Tampere University

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TIME- AND FREQUENCY-ASYNCHRONOUS ALOHA FOR ULTRA NARROWBAND COMMUNICATIONS

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ABSTRACT

MD ASHIQUR RAHMAN: TIME- AND FREQUENCY-ASYNCHRONOUS ALOHA FOR ULTRA-NARROWBAND COMMUNICATIONS
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A low-power wide-area network (LPWAN) is a family of wireless access technologies which consume low power and cover wide areas. They are designed to operate in both licensed and unlicensed frequency bands. Among different low-power wide-area network (LPWAN) technologies, long range (LoRa), Sigfox, and Narrowband Internet of Things (NB-IoT) are leading in IoT deployment in large-scale. However, Sigfox and LoRa both have advantages in terms of battery lifetime, production cost and capacity whereas lower latency and better quality of service are offered by Narrowband Internet of Things (NB-IoT) operating licensed cellular frequency bands. The two main approaches for reaching wide coverage with low transmission power are (i) spread spectrum, used by LoRa, and (ii) ultra-narrow band (UNB) which is used by Sigfox.

This thesis work focuses on the random-access schemes for UNB based IoT networks mainly. Due to issues related to receiver synchronization, two-dimensional time-frequency random access protocol is a particularly interesting choice for UNB transmission schemes. However, UNB possess also some major constraints regarding connectivity, throughput, noise cancellation and so.

This thesis work investigates UNB-based LPWAN uplink scenarios. The throughput performance of Time Frequency Asynchronous ALOHA (TFAA) is evaluated using MATLAB simulations. The main parameters include the interference threshold which depends on the robustness of the modulation and coding scheme, propagation exponent, distance range of the IoT devices and system load. Normalized throughput and collision probability are evaluated through simulations for different combinations of these parameters. We demonstrate that, using repetitions of the data packets results in a higher normalized throughput. The repetition scheme is designed in such a way that another user's packets may collide only with one of the target packets repetitions. The power levels as well as distances of a user's all repetitions are considered same. By using repetitions, reducing the distance range, and increasing the interference threshold, the normalized throughput can be maximized.

Keywords: LPWAN, IoT, NB-IoT, UNB, RF, TFAA, M2M, LoRa, Sigfox.

PREFACE

This thesis work was done at Tampere University as a requirement to complete my Master of Science degree in Information Technology. The thesis work is done under the supervision of **Professor Markku Renfors** and **Associate Professor Elena-Simona Lohan**. Without support and guideline of my supervisors, it would not have been possible to complete my thesis work, so I want to thank both of my supervisors and will be grateful to them. I also want to thank my parents, family members and friends for their continuous support and motivation towards me.

Finally, I thank Almighty God for guiding and helping me throughout my whole life.

Tampere, 25 February 2020

MD ASHIQUR RAHMAN

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LIST OF SYMBOLS AND ABBREVIATIONS

LPWAN	Low Power Wide Area Network
IoT	Internet of Things
NB-IoT	Narrowband Internet of Things
D-BPSK	Differential Binary Phase-Shift Keying
M2M	Machine-to-Machine
UNB	Ultra-Narrowband
RF	Radio Frequency
TFAA	Time Frequency Asynchronous ALOHA
LTE	Long Term Evolution
GSM	Global System for Mobile
CR-TFAA	Contention Resolution Time Frequency Asynchronous ALOHA
ACRDA	Asynchronous Contention Resolution ALOHA
LAPs	LTN Access Points
LEPs	LTN End Points
CRA	Central Registration Authority
BPSK	Binary Phase-Shift Keying
SRRC	Square-Root-Raised-Cosine
GFSK	Gaussian Frequency Shift Keying
MAC	Media Access Control
DSSS	Direct Sequence Spread Spectrum
CSS	Chirp Spread Spectrum
FEC	Forward Error Correction
SNR	Signal to Noise Ratio
FSK	Frequency-Shift Keying
SF	Spreading Factor
WLAN	Wireless Local-Area Network
SIC	Successive Interference Cancellation
PER	Packet Error Rate
SINR	Signal-to-Interference-plus-Noise Ratio

T	Throughput
B	Packet bandwidth
W	System bandwidth
T_p	Packet duration
G	Channel load
n_{rep}	Number of packet replicas
L_b	Payload
N_{slots}	Time slots per frame

1. INTRODUCTION

Internet of Things (IoT) is widely considered as a central element of the future connected world. Internet of things refers to a network consisting of physical devices, home appliances, automobiles and any other items which are used in accordance with sensors, software, actuators, and electronics for the enhancement of data exchange. IoT provides a platform for connecting these devices with people and Internet, creating huge opportunities. Internet of things promotes economic and environmental benefits, performance efficiency and minimizes human involvement. Internet connectivity is extended beyond mobile devices and personal computers with the help of IoT, allowing to reach various non-internet enabled devices. Internet of things plays an important role in this digital technology world by creating an ecosystem where many systems are linked for providing smart performance. Within 2020, the world is set to be IoT oriented completely. IoT guarantees secured data processing and high-quality data, also reduces production cost while maximizing outcome.

Wireless network operators are widely deploying dedicated IoT or machine-to-machine (M2M) communication networks for enabling better service with wireless IoT. With the commercial applications growing rapidly, it is clearly seen and understood that there are many cases of mobile IoT applications for which existing devices and networks are not fitting properly. Production cost, battery life and network coverage are the central reasons for that. When discussing about network coverage, an important thing to mention that, current cellular networks can provide very good wide area coverage. However, many connected devices which are in remote areas, far from the next base station. In a place with weak network signal, it makes necessary for a device transmitter to keep functioning at very high power, hence draining the device battery. Current cellular standards do not support power saving mechanisms and lead to not supporting battery life for several years. Another important factor is device costs. Messaging, data transmission with good speed, and entailing mobile voice these are the services intended for mobile devices working on Long Term Evolution (LTE), Third Generation (3G), and Global System for Mobile (GSM). Machine type communication applications require relatively low speed, but they need reliable date connection and low device cost, and practical factors like installation simplicity are important. It is rather important for public having knowledge of different LPWAN technologies and knowing how to implement them in different situations. Different LPWAN systems, technologies, protocols and applications, benefits and potential challenges are discussed and examined in this thesis work.

1.1 Background

In recent times, IoT represented latest innovations in smart sensor, Radio Frequency Identity (RFID), important internet protocols, enhanced communication technologies and more for users. IoT relies on Machine to Machine communications or M2M, having less interception, human involvement, and interference, hence increasing productivity, authenticity and performance. The main idea behind IoT is, lower production cost, more transparency, portability, and greater effectiveness and making it compatible with rapidly changing technology industries such as telecom industry facing issues like production cost, technological inputs, competencies, scalability at present and upcoming future.

Thus, for upcoming years, it is assumed that, IoT will have a critical impact in information technology sector, focusing on critical growth, diversification, propagation and progression globally, especially for M2M communications and interfacing dissemination, identification and dispersion of Big Data through IoT deployment.

IoT, possess significant advantages as well as suffering major drawbacks which are also focused in this thesis work. Generally, IoT technology study involves benefits, motivators, and applications, as well as technical issues like power consumption and support of massive number of devices for saving costs and adding high utility value, offering extensive scope for M2M expansion and growth.

1.2 Work description

Thesis theoretical part involves LPWAN study having focus on ultra-narrowband and spread spectrum based IoT technologies. These are the main modulation schemes for supporting transmission over channels with high path loss, which is necessary in wide-area IoT operation. Both approaches are available commercially: Sigfox is based on UNB and LoRa on spread spectrum schemes.

The technical part of this thesis work includes overview of Time Frequency Asynchronous ALOHA (TFAA) and its throughput performance and scalability issues. Two different channel models, collision model and capture channel model are discussed along with throughput analysis of the capture channel model. Finally study of throughput performance of TFAA is done using MATLAB simulations. The main parameters include the interference threshold, propagation exponent, distance range of the IoT device, and system load. Normalized throughput and collision probability are evaluated through simulations for different combination of these parameters.

Research Methodology

- Scientific literature review.
- Study of the materials to develop good and detailed understanding about UNB IoT.
- Analytical TFAA models and earlier numerical studies in literature.
- Developing Matlab code for simulation.
- Adding repetition pattern in the code.
- Preliminary simulation result with limited statistics.
- Final simulation results with graph.

Writing part of the thesis is done as following:

Chapter 2 describes LPWAN technologies focusing on Sigfox and LoRa. Time frequency asynchronous ALOHA (TFAA) overview, throughput performance and some issues are discussed in chapter 3. Technical aspects of the thesis are addressed in chapter 4 where two different channel models are studied, and the capture channel model is analysed in detail. Chapter 5 focuses on Contention resolution time frequency asynchronous ALOHA (CR-TFAA). Chapter 6 presents simulation-based analysis of TFAA, its' throughput performance is evaluated and discussed.

Finally, conclusion part of the thesis work is in chapter 7.

2. LPWAN

Low-power wide-area network (LPWAN) is a family of wireless access technologies which consume less power and cover wide areas. They are able to operate in both licensed and unlicensed frequency bands. LPWANs have gained popularity for low-rate and long-range radio communication technology with the growth of IoT market. Among different LPWAN technologies, Sigfox, LoRa, and NB-IoT are leading in IoT deployment in large-scale. However, Sigfox and LoRa both have advantage in case of battery lifetime, production cost and capacity whereas latency and quality of service are offered by NB-IoT [1]. Two main LPWAN technologies Sigfox (Ultra narrowband) and LoRa (spread spectrum) are being discussed in detail in this chapter.

2.1 Sigfox

Sigfox is a network operator based in France and it builds wireless networks for connecting low-power objects that need to emit small data infrequently. Sigfox technology is one of the LPWAN technologies, mainly employed for the IoT network development having low volume of data which need to be sent within long operating range and low power consumption during the transmission. Sigfox uses Differential Binary Phase-Shift Keying (D-BPSK) modulation in which the message possesses a fixed bandwidth of 100 Hz and the transmission speed is 100 bps for Europe region. It is operated in below 1 GHz unlicensed frequency spectrum that varies within region, 868 MHz for Europe and 915 MHz for U.S. region. To provide communication service across the globe like cellular communication service Sigfox follows business-to-business model (B2B). The technology provides low data rate which is 100 bps, maximum payload (uplink/downlink) of 12/8 octets and a maximum transmission of 140/4 per day, which is very limited [3].

In Sigfox, IoT device transmission initiation is done by sending three uplink packages sequentially onto three carrier frequencies randomly. Even if two transmissions get lost due to collision or interference, the base station will receive the package successfully. In the EU ISM band (868 MHz) the duty cycle restriction is 1 percent, hence a device can transmit 36 seconds per hour only and having 6 second air time per package allows 6 messages per hour to transmit with payload of 4,8, or 12 bytes [4].

Table 1. *Sigfox features.*

Specifications	Sigfox
Frequency band	868 MHz in Europe and 902 MHz in U.S.
System band-width	200 kHz
Distance	Urban area (3-10 km), Rural area (30-50 km)
Data rate	10-1000 bps (100 bps ideal for IoT applications)
Message/data size	12 bytes (frame 26 bytes)
Modulation scheme	D-BPSK
Applications	M2M and IoT
Capacity	Sigfox base station can handle 30,00000 devices
Architecture	Star consisting of Sigfox objects, Customer IT server, and Sigfox cloud

2.1.1 LTN network architecture

LAPs (LTN access points), WAN/cloud port, LEPs (LTN end points) and various type of servers are parts of a typical LTN network architecture, as shown in figure number 1. BSS/OSS or Central Registration Authority (CRA) and LTN server are included in various servers for LTN network architecture [5]. Different interfaces are used to connect different entities of LTN network and all the interface types from interface A to F are described below in table number 2.

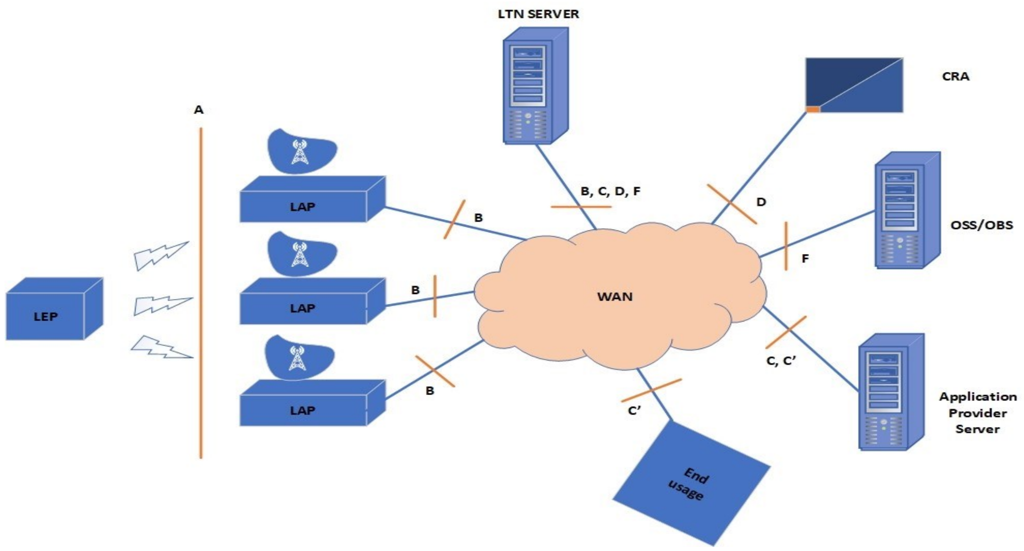

Figure 1. LTN network architecture

Table 2. LTN network interface

Interface type	Description
Interface A	Radio access technologies are used for creating connection between LAP (base station) and LEP (end device) in this interface type.
Interface B	This interface is utilized via WAN mediums (satellite, ADSL, microwave links) between LTN servers and LAPs.
Interface C	Between application provider server and LTN server this interface is being found which ensures usage of IP protocols.
Interface D	Interface D is used between LTN servers and LTN CRA.
Interface E	Interface E is used between different LTN servers (used mostly during roaming).
Interface F	This interface is used to exchange information for network status and registration between OSS servers and LTN servers.
Interface A’	This interface is used inside LEP, between LTN module and Data Collection System (DCS). For execution AT commands are employed over serial connection.
Interface C’	Application provider provides this interface. This interface is used as an end user interface.
Interface F’	This interface is being applied between OSS servers and application provider.

2.1.2 Sigfox Architecture

The Sigfox cloud, Sigfox objects, servers, and gateway these are the main components of the Sigfox architecture. For connecting the gateways with the objects star topology is used in Sigfox technology. For interfacing the server with the cloud, HTTP, MQTT, SNMP, and IPv6 these different protocols are applied depending on end applications [4]. Sensing or control are done by objects which is the main purpose for the network. Allocating locations of the elements and communicating with the Sigfox gateway are done remotely. From the objects, signals are received by the Sigfox gateway and then the signals are passed on the Sigfox cloud which supports many Sigfox services such as management of the objects and message retrieval. Ethernet, cellular and other telecommunication connections are elements of the network which are either wired or wireless. For connecting Sigfox cloud with the gateways, secured IP connections are being used which are basically a direct secure point to point (P2P) links which are located in between the cloud and gateway. Data utilization following a standard protocol are done in this way which also can be linked with public or private telecommunication network. The backhaul network's spare capacity can be used by co-locating one of the Sigfox gateways and a cellular base station.

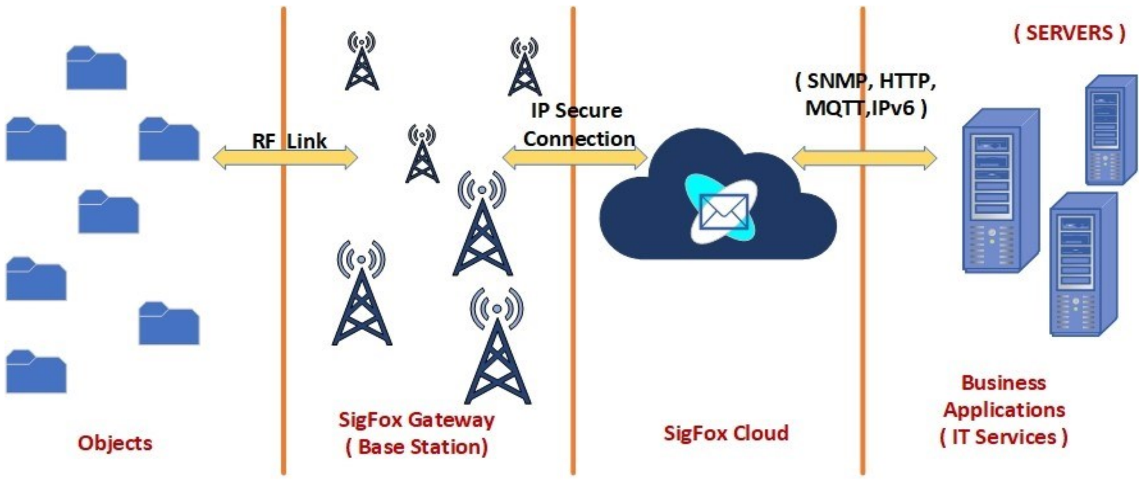

Figure 2. Sigfox architecture

The above figure illustrates simple Sigfox network architecture which is almost the same as LTN architecture having difference in terminologies. LAPs are termed as Sigfox gateway or base station while the LEPs are designated as objects. Sigfox cloud is represented by WAN and it links base stations via different interfaces with business applications [7]. Uplink transmissions are directed from LTN end points towards the network which can be either gateways or base stations whereas downlink transmissions are directed from the network towards the LTN end points.

2.1.3 Sigfox Protocol Stack

Physical layer, MAC layer, Radio layer, and application layer, these are the four layers of Sigfox Protocol Stack where each of the layers possess unique characteristics that enables to perform specific functions. Frequency assignment and setting the transmission or reception power for Sigfox end points and base stations are done by Radio layer. Two different transmission schemes, Orthogonal Sequence Spread Spectrum (OSSS) and UNB are also supported by the Radio layer, as well as upholding different frequency spectrum which depends on region (Europe 868 MHz, United States 902 MHz, and China 433 MHz). Sigfox receiver sensitivity is also ensured by the layer which is better than -135 dBm as well as maximum transmission power for UNB uplink transmissions (Europe) which is 25 mW in Europe.

During transmission and reception, handling the MAC frames are done by the physical layer. Inserting preamble (for synchronization purposes) at the time of transmission at the transmit end and at the receive end during reception removing the preamble is also done by the physical layer also. In the uplink, Binary Phase-Shift Keying (BPSK) modulation is applied and, in the downlink, Gaussian Frequency Shift Keying (GFSK) modulation is applied by it. Managing the MAC messages is dealt by the Media Access Control (MAC) layer as well as preparing frames according to the format of the uplink and downlink, which will be discussed in the following section.

Finally, application layer which is a LTN technology supporting various applications uses different interfaces or protocols between servers and clouds, for example, HTTP, IPv6, SNMP and hence defining different applications as per user requirements.

2.1.4 Sigfox Frame Structure

Uplink MAC frame and downlink MAC frame are the two-frame structures that Sigfox MAC has. Certain characteristics for each of the frame structures can be seen in the figure 3. For the uplink MAC frame (UNB implementation) the preamble is 4 bytes and the frame synchronization consist of 2 bytes, 4 bytes is the end device identification and the payload are from 0 to 12 bytes. Error detection by FCS is 2 bytes but the authentication varies in length [8]. The preamble for downlink MAC frame is the same as uplink MAC frame, 32 bits or 4 bytes but the frame synchronization consists of 13 bits. FCS and authentication are 8 bits and 16 bits respectively. Error codes and payload for downlink MAC frame varies in length and flags are 2 bits.

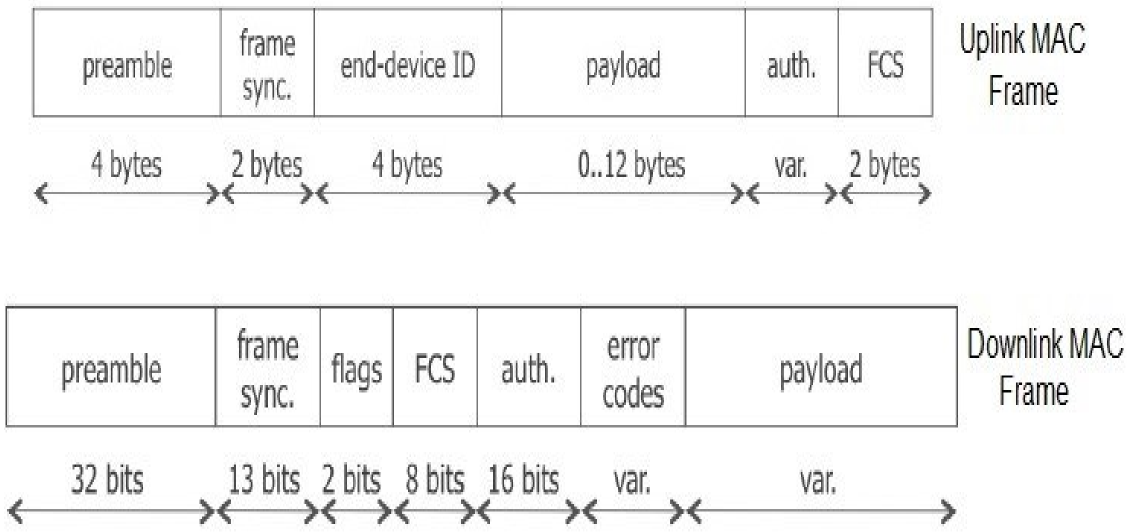

Figure 3. Sigfox frame structure

2.2 LoRa

LoRa is a wireless technology and based on spread spectrum transmission module and it operates on the ISM radio bands of varying frequencies depending on the region. LoRa operates in 51 countries including 100 deployed LoRa-WANs and it is a non-profit association (open standard) for over 500 companies with commitment of enabling deployment of LPWAN IoT in larger scale using the LoRaWAN promotion and deployment [9].

LoRa operates on the same frequency bands as of Sigfox. It has a cellular topology where gateways or base stations receive packets from devices and transmit the data on TCP connection to a server [10]. LoRaWAN has capacity of providing service of wide area network and the network consists of different elements such as server, LoRa gateways, endpoints, and remote computer [11]. Having a spectrum range between 863 and 928 MHz allows to transmit over long distances and through obstacles consuming very low power, which is the main goal for IoT technology.

For M2M (machine-to-machine) applications and IoT applications, LoRa which is a physical layer protocol enables low power and long-range communication. For transmitting at different frequencies and data rates, a spread spectrum approach is used by LoRa within the sub-GHz spectrum [12]. LoRa technology allows to connect many applications that operate in the same proprietary or public network with multiple users. Unlike Sigfox, LoRa modules allow for granular configuration and course of action, suggesting if two devices are designed differently, they will encounter problems while communicating with themselves [13].

2.2.1 Features of LoRa

Some of the LoRa features are mentioned in the table below.

Table 3. LoRa features

Specification	Feature
Frequency bands	868 MHz (Europe), 915 MHz (U.S)
Range	2-5 km (urban area), 15 km (suburban area)
Standard	IEEE 802.15.4g
Transmission BW	125 kHz and 250 kHz
Modulation	LoRa DSSS
Bandwidth	250 kHz
Latency	Insensitive
Data rates	0.250-11 kb/s (Europe)
Spectrum	Spread spectrum
Applications	M2M and IoT based
Synchronization (Time)	Supported

2.2.2 Physical Layer

Physical layer of LoRa technology enables operating effectively low power transmission over long distances for data links. Over the radio interface, the physical layer encloses all direct contacts with outer world [14]. Parameters of the layer includes modulation, frequencies, bands, basic RF protocols, and power levels which can be encapsulated with attributes of LoRa physical layer.

2.2.3 LoRa Network

Having capacity of providing service of wide area network, LoRa is also referred to as LoRaWAN. Server, LoRa gateway, endpoints, and remote computer are the different elements of a LoRa network [4]. Endpoints is an important part of LoRa network where sensing or control takes place. All the elements have communication with LoRa gateway and mostly remotely located which can be seen in figure 4. From the endpoints, signals are received by the LoRa gateway and then passed to the backhaul system. The network element might be ethernet, cellular or other connection (telecommunication) which is either wireless or wired [14]. Standard IP connections are being used for connecting gateways with the network server and by this way a standard protocol is being utilized by the data which is possible to be linked with a telecommunication network, either public or private. Co-locating LoRa gateways within cellular base station can be done frequently while observing similarities between LoRa and a cellular network that allows using the spare capacity of the backhaul network. Server which is another important element of LoRa network controls the network. Scheduling acknowledgements and adapting data rates are tasks done by the server for managing the network [14]. Server which is a part of the network can easily be deployed and connected, which enables network's easy implementation. Finally, for gathering information, a remote computer controls the endpoint operation having the network being transparent. Multicast operation is possible while having bi-directional communication to the endpoints and this is useful for upgrade of software and other mass distribution data.

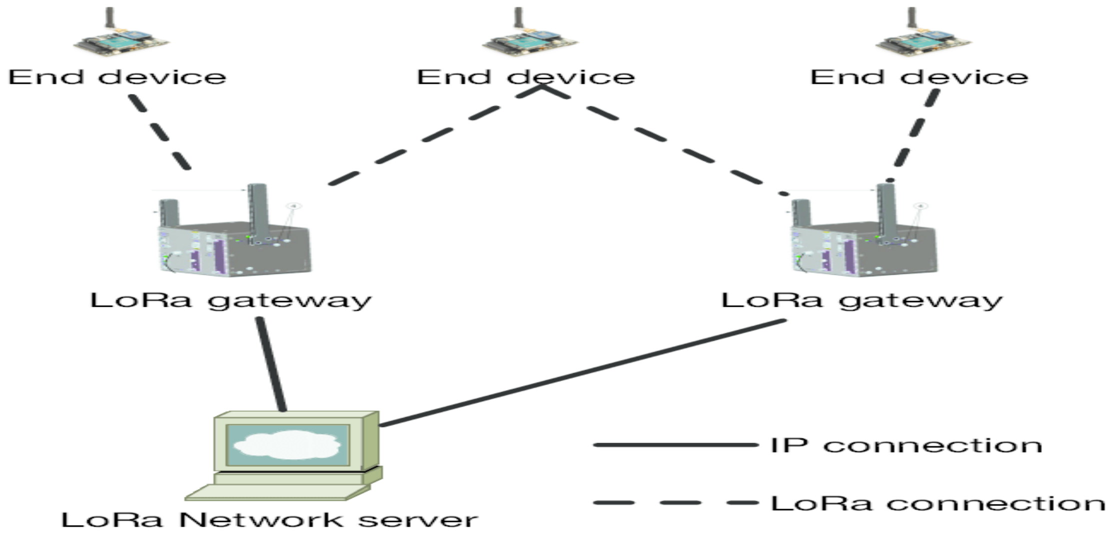

Figure 4. LoRa network architecture [14].

2.2.4 Modulation

CSS (Chirp Spread Spectrum), a spread spectrum modulation is used by the LoRa physical layer. Wide-band modulation pulses having linearly time-varying frequency is utilized by the LoRa modulation scheme [14]. Increase or decrease of frequency over time can be applied for encoding the information that needs to be conveyed. In this LoRa modulation technique spread spectrum can be achieved by producing a chirp signal that continuously changes within frequency [15]. Depending on this, for signal detection, timing offset and frequency offset are not considered critical, which makes the receiver design simple because of avoiding complex algorithms. A correspondence is seen between chirp frequency bandwidth and system's spectral bandwidth. This modulation technique allows demodulation of the received signal at 20 dB below the noise with the help of effective Forward Error Correction (FEC) [16]. The FEC of LoRa allows recovery of data bits with 25 dB lower SNR comparing with basic FSK system.

2.2.5 Modulation parameters

Some basic parameters for LoRa modulation include bandwidth (difference between minimum and maximum frequency), spreading factor (quantity of encoded bits per symbol), and the code rate (measure for level of FEC). LoRa technology uses the spreading factor (SF) as the number of transmitted data bits per symbol. The parameter SF defines the bit-rate, robustness of detection, and interference and noise resistance [16]. Among all LoRa modulation parameters the most significant one is the bandwidth. The frequency of the LoRa signal varies during every chip interval over the whole frequency band, which is known as chirp, and SF chirps make each single LoRa symbol. At the beginning of every symbol interval, the initial frequency represents the symbol value where SF bits are carried by each symbol. Wrapping around from highest frequency to lowest one during symbol interval at some point is done by the chirp and it depends on the value of the symbol. The following figure illustrates LoRa transmission where BW denotes bandwidth and f_c is the channel centre frequency.

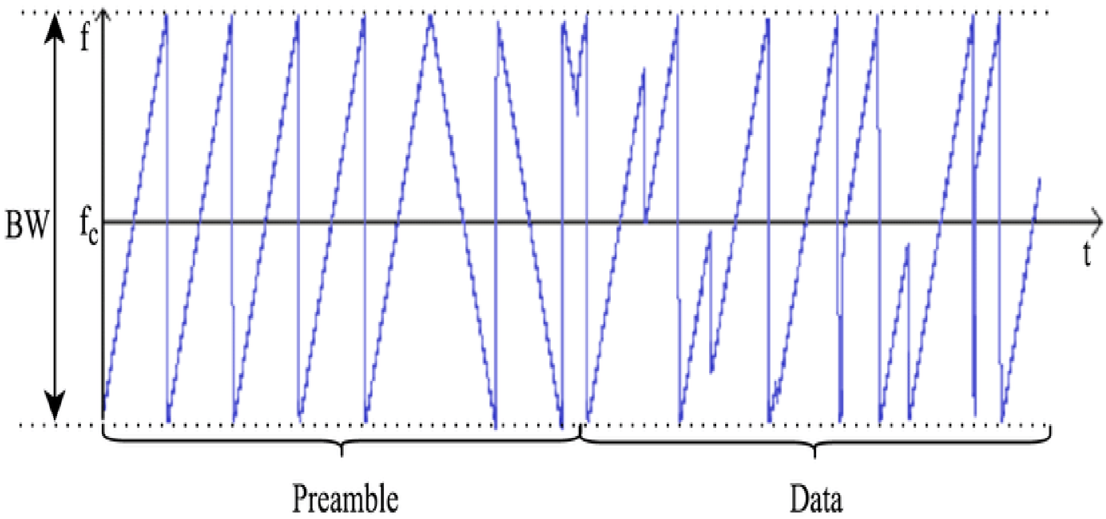

Figure 5. *Variation of frequency of a signal over time emitted by LoRa transmitter[14]*

2.2.6 Frequency bands (LoRa)

The unlicensed ISM frequencies which can be accessed in various parts of the world are utilized by the LoRa system. Depending on region the mostly utilized frequencies for North America is 915 MHz, for Europe 868 MHz, and 433 MHz for Asia [17]. For gaining better coverage especially for indoor nodes, the system utilizes lower frequencies than the 2.4 GHz ISM bands widely used, e.g., by WLANs. However, it is possible to use different available frequency bands by LoRa technology that is not particular for any fixed frequency.

3. TIME FREQUENCY ASYNCHRONOUS ALOHA

TFAA or Time and Frequency Asynchronous Aloha is a random-access scheme for uncoordinated packet transmission scheme both in the time and the frequency domains. TFAA originally allows reduction in packet collision rate down to a level that is not achievable in traditional time-domain Aloha systems. TFAA in combination with ultra-narrowband (UNB) transmission can be considered as an alternative of spread spectrum, since it allows similar reduction in transmission power and increase in communication range, which is necessary in LPWAN systems. UNB concentrates the transmitted energy within a very narrow bandwidth, which provides high signal-to-noise ratio (SNR) at the receiver due to reduced noise power. However, the frequency synchronization of UNB transmissions from different devices becomes very difficult. This issue can be circumvented from the device point of view by using significant intentional random frequency offsets for different devices. TFAA becomes a natural transmission scheme in such uplink IoT transmission scenarios.

3.1 TFAA overview

In TFAA, frequency synchronization is relaxed significantly. Within the system bandwidth, packets can be transmitted easily with randomized frequency offsets. The frequency synchronization of received packets is handled at the gateway receiver side, where complexity and power consumption are not critical. Hence the need for precise oscillators is avoided and cheaper transmitters can be considered for devices which is a general advantage of TFAA. Another advantage of TFAA is robustness to Doppler shifts. TFAA is mainly designed for supporting frequency uncertainty in a high amount and because of this relatively high Doppler shifts can be managed [18]. Using low rate FEC helps to cope with MAI (Multiple Access Interference) in TFAA. This characteristic has already been known from time asynchronous Aloha, and for time-frequency asynchronous case it was studied in [19][20]. In spread spectrum systems the throughput drops very fast when there is power imbalance [21], whereas for TFAA the throughput performance increases in such scenarios, which is an important feature for LPWANs having simplified power control system.

UNB TFAA is gaining more interest for LPWAN applications because radio interface of UNB TFAA allows increasing the communication range significantly or reducing needed transmission power. This is done by reduction in transmission bandwidth under the level which is needed for conventional FDMA systems. However, the application of TFAA for LPWANs possess some issues also. In the demodulation process, the TFAA scheme increases the receiver complexity in gateways. For M2M satellite systems, UNB TFAA has also become popular. It is shown in the study of TFAA application for low earth orbit satellite system under collision channel model that having low transmission rate compared with Doppler rate, the MAC performance is affected by timing issues [22].

3.2 TFAA Throughput Performance

According to the collision channel model [20], if and only if any other packet is not being transmitted over region (see figure 6) $[f_i-B,\ f_i+B]\times[t_i-T_p,\ t_i+T_p]$, only then a TFAA packet is considered to be transmitted successfully. Here T_p denotes packet duration and B is the packet bandwidth whereas W is the total system bandwidth, with W>>B. For a given channel load G, the throughput T of TFAA can be shown as

$$T=G\cdot\exp[-4G] \tag{1}$$

when $B/W \rightarrow 0$. Equation (1) can be seen in figure 7 which also shows comparison with basic ALOHA throughput. Under the collision channel model the pure (1- dimensional) ALOHA performance is better than that of TFAA, but allowing non-zero packet error probability can reduce the gap of performance significantly [20].

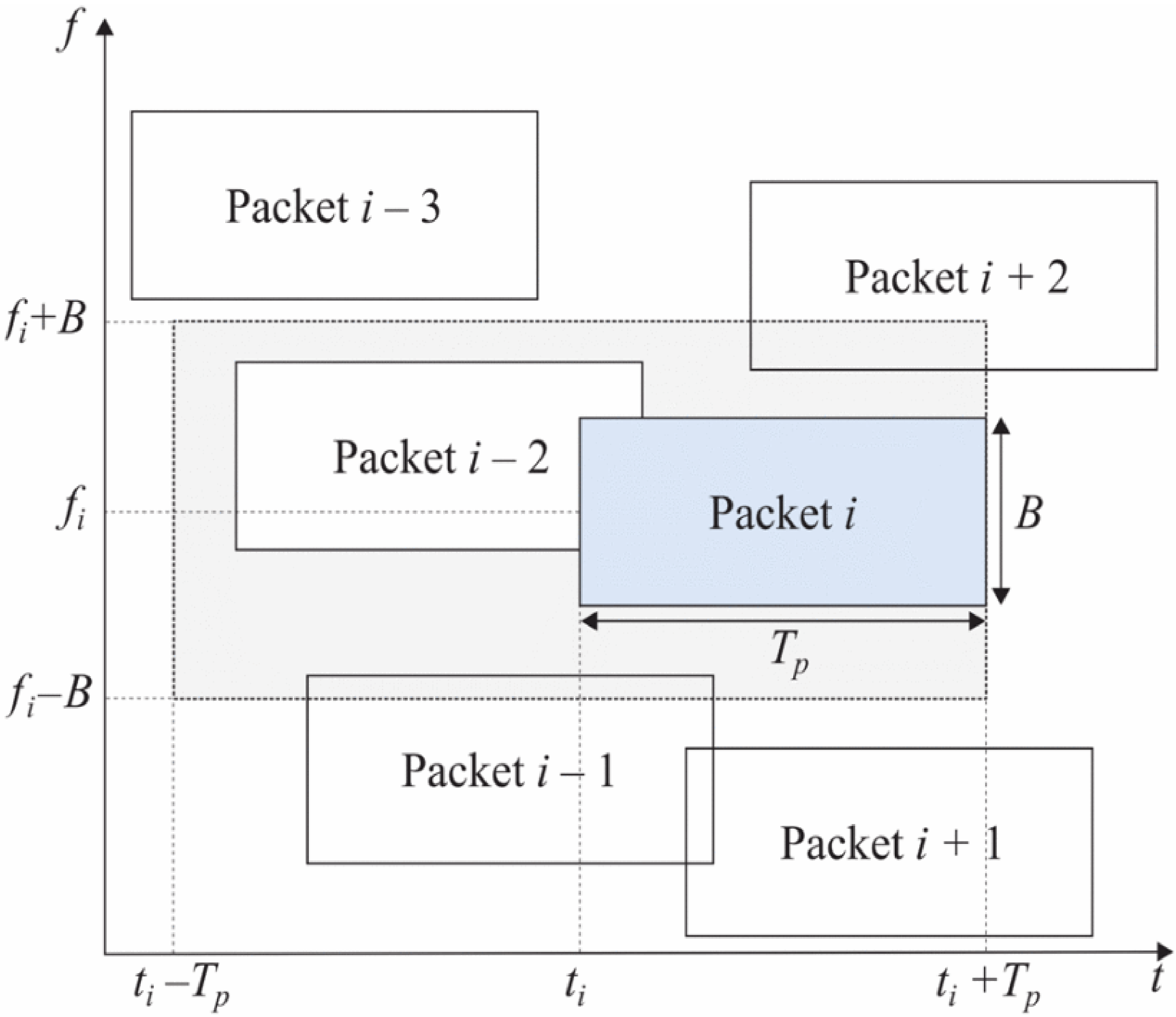

Figure 6. *Two-dimensional representation of TFAA.*

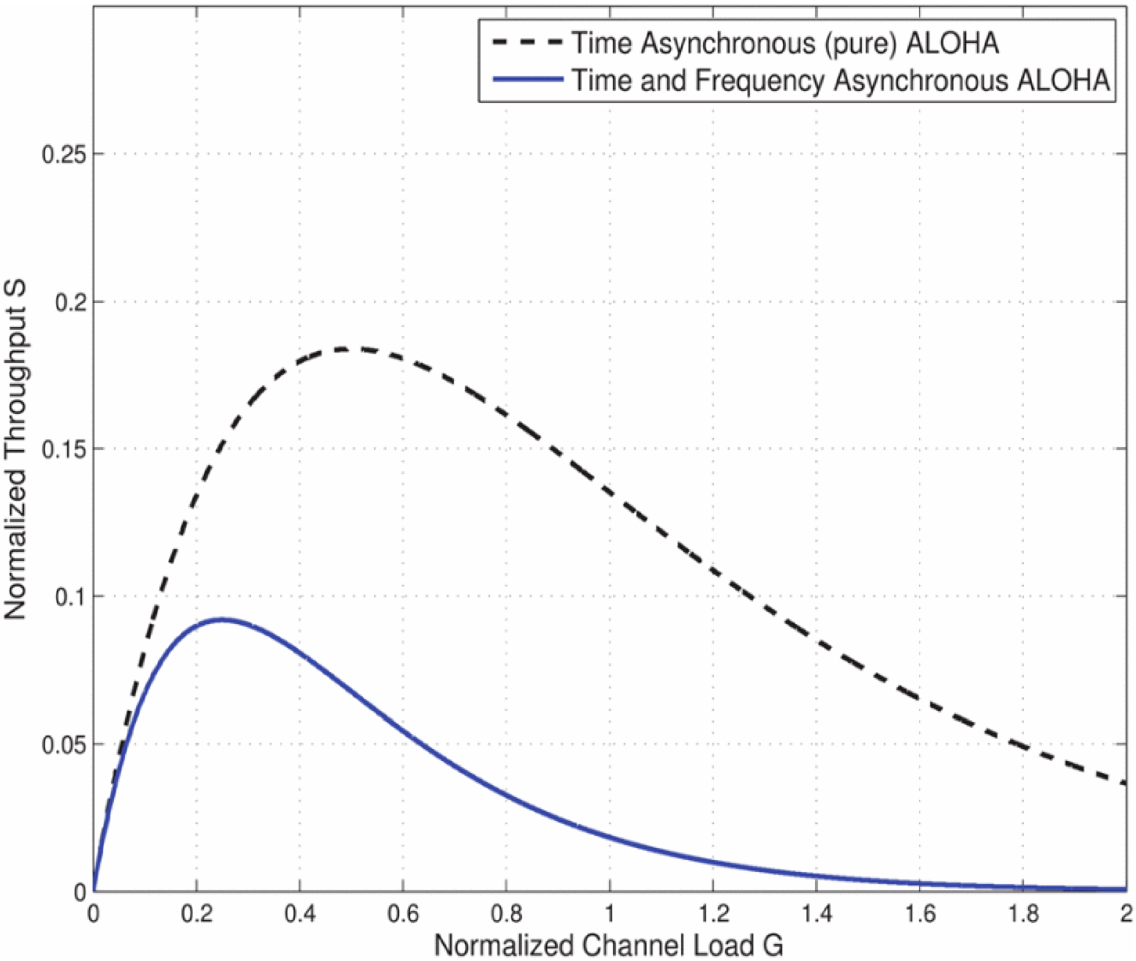

Figure 7. Normalized throughput vs normalized channel load for ALOHA and TFAA under the collision channel model.

3.3 TFAA Scalability Issues

For efficient RA operation, using TFAA in its simplest form is not enough. Additionally, one access point covers a wide area in LPWAN hence making it difficult to reutilize frequency, which is a major drawback for LPWAN. To improve the capacity in of TFAA based UNB, making use of collision resolution techniques at the receiver side can be considered as an alternative.

4. CHANNEL MODELS

4.1 Collision Channel Model

A communication situation where packets containing messages of fixed length are transmitted over the channel is commonly known as multiple access collision channel. The packets are synchronized, and one packet's transmission length correspond to a time slot considered as time limit. Channel input users are unlimited in number without cooperating with each other, hence different packet senders are not able to exchange information. A test packet is considered successfully being transmitted if and only if no other packet overlaps with the target one in any extent, under the collision channel model. A packet collision is considered destructive always under the collision channel model.

4.2 Capture Channel Model

The capture channel model assumes that collision of the target packet with one or more interfering packets does not necessarily affect the packet. The receiver can detect preambles of all the arriving packets and are able to extract necessary control data. This statement is justified only if, probability of two time-frequency aligned packets is very small at the receiver end. The test packet detection success after synchronization completely depends on total interference from partially colliding packets. SIC technique helps both packet synchronization and PER performance improvement. On the other hand, using low-rate FEC improves PER performance greatly. [20].

4.3 TFAA Throughput Analysis under Capture Channel Model

In the TFAA random-access scheme, packet transmissions are not being coordinated either in time or in frequency domain. The capture channel model increases the probability of successful detection, and this effect can be enhanced by effective feed-forward error control coding (FEC) and/or advanced receiver signal processing, like successive interference cancellation (SIC). Furthermore, these benefits can be expected to be increased in TFAA schemes because the number of alternative transmission instances is greatly increased without increasing the frame size in time and frequency beyond practical limits. Keeping the collision effect in mind, TFAA performance evaluation is needed. Two models, collision model and capture channel model are considered by Almonacid and Franck[18]. Using semi-analytical process, the throughput for capture channel mode is derived whereas throughput for collision channel model is obtained through a closed-form analytical model. To improve TFAA performance, a low-rate FEC can be deployed for TFAA performance improvement [18]. A very basic low-rate coding scheme is repetition coding, i.e., transmitting the same data packet multiple times in non-overlapping positions in time-frequency domain. This scheme is adopted for our study below.

Under the capture channel model, TFAA throughput performance is analysed by transmitting all the packets using BPSK (binary phase shift keying) and SRRC (square-root-raised-cosine) pulse shaping. A conventional filter architecture (single user) is followed by the receiver and the focus is on the test packet reception. The interference is varied depending on the time and frequency overlaps of the colliding packets which have random time and frequency offsets in with respect to the test packet. Every packet is characterized by its arrival time, transmission frequency, amplitude, and initial phase, which are all randomized parameters and independent for each packet. Within the transmission time of the packet, packet amplitude remains constant and independent [20].

In the capture channel model, the receiver is assumed to have the capability to synchronize to all the arriving packets. Probability of two packets being aligned completely in the time-frequency is very small at the receiver end. The test packet detection success depends on total interference which comes from the interfering packets that are collided partially after synchronization. Successive interference cancellation (SIC) techniques improve the packet error rate (PER) performance and help also in packet synchronization. Additional performance improvements of PER and throughput can be obtained using low-rate FEC , both with and without the SIC element [18][20].

5. CR-TFAA SYSTEM MODEL

The high PER problem has been examined in [18] by Almonacid & Franck that offers a protocol named 'Contention Resolution Time and Frequency Asynchronous ALOHA (CR-TFAA)' for high throughput random access LPWAN networks. This is an advanced and modified version of TFAA, and it works by applying diversity by making multiple copies of a packet and transmitting them in different time and frequency locations randomly. PER issue and its mitigation to reach higher throughput has also been addressed by another protocol named Asynchronous Contention Resolution ALOHA (ACRDA) [18] and it has been compared with the performance of CR-TFAA. Increasing the throughput, like doubling it, is possible by using these post-ALOHA protocols which makes these protocols preferable for systems like mobile and satellite networks [18]. Employing CR-TFAA in UNB LPWANs enhances performance and offers an interesting alternative to spread spectrum techniques. Integrating SIC techniques into TFAA and transmitting packets randomly in both time and frequency results in the CR-TFAA protocol, which offers improved and enhanced performance for UNB LPWANs through diversity scheme [18].

5.1 Simulation Based Analysis

In this thesis, a throughput analysis study of a two-dimensional random-access scheme has been done using a MATLAB code for simulation. The main parameters include the interference threshold, propagation exponent of the wireless channel, distance range of the IoT devices, and the system load. Normalized throughput and collision probability were evaluated through simulations for different combinations of these parameters.

The overall packet arrival rate is λ packets/s. Available total system bandwidth is denoted as W whereas the fixed packet duration is T_p and its bandwidth is B. For an UNB signal, the packet bandwidth B is much smaller than system bandwidth W. Each packet is carrying payload of L_b information bits. The offered traffic, i.e., total packet arrival number with packet duration T_p, over system bandwidth W can be given as $G_a=\lambda T_p$. G_a is usually greater than 1 since TFAA allows many packet transmissions and decoding simultaneously. Hence, normalized throughput can be determined as

$$T(G) \triangleq G \times (1-P_e), \tag{2}$$

Here the normalized average channel load is $G=G_a \times B/W$ and PER is P_e. Over a packet bandwidth B, the average offered traffic is represented by G.

Framework introduced in [23] for ACRDA, organizes packet transmissions in virtual frames (VF). Having N_{slots} as time slots per frame, $TF=N_{slots} \times T_p$ is the duration for a VF. At the MAC unit when a new packet has been generated, N_{rep} packet replicas as well as a new VF are generated. The packets are placed at random time slots and random carrier frequencies within the VF, also keeping in mind that packet replicas do not overlap each other. It is also assumed that the replicas' energy is fully held within a bandwidth B. The system spectrum is centered at f=0 and the carrier frequencies must be chosen in the interval $[f_m, f_M]$, where $f_m = -B([W/B]-1)/2$ and $f_M = B([W/B]-1)/2$.

In CR-TFAA the frame size is defined as the number of time-frequency points without overlapping. It can be expressed as $N_{slots} \times N_f=TF/T_p \times W/B$. Each user terminal generates and transmits VFs in an asynchronous manner and hence arrival at the receiver end happens with random time offsets. Main difference of ACRDA and CR-TFAA VF structures is that VF spans much greater bandwidth compared to the packet bandwidth, allowing packet replicas to be transmitted freely within the system bandwidth W. Having $N_{rep}=2$, W/B=10 and $N_{slots}=5$ an example is shown in figure 8 where four different users' transmissions are shown.

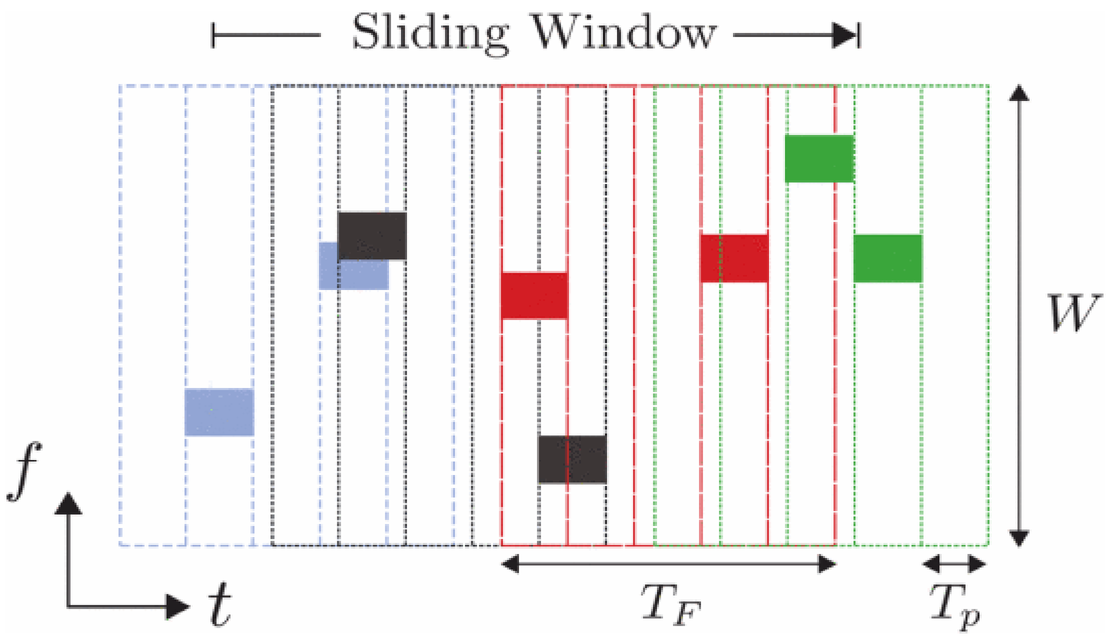

Figure 8. *CR-TFAA frame structure. Four different colours represent four different users.*

The SIC-based CR-TFAA scheme of [23] assumes that each replica has the information about the other N_{rep-1} replicas' relative positions in extra few bits along with payload bits

L_b. In the adopted diversity scheme, the frequency axis is not divided in any slots since the use of frequency slots requires frequency synchronization and very good oscillator stability which is difficult to achieve in simple IoT devices.

Sliding window approach is used for sampling the incoming signal at the receiver side [23]. The sliding window extends over WVF VFs having a step size of ΔWVF which is expressed as fraction of one VF. For detecting the replica presence, the SIC process scans sliding window samples over W. After locating a replica correctly, it is demodulated by a filter detector and then turbo decoded. From sliding window buffer, interference contribution is removed after successful decoding of one replica. Other replicas' interference on colliding other users' packets are removed from the sliding window after that. The SIC process is repeated up to Nit iterations. During the iterations, the packets of all or most of the different user's data packets are decoded successfully. After that, the sliding window is shifted by ΔWVFTF seconds and the process is repeated.

6. SIMULATION BASED TFAA ANALYSIS

Experimental throughput study of a two-dimensional random access is done in this chapter. For the simulation of time and frequency asynchronous ALOHA (TFAA), a MATLAB code is generated and analysed. The main parameters include the interference threshold, propagation exponent, distance range of the IoT devices, and system load. Normalized throughput and collision probability are evaluated through simulations for different combination of these parameters.

CR-TFAA protocol model explained by Almonacid & Franck differs a lot from TFAA analysis presented here both regarding the system model and scenarios. No power control is assumed in the analysis of TFAA here and there are big variations in the power levels of the target packets and interfering packets, whereas CR-TFAA model assumes very good power control for the uplink signals. A simpler scheme for implementation is considered in the analysis here assuming maximum ratio combining (MRC) of the repeated packets while all packet repetitions from a device are assumed to be received at the same power level. CR-TFAA makes use of a cleaver (and rather complicated) successive interference cancellation (SIC) scheme, including also physical layer simulations and error-control coding, as well as receiver process to synchronize to the received packets.

6.1 Analysis process

Parameters for this study are given and defined below.

6.1.1 Load

The channel load is defined by the ratio of active device number or transmitted packet number within a virtual frame to the maximum number of transmitted packets without collision, T/T_p x W/B.

6.1.2 Throughput

At the receiver end, product of the transmission rate and success probability of a scheme is defined as throughput. Normalized throughput is evaluated by dividing evaluated throughput by the throughput of the ideal orthogonal transmission scheme supporting T/Tp x W/B packets per frame without collisions.

6.1.3 Collision

Transmission of data packets are done randomly with uniform distribution over the virtual frame, leading collisions between different users' transmitted data. If the interference threshold is not exceeded, the collisions with other users' packets are not considered harmful. The probability of successful transmission of data is increased within low SINR threshold.

6.1.4 Interference threshold

Interference threshold is a parameter which defines the assumed robustness of the demodulation and decoding scheme, in terms of the minimum signal-to-interference-plus-noise ratio (SINR) allowing enough detection. The relative interference power produced by a colliding packet in terms of time and frequency offset between the packets is evaluated using a separate physical layer simulator. The TFAA simulator obtains this information from a table containing 100 different offset values in both dimensions. All colliding packets' powers are combined when calculating the SINR. The received signal powers depend on the path losses of the target and interfering signals. For simplicity, the transmission powers of all devices are assumed to be equal.

6.1.5 Propagation exponent

Path loss exponent or propagation exponent is defined by the ratio of transmission power and received power as a function of the transmission distance. The propagation exponent is 2 in free-space, and in urban areas typically 4 or more.

6.1.6 Distance range

Different packets have variation in power levels at the access point and the throughput depends on this. One user's strong packet can prevent detecting the target users' weak packet even when having slight overlap of the packets. Variation in power depends on propagation exponent and distance. In order to avoid excessive differences in received power levels, we assume that the distances of all devices from the access point are limited to a certain range, defined by the shortest and longest distance.

6.2 Code explanation

Initialization of various constants are done at the beginning of the code such as symbol interval which is set 0.01 having unit in seconds (here symbol interval corresponds to symbol rate of 100 Hz), length of packet is considered to be 100 symbols, length of packet tail is 2 symbols, time window length is set to 10000 symbols, signal bandwidth is considered 200 Hz, the total channel bandwidth is set to 10000 Hz. Since theoretically the minimum frequency distance needed for transmitting orthogonal packets simultaneously is 100 Hz, so 10000 is the maximum number of non-colliding packets. The minimum distance from access point is set to 100 m and the maximum distance is 300 m or 1000 m in different simulations. A loop starting from 500 and ending at 10000 having an increment of 500 denotes the selection of device number and full load is represented by the last value obtained using the loop.

We assume uniform 2-dimensional geographical distribution of the IoT devices within the ring-shaped region defined by the minimum and maximum distances. Results are gathered taking the average over 10000 simulation instances which are independent for getting relatively smooth output plots. A separate waveform simulation is used for obtaining the normalized interference power which is caused because of packet overlapping and the interference powers are then stored in a matrix. The matrix row and column correspond to the time and frequency distances among the colliding packets, and in the matrix the interference values correspond to the scenario where at the receiver the target signal and the interfering signal have the same power level. Selection of each active device is done randomly having an assumption of uniform distribution within the used distance range for each simulation instance. Having uniform distribution within transmission time interval and frequency band, each packet's timing and frequency are also selected randomly. Based on the pathloss model mentioned above, each packet's power levels at the access point is evaluated. The first packet and its replicas are considered as the target one and from all the other packets the total interference is calculated. If there is a possibility of interference for any of the target replicas, first it is checked whether it is overlapping the target one. In case there happens an overlap, from interference matrix the normalized interference value is obtained first and after that it is scaled by the ratio of the interfering signal and the target signal for obtaining actual interference power. The resulting interference powers are accumulated independently for each target replica. Then the overall SINR is calculated using the MRC principle. If the interference threshold is exceeded during the accumulation, it is decided that the target packet transmission is lost and for the ongoing simulation instance the process can be stopped.

Two different interference power thresholds, 0.25 and 1, are considered, corresponding to minimum SINR values of 6 dB and 0 dB, respectively. In the simulation, the propagation exponents of 2 and 4 are used. We consider 1, 2, and 4 number of repetitions for the simulation process.

6.3 Results having 100-300 m distance range from access point

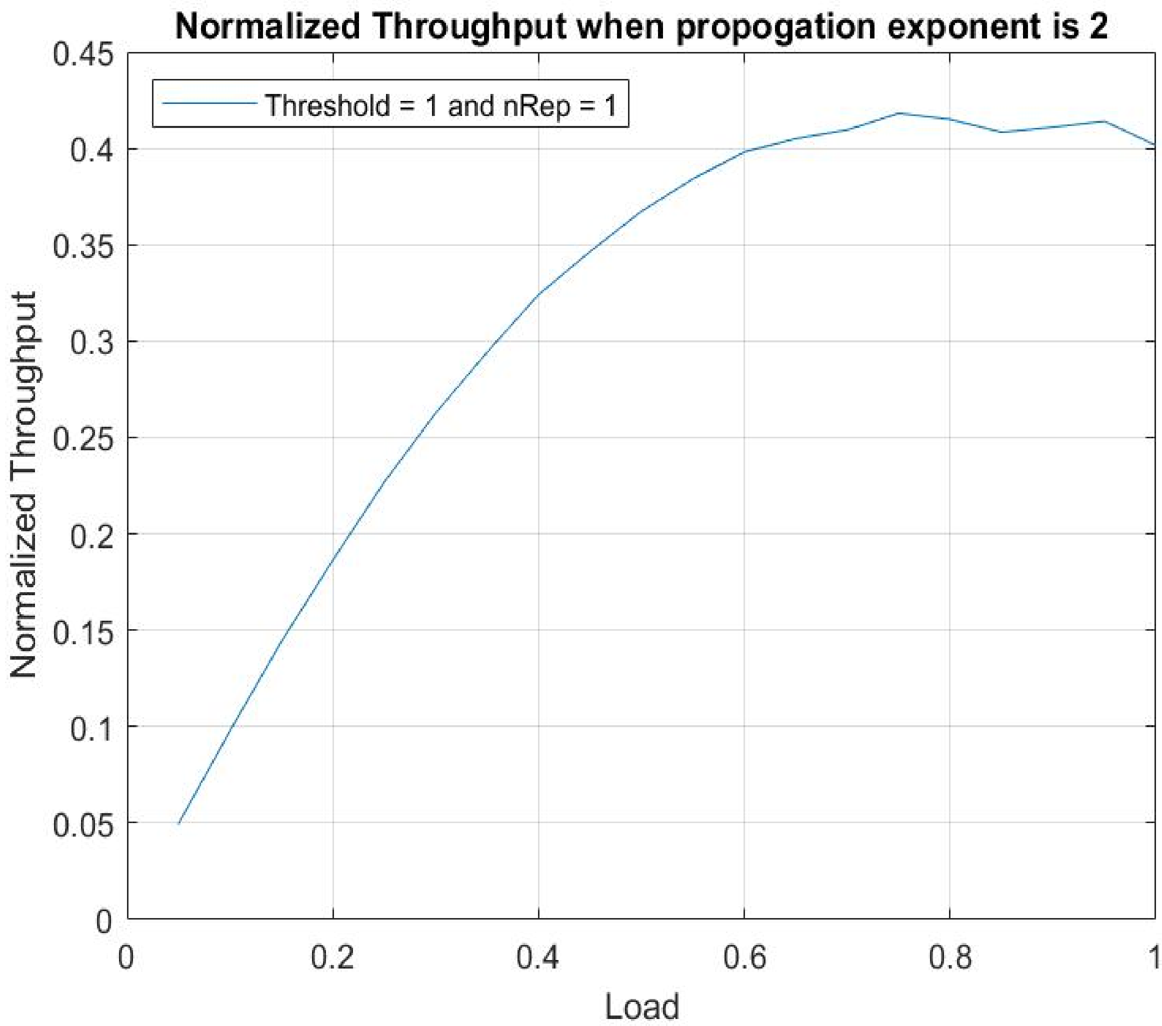

Figure 9. Normalized throughput with repetition factor 1, propagation exponent 2 and 100-300 m distance ranges from access point.

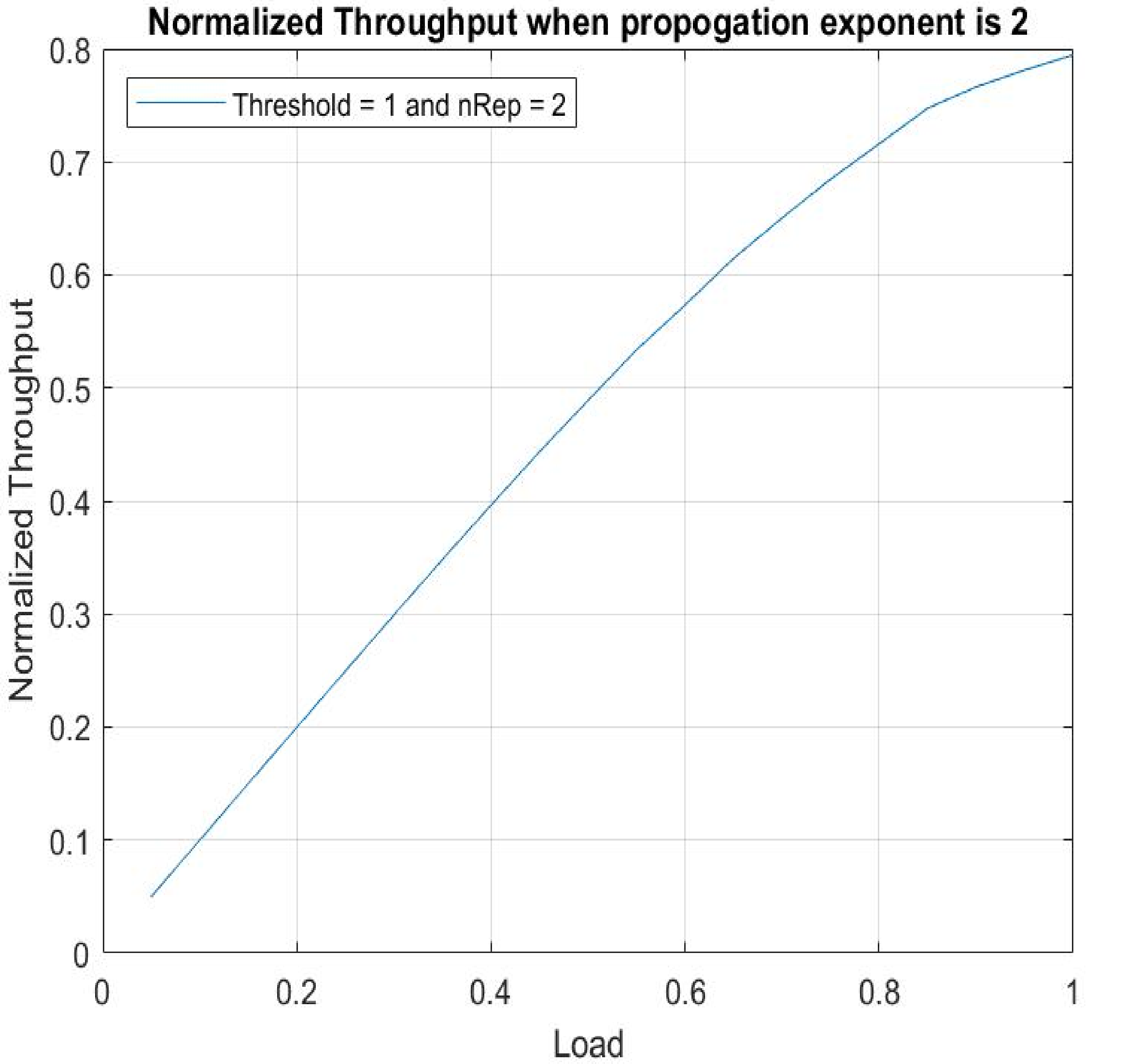

Figure 10. Normalized throughput with repetition factor 2, propagation exponent 2 and 100-300 m distance ranges from access point.

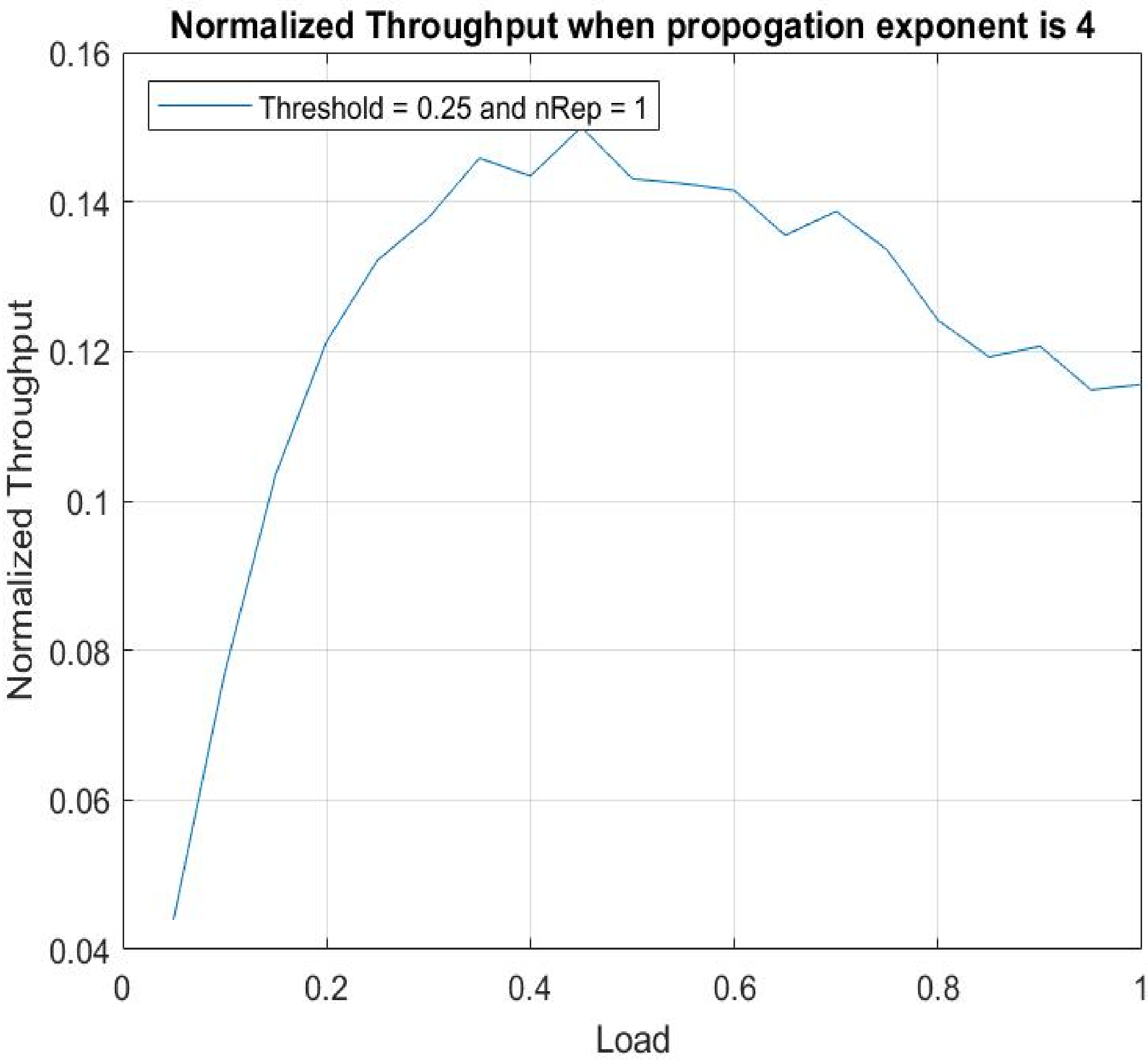

Figure 11. Normalized throughput with repetition factor 1, propagation exponent 4 and 100-300 m distance ranges from access point.

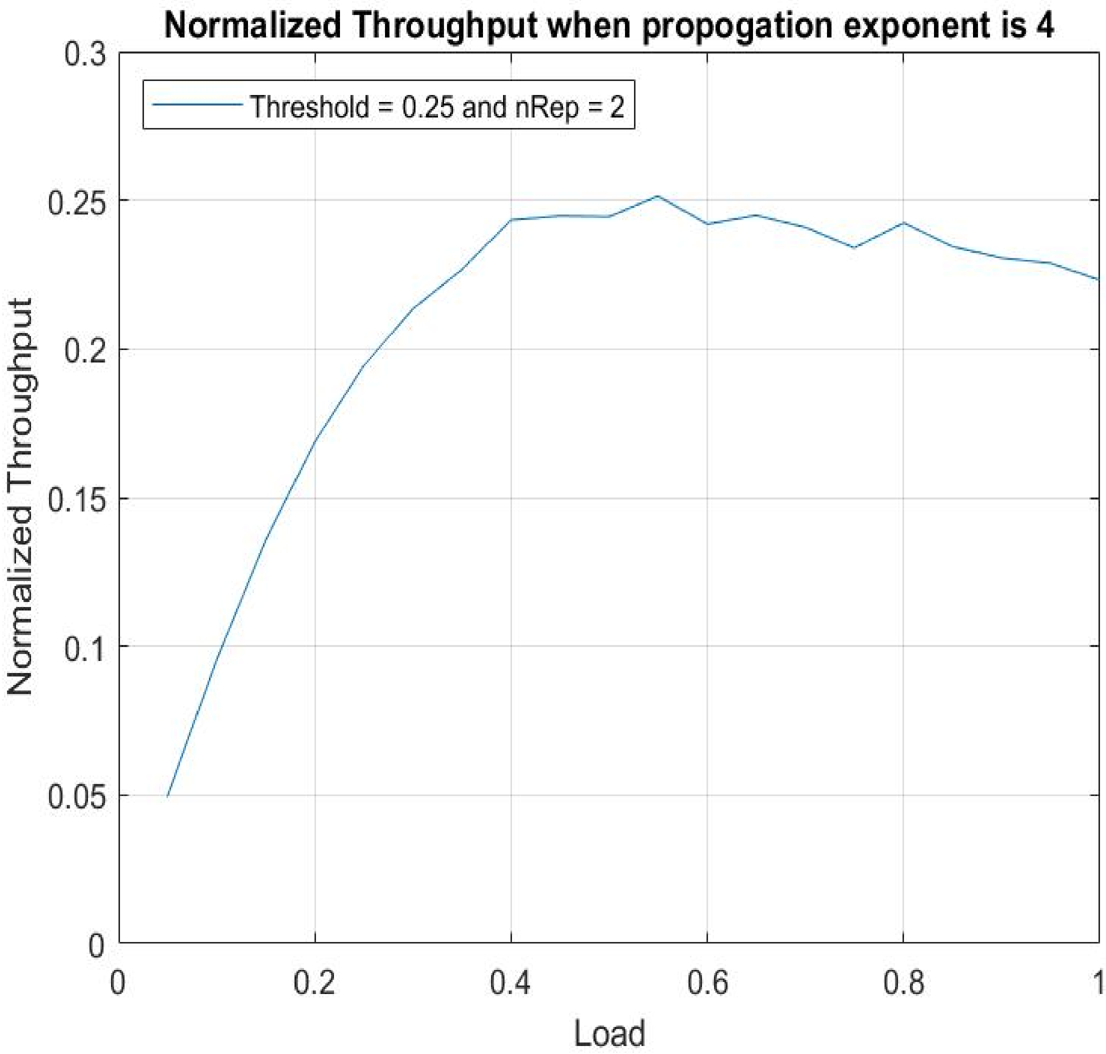

Figure 12. Normalized throughput with repetition factor 2, propagation exponent 4 and 100-300 m distance ranges from access point.

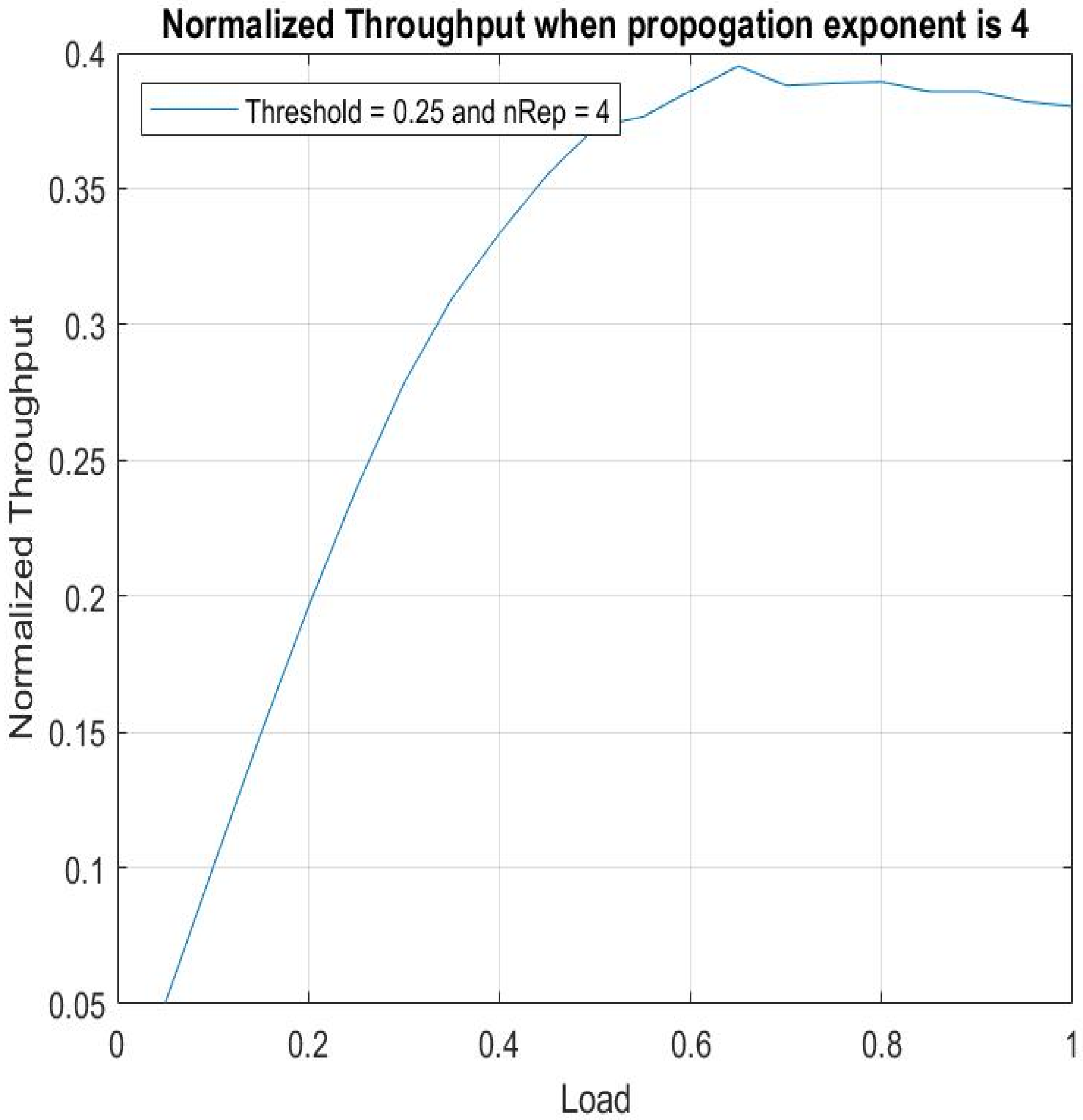

Figure 13. Normalized throughput with repetition factor 4, propagation exponent 4 and 100-300 m distance ranges from access point.

6.4 Results having 100-1000 m distance range from access point

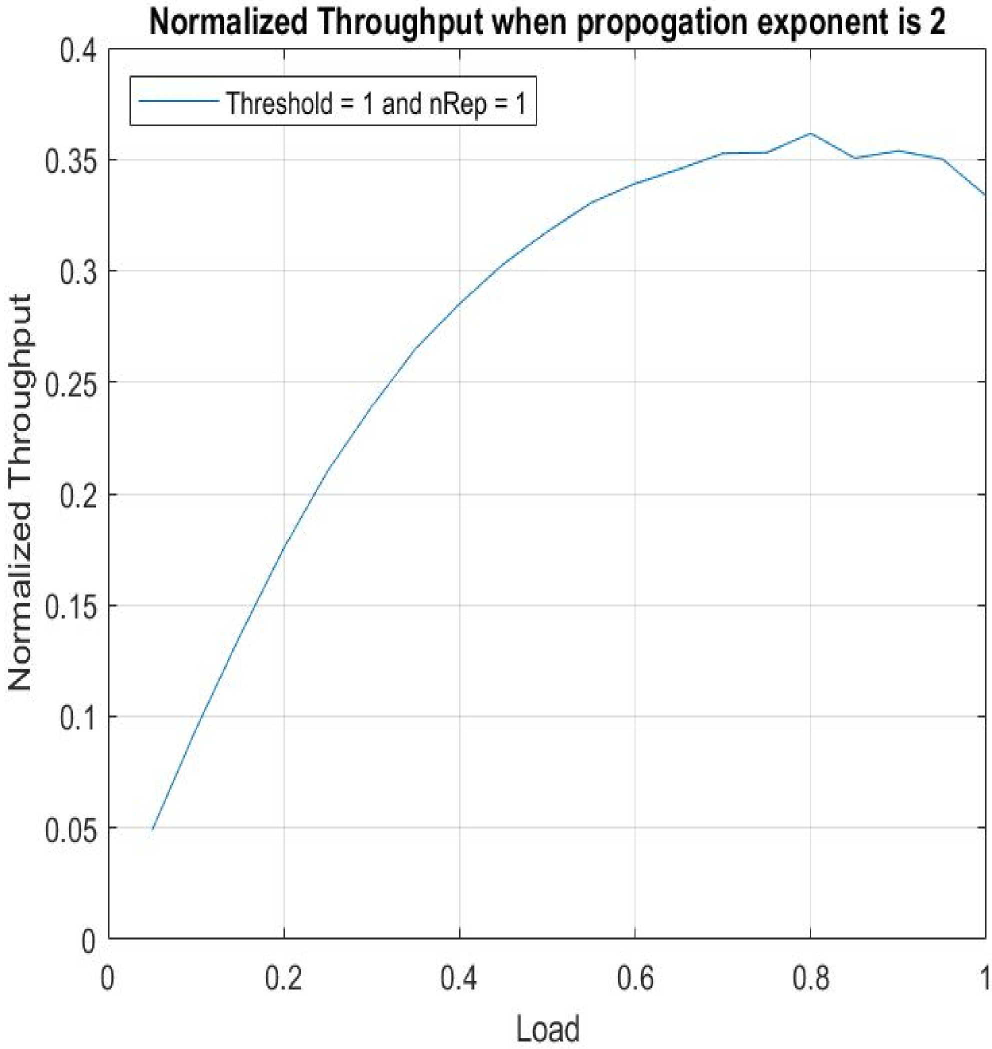

Figure 14. Normalized throughput with repetition factor 1, propagation exponent 2 and 100-1000 m distance ranges from access point.

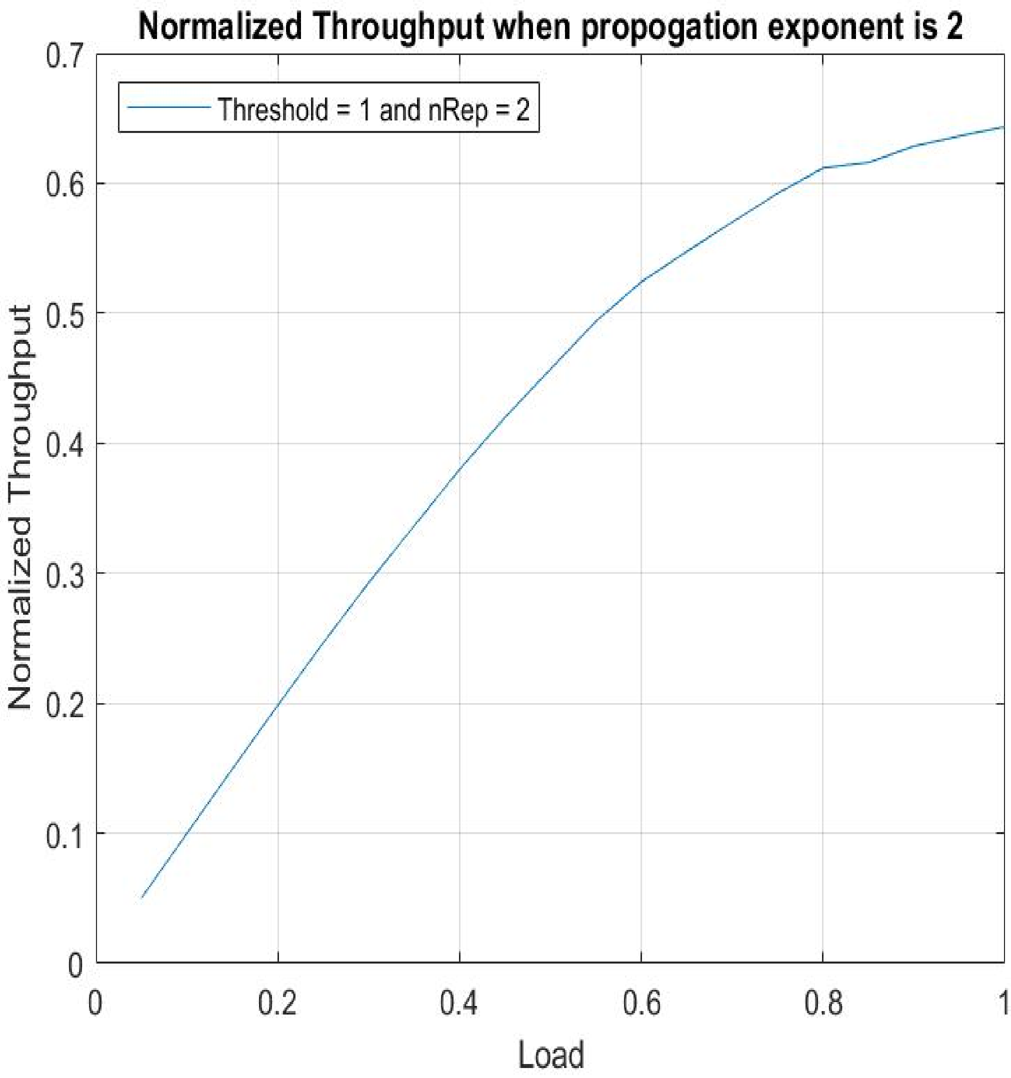

Figure 15. Normalized throughput with repetition factor 2, propagation exponent 2 and 100-1000 m distance ranges from access point.

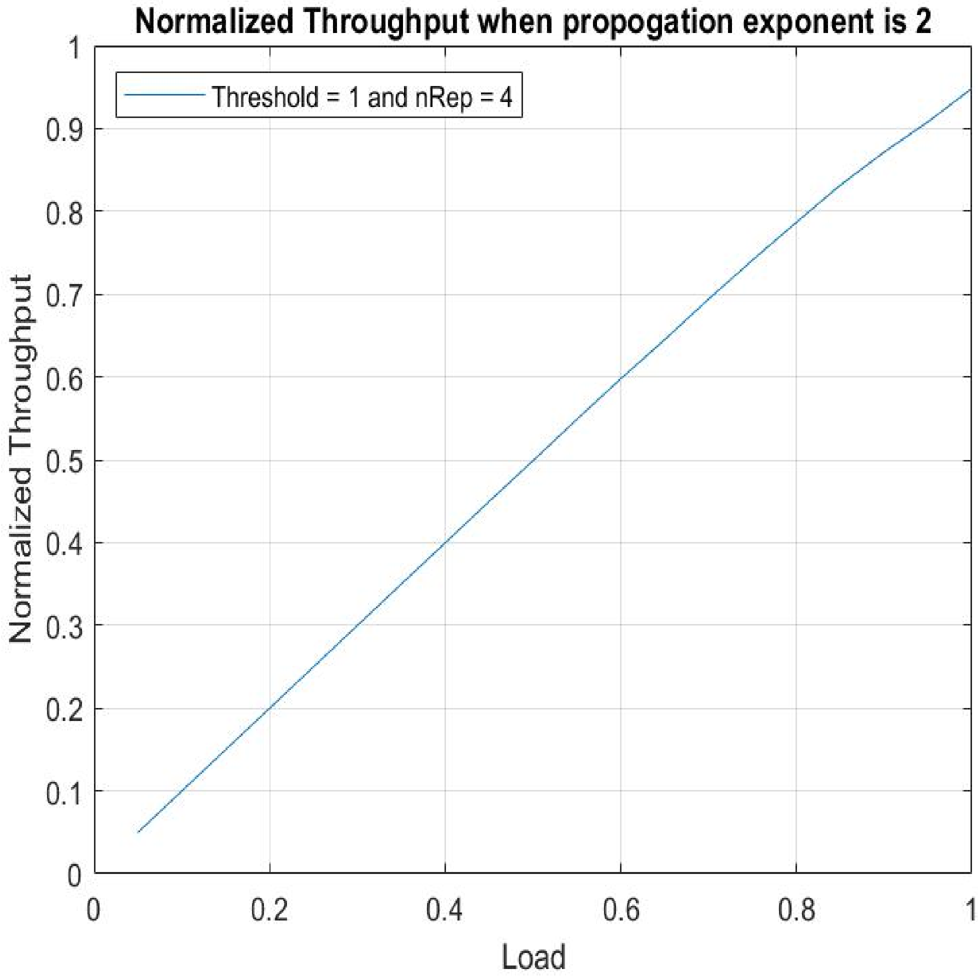

Figure 16. Normalized throughput with repetition factor 4, propagation exponent 2 and 100-1000 m distance ranges from access point.

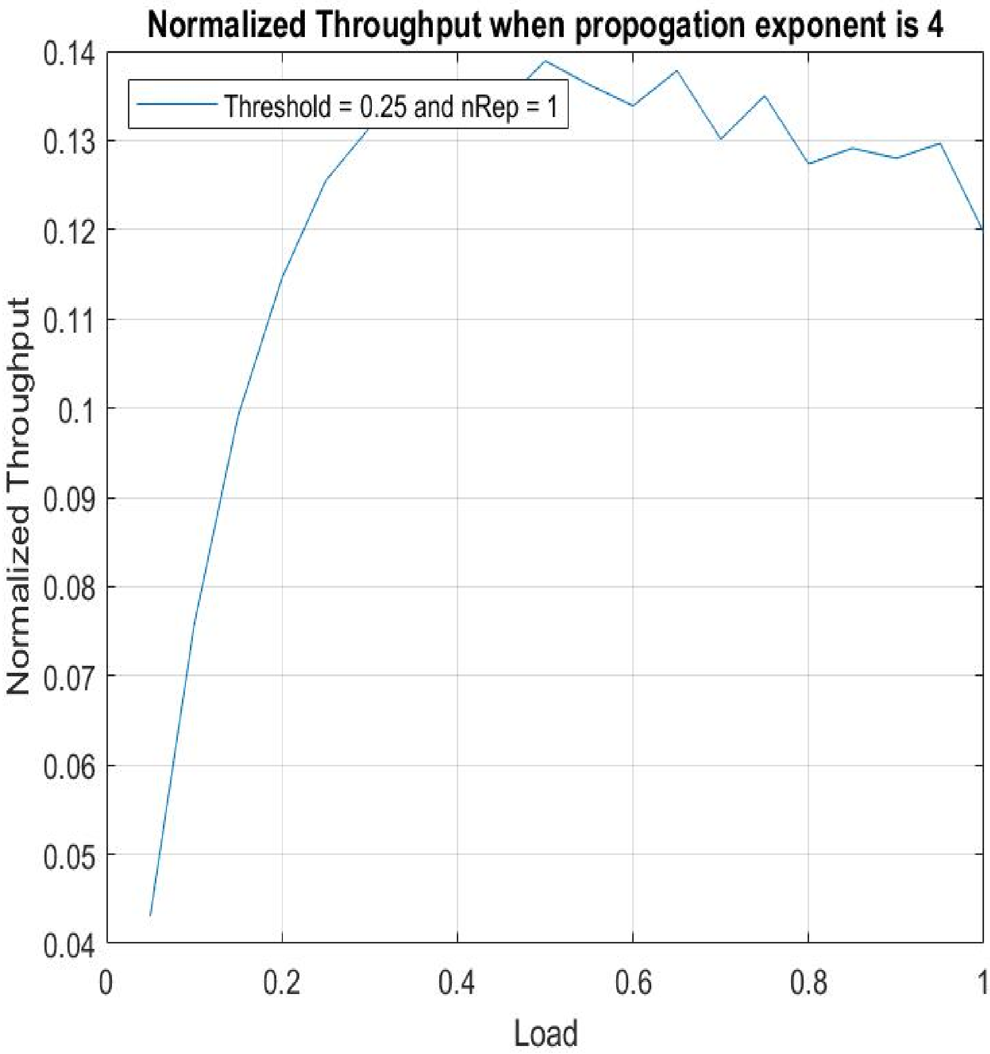

Figure 17. Normalized throughput with repetition factor 1, propagation exponent 4 and 100-1000 m distance ranges from access point.

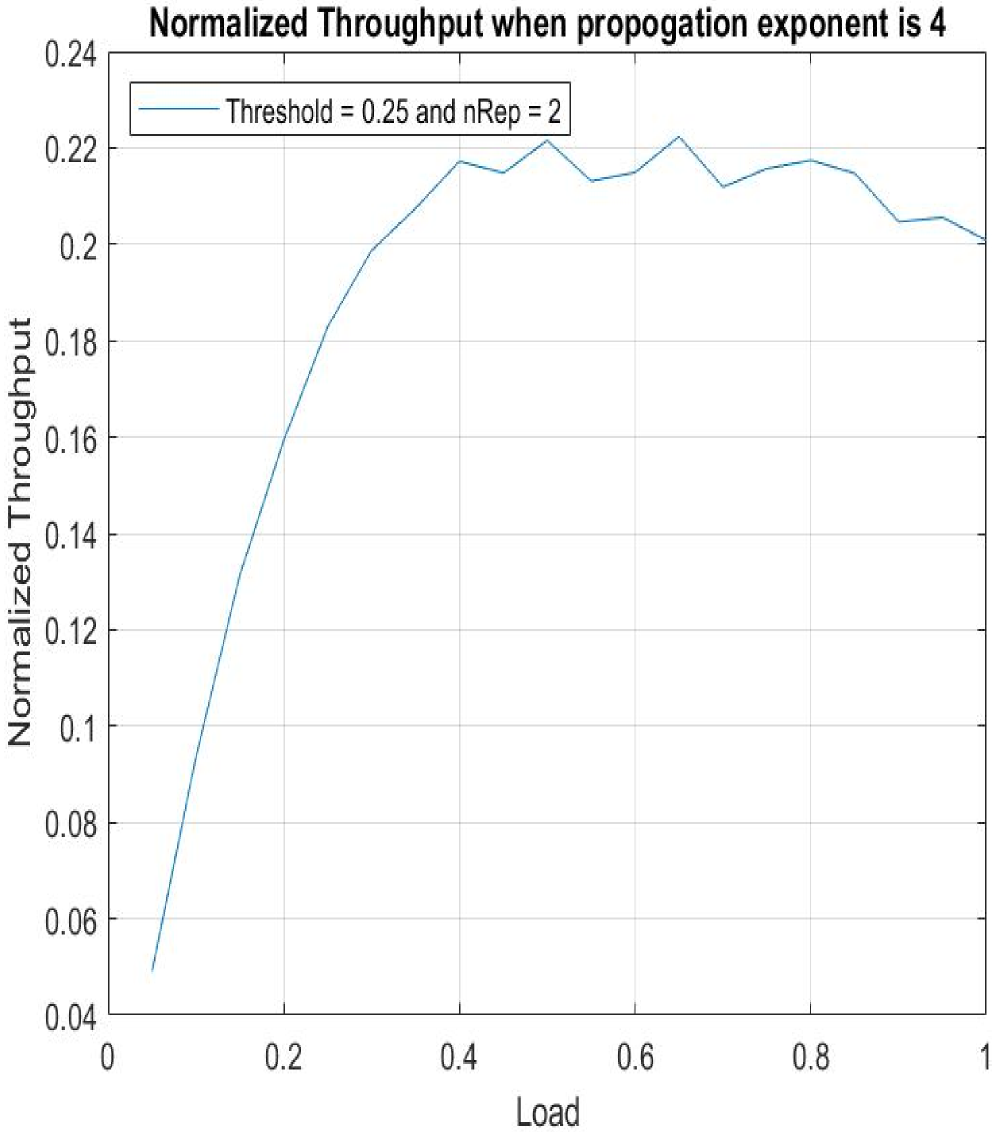

Figure 18. Normalized throughput with repetition factor 2, propagation exponent 4 and 100-1000 m distance ranges from access point.

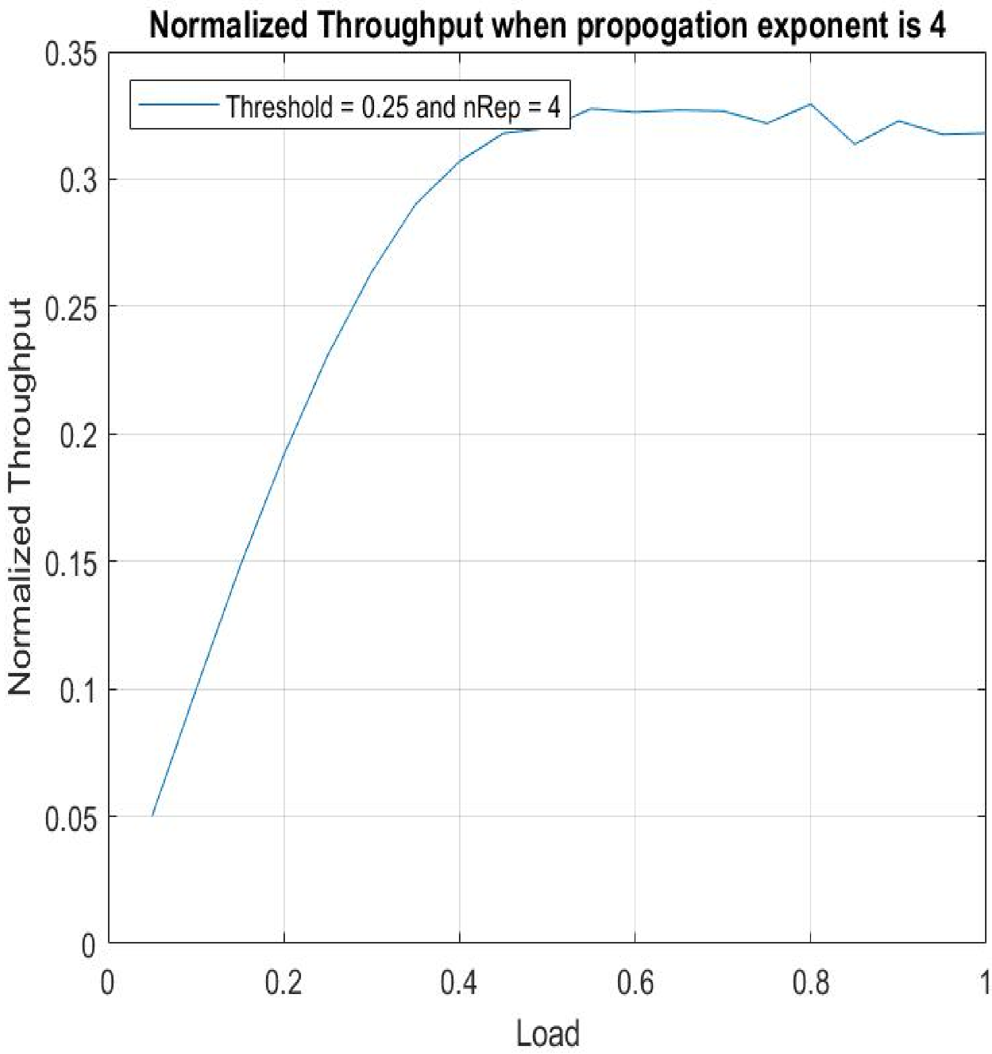

Figure 19. Normalized throughput with repetition factor 4, propagation exponent 4 and 100-1000 m distance ranges from access point.

6.5 Result comparison

Table 4. Normalized throughput for different combinations for 100-300 m distance range.

System load	Repetition	Threshold	Propagation exponent	Normalized throughput
0.4	1	0.25	4	0.15
		1	2	0.32
	2	0.25	4	0.24
		1	2	0.40
	4	0.25	4	0.34
		1	2	0.40
0.8	1	0.25	4	0.13
		1	2	0.42
	2	0.25	4	0.23
		1	2	0.71
	4	0.25	4	0.39
		1	2	0.80

Table 5. Normalized throughput for different combinations for 100-1000 m distance range.

System load	Repetition	Threshold	Propagation exponent	Normalized throughput
0.4	1	0.25	4	0.12
		1	2	0.28
	2	0.25	4	0.21
		1	2	0.39
	4	0.25	4	0.31
		1	2	0.40
0.8	1	0.25	4	0.127
		1	2	0.36
	2	0.25	4	0.218
		1	2	0.61
	4	0.25	4	0.33
		1	2	0.78

6.6 Discussion

The throughput of the system decreases with the increase in the propagation exponent, because the variation of the power levels of different packets at the receiver are increased by it. Increasing the interference threshold increases the normalized throughput because it means more robust modulation and coding scheme tolerating higher interference. So basically, with increase in interference threshold and decrease in the propagation exponent, and repetition factor set to 4 the normalized throughput can be maximized. With threshold set to 1, propagation exponent 2, and n_{rep} 4, the throughput is seen at maximum value of 0.40 for load value 0.4 and 0.80 for load value 0.8 with the distance range 100-300 m and 0.40 for load value 0.4 and 0.78 for load value 0.8 with the distance range 100-1000 m. When the threshold is decreased to the minimum 0.25, the propagation exponent is increased to the maximum value of 4, and n_{rep} is 1, the normalized throughput can be seen to be as low as 0.15 for load value 0.4 and 0.13 for load value 0.8 with the distance range of 100-300 m and 0.12 for load value 0.4 and 0.127 for load value 0.8 with the distance range of 100-1000 m.

7. CONCLUSIONS

The presented thesis work has investigated different aspects of ultra-narrowband (UNB) technologies and its' applications, emphasizing the 2-dimensional ALOHA protocol with two different channel models which are important elements of UNB technology.

The narrow bandwidth of UNB technology involves both benefits and some concerns as well, while considering reachability over large network area with low energy consumption along with minimal cost. But, in terms of connectivity and throughput, it possesses some major constraints. Most importantly, UNB is not suitable for applications requiring higher data rates. Main utility of it lies in M2M applications like smart grid, smart parking system, traffic management, smart meters, waste management and other centrally controlled systems. UNB is beneficial in for application requiring low data rate and in-frequent (sporadic) packet transmissions, e.g., fitness or health tracking, self-monitoring patients, remotely done health management system and many more.

The throughput study carried out in the thesis work indicates that high throughput gain is possible with the robust transmission scheme using packet repetitions, which improves the tolerance to higher interference levels. In this study, throughput is measured by considering successful transmission of packets. It is important to mention that, no power control is assumed in the analysis of TFAA in this thesis work and there are big variations in the power levels of the target packets and interfering packets. Adding packet repetitions increases the success rate of packet transmission, hence providing much improved normalized throughput. Also, higher interference threshold value (i.e., lower SINR threshold) leads to a higher successful packet transmission probability. This corresponds to robust modulation and coding scheme, which provides smaller data rate per packet compared with transmission schemes which require higher SINR value.

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