TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

OBINNA JUDE JOSEPH

ULTRA-NARROWBAND INTERNET-OF-THINGS TECHNOLOGIES

Master of Science Thesis

Examiner: prof. Markku Renfors
Examiner and topic approved on
30th November 2017

ABSTRACT

OBINNA JUDE JOSEPH: Ultra-Narrowband Internet-of-Things Technologies
Tampere University of Technology
Master of Science Thesis, 43 pages, 8 Appendix pages
May 2018
Master's Degree Programme in Information Technology
Major: Communication Systems and Networks
Examiner: Professor Markku Renfors

Keywords: Low Power WAN, Ultra-Narrowband IoT, Spread Spectrum, Sigfox, Time Frequency Asynchronous ALOHA.
Low Power Wide Area Networks (LPWANs) are a class of wireless network technologies that enable low power consumption and wide area coverage. It can utilize licensed or unlicensed frequency bands and also open or proprietary standards, such as Sigfox, LoRa, NB-IoT, or EC-GSM-IoT.

Ultra-Narrowband (UNB) Internet-of-Things (IoT) is usually a technology deployment supporting low-rate sporadic communications and operating over very narrow spectrum channels, usually less than 1 kHz, in order to attain long distance links, normally 5 km in urban or over 25 km in rural or suburban areas in order to gain noise-free, undisturbed and high-quality data links between transmitter and receiver, Sigfox is an ultra-narrowband LPWAN technology for IoT applications, and it operates on the sub-GHz license-free ISM frequency bands depending on the region. In the United States it operates at frequencies around 902 MHz and around 868 MHz in Europe.

LoRa is another LPWAN technology, supporting similar application scenarios as Sigfox and operating in the same ISM bands. However, LoRa it is a spread spectrum technology operating with wider frequency channels. Narrowband Internet-of-Things abbreviated as NB-IoT or LTE-CATM1, is a LPWAN technology which came out as part of the third Generation Partnership Project (3GPP) release 13 standards in the second quarter of June 2016.

This thesis focuses on the random-access schemes for UNB-based IoT networks. Due to receiver synchronization issues in UNB communications, two-dimensional time-frequency random access protocols are a natural choice for UNB systems. As a case study, the throughput performance of a Time Frequency Asynchronous ALOHA (TFAA) protocol is evaluated in a LPWAN UNB uplink scenario using Matlab simulations.

PREFACE

The thesis was done under the supervision of Prof. Markku Renfors and is part of the requirement to fulfil my Master of Science degree program in Information Technology in the faculty of Computing and Electrical Engineering at Tampere University of Technology, Tampere, Finland.

My sincere gratitude to my supervisor and examiner Prof. Markku Renfors for providing all the necessary materials, explanations, feedbacks and time towards the completion of this thesis.

I am thanking my lovely parents Mr. Joseph Ifeanyi Onah and Mrs. Judith Ukamaka Onah for their parental support, advice and encouragement throughout my master's degree program. I appreciate my lovely siblings Mary Rose, Mercy, Martina, Grace and Emmanuel for their kind support has given the strength not to give up in my studies.

Special thanks to my study mates and lecturers of the faculty of computer and electrical engineering which through their teachings and the knowledge impacted on me and made this project a successful one.

Finally, I thank God almighty for the gift of life, knowledge and wisdom.

Tampere, 23.05.2018
Obinna Jude Joseph

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

ALOHA	Additive Links On-line Hawaii Area
BSS	Business Support System
BW	Bandwidth
BPSK	Binary Phase Shift Keying
CR-TFAA	Uniform Resource Locator
CR	Code Rate
CRC	Cyclic Redundancy Sequence
CSS	Chirp Spread Spectrum
CRA	Central Registration Authority
CDMA	Code Division Multiple Access
DCS	Data Collection Centre
EGPRS	Enhance General Packet Radio Service
EC-GSM-IoT	Extended Coverage GSM Internet of Things
FDD	Frequency Division Duplex
FCS	Frame Check Sequence
FDMA	Frequency Division Multiple Accesss
FEC	Forward Error Correction
FSK	Frequency Shift Keying
GSM	Global System Evolution
GPRS	General Packet Radio Service
GFSK	Guassiaan Phase Shift Keying
GMSK	Guassiaan Minimum Shift Keying
HSPA	High Speed Packet Access
HTTP	Hypertext transfer Protocol
IP	Internet Protocol
IPV6	Internet Protocol version 6
ISM	Industrial Scientific and
IoT	Internet of Things
LTN	Low Throughput Network
LAPs	LTN Access Points
LEPs	LTN End Points
LPWA	Low Power Wide Area
LTE	Long Term Evolution
LTE-M	Long Term Evolution for Machine Type Communication
LTE-CAT1	Long Term Evolution-Cellular Modem Implementation One
MTC	Machine Type Communication
M2M	Machine to Machine
MAC	Medium Access Control
MQTT	Message Queuing telemetry Transport
NB-IoT	Narrowband Internet of Things
OSS	Operation Support System
OSSS	Orthogonal Sequence Spreading Spectrum
PRB	Physical Packet Block
PHY	Physical Layer
PER	Packet Error Rate
RFID	Radio Frequency Identification
Rb	Bit Rate
SNMP	Simple Network Management Protocol

SF	Spread Factor
TDD	Time Division Duplex
TFAA	Time, Frequency Asynchronous ALOHA
TS	Symbol Rate
TDMA	Time Division Multiple Access
UNB	Ultra-Narrowband
UMTS	Universal Mobile Telecommunication System
WAN	Wide Area Network
WiFi	Wireless Fidelity
3G	3^{rd} Generation
3GPP	3^{rd} generation Partnership Project
4G	4^{th} Generation
8PSK	Eight Phase Shift Keying

1. INTRODUCTION

The world of technology is eventually realizing the movement of the Internet of Things (IoT) from an imaginary tale to a reality. It is estimated that, by 2020, more than 14 billion network-enabled devices will be in use (Li et al 2015). This compares to approximately 3.2 billion internet users today (Gangadharan 2017). IoT significantly widens the capacity from manually-operated computers towards self-directed smart devices. Usually, these devices are linked to the internet for purposes of remote diagnostics and control, resulting in cost savings. Additionally, ground-breaking IoT hardware and services can create new revenues, for instance, more effective logistics serving novel market segments, connected glasses utilized for industrial applications, or business appliances marketed in per-usage business model (Patel 2017). According to Patel (2017), the Internet of Things (IoT) may lead to combined lower costs and increased revenue of more than $14 trillion from 2013 to 2022. In most situations, private users and business users can take charge of their IoT application via existing tablets and smartphones, by using mobile applications that network with web servers which the connected items link to.

Many mobile operators have established dedicated IoT/M2M units to enable quick service provision to the increasing numbers of firms looking to reap the benefits that come with mobile IoT. Larger organizations have even gone the extra mile to acquire these devices in a bid to achieve the capacity to serve a more extensive part of the value chain and capture income beyond pure connectivity (Patel 2017). As the business world grows, it is becoming evident that there are numerous mobile IoT application cases for which current cellular network are not fitting. The reasons are straightforward: Device cost, coverage and battery life. When talking about coverage, it is important to note that the current cellular networks already provide wonderful area coverage in established and mature markets (Al-Fuqaha et al. 2015) However, many prospective "connected objects" are situated in vast remote places, far-off from the next cellular base station. In places where there is coverage, it is usually weak which necessitates the device transmitter to function at high power, often draining the battery (Chen et al 2017). Moreover, there is lack of optimization of cellular networks for applications that intermittently transmit small amounts of information. The current cellular standards cannot support a battery life of several years that is combined with a reasonably priced device, as they do not support the necessary power saving mechanisms.

The third factor is the cost of devices. Mobile devices working on 3G, GSM and LTE are intended for a number of services, entailing mobile voice, high-speed data transmission, and messaging. However, massive machine-type communication applications do not use any of these; they simply need relatively low speed but unswerving data connection, and a suitable level of dependability (Do et al 2014). Thus, utilizing existing cellular devices for NB-IoT applications implies the use of devices that are too costly for the application. Most of the NB-IoT utility cases need a low device price, not merely for purposes of having a positive business case, but due to practical factors such as simplicity of installation or possibility of theft. Simply put, there are strong market tendencies pointing at an expanding demand for NB-IoT applications, while the systems that can efficiently serve such demands are not yet in place. It would be important for the public to be aware of the various NB-IoT technologies and how to apply them in various situations. This paper examines the various Ultra NB-IoT technologies, systems, and protocols and their applications, potential benefits and challenges.

1.1 Background

Indeed, in its current avatar, IoT has come to represent latest innovations in Radio Frequency Identity (RFID), smart sensor, enhanced communication technologies, not forgetting the ubiquitous, all important Internet Protocols, or IPs and the many derivatives gained from invasive, hi technology, just waiting to be exploited for human and machine uses.

The driving factor being UNB is to rely more heavily on M2M, or Machine to Machine communications, with least interference, interception and involvement of humans, thereby heightening authenticity, productivity, performance and progression (Al-Fuqaha 2015).

Thus, the core idea behind IoT, practically, is to effect greater effectiveness, lower cost impacts and greater portability, transparency and alacrity in enterprise planning activities through machines usages and deployment and to make it compatible with dynamic, evolving and rapidly changing technology especially in telecom and allied areas with pending issues like costs, scalability, technological inputs and attainable levels of professional competencies, for the present and also for the uncertain future.

This encompasses studies of the chief drivers of UNB technology, its motivators, and most of all, its major benefits, especially in terms of high traverse ability, portability with low power consumption, thus adding to cost savings and higher utility value- addition and also, offering larger, extensive and broader scope for Machine-to-Machine (M2M) expansion, growth and diversification.

Thus, in the years to come, it is envisaged that IoT shall be playing well- defining and critical role in technology scheme of things, aiding and abetting critical growth, propagation, diversification and progression paths in global and international arena, especially in areas of M2M communications, correspondences and interfacing especially in areas of identification, dissemination and dispersion of Big Data and other technology- aided constructs at both macro and micro industry levels, aiding, abetting and even reconfiguring gamut of business decision making through greater, intensified use of IoT deployment.

IoT, especially in UNB, and its innumerable IPs have significant benefits and advantages along the technology continuum. It also suffers from major drawbacks and deficits which shall also be focus of this paper.

1.2 Third Generation Partnership Program

The 3GPP (3rd Generation Partnership Project) refers to an international wireless communications organization that jointly comes up with specifications or standards for radio, core network and the system architecture. Part of the second generation (2G) releases by the 3GPP was the GSM which provides both voice and circuit-switched data services (Nelson 2017). The GSM is also the network that later evolved to the Universal Mobile Telecommunications System (UMTS), a component of 3rd generation (3G) technologies. UMTS is the most widely utilized mobile broadband technology globally in form of HSPA (High Speed Packet Access). HSPA includes a combination of 3GPP release 5 (HSDPA) and 3GPP release 6 (HSUPA) technologies in a network (Nelson 2017). On the other hand, HSPA+ in Release 7 and beyond is a component of the HSPA technology and is useful in extending an operator's venture in the network before their next step to LTE (Long Term Evolution) or 3GPP Release 8 and beyond. As of June 2014, about 550 HSPA and HSPA+ networks were available for commercial use in more the 200 countries globally.

The 3GPP's fourth generation (4G) of technology is Long Term Evolution (LTE) which is one of the fastest expanding mobile technologies. As of mid-2014, LTE had more than 300 commercial networks operating in more than 100 countries (Gangadharan 2017). Other 3GPP technologies commercially deployed in the same year include Release 10 LTE-Advanced which was to be used in different countries across the globe.

Inspired by a vision of a digital world with billions of devices interacting over cellular radio access technologies, 3GPP developed no less than three novel technologies for the support of internet of things in Release 13. These include LTE for Machine-Type Communications (LTE-M), Extended Coverage GSM Internet of Things (EC-GSM-IoT), and Narrowband Internet of Things (NB-IoT) (Gangadharan 2017). Each one of these technologies has been standardized to ensure that progressively more diverse application and device types are supported by 3GPP networks, across various countries.

1.3 Work description

The theoretical part of this thesis involves the study of low power wide area network technologies (Sigfox, Lora, NB-IoT, EC-GSM-IoT) focusing on ultra-Narrowband IoT (Sigfox) and spread spectrum (LoRa).

The Technical aspect of the thesis involve the study of Time Frequency Asynchronous ALOHA (TFAA) protocols considering both one-dimensional and the two dimensional cases. Then a simulation to study the throughput of random access protocol Time Frequency Asynchronous ALOHA was done using Matlab. The Matlab code is modelled to generate TFAA and as a result of it collision probability and normalized throughput are obtained as function of the load, distance range of the IoT device, propagation exponent and interference threshold.

Research Methodology

The first step for the thesis is research:

- Researching the scientific books, literatures related to Utra-Narrowband IoT online and from different Universities library in Tampere, Finland.
- Studying the materials to understand Ultra-Narrowband IoT in details.
- Writing the first literature review.

The second step for the thesis is the technical and modeling part of the thesis.

- Case study for the thesis is TFAA.
- Studying TFAA analytical and theoretical model for understanding.
- Simulating the TFAA into Matlab.
- First simulation result with some errors.
- Second simulation results without graph.
- The final simulation results with graph.

This thesis is organized in the following way: Chapter 2 introduce the main low-power wide-area network technologies with emphasis on Sigfox and LoRa in this chapter other types of low-power-wide-area network such as narrowband internet of things, extended coverage global system mobile and their features and mode of operations are also discussed.

Chapter 3 focuses on ultra-narrowband techniques, discussing its features, benefits and challenges and applications.

Chapter 4 is the technical aspect of the thesis. Frequency Time Asynchronous ALOHA (TFAA), one Dimension ALOHA, random spectrum access and pure ALOHA protocol analytical model are discussed in detail.

In chapter 5 the throughput performance of Time Frequency Asynchronous ALOHA and the evaluation in low power wide area network ultra-narrowband uplink scenario using Matlab simulator.

Finally, chapter 6 is the conclusion part of the thesis.

2. LOW POWER WIDE AREA NETWORK

LPWAN is the acronyms for Low Power Wide Area Network. LPWAN is a wireless network technology that enable low power consumption and long area coverage. It can utilize licensed or unlicensed frequency and also open standard and proprietary. In this chapter the two major types of LPWAN technologies the Ultra Narrowband (Sigfox) and the Spread spectrum (LORA) will be discussed in this chapter in details.

2.1 Sigfox

SigFox is a French organization with the main objective of becoming one of the first international IoT providers. The company positions itself as an IoT service provider. As devices send information through the network, SigFox ensures that the transfer of the messages takes place through a HTTP callback to a pre-configured backend (Torğul et al. 2016). It is one of the UNB technologies that operate on varied sub-GHz ISM frequency bands depending on the region. For instance, in the United States, the SigFox operates at frequencies around 902 MHz and around 868 MHz in Europe. As of 2016, the SigFox network offered services in 23 countries and more than 1.3million km^2 (Meshram et al. 2017). The main features of SigFox are summarized in table 1.

Similar to LoRa, Sigfox is used for IoT and machine-to-machine (M2M) applications which transmit only a few bytes in a day. The company enforces various constraints on the messages sent over the network. Only 140 messages, each 12 bytes long, can be transferred in 24 hours with a limit of maximum 7 messages every hour. SigFox radio modules for IoT devices have also the capacity to receive 4 incoming transmissions per day (Meshram et al. 2017). The technology is based on Low Throughput Network (LTN) and is among the LPWA technologies that support transmission of small amounts of data over large distances. Through interfacing, it can also coexist with cellular wireless technologies such as LTE, GSM, and CDMA, among others.

Table 1. *Sigfox Features.*

Specification	**Sigfox**
Frequency band	902 MHz in USA and 868 MHz in Europe
Bandwidth	200 kHz
Data rate	10 to 1000 bps
Distance	Rural (30-50 km), Urban (3-10 km)
Data size	12 bytes

Modulation scheme	Binary Phase Shift Keying (BPSK)
Applications	IoT and M2M based applications
Architecture	Star consisting of base stations, Sigfox objects, Cloud and Customer IT server
Capacity	Base Station can handle 3,000000 devices

2.1.1 LTN Network/ Sigfox architecture

As shown in figure 1, a typical LTN network architecture consists of LAPs (LTN Access Points), LEPs (LTN End Points), WAN or cloud part, and various types of servers. The different severs include LTN server, BSS/OSS/, CRA (Central Registration Authority), and application provider server (Trasviña-Moreno 2016). The various entities of the Sigfox system are connected using different interfaces. The interface types, interface A to interface F', are described in table 2 below.

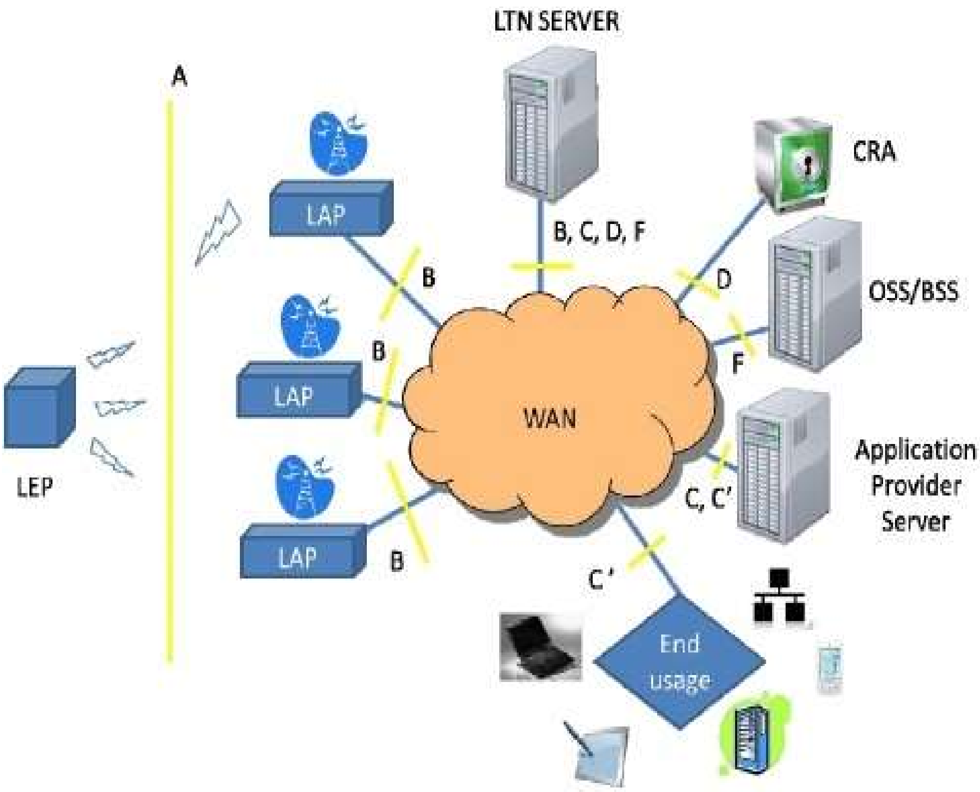

Figure 1. *LTN Architecture. Source: Vejlgaard (2017)*

Table 2. *LTN Network Interface Type.*

LTN Interface Type	Description
Interface-A	This type of interface uses radio access technologies to create a connection between LEP (end devices) and LAP (Base station or gateway).

Interface-B	This interface is utilized between LAPs and LTN servers via WAN mediums. The WAN mediums can be ADSL, satellite, fiber or microwave links.
Interface-C	This type of interface is found between LTN server and Application provider server. It makes use of IP protocols.
Interface-D	This interface type is used between LTN CRA) and LTN servers.
Interface-E	This interface is utilized between multiple LTN servers. It is mainly used during roaming.
Interface-F	This interface is used for exchanging information for registration and network status between LTN servers and OSS/BSS servers.
Interface-A'	This interface is used between DCS (Data Collection System) and LTN module, inside LEP. AT commands over serial connection are employed for the execution.
Interface-C'	This interface is provided by application provider and is used as End User interface.
Interface-F'	This interface is applied between application provider and OSS/BSS servers.

2.1.2 Sigfox Architecture

The Sigfox architecture consists of the Sigfox objects, gateway, the Sigfox cloud and the servers. In Sigfox technology, star topology is applied to connect objects with the Gateways. To interface the cloud with server, different protocols such as HTTP, SNMP, MQTT, and IPv6 are applied based on the end applications (Vejlgaard 2017). As an important element of the network, the objects are the parts where the control or sensing takes place. The elements are usually remotely located (see figure 2 below) and communicate with the Sigfox gateway. The Sigfox gateway receives signals from the objects and passes them onto the Sigfox cloud. The Sigfox Cloud supports the various Sigfox services, including message retrieval and management of all the objects. This element of the network can be cellular, Ethernet or other telecommunications connection that is either wired or wireless. To connect the gateways to the Sigfox Cloud, Secure IP connections are used. These are usually direct secure point to point links located between the two. This way the data utilizes a standard protocol, but can be linked to any telecommunications network, whether private or public. When looking at the similarity between a cellular network and that one of Sigfox gateways may frequently be co-located within a cellular base station, thus making them able to use the backhaul network's spare capacity.

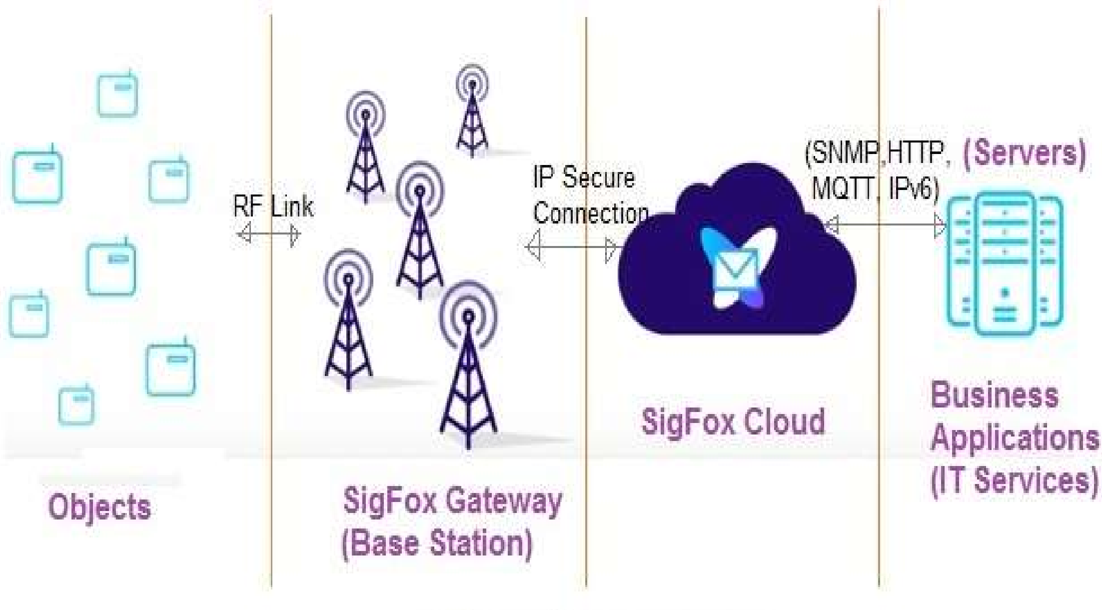

Figure 2. Sigfox Architecture (*Whitmore et al 2015)*

Figure 2 above shows the simple architecture of the Sigfox network. The architecture is similar to the LTN one, except for the terminologies employed. The LEPs are termed as objects while LAPs designated as Base stations or Gateways. WAN represents the cloud which links BSs with business applications via various interfaces (Bonavolontà et al.2017). The transmissions from LTN End Points to the network (i.e., Gateways or BSs) are known as uplink transmissions while those from the network to LTN End Points are known as downlinks.

2.1.3 Sigfox Protocol Stack

Sigfox Protocol Stack of the wireless system consists of four layers, namely Radio (RF) layer, Physical Layer, MAC layer, and application layer . Each of these layers has its unique characteristics which enable it to perform certain functions. The Radio layer is responsible for assigning frequency and transmitting/receiving power needs of Sigfox end points and base stations. The RF layer supports the two implementations in the Sigfox system, that is, the UNB and OSSS (Orthogonal Sequence Spread Spectrum). It also upholds the different frequency spectrum allocated in the United States, (902 MHz), Europe (868 MHz), and China (433 MHz). The maximum transmit power of 25 mW is particular for Ultra Narrow Band uplink transmissions for 868 MHz Band. The layer also ensures that the sensitivity of the Sigfox receiver is better than -135 dBm.

The PHY layer handles the MAC frames at the times of transmission as well as during reception. It plays the role of inserting the preamble at the transmit end as well as removing it as the receive end. It applies BPSK and GFSK modulations in the uplink and downlink, respectively. The preamble is needed for synchronization purposes. The MAC layer, on the other hand, deals with the management of MAC messages. The MAC layer does the preparation of frames as per formats of the uplink and downlink discussed in the next section. Although the Sigfox system is mainly deployed for uplink transmissions, it can also be applied for downlink communications. The downlink transmission of messages can be executed either using broadcast or piggy backing. The layer also takes care of error detection using frame check sequence (FCS) as well as handling authentication of end users.

Lastly, the application layer is a LTN technology that supports different applications. The layer contains various protocols/interfaces between cloud and servers, e.g., SNMP, MQTT, HTTP, IPv6. Thus, it defines various applications as per the requirements of the user, that is, whether it is a message, web, among others.

2.1.4 Sigfox Frame Structures

Sigfox MAC has two frame structures, one for the uplink direction and the other for downlink direction. Each of the frames has certain characteristics as indicated in figure 3 below. The preamble for the uplink MAC frame for UNB implementation is 4 bytes while the frame synchronization takes two bytes, end-device identification 4 bytes, and payload 0-12 bytes. The authentication varies in length and the FCS for error detection consists of 2 bytes (Nelson 2017). Conversely, the downlink MAC frame has a preamble of 4 bytes or 32 bits and a frame synchronization sequence of 13 bits. As shown in figure 3 below, its FCS is 8 bits and authentication 16 bits. It has variable length error codes and payload.

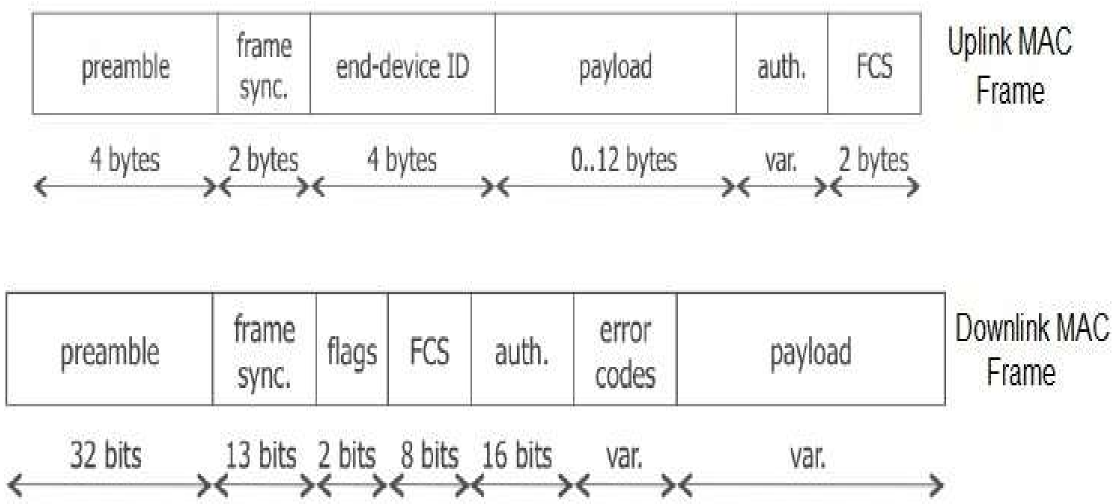

Figure 3. *SigFox frame structures. Source: Chen et al. 2017*

2.2 LORA

LoRa is a long-range wireless technology that operates on the ISM radio bands of varying frequencies depending on the region. The technology is based on a spread spectrum transmission scheme (Mo et al. 2014). LoRa technology has a frequency spectrum range of 863 to 928 MHz. These frequencies are low enough to go through obstacles and travel long distances while using fairly little power, which is the ultimate goal for many IoT devices, which are frequently limited by battery life.

The technology is a PHYsical layer protocol that provides low-power and long range communication medium for IoT and machine-to-machine (M2M) applications. Within the sub-GHz spectrum, LoRa utilizes a spread-spectrum approach to transmit at different data rates and frequencies (Sikken 2016). That permits the gateway to become accustomed to varying conditions and optimize the way it communicates with each device. Thus, the technology enables public or multi-user networks to connect to several applications operating in the same network. Unlike Sigfox, LoRa modules permit for granular configuration and arrangement implying that, if two devices are configured differently, they will experience challenges communicating to each other (Al-Fuqaha et al 2015). As such, the setup is more prone to errors but offers users more control over their devices' energy consumption. The technology is expected to enable the creation of smart city with the assistance of LoRa sensors and automated applications/products.

2.2.1 LORA Features

Table 3 contains some of the key features of the LoRa protocol such as range, capacity, and modulation scheme.

Table 3. *Description of LoRa features*

Specification	LoRa Feature
Range	2-5 km urban and 15 km suburban
Frequency	ISM 868/915 MHz
Modulation	Spread spectrum modulation type based on FM pulses which differ.
Standard	IEEE 802.15.4g
Capacity	One gateway supports thousands of nodes
LoRa Physical layer	Frequency, power, modulation, signaling between gateways and nodes
Battery	Long battery life; up to ten years

2.2.2 Lora Physical Layer

The LoRa technology has a physical layer that gives it the ability to operate effectively, enabling low power transmissions to keep up data links over very long distances. The physical layer encapsulates all the direct contact with the external world over the radio interface (Augustin et al. 2016). Its parameters which include bands, frequencies, modulation, power levels, and the basic RF protocols are encapsulated in the LoRa physical layer attributes.

2.2.3 Lora Network

Since LoRa technology has the capacity to provide a wide area network service, it is commonly referred to as LoRaWAN. A LoRa network is composed of various elements including the endpoints, LoRa gateway, server, and a remote computer (Vejlgaard et al 2017). As an important element of the network, the endpoints are the parts where the control or sensing takes place. The elements are usually remotely located (see figure 4 below) and communicate with the LoRa gateway. The LoRa gateway receives signals from the endpoints and passes them onto the backhaul system. This element of the network can be cellular, Ethernet or other telecommunications connection that is either wired or wireless (Augustin et al. 2016). To connect the gateways to the network server, standard IP connections are used. This way the data utilizes a standard protocol, but can be linked to any telecommunications network, whether private or public. When looking at the similarity between a cellular network and that one of LoRa, one can realize that LoRa gateways may frequently be co-located within a cellular base station, thus making them able to use the backhaul network's spare capacity.

Another element of the network is the server which controls the network. As part of managing the network, the server also plays the role of scheduling acknowledgements, as well as adapting data rates (Augustin et al. 2016). The server is one of the elements that are easy to deploy and connect, enabling easy implementation of a LoRa network. Lastly, with the network being almost transparent, a remote computer is required to control the operations of the endpoints or gather information from them.

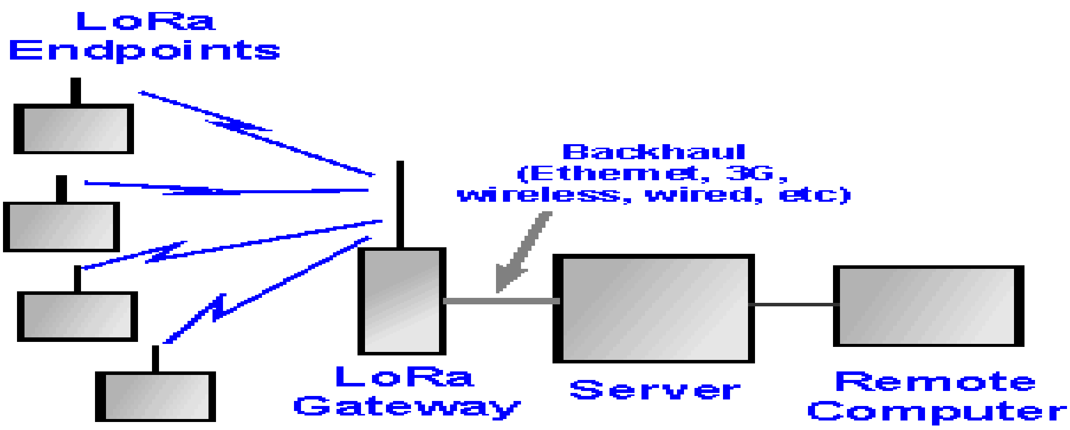

Figure 4. *Lora network architecture. (source: Radio-electronics.com. Ref. 47)*

When talking about the actual architecture of the LoRa technology, the nodes characteristically assume a star-of-stars typology with gateways creating a transparent bridge. These convey data between end-devices and a central network server situated in the backend (Augustin et al. 2016). Although the communications to endpoints is usually bi-directional, it is also possible to hold up multicast operation, and this is handy for features such as software upgrades, among other mass distribution data.

2.2.4 LoRaWAN Endpoint Classes

There are numerous different needs to LoRa endpoints and, therefore, the LoRaWAN supports three categories of endpoints - classes A, B, and C. The Class A endpoints are bi-directional end-devices and thus, provide bidirectional communications (Augustin et al. 2016). To enable this type of communications, an endpoint transmission is tagged along by a pair of short downlink receive windows. The needs of the particular endpoint are considered when scheduling the transmission slot. There is also a small variation scheduled utilizing a random time basis (Augustin et al. 2016). The operation of this class gives the lowest power option for endpoints that simply need downlink transmission from the server in a moment after the end-device has transferred an uplink communication. Downlink transmissions from the server at any other moment wait till the subsequent scheduled uplink time.

Class B endpoints are bi-directional end-devices that have scheduled receive slots. As a result, they can provide the functionality of Class A end points as well as open additional receive windows at predetermined times (Augustin et al. 2016). To achieve the necessary synchronization with the network, the endpoint must receive a time harmonized beacon sent from the gateway. This enables the server to know when the end-device is listening (Chen et al. 2017). Similarly, Class C end-points are bi-directional end-devices but with maximal receive slots. As a result, they provide practically constantly open receive windows that only close when there is transmission by the endpoint. Due to their maximal functionality at the receive slots, Class C endpoints are suitable where large amounts of information are required to be received compared to the amount of transmitted data.

2.2.5 Physical frame format

Although the modulation method used in LoRa can be applied in transmitting arbitrary frames, Simtech's receivers and transmitters specify and implement a specific physical frame format. The spreading factor and bandwidth are constant for a frame. The LoRa frames open with a preamble which starts with a series of constant up chirps covering the entire frequency band (Furht and Ahson 2016). The last two up chirps of the series encode the sync word.

The sync word is characterized by a one-byte value that is utilized to distinguish LoRa networks that make use of the same frequency bands. In its operation, a device configured with a certain word will stop listening to a communication if the decoded sync word fails to match its configuration. Following the sync word are two and a quarter down chirps that last for a period of 2.25 symbols. The total time of this preamble can be set between 10.25 and 65,539.25 symbols. The arrangement of the preamble is indicated in figure 7.

An optional header follows the preamble, which when present is transmitted with a code rate of 4/8 (Augustin et al. 2016). This indicates the code rate CR applied for the rest of the transmission, the quantity of bytes in the payloads, and whether a 16-bit CRC for the payload is present at the end of the frame or not. The header also entails a CRC to enable the receiver to get rid of packets that have invalid headers. The size of the payload is stored using one byte, restricting the maximum size of payload to a total of 255 bytes (Do et al. 2014). The header is optional to enable its disabling in events where it is not required, for example when the coding rate, payload length and CRC presence are predetermined in advance. The payload comes after the header, and at the end of the frame is the optional CRC. A graphical representation of the frame format can be seen in Figure 5.

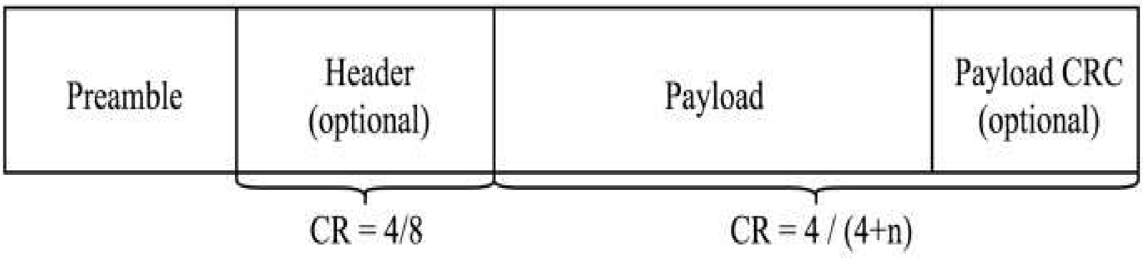

Figure 5. *The LoRa frame structure (Source: Aloÿs Augustin 1, Jiazi Yi 1 et al. 2016)*

The equation below provides the number of symbols, ns, needed to transmit a payload, as a function of various parameters. This number should be topped up to the total number of the symbols of the preamble, so as to calculate the total size of the packet in the symbols. In the equation, CRC is 16 if the CRC is existent and zero if it is disabled, PL is the size of the payload in bytes, H is 20 if the header is enabled and zero when disabled and DE is two in cases where there is optimization of low data rate enabled and zero otherwise. In this equation, in is shown that the smallest size of a packet is eight symbols.

$$n_s = 8 + max\left(\left\lceil \frac{8PL - 4SF + 8CRC + H}{4 * (SF - DE)} \right\rceil * \frac{4}{CR}, 0\right)$$

2.2.6 LoraWAN Message Format

LoRaWAN utilizes the physical frame format explained in section 2.2.3 above. For the uplink messages, the header and CRC must be present, which makes it unfeasible to use a spreading factor of six in LoRaWAN. On the other hand, the header is mandatory for downlink messages but not the CRC (Torğul et al. 2016). There is also no specification of the code rate to be used as well as when the end-devices should make use of the low data rate optimization.

As shown in detail, the figure below contains information on the LoRaWAN message format where DevAddr denotes the device's short address and FPort a multiplexing port field. The value zero implies that the payload consists only MAC commands, which then leads to the resultant zero in the FOptsLen field. FCnt denotes a frame counter. On the other hand, MIC represents a cryptographic message integrity code which is calculated from the fields MHDR, FPort, FHDR, and the encrypted FRMPayload. The message type, that is, whether it is a downlink or an uplink message and whether it is a confirmed message or not, among other things, is indicated by MType. Responses are requested for messages that have been confirmed. Major is the version of LoRaWAN, for which currently only a value of zero is valid. ADRAckReq and ADR regulate the data rate adaptation method by the network server. The last received frame is acknowledged by ACK. FPending points out that the network server has extra information to transfer and the end-device should transmit another frame within the shortest time possible so that it has the window open for reception. FOptsLen indicates the length of the FOpts field in bytes. FOpt, on the other hand, is utilized to piggyback the commands of MAC on a data message. The MAC command identifier is represented by CID, and the non-mandatory arguments of the command by Arg. FRMPayload is the payload and it is encrypted by AES with a key length of a total of 128 bits. The MAC header contains a minimum of 13 bytes and a maximum of 28 bytes. With this information, it is possible to calculate the maximum channels capacity obtainable for application data payloads with specified modulation parameters by using equations below. Since packets are transmitted from a device to the network, there are no destination address and source address for the uplink packets and downlink packets, respectively.

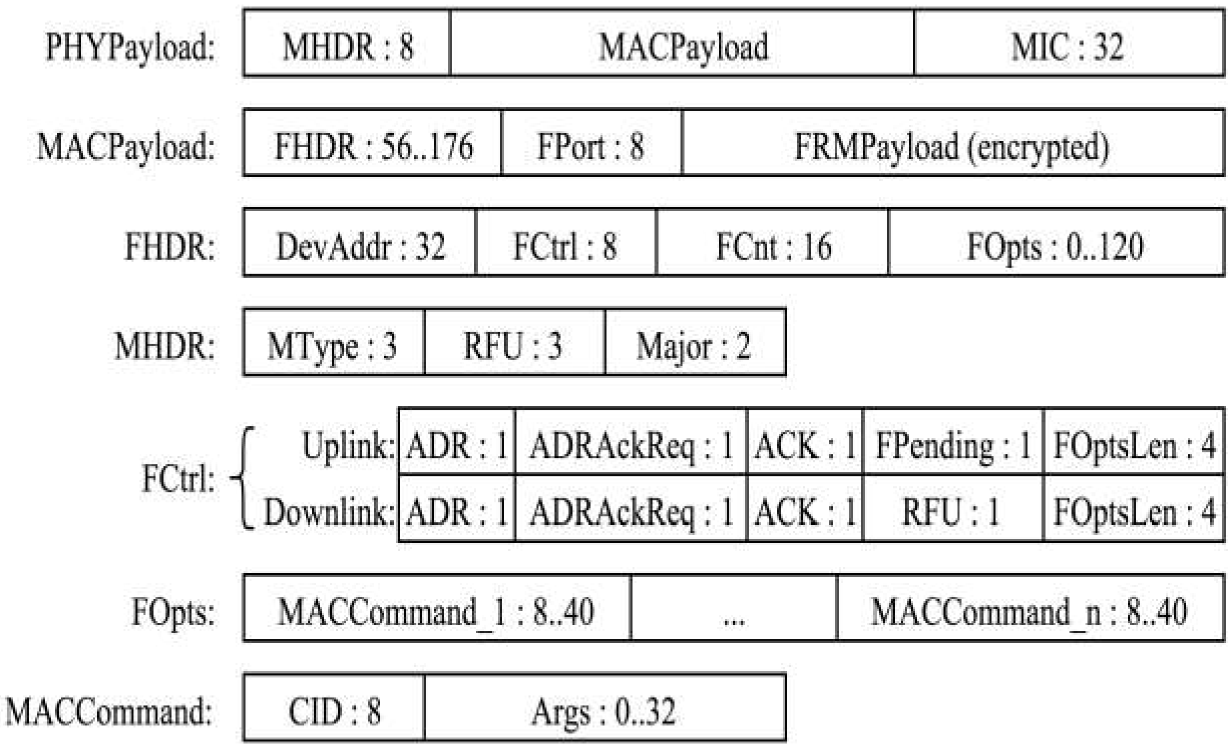

Figure 6. LoRaWAN frame format - sizes of the fields are in bits.
Source: (Aloÿs Augustin 1, Jiazi Yi 1 et al. 2016)

2.2.7 Lora Modulation

The LoRa physical layer makes use of a specific type of spread spectrum modulation, referred to as the Chirp Spread Spectrum (CSS) modulation. The LoRa modulation scheme utilizes wide-band linear frequency modulated pulses (Augustin et al. 2016). In LoRa modulation, the level of frequency decrease or increase over time is applied to encode the information to be conveyed, that is a form of chirp modulation. In this technique of LoRa modulation, spreading of spectrum is achieved by production of a chirp signal which changes continuously in frequency (Chen et al. 2017). As a result of this, frequency offset and timing offset are not critical for signal detection, making the design of the receiver uncomplicated as complex algorithms are avoided. Additionally, there is correspondence between frequency bandwidth of chirp and spectral bandwidth of the system's modulated signal. This form of modulation enables the technology's systems to demodulate signals that are below the noise floor by 20 dB when the demodulation is merged with forward error correction (FEC) (Do et al. 2014). The FEC allows for the recovery of bits of data as a result of corruption by interference, which necessitates for a some overhead due to FEC encoding of the information in the transmitted packet. This implies that, when compared to the traditional FSK system, the link budget for LoRa technology can offer an improvement of more than 25 dB.

2.2.8 Lora Modulation Parameters

The LoRa modulation is essentially defined by some basic parameters which include: the bandwidth (BW), which is the difference in minimum frequency and maximum frequency; the spreading factor (SF), which is the indicator for the quantity of bits encoded per symbol; and the code rate (CR), which is the measure for the level of forward error correction. LoRa technology makes use of an exceptional definition of the SF as the logarithm, in base 2, of the quantity of chips per symbol. These parameters affect the efficient bitrate of the modulation, its ease of decoding and its resistance to interference and noise (Do et al. 2016). Of all the parameters of the LoRa modulation, the bandwidth is the most significant. A single LoRa symbol is made of 2SF chips, and its frequency varies over the whole frequency band during each symbol interval, also know as chirp. Each symbol carries SF bits, and the symbol value is represented by the initial frequency in the beginning of each symbol interval. Depending on the symbol value, the chirp wraps around from the highest to the lowest frequency at some point during the symbol interval. Figure 7 below provides an illustration of a LoRa transmission as the frequency alteration over time, where BW is the bandwidth and fc denotes the center frequency of the channel.

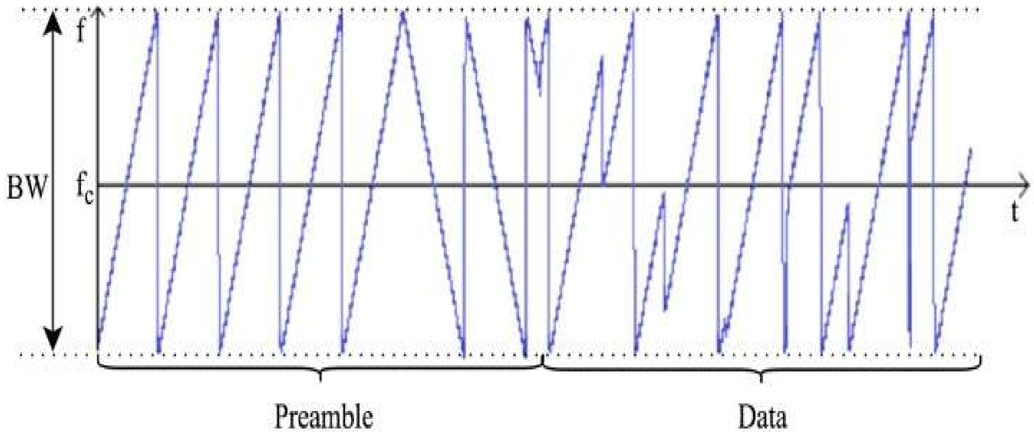

Figure 7. *Frequency variation over time of a sample signal emitted by a LoRa transmitter. Source: (Aloÿs Augustin 1, Jiazi Yi 1 2016)*

Additionally, the bandwidth determines the chip rate in LoRa as the chip rate is equivalent to the bandwidth. This has a number of effects on the modulation as an increase by one of the spreading factor will increase the frequency span of the chirp by the factor of two if the symbol rate is fixed or increase the symbol period by two if the bandwidth is fixed. However, as one additional bit will be transferred in each symbol, the bit rate is increased by two in the former case and remains the same in the latter (Almonacid and Franck 2017). Furthermore, the bit rate and the symbol rate with a certain spreading factor are proportional to the frequency bandwidth, so doubling of the bandwidth efficiently doubles the rate of transmission. This is interpreted in the equation below, which shows the relationship between the symbol duration (TS) and the spreading factor and the bandwidth. TS=2SF /BW

The CR, on the other hand, is a measure for the level of forward error correction. The code rate R equals 4/(4 + CR), where CR =1,2,3,4. Considering this, in addition to the facts that spreading factor (SF) bits of data are transmitted per symbol, the equation indicated below allows for the computation of the useful bit rate, Rb. Rb=SF×BW/2SF×R

The three parameters (BW, SF, and CR) also have an influence on the sensitivity of the decoder. As a general rule, an increase of the bandwidth degrades the receiver sensitivity, while an increase in the SF leads to an improvement in the receiver sensitivity. On the other hand, reducing the code rate aids in the reduction of the Packet Error Rate (PER) which can occur as a result of short bursts of interference (Trasviña-Moreno et al. 2016). This implies that a packet being transmitted with a code rate of 4/8 will tolerate interference better than one being transmitted with a code rate of 4/6. The figures in the table below, retrieved from the SX1276 datasheet, gives an illustration.

Table 4. *Semtech SX1276 LoRa receiver sensitivity in dBm at various spreading factors and bandwidths Source: Semtech (2015)*

SF / BW	7	8	9	10	11	12
125 kHz	−123	−126	−129	−132	−133	−136
250 kHz	−120	−123	−125	−128	−130	−133
500 kHz	−116	−119	−122	−125	−128	−130

2.2.9 Lora Frequency Bands

The LoRa system utilizes the unlicensed frequencies that are accessible from different parts of the world. Some of the commonly used frequencies are 915 MHz for North America, 868 MHz for Europe, and 433 MHz band for Asia (Meshram et al. 2017). The system's utilization of lower frequencies than those of 5.8 or 2.4 GHz ISM bands makes it possible for a better coverage to be attained, particularly when the nodes are placed within buildings. Although the LoRa system usually uses the sub-GHz ISM bands, the technology is not particular to any one frequency and can be used on a variety of available frequencies without fundamental adjustment.

2.3 LPWAN GENERALIZATION

Both UNB and SS approaches are competent enough to address the issues caused by high path loss link budget requirements of LPWA systems, especially due to the benefits and advantages in terms of costs, low power demands and high coverage (RealWireless 2015).

However, from the LPWA propagation channel perspective, limited quantum of spectrum availability, need for licensing regulatory regimes, and most of all, high 250 kHz power associated with this is really inadequate to provide mitigatory impacts for fading, and thus, these benefits, which are available under Spread Spectrum Systems, is not available under UNB and for best reasons also, since the competencies of SS is constrained by its own noise and other pollutions.

Besides, other traditional benefits and gains associated with spread spectrums, in terms of lower fading margins do not yield benefits under LPWA networking. Besides under asynchronous communication systems, maintaining tight power controls would be most likely difficult and impossible to fully achieve, given set of provided circumstances and other situational advantages or otherwise. Thus, theoretically speaking, multi-user detection spread spectrum methods with perfect power controls would seek to allow similar capacity achievements, but at higher complexity levels, than under UNB approach systems which seek to narrow down bandwidth space in order to cover greater distances at minimal costs and efficiencies, both in the short and long terms of their applications (Real Wireless 2015). Thus, coming to the aspects of LPWA networking, either UNB or spread spectrum approaches would needed to be preferred or better still, there is need for UNB to be applied uniformly over many narrowed channels and Spread Spectrum Approach does separate users by codes and would thus require greater, effective power control to limit self-noise (Real Wireless 2015).

Thus, it is evidenced that, for instance, when LPWA system needs to perform in the presence of another competing LPWA system, the DSSS would not be very compatible and may even offer conflicts, thus rendering weak the LPWA system itself. The repercussions would be more palpable on uplink and range of victim's uplinks could help reduce aggressor network loading increments (Real Wireless 2015).

Besides, other weakness could stem from the fact that interferences from Aggressor end points near victim's BS could effectively block victim's BS and make communications and correspondences difficult if not virtually impossible.

However, in the event of co-existence or 2-D approach, things would be less problematic and also, inter-systems interferences could be easily mitigated by using multi channels for each system. While this would require BS to process more channels.

2.4 Cellular MTC Technologies

The IoT sets in a wide range of applications, and among the various types is Machine Type Communications (MTC), also referred to as Machine to Machine Communications (M2M). MTC is also a part of the technologies developed by the 3GPP (Do et al 2014). MTC is one of the cellular industry's trials for allowing devices that function on carrier networks to be less costly and more power effective, therefore influencing the Internet of Things. This segment entails such applications like smart metering, real estate monitoring, agriculture as well as different types of fleet management and tracking. Commonly known as low power wide area (LPWA), networks that permit connectivity to MTC applications need a radio access technology that can provide capacity to support extensive number of low-rate devices, extensive coverage, and low power consumption.

One of the most popular cellular technologies for MTC is the EC-GSM-IoT which is building on GPRS/EGPRS for its success. Currently, GPRS/EGPRS is thriving in the MTC market due to its minimal device cost and worldwide presence which can be associated with the various GSM frequency bands 1900, 1800, 900 and 850 MHz, which enable roaming across most parts on the planet (Furht and Ahson 2016). To these features EC-GSM-IoT appends enhanced coverage by 20 dB over EGPRS, power efficient operation, LTE-grade security and even further increased device simplicity beyond what is obtained from EGPRS.

The chief constituents of LTE-M, which is the short form commonly utilized for the LTE enhancements for MTC, are a succession of low-cost categories of devices (for example Cat-MI and Cat-M2) as well as two coverage improvement modes, that is, CE modes A and B. The original reason behind the LTE-M designing was to reduce the device complexity and increase its competitiveness with EGPRS in the MTC market (Furht and Ahson 2016). Other than its simplicity, LTE-M has the capacity to support secure communication, high system capacity, and ubiquitous coverage. The technology's ability to function as a full-duplex system over a superior bandwidth also gives it supplementary aspect with its potential to provide services with higher throughput and lower latency than NB-IoT and EC-GSM-IoT, features that allow it to support such services as voice over IP. LTE-M has the capacity to support both half-duplex frequency division duplex (FDD), full-duplex FDD, and time division duplex (TDD) which are described in the next section.

3. ULTRA NARROW-BAND IOT SYSTEMS

Ultra-Narrow Band (UNB) involves the transmission of data occupying a very narrow frequency channel, typically with basic single-carrier digital modulation schemes, like binary-phase-shift-keying (BPSK) (Do et al. 2014). The deployment is usually less than 1 KHz., in order to attain long distance linkages, normally 5 kms in urbanized or over 25 kms in rural or suburban areas in order to gain noise-free, undisturbed and high-quality data linkages between transmitter and receiver (Wei & Webb 2016).

Different Ultra Narrow Band IoT Technologies have been created to offer wireless connectivity for the actuators and sensors that make up the IoT. The new technologies are developed to provide extended coverage, low cost, scalability, and power efficiency for the end user devices (Almonacid and Franck 2017). Although some Internet of Things devices will operate using local area networks such as Bluetooth and WiFi, there is increasing demand for the wide area coverage. Today, GSM, and its enhancements EDGE and GPRS, is the chief connectivity technology for wide area IoT. On the other hand, operators are working on replacing the technology, which are established in almost thirty years ago, with LTE and 3G. Both LTE and GSM have been modernized in the latest 3GPP standardization releases to enhance the abovementioned key performance indicators (KPIs) related to IoT (Furht and Ahson). The improvements are Narrowband-IoT (NB-IoT) for LTE, and Extended Coverage GSM, for GSM. Although the NB-IoT can be utilized in refarmed GSM carriers, it can also be deployed in the the LTE guard band as well as in a single physical resource block (PRB) of existing LTE establishments.

Other than the cellular technologies there are also several Low-Power Wide-Area (LPWA) network technologies, which function in the unlicensed bands, that is the industrial scientific, and medical (ISM) bands (Almonacid and Franck 2017). Sigfox and Long-Range WAN (LoRa) are possibly the two most commonly known LPWA-type IoT connectivity technologies. While LoRa is based on spread-spectrum techniques utilizing relatively wide transmission band, SigFox is an ultra-narrow band (UNB) system. UNB technology is presently deployed in Sigfox networks. UNB-IoT has been included also in the 3GPP standardization. Generally, the unlicensed spectrum technologies are rather new and require more research work on their operation, features, applications, benefits and challenges.

3.1 Benefits

One of the major benefits of Sigfox Signaling in UNB channels, especially over 200 Hz widths, is that of power usages, especially in the domains of transmitting or dispersing data over wide area with lower air data dates. While the usages of UNB may be restricted to one-way- traffic, from Sensor Terminal device to Base Station, this may also envisage two-way- transmission in the context of UNB (Wei & Webb 2016).

Besides, the increasing benefits and deployability of versatile, value-additive and visibility of technologies of the likes of Sigfox could be evidenced from truth that by year 2020, nearly 50 billion devices would be connected through radio communications in sync with proliferative growth and progression of the IoT, especially explosive growth of Low Power Wide Area Networks (LPWAN), with three of its major exponents – Sigfox, LoRa and NB- IoT vying for market shares and large-scale IoT deployability (Mekke et al. 2017).

3.2 Challenges/Problems

Thus, the main challenge facing UNB system has been that of higher Radio Frequency (RF) crystal demands, which effectively pushes signals outside of channels in the event the frequency gets too large, thus negating the very validity and rationale for its continued usage (Wei & Webb 2016).

3.3 Applications

Sigfox application across all industries.

Figure 8: *Sigfox Application (source: slidesharecdn. Ref. 45)*

- **Smart Cities**
  Sigfox can be used to monitor or track car location, free parking lots, pollution level and free bicycle with in the smart city.
- **Medical**
  Sigfox sensors can be used in the hospital to monitor patient health condition and simultaneously send the patient result to the doctor. It can also be used to monitor the temperature and pollution rate within the hospital.
- **Logistics**
  The transport and the logistics companies use Sigfox to monitor the location of freight, car, truck.
- **Position tracking**

Sigfox is used to track the location of cars, bicycles. In Singapore Sigfox is used to track the location of bicycle with in the city.

- **Utilities**
  Sigfox devices are used for metering the consumption of electricity, gas and water.
- **Manufacturing Industries**
  Sigfox monitoring sensors are used in the manufacturing industries to monitor the working system of the machine components to detect faults earlier to avoid breakdown of the entire machine.
- **Agriculture**
  Ultra-Narrowband technology is used in the agricultural industries by the famers or land managers to monitor the health of their livestock, crops, and also the temperature of the environment.
- **Food temperature**
  The temperature of food can be monitored by using Sigfox temperature monitoring sensor. UNB IoT solution can help mitigate the rate of food contamination by monitoring the food storage facilities.
- **Remotely monitoring Staff attendance**
  Staff attendance can be monitored remotely by connecting time clock to the internet through Sigfox global IoT network.

4. CELLULAR IOT TECHNOLOGIES

This sub-chapter discuss other Low Power Wide Area technologies like Narrowband IoT (NB-IoT) and Extended Converge Global System for Mobile like, will be disused.

4.1 Narrowband IoT

Narrowband Internet of Things abbreviated as NB-IoT or LTE-CATM1 is a Low Power Wide Area Network wireless technology which came out as part of the third Generation Partnership Project (3GPP) release 13 standards in the second quarter of June 2016. NB-IoT uses 200 kHz of bandwidth and support half duplex with maximum data rate of 250 kbps. NB-IoT is targeted on devices with a very low throughput for example gas meter, water meter, electricity meter etc. NB-IoT can be used the spectrum of 2G, 3G and 4G (example 450 MHz to 3.5 GHz), and for the purpose of quality coverage Sub-2 GHz bands are preferable.

4.2 Features of Narrowband IoT

Table 5: *NB-IoT Features*

Bandwidth	200 kHz
Duplex	Half Duplex
Data Rate	250 kbps
Latency	1.6s – 10s
Battery life	10 years
Cost	low cost (5 USD to 10 USD)
Release	Release 13 3GPP specification
Initial Region	Europe
Modulation	QPSK, BPSK
Message Payload	1600 bps
Channel Access Method	Downlink: OFDMA Uplink: FDMA
Frequency	Subset of LTE bands, standalone on GSM bands.

4.3 NB-IoT mode of operation

- NB-IoT operates as standalone technology in the GSM band using 200 kHz.

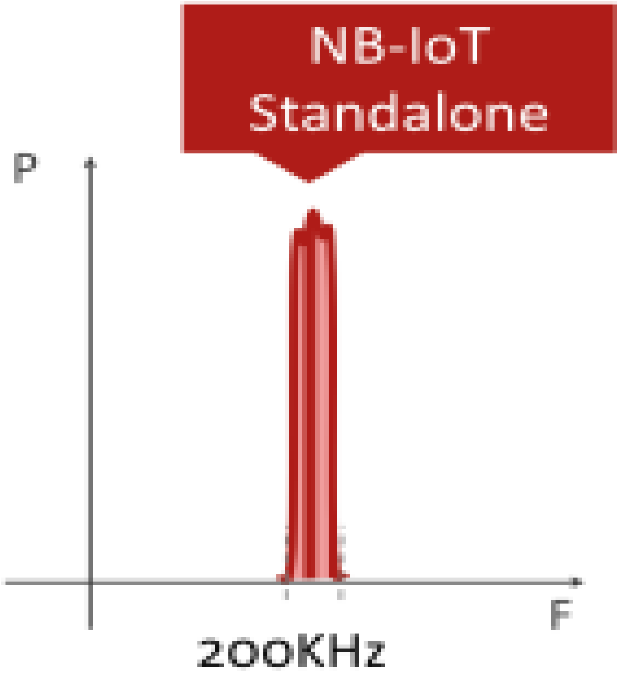

Figure 9: *NB-IoT Standalone (Source: Viavi solutions. Ref. 48)*

- NB-IoT operates within the LTE in-band using 180 kHz.

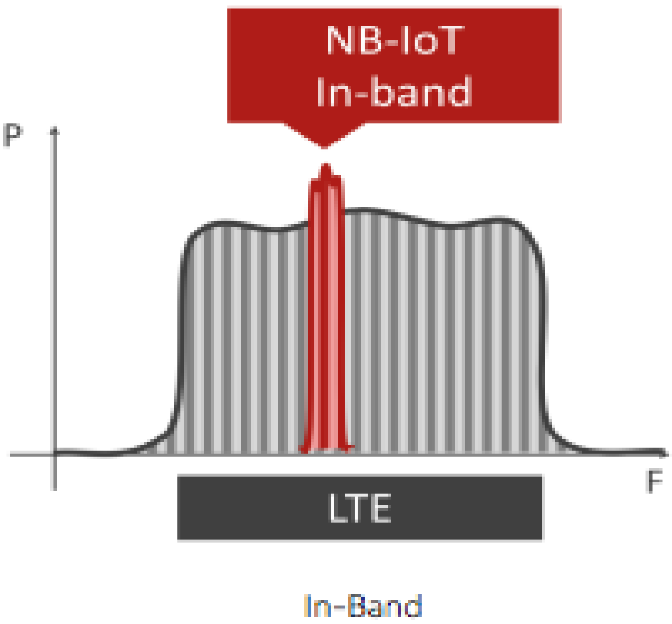

Figure 10: *NB-IoT In-band (Source: Viavi solutions. Ref. 48)*

- And it also operates within the LTE in the guard band using 200 kHz

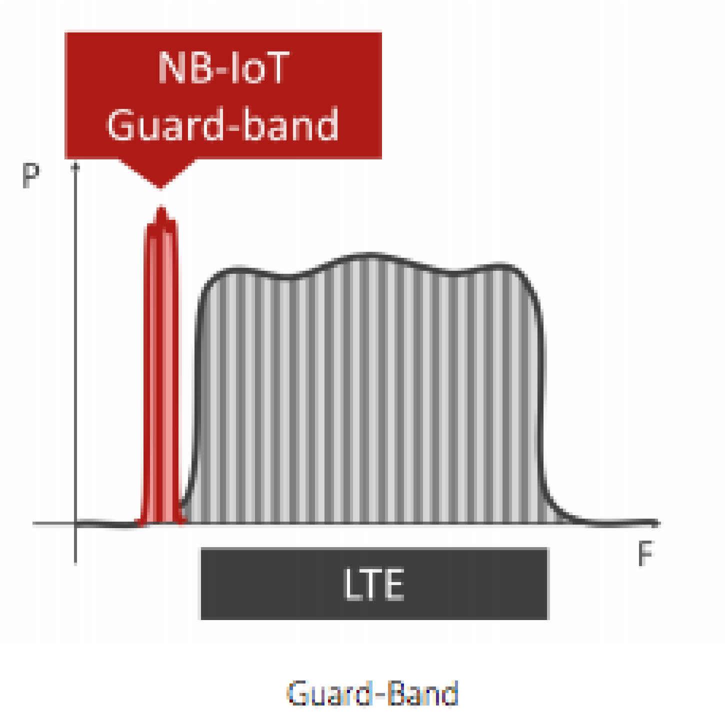

Figure 11: *NB-IoT Gaurd-Band (Source:Viavi solutions. Ref. 48)*

4.4 NB-IoT transmission bandwidth by 3GPP

Table 6 *NB-IoT Transmission by 3GPP*

	NB-IoT IoT Standalone	NB-IoT IoT In band	NB-IoT IoT Guard band
Channel BW	200	Per LTE Channel	Per LTE Channel edge ≥5 MHz
Transmission BW (LTE- Resource Block	1	1	1
N-Tone 15 kHz	12	12	12
N-Tone 3.75 kHz	48	48	48

4.5 NB-IoT application

Narrowband IoT technology is applicable in the following areas:

Manufacturing industries, Agricultural industries, Transportation, Logistics, Smart cities, smart, building, smart parking, location positioning and for utility purposes.

4.6 EC-GSM-IoT

EC-GSM-IoT is an acronym for Extended Coverage Global System Mobile Internet of Things which was standardized by 3GPP. The technology is a low power wide area network that operate in the licensed spectrum. EC-GSM-IoT technology is based on eGPRS. The technology can be implemented by upgrading the software to the existing GSM network to ensure wider coverage. EC-GPRS-IoT is built as a high capacity, long range and less power consumption and low cellular complexity for internet of things communications.

4.7 Features of EC-GSM-IoT

***Table** 7 Features of EC-GSM-IoT*

LPWAN type	Cellular
Frequency	GSM Bands
Data rate	70 – 240 kpbs
Channel Bandwidth	200 kHz
Channel Access Method	TDMA/FDMA
Range	Within existing GSM coverage
Battery life	Up to 10 years
Modulation	GMSK/8PSK

5. ALOHA PROTOCOL

The ALOHA scheme was first developed in the year 1970 when Prof. Norman Manuel Abramson of the university of Hawaii utilized UHF radio channels to connect computers of one campus to others in Oahu and Maui. ALOHA has been modeled in very different variations and has been studied on since then. The random access or direct access is the basic theme of the scheme stated above.

It is now a widely implemented scheme which is used to coordinate the transmitters of data in a single shared communication channel. ALOHA channel transmits the data in packets from each transmitter at random times and manages the data rate accordingly. The transmission in most of the ALOHA channels tries to transmit the data with best effort and leaves the receiver to figure out the lost data. ALOHA is a very simple scheme, and to make more effective of transmission resources, more advanced protocols such as slotted ALOHA and various others have been devised.

The Aloha protocol has gained major credibility in context of IoT, especially in the domains of Ultra-Narrow Band. UNB is indeed undermined by its lack of precision and accuracy in the frequency of the transmission carrier, leading to characteristic unslotted random access conduct (Goursaud & Mo 2016). Thus, given such a set of circumstances, it becomes necessary for this thesis to offer generalized versions of the degree of achievable success probability and throughput, in typical unslotted UNB systems (Goursaud & Mo 2016). Besides, in generalized domains of ALOHA systems, it is needed to consider critical aspects of randomized time-frequency, also that of duality of time and frequency in select domains (Goursaud & Mo 2016). At the outset, it is necessary to consider the carrier frequency uncertainties surrounding the conduct of ALOHA behavior. It is the Base Station (BS) that collects signals that randomly occur, which is the typical situation in the unslotted random access traffic of the uplink system, both in relation to time and frequency domains. This is a two-dimensional random access procedure called R-FTMA or Random Frequency and Time Multiple Access. Due to the poor frequency accuracy of the low-cost IoT devices, different devices' signals are often partially overlapping in frequency, with the result that interference cannot be easily processed, either by transmitter cooperation nor by signal post-processing at the receiver. This being the case, it becomes necessary and important to enforce innovative R-FTMA design which could address the problems and offer solutions, especially for the issues arising out of the unavoidable frequency offsets. (Goursaud & Mo 2016). Generally it is assumed that the number of packets created during specified time period is Poisson-distributed, with the average generation rate as a parameter.

5.1 One Dimensional ALOHA with Random Spectrum Access

There is clear evidenced that both frequency randomness as well as time randomness dually impact the throughput, and these could be interchanged, without loss of performance. The gained importance of this duality assumes critical significance, in the context of ALOHA protocols. It is also seen all existing results of tine-domain ALOHA performance analysis can be applied in frequency-domain random spectrum access schemes. Also, more advanced ALOHA variants have their dual frequency-domain schemes (Goursaud & Mo 2016).

In their article entitled "On the Benefits of Successive Interference Cancellation for Ultra Narrow Band Networks: Theory and Application to IoT', its joint authors Yoqu, Goursand and Gorce have argued that interference in relaying could be mitigated by the deployment of Successive Interference Cancellation (SIC), which may provide remedial solutions for interference issues which continue to plague UNB (Yuqi, Goursand and Gorce 2017).

According to the assumptions and arguments of this paper, a network with singe Base Station (BS), located at cell center is envisaged. This BS is constantly in state of reception and devices or nodes are placed randomly and uniformly in a disk area as characterized by a radius, which corresponds to an exclusion area around the BS, wherein no devices are placed. (Yuqi, Goursand and Gorce 2017). In this study, the free-space propagation model is utilized. Assuming that all nodes have similar characteristics, information packets have similar sizes and they are sent with similar emission powers and antenna gains, with nodes having similar wake-up duty cycles. Assuming nodes with random positions, path losses are quantified based on the distances from each node to the BS, and the received powers of the packets transmitted from different nodes at the BS receiver are obtained.

The characteristic aspect is that node selection is purely on randomized basis, and thus, uncontrollable interferences may occur which may lead to transmission errors (Yuqi, Goursand and Gorce 2017). Further, a benchmark which is selected for quantifying the network performance is that of Packet Error Rate (PER), which is based on the Signal to Interference Ratio (SIR). In other words, if the SIR of a packet is lower than its predetermined benchmark, packet is believed to be lost. The performance is evaluated by identifying and analyzing network status at that time, with one node considered as selected one and others as potential interfering nodes, or devices. (Yuqi, Goursand and Gorce 2017). That being the case, the interference levels could be caused by single interferer or as combined effect of several interferers, albeit collisions occur mostly between 2 nodes simultaneously.

The very idea of UNB network with narrow signal bandwidth compared to the composite available bandwidth, is that collisions with multiple interferers rarely occurs, which simplifies analytical performance evaluation. Thus, it may be expressed that with desired node transmitted at frequency f_1 and potential interfering node at frequency f_2, the paramount parameter is frequency spacing $\Delta f = |f_1 - f_2|$, which determines the interference contribution of each interfering node. Thus packet losses would occur when two nodes frequencies too close to each other, thus rendering them on a collision course (Yuqi, Goursand and Gorce 2017).

In case of colliding packets, it is possible to mitigate the interference by advanced receiver signal processing. Here it should be noted the while the IoT devices are expected to be quite simple, the BS may have the processing capability for quite advanced signal processing algorithms. For example, if the interfering packet has stronger power than the target one, the interfering packet's data can be first detected. Then the interfering packet can be regenerated in clean form at the BS receiver and subtracted from the received signal. After this, there are better chances to detect the target packet successfully. Suffice to conclude that packet error rate is always lower with SIC Receiver and therefore, it may be concluded that SIC is beneficial in the mitigation of interference caused by Random Spectrum Access, for better or for worse (Yuqi, Goursand and Gorce 2017).

Next, coming to critical aspects and limitations of network capacity of LPWAN, the correct and judicious choice of the Random Access (RA) based Medium Access Control (MAC) protocol is indeed of critical significance (Almonacid & Franck 2017).

Indeed, UNB networks characterized by Time and Frequency Asynchronous ALOHA (TFAA) have significant benefits in terms of power savings, low terminal costs, and long-range communication competence, but there are also drawbacks in terms of low throughput and increased Packet Error Rates with increasing traffic volume, which reduces the real time effectiveness of UNB to large extent (Almonacid & Franck 2017).

5.2 Pure ALOHA protocol analytical model

The core idea behind pure ALOHA protocol is that the station sends whenever it has frame to send. During the process of sending transmission there will be collision and the colliding frames will damage. When a frame is sent the sending station will thus broadcast to all the stations and then listen to know if the frame successfully reached its destination. If the frame was damaged during the transmission, then the sending station will resend again after a random time. The waiting time have to be random else the frame will collide over and over again. Contention system is the common channel used by multiple users (A.S. Tanenbaum 2003).

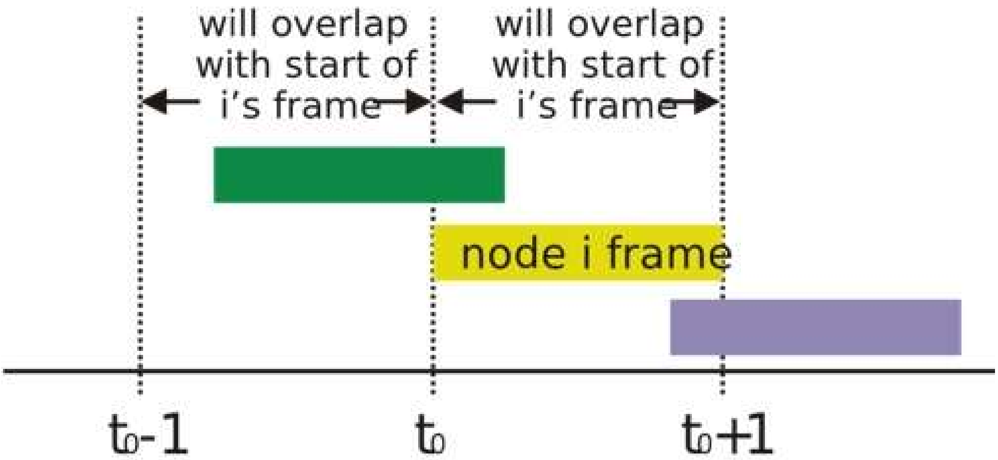

Figure 12: *Pure ALOHA protocol (Source: Wikipedia. Ref. 49)*

- 'T' is considered to be the time to transmit one frame on the channel.
- The frame time is unit of time equal to 'T'
- 'G' is considered as the mean used in the Poisson distribution over the amount of attempted transmission. There are G transmission-attempts per frame-time in an average.
- To consider exactly what will happen for frame to successfully transmit true a channel. 't' will be the time which a frame is intended to be sent.
- The probability that there will be a k transmission attempts during the frame-time is:

$$\frac{G^k e^{-G}}{k!}$$

- The average amount of two repetitive frame-time, the probability of k transmission in the process of those two frame-time is:
  -

$$\frac{(2G)^k e^{-2G}}{k!}$$

- So, the probability ($Prob_{pure}$) of having zero transmission-attempts between t-T and t+T is:

$$Prob_{pure} = e^{-2G}$$

- To calculate the throughput the rate of transmission -attempts is multiplied by the probability of success. So, throughput S_{pure} is:

$$S_{pure} = e^{-2G}$$

- Vulnerability time = 2*T
- Therefore 0.5/e frames per frame-time is the maximum throughput. Approximately 0.184 about it will take 18.4%. of time for transmission to be successful.

5.3 Throughput performance of TFAA with collision capture channel model

As discussed earlier, TFAA is a random-access scheme, under which packet transmissions are neither coordinated in time nor in frequency domain. It can offer unique opportunities for reducing the signal bandwidth, along with the very low transmission data rate, down to a level which is unachievable by traditional synchronized transmission schemes, and greatly facilitating the UNB IoT idea This opens avenues for minimizing transmission powers to suit the evolving demands in power-restrained wireless applications (Almonacid and Franck 2017).

There is a need for the performance evaluation of TFAA under relevant alternative models regarding the effects of collisions. Almonacid and Franck consider so-called collision and capture channel models. For the former, an accurate, closed-form analytical model is derived, while the throughput of the latter one is obtained through a semi-analytical approach. Besides, deployment of a low-rate forward error correction can greatly improve TFAA performance. (Almonacid and Franck 2017)

Under collision channel model, a test packet is successfully transmitted, if and only if it is not overlapped by any other packet in time or frequency. In other words, a packet collision is always assumed to be destructive.

The capture channel model, it is assumed that the receiver is able to synchronize to all arriving packets and detect their preambles to extract the necessary control data. This is justified by the fact that the probability of two completely time-frequency aligned packets at the receiver is very small. After synchronization, the success of detecting the test packet depends on the total interference coming from the partially colliding interfering packets. SIC techniques help both in the packet synchronization task, and help to improve the PER performance, while the use of low-rate FEC offers greater PER performance improvements.

5.4 Contention Resolution Time and Frequency ALOHA (CR-TFAA)

Solutions to the high PER issues have been examined and investigated in the paper by Almonacid & Franck entitled, “An Asynchronous High-Throughput Random Access Protocol for Low Power Wide Area Networks” which offers protocol design termed ‘Contention Resolution Time- and Frequency-Asynchronous ALOHA (CR-TFAA). This is a modified version of TFAA, which applies diversity by transmitting multiple copies of each packet at randomized time-frequency locations. The scheme is compared against a protocol called Asynchronous Contention Resolution ALOHA (ACRDA) which is specifically meant to address and mitigate issues created by the PER issues on throughput (Almonacid & Franck 2017). With post-ALOHA protocols, it is possible to double the packet transmission rate, thus making these more popular and preferred models for several systems, including, mobile terrestrial and satellite networks, wherein the usage of RA channels are in constant demand (Almonacid & Franck 2017).

Thus, the above mentioned TFAA employed in UNB LPWANs deploys the state-of-the-art signal processing techniques implemented in current high-throughput protocols and this has also gained reasonable degree of performance, offering challenge to spread-spectrum techniques. SIC techniques have been integrated into TFAA, pure ALOHA access approach wherein packet transmission is randomly devised in both frequency and time domains, and the resultant innovative protocol, termed CR-TFAA seeks to offer enhanced and improved performance for LPWAN based on UNB networks through the diversity scheme (Almonacid & Franck 2017).

Numerical results for two main scenarios have been presented, namely with and without time-frequency diversity. In both cases, it is shown that CR-TFAA significantly improves the performance of TFAA. For the scenario including time frequency diversity, the CR-TFAA performances were also compared with those of ACRDA, indicating highly improved performance.

6. SIMULATION BASED ANALYSIS OF TFAA

In this chapter, an experimental study of the throughput of two-dimensional random access scheme is reported. A Matlab code is generated to simulate the time and frequency asynchronous ALOHA scheme (TFAA). As a result, the collision probability and normalized throughput are obtained as functions of the load, distance range of the devices from the access point, propagation exponent, and the interference threshold. This threshold is defined based on the minimum signal-to-interference + noise ratio (SINR) for successful signal detection. The main terms and parameters considered in this particular study are listed and defined below.

6.1 Interference Threshold

Interference threshold defines the minimum SINR that is considered sufficient for detecting the packet without errors. On one hand, the SINR depends on the power of noise at the receiver and on the interference power due to other users' packets that are partially colliding with the target user's packet. The interference power due to each collision depends also on the time and frequency distances between the colliding packets. On the other hand, the SINR depends on the received useful signal power through the transmission power and the pathloss of the target user's channel. The minimum SINR depends on the modulation order and waveform used by the IoT devices.

6.2 Propagation Exponent

The propagation exponent (also known and path loss exponent) ε defines the ratio between transmitted power and the power received at the receiver end of the transmission link based on the distance between the transmitter and receiver, d. The signal attenuation is proportional to d^{ε}. In free-space propagation, the propagation exponent is 2, whereas in urban areas it can be 4, or even more.

6.3 Throughput

The throughput of a particular approach or scheme can be defined as the product of transmission rate and the success probability at the receiver end. Normalized throughput is obtained by dividing the throughput by the maximum rate of (orthogonal) packets that could be ideally transmitted without collisions.

6.4 Collisions

Since the transmission is done on the basis of randomness, so the idea of two or more deceives using same facility or domain and portion of domain is very much possible. The transmitted data can collide with each other at any instance and hence, the collisions are modeled in the Matlab program. A target user's packet may collide with several other users' packets while the interference threshold is still not exceeded. This can happen when the other user's pathloss is high compared to that of the target user. Low SINR threshold increases the probability of successful transmission.

6.5 Load

The load on the channel is defined as the ratio of the number of transmitted packets (i.e., number of active devices) to the maximum number of (orthogonal) packets that could be ideally transmitted without collisions in the used frequency band within the used time interval.

6.6 Distance range

The throughput depends critically on the power level variations of different packets received at the access point. A strong packet from another user may prevent the detection of a weak packet from the target user even if the packets overlap only slightly. The power variation depends on the shortest and longest distance from the devices to the access point, and also on the propagation exponent. By assuming that the distance range is limited, the throughput of the scheme can be improved. Various mechanisms for controlling the distance range (or received packet power range) can be envisioned, based e.g., on the received power levels at the devices of the signals transmitted by the access point.

6.7 MATLAB CODE EXPLANATION

The interference model corresponds to a basic single-carrier transmission link with root-raised-cosine pulse shaping and binary PSK modulation. The beginning of the code initializes the constants like symbol interval in seconds that is set to be 0.01 (corresponding to symbol rate of 100 Hz), packet length is set to be 100 symbols, packet tail length is considered to be 2 symbols, the time window length is selected to be 10000 symbols, the bandwidth of the signal is 200 Hz, while the total bandwidth of the channel is 10000 Hz. The theoretical minimum frequency distance of simultaneously transmitted orthogonal packets is 100 Hz. Therefore, the maximum number of non-colliding packets is 10000. The minimum distance from access point is 100 m and maximum distance is 300 m for one simulation and 1000 m for the other. The number of devices is selected in a loop with increment of 500 starting from 500 and ending at 10000 devices, the last value corresponding to the full load.

To obtain relatively smooth plots, the results are obtained as the average of 10000 independent simulation instances assuming that the IoT devices are uniformly distributed in the distance range.

The normalized interference power due to packet overlap is obtained through a separate waveform simulation and then stored in a matrix for throughput simulations. The rows and columns of the matrix correspond to time and frequency distances between the colliding packets, and the interference values in the matrix correspond to the case where the target signal and interfering signal have the same power level at the receiver.

In each simulation instance, the distance of each active device is selected randomly, assuming uniform distribution within the used distance range. The timing and frequency of each packet are also selected randomly, with uniform distributions within the frequency band and transmission time interval. The power levels of each packet at the access point are then evaluated based on the pathloss model mentioned above. The first packet is assumed as the target one, and the total interference from all the other packets is calculated. For each potentially interfering packet, it is first checked whether it overlaps with the target one. In case of overlap, the normalized interference value is first obtained from the interference matrix and is then scaled by the ratio of the attenuations of the interfering signal and the target signal to obtain the actual interference power. The interference powers from different packets colliding with the target packet are accumulated. If the interference threshold is exceeded during the accumulation, it can be decided that the target packet transmission was successful, and the process can be stopped for the on-going simulation instance.

Three different interference thresholds are used: 0.25, 0.5 and 1, corresponding to minimum SINR values of 6 dB, 3 dB, and 0 dB.

Propagation exponents of 2, 3, and 4 are used in the simulations.

6.8 Results when the distance range from access point is 100-300 meters

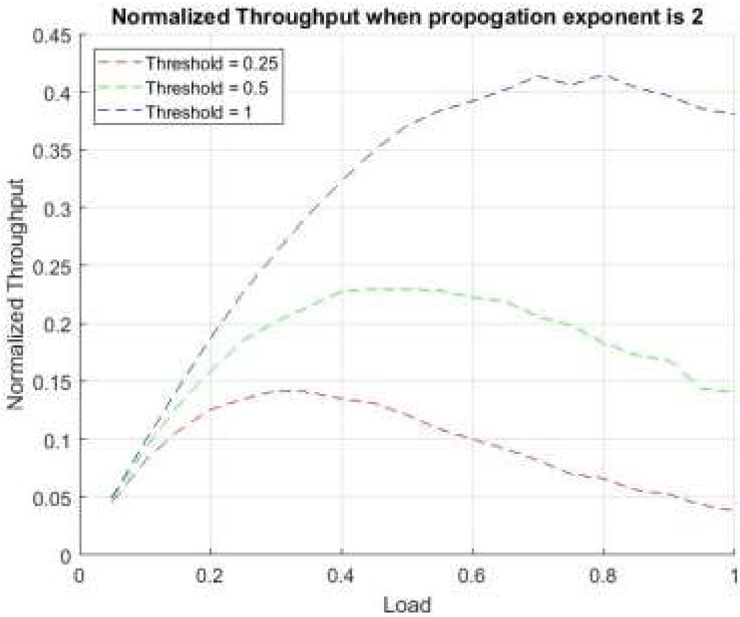

***Figure 13**. Normalized throughput when the propagation exponent is 2 and the IoT device distance range is 100-300m.*

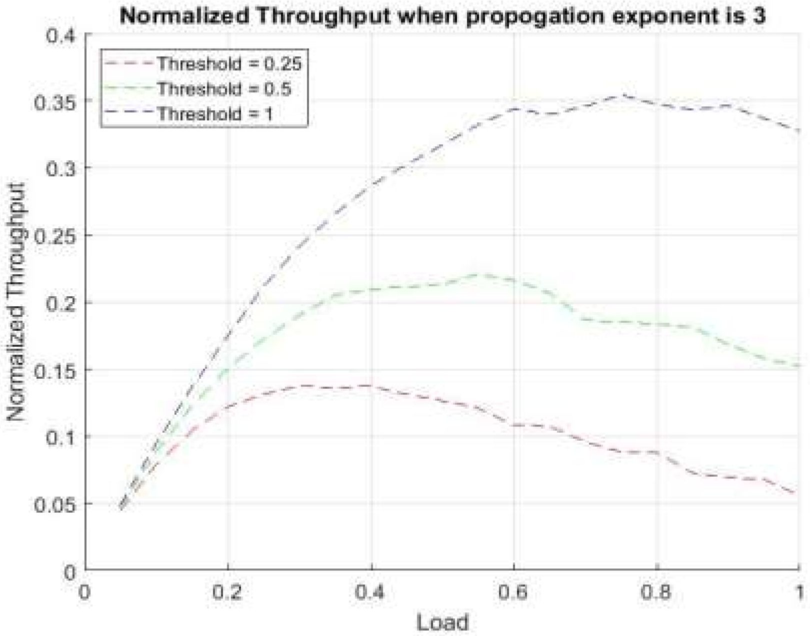

Figure 14 *Normalized Throughput when propagation exponent is 3 and the IoT device distance range is 100-300m.*

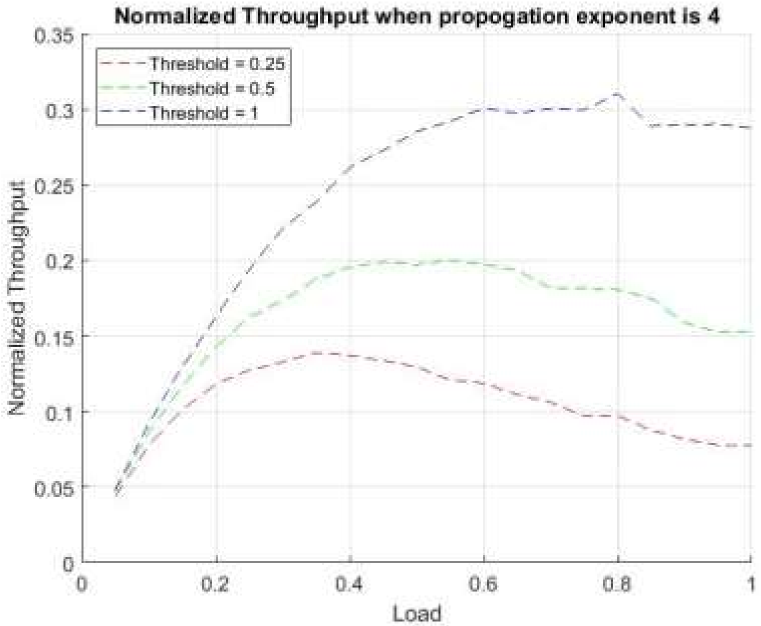

Figure 15. *Normalized throughput when the propagation exponent is 4 and the IoT device distance range is 100-300m.*

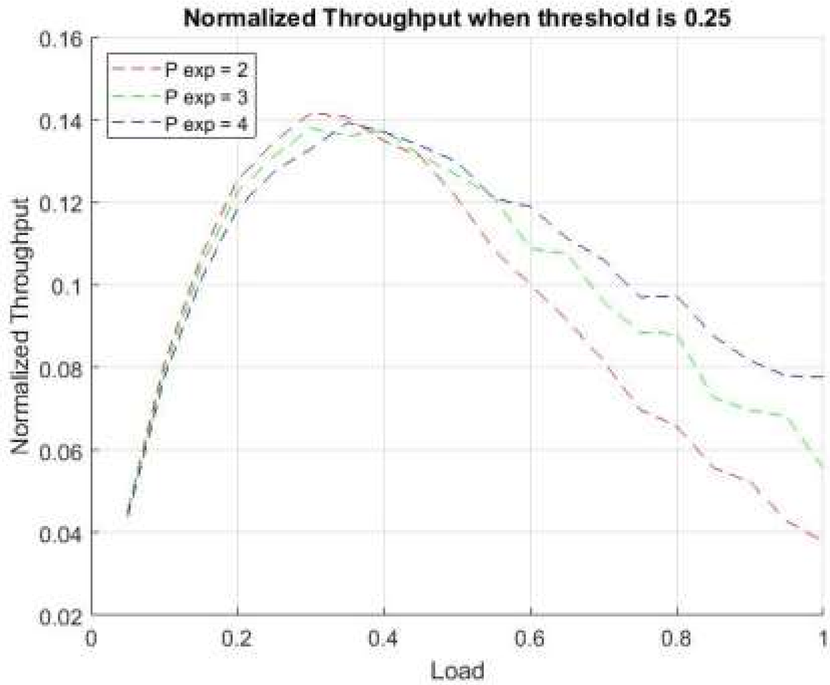

Figure 16. *Normalized throughput when the propagation exponent is 0.25 and the IoT device distance range is 100-300m.*

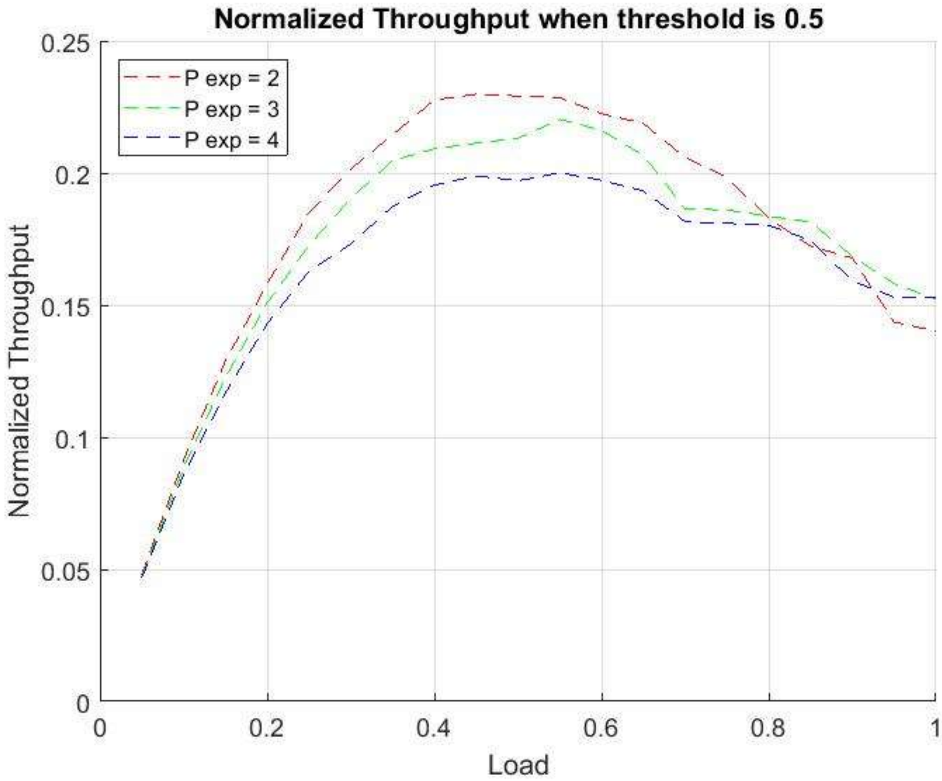

Figure 17. *Normalized throughput when the propagation exponent is 0.5 and the IoT device distance range is 100-300m.*

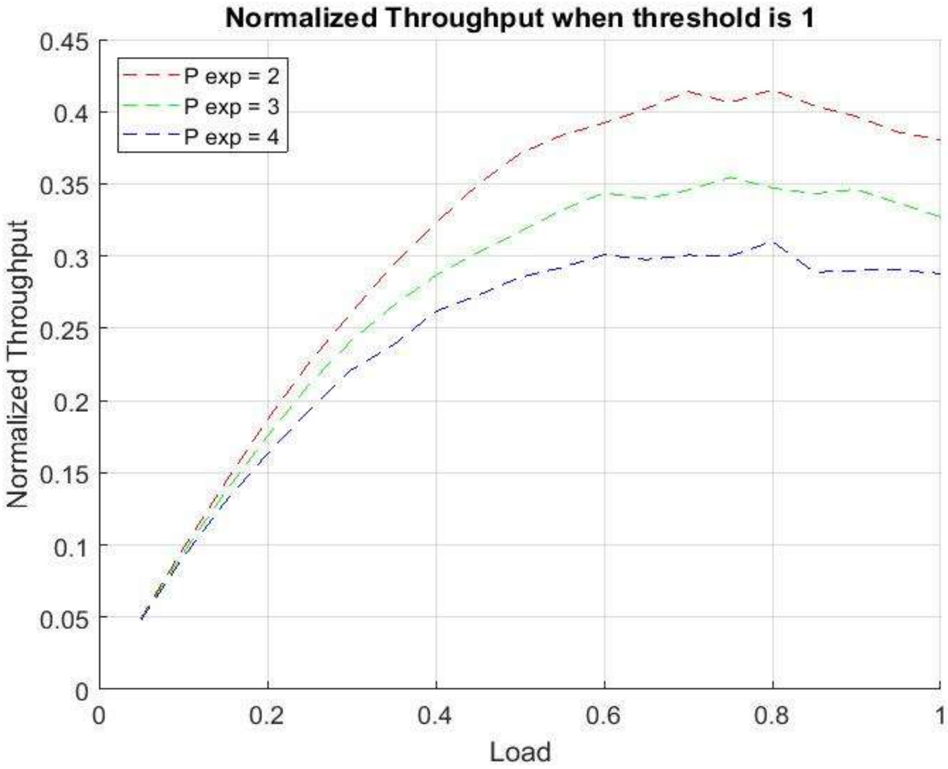

Figure 18. *Normalized throughput when the propagation exponent is 1 and the IoT device distance range is 100-300m.*

6.9 Results when the distance range from the access point is 100-1000 meters

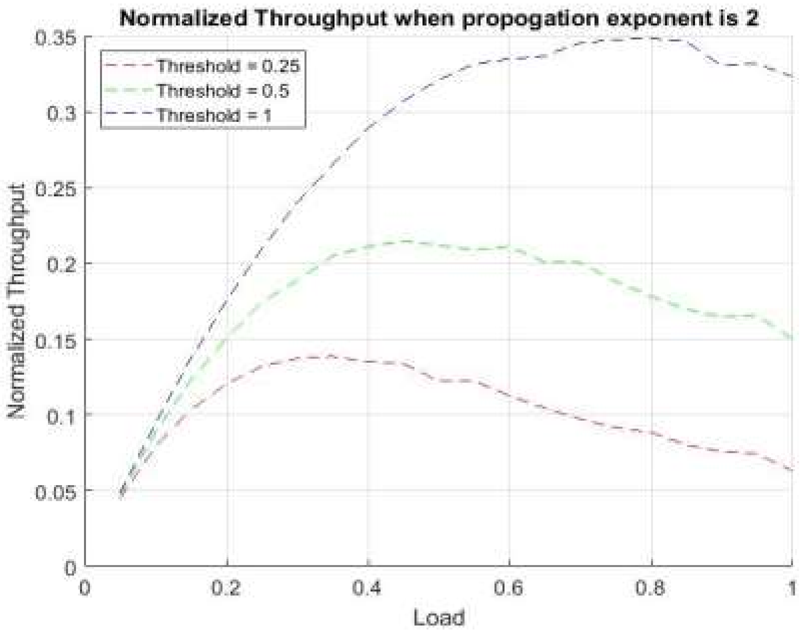

Figure 19. *Normalized throughput when the propagation exponent is 2 and the IoT device distance range is 100-1000m.*

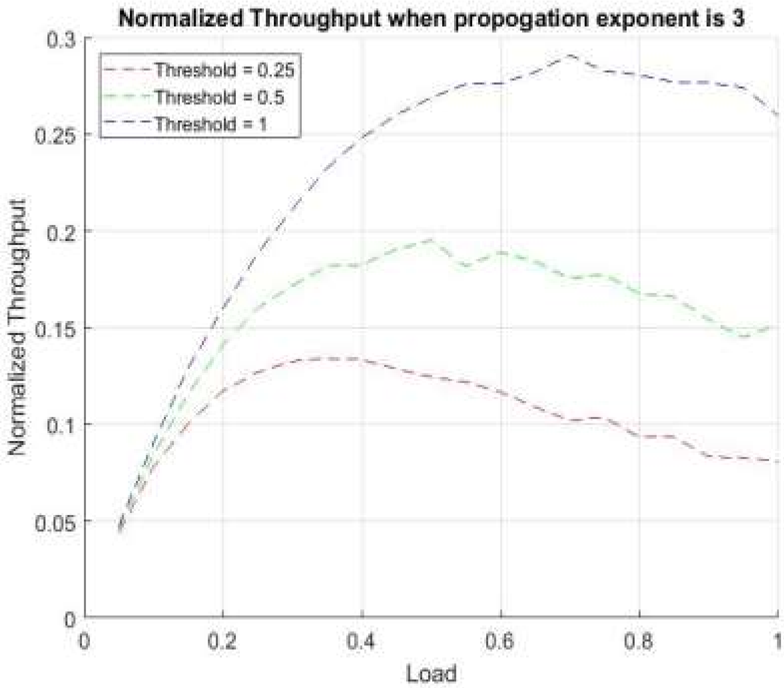

Figure 20. *Normalized throughput when the propagation exponent is 3 and the IoT device distance range is 100-1000m.*

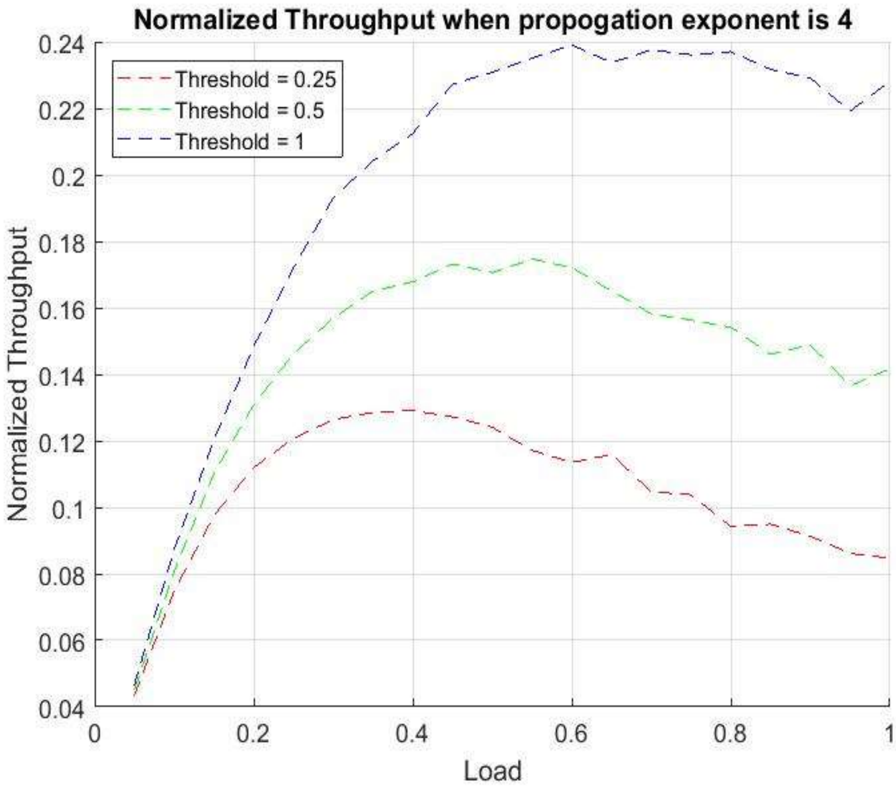

Figure 21. *Normalized throughput when the propagation exponent is 4 and the IoT device distance range is 100-1000m.*

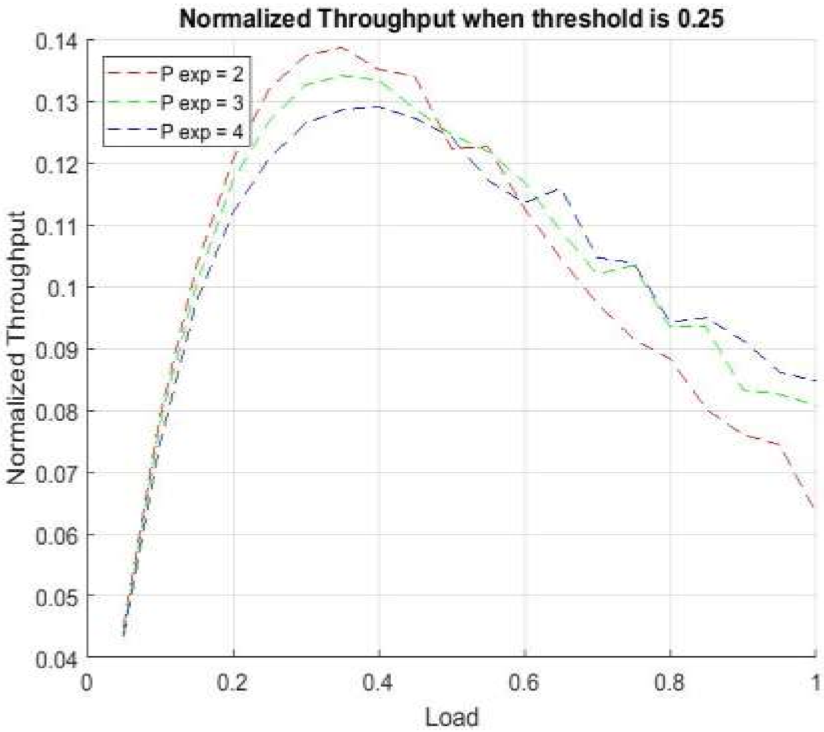

Figure 22. *Normalized throughput when the propagation exponent is 0.25 and the IoT device distance range is 100-1000m.*

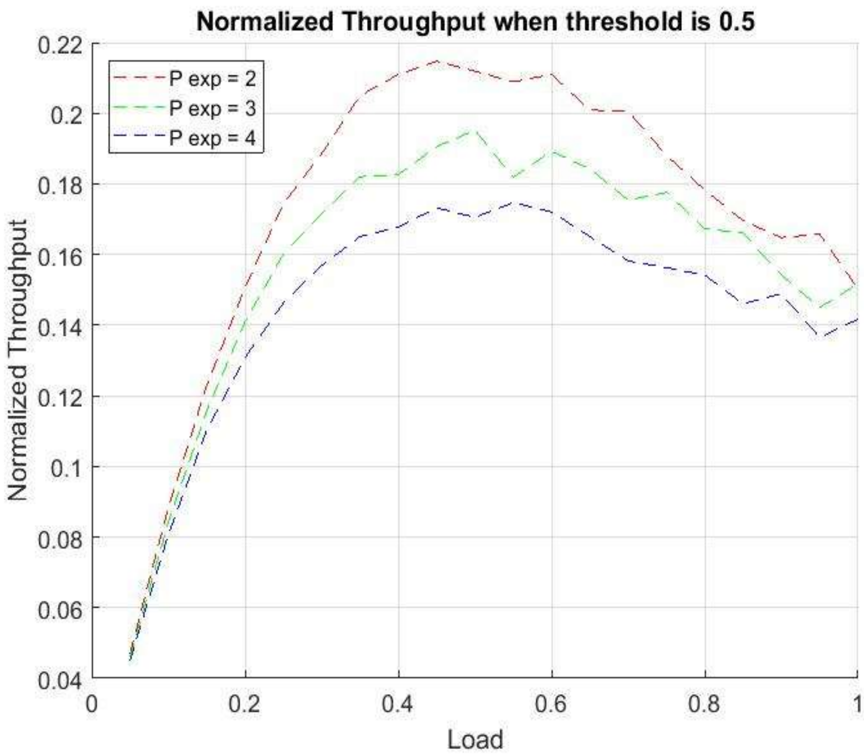

Figure 23. *Normalized throughput when the propagation exponent is 0.5 and the IoT device distance range is 100-1000m.*

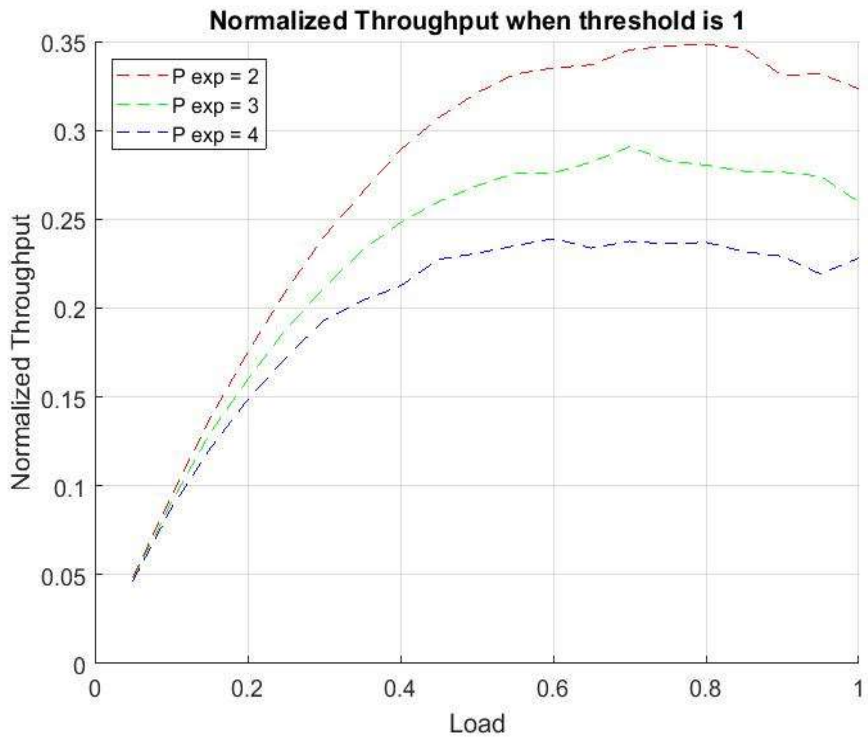

Figure 24. *Normalized throughput when the propagation exponent is 1 and the IoT device distance range is 100-1000m.*

6.10 **Discussion**

When the propagation exponent is changed, the throughput of the system decreases with the increase in the propagation exponent, because this increases the variation of the power levels of different packets at the receiver. With the increase in the interference threshold, the normalized throughput increases, because this means more robust modulation and coding scheme tolerating higher interference. In other words, with the increase in threshold and decrease in the propagation exponent, the normalized throughput can be maximized. With threshold set to 1 and propagation exponent 2, the throughput is seen to be approaching the maximum value of 0.42 with the distance range 100-300 m and 0.35 with the distance range 100-1000 m. Once the threshold is decreased to 0.25 and the propagation exponent is increased to the maximum value of 4, the maximum normalized throughput can be seen to be as low as 0.14 with the distance range of 100-300 m and 0.125 with the distance range of 100-1000 m.

7. CONCLUSIONS

This thesis has identified, considered and investigated on several aspects of UNB technologies and applications with special emphasis on ALOHA Protocols and how this protocol along with Sigfox Signaling, could be determinant factors within the realms of Ultra-Narrow Band or UNB technology, both for the present and also for the future.

While UNB is indeed invasive technology, whose narrow bandwidth causes both benefits as well as concerns, in terms of reaching over larger network area with minimal power, costs and energy usages, it also has major constraints in terms of throughput, connectivity, noise elimination and so on. Besides, this cannot serve as one-fit-serves-all method, since this is to be addressed on case to case method and more importantly, the main challenges now facing UNB lies in that of higher Radio Frequency (RF) demands, which effectively, pushes out channels in the event of large frequencies which it is unable to handle, thus placing its very existence in doubtful jeopardy.

Besides, and more importantly, UNB may not be suitable for all kinds of devices or for all market demands and their main utility would lie in Machine 2 Machine applications, especially in utilities, like Meters, Smart grid, Asset Management, also, Smart City traffic, parking and other ancillary, centrally -control systems, Waste Management and so on. UNB may be used in low volume, less power demanded functions like Healthcare fitness tracking, patient self- monitoring and remote health management and so on and so forth.

Indeed, the full exploitation and usages of UNB is still to be realized, not only due to technological constraints and economic factors, but also due to competing and impeding technology presence which may have differential, although not overriding advantages over UNB model.

UNB is indeed technology for the future, but this needs to be well integrated, inclusive and collaborative in both its outlooks and in its applications for optimal use along value change additive continuum for now and for the future. Like any other tool or stratagem, its effectiveness would heavily depend upon the manner in which it is utilized, its functional scope and most of all, what beneficial gains could be derived and how M2M could help human progression, performance and propagation in the times to come.

The throughput simulations indicated that the key to high throughput is the use of robust transmission scheme able to tolerate high interference level. It is important to notice that here the throughput is measured in terms of successful transmitted packets. The data rate in bits per packet is smaller with robust modulation and coding schemes than what is achievable with transmission schemes requiring higher SINR. On the other hand, also the probability of successful transmission of packets is increased with lower threshold. One interesting topic for future studies is to maximize the throughput in bits per transmission frame through the optimum choice of the modulation and coding scheme.

REFERENCES

[1] Al-Fuqaha, A., Guizani, M., Mohammadi, M., Aledhari, M. and Ayyash, M., 2015. Internet of things: A survey on enabling technologies, protocols, and applications. *IEEE Communications Surveys & Tutorials*, *17*(4), pp.2347-2376.

[2] Bonavolontà, F., Tedesco, A., Moriello, R.S.L. and Tufano, A., 2017, September. Enabling wireless technologies for industry 4.0: State of the art. In *Measurement and Networking (M&N), 2017 IEEE International Workshop on* (pp. 1-5). IEEE.

[3] Chen, Y., He, S., Hou, F., Shi, Z. and Chen, J., 2017. Promoting device-to-device communication in cellular networks by contract-based incentive mechanisms. *IEEE Network*, *31*(3), pp.14-20.

[4] Gangadharan, S.P., 2017. The downside of digital inclusion: Expectations and experiences of protocol for low power wide area networks. In *Communications (ICC), 2017 IEEE International Conference on* (pp. 1-6). IEEE.

[5] Furht, B. and Ahson, S.A. eds., 2016. *Long Term Evolution: 3GPP LTE radio and cellular technology*. Crc Press.

[6] Li, S., Da Xu, L. and Zhao, S., 2015. The internet of things: a survey. *Information Systems Frontiers*, *17*(2), pp.243-259.

[7] Meshram, R.A., Hole, K.R., Gulhane, R.A., Deshmukh, P.P., Thakare, Y.A. and Deshmukh, M.A., 2017. Internet of Things: Recent Applications and Challenges. *International Journal of Engineering Science*, *10679*.

[8] Nelson, R., 2017. Building and testing cloud-connected wireless sensors. *EE-Evaluation Engineering*, *56*(6), pp.20-24.

[9] Privacy and surveillance among marginal Internet users. *new media & society*, *19*(4), pp.597-615.

[10] Patel, K., 2017. Benefits of IoT for hospitals and healthcare. *IBM Internet of Things blog, January*, *9*.Semtech, 2015. [(accessed on 5 November 2017)]. LoRa SX1276/77/78/79 Datasheet, Rev. 4. Available online: http://www.semtech.com/images/datasheet/sx1276_77_78_79.pdf

[11] Semtech; 2015. [(accessed on 7 November 2017)]. LoRa SX1276/77/78/79 Datasheet, Rev. 4. Available online: http://www.semtech.com/images/datasheet/sx1276_77_78_79.pdf.

[12] Trasviña-Moreno, C.A., Blasco, R., Casas, R. and Asensio, Á., 2016. A Network Performance Analysis of LoRa Modulation for LPWAN Sensor Devices. In *Ubiquitous Computing and Ambient Intelligence: 10th International Conference, UCAmI 2016, San Bartolomé de Tirajana, Gran Canaria, Spain, November 29–December 2, 2016, Part II 10* (pp. 174-181). Springer International Publishing.

[13] Torğul, B., Şağbanşua, L. and Balo, F., 2016. Internet of Things: A Survey.Whitmore, A., Agarwal, A. and Da Xu, L., 2015. The Internet of Things—A survey of topics and trends. *Information Systems Frontiers*, *17*(2), pp.261-274.

[14] Vejlgaard, B., Lauridsen, M., Nguyen, H., Kovács, I., Mogensen, P. and Sørensen, M., 2017. Coverage and Capacity Analysis of Sigfox, LoRa, GPRS, and NB-IoT. In *Vehicular Technology Conference*. IEEE.

[15] Internet engineering task force (ietf). [Online]. Available: https: //www.ietf.org/

[16] P. Massam, P. Bowden, and T. Howe, "Narrow band transceiver," Jan. 9 2013, eP Patent 2,092,682. [Online]. Available: http: //www.google.com/patents/EP2092682B1?cl=pt-PT

I. Demirkol, C. Ersoy, F. Alagoz et al., "Mac protocols for wireless sensor networks: a survey," IEEE Communications Magazine, vol. 44, no. 4, pp. 115–121, 2006.

[17] U. Raza, "From energy efficient to energy neutral wireless sensor networks," Ph.D. dissertation, University of Trento, 2015.

[18] Mobile edge computing. [Online]. Available: http://www.etsi.org/ technologies-clusters/technologies/mobile-edge-computing

[19] K. Mikhaylov, . J. Petaejaejaervi, and T. Haenninen, "Analysis of capacity and scalability of the lora low power wide area network technology," in European Wireless 2016; 22th European Wireless Conference, May 2016, pp. 1–6.

[20] B. Reynders, W. Meert, and S. Pollin, "Range and coexistence analysis of long range unlicensed communication," in 2016 23rd International Conference on Telecommunications (ICT), May 2016, pp. 1–6.

[21] P. Neumann, J. Montavont, and T. Nol, "Indoor deployment of lowpower wide area networks (lpwan): A lorawan case study," in 2016 IEEE 12th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), Oct 2016, pp. 1–8.

[22] Lorasim. [Online]. Available: http://www.lancaster.ac.uk/scc/sites/lora/ lorasim.html

A. Zanella, "Best practice in rss measurements and ranging," IEEE Communications Surveys Tutorials, vol. PP, no. 99, pp. 1–1, 2016.

[23] Hazmi, J. Rinne, and M. Valkama, "Feasibility study of i 802.11ah radio technology for iot and m2m use cases," in 2012 IEEE Globecom Workshops, Dec 2012, pp. 1687–1692.

[24] Do, M.T., Goursaud, C. and Gorce, J.M., 2014, July. Interference modelling and analysis of random FDMA scheme in ultra narrowband networks. In *AICT 2014*.

[25] Almonacid, V. and Franck, L., 2017, May. An asynchronous high-throughput random access Augustin, A., Yi, J., Clausen, T. and Townsley,

W.M., 2016. A study of LoRa: Long range & low power networks for the internet of things. *Sensors*, *16*(9), p.1466.

[26] Mo, Y., Goursaud, C. and Gorce, J.M., 2017, May. On the benefits of successive interference cancellation for ultra narrow band networks: Theory and application to IoT. In *Communications (ICC), 2017 IEEE International Conference on* (pp. 1-6). IEEE.

[27] Sikken B. Project DecodingLoRa. 2016. [(accessed on 5 November 2017)]. Available online: https://revspace.nl/DecodingLora.

[28] Gartner, "Gartner says the internet of things installed base will grow to 26 billion units by 2020," White Paper, Dec. 2013.

[29] A. Laya, C. Kalalas, F. Vazquez-Gallego, L. Alonso, and J. Alonso-Zarate, "Goodbye, ALOHA!", vol. 4, pp.2029–2044, Apr. 2016.

[30] S. Sudevalayam and P. Kulkarni, "Energy Harvesting Sensor Nodes: Survey and Implications," Surveys Tutorials, vol. 13, no. 3, pp. 443–461, Third 2011.

[31] G. Margelis, R. Piechocki, D. Kaleshi, and P. Thomas, "Low throughput networks for the IoT: Lessons learned fromindustrial implementations," 2nd World Forum on Internet of Things (WF-IoT), Milan, IT, Dec. 2015, pp. 181–186.

[32] H. S. Dhillon, H. C. Huang, H. Viswanathan, and R. A. Valenzuela, "Power-efficient system design for cellular-based machine-to-machine communications," Wireless Commun., vol. 12, no. 11, pp. 5740-5753, Nov. 2013.

[33] M. Z. Shafiq, L. Ji, A. X. Liu, J. Pang, and J. Wang, "Large-Scale Measurement and Characterization of Cellular Machine-to-Machine Traffic," Networking, vol. 21, no. 6, pp. 1960-1973, Dec. 2013.

[34] H. S. Dhillon, H. C. Huang, H. Viswanathan and R. A. Valenzuela, "Fundamentals of Throughput Maximization with Random Arrivals for M2M Communications", vol. 62, no. 11, pp. 4094-4109, Nov. 2014

[35] P. Viswanath, Fundamentals of Wireless Communication. Cambridge University Press, 2005.

[36] Almonacid V. and Franck L.2017'Throughput Performance of Time- and Frequency-Asynchronous ALOHA' *SCC* 2017 · February 6 – 9, 2017 Available from:https://msysmhsptkazqgnbycne.s3.amaznaws.com/user/LA_152 5069962_ 8868_4.pdf

[37] Minh-Tien Do, Claire Goursaud, Jean-Marie Gorce. Interference Modelling and Analysis of Random FDMA scheme in Ultra Narrowband Networks. AICT 2014, Jul 2014, Paris, France.https://msysmhsptkazqgnbycne.s3.amazonaws.com/user/LA_1525069962_8868_3.pdf

[38] Goursaud C. and Mo Y 2016 'Random Unslotted Time-Frequency ALOHA: Theory and Application to IoT UNB Networks *'HAL* pps.1 - 5 Available from: https://hal.inria.fr/hal-01389362/document

[39] Mekki K., Bajic E., Chaxel F., and Meyer F.2017 'A comparative study of LPWAN technologies for large-scale IoT deployment' Science Direct pps.1-6 Available from: file:///D:/file%201-%2055680.pdf

[40] Real Wireless 2015 'A Comparison of UNB and Spread Spectrum Wireless Technologies as used in LPWA M2M Applications'R*eal Wireless Systems* pps 6 Available from: file:///C:/Users/MyPc/Downloads/Real-Wireless%E_2%80%93_LPWA-2016.pdf
[41] Umehara D., Satoshi D., Morikura M. and Sugiyama T 2010 'Performance analysis of slotted ALOHA and network coding for single-relay multi-user wireless networks '*ELSEVIER* Available from: https://www.scribd.com/document/79874866/Performance-Analysis-of-Slotted-ALOHA-and-Network-Coding-for-Single-relay-Multi-user-Wireless
[42] Yuqi M.O., Goursaud C and Gorce J.M.2017'On the Benefits of Successive Interference Cancellation for Ultra Narrow Band Networks: Theory and Application to IoT' *IEEE ICC 2017 SAC Symposium Internet of Things Track* pps.1-6.Available from:https://msysmhsptkazqgnbycne.s3.amazonaws.com/user/LA_1525069962_8868_1.pdf
[43] Wei, D.C and Webb W. 2016 'WAN –Ultra-Narrow Band 'Opportunities and Challenges in Low-power Wide-Area Networks'*M2COMM* Available from:https://www.m2comm.co/front-page/technology/wan-ultra-narrow-band-unb/
[44] http://iips.icci.edu.iq/images/exam/Computer-Networks---A-Tanenbaum---5th-edition.pdf
[45] http://www.mdpi.com/1424-8220/16/9/1466/htm
[46] https://image.slidesharecdn.com/sigfoxoverviewapr2017-170414190651/95/sigfox-us-overview-apr-2017-7-638.jpg?cb=1492627177
[47] http://www.radio-electronics.com/info/wireless/lora/lorawan-network-architecture.php
[48] https://www.viavisolutions.com/en-us/literature/narrowband-internet-things-nb-iot-celladvisor-jd700b-series-application-notes-en.pdf
[49] https://en.wikipedia.org/wiki/ALOHAnet

APPENDIX A: MATLAB CODE FOR THE TFAA SIMULATION

```
clc; clear all; close all
% Symbol interval in seconds
TS = 0.01;
% Packet length in symbols
TP = 100;
% Packet tail length in symbols (, depends on the interference)
Ttail = 2;
% Time window length in symbols (, corresponds to 100 packets)
TW = 10000;
% Signal bandwidth in Hz (, depends on the interference model)
B = 200;
% Operation bandwidth in Hz ()
W = 10000;
% Minimum distance from access point in meters ()
Rmin = 100;
% Maximum distance from access point in meters ()
%maxDist
Rmax = 300;
% Number of active devices: variable (
N = 500:500:10000;
for iter = 1:length(N)
% System load:
L(iter) = N(iter) /(TS*W*TW/TP);
% Propagation exponent
% Maximum interference level for successful packet transmission in dB
()
Insts=10000;
Threshold=[0.25,0.5, 1] ;
Pexp=[2,3,4];
% Intereferncе power threshold, normalized to target signal power
             % 0.5 correcponds to 3 dB SIR requirement, which could be
realistic
             % 1 corresponds to 0 dB SIR
for T = 1 : 3
    for PE = 1 : 3
[PinterfT,Collisions(T,PE,iter),N_T(T,PE,iter)] = colli-
sionsMR(N(iter),Insts,Pexp(PE),Thresh-
old(T),W,B,TW,TP,Ttail,Rmin,Rmax,L(iter));
fprintf('The normalized throughput when Pathloss exponents is
%d,\nNumber of Active Devices are %d and Threshold is %0.2f is
%0.5f\n',...
    Pexp(PE),N(iter),Threshold(T),N_T(T,PE,iter))
    end
end
end

%%
save('Collisions.mat','Collisions')
save('Normalized_throughput.mat','N_T')
save('Load.mat','L')

for l = 1:length(N)
N_TatP2(:,l) = N_T(:,1,l);
N_TatP3(:,l) = N_T(:,2,l);
N_TatP4(:,l) = N_T(:,3,l);
end
for l = 1:length(N)
N_PatTpt25(:,l) = N_T(1,:,l);
```

```
N_PatTpt5(:,l) = N_T(2,:,l);
N_PatT1(:,l) = N_T(3,:,l);
end
%% plotting with respect to p_exp
figure
Color={'red','green','blue'};
for q = 1:3
line(L,N_TatP2(q,:),'Color',Color{q},'LineStyle','--')
end
xlabel('Load')
ylabel('Normalized Throughput')
title('Normalized Throughput when propagation exponent is 2')
legend('Threshold = 0.25','Threshold = 0.5','Threshold = 1')
grid on

figure
for q = 1:3
line(L,N_TatP3(q,:),'Color',Color{q},'LineStyle','--')
end
xlabel('Load')
ylabel('Normalized Throughput')
title('Normalized Throughput when propagation exponent is 3')
legend('Threshold = 0.25','Threshold = 0.5','Threshold = 1')
grid on

figure
for q = 1:3
line(L,N_TatP4(q,:),'Color',Color{q},'LineStyle','--')
end
xlabel('Load')
ylabel('Normalized Throughput')
title('Normalized Throughput when propagation exponent is 4')
legend('Threshold = 0.25','Threshold = 0.5','Threshold = 1')
grid on

%% plotting with respect to Threshold
figure
for q = 1:3
line(L,N_PatTpt25(q,:),'Color',Color{q},'LineStyle','--')
end
xlabel('Load')
ylabel('Normalized Throughput')
title('Normalized Throughput when threshold is 0.25')
legend('P exp = 2','P exp = 3','P exp = 4')
grid on

figure
for q = 1:3
line(L,N_PatTpt5(q,:),'Color',Color{q},'LineStyle','--')
end
xlabel('Load')
ylabel('Normalized Throughput')
title('Normalized Throughput when threshold is 0.5')
legend('P exp = 2','P exp = 3','P exp = 4')
grid on

figure
for q = 1:3
line(L,N_PatT1(q,:),'Color',Color{q},'LineStyle','--')
end
```

```
xlabel('Load')
ylabel('Normalized Throughput')
title('Normalized Throughput when threshold is 1')
legend('P exp = 2','P exp = 3','P exp = 4')
grid on
```

Program 1. *Code for Time and Asynchronize ALOHA (TFAA) when Rmin is 300 meters*

```
clc; clear all; close all
% Symbol interval in seconds
TS = 0.01;
% Packet length in symbols
TP = 100;
% Packet tail length in symbols (, depends on the interference)
Ttail = 2;
% Time window length in symbols (, corresponds to 100 packets)
TW = 10000;
% Signal bandwidth in Hz (, depends on the interference model)
B = 200;
% Operation bandwidth in Hz ()
W = 10000;
% Minimum distance from access point in meters ()
Rmin = 100;
% Maximum distance from access point in meters ()
%maxDist
Rmax = 1000;
% Number of active devices: variable (
N = 500:500:10000;
for iter = 1:length(N)
% System load:
L(iter) = N(iter) /(TS*W*TW/TP);
% Propagation exponent
% Maximum interference level for successful packet transmission in dB
()
Insts=10000;
Threshold=[0.25,0.5, 1] ;
Pexp=[2,3,4];
% Interefernce power threshold, normalized to target signal power
             % 0.5 correcponds to 3 dB SIR requirement, which could be
realistic
             % 1 corresponds to 0 dB SIR
for T = 1 : 3
    for PE = 1 : 3
[PinterfT,Collisions(T,PE,iter),N_T(T,PE,iter)] = colli-
sionsMR(N(iter),Insts,Pexp(PE),Thresh-
old(T),W,B,TW,TP,Ttail,Rmin,Rmax,L(iter));
fprintf('The normalized throughput when Pathloss exponents is
%d,\nNumber of Active Devices are %d and Threshold is %0.2f is
%0.5f\n',...
    Pexp(PE),N(iter),Threshold(T),N_T(T,PE,iter))
    end
end
end
%%
save('Collisions.mat','Collisions')
save('Normalized_throughput.mat','N_T')
save('Load.mat','L')
for l = 1:length(N)
N_TatP2(:,l) = N_T(:,1,l);
N_TatP3(:,l) = N_T(:,2,l);
N_TatP4(:,l) = N_T(:,3,l);
```

```
end
for l = 1:length(N)
N_PatTpt25(:,l) = N_T(1,:,l);
N_PatTpt5(:,l) = N_T(2,:,l);
N_PatT1(:,l) = N_T(3,:,l);
end
%% plotting with respect to p_exp
figure
Color={'red','green','blue'};
for q = 1:3
line(L,N_TatP2(q,:),'Color',Color{q},'LineStyle','--')
end
xlabel('Load')
ylabel('Normalized Throughput')
title('Normalized Throughput when propagation exponent is 2')
legend('Threshold = 0.25','Threshold = 0.5','Threshold = 1')
grid on
figure
for q = 1:3
line(L,N_TatP3(q,:),'Color',Color{q},'LineStyle','--')
end
xlabel('Load')
ylabel('Normalized Throughput')
title('Normalized Throughput when propagation exponent is 3')
legend('Threshold = 0.25','Threshold = 0.5','Threshold = 1')
grid on
figure
for q = 1:3
line(L,N_TatP4(q,:),'Color',Color{q},'LineStyle','--')
end
xlabel('Load')
ylabel('Normalized Throughput')
title('Normalized Throughput when propagation exponent is 4')
legend('Threshold = 0.25','Threshold = 0.5','Threshold = 1')
grid on
%% plotting with respect to Threshold
figure
for q = 1:3
line(L,N_PatTpt25(q,:),'Color',Color{q},'LineStyle','--')
end
xlabel('Load')
ylabel('Normalized Throughput')
title('Normalized Throughput when threshold is 0.25')
legend('P exp = 2','P exp = 3','P exp = 4')
grid on
 figure
for q = 1:3
line(L,N_PatTpt5(q,:),'Color',Color{q},'LineStyle','--')
end
xlabel('Load')
ylabel('Normalized Throughput')
title('Normalized Throughput when threshold is 0.5')
legend('P exp = 2','P exp = 3','P exp = 4')
grid on
figure
for q = 1:3
line(L,N_PatT1(q,:),'Color',Color{q},'LineStyle','--')
end
xlabel('Load')
ylabel('Normalized Throughput')
title('Normalized Throughput when threshold is 1')
```

```
legend('P exp = 2','P exp = 3','P exp = 4')
grid on
```

Program 2. *Code for Time and Asynchronize ALOHA (TFAA) when Rmin is 1000 meters*

```
function [PinterfT,Collisions,Normalised_Througput] = colli-
sionsMR(N,Insts,Pexp,Threshold,W,B,TW,TP,Ttail,minDist,maxDist,L)
%% This script calculates the average number of collsions over 'Insts'
%  simulation instances, when N packets are transmitted in each of
them
%% Parameters, input:
%    N         number of packets transmitted
%    Insts     number of simulation instants
%    Pexp      propgation exponent
%    Threshold maximum acceptable interference power, normalized to
power
%              of the target packet
%    others:   general intereference model parameters

%    Output:
%    PinterfT   vector of interference powers in successful
transmission
%    Collisions number of unsuccessful instances in with the
interference
%               power exceeds the threshold
load('interfModel_100_05','leng','tail','maxT','maxF','beta','osf','sp
an','interfM');
Collisions=0;
PinterfT=[];
for loop = 1:Insts
  %   packet center ferquency 'Freq'
    Freq = randi([(B/2) ((W-B)/2)],1,N);
    %   arrival time    'Time'
    Time = randi([(Ttail +1) (TW-TP-Ttail)],1,N);
    %   and power level 'P'

    Pinterf=0;
    n=1;
    while n<=N;
%       maxDist=1000;% Collecting N cases with distance in the target
range
%       minDist=100;
        Xdist=maxDist*(2*rand(1,1)-1);
        Ydist=maxDist*(2*rand(1,1)-1);
        Distance=sqrt(Xdist^2+Ydist^2);  % Uniform distribution in a
square reqion
                                          % containg the circular
coverage area of
                                          % radius 'maxDist'
        if Distance>minDist & Distance<maxDist  % Include only cases
with distance in the traget range

            P(n)=minDist.^Pexp/Distance.^Pexp;    % Scaling is
arbitrary, this gives
                                                  % power 1 at 100 m
distance
```

```
            if n>1
                Pratio(n) = P(n)/P(1);
            end
        end
        n=n+1;
    end
    Fdist = abs(Freq-Freq(1));
    Tdist = abs(Time-Time(1));

    n=2;
    while Pinterf<=Threshold & n<=N
        if Fdist(n)<=maxF & Tdist(n)<=maxT
            Fdis=max(min(Fdist(n),maxF),1);
            Tdis=max(min(Tdist(n),maxT),1);
            Pinterf=Pinterf+Pratio(n)*interfM(Fdis,Tdis);
        end
        n=n+1;
    end
    if Pinterf<=Threshold % no collision
        PinterfT=[PinterfT,Pinterf];
    else
        Collisions=Collisions+1;
    end
end
Normalised_Througput  = L*( Insts - Collisions)/(Insts);
```

Program 3. **This script the average number of collsions over 'Insts' simulation instances**

APPENDIX B: EXPLANATION OF THE TFAA MATLAB CODE

A loop equal to the length of Number of devices array is started, to start the simulation. The first thing the loop will recognize is the Load in the channel and is calculated using the number of devices divided by the product of bandwidth of channel, time window and symbol interval whole divided by the length of the packets. The number of instances a packet is transmitted is selected to be 1000. An array for threshold of the receiver is made to be 0.25, 0.5 and 1. Propagation exponent is also a vector initiated with values of 2, 3 and 4.

In the beginning of a "for" loop, the threshold selected to be 0.25, is opened and it will operate when the sub loop has run for propagation exponent of 2, 3 and 4. Threshold will change with each conductance of the nested loop and calculate the terms like collisions and throughput according to these values. In the loop, a sub function known as "collisionsMR" is called and it is responsible for the calculation of collisions in the system and throughput of the system.

These values are recorded into the 3-dimensional matrix that is indexed by the throughput, propagation exponent and the number of device indexes. Each throughput is printed on the command window with each completion of a loop with its threshold, propagation exponent and the number of devices mentioned.

The section of code after this necessary code is just the manipulation of the results to view in an informative form. The line below would save the collisions data set into a "collisions.mat" file, similarly, Load is saved in a separate "Load.mat" file and Normalized throughput is saved in the same named mat file.

The manipulation of these Normalized throughput results is done in such a way that the results at each threshold and propagation exponent are placed in new different variables. These variables are then used to plot the line curves on a graph to make some informative sense of the data proceeded and computed through the function file named collisionsMR.

In the function file collisionsMR, several inputs are given by the main file and it used these inputs in various locations. The very first thing it does is load the given parametric values of the channels with frequency and time mentioned. It then initializes parameters like collisions and the intermediate PinterfT values for calculation purposes. A loop of Instances starts in which, a random frequency in between the values of half of the bandwidth and the half of the difference in channel and packet bandwidth is initialized.

A random time variable is also initialized that is in between the packet tail length +1 and difference of window length and the packet length and its tail length is produced by the software. A while loop is initiated that will run for the value of number of devices. Each device is assigned a random distance that does not leave the boundary of the minimum and the maximum distance between device and access point.

The power used to transmit the signal at each device is calculated by multiplying the minimum distance and propagation exponent and dividing it with the product of maximum distance and propagation exponent. The ratio for the power is calculated by dividing the power for the current device to the power of the first device. The frequency distance and the time distance is also calculated by simply subtracting the random frequency and random time selected in the loop with the initial Frequency and Time selected in the loop beginning.

A simple test is initialized which will go in the loop while the "pinterf" value is less than the current threshold and the maximum number of devices is reached. The test will check if the current distance value calculated above for time and frequency is less than the maximum frequency and time allowed or not. It will only process the lines given below if the condition above is satisfied. The lines below would make a new variable that places the maximum value of the comparison between the distance and maximum values of the given domain. The pinterf variable would be added to the product of the given matrix location of the variable computed above. The pinterfT is calculated at each loop time and it is then concatenated to the pinterf value computed above. Now if the comparison that the current pinterf value is less than the threshold value is satisfied that would mean that no collision took place. If the condition is not satisfied, then the collision has happened, and it is added in the previous number of collisions for each loop. The last thing for the loop is to calculate the normalized throughput and it is calculated using the equation given below:

Normalised_Througput = L*(Insts - Collisions)/(Insts);

Here L is the load of the system calculated above.