Optimal QoS Provisioning For Narrow Band IoT Devices Using Machine Learning

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CERTIFICATE

We accept the work contained in this report as a confirmation to the required standard for the partial fulfilment of the degree of MS(EE).

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DEDICATION

This work is dedicated to my parents, siblings, supervisor Dr. Saleem Aslam, friends and everybody who guided me to continue education and strive for knowledge and excellence.

DECLARATION OF AUTHORSHIP

I hereby declare that content of this thesis is my own work and that it is the result of work done during the period of registration. To the best of my knowledge, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgment has been made in the text.

(Student Signature)

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ABSTRACT

With the prediction of thousands of IoT devices within a single cell in the future, it is the need of the hour to come up with solutions to mitigate the expected problems among these devices. The competition to acquire up and downlink channels for operations would become intense for these large numbers of devices as 3GPP approved NB-IoT bandwidth for long-range communication is only 200khz with a subcarrier spacing of 15khz. In addition, the competition would also contribute to the problems of lower data rate, decrease devices battery lives and disrupt continuity for devices that require continuous communication. The thesis study focuses on introducing device to device connection among IoT devices which would help save the battery life of the devices. The new connections made among the devices will utilize lower power as the algorithm designed focuses on ideal potential pairing devices with least bit error rate, least distance, and lowest transmission power. The results show the supremacy of the proposed solution which can be used to reduce the interference among device to device IoT network in addition, to the power saving capability. Deployment of the proposed cognitive power-based device to device pairing solution can help reduce the power consumed by the IoT network which can be put in the network security algorithms to make the IoT network communication more secure. Moreover, machine learning is deployed to further speed up the device to device link formation between IoT devices after the initial set of training data is produced and processed at the operator end.

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ABBREVIATIONS

NB-IoT	Narrow Band Internet of Things
3GPP	3rd Generation Partnership Project
BER	Bit Error Rate
PDR	Packet Delivery Ratio
RSSI	Received Signal Strength Indicator
BW	Bandwidth
eNB	enhanced Node B
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GPS	Global Positioning System
WLAN	Wireless Local Area Network
LPWAN	Low-Power Wide-Area Network
LTE	Long Term Evolution
LTE-M	LTE for Machine-type Communication
IoT	internet of Things
WAN	Wireless Area Network
PAN	Personal Area Network
MAN	Metropolitan Area Network
ISM	Industrial, Scientific and Medical
mm-wave	Millimetre Wave
Tx	Transmitter
Rx	Receiver
UnB	Ultra narrow Band
UWB	Ultra-Wide Band
3GPP	3rd Generation Partnership Project
D2D	Device to Device
V2V	Vehicle to Vehicle
M2M	Machine to Machine
LPWAN	Low Power Wide Area Network

RF	Radio Frequency
UHF	Ultra-High Frequency
FDD	Frequency Division Duplexing
TDD	Time Division Duplexing
LoRa	Long Range
WiFi	Wireless Fidelity
eMTC	Enhanced Machine Type Communication
SINR	Signal-to-Interference-plus-Noise Ratio
SNR	Signal-to-Noise Ratio
QoS	Quality of Service
PSM	Power Saving Mode
PRB	Physical Resource Block
NF	Noise Figure
mMTC	Massive Machine Type Communications

Chapter 1

Introduction

CHAPTER 1. INTRODUCTION

1.1. Brief Introduction of Internet of Things

The Internet has brought the world together. After the initial boom of the world wide web, VoIP and multimedia content internet has transferred to our everyday utilities. Now a home can have the internet on its Television, Refrigerator, Air Conditioner, LED Bulbs, Doors, Sound System. The industry can have internet deployed in the production assembly line. Each manufacturing module can have a series of sensors collecting data sending it to the central processing unit wirelessly [1]. Villages can have internet smart devices that can monitor the soil quality, water level, pests and other important aspects to promote productivity.

The internet is now transferred to small things that have increased the human control on activities that were analyzed after an event has taken place. Now someone at home can set up the whole security system wireless connection to a mobile app. Measure the performance of electrical appliances such as Television, Air conditioners etc and takes corrective steps to optimize the condition of the home ecosystem [2]. Similarly, the data generated by an oil rig sensors can help evaluate what is the most optimized way to approach maximum productivity [3]. In the crops, a malnutritional soil patch or an area with low water can be quickly corrected thanks to the sensors that can detect the problems and report to the human user [4].

The internet is now transferred to things hence it is called the Internet of Things. Just like all wireless communication all IoT devices need means for communication. One of them is them is the wireless medium they can communicate with [5]. Because IoT devices' growth has seen a recent rapid boom there was initial confusion on what communication technology these devices will use to connect with each other, central processing unit and most importantly to the user [6].

After detailed analysis, it was found out that IoT devices' communication technology is dependent on the distance [7]. Some devices are far away while the others are near. So there is a classification of Short Range IoT devices and Long Range IoT devices. Devices working within a 100-meter range of communication are classified as short-range while devices spread out in a wider area typically under 15Km are associated with long-range communication [8].

Initially, it was thought to connect home-based IoT devices with WiFi [9]. But a typical router has only 7 access points and to include a large number of devices around 40 for an average household WiFi is not the solution. Therefore, the use of Bluetooth evolved, Z Wave and ZigBee were proposed to allow a large number of devices to communicate with each other. So there would be a network of devices operating in different modes of communication for short-range communication in an unlicensed spectrum [10].

For long-range communication, many communication technologies came under consideration like the unlicensed spectrum of Lora, SIGFOX, INGENU, Weightless P and LTE-M, ECGSM-IoT, Nb-IoT for long-range communication [8]. Many start-ups began offering long-range communication using the above communication technologies but the problem was apparent, new hardware would have to be deployed to support the IoT devices [11]. IoT devices are on the surge, new hardware installation would increase the initial deployment cost and push away the realization of the internet of things. Therefore, 3GPP standardized Narrowband IoT as one of the three licensed mode of communication for IoT devices.

Nb-IoT can work on the existing infrastructure of the LTE and GSM. It can either have stand-alone, in-band, or guard band spectrum allotted to do its operation. There would be only 12 subcarriers each of 15Khz with a total bandwidth of 180 kHz. This, however, looks very small to support a large number of devices to support in an IoT Cellular structure. When all devices will be competing to get a channel and there will be unavailability to transmit data it can cause problems in data transfer. Moreover, due to the low number of channels, there will be inter and intra channel interference.

The purpose of this research is to maximize the potential of Nb-IoT. The research is based on using the concept of D2D mode in IoT devices to form a chained network that would relay information to the base station. Devices will cooperate with each other in sharing the best possible transmission power to transfer the data in the least power consuming way. It will increase the IoT devices' battery life and reduce interference.

1.2. Motivation

IoT devices network needs a comprehensive solution that would enable a massive number of devices above 50 thousand to interconnect with each other, transmit data to the base station and perform the intended functions. Nb-IoT because of the existing infrastructure of the LTE and GSM is promising to provide long-range communication of IoT devices. However, the repeated transmission at 23dbm for IoT devices can drain the battery quicker because of their inability to reach the base station under interference influence.

Although according to 3GPP the batteries are intended to last for 10 years but increased number of repeated transmissions can make hamper the fundamental goals of communication networks which are to operate a network with large capacity with optimized power consumption. The higher number of repeated transmissions in addition to increased transmission power can also increase the interference among the neighboring cells. Furthermore, IoT devices can attain a communication channel for a longer time and increase the queue time for the waiting IoT devices.

For deep indoor devices that are unable to communicate with the base station as a result such devices would quickly drain out their batteries because of repeated transmissions. If proper planning is not done, such network will have many IoT nodes that would be counterproductive not only they would not be able to communicate with the base station but also increase difficulties for the other devices in the network by increase the interference and causing latency issues for devices which are intended to do time-sensitive communication.

1.3. Objectives

The focus of this dissertation is to present a mathematical model which would help improve the quality of service parameters set by third-generation partnership project for IoT devices by:

1) Allowing the devices to form device to device pairs based on the least bit error rate which would help in identifying the potential relay nodes through which data can be transmitted with minimum corrective measures.

2) By identifying the potential relay devices with the least BER, allow the D2D pair to lower down their transmission power maintaining the acceptable bit error rate with the connecting potential relay device.

3) The D2D network formed will lower the overall interference of the network and save power to increase the longevity of the IoT devices.

1.4. Contribution

The output of this research presents mathematical modeling for finding potential device to device relay connection. The model helps in saving power for the IoT devices for an NB-IoT network by forming D2D pairs based on minimum distance, minimum bit error rate and lowest distance.

1.5. Dissertation Structure

The dissertation is divided into five chapters

Chapter 1 is to give a brief overview of the internet of things devices, the motivation behind the research, the set objectives for the problems discussed and finally the contribution of the research completed.

Chapter 2 discusses what are different wireless technologies that can be used for communication for the IoT network in detail. The intercomparison of different technologies help form the theoretical base which leads to the answer why narrowband IoT is chosen as the candidate for the mathematical modeling to form device to devise pairs.

Chapter 3 shows the mathematical model which will help form the device to device pairs based on the least distance, least BER and least transmitted power. This section is the theoretical model for designing an IoT network with the potential to save transmission power.

Chapter 4 discusses the simulation results for the proposed mathematical model and explains the results in line with the mathematical predictions. It also compares the impact of the increase in the number of devices on the performance of any IoT network.

Chapter 5 concludes with the implications of the dissertation and the potential future work that could be done to improve the overall IoT network performance in terms of the effect of the number of repeated transmissions, power management and security of the IoT network.

Chapter 2

Wireless Technologies for Internet of things

CHAPTER 2. WIRELESS TECHNOLOGIES FOR INTERNET OF THINGS

The main focus of this chapter is to discuss different wireless technologies both in licensed and unlicensed spectrum, compare them with each other and discuss their pros and cons. The sections lay the foundations of why we have categorized wireless technologies in terms of distance, how an increase in distance influences the transmission of these technologies and why there are different wireless technologies to do IoT wireless communication. Lastly, this section concludes by explaining why Narrowband IoT is prioritized and is chosen for this research.

2.1. Short Range Wireless Communication Technologies

There are four major short-range wireless communication technologies used for the internet of things communication. These technologies are Bluetooth, Wi-Fi, ZigBee and Z-Wave. By short-range communication it is meant that these technologies can only communicate up to 100 meters from the transmission end to the reception end. Communication beyond this range would require additional conditions that would ensure the communication signal is received and understandable. Although the communication ranges for each technology vary but on average it is understood to not consider effective communication outside the 100-meter range for Bluetooth, Wi-Fi, ZigBee and Z-Wave. This section will discuss each of these techniques in detail with respect to usage for the IoT devices.

2.1.1. Bluetooth

A promising technology used for the internet of things devices for effective distance from 10 centimeters to 10 meters [12] . It is based on the architecture where there is one server that is connected to the application server or the middle platform. All IoT Bluetooth devices are authenticated with the main server and communicate with it to pass on the data to the application servers. The main advantage of Bluetooth is its large capacity because of different hopping techniques used in the frequency usage of the devices the chances for interference becomes relatively lower. However, because the distance is very low for normal mode of power transmission it is often not used for distance larger than 10 meters because of the fact that in order to increase the transmission distance, transmission power has to be increased which would drain out the battery quicker than the normal mode of operation [13].

With an increase in distance and increase power interference would also increase for the parallel IoT devices in close proximity hence, it is preferred to use the Bluetooth within its normal transmission power for distance as much as 10 meters. Although increased power distance can be increased to 100 meters but due to the negative effects mentioned already other wireless technologies are preferred for distances up to 100-meter range [14]. So if the intention is to form a wireless network comprising of devices in proximity as much as 10 meter Bluetooth can be used as the technology for transmission.

The data rate as much as 1 megabyte per second can be achieved with the Bluetooth devices which is very high compare to that of the main research technology of long-range communication discussed in this dissertation [15]. The device to device communication can be also fruitful for Bluetooth IoT devices with this data rate but because of distance Bluetooth finds its application in small size IoT ecosystems.

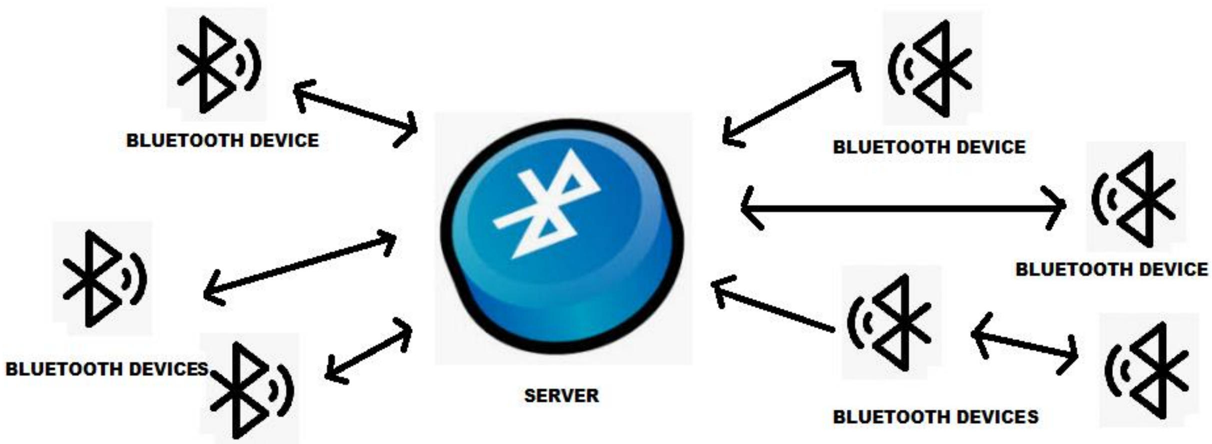

Figure 1: A typical bluetooth IoT network [52]

2.1.2. Wireless Fidelity - Wi-Fi

Wireless Fidelity is one of the most common wireless technology that has been deployed from household to industrial Wi-Fi networks. The main advantage of Wi-Fi is the ability to reach at higher distances as compared to Bluetooth. Both devise however use the 2.4 GHz spectrum however, Wi-Fi can be deployed at 5GHz as well however, the deployment as this frequency range is not as common as the 2.4 GHz requirement [16].

Different data rates can be used based on the kind Wi-Fi version used for example 11b can provide data rate 11 Mb/second, 11g can reach 54 Mb/second, 11n can provide 600 Mb/second while 11ac can achieve data rate as high as 1 Gb/second [17]. The range of Wi-Fi is from 50 to 100 meters which is significantly larger than what Bluetooth can offer however the drawback is the higher power consumption of the Wi-Fi devices [18].

Depending on the application scenarios, a typical IoT Wi-Fi network comprises of the Wi-Fi IoT devices at the terminal ends which are further connected to the mid server commonly known as the Trunk and Hotspot. At this middle spot the data is processed and passed on to the master concentrator which does the remaining processor and passes on the higher-level instructions to the Wi-Fi IoT devices [19].

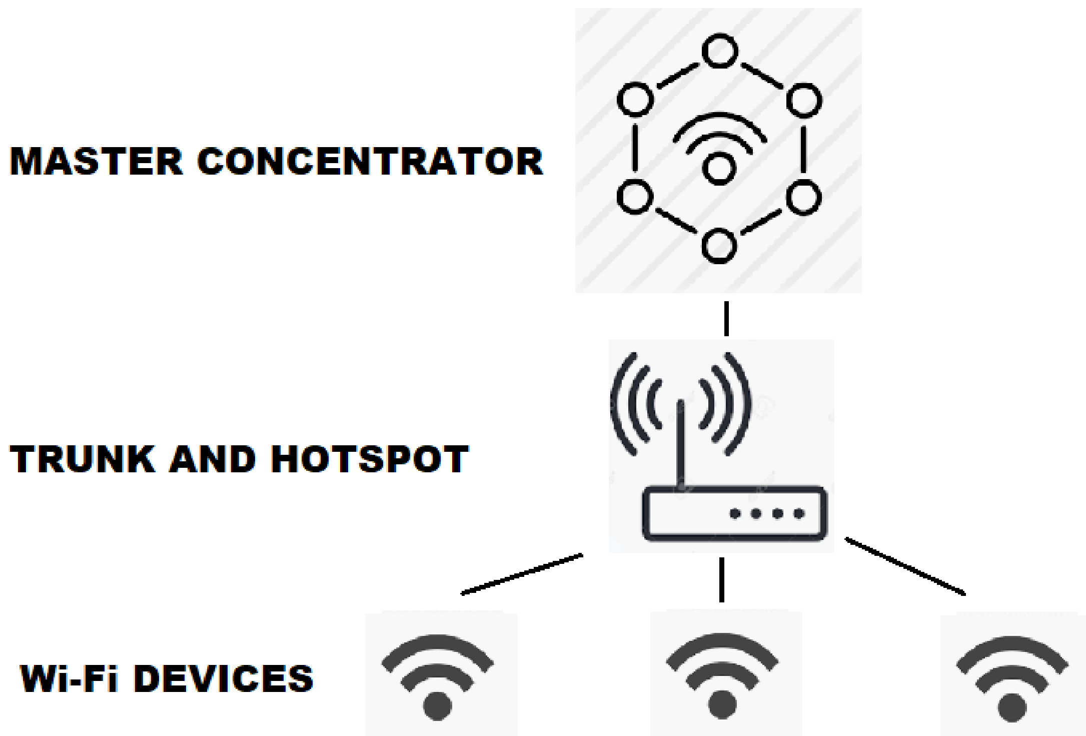

Figure 2: A typical Wi-Fi network [52]

2.1.3. Zigbee

ZigBee is another short-range wireless communication technology that can operate in the range from 10 to 100 meters. It is a cost-effective wireless chip with cost as low as 2 dollars because there is no patent fee associated with the ZigBee. The power consumption of the ZigBee IoT device is also considerably low with two batteries that can operate for 6 to 24 months [20].

The deployment of the ZigBee network is flexible but difficult to maintain because as much as 254 ZigBee devices can be set up in close vicinity of the Master Concentrator. It operates in the grant free frequency spectrum of 915 MHz, 868 MHz and 2.4 GHz with data rates as much as 20 Kb/sec for 868 MHz, 40 Kb/sec for 915 Khz and 250 Kb/sec for 2.4 GHz spectrum [21]. The latency tolerance is from 15-30 milliseconds which is good for devices that are operating for time-sensitive applications.

With a large amount of nodes integration, mesh and ad-hoc networks can be formed with the ZigBee IoT devices. This is also the drawback of ZigBee because of its flexible nature to form IoT networks it also becomes difficult to maintain the ad-hoc networks forming with mobile nodes. Furthermore, compatibility of different chips with each other and the master concentrator vary with the manufacture therefore, it becomes challenging to operate and maintain all ZigBee IoT devise at the same level of service [22].

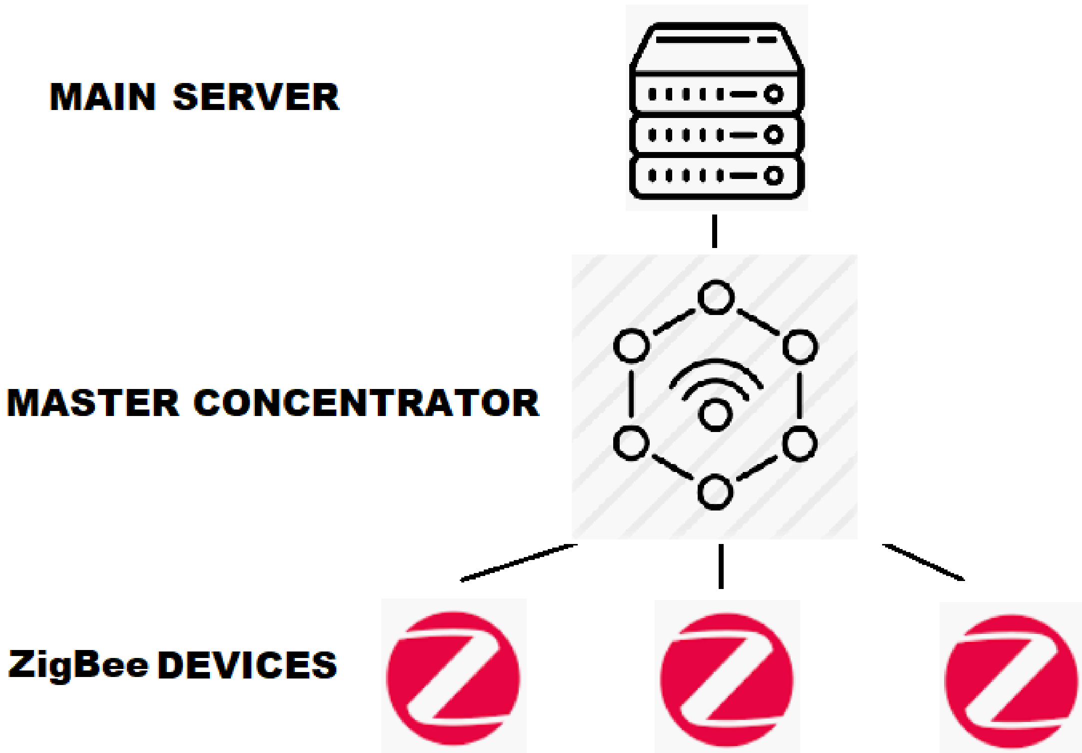

Figure 3: ZigBee IoT network [52]

2.1.4. Z-wave

Z-Wave is another wireless technology used for wireless IoT devices with performance metrics similar to that of the ZigBee [23]. It operates at 868.42 MHz in Europe and at 908.42 MHz for the USA. The data rate is limited to 9.6Kb/sec or 40Kb/sec for the mentioned frequency spectrums [24].

The range of communication that can be done with Z-Wave is categorized into indoor and outdoor communication. For indoor communication, it can operate up to 30 meters while for outdoor communication the transfer of data can be done till 100-meter range [25]. So it performs better than Bluetooth in terms of the distance but from the data rate point of view Bluetooth is better than Z Wave as its data rate is significantly lower than that of the Bluetooth network.

Another drawback of Z-Wave is that it is not an open technology and its chips can only be bought from the Sigma technologies which hinder flexibility in the heterogeneous nodes deployment but also is convenient if the network to be designed must have all nodes operating at the same service level. Such networks are easy to maintain and can bring forth lower operation and maintenance costs for the operator [26].

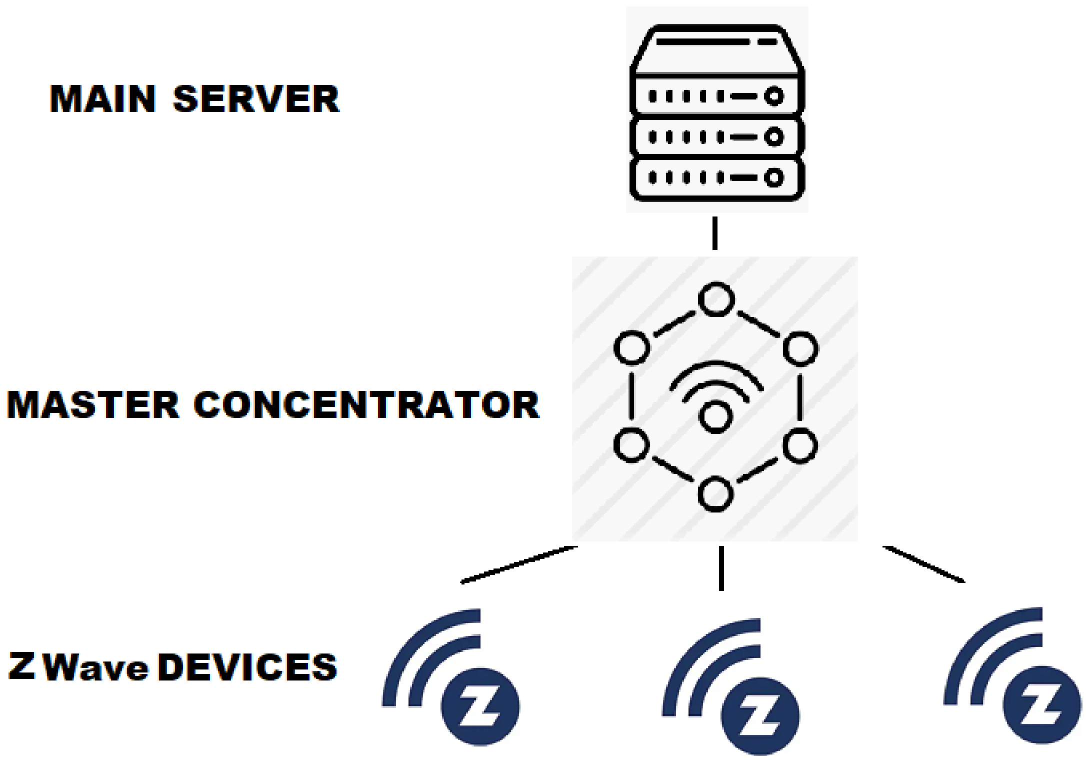

Figure 4: Z-wave IoT network [52]

Table 1: Comparison of short range wireless technologies [52]

	Frequency	Data Rate	Distance	Applications
Bluetooth	2.4 GHz	1-24 Mb/s	10cm-10m	Mouse, headset etc
Wi-Fi	2.4 GHz, 5 GHz	11Mb/s- 1Gb/s	50-100m	Indoor internet

ZigBee	868/915, 2.4 GHz	20 – 250 Kb/s	10-100m	Home automation
Z-Wave	868.42/908.42 GHz	9.6 – 40 Kb/s	30-100m	Monitoring devices

2.2. Cellular Mobile Network

The cellular network also finds application in the IoT networks. Instead of separately allotting a fixed frequency spectrum, devices can have sim slots and operate like usual mobile devices. Different applications such as POS machines, time-sensitive wearable technologies, vending machines, smart home appliances, intelligent terminals, video surveillance, artificial reality, virtual reality, assisted driving, virtual driving and as well as telemedicine.

2.2.1. 2G Cellular Mobile Networks

The global system for mobile communications is the 2nd generation of wireless mobile communication technology with a data rate of up to 9.6 Kb/sec. GPRS is an extension of the GSM which can increase the data rate up to 114Kb/sec for the IoT devices. It operates at the authorized 900 MHz frequency range. The IoT applications are found for Pos machines and wearable IoT Devices [27].

Figure 5: Cellular networks for IoT devices

2.2.2. 3G Cellular Mobile Networks

Third-generation mobile communication technology that can integrate voice and internet data transmission simultaneously at a few hundred kb/sec. It finds it applications for vending machines and smart home appliances. Depending on the kind of technology used the data rate can vary from 2.8 Mb/sec to as much 14 Mb/sec if WCDMA is employed. The spectrum of operation is usually 900 MHz and 1800 MHz [28]

Figure 6: 3G for IoT devices

2.2.3. 4G Cellular Mobile Network

The fourth generation of mobile network technology which either uses time division duplexing or frequency division duplexing. 4G technology is ideal for IoT devices which need a high data rate typically up to 100 Mb/sec. It founds its application for a video surveillance IoT network. The band of deployment is 1800 Mhz and 2600 Mhz [29].

Figure 7: 4G for IoT devices

2.2.4. 5G Cellular Mobile Network

It is the fifth generation of the cellular mobile networks that can provide data rate up to 10 Gb/sec hence, making it a viable technology for IoT applications offering service as virtual reality or automated driving [30]-[31]. ITU-R has identified three modes of deployment for the 5G networks divided into the enhanced mobile networks, massive machine-type communications and ultra-reliable low latency communication [31].

Figure 8: 5G for IoT devices

Table 2: Comparison of cellular technologies for IoTs [52]

	Frequency	**Data Rate**	**Applications**
2G	900 MHz	114Kb/s	POS devices
3G	900 MHz, 1800 MHz	2.8 -14.4Mb/s	Smart Home
4G	1800MHz, 2600 MHz	220– 330Mb/s	Video Devices
5G	C-Band	10 Gb/s	Automated Driving

2.3. Low Power Wide Area Technologies

These technologies are meant for long-distance communication. The bandwidth of these wireless technologies is lower than that of short-range wireless communication technologies but they differ in a sense that can transmit data to large distances from 1 kilometer to 20 kilometers' and as much as 50 kilometers in the case of Sigfox wireless communication [32]-[34]

These are wireless technologies found various applications from smart home appliances, smart agriculture, water, and electricity meters, shared bicycle to power grid technologies [35][36].

2.3.1. Sigfox

SigFox has an ultra narrowband bandwidth comprising of the only 100Hz that can travel to as much as 3 to 10 kilometers. The deployment band is from 915 to 928 MHz in the unlicensed region [37]. The data rate is very low around 100bps, the cost of the chip is relatively lower and transmission power is considerably low because the bandwidth is very thin, data can still travel to higher distance because of the higher power spectral density for the SigFox communication [38].

Among the disadvantages is the lack of security, the technology is still in development, the base stations can inability to provide support for different divisions [39].

Figure 9: SigFox a wireless technology for IoT devices

2.3.2. Long Range – Lora

It is another low power wide area network communication technology that operates in the unlicensed spectrum at 868 MHz and 918Mhz having channel bandwidth at 125Khz [40]. The data rate is higher than that of the SigFox at approximately 50Kbps. The battery of LoRa devices can last for over 10 years and it is safe from interference. Under a different environment, the transmission of LoRa can travel from 2 to 15 kilometers [41][42].

Among the disadvantages is the inflexibility in the size of packets. The latency is higher than the other communication technologies and a need for a gateway for communication to make its way through the network. It can be deployed in applications related to environmental monitoring such as air pollution detectors or alarm signals in case of fire in the installed area [43]..

Figure 10:LoRa a wireless technology for IoT devices

2.3.3. eMTC

Designed by Ericsson for IoT devices that need to offer voice communications. In addition, it also offers a higher data rate as much as 1 Mb/sec that can even be used for devices that require video surveillance[44][45]. The main deployment scenarios are for devices that are placed in deep zones and require low power utilization.

Although designed to consume low power but when compared to narrowband IoT the power consumption of eMTC is still higher than that of Nb-IoT [46]. The capacity in terms of the number of the devices eMTC can support is also lower than that of eMTC [47].

Figure 11: eMTC a wireless technology for IoT devices

2.3.4. Nb-iot

With the range of 10 to 15 Kilometers at deployment spectrum 700,800,900 Mhz having data rate up to 200 Kbps for the bandwidth of 180Khz [48]. The reason why Nb-IoT is preferred over wireless technologies is that the hardware needed to start Nb-IoT services is already in place.

The IoT service provider can roll out their services by getting services from the telecom operators. At the telecom operator ends, a simple software upgrade can set their system up to support Nb-IoT devices[49][50]. Nb-IoT devices have a battery life of up to 10 years. Typical applications are in smart metering, agriculture etc. Although the Nb-IoT uses the standard of cellular mobile technologies yet the hand over support is not available and interference is higher in case the deployment is made in the guard band mode of deployment [51].

Figure 12: : NB-IoT a prominent wireless technology for IoT devices

CHAPTER 3:

THEORETICAL MODELLING

CHAPTER 3. : THEORETICAL MODELLING

After introducing different communication technologies and doing intercomparison of them with each other, this chapter focuses on how to efficiently connect narrowband internet of things devices with each other. The chapter introduces the mathematical model to connect narrowband IoT devices with each other based on their bit error rates, least distance and higher received power. Once the relative distance with each other is calculated, from the received power the loss in power can be calculated. The loss in power can help determine the new power to transmit based on the acceptable BER selected for the pairing of IoT devices.

3.1.1. Problem Formulation

With the prediction of 50 billion IoT devices in the next 5 years the incapability of the Nb-IoT communication system to support all the devices simultaneously calls for new novel solutions to resolve the complicated nature of the connectivity problem. The bandwidth of the narrowband is only 200khz while the number of channels are only 12 with the channel width of 15khz only. The situation is grave to the extent that there are no control channels allocated for the narrowband IoT for the uplink channels.

The lack of resources, the competition to grab communication resources is exacerbated by the fact that neighboring cells can add interference to the current cell. Like cellular technology, there are cells in the narrowband communication as well. The phenomenon of co-channel interference can get worse in nb-iot because there are already a low number of channels to communicate in and the requirement of some devices to transmit in a higher power to ensure data delivery can increase problems for devices operating in the neighboring cell. So in the current cell, a device will be required to transmit again reducing its battery life but also the queued time for the waiting devices would also increase.

To make the situation more complex, narrowband devices are required to communicate repeatedly with the base station to ensure that their data is transmitted onto the base station. This results in loss of the frequency spectrum. While the Nb-IoT device is using the channel to do repeated transmission if it had done it only once then the next in queue device would have got the channel and communication would have been faster in the network.

Similarly, there are deep indoor devices in the IoT network which may be operating in the basement or deep inside a confined room in a building that may require to connect immediately with the base station to receive commands based on the sensitive data it may have been trying to transmit unsuccessfully to the base station.

IoT devices are supposed to have long battery life typically around 10 years time as proposed by the recent release of the 3GPP for standards of the Nb-IoT communication. The challenge to conserve the battery and retain the battery life is huge. Although narrowband IoT is a low power wide area range communication technology but repeated transmission and needs to transmit at higher power to ensure delivery of data to the base station consumes the battery faster hence repeated recharging and ineffective modes of refueling the battery energy can significantly reduce the battery lifetime. Therefore, data transmission once and with confirmed delivery to the endpoint has be resolved as an exigency to ensure compliance of Nb-IoT communication in accordance with the latest release of the 3GPP.

IoT devises network is dynamic it will not remain especially due to wearable IoT devices. A cell may experience a surge of IoT devices at some hours of the day while it may experience low load at other times. Fast-moving equipment communicating with the traffic signals such as in V2V communication can require urgent allocation of the channel in comparison of the static device which may not require to communicate or can wait to have the resource block allocated to communicate with the base station. Hence, a system sophisticated enough should be made to reduce network traffic intelligently and allocate channels to the most deserving as a priority.

The maximum data rate that can be achieved by Nb-IoT can achieve is around 150-200kbps depending on the channel conditions. Devices which require to send large amounts of data can make other devices wait in a queue to a long period of time. If such devices are allocated more channels then they can quickly transmit the data but adding such sophisticated scheduling would require other devices to sacrifice their own channels for a certain period of time.

3.1. Proposed Solutions

The above-mentioned problems require solutions that are novel and can be implemented with less overhead expenses. Because Nb-Iot can be integrated with the existing deployed LTE network, therefore, improvements can be done in the way connections are built with in the devices.

One of the ways to form D2D connections among the IoT devices is by measuring the BER of each device with its neighbor through the neighbor discovery. The measurement of the BER will help the devices gather data of the potential relay devices and then pass it on to the eNodeB and processing of the data.

3.1.1. Why Ber Is Used

Bit Error Rate is a simple metric that means to find out the unsuccessfully received bits in comparison to the total transmitted bits. The Ratio gives the quality of the channel and also is an indirect indication of the amount of noise or interference in the channel. Therefore, usage of the BER can take out the calculation of SINR or SNR and make the calculation of IoT base station easier. The higher the BER lower will be the signal quality because it means that more number of bits is not successfully received by the potential pairing IoT device.

3.1.2. Why Rssi Is Not Used:

RSSI is used as a metric to measure link quality for low data rate communication. Because IoT devices mainly require a low data rate hence it makes RSSI a good feature to determine the quality of a link. In the current case, BER is prioritized over the BER because although signal strength may be higher but it does not always mean that all the bits have been successfully received. RSSI is a raw criterion for measuring the quality of the link.

3.1.3. Why Sinr Is Not Used

Signal to Interference + Noise Ratio is a very difficult indicator to measure for a communication system. It would add more complexity to the physical capabilities of the IoT devices. Therefore, this metric is dropped although it is a very good indicator to measure link quality. The reason why it is more complex than the other metrics is because not only it requires to measure the interference but also the noise that is in the signal. It increases the signal processing complexity for the IoT device, in comparison for BER a device can simply count the unsuccessfully received bits in the signal.

3.1.4. Why Pdr Is Not Used

Packet Delivery Ratio is another good metric to measure the link quality but the number of packets that can be delivered can vary significantly based on the packet size. Some packets can be larger in size while the others can be smaller and the number of packets received successfully can vary significantly based on the packet size. Also, a packet comprises of bits, a packet may still be marked as received it missed 10 out of 100 bits and also if it missed 11. The quality of signal for a device that missed 10 bits will be higher but from the PDR perspective, both signals are of equally good quality. Therefore, PDR is not used as a metric in this study to measure the link quality for the IoT Devices as it provides lesser resolution into the quality of the link encountered by the IoT device.

3.1.5. Modeling Through BER

As mentioned above D2D controlled connections is one of the ways to solve connectivity issues. The proposed solution focuses on building dynamic relationships between the IoT devices that can help solve the problem of resource allocation. Devices can transmit pilot signals periodically and also at the same time receive pilot signals from the neighboring devices to discover each other. Based on the received signal BER devices can receive a range of signals varying in terms of their error rates, received power of the devices in their proximity, and also from the base station. The table below shows how the data received by the base station would look like based on the BER of each device has received from n number of devices existing in the NB-IoT cell.

Table 3: Bit error received by N devices from potential relay IoT devices

	D_1	D_2	D_3	D…	D_n
D_1		BER_{1-2}	BER_{1-3}	$BER_{1-...}$	BER_{1-n}
D_2	BER_{2-1}		BER_{2-3}	$BER_{2-...}$	BER_{2-n}
D_3	BER_{3-1}	BER_{3-2}		$BER_{3-...}$	BER_{3-n}
D_4	BER_{4-1}	BER_{4-2}	BER_{4-3}	$BER_{4-...}$	BER_{4-n}
….	…	…	…	…	…
D_n	BER_{n-1}	BER_{n-2}	BER_{n-3}	$BER_{n-...}$	

Upon receiving the BER of each device, eNodeB will calculate the relative distance of each device from the other device. This measurement of distance is important because it will help relate the amount of power lost as the signal makes its way towards the potential relaying IoT device. In order, to calculate the distance the fading SNR must be calculated. SNRf can be calculated from (1) where M is equal to 4 as Nb-IoT employs QPSK with K=2 as two bits are distributed in a circle.

$$SNR_f = \frac{1}{2}\frac{\left(Q^{-1}\left(\frac{K}{2}BER\right)\right)^2}{sin^2\left(\frac{\pi}{M}\right)} \tag{1}$$

Narrowband IoT deploys QPSK as a mode of modulation because of the simpler nature of the data to be transmitted and to reduce the transmission complexity for the resource constraint IoT devices. From SNR_f we can calculate the final SNR from (2). Where Nrep is the number of times repeated transmission is done by the devices and f is the frequency factor used for the communication calculated from (5).

$$SNR = \frac{SNR_f}{N_{rep} \times f} \tag{2}$$

After calculation of total SNR for a connection, the received power Prx can be calculated from (3). Where No is the thermal noise power, NF is the noise power spectral density, BW is the bandwidth used by the device. This is the power received by the IoT device from the potential pairing IoT devices. The higher the received power better is the quality of the signal and lower was the BER of the signal. This indirect measurement of the received power from the BER helps in determining the power that was lost along the way as all devices are supposed to be transmitting at an equal power level of 23 dBm which is set for the LTE Nb-IoT devices.

$$P_{rx} = SNR \times N_o \times NF \times BW \tag{3}$$

Where Bandwidth can be calculated from (4) and (5). Frequency factors is dependant on the number of tones used. If only one tone is used then the bandwidth would be only 15KHz. A device that is allocated 12 tones would have the entire resource block for its communication and will have the maximum 180Khz of bandwidth. For this research, only one tone is allotted to the devices to keep bandwidth fixed at 15Khz. Allotting the whole bandwidth chunk to an IoT device would grant it a higher data rate and utilize the full potential of the frequency block. This condition can be ideal for devices that are looking to transmit big amount of data. In the case of devices, such as smart meters, where the need to transmit data is a much smaller allocation of full bandwidth is not recommended.

$$BW = \frac{180KHz}{Frequency\ factor} \tag{4}$$

$$\text{Frequency factor} = \frac{12}{tones} \quad f \in [1,2,4,6,12] \tag{5}$$

After the received power is calculated the power loss Ploss can be calculated from (6) where Pt is transmitted power. This is the power loss when a device discovery signal is received by the potential relay device. The higher the power loss is the lower the quality of the signal. For the solution in this dissertation, it is recommended to find the devices that offer lower power loss. The lower the power loss is more will be the opportunity to lower the transmit power.

$$P_{loss} = P_t - P_{rx} \tag{6}$$

The acquisition of lost power can help attain the relative distance between the two devices through (7). Where γ is the path loss exponent, Kdb is free space path gain at distance do = 10 * λ. The distance outcomes after calculations are depicted in Table 2. The distance between the devices remains fixed because of the quality of the signal received which helped in calculating the power loss encountered by the devices.

$$d = do * 10^{\frac{Ploss\, db\ \times Kdb}{10 * \gamma}} \tag{7}$$

Table 4: Distance of N devices from potential relay IoT devices

	D_1	D_2	D_3	D…	D_n
D_1		$d_{1\text{-}2}$	$d_{1\text{-}3}$	$d_{1\text{-}\ldots}$	$d_{1\text{-}n}$
D_2	$d_{2\text{-}1}$		$d_{2\text{-}3}$	$d_{2\text{-}\ldots}$	$d_{2\text{-}n}$
D_3	$d_{3\text{-}1}$	$d_{3\text{-}2}$		$d_{3\text{-}\ldots}$	$d_{3\text{-}n}$
D_4	$d_{4\text{-}1}$	$d_{4\text{-}2}$	$d_{4\text{-}3}$	$d_{4\text{-}\ldots}$	$d_{4\text{-}n}$
….	…	…	…	…	…
D_n	$d_{n\text{-}1}$	$d_{n\text{-}2}$	$d_{n\text{-}3}$	$d_{n\text{-}\ldots}$	

After the relative distance between the devices is calculated, new transmitted power can be calculated by fixing the desired BERdes. The minimum acceptable BERdes will give the fading SNRf through which SNR can be calculated from (9). The new series of calculations will help determine the new power to transmit. Because higher the received power by the IoT also means indirectly that there is indirect power loss because of the fact that the power loss along the path is fixed and minimum BER is still achievable if the transmit power can be reduced. This higher received power has the same potential as that of the lower received power when both of them offer at least the minimum acceptable BER_{des}.

$$SNR_{fdes} = \frac{1}{2}\frac{\left(Q^{-1}\left(\frac{K}{2}BERdes\right)\right)^2}{sin^2\left(\frac{\pi}{M}\right)} \tag{8}$$

$$SNR_{des} = \frac{SNR_{fdes}}{N_{rep}\times f} \tag{9}$$

The new total desired SNR_{fdes} des will help to estimate the accurate amount of received power Prx des for the device to attain the required desirable BER_{des}. The bandwidth would remain the same as it was earlier at 15Khz. No, and NF will also remain constant only the SNR_{des} have differed because of the change in the minimum acceptable BER_{des} or desirable bit error rate. Because we are aware of the power loss along the path we can fix the value of BER above and find subsequent elements which would help to determine the lower or the desired power to transmit for the IoT devices.

$$P_{rx\ des} = SNR_{des} \times N_o \times NF \times Bandwidth \tag{10}$$

From the new received power P_{rxdes}, enodeB can calculate the new power to transmit $P_{t\ new}$ (Table 3) which would help save power for the devices which are able to form pair in close proximity. Devices which are farther and not able to find pair in close distance will have to improve the transmit power to achieve the required BER_{des} with a potential pairing device. The devices in NB-IoT are designed to operate at 23dbm or 20dbm or 17dbm there is room to save power as much as 6dbm for certain devices. Based on the mathematical model more power can be saved if the hardware permits to lower the power. Where $P_{t\ new}$ is the new power to transmit.

$$P_{t\ new} = P_{rx\ des} + P_{loss} \tag{11}$$

Table 5: New power to transmit of N devices for potential relay IoT devices

	D_1	D_2	D_3	D…	D_n
D_1		$P_{tnew\ 1\text{-}2}$	$P_{tnew\ 1\text{-}3}$	$P_{tnew\ 1\text{-}...}$	$P_{tnew\ 1\text{-}n}$
D_2	$P_{tnew\ 2\text{-}1}$		$P_{tnew\ 2\text{-}3}$	$P_{tnew2\text{-}...}$	$P_{tnew\ 2\text{-}n}$
D_3	$P_{tnew\ 3\text{-}1}$	$P_{tnew\ 3\text{-}2}$		$P_{tnew3\text{-}...}$	$P_{tnew\ 3\text{-}n}$
D_4	$P_{tnew\ 4\text{-}1}$	$P_{tnew\ 4\text{-}2}$	$P_{tnew\ 4\text{-}3}$	$P_{tnew4\text{-}...}$	$P_{tnew\ 4\text{-}n}$
….	…	…	…	…	…
D_n	$P_{tnew\ n\text{-}1}$	$P_{tnew\ n\text{-}2}$	$P_{tnew\ n\text{-}3}$	$P_{tnewn\text{-}...}$	

Algorithm Power Saving Procedure for D2D Nb-IoT devices Pairing

Input:

Random BER; Nrep; No; Number of Tones; Old Transmit Power; Gamma; Do

Initialization:

Initialize random number of devices

Generate random BER for these devices

```
for x in number of devices
    for y in number of pairing devices available
        Calculate SNR for potential pairing device from (1)and(2)
        Calculate Received power from (3)
        Find corresponding device distance from (7)
    end
end
for x in number of devices
    for y in number of pairing devices available
        Sort a device potential pairing device in ascending BER
        Set potential pairing device with minimum BER to desried BER
        Calculate corresponding received power(10)
        Find new power to transmit from (11)
    end
end
```

Ouput:

1) Distance of devices from one another

2) Powerlost in each pairing

3) New lower power to transmit

After getting the knowledge of the network topology, devices now know the best-paired device to communicate with. In this situation, there is no need to transmit at the same power as which the devices were linked with each other. In order to save the battery power now, the devices paired can retransmit again by periodically lowering the transmission power. By acknowledging with each other of the received signal devices can store the transmission power which is enough to do the communication without losing the data. The figure shows how devices are now connected with one another with better chances of saving transmitted power.

	D1	D2	D3	D4	D5
D1		min pow			
D2	min pow				
D3				min pow	
D4			min pow		
D5				min pow	

Figure 13: D2D pairs formed with least transmitting power

After the power is adjusted now the minimum signal strength is known to transmit the data between two d2d devices. Now is the time to check whether the channel used for communication is right to communicate in or not. Devices which need more data and need secure channel characteristics now measure all the 12 channels characteristics such as load to through put ratio, blocking probability, signal to noise ratio, and Jain fairness index.

CHAPTER 4:

Model Verification

CHAPTER 4. MODEL VERIFICATION

The section is based on the verification of the model proposed in the previous section. The model is set up and results are compiled in line with the theoretical and mathematical model discussed in the previous chapter. Lastly, the results attained with the steps mentioned in the last chapter are explained with respect to the simulation results.

The simulation is run for 10 devices. The equations above have been used according to the algorithm specified. Some values are taken as a constant which are specified in table at the end of this section. It is assumed that all devices will make pairs based on one channel which is of 15000 Khz bandwidth. The aim of the work is to optimize power usage and to maximize the reach of each device.

The below figure shows that the 10 devices and their corresponding BER which they are receiving from the potential pairing relay device. The values of BER for all devices are depicted in relation to each other in the below figure. Each device collects the BER data of all the devices it can receive a signal from and pass it on to eNodeB. For example, for device 6 there is a device that is offering the BER of 10-2 which is the most desirable or the best potential relay device available for device 6 to form pair with. In comparison, the other end other red line represents the worst BER received by the device from a potential pairing device. This device is not favorable for the device to form the device to the device pair with.

From BER calculation, the distance of each device from one another can be calculated through a series of equations from (1) to (7) and is shown in the below figure. Potential pairing devices with lower BER will be nearer to the device. As the BER increases from calculations depicted in figure it is evident that the distance also increases. Such devices are not favorable to form the D2D pair rather the device with the lowest distance will be the ideal to form the D2D pair.

From the below figure the loss of power can also be calculated from equation (6) as explained in the previous section. Devices are nearer to each other experience lower power loss than the devices further away from one another as shown in the below figure. This can be confirmed by correlating the distance and BER as explained earlier. As a reference, device four which was farthest away also has the maximum power loss in transmission or in other words is the worst device for device 4 to make a D2D pair with. Similarly, the topmost is the least amount of power lost by the potential pairing device attempting to connect with the IoT device.

After the calculation of the distance and the power loss, eNodeB can direct devices to form D2D pairs. Devices will form pair with that device which has least BER, least distance and least power loss. The figure below shows the logical pairing from the last three figures by making pairs with what is the most optimized pair. For example, from the simulation, device 5 is pairing with 3 different devices. Such pairs can be sent an instruction to transmit in their allocated time frame of channel allocation. This pairing of IoT devices will allow the IoT device to form with that IoT device which has the least power loss, in addition, it also represents that a device can be an ideal potential pair for more than one device. The cluster of devices in close proximity of each other can form a D2D pair with each other and have more potential to save pt.

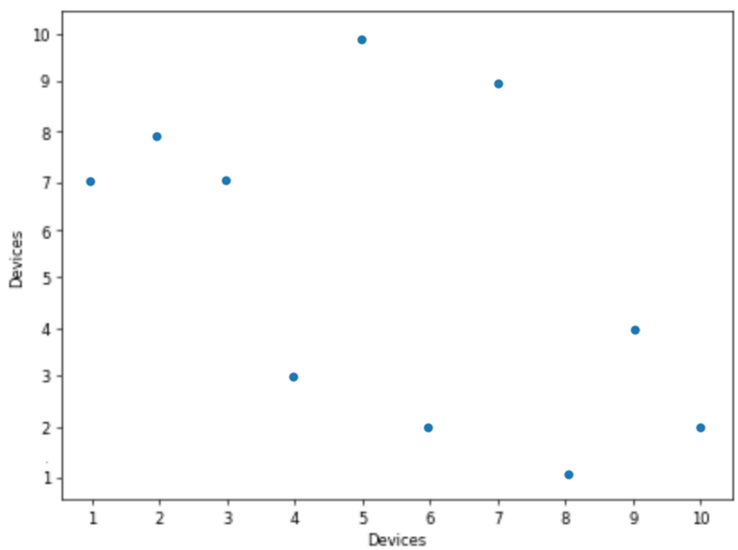

Figure 14: D2D pairs formed based on least power to transmit

The device pairing can be seen pairing with the device nearest and with the least BER. From the below, it is evident that the devices with least BER are nearest to each other. As in the case of device 6, its pair has the lowest BER and is the closest forming pair in terms of distance as well. The figure helps to validate the results that the lowest BER also ensures close proximity. The results are in line with the theoretical modeling done in the previous chapter which confirms the fact that higher the BER of a device with another device more further it will be away.

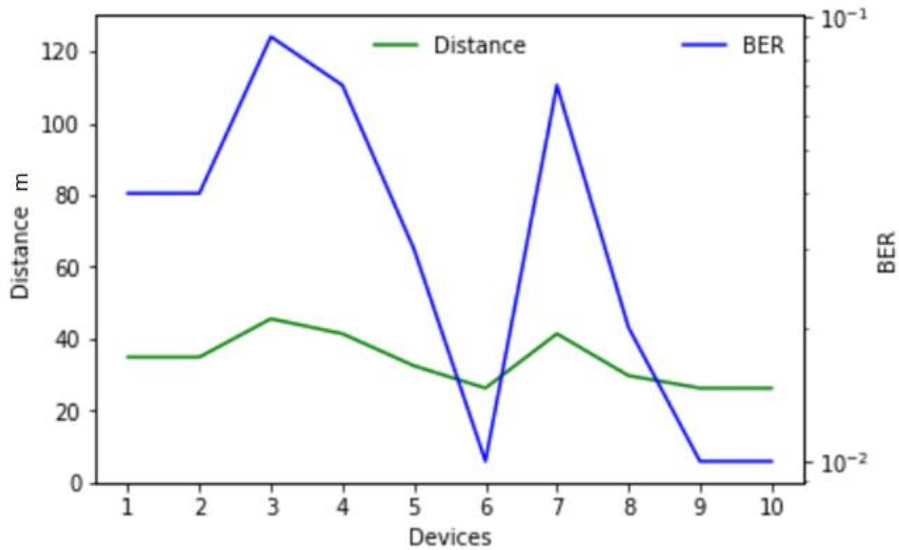

Figure 15: Distance and BER of the formed D2D pairs

After forming pairs each device now can readjust its power to transmit. The old power to transmit was fixed at 23dbm as default for LTE devices but after forming pairs, devices that are nearer to each other can lower their power to transmit and save the power consumption. This lowering down of power will also reduce the interference between the neighboring IoT devices as the power to transmit has reduced. From figure 6 it is evident that the device which had a pairing device with least BER, distance and power was able to save the most power calculated from equation (11).

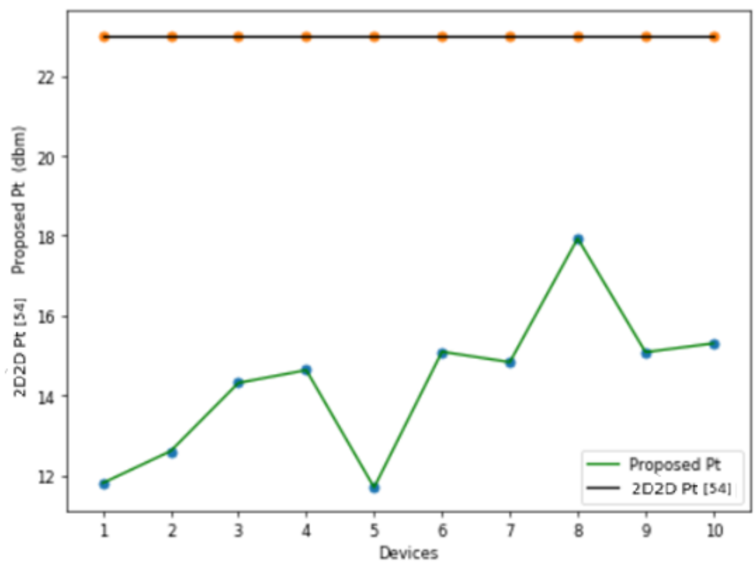

Figure 16: Power saved by the formed D2D pairs

In comparison with the intelligent deterministic D2D [54] method to form a device to devise pair, the technique proposed in this dissertation helps to save power in forming D2D pairs. The 2D2D pair technique does not focus on saving power but rather it is focused on optimizing the number of hops by converting Nb-IoT device with the cellular user equipment. The attached cellular user equipment would also transmit at 23dbm thereby making the total transmit power equal to 46dbm. The technique discussed in this dissertation only forms D2D pair with that Nb-IoT device which is able to communicate data with the base station. Hence the number of hops are already optimized to 2 while the power saving mechanism is also introduced to reduce the overall power used by the system. Therefore, the first D2D hop has lower power to transmit while the second device which connects with the base station transmits at 23dbm. Therefore, the overall total power to transmit becomes lower than that of the 2D2D pair forming technique. The figure below shows that if 2D2D technique is used, then only D2D pairs can be formed there is no room to lower the power of the Nb-IoT devices while the technique discussed in the dissertation mathematically helps to lower the transmitted power with the attached Nb-IoT device.

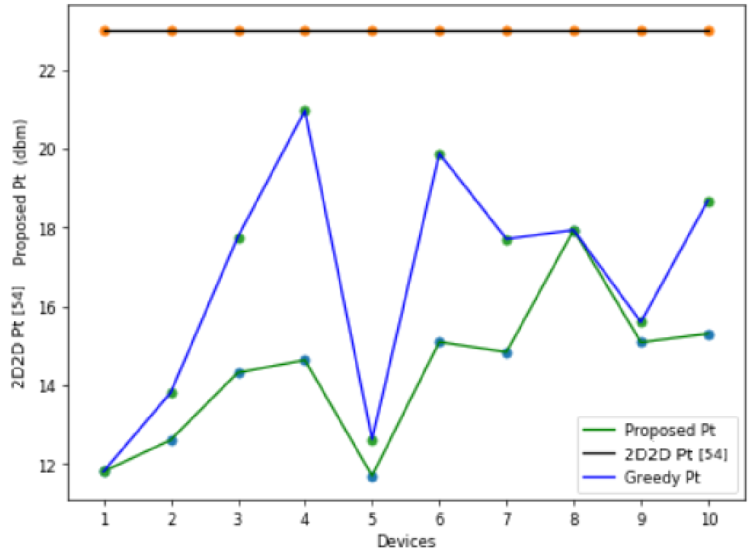

Figure 17: How Mathematical Model is better Than Greedy Model

The graph shows that when BER is chosen in a specific range for devices rather then selecting the least available BER available for a device the algorithm is faster but at the expense of higher power consumption.

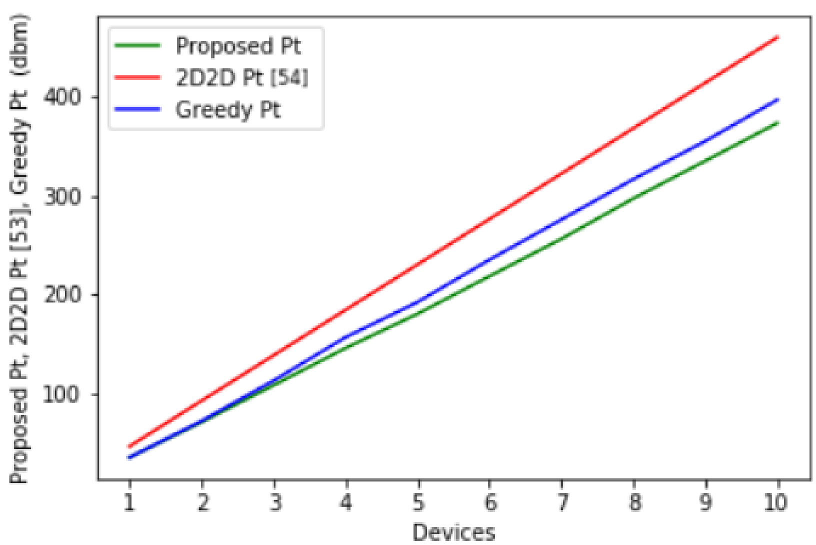

Figure 18: Power is saved For proposed Pt in comparison with 2D2D and Greedy Algorithm

The graph above shows the same results but in the form of cumulative representation. The Greedy algo is although better than the red reference technique to form D2D pair but as the number of devices increase the distance among the lines will also increase showing that on a whole at network level the potential to save more power is not fully utilised.

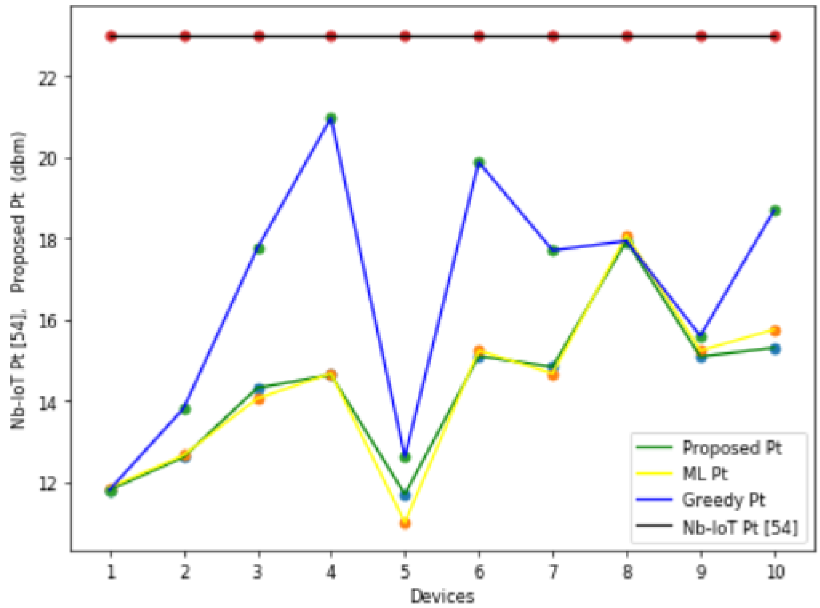

Figure 19: Results of Machine Learning

The figure in 19 shows the benefit of using machine learning. Given that the node in the operation centre knows the values of corresponding new power to transmit for a particular BER a model can be generated that can quickly assign a relay device to an IoT device looking to form a device to device pair. The yellow line in the figure depicts the machine learning results. For some devices it is very close to that of the actual mathematical model values but for other there is a slightly off. Over all the values produced by the machine learning model is very close to the actual results which would speed up the process of D2D pair formation without doing the calculations over again as explained in the mathematical modelling section.

Table 6: Parameter values for simulation

Parameters	**Value**
Noise Figure NF	5db
Transmit Power	23dbm
Number of Repetitions	3
Number of Tones	1
Bandwidth	15000KHz
Thermal Noise Density	-174dbm
Frequency	900MHz
γ	2

The research was carried out for a limited number of devices, however, if the number of devices is increased then the probability of finding a device offering a better BER is also possible. As more devices are present in the IoT cell, there will be more candidates to form an IoT pair with. So when implemented on a larger scale, the solution has the potential to save a higher amount of power when viewed for the network perspective.

CHAPTER 5:

Conclusion And Future Work

CHAPTER 5. RESEARCH CONCLUSION AND FUTURE WORK

IoT devices will become an integral part of daily lives in the future. It is important to find the quality of service improvement methods. Power is one of the critical factors to improve service quality. With estimated almost 50k devices in an IoT cell, it would be hard to change the batteries of all of the devices manually. Therefore, to come up with solutions that can optimize the battery consumption will help improve battery life and can also ensure that the network remains stable for a longer period of time.

The above simulation is run for only for 10 devices in actual cases when there will be as much as 50k devices within an NB-IoT cell there will be more opportunities for devices to form more power-saving pairs because there will be more devices closer to one another.

Device to device communication is a promising solution to keep the power consumption lower. This is particularly critical for deep indoor IoT devices which have to do more repeated transmission in order to transmit data to enodeB in comparison to those which are nearer to the station. Because the power is lowered to the minimum acceptable level the interference in the vicinity of the devices will be reduced. Devices need to send data only once now because they are connected to a reliable neighboring device in the D2D mode. The above solution brings forth the power saving mechanism and an indirect way to lower the interference of the IoT network. The solution can be expanded to even save more power by optimizing the number of transmissions.

The dissertation has fixed the number of transmissions an IoT device supposed to do, the power is lower based on the desirable BER, however, the number of transmissions can also be lowered if the devices are also in close proximity of each other.

The saved power can be used by the devices to make the network connection more secure. IoT devices are resource-constrained and putting in a sophisticated network security algorithm can further drain the battery of the IoT device. The saved power in the above mentioned D2D mechanism is an opportunity for the network security experts to devise new techniques that can utilize the saved power for making the IoT network more secure from cyber-attacks.

If the need for the IoT devices is to have a higher data rate than devices that are in close distance with each other can be allotted more bandwidth. The chained link to the base station has the potential to transfer a higher amount of data to the base station.

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