov, "On the limits of lorawan channel access," *International Conference on Engineering and Telecommunication (EnT),* pp. 10–14, 2016.
13. J. Haxhibeqiri, A. Karaagac, F. V. D Abeele, Wout Joseph, Ingrid Moerman, and J. Hoebeke, "LoRa Indoor Coverage and Performance in an Industrial Environment: Case Study," *Department of Information Technology, Ghent University, Belgium,* 2018.

14. Sigfox Technical Overview, [online] Available: https://www.disk91.com/wp-content/uploads/2017/05/4967675830228422064.pdf , [Date accesed: 15 Nov 2018]

15. P. D. Gennaro, L. Domenico, D. Vitanio, P. Tedeschi1, P. Boccadoro, "WaterS: A Sigfox-compliant prototype for water monitoring", *Wiley online libarary* , 19 September 2018.
16. N.L. Ismail, M. Kassim, M. Ismail, R. Mohamad, "A Review of Low Power Wide Area Technology in Licensed and Unlicensed Spectrum for IoT Use Cases", *Bulletin of Electrical Engineering and Informatics*, Vol. 7, No. 2, June 2018.

17. K. Mekkia, E.Bajica, F. Chaxela, F.d Meyerb, "A comparative study of LPWAN technologies for large-scale IoT deployment" , *ICT Express* , vol no.2, 20 December 2017.
18. V. Benny, L. Mads, N. Huan Cong, K. Istvan, M, Pereben Elgaard, S. Mads ,"Coverage and Capacity Analysis of Sigfox, LoRa, GPRS, and NB-IoT", *Proceedings of the IEEE 85th Vehicular Technology Conference (VTC Spring)*, 2017.
19. R. S. Sinha, Y. Wei, S-H. Hwang, "A survey on LPWA technology: LoRa and NB-IoT", *ICT Express*, Volume 3, March 2017.
20. P. Neumann, J. Montavont and T. Noël "Indoor Deployment of Low-Power Wide Area Networks (LPWAN): a LoRaWAN case study", *Proceedings of IEEE 12th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), 2016.*
21. K. Mikhaylov, J. Petaejaejaervi, T. Haenninen, "Analysis of Capacity and Scalability of the LoRa Low Power Wide Area Network Technology" *Proceedings of the IEEE European Wireless 2016; 22th European Wireless Conference*, 18-20 May 2016. Oulu, Finland.
22. M. Lauridsen,; B. Vejlgaard, I. Kovács, H. C Nguyen, P. E. Mogensen, "Interference Measurements in the European 868 MHz ISM Band with Focus on LoRa and SigFox" *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC)*, 19-22 March 2017, San Francisco, CA, USA.
23. T. Petrić, M. Goessens, L. Nuaymi, Al. Pelov, L. Toutain ," Performance and Analysis of LoRa FABIAN, a real-world implementation of LPWAN" *Proceedings of IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, Sept. 2016. Valencia, Spain.

Appendices

Appendix A: LoRa Simulation

The simulation starts by selecting the desired LPWA technology (LoRa), bandwidth and maximum number of devices. It sets the current number of devices to zero.

```
function [collisions,PER,BR,nrofdevices] =
loraSim(n,b)
timespan = 60*1000; %ms
timeinterval = 10; %ms
```

The simulation generates specific packet duration values according to each technology specifications. The first step in the simulation is calculating the number of time slots which is found by:

```
nrofslots = timespan/timeinterval;
```

For LoRa it randomly generates the spreading factor according to the number of channels. The simulation generates specific packet duration values according to LoRa technology specifications

```
lora_duration = [12  293 682;
        11  547 365;
        10  976 204;
        09 1757 113;
        08 3125  64;
        07 5478  36;
        06 9375 21];

packetduration = lora_duration(:,3);
start_channel = 1;
end_channel = 6;
nrofchannels = end_channel;
```

For each number of devices the time offset is calculated. Then time offset values are randomly generated as follows:

```
time_offset = floor((nrofslots -
(packetduration(sf(i))*nrofpackets)/timeinterval)
* rand(1,1));%time(i, 1);
```

The time offset is generated for all simulated devices which represents the offset between each device packet transmission, each device is considered to send one message or packet.

```
collisions=results(:, 1);
PER = results(:, 2);
totalRate=sum(collisions)/sum(nrofdevices);
```

Appendix B: Sigfox Simulation

Same as LoRa ,the simulation starts by selecting the desired LPWA technology (Sigfox), bandwidth and maximum number of devices. It sets the current number of devices to zero

```
function [collisions,failed,per,nrofdevices] =
sigFoxSim(n)
timespan = 60*1000; %ms
timeinterval = 10; %ms
```

The simulation generates specific packet duration values according to each technology specifications. The first step in the simulation is calculating the number of time slots which is found by:

```
nrofslots = timespan/timeinterval;
```

For SigFox, The simulation generates specific packet duration values according to Sigfox technology specifications

```
freqspan = 200e3; %hz : 125khz
freqinterval = 100; %hz
nrofchannels = ceil(freqspan / freqinterval);
```

For each number of devices the time offset is calculated. Then time offset values are generated as follows:

```
time_offset = time_offset
+packetduration/timeinterval;
```

The time offset is generated for all simulated devices which represent the offset between each device packet transmission, each device is considered to send one message or packet.

```
collisions=results(:, 1);
failed=results(:, 2);
per=results(:, 3);
totRate=sum(collisions)/sum(nrofdevices);
```