Performance of Narrow Band Internet of Things (NBIoT) Networks

by

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Declaration

I declare that this dissertation is my own, unaided work. It is being submitted for the degree of Master of Engineering in the University of Cape Town. It has not been submitted before for any degree or examination in any other university.

Signature of Author:

Signed by candidate

Cape Town

THE DATE 17 September 2019

Dedication

I would like to dedicate this work to my fellow work mates and family, who accorded me with the moral and technical support I so much needed to be successful.

Abstract

Narrow Band Internet of Things (NBIoT) is a Low Power Wide Area Network (LPWAN) technology that has been standardised by 3GPP in Release 13 to work in cellular networks [15]. The main characteristics of NBIoT are its extended coverage compared to other cellular technologies such as LTE; its high capacity is due to its narrow channel bandwidth of 180 KHz, which also supports the possibility of these devices having a long battery life of up to 10 years, as well as low device complexity – all of which result in low device costs [2]. NBIoT can be deployed in one of three different options, namely: a) standalone, b) in-band and c) guard band deployment mode. These characteristics of NBIoT makes it very useful in the IoT industry, allowing the technology to be used in a wide range of applications, such as health, smart cities, farming, wireless sensor networks and many more [1] [25]. NBIoT can be used to realise the maximum possible spectral efficiency, thereby increasing the capacity of the network. Penetration of NBIoT in the market has dominated other LPWANs like Sigfox and LoRA, with NBIoT having a technology share of close to 50 percent [31].

This study is aimed at exploring the deployment options of NBIoT and determining how network operators can realise the greatest value for their investment by efficiently utilising their allocated spectrum. The main target is to derive the best parameter combination for deployment of the NBIoT network with acceptable error rates in both the uplink and the downlink. Different characteristics of NBIoT were discussed in this study, and the performance of the various approaches investigated to determine their efficiency in relation to the needs of the IoT industry. The error rates of NBIoT, when used in an existing LTE network, were the main focus of this study. Software simulations were used to compare the different parameter settings to see which options provide the best efficiency and cost trade-offs for structuring an NBIoT network.

The results of the tests done in this study showed that the error rates are lower for standalone deployment mode than for in-band mode, which is mainly due to less interference in standalone mode than in in-band mode. The results also show that data transmitted in smaller Transport Block Size (TBS) in the Down Link (DL) has less errors than if it's transmitted in larger blocks. The results also show that the error rate gets lower as the number of subframe repetition increases in the downlink, which is mainly due to the redundancy in sending the same data multiple times. However in the uplink, the results show that the error rates are comparable when the signal has poor quality.

Acknowledgements

I would like to acknowledge, with sincere thanks, the support and guidance I received from my two supervisors, Simon Winberg and Yaseen Zaidi. I wouldn’t have managed to go all the way without their support.

Nomenclature

3GPP	3rd Generation Partnership Project
BER	Bit Error Rate
BLER	Block Error Rate
CE	Coverage Enhancement
DCI	Downlink Control
EDRX	Extended Discontinues Reception
GPRS	General Packet Radio Service
GSM	Global System for Mobile communications
LPWA	Low Power Wide Area
LTE	Long Term Evolution
MAC	Media Access Control
MCL	Maximum Coupling Loss
MTC	Machine Type Communication
NAS	Non Access Stratum
NBIoT	Narrow Band Internet of Things
NPBCH	Narrowband Physical Broadcast Channel
NPDCCH	Narrowband Physical Downlink Control Channel
NPDSCH	Narrowband Physical Downlink Shared Channel
NPRACH	Narrowband Random Access Channel
NPUSCH	Narrowband Physical Uplink Shared Channel
NSS	Narrowband Synchronization Signal
OFDMA	Orthogonal Frequency Division Multiple Access
PDCP	Packet Data Convergence Protocol
PRB	Physical Resource Block
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
RLC	Radio Link Control
RRC	Radio Resource Control
SC-FDMA	Single Carrier Frequency Division Multiple Access
WCDMA	Wide band Code Division Multiple Access

Contents

1 Introduction 1

- **1.1 Background** 1
- **1.2 Important terminology** 1
- **1.3 Objectives** 2
- **1.4 Problem statement** 2
- **1.5 Scope and limitations** 3
- **1.6 Document outline** 3

2 Theoretical Framework 5

- **2.1 NBIoT design objectives** 6
  - *2.1.1 Ultra-low complex devices 6*
  - *2.1.2 Improved indoor coverage 6*
  - *2.1.3 Support of massive number of low-throughput devices 7*
  - *2.1.4 Improved power efficiency/ long battery life 7*
  - *2.1.5 Uplink latency 7*
- **2.2 NBIoT deployment modes** 8
  - *2.2.1 In-band deployment 8*
  - *2.2.2 Guard band deployment 8*
  - *2.2.3 Standalone deployment 9*
- **2.3 NBIoT frame structure** 9
  - *2.3.1 NBIoT downlink frame structure 9*
  - *2.3.2 NBIoT uplink frame structure 10*
- **2.4 NBIoT protocol stack** 12
- **2.5 NBIoT physical channels** 13
  - *2.5.1 Narrowband Physical Downlink Control Channel (NPDCCH) 13*
  - *2.5.2 Narrowband Physical Downlink Shared Channel (NPDSCH) 14*
  - *2.5.3 Narrowband Physical Broadcast Channel (NPBCH) 14*
  - *2.5.4 Narrowband Synchronization Signal (NSS) 14*
  - *2.5.5 Narrowband Physical Uplink Shared Channel (NPUSCH) 15*
  - *2.5.6 Narrowband Physical Random Access Channel (NPRACH) 15*
- **2.6 NBIoT key parameters** 15
  - *2.6.1 Bandwidth 16*
  - *2.6.2 Maximum Coupling Loss (MCL) 17*
  - *2.6.3 Repetitions 17*
  - *2.6.4 Transport Block Size (TBS) 17*
- **2.7 NBIoT related work** 17
- **2.8 Chapter 2 summary** 19

3 Methodology 20

3.1 Research main objective 20
3.2 Method of procedure 21
3.2.1 Comparison of standalone vs in-band mode 22
3.2.2 Comparison of different transport block sizes 22
3.2.3 Comparison of different number of repetitions 23
3.3 Background and rationale for the design 23
3.4 Limitations of the design 24
3.4.1 Communication channel model 24
3.4.2 3GPP Release 24
3.4.3 Uplink transmission 25
3.4.4 NPDSCH data type 25
3.4.5 Modulation and Coding Scheme (MCS) 26
3.4.6 Chapter 3 summary 29
4 Design 30
4.1 NPDSCH BER simulation 30
Figure 10 - NPDSCH BER simulation block diagram 30
4.1.1 Transport block input 30
4.1.2 CRC attachment, convolutional coding and rate matching 32
4.1.3 Sub-frame repetition 33
4.1.4 Scrambling 33
4.1.5 Modulation mapping, layer mapping and precoding 34
4.1.6 Receiving process of the transmitted data 35
4.2 NPUSCH BER simulation 35
4.2.1 Transport block input 36
4.2.2 Data bit interleaving 38
4.2.3 NPUSCH subframe repetition 39
4.3 Summary of parameters used for the simulations 39
4.3.1 NPDSCH (downlink) parameters 40
4.3.2 NPUSCH (uplink) parameters 40
4.3.3 Chapter 4 summary 41
5 Simulation results 42
5.1 NPDSCH BER simulation – In-band vs Standalone mode 42
Figure 13 - NPDSCH BER simulation – In-band vs Standalone mode 43
5.2 NPDSCH BER simulation – Transport Block Size 44
Figure 14 - NPDSCH BER simulation – Transport Block Size 44
5.3 NPDSCH BER simulation - Subframe repetition 45
Figure 15 - NPDSCH BER simulation - Subframe repetition 45
5.4 NPUSCH BER simulation – Transport Block Size 46
Figure 16 - NPUSCH BER simulation – Transport Block Size 47

5.5 NPUSCH BER simulation - Subframe repetition ... 48

Figure 17 - NPUSCH BER simulation - Subframe repetition ... 48

5.6 Chapter 5 summary ... 49

6 Conclusion ... 50

6.1 General conclusion ... 50

6.2 Future work ... 52

6.3 Chapter 6 summary ... 53

7 References ... 54

List of Figures

Figure 1 - NBIoT deployment options [1] 1

Figure 2 - NBIoT deployment options [1] 8

Figure 3 - NBIoT downlink frame [Adapted from 3GPP] 10

Figure 4 - NBIoT UL frame structure [12] 11

Figure 5 - NBIoT protocol stack [18] 12

Figure 6 - NBIoT physical layer channels (Adapted from [1] [8] [12]) 13

Figure 7 - Bandwidth of one NBIoT resource block 16

Figure 8 – Methodology flow chart 20

Figure 9 - NBIoT UL and DL simulation procedure 21

Figure 10 - NPDSCH BER simulation block diagram 30

Figure 11 – NPDSCH scrambling 34

Figure 12 – NPUSCH BER simulation block diagram 36

Figure 13 - NPDSCH BER simulation – In-band vs Standalone mode 43

Figure 14 - NPDSCH BER simulation – Transport Block Size 44

Figure 15 - NPDSCH BER simulation - Subframe repetition 45

Figure 16 - NPUSCH BER simulation – Transport Block Size 47

Figure 17 - NPUSCH BER simulation - Subframe repetition 48

List of Tables

Table 1 : NBIoT key parameters 15

Table 2 - Modulation method 26

Table 3 - Modulation and TBS index table for PDSCH (source: 3GPP TS 36.213 Table 7.1.7.1-1) 27

Table 4 - Modulation and TBS index table 2 for PDSCH (source: 3GPP TS 36.213 Table 7.1.7.1-1A) 28

Table 5 - Modulation, TBS index and redundancy version table for PUSCH (source: 3GPP TS 36.213 Table 8.6.1-1) 29

Table 6 - Modulation and TBS index table for PDSCH (source: 3GPP TS 36.213 Table 7.1.7.1-1) 31

Table 7 - Number of subframes (N_{SF}) for NPDSCH (source: 3GPP TS 36.213 Table 16.4.1.3-1) 32

Table 8 - Transport block size (TBS) table (source: 3GPP TS 36.213 Table 16.4.1.5.1-1) 32

Table 9 - Number of repetitions (N_{REP}) for NPDSCH (source: 3GPP TS 36.213 Table 16.4.1.3-2) 33

Table 10 - NBIoT QPSK modulation mapping 35

Table 11 – NPUSCH format supported combinations (source: 3GPP TS 36.211 V13.2.0 Table 10.1.2.3-1) [19] 36

Table 12 - Number of resource units (N_{RU}) for NPUSCH (source: 3GPP TS 36.213 Table 16.5.1.1-2) 37

Table 13 - Modulation and TBS index table for NPUSCH (source: 3GPP TS 36.213 Table 16.5.1.2-1) 37

Table 14 - Transport block size (TBS) table for NPUSCH (source: 3GPP TS 36.213 Table 16.5.1.2-2) 38

Table 15 - Number of repetitions (N_{REP}) for NPUSCH (source: 3GPP TS 36.213 *Table 16.5.1.1-3)* 39

1 Introduction

1.1 Background

Narrow Band Internet of Things (NBIoT) is a Low Power Wide Area (LPWA) technology that has been standardised by 3GPP in Release 13 to work in cellular networks. NBIoT inherits many features from Long Term Evolution (LTE), and as such, the design and behaviour of these two technologies is closely linked [33].The main characteristics of NBIoT are the extended coverage compared to other cellular technologies like LTE, high capacity due to its narrow channel bandwidth of 180 KHz, long battery life of devices of up to 10 years, low device complexity resulting to low device cost and latency of up to 10s. NBIoT can be deployed in one of three different options as shown in *Figure **1***. These options are standalone, in-band and guard band deployment. The characteristics of NBIoT mentioned above makes it very useful in the IoT industry and can be used in many applications such as the health sector, smart cities, smart farming, wireless sensor networks and many more. NBIoT can be used to realise the maximum possible spectral efficiency, thereby increasing the capacity of the network.

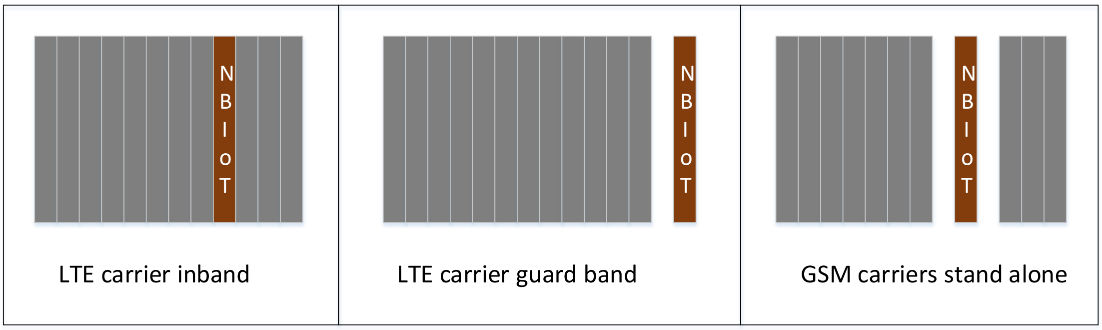


Figure 1 - NBIoT deployment options [1]

NBIoT is an emerging technology in the cellular and IoT industry and many players are keen to use it. Global technology leaders are currently piloting NBIoT and many other will soon follow suit [19]. The performance of the LPWA technology is a very critical issue that will need to be heavily scrutinised before commercial deployments are done.

1.2 Important terminology

Internet of Things (IoT) refers to the connection of gadgets/ devices with some level of computing, enabling them to send and/ or receive data. IoT can be realised in many forms, but the form which is discussed in this study is by Narrow Band deployment, i.e. Narrow Band IoT (NBIoT). NBIoT refers to the realisation of IoT through a narrower band than the traditional legacy wider band of LTE. The LTE carrier bandwidth can be 1.4MHz, 3MHz, 5MHz, 10MHz, 15MHz or 20MHz. On the other hand, the narrow bandwidth of NBIoT can be 180 KHz or 200 KHz only. The smaller bandwidth, though translating to lower peak throughputs, is ideal for low throughput services (IoT specifically) and has high bandwidth efficiency.

Low Power Wide Area (LPWA) networks are wireless communication networks intended for low range communication at relatively lower bit rates compared to usual systems like LTE and Wi-Fi. NBIoT is classified as one such network, together with many other like Sigfox, LoRa and many more. The main difference is that NBIoT is standardised by 3GPP, while the others are proprietary.

1.3 Objectives

This study is aimed at exploring the deployment options of NBIoT and determining how network operators can realise value for their money by efficiently utilising their allocated spectrum. Different characteristics of NBIoT were looked at and their performance studied to determine its efficiency in the IoT industry. The coverage, bandwidth limitations and error rates of NBIoT when used in an existing LTE network were the main focus of this study. Software simulations were done to compare different parameter settings in the NBIoT network.

1.4 Problem statement

With the emergence of IoT, operators are desperate to embrace this technology by deploying technologies specifically meant for IoT, which is mainly about small data transmission and narrowband technologies are on the rise to be used in this field. NBIoT is one of the technologies that are being targeted by most operators.

The main problem for many operators who are considering deploying NBIoT is that they are not certain of the error performance of this technology as it is still relatively new on the market. Operators have limited spectrum, the deployment of NBIoT, which shares parts of this existing spectrum, poses an interference threat that may result in poor performance of the NBIoT network and possibly the host wireless network onto which this data is piggybacked. The deployment of NBIoT involves Capital Expenditure (CAPEX) and mobile network operators would need to be certain that the technology they intend to invest in has satisfactory error performance in targeted areas of deployment.

This study is therefore intended to show the error performance of NBIoT in different deployment modes and with different key parameter settings. This will help operators to know the best parameter settings before the deployment so that they can guarantee their return on investment (ROI).

1.5 Scope and limitations

NBIoT can be implemented in existing GSM or LTE networks [27]. This study was confined to looking at the deployment of NBIoT in LTE or as standalone. Due to the fact that the NBIoT frequency band is licensed, real practical tests were not be done as the licensing process is complicated and expensive, and most likely would not cater for such studies. Also, bearing in mind the time constraints, the simulations that were done were only for determining the power, coverage and capacity related aspects of NBIoT. Furthermore, due to time limitations, only basic functionalities of NBIoT were covered in this study and since software tools were used to simulate and produce the results as the study could only go as far as the tools were capable of doing.

1.6 Document outline

This document is structured around a sequencing that allows the reader to easily follow the progression of this research, which started with establishing a literature-based theoretical framework and proceeded to carrying out accurate, literature-guided simulations that aimed to capture many characteristics of the challenges exhibited in the real world. The final chapter provides the conclusion and plans for future research projects that could be supported by and built upon these findings. A brief outline of the proceeding chapters are provided below.

Chapter 2 lays the theoretical framework of 3GPP NBIoT. The NBIoT design objectives and advantages are outlined, which are the reasons why NBIoT is preferred in IoT applications. Chapter 2 goes on to discuss the NBIoT deployment modes, their pros and cons. The uplink and downlink frame structure of NBIoT is also discussed in detail, and all the relevant channels in both the uplink and downlink are looked at in detail. The chapter proceeds to look at the NBIoT key parameters which are critical in the design of the NBIoT network. Lastly in this chapter, the related work in this field is outlined and achievements made so far are summarised.

Chapter 3 discussed the methodology to be followed in this work. A flow is shown which focusses on the simulation procedure of the key parameters, which are NBIoT deployment mode, number of transport blocks and number of repetitions (both uplink and downlink). The chapter ends by outlining some of the key assumptions that were made in order to work with the proposed method of procedure.

Chapter 4 discusses the actual design of this work. The block diagrams of the flow (both uplink and downlink) are shown and each blocked briefly discussed. The actual parameters used in the simulations are also summarised, with reference to 3GPP TS 36.213 [14]. The Transport Block Size (TBS) derivation, number of repetitions derivation and other related parameters are clearly shown with reference to the relevant 3GPP tables in 3GPP TS 36.213.

Chapter 5 presents the simulation results. There are five sets of simulation results that are presented. The chapter firstly presents the results of the comparison of the standalone and in-band deployment modes error performance. Secondly, results of comparison of error performance in the downlink using different transport block sizes are presented. The third set of results is the comparison of the error performance in the downlink using different number of repetitions. The fourth and fifth set of results are those of number of transport block sizes and number of repetitions in the downlink. The results are then discussed briefly and conclusions drawn.

Chapter 6 summarizes the whole work and draws main conclusions to the work done. Key highlights are mentioned on each chapter and some recommendations to operators are offered. The obtained results are also explained and an assessment on how they tally with expectations is done. Lastly, some future work is proposed on this subject that will help to shed even more light to operators who might be considering deploying NBIoT.

2 Theoretical Framework

NBIoT is intended for sensing and data collection applications, such as intelligent electric meters and environment supervision [4]. NBIoT is built from existing LTE functionalities and like LTE [33], it also uses orthogonal frequency-division multiple-access (OFDMA) in the downlink, and single-carrier frequency division multiple-access (SC-FDMA) in the uplink [4] [22]. This means that it is possible to reuse the same LTE hardware and also to share spectrum without coexistence issues. In addition, NBIoT can simply plug into the LTE core network. This allows all network services such as authentication, security, policy, tracking, and charging to be fully supported [7]. Furthermore, the rolling of NBIoT as a software on top of existing LTE network shortens the time-to-market and helps realise the benefits of standardisation and economies of scale [2]. NBIoT provides low cost and low power connectivity for the Internet of Things devices. This is achieved at the expense of higher latency (up to 10 seconds) and lower throughput (66.7kbps uplink and 32.4kbps downlink) [1] [5]. The fact that NBIoT can share spectrum with legacy cellular systems means that it is required to avoid causing any adverse impact to them while also adhering to regulatory requirements for the band [1] [10]. NBIoT uses very low cost devices to achieve extensive coverage [2]. NBIoT operation requires a minimum bandwidth of 180 kHz, which is equal to the size of the smallest LTE Physical Resource Block (PRB) [8]. NBIoT can be deployed by either refarming GSM or LTE spectrum in three different ways that will be discussed later [12].

The main application of NBIoT is anticipated to be in the sensor networks of the IoT industry, examples of applications are listed below [16]:

- Smart metering: e.g. water and electricity meters.
- Smart cities: e.g. street lighting, waste management and smart parking.
- Smart buildings: e.g. access control and security alarm systems.
- Smart agriculture: e.g. environment monitoring and animal tracking.
- Smart health: e.g. patient monitoring and tactile internet.
- Consumer intelligence: people, vehicle and asset tracking.

2.1 NBIoT design objectives

The 3GPP started the study of the standardisation of NBIoT in the year 2014, mainly to determine the requirements for low data rate Machine Type Communication (MTC) and to investigate if the proposed radio access designs would meet the requirements [2] [13]. The study also aimed to achieve a very high level of deployment flexibility by exploiting synergies with LTE in order to meet time to market requirements [2] and be able to transmit small amounts of data over long distances [28]. This study resulted in five main design targets which are discussed in the following section [1] [2].

2.1.1 Ultra-low complex devices

The average revenue per user (ARPU) for NBIoT devices is expected to be very low compared to that of broadband smart phone access. For the business case of NBIoT to be strong, the total cost of ownership (TCO) and that of the device should be very low [9]. NBIoT simplifies the device types (no fancy features) and the cost of each device is expected to be US $5 and below [2] [9]. This is made possible by the simplified protocol stack in the 180 kHz channel resulting in low baseband complexity and low cache memory requirement [4]. The low cost of the NBIoT devices will make it possible for them to be deployed in very big numbers with a relatively very low cost compared to that of legacy cellular networks with expensive devices.

2.1.2 Improved indoor coverage

The NBIoT technology should enable connectivity for the devices that are located in challenging indoor places such as in basements [13] [27]. This has prompted researchers to look for methods to increase coverage by tolerating lower signal strength than is usually required for other devices in legacy networks [9]. For this reason the coverage target of NBIoT is expected to be 20 dB better than that of legacy GSM networks [7] [32]. This is because of its high Maximum Coupling Loss (MCL) of 164 dB [2] [7] [20]. NBIoT also has better coverage compared to other LPWANs like Sigfox and LoRA [34]. The data rate of at least 160 bps should be supported at the application layer for both the uplink and downlink [7]. This data rate is relatively lower than that of legacy networks but is enough for NBIoT applications since the devices transmit small amounts of data periodically. NBIoT also uses self-decodable retransmissions/ repetitions in uplink to enhance uplink coverage [4] [6] [12].

2.1.3 Support of massive number of low-throughput devices

It is projected that by the year 2025 there will be seven billion connected devices over cellular IoT networks [9]. This means the device density per site will be very high and there is need for NBIoT cells to have very high capacity. The capacity target of NBIoT is at least 52547 devices per cell [1], assuming 40 devices per house hold [2] [7] or 20 devices per person [13]. This high capacity is due to the high spectrum efficiency of the narrowband technology [4]. Also, the very low frequency of connections by the devices (devices not always connected, occasionally transmit small packets of data [13]) makes the capacity of the NBIoT system very high [12]. The scope of NBIoT will have to be restricted to low throughput devices so that the said capacity can support a massive number of those devices.

2.1.4 Improved power efficiency/ long battery life

The complex devices of legacy 3G and LTE networks have a very short battery duration of a few hours to a few days. The batteries of NBIoT devices are targeted to last as long as up to 10 years [2] [34], with battery capacity of 5 Watt hours at 164 dB MCL [7]. This will make the operation of the NBIoT network easier and less costly [27]. The long battery life is achieved by the simplified air interface signalling, power saving mode feature, extended discontinues reception (eDRX) and reduced number of location updates sent by the devices (approximately 2 hour interval between each uplink reporting interval) [4] [13] [33].

2.1.5 Uplink latency

NBIoT is mainly for sensor networks where a relatively longer delay than that of legacy networks can be tolerated. The target uplink latency is 10s [1] for up to 99% of the devices [6], which is very suitable for non-latency-sensitive and low-bitrate applications for the Internet of Things (IoT) [4]. The NBIoT technology specifically targets applications that have relaxed delay requirements [13], e.g. sensor networks.

2.2 NBIoT deployment modes

The 3GPP standard defines that NBIoT can be deployed in three modes, i.e. in-band, guard band and standalone mode. The deployment can either be in the existing GSM or LTE spectrum in order to reduce deployment costs [17]. These three modes of deployment provide great deployment flexibility and very high spectrum efficiency [2] [6]. The selection of which mode to use can be influenced by an operator's usage of existing spectrum [9]. Figure **2** shows the three deployment options, which are briefly discussed in the following section.

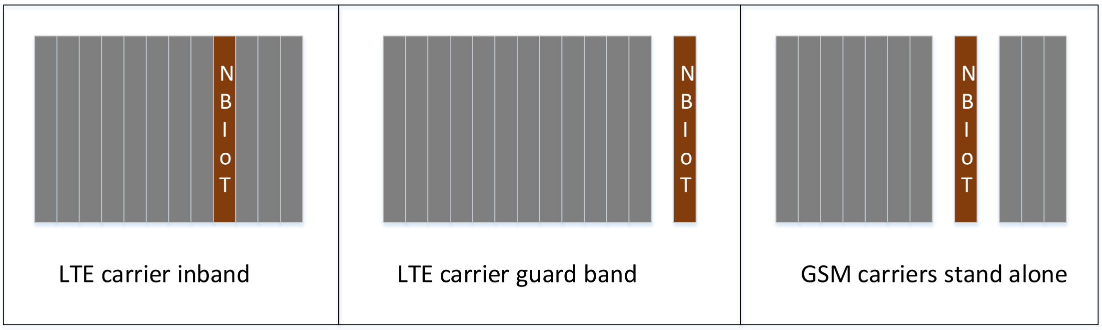


Figure 2 - NBIoT deployment options [1]

2.2.1 In-band deployment

In this deployment mode, a single NBIoT carrier occupies the bandwidth of one LTE physical resource block (PRB) [1] which is 180 kHz [4]. This deployment mode has a negative impact on the capacity of the LTE network in that it uses one or more of the LTE PRBs [1]. For in-band deployments with no IoT traffic present, the PRB can be used by LTE for other purposes, as the infrastructure and spectrum usage of LTE and NBIoT are fully integrated.

2.2.2 Guard band deployment

In guard-band operation, NBIoT will be deployed within the guard-band of an LTE carrier [1] and its band bandwidth will be the same as the LTE physical resource block (PRB), i.e. 180 kHz [4]. The main advantage of this deployment mode is that it does not use LTE resources to affect the LTE system capacity [1].

2.2.3 Standalone deployment

In standalone operation, a single NBIoT carrier is deployed in a bandwidth of 200 kHz (same as a single GSM carrier, to facilitate technology migration) [1] [4]. Network Operators can steer broadband traffic to LTE and WCDMA networks to free GSM spectrum (available globally) for NBIoT. The reuse of the existing GSM spectrum helps to shorten the time to market and quickens the return on investment period [2].

2.3 NBIoT frame structure

The NBIoT standard is based on LTE and as such is very similar in design to LTE. Furthermore, as is the case for LTE, NBIoT also uses OFDMA in the downlink and SC-FDMA in the uplink [4]. The downlink and uplink frames are different, and these two are briefly discussed below.

2.3.1 NBIoT downlink frame structure

The downlink transmission bandwidth of NBIoT system is 180 kHz with 15 kHz subcarrier spacing (same as LTE) [4]. Figure **3** shows the downlink NBIoT frame.

The bandwidth of one resource block is 180 kHz, with 12 subcarriers of 15 kHz each. In the time domain, the duration of one frame is 10ms, with 20 timeslots of 0.5ms each (one time slot with 180 kHz bandwidth is a resource block). Two time slots make up one sub frame equivalent to 1ms [4].

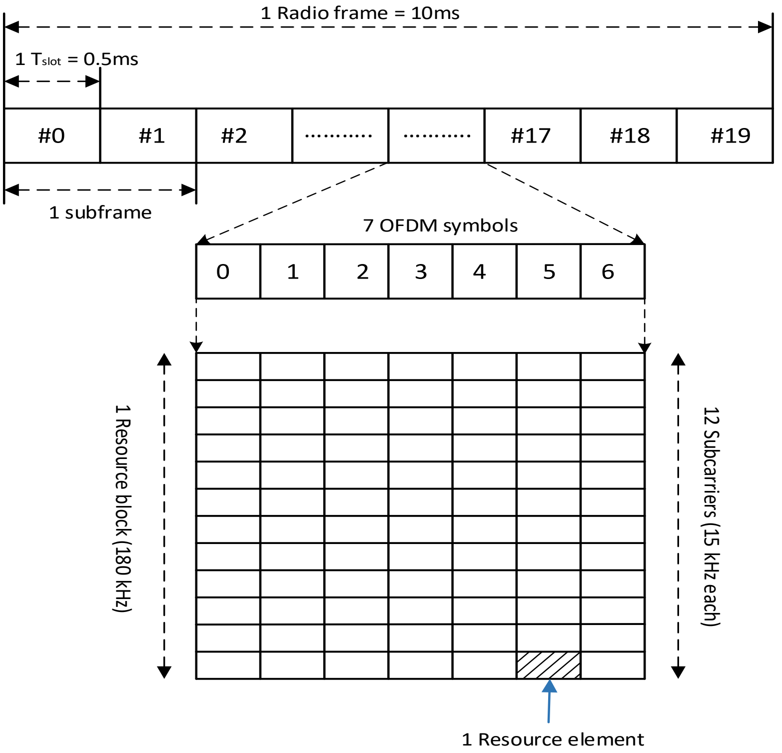


Figure 3 - NBIoT downlink frame [Adapted from 3GPP]

2.3.2 NBIoT uplink frame structure

NBIoT uplink transmission bandwidth is also 180 kHz, with two subcarrier spacing of 15 kHz and 3.75 kHz, both using SC-FDMA [32]. The 3.75 kHz spacing is used for coverage enhancement while the 15 kHz spacing has the advantage of better LTE compatibility than the 3.75 kHz spacing [4]. Two types of transmission are supported in uplink, which are:

(1) Single tone - this is mandatory uplink transmission intended to provide capacity in low coverage areas [12]. This is achieved through a compromise in interference as this transmission method interferes with LTE [6]. It has one subcarrier with either 3.75 kHz or 15 kHz spacing. Time slot duration for 15 kHz spacing is 0.5ms and 2ms for 3.75 kHz.

(2) Multi tone - this is optional uplink transmission intended to provide higher data rates for devices in normal coverage [12]. It has less interference with LTE

compared to single tone transmission [6]. Number of subcarriers can be 3, 6 and 12, with 15 kHz spacing and 0.5ms time slot duration.

The two uplink transmission methods are illustrated in *Figure **4*** below.

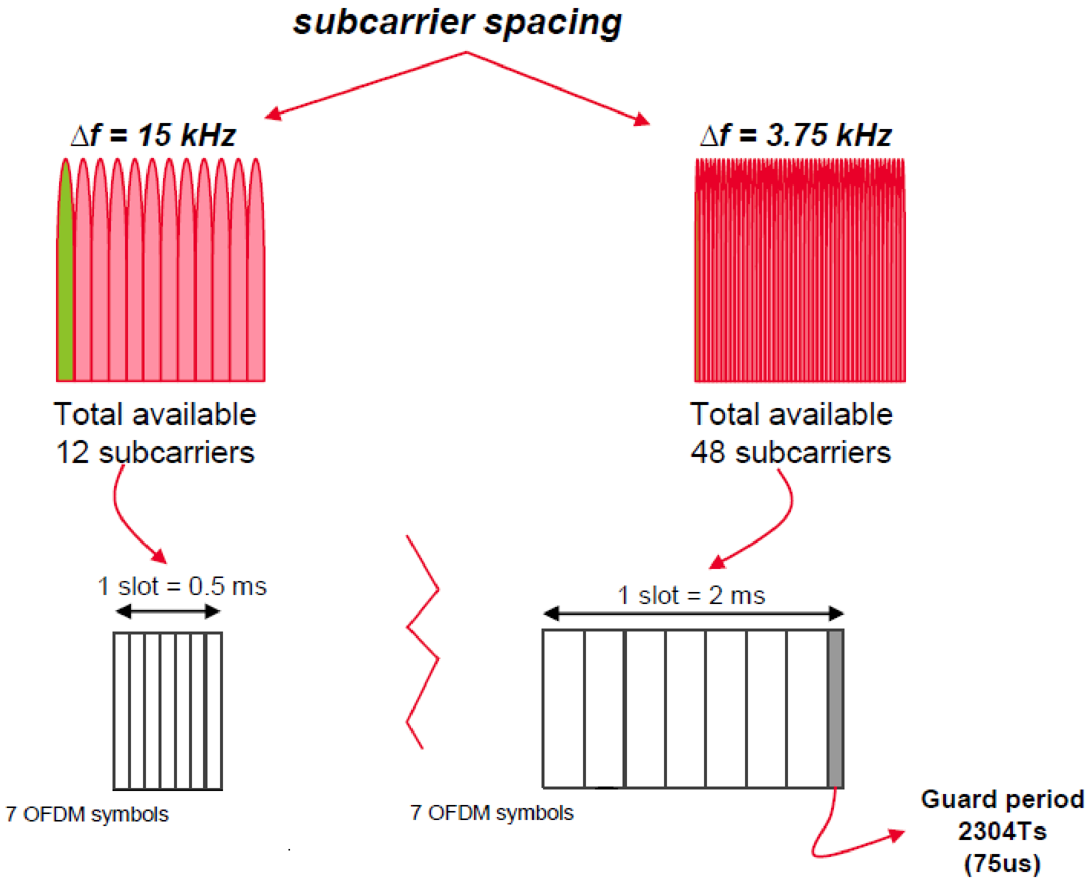


Figure 4 - NBIoT UL frame structure [12]

2.4 NBIoT protocol stack

The NBIoT protocol stack is shown in the figure below with various layers for both the user plane (actual data carrying part) and control plane (signalling part). The protocol stack layers are based on the OSI model.

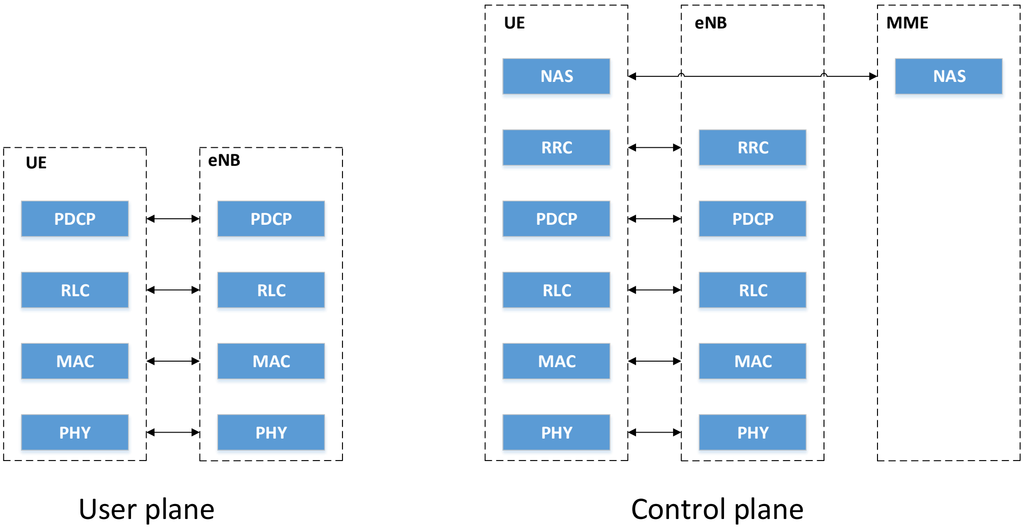


Figure 5 - NBIoT protocol stack [18]

Data in the NBIoT system flows through all the layers in the protocol stack. The function of each layer is summarised as below:

- The NAS layer - it is used for the exchange of non-radio signalling between the UE and the MME.
- The RRC layer - It is used for the initial service request by the UE to the network.
- The PDCP layer - It is used for data compression/ decompression, data ciphering/ deciphering and integrity protection and verification of control plane data.
- The RLC layer - It is used for the transfer of the upper layer PDUs, error correction through ARQ, concatenation, segmentation and re-assembly of RLC data.
- The MAC layer - It is used for mapping of logical channels onto transport channels, error correction through HARQ, transport format and transport block

size selection. The random access procedure to get services from the network is also done in this layer [25].

- The Physical layer - it is used for the exchange of data and control information eNB and UE and the transportation of data to and from higher layers. The physical layer consists of physical channels that are used to carry both user and control data. These physical channels are discussed in the following section.

2.5 NBIoT physical channels

The NBIoT system adopts LTE channels as much as possible [31]. The main difference is in the uplink where NBIoT does not have the equivalent of the LTE control channel (PUCCH). The acknowledgement is transmitted in the equivalent of the LTE PUSCH, which is the NPUSCH, while the scheduling is in the random access (NPRACH) [6]. Figure 6 shows the main NBIoT downlink and uplink physical channels, which are briefly discussed in the following section.

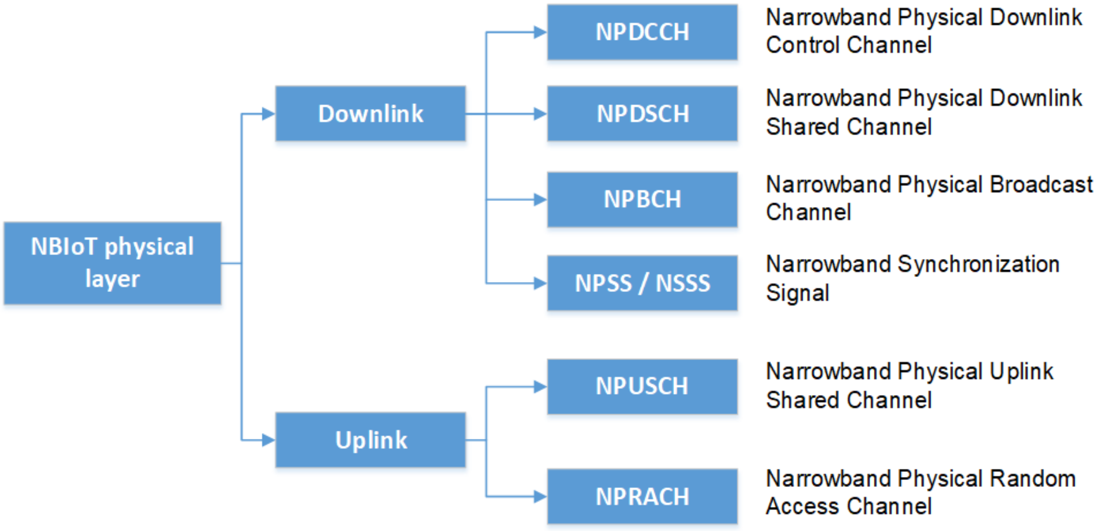


Figure 6 - NBIoT physical layer channels (Adapted from [1] [8] [12])

2.5.1 Narrowband Physical Downlink Control Channel (NPDCCH)

This is equivalent to LTE PDCCH. The NPDCCH is used to carry Uplink and downlink scheduling information and is the control/ signalling channel in the downlink [1] [8]. The size of the control information is fixed at 23 bits, and is encoded over 1 sub frame. The use of up to a maximum of 2048 repetitions in this channel helps achieve coverage extension [8]. The NPDCCH mainly carries three types of Downlink Control Information (DCI), which are uplink transmission scheduling (denoted as N0), downlink transmission scheduling (denoted as N1) and paging/ direct indication (denoted as N2) [12].

2.5.2 Narrowband Physical Downlink Shared Channel (NPDSCH)

This is equivalent to LTE PDSCH. The channel is used to carry dedicated and common data in the downlink, paging, system information and the random access response [1] [8]. Just like in the uplink, up to a maximum of 2048 repetitions can also be used in this channel to achieve coverage extension [8] [31]. The NPDSCH has a period of 2560ms with 4, 8 or 16 repetitions within that period, and is transmitted in sub frame number 4 of every even frame during 16 consecutive frames [12].

2.5.3 Narrowband Physical Broadcast Channel (NPBCH)

The NPBCH is transmitted in every sub frame number 0 in the downlink [12]. The broadcast channel is used to transmit system information through a 34 bit Master Information Block (MIB) in the downlink for system access [1]. It has a periodicity of 10ms and occupies the first sub frame of every 10ms frame [8]. The NPBCH carries vital system information such as the scheduling information (number of repetitions), operation mode (standalone, guard band or in-band), system frame number, etc. [12].

2.5.4 Narrowband Synchronization Signal (NSS)

The NSS consists of two signals, which are the Narrow band Primary and Secondary Synchronisation Sequence (NPSS and NSSS). The NPSS is used to obtain a coarse estimate of the symbol timing and carrier frequency, while the NSSS is used to obtain the cell identity, the frame boundary and further refine the coarse estimates [8]. The NPSS is transmitted in sub frame number 5 in all frame whereas the NSSS is transmitted in sub frame number 9 of all even frames [12].

2.5.5 Narrowband Physical Uplink Shared Channel (NPUSCH)

This is the equivalent of the LTE PUSCH. The NPUSCH is used to transmit uplink dedicated data and some uplink control information like acknowledgement [1] [8]. Two formats are used to distinguish between user date and control date in the NPUSCH, the first format is used to carry user data and uses turbo codes for error correction. The second format is used for control data and uses repetition codes for error correction [8].

2.5.6 Narrowband Physical Random Access Channel (NPRACH)

This is the equivalent of the LTE PRACH. The NPRACH is used for random access in the uplink. This is when user equipment will be accessing the network initially [1] [8]. The base station uses the random access preamble sent by a user terminal to estimate the uplink timing, which is necessary to issue a timing advance command in order to maintain uplink orthogonality among different users [8].

2.6 NBIoT key parameters

There are many parameters in the NBIoT system. The section below discusses a few selected NBIoT parameters which are considered to be key by the industry players in this field.

Table 1 : NBIoT key parameters

Parameter	**Parameter setting**
Frequency range	Conventional LTE FDD bands (700MHz, 900MHz, 1800MHz, 2600MHz)
Bandwidth	180kHz (1 Physical Radio Bearer (PRB))
Multiple Access	Downlink→ OFDMA
	Uplink → SC-FDMA
Modulation scheme	Downlink → QPSK
	Uplink → Single tone-QPSK/ BPSK
	Uplink → Multi tone-QPSK
Maximum Coupling Loss (MCL)	164 dB
Throughput	Downlink → 32.4kbps
	Uplink → 66.7kbps

Latency	<10s
Transmit power	23dBm
Repetitions	Downlink → Up to 2048
	Uplink → Up to 128
Transport Block Size (TBS)	Downlink → <= 680 bits, minimum = 16 bits
	Uplink → <= 1000 bits, minimum = 16 bits

The following section briefly provides more information on the main parameters of the NBIoT system.

2.6.1 Bandwidth

NBIoT uses a similar frame structure to that of LTE. The smallest unit that can be allocated/ scheduled is called the Physical Resource Block (PRB), with a bandwidth of 180 kHz, comprised of 12 equal subcarriers of 15 kHz each. The duration of each PRB is 0.5ms which is equivalent to one time slot in the LTE frame structure.

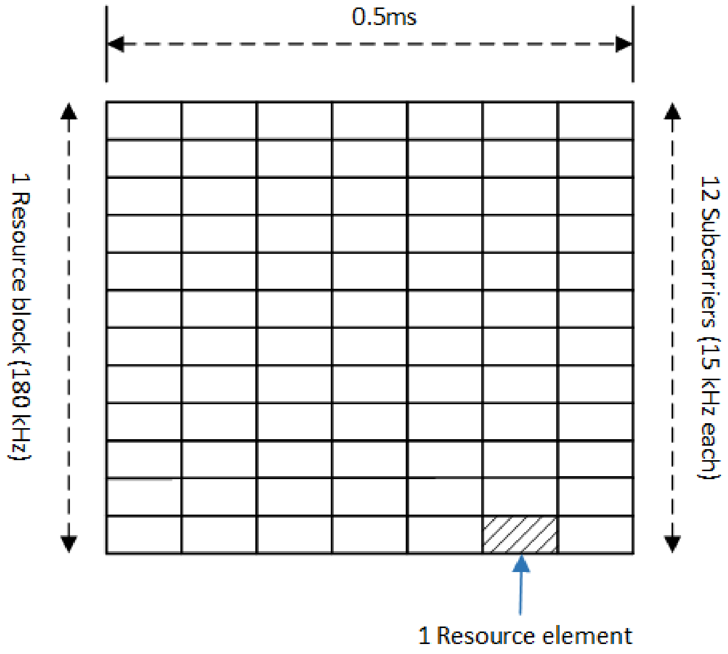


Figure 7 - Bandwidth of one NBIoT resource block

2.6.2 Maximum Coupling Loss (MCL)

The MCL is the minimum connectivity target of a system. It is viewed as the minimum receiver sensitivity. It directly relates to the coverage of a system. NBIoT defines three Coverage Enhancement (CE) levels which are:

- CE0 - defined for normal coverage, with MCL = 144dB
- CE1 - defined for robust coverage, with MCL = 154dB
- CE2 - defined for extreme coverage, with MCL = 164dB

The higher the MCL the more the expected coverage of a communication system as this would mean communication or connectivity is possible with very low signal strength.

2.6.3 Repetitions

This is a concept introduced in release 13 NBIoT, whereby the same data is sent multiple times to increase the chances of it being successfully received. This concept increases coverage by up 20dB compared to similar low data rate technologies like General Packet Radio Service (GPRS) [15]. NBIoT allows excessive repetitions of up to 2048 in the downlink and 128 in the uplink [15]. Increasing the number of repetitions enhances NBIoT coverage. However, too many repetitions can degrade the system performance by reducing throughput, reducing device battery life and increasing the system maintenance cost [29].

2.6.4 Transport Block Size (TBS)

The TBS is the block size of data transmitted at an instant in NBIoT. The TBS size ranges from 16 bits to 680 bits in the downlink, and from 16 bits to 1000 bits in the uplink. The selection of the TBS is specified in the tables in 3GPP TS36.213. These tables are discussed in detail in chapter 3 and chapter 4.

2.7 NBIoT related work

There is a lot of research on NBIoT that has been going on in recent years, and some work which has been done in this regard is discussed below.

In [1], the deployment of LTE in the guard band is discussed. The key areas which were looked at were the throughput comparison of the three deployment modes, throughput of multi tone vs single tone transmission and how the error rate varies with the number of repetitions. It was seen that for low Maximum Allowable Path Loss (MAPL), i.e. good radio conditions, the throughput of the three deployment modes was almost the same. For poor radio conditions, the throughput of standalone mode was the highest, followed by that of guard band and the in-band mode was the lowest. It was also seen that multi tone transmission has a fairly higher throughput than single tone for very good radio conditions. The study also illustrated that for both NPUSCH and NPDSCH, the error rate (BLER) becomes less as the number of transmission repetitions increase. It was concluded that even though there is mutual interference between NBIoT and LTE in guard band mode, the impact is very small and the two can coexist.

In [3], come challenges of NBIoT in the health care sector are discussed. It is stated that one of the main drawbacks in healthcare IoT is that hospitals in rural areas are not well equipped with health monitoring system that can be upgraded with evolving technologies like IoT. Also, the lack of adequate security in the data transfer imposes a security breach since some of the patient data is very sensitive and confidential. The use of different devices with differing standards also makes it difficult to coordinate in the NBIoT application. It is also noted that there are several applications in healthcare that demand real-time communication and information exchange. The 180 kHz bandwidth of NBIoT is not capable to support these requirements.

In [4], a model NBIoT network is constructed using a software called OPTNET to verify the characteristics of NBIoT. The simulations done verified, as defined by the 3GPP, that the main characteristics of NBIoT, i.e. wide coverage, latency less than 10s and high channel utilization. It was seen that in comparison with LTE network with channel bandwidth of 3MHz, 5MHz, 10MHz, 15MHz and 20MHz, respectively, PUSCH Utilization, PDSCH Utilization and PDCCH Utilization of NBIoT are higher, 40%, 42% and 57% respectively.

In [6], a study of NBIoT partial deployment is done. This is the case when only a fraction of the existing LTE cell sites support NBIoT. It is seen that NBIoT devices cannot attach to the best cell if that cell does not yet support NBIoT, resulting in very high path loss. The NBIoT cells also suffer interference from non NBIoT cells. It is proven that the high path loss can be compensated by techniques like power boosting, narrowband transmission, coverage extension using repetition, and interference mitigation techniques such as resource blanking.

In [8] a detailed evaluation of the coverage performance of NBIoT is provided. Simulations done show that compared with existing LTE technology, NBIoT can provide up to 20 dB coverage enhancement in various deployment scenarios.

In [30], research is done to enhance the coverage of NBIoT beyond the 3GPP specified 35km. This is achieved by proposing to set a traffic delay in the baseband unit that supposes the radio unit transmitter is at a far distance that it really is. In so doing, the coverage of the NBIoT system will extend beyond 35km.

2.8 Chapter 2 summary

In this chapter, the theoretical framework of 3GPP NBIoT was discussed. The NBIoT design objectives and advantages are outlined, showing why NBIoT is preferred in low throughput IoT applications. The NBIoT deployment modes were also discussed, looking more into their pros and cons, which basically informs the decision making on which mode to use for any particular application. Both the uplink and downlink frame structures of NBIoT were discussed in this chapter, and all the relevant channels in both the uplink and downlink were looked at in detail. The NBIoT key parameters which are critical in the design of the NBIoT network were also explored, showing how each parameter contributes to the design of the NBIoT network. Lastly, this chapter looked at the related work and achievements made so far in the IoT industry, closely looking at the NBIoT industry in particular.

3 Methodology

The flow chart below shows how the work of this research was done. Firstly is the problem formulation which is followed by literature review. The methodology follows, explaining how this research flowed from start to finish. Lastly, simulations are done using Matlab. The results are presented and an analysis of each set of results is done, and conclusions are drawn thereof.

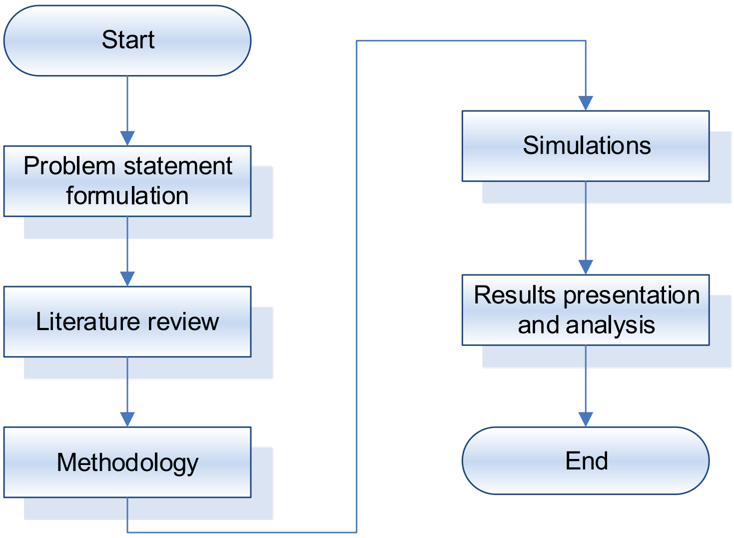


Figure 8 – Methodology flow chart

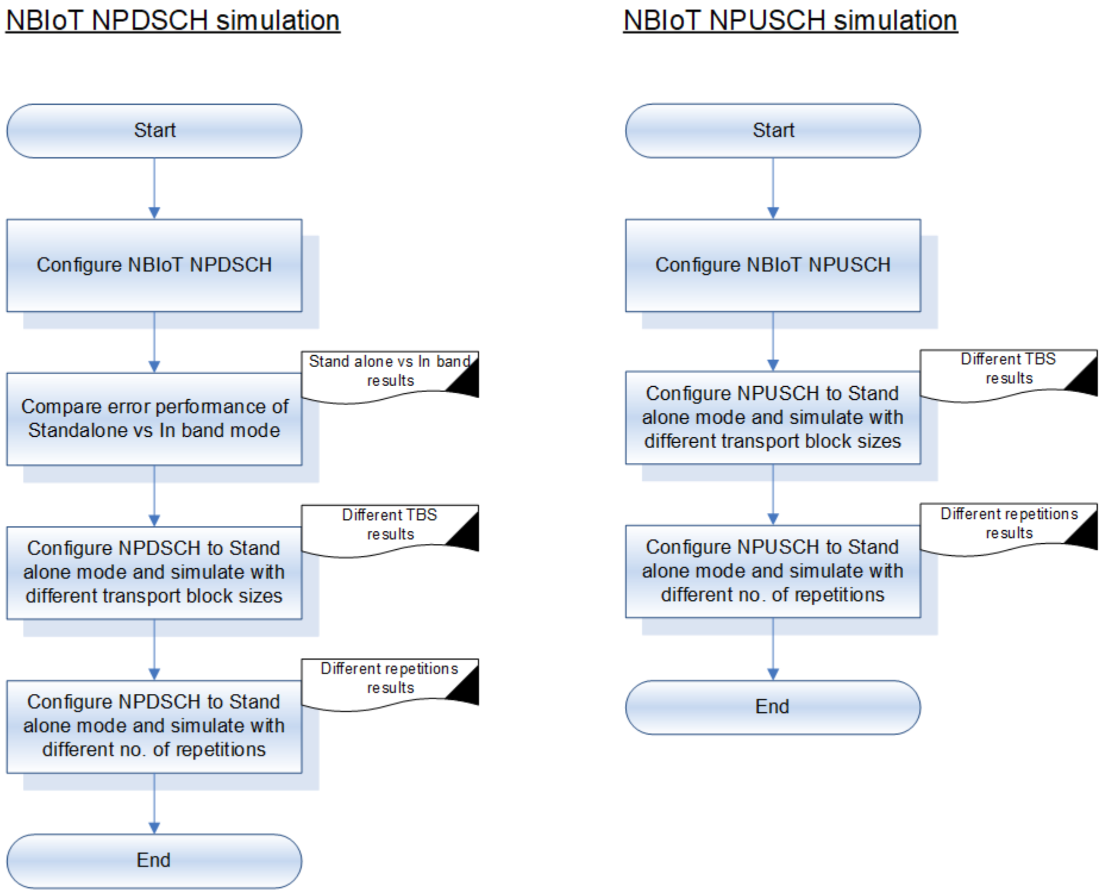
3.1 Research main objective

The key problem about NBIoT for prospective operators is on the uncertainty of the error performance of this technology as it is still relatively new on the market, have just joined the LPWAN community with strong competitors like Sigfox and LoRA [33]. Spectrum is a limited resource and NBIoT will in many cases share spectrum with existing technologies, thereby introducing an interference threat both on the NBIoT system and to the host system [1] [4] [16].

The main objective of this research was therefore to simulate the error performance of the NBIoT system under different deployment modes and different key parameter settings. The main derivative was to see how the different deployment modes and parameter settings affect the error performance. This led to some recommendations made to prospective NBIoT operators on the best parameter settings to achieve acceptable error rate in the NBIoT system.

3.2 Method of procedure

In order to achieve the results of this research, simulations were done using the NBIoT physical channels both on the uplink (NPUSCH) and downlink (NPDSCH). The physical channels are the ones that transport the actual payload in the NBIoT system hence simulating the error performance in these channels showed a true picture of the subscriber experience. The two flow charts below show the actual test procedure for both the uplink and the downlink.



NBIoT NPDSCH simulation

NBIoT NPUSCH simulation

Figure 9 - NBIoT UL and DL simulation procedure

The NBIoT parameters that were used to simulate the errors are:

- NBIoT deployment mode
- Number of transport blocks
- Number of repetitions

The above three parameters were varied according to the above flowchart in order to get the error performance of the NBIoT system. The following subsections briefly explain how each of these three parameters were varied to get the expected results.

3.2.1 Comparison of standalone vs in-band mode

In [1] an overview of NBIoT in the guard band is provided. It is shown that NBIoT and LTE can coexist with negligible interference. In [6] and [8], the error performance of the NBIoT system in the in-band mode is studied and presented.

This study seeks to compare the error performance of two different deployment modes in the NBIoT system. Two of the three possible deployment modes for NBIoT are standalone and in-band. The first step of the tests was to compare these two modes to see the error performance. It was expected that standalone mode will have better performance than in-band as there is less interference from other technologies (usually LTE). The results were plotted and conclusions drawn thereof.

3.2.2 Comparison of different transport block sizes

Transport block is data from the upper layer (or MAC) given to the physical layer in LTE/ NBIoT system. The size of this block of data is referred to as Transport Block Size (TBS). In the uplink, the TBS ranges from 2 bytes (16 bits) to 125 bytes (1000 bits). In the downlink, TBS ranges from 2 bytes (16 bits) to 85 bytes (680 bits). TBS is determined by the number of sub frames according to the specifications 3GPP TS 36.213 in table 16.4.1.5.1-1 [14].

In order to get the results of the error performance of the NBIoT system in relation to different transport block sizes, the parameter TBS was varied and simulations done with each TBS value. It was expected that a too big TBS value will result in poor error performance as sending a big chunk of data at once makes the error correction process more difficult that when data is sent in smaller bits.

3.2.3 Comparison of different number of repetitions

NBIoT allows excessive repetitions of up to 2048 in the downlink and 128 in the uplink. Repetition is a technique of transmitting several self-decodable signals multiple times to achieve extra coverage [13]. NBIoT defines three different Coverage Enhancement (CE) levels through the System Information Block SIB2-NB, these are CE0 (normal coverage), CE1 (robust coverage) and CE2 (extreme coverage) [15]. The number of repetitions relate to other parameters like the variable scheduling info SIB1 according to the specifications 3GPP TS 36.213 in table 16.4.1.3-2 and table 16.4.1.3-3 [14]. Different number of repetitions were used to simulate the error performance of the NBIoT in this design to see how the number of repetitions affect the performance of the system.

3.3 Background and rationale for the design

As shown in chapter 2, the NBIoT system uses channels both for signalling and payload transportation. The NPUSCH and NPDSCH physical channels are specifically used for payload transportation in the uplink and downlink respectively [18]. The user experience is mainly measured on these payload carrying channels since they are the ones that transport the actual user data. For this reason, the simulations were done on these two channels for the purpose of this research.

It was also chosen to do simulations comparing two different deployment modes, i.e. standalone and in-band. These two were chosen because standalone is likely to be used by operators with excess GSM spectrum, where as in-band is likely to be used by operators who do not have spectrum to dedicate to NBIoT. Guard band was not be done because its error performance is likely to be similar to that of in-band as the two are technically very close to each other.

The two other chosen parameters (TBS and number of subframe repetitions) were preferred for simulation because amongst other parameters listed in chapter 2, these two are the ones which operators have most control of and they can tune these in order to optimise the performance of the NBIoT network.

3.4 Limitations of the design

The work done in this research was limited to software simulations. This is because in the country where this research was done, there was no NBIoT live network to do the actual tests on. Also, the NBIoT spectrum is licensed and even if there was equipment to use for this work, there would still be need for the licencing of the work and this licensing process takes a long time and requires significant amounts of money.
The NBIoT system has many parameters, it would be difficult to get a perfect all round simulation to satisfy all parameter settings. For this reason, certain assumptions had to be made. The following section summarises the assumptions made in this work.

3.4.1 Communication channel model

For the purposes of this research, Additive White Gaussian Noise (AWGN) was assumed in the communication channel. The AWGN is statistically random radio noise characterized by a wide frequency range, which assumes a linear addition of wideband or white noise with a constant spectral density and a Gaussian distribution of amplitude, without accounting for fading, frequency selectivity, interference and non-linearity or dispersion.

In real live communication, the propagation channel is characterized by either Rician or Rayleigh propagation channel models. Rician is where there is a dominant signal in the signal line of sight, whereas Rayleigh has no dominant signal in the line of sight, typically in built up areas like CBDs where there is a lot of signal reflection.

The AWGN channel is theoretical and was assumed because real practical simulations could not be done due to reasons explained in the beginning of section 3.4.

3.4.2 3GPP Release

3GPP is a collaboration of a number of telecommunication standards associations that focus on the development of telecommunication standards. The standards are classified into releases, with each release focusing on specific technologies like 2G, 3G, LTE, NBIoT, etc. NBIoT is standardise in 3GPP release13 and a single NBIoT UE category, namely Cat-NB1, is defined. Release 14 adds Cat-NB2 which allows for larger transport block sizes.

For the purpose of this work, 3GPP release 13 and 14 were assumed in order to simulate for large TBS size and get significant results on the variation of error performance with TBS.

3.4.3 Uplink transmission

In the uplink, NBIoT can use either single tone or multi tone transmission modes. Single tone is mandatory and used to provide capacity in poor coverage areas. It can be implemented with a carrier spacing of either 15 kHz or 3.75 kHz with time duration of 0.5ms and 2ms respectively. Multi tone is optional and used to provide higher data rates for devices in normal coverage. It is implemented with carrier spacing of 15 kHz and 0.5ms duration.

For the purposes of this work, a standard 15 kHz spacing frame of 0.5ms duration was assumed. This has advantages in that it has better compatibility with LTE since LTE uses the same frame size, and hence very practical for consideration by operators who intend to deploy NBIoT.

3.4.4 NPDSCH data type

In NBIoT, the physical channel NPDSCH can be one of the below three types:

- SIB1NB: which indicates that the NPDSCH is carrying BCCH.
- BCCHNoTSIB1NB: which indicates that the NPDSCH is carrying BCCH.
- NotBCCH: which indicates that the NPDSCH is not carrying BCCH.

NBIoT uses the parameter ***NPDSCHDataType*** to define the type of the NPDSCH.

For the purposes of this work, ***NPDSCHDataType = NotBCCH*** was assumed to make sure the whole data sent has no other control information related to broadcast parameters.

3.4.5 Modulation and Coding Scheme (MCS)

When transmitting data in a communication channel, depending on the RF environment, a coding scheme and modulation type is chosen and the combination of the two (referred to as MCS) determines the data rate of the transmission.

The Modulation Coding Scheme (MCS) is related to the Modulation Order, defined as Q_m in 3GPP. The general mapping of Q_m to modulation method is shown in the table below, and NBIoT uses $Q_m = 2$, i.e. QPSK.

Q_m	Modulation method
2	QPSK
4	16 QAM
6	64 QAM
8	256 QAM

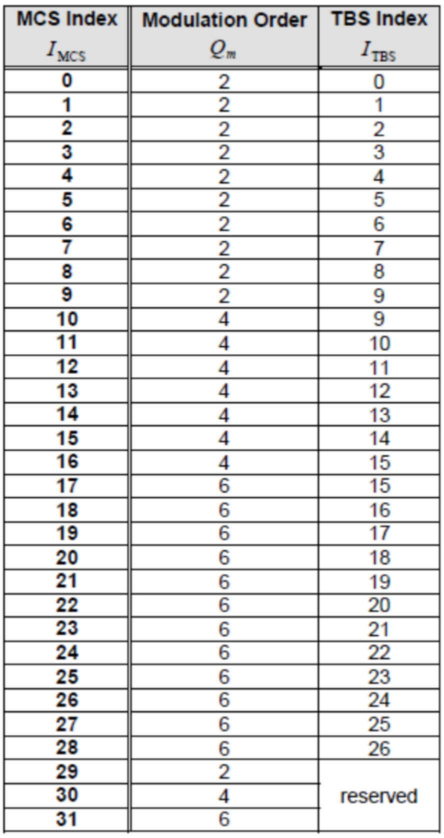
Table 2 - Modulation method

For downlink MCS, the following 3GPP TS 36.213 tables are used to map MCS to Q_m:

1. Table 7.1.7.1-1: Modulation and TBS index table for PDSCH
2. Table 7.1.7.1-1A. Modulation and TBS index table 2 for PDSCH

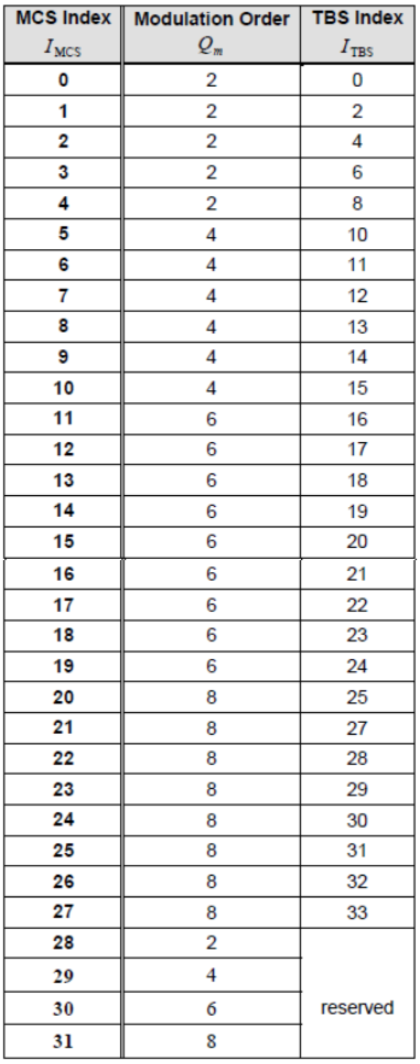
These two tables are shown below. The first table (Table 7.1.7.1-1) is for UEs that do not support 256QAM while the second table (Table 7.1.7.1-1A) if for UEs that support 256QAM. The eNodeB becomes aware of the UE capability through the UE Capability Information message sent by the UE to the eNodeB.

For the purposes of this work, UEs that do not support 256QAM were assumed. This means that the first table (i.e. Table 7.1.7.1-1) was used.



MCS Index I_{MCS}	Modulation Order Q_m	TBS Index I_{TBS}
0	2	0
1	2	1
2	2	2
3	2	3
4	2	4
5	2	5
6	2	6
7	2	7
8	2	8
9	2	9
10	4	9
11	4	10
12	4	11
13	4	12
14	4	13
15	4	14
16	4	15
17	6	15
18	6	16
19	6	17
20	6	18
21	6	19
22	6	20
23	6	21
24	6	22
25	6	23
26	6	24
27	6	25
28	6	26
29	2	reserved
30	4	
31	6	

Table 3 - Modulation and TBS index table for PDSCH (source: 3GPP TS 36.213 Table 7.1.7.1-1)



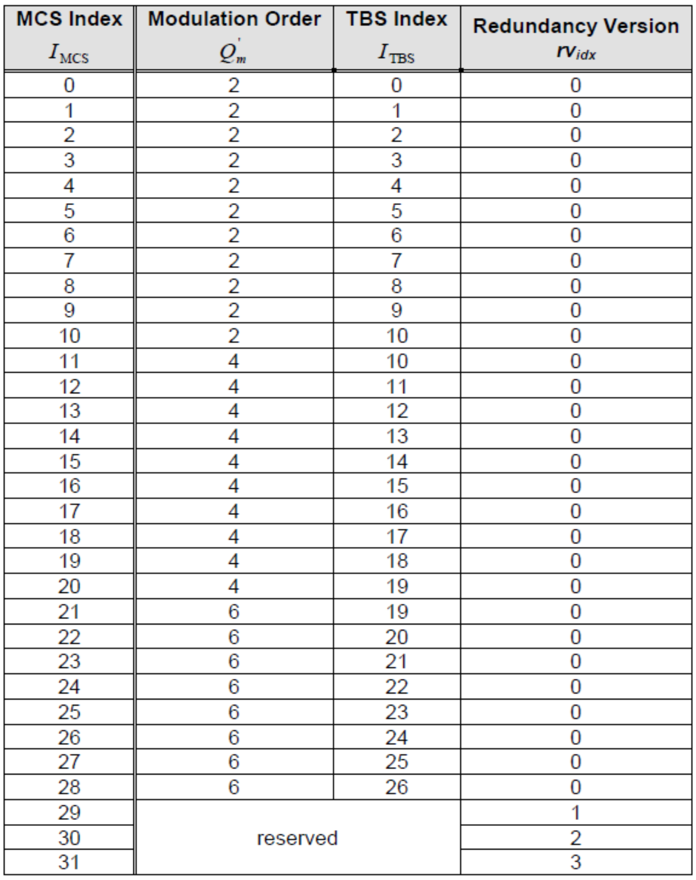
MCS Index I_{MCS}	Modulation Order Q_m	TBS Index I_{TBS}
0	2	0
1	2	2
2	2	4
3	2	6
4	2	8
5	4	10
6	4	11
7	4	12
8	4	13
9	4	14
10	4	15
11	6	16
12	6	17
13	6	18
14	6	19
15	6	20
16	6	21
17	6	22
18	6	23
19	6	24
20	8	25
21	8	27
22	8	28
23	8	29
24	8	30
25	8	31
26	8	32
27	8	33
28	2	reserved
29	4	
30	6	
31	8	

Table 4 - Modulation and TBS index table 2 for PDSCH (source: 3GPP TS 36.213 Table 7.1.7.1-1A)

For Uplink MCS, the 3GPP TS 36.213 Table 8.6.1-1 (Modulation, TBS index and redundancy version table for PUSCH) is used. The difference in the Q_m values for DL and UL is that in the UL, the mapping of Q_m = 6 varies depending on UE capability as follows:

1. Q_m = 6 means 16QAM if UE does not support 64QAM
2. Q_m = 6 means 64QAM if UE support 64QAM

The 3GPP TS 36.213 Table 8.6.1-1 is shown below.



MCS Index I_{MCS}	Modulation Order Q'_m	TBS Index I_{TBS}	Redundancy Version rv_{idx}
0	2	0	0
1	2	1	0
2	2	2	0
3	2	3	0
4	2	4	0
5	2	5	0
6	2	6	0
7	2	7	0
8	2	8	0
9	2	9	0
10	2	10	0
11	4	10	0
12	4	11	0
13	4	12	0
14	4	13	0
15	4	14	0
16	4	15	0
17	4	16	0
18	4	17	0
19	4	18	0
20	4	19	0
21	6	19	0
22	6	20	0
23	6	21	0
24	6	22	0
25	6	23	0
26	6	24	0
27	6	25	0
28	6	26	0
29	reserved		1
30			2
31			3

Table 5 - Modulation, TBS index and redundancy version table for PUSCH (source: 3GPP TS 36.213 Table 8.6.1-1)

3.4.6 Chapter 3 summary

In this chapter, a discussion of the methodology was done. A basic flow of this design was illustrated, and the main research objective was stated. A method of procedure for the simulation process, both uplink and downlink, was discussed as well. A high level look on the three deployment modes of NBIoT was done, showing which mode is best fit to use for which deployment scenario. In addition, a rationale for the design was revealed, and lastly, the limitations of this design we discussed.

4 Design

The simulation of the error performance of the NBIoT system was done according the procedure outlined in chapter 3. The following subsections give detail on the actual design used for simulating the error performance of the NBIoT system. Firstly, the simulation in the uplink is discussed, stating all the relevant 3GPP tables used for parameter derivation. The downlink simulation process was discussed next and the best parameter setting for both the uplink and downlink was recommended.

4.1 NPDSCH BER simulation

The NPDSCH simulation block diagram is shown below. The blocks are discussed briefly in the following sub sections.

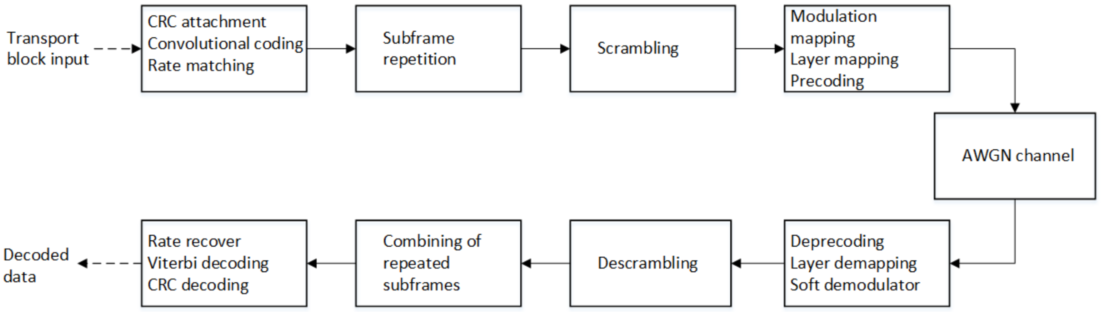


Figure 10 - NPDSCH BER simulation block diagram

4.1.1 Transport block input

This is the actual initial data that is to be sent through the NBIoT system. The size of this data is called the Transport Block Size (TBS). The TBS is derived from a combination of the tables in 3GPP TS 36.213 [14] indicating modulation, subframe sizing and transport block sizes, which have been provided by Table 6, 7 and 8 below.

We begin with table 6 (3GPP TS 36.213 table 7.1.7.1-1), with a given Modulation and Coding Scheme (MCS) Index (I_{MCS}), we can get the Transport Block Size Index (I_{TBS}) (knowing that modulation order is QPSK in NBIoT).

In table 7 (3GPP TS 36.213 table 16.4.1.3-1), we can determine the number of subframes (N_{SF}) using the resource assignment Index I_{SF}).

With all these values, we can then determine the actual TBS from table 8 (TS table 16.4.1.5.1-1).

For the purposes of this work the following values were used:

I_{SF} = 0 (one subframe)

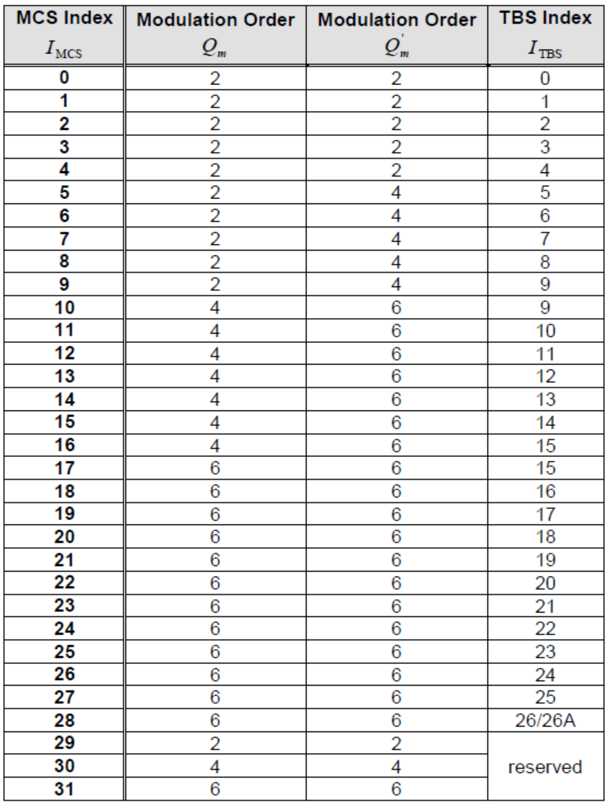
I_{MCS} = 4→ I_{TBS} = 4

Therefore:

TBS = 56.

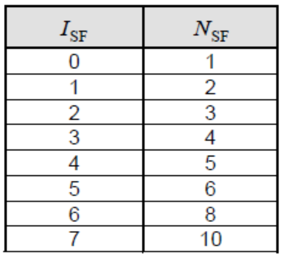
The parameter I_{SF} was varied to 6 (8 subframes) which is TBS = 552.

Therefore, error performance for two TBS values (56 and 552) was simulated and a comparison done.



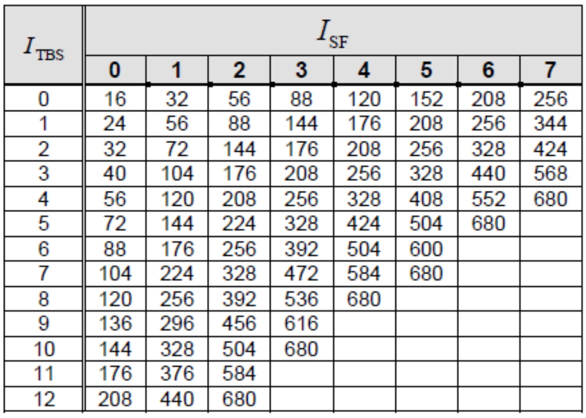
MCS Index I_{MCS}	Modulation Order Q_m	Modulation Order Q'_m	TBS Index I_{TBS}
0	2	2	0
1	2	2	1
2	2	2	2
3	2	2	3
4	2	2	4
5	2	4	5
6	2	4	6
7	2	4	7
8	2	4	8
9	2	4	9
10	4	6	9
11	4	6	10
12	4	6	11
13	4	6	12
14	4	6	13
15	4	6	14
16	4	6	15
17	6	6	15
18	6	6	16
19	6	6	17
20	6	6	18
21	6	6	19
22	6	6	20
23	6	6	21
24	6	6	22
25	6	6	23
26	6	6	24
27	6	6	25
28	6	6	26/26A
29	2	2	reserved
30	4	4	
31	6	6	

Table 6 - Modulation and TBS index table for PDSCH (source: 3GPP TS 36.213 Table 7.1.7.1-1)



I_{SF}	N_{SF}
0	1
1	2
2	3
3	4
4	5
5	6
6	8
7	10

Table 7 - Number of subframes (N_{SF}) for NPDSCH (source: 3GPP TS 36.213 Table 16.4.1.3-1)



I_{TBS}	I_{SF}							
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**
0	16	32	56	88	120	152	208	256
1	24	56	88	144	176	208	256	344
2	32	72	144	176	208	256	328	424
3	40	104	176	208	256	328	440	568
4	56	120	208	256	328	408	552	680
5	72	144	224	328	424	504	680	
6	88	176	256	392	504	600		
7	104	224	328	472	584	680		
8	120	256	392	536	680			
9	136	296	456	616				
10	144	328	504	680				
11	176	376	584					
12	208	440	680					

Table 8 - Transport block size (TBS) table (source: 3GPP TS 36.213 Table 16.4.1.5.1-1)

For the purposes of this work, two values of TBS were used as follows to compare the error performance of the NBIoT system in the downlink:

1. TBS = 56 ($I_{SF} = 0$, $I_{MCS} = 4$)
2. TBS = 552 ($I_{SF} = 6$, $I_{MCS} = 4$)

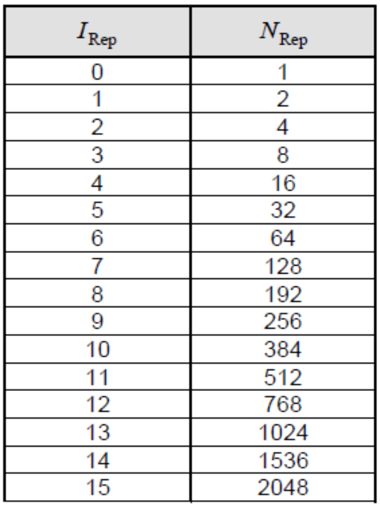
4.1.2 CRC attachment, convolutional coding and rate matching

This is the first step of the simulation. The desired Transport Block Size (TBS) is attached with a Cyclic Redundancy Check (CRC) code for error detection. The signal is then convolutional coded to ensure the reliability and security of the data. The following step will be that of rate matching, where the exact set of bits to be transmitted within a Transmission Time Interval (TTI) is extracted. After this step, a frame of data is ready to be pushed forward and the next step is the repetition of this data.

4.1.3 Sub-frame repetition

NBIoT employs the concept of repetition, i.e. sending the same data multiple times to ensure its successful delivery and increase the coverage. The number of repetitions (N_{rep}) in NBIoT is defined using the repetition index (I_{rep}) according to table 9 (3GPP TS 36.213 table 16.4.1.3-2) shown below [14]. I_{rep} ranges from 0 to 15, which translates to number of repetitions from 1 to 2048 in the downlink.

For the purposes of this work, two values of repetition index, I_{rep} = 0 and I_{rep} = 1 (corresponding to N_{rep} =1 and N_{rep} = 2 respectively) were used to see how the error performance varies with different number of repetitions.



I_{Rep}	N_{Rep}
0	1
1	2
2	4
3	8
4	16
5	32
6	64
7	128
8	192
9	256
10	384
11	512
12	768
13	1024
14	1536
15	2048

Table 9 - Number of repetitions (N_{REP}) for NPDSCH (source: 3GPP TS 36.213 Table 16.4.1.3-2)

4.1.4 Scrambling

The next step will be that of scrambling. The data will be sent repeatedly according to the set number of repetitions. The same block of data might not fit into one TTI. i.e. some blocks might overlap and be sent in different times. The purpose of scrambling is to have all repetitions of data share the same scrambling mask. This means that the transmitted symbol in one subframe will be identical to those in another subframe carrying the same data, i.e. have the same scrambling mask. The figure below illustrates the concept of scrambling in the case of data transmitted with eight repetitions.

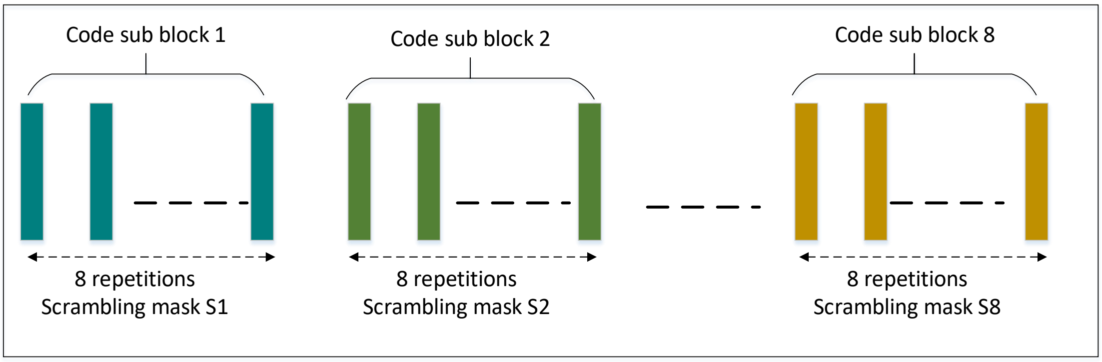


Figure 11 – NPDSCH scrambling

4.1.5 Modulation mapping, layer mapping and precoding

After the data has been scrambled, the next step is modulation mapping. This is where the data is converted into the IQ signals to be transmitted. Table 10 shows the NBIoT QPSK modulation mapping table. The next step will be that of Layer mapping. This is where streams that can be transmitted per antenna port are created. The maximum number of streams that can be created equals the number of the physical antenna ports to be used to transmit the data. Then the next stage will be precoding, where the formed streams are distributed into available antenna ports. The streams are mixed and equally weighted such that each stream is precoded to carry a particular content of every code word to be transmitted.

b(n), b(n+1)	I	Q
00	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$
01	$\frac{1}{\sqrt{2}}$	$-\frac{1}{\sqrt{2}}$
10	$-\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$
11	$-\frac{1}{\sqrt{2}}$	$-\frac{1}{\sqrt{2}}$

Table 10 - NBIoT QPSK modulation mapping

The data is then sent through the communication channel, which in this case is assumed to be Additive White Gaussian Noise (AWGN) channel.

4.1.6 Receiving process of the transmitted data

The receiving process is simply a reverse of all the transmit processes in the reverse order. The process begins with deprecoding, where various streams are recovered from the receiving antenna ports, before they are combined in the layer demapping process. The data is then demodulated into bits and scrambling masks are then used to identify bits of the same code word in the descrambling process. The repeated subframes are combined to form the received data. The CRC codes are checked for data integrity to check for errors. The decoded data is then successfully recovered. The Block Error Rate (BLER) is then calculated as the rate of errors in the received decoded data.

4.2 NPUSCH BER simulation

NPUSCH simulation block diagram is shown below. Most of the processes are similar to the downlink processes discussed above. The blocks that are not part of the downlink process and other relevant ones are discussed briefly in the following sub sections.

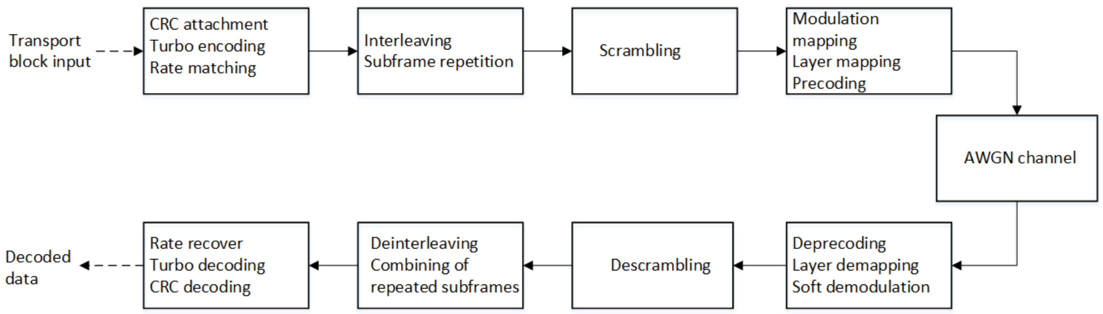


Figure 12 – NPUSCH BER simulation block diagram

4.2.1 Transport block input

The input to the uplink simulation process is the transport block, with a specific size determined by a combination of the tables in 3GPP TS 36.213 [14], which have been provided by Table 12, 13 and 14 below.

Table 12 (3GPP TS 36.213 table 16.5.1.1-2) gives the number of resource units from the resource index. The Resource Unit (RU) is the basic unit of resource allocation for NPUSCH. The table below shows the supported combinations of the following three parameters:

1. Number of RUs per subcarrier (N^{RU}_{SC})
2. Number of uplink time slots per RU (N^{UL}_{slots})
3. Number of symbols per time slot (N^{UL}_{symb})

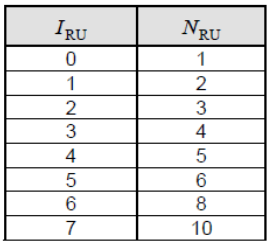
NPUSCH format	Δf	N^{RU}_{SC}	N^{UL}_{slots}	N^{UL}_{symb}
1	3.75 kHz	1	16	7
	15 kHz	1	16	
		3	8	
		6	4	
		12	2	
2	3.75 kHz	1	4	
	15 kHz	1	4	

Table 11 – NPUSCH format supported combinations (source: 3GPP TS 36.211 V13.2.0 Table 10.1.2.3-1) [19]

For the purpose of simulation the simulation design was restricted to using the following parameters:

1. NPUSCH format = 1
2. NPUSCH subcarrier spacing = 15kHz
3. NPUSCH number of RUs per subcarrier = 1
4. NPUSCH number of time slots per RU = 16
5. NPUSCH number of symbols per time slot = 7

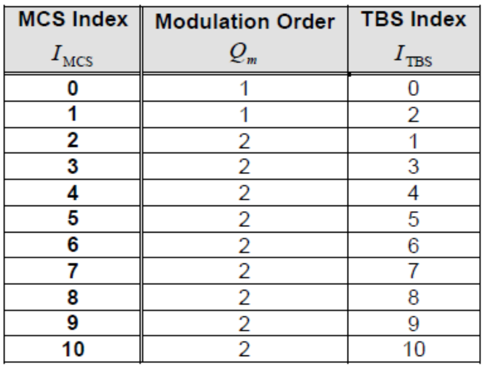
With the above parameter setting, the RU Index (I_{RU}) from table 12 will be 0.



I_{RU}	N_{RU}
0	1
1	2
2	3
3	4
4	5
5	6
6	8
7	10

Table 12 - Number of resource units (N_{RU}) for NPUSCH (source: 3GPP TS 36.213 Table 16.5.1.1-2)

The Modulation and Coding Scheme Index (I_{MCS}) 4 was used as in the case with downlink. From Table 13 (3GPP TS 36.213 table 16.5.1.2-1), the Transport Block Size Index (I_{TBS}) was set to 4.



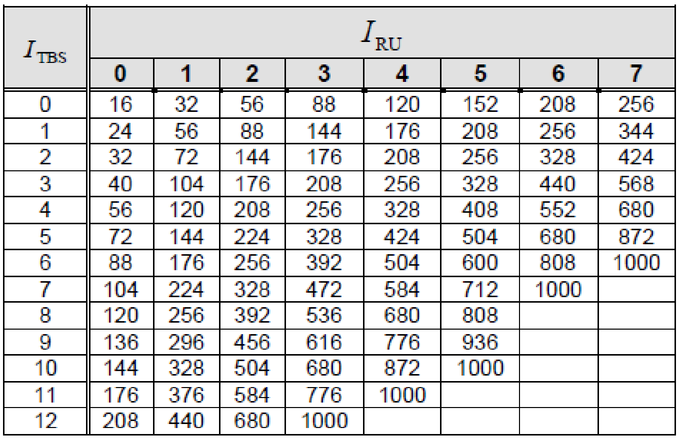
MCS Index I_{MCS}	**Modulation Order** Q_m	**TBS Index** I_{TBS}
0	1	0
1	1	2
2	2	1
3	2	3
4	2	4
5	2	5
6	2	6
7	2	7
8	2	8
9	2	9
10	2	10

Table 13 - Modulation and TBS index table for NPUSCH (source: 3GPP TS 36.213 Table 16.5.1.2-1)

We now make use of Table 14 (3GPP TS 36.213 table 16.5.1.2-2) to derive the Transport Block Size (TBS).

Two simulation sets were done with the following parameter settings:

1. $I_{TBS} = 4$, $I_{RU} = 0$ → TBS = 56
2. $I_{TBS} = 4$, $I_{RU} = 6$ → TBS = 552



I_{TBS}	I_{RU}							
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**
0	16	32	56	88	120	152	208	256
1	24	56	88	144	176	208	256	344
2	32	72	144	176	208	256	328	424
3	40	104	176	208	256	328	440	568
4	56	120	208	256	328	408	552	680
5	72	144	224	328	424	504	680	872
6	88	176	256	392	504	600	808	1000
7	104	224	328	472	584	712	1000	
8	120	256	392	536	680	808		
9	136	296	456	616	776	936		
10	144	328	504	680	872	1000		
11	176	376	584	776	1000			
12	208	440	680	1000				

Table 14 - Transport block size (TBS) table for NPUSCH (source: 3GPP TS 36.213 Table 16.5.1.2-2)

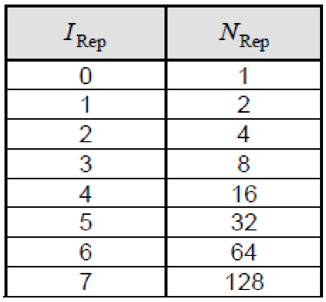
4.2.2 Data bit interleaving

After the process of rate matching, the next step will be that of Interleaving. This is where a technique to separate successive bits is employed. This is done to make sure that successive bits are not affected by impulse noise since they are transmitted dispersed by this technique, and makes error detection and correction more successful. Interleaving is necessary in the uplink because the devices transmit with low power in the uplink than the eNode B does in the downlink. This exposes uplink data to interference and hence the use of interleaving is very critical.

In the receiver end, the reverse process, i.e. deinterleaving, is carried out after the combining of repeated frames. This is part of the error detection process where errors are detected and corrected.

4.2.3 NPUSCH subframe repetition

Subframe repetition in the uplink is similar to that of the downlink discussed earlier. The number of NPUSCH repetitions (N_{rep}) in NBIoT is defined using the repetition index (I_{rep}) according to table 15 (3GPP TS 36.213 table 16.5.1.1-3) shown below [14]. In the uplink, I_{rep} ranges from 0 to 7, which translates to the number of repetitions from 1 to 128. For the purposes of this work, two values of repetition index, $I_{rep} = 0$ and $I_{rep} = 1$ (corresponding to $N_{rep} =1$ and $N_{rep} = 2$ respectively) were used to see how the error performance varies with different number of repetitions.



I_{Rep}	N_{Rep}
0	1
1	2
2	4
3	8
4	16
5	32
6	64
7	128

Table 15 - Number of repetitions (N_{REP}) for NPUSCH (source: 3GPP TS 36.213 *Table 16.5.1.1-3)*

4.3 Summary of parameters used for the simulations

The simulation was divided into two sections which are:

- downlink (NPDSCH) simulation
- uplink (NPUSCH) simulation

Each section was further divided into two subsections which are:

- TBS simulation
- Subframe repetition simulation

The summary presented below show the parameters that were used according to these two simulation sections.

4.3.1 NPDSCH (downlink) parameters

This section summarises the parameters that were used in the downlink simulation. The parameters were derived from the 3GPP tables discussed in sections above.

Transport block size parameters

- Modulation method Q_m = 2 which means QPSK
- Subframe Index I_{SF} = 0, giving Number of subframes N_{SF} = 1
- Modulation and Coding Scheme Index I_{MCS} = 4, giving Transport Block Size Index I_{TBS} = 4
- The above parameters give Transport Block Size TBS = 56
- I_{SF} was varied to 6, giving N_{SF} = 8, resulting in TBS = 552

Subframe repetition parameters

- Repetition Index IREP = 0, giving Number of repetitions NREP = 1
- IREP was varied to 1, which gives Number of repetitions NREP = 2

4.3.2 NPUSCH (uplink) parameters

This section summarises the parameters that were used in the uplink simulation. The parameters were derived from the 3GPP tables discussed in the sections above.

Transport block size parameters

- Modulation method Qm = 2 which means QPSK
- NPUSCH format = 1 (NPUSCH subcarrier spacing = 15kHz, NPUSCH number of RUs per subcarrier = 1, NPUSCH number of time slots per RU = 16, NPUSCH number of symbols per time slot = 7)
- Resource Unit Index IRU = 0, giving number of Resource Units NRU = 1
- Modulation and Coding Scheme Index IMCS = 4, giving Transport Block Size Index ITBS = 4
- The above parameters give Transport Block Size TBS = 56
- IRU was varied to 6, which is NRU = 8, giving TBS = 552

Subframe repetition parameters

- Repetition Index IREP = 0, giving Number of repetitions NREP = 1
- IREP was varied to 1, which gives Number of repetitions NREP = 2

4.3.3 Chapter 4 summary

In this chapter, the actual design of the project was discussed. The block diagrams of the flow (both uplink and downlink) were shown and each blocked briefly discussed to show its purpose in the flow. The actual parameters used in the simulations were also summarised, with reference to 3GPP TS 36.213. The Transport Block Size (TBS) derivation, number of repetitions derivation and other related parameters are clearly shown with reference to the relevant 3GPP tables in 3GPP TS 36.213.

5 Simulation results

This section presents the results of the simulations that were done according to parameter settings in chapter 4. The following five sets of simulation results are presented:

- BER simulation of In-band vs standalone mode
- BER simulation of different TBS in the downlink
- BER simulation of different repetitions in the downlink
- BER simulation of different TBS in the uplink
- BER simulation of different repetitions in the uplink

The following subsections present and discuss these results in the above listed order. The x-axis is the signal to noise ratio (SNR), which is defined as the ratio of the wanted signal power to the unwanted signal power, given by the following formula:

$$SNR = \frac{Signal\ power}{Noise\ power}$$

Higher SNR values means signal quality is good and there is less interference.

The y-axis is the bit error rate (BER) which is defined as the ratio of bit errors to the total number of transmitted bits, given by the following general formula:

$$BER = \frac{Number\ of\ bit\ errors}{Total\ number\ of\ transmitted\ bits}$$

5.1 NPDSCH BER simulation – In-band vs Standalone mode

NBIoT can be deployed in the following possible three deployment modes:

- Standalone mode
- In-band mode
- Guard band mode

The first simulations done were to compare the error rate of the NBIoT system when deployed in standalone mode compared to in-band mode. Figure 13 shows the outcome of the simulation,

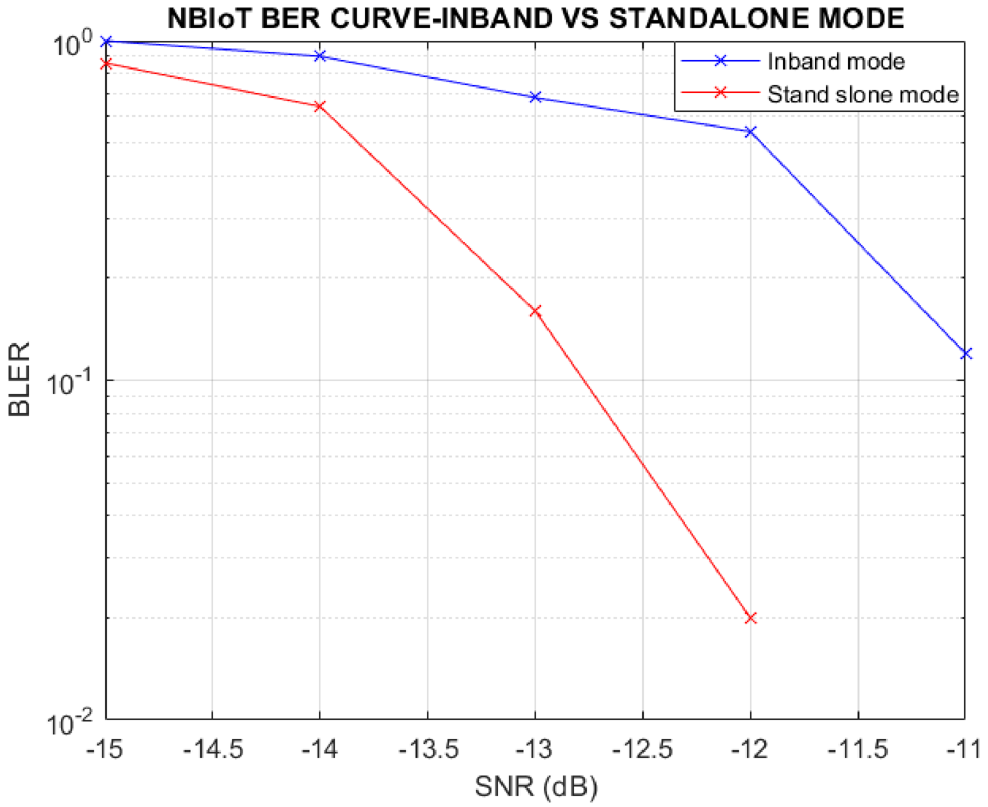


Figure 13 - NPDSCH BER simulation – In-band vs Standalone mode

<u>Result analysis and discussion</u>

From the above figure, it can be observed that for the same signal quality, i.e. for the same Signal to Noise Ratio (SNR), the error rate of Standalone mode is less than that of In-band mode. The error rates of the two mode are close for poor quality signal, but the gap increases as the signal quality improves.

The above observation is expected since in standalone deployment mode there is less interference from other technologies than in In-band mode. NBIoT deployed in standalone mode has a better error performance that that deployed in In-band mode due to less interference in the former compared to the later.

5.2 NPDSCH BER simulation – Transport Block Size

The second simulation was to compare the error performance of the NBIoT system using different transport block sizes (TBS) in the downlink, which ranges from 16 to 680 bits. TBS is the block size of data that is transmitted at an instant. Figure 14 shows the result of this simulation. Two TBS values were chosen, one that is small and the other big to make the comparison very clear.

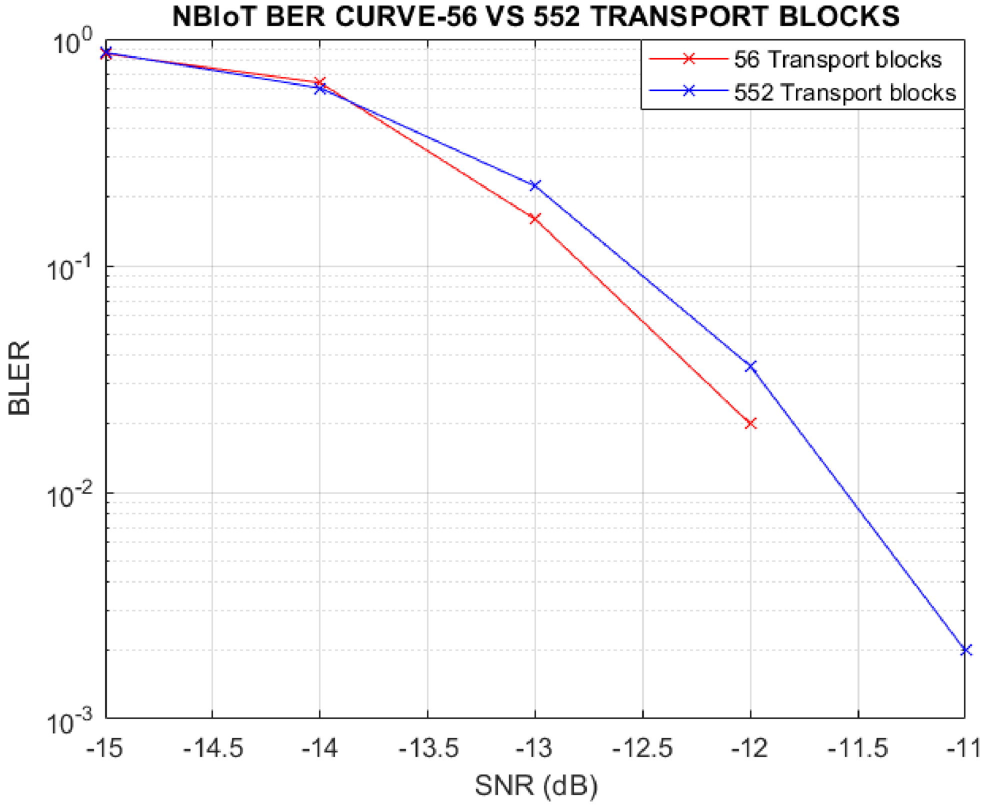


Figure 14 - NPDSCH BER simulation – Transport Block Size

Result analysis and discussion

The results above show that the error rate is higher when data is transmitted with higher transport block sizes than with smaller ones.

If data is transmitted as a bigger block, the probability of error becomes higher and that explains the above results. For NBIoT operators, information should be transmitted in smaller transport block sizes so as to minimise the error rate. This should not be a problem since the amount of data to be sent on NBIoT networks is relatively very low compared to other legacy networks like 3G and LTE.

5.3 NPDSCH BER simulation - Subframe repetition

The third simulation was to compare the error performance using different number of subframe repetition in the downlink. The concept of subframe repetition is used in NBIoT, where the same data is transmitted multiple times to increase the changes of receiving it. Two values (1 and 2) were chosen for the simulations. Figure 15 shows the result of this simulation.

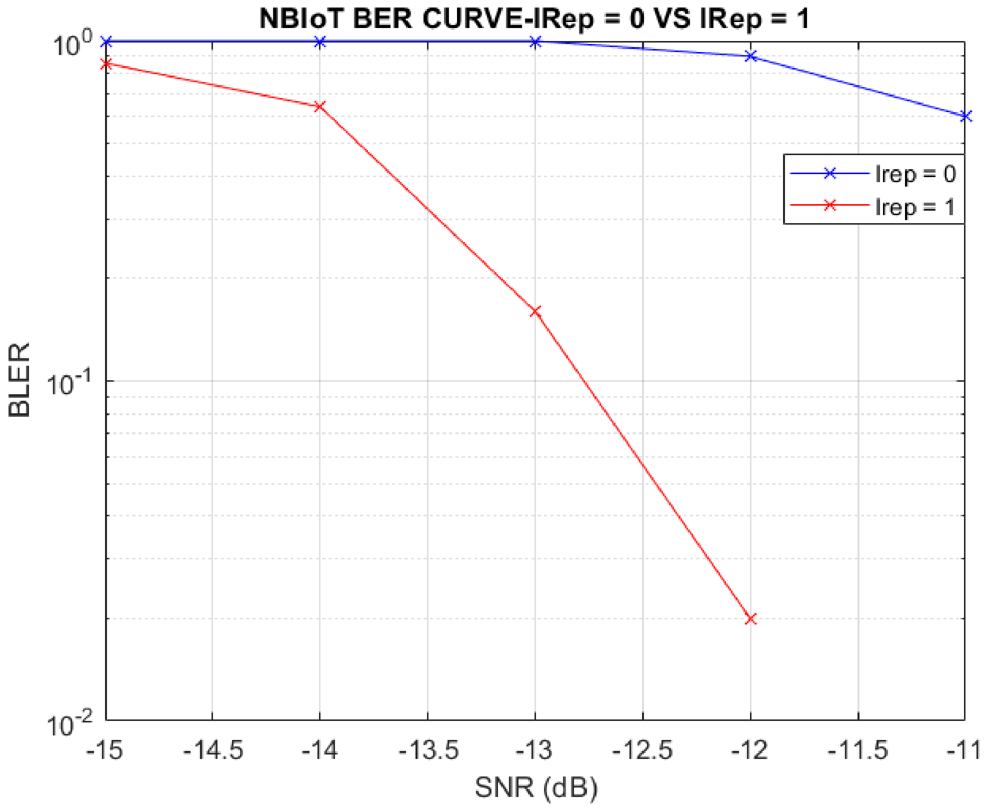


Figure 15 - NPDSCH BER simulation - Subframe repetition

Result analysis and discussion

The result above show that the error rate becomes relatively very low with a higher number of subframe repetition. The difference becomes more as signal quality improves (higher SNR).

NBIoT uses the concept of subframe repetition to improve signal reception by sending the same data multiple times. The results have shown that the more the repetitions the lower the error rate. It is however important to strike a balance as to many repetitions can introduce an unwanted latency. Depending on the application, a good balance has to be struck between lowering the error rate and avoiding latency that is beyond acceptable levels for that particular service.

5.4 NPUSCH BER simulation – Transport Block Size

The fourth simulation that was done was for the error performance of the NBIoT system using different TBS in the uplink. As in the case with downlink, the same two values were chosen for the same reason to have a clear contrast and comparison. Figure 16 below shows the results of this simulation.

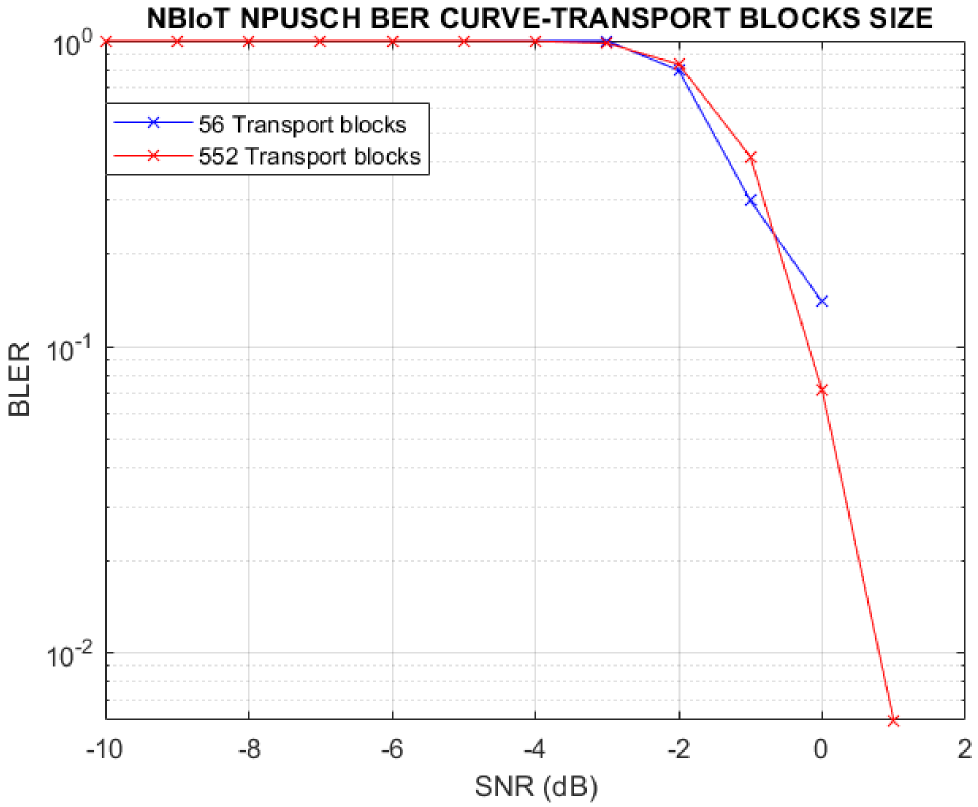


Figure 16 - NPUSCH BER simulation – Transport Block Size

Result analysis and discussion

The above results show that error rate is low when TBS is small for SNR below 0. For SNR above 0 (good signal quality) the error rate becomes comparable for smaller and bigger TBS.

The uplink of NBIoT (NPUSCH) has very small transmit power from the low power devices. The amount of data transmitted can have high or low error dependant on the transmission environment, i.e. if there is high interference (poor signal quality) then smaller TBS will help minimise the error rate. For a good and less interference environment, the error rate is comparable for both big and small TBS because despite the low transmit power of the device, for high TBS, the error correction needed will be less.

5.5 NPUSCH BER simulation - Subframe repetition

The fifth simulation that was done was for comparing the error performance of the NBIoT system using different number of repetitions in the uplink. Two values (1 and 2) were used as in the case with the downlink. Figure 17 below presents the results of this simulation.

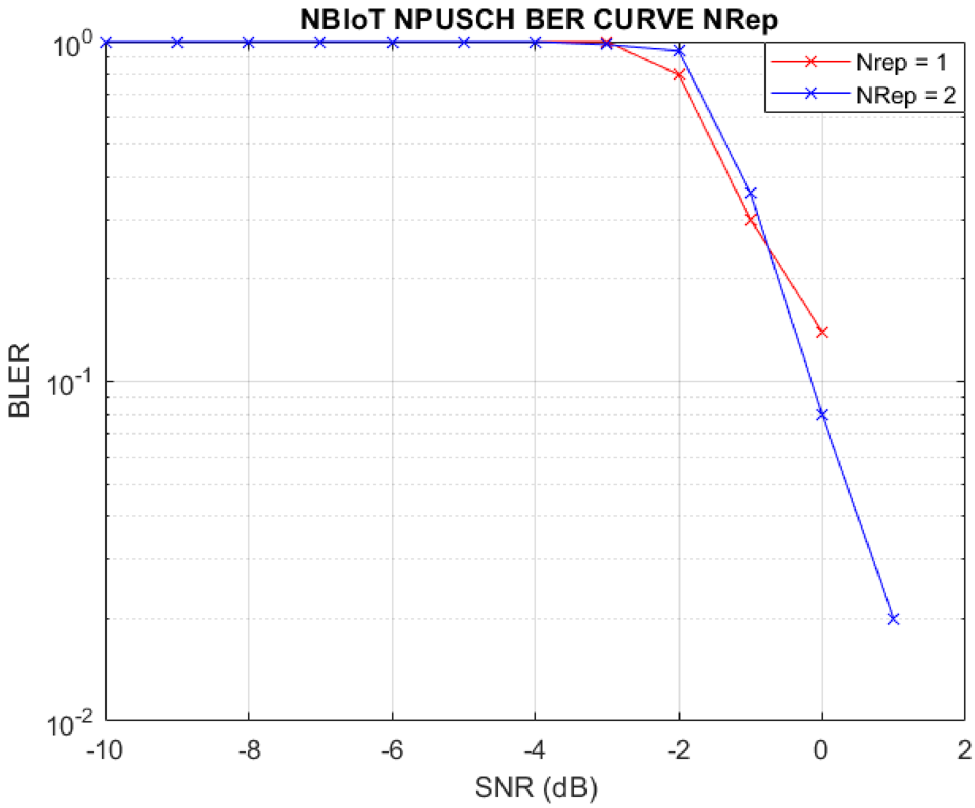


Figure 17 - NPUSCH BER simulation - Subframe repetition

Result analysis and discussion

The result above show that the error rate for poor quality signal is comparable for both repetition scenarios. However, as the signal quality improves, the more the number of repetitions the lower the error rate.

In the NPUSCH, when the signal quality is poor, it is shown above that repeating the signal transmission will not help much as the error rate remained comparable to the non-repeated signal transmission. This is because of the low transmit power of the NBIoT devices. The benefit of repeating the signal becomes more in good signal environments, where, as shown above, the more the repetitions the lower the error rate in the transmitted signal.

5.6 Chapter 5 summary

This chapter presented five set of simulation results, firstly the results of the comparison of the standalone and in-band deployment modes error performance. Secondly, results of comparison of error performance in the downlink using different transport block sizes are presented. The third set of results is the comparison of the error performance in the downlink using different number of repetitions. The fourth and fifth set of results are those of number of transport block sizes and number of repetitions in the downlink. The results were discussed and conclusions drawn.

6 Conclusion

This section summarises the work done in this dissertation and key conclusions are drawn from the simulation results that were done. The closing section of the chapter introduces some potential future work that can be pursued by prospective researchers the in the field of NBIoT.

6.1 General conclusion

NBIoT is an emerging technology in the IoT industry. The narrowband technology requires low bandwidth and can reuse or share bandwidth with other existing technologies. The technology is best suited for low power IoT applications because of the advantages of its design objectives, particularly the technology's low complexity of devices, improved indoor coverage, and high capacity of low throughput devices. Long battery life and relaxed uplink latency are additional highly desirable qualities of this approach. NBIoT is a very flexible technology in terms of deployment, allowing for three different modes of deployment (namely: standalone, in-band and guard band). The frame structure, uplink and downlink channels of the technology are the identical to those of LTE, which makes it easy for NBIoT to coexist with LTE. Just like LTE, NBIoT has many parameters, of which subframe repetition is a particularly useful one. The repetition technique is used for both uplink and downlink of NBIoT in order to greatly improve signal reception.

The main aim of this investigation was to study the error performance of NBIoT. This included investigating the key parameters of NBIoT, their range as defined by the 3GPP, how each parameter setting relates to the error performance of the NBIoT network and determining the best parameter settings, in order to make recommendations to NBIoT network operators.

The research methodology followed in this dissertation focused on studying three separate areas of NBIoT operation, i.e. deployment modes, subframe repetition and transport block size. The downlink channel (NPDSCH) was configured first, using two different modes (standalone and in-band) and simulations were done to see how each mode relates to the error performance. The next experiment involved configuring NPDSCH with different numbers of subframe repetitions, with the error performance simulated at each repetition number. Lastly for NPDSCH, different transport block sizes were configured and the error performance simulated for each TBS value. The second and third step above (sub frame repetition and TBS simulation) were repeated for the uplink channel (NPUSCH) and simulations done for each scenario to see how the parameter settings affect the error performance of the NBIoT system. The values of the parameters used were derived from the 3GPP TS 36.213 tables discussed in chapter 4.

The results showed that the error performance is dependent on the main NBIoT parameter settings.

The higher the number of subframe repetitions, the better the error performance, and the smaller the transport block size, the better the error performance. Technically, when data is transmitted, the more the same data is transmitted repeatedly, the less the probability of error. As for the TBS, the more the data you transmit at once, the higher the probability of error.

It was also established that of the three NBIoT deployment options (standalone, in-band and guard band), standalone mode has a better performance. This is because in standalone mode, the interference from other technologies is very minimal compared to other deployment modes.

For operators considering the deployment of NBIoT, it will be important for them to understand their environment with regards to the radio conditions, i.e. interference. For subframe repetition, a good balance has to be struck between repeating sub frames a number of times enough to give an acceptable error performance, and not repeating too much to introduce unacceptable latencies. Operators considering to deploy NBIoT in clean radio conditions (less interference in standalone mode) should configure the least possible subframe repetition number, which should be sufficient to achieve an acceptable error performance. Configuring too many repetitions will be an unnecessary over kill and may end up degrading the performance of the system.

Operators who opt to deploy in interference prone environments (NBIoT coexisting with other technologies) must configure a higher number of subframe repetition in order to counter the interference from other technologies and improve the system error performance by increasing the probability of the reception of data.

For the parameter TBS, again depending on the transmission environment the operator will be in, there is need for a balance to send data in block sizes enough not to slow the data throughput, but at the same time avoid sending too big a block to make the error correction process poor hence resulting in poor error performance of the system.

This dissertation has shown that when it comes to the deployment of NBIoT, there cannot be a one-size-fits-all parameter setting. Operators will have to evaluate the environment they intend to deploy and configure parameters that best suits their case. It will be best for operators to deploy in standalone mode if the spectrum is available. However, should there be a constraint in spectrum, the other two modes are still good enough as they can still achieve acceptable levels of interference when correct parameter settings are configured.

6.2 Future work

In future, work has to be done to explore more NBIoT parameters especially in the uplink where device transmit power is limited. The following areas can be considered for future work on this subject:

- How to achieve higher efficiency on NBIoT uplink transmission: - NBIoT uses SC-FDMA in the uplink, and the model of design was inherited from LTE. However, LTE devices have higher power capability than the small NBIoT devices hence there is need to finds ways of improving the uplink modulation techniques in order to save power.
- How to use even smaller TBS in the uplink: - NBIoT devices have very limited power in the uplink and in interference prone RF conditions, uplink transmission is compromised, leading to the need for a higher number of subframe repetitions, which solves the problem at the expense of consuming more resources and introducing a higher latency. The use of smaller TBS which are less prone to errors would help solve this challenge. The future work will need to explore how a good balance can be struck between reducing the number of repetitions and making use of smaller TBS.
- How to use lower device transmit power in the uplink: - the power for uplink device transmission is 23dBm in the NBIoT system. One of the main design targets of NBIoT is long device battery life. Finding ways of achieving lower uplink transmit power will help save power and see the battery last even longer. The future work will need to study ways of amplifying weak received signals at

the NBIoT eNode B to allow for low power device transmission. This may involve using highly complicated error detection and correction algorithms. Care will need to be taken because this complicated algorithms may chew a lot of resources, so a good balance will need to be reached for efficient data transmission.

6.3 Chapter 6 summary

In this final chapter, a summary of the whole work was presented. Key highlights were mentioned on each chapter and some recommendations to operators were offered. The obtained results were also explained and an assessment on how they tally with expectations was done. Lastly, some future work was proposed on this subject that will help to shed even more light to operators who might be considering deploying NBIoT. This will also help inform future research that might be meant to improve the work done.

7 References

[1] R. Ratasuk, J. Tan, N. Mangalvedhe, M. H. Ng and A. Ghosh, "Analysis of NB-IoT Deployment in LTE Guard-Band," 2017 IEEE 85th Vehicular Technology Conference (VTC Spring), Sydney, NSW, 2017, pp. 1-5.

[2] S. Landström, J. Bergström, E. Westerberg, D. Hammarwall, "A Sustainable Technology for Connecting Billions of Devices" 2016 Ericsson Technology Review, Stockholm, Sweden

[3] S. Anand and S. K. Routray, "Issues and challenges in healthcare narrowband IoT," 2017 International Conference on Inventive Communication and Computational Technologies (ICICCT), Coimbatore, 2017, pp. 486-489.

[4] Y. Miao, W. Li, D. Tian, M. S. Hossain and M. F. Alhamid, "Narrow Band Internet of Things: Simulation and Modelling," in IEEE Internet of Things Journal, vol. PP, no. 99, pp. 1-1.

[5] M. Chen, Y. Miao, Y. Hao and K. Hwang, "Narrow Band Internet of Things," in IEEE Access, vol. 5, pp. 20557-20577, 2017.

[6] N. Mangalvedhe, R. Ratasuk and A. Ghosh, "NB-IoT deployment study for low power wide area cellular IoT," 2016 IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), Valencia, 2016, pp. 1-6.

[7] R. Ratasuk, B. Vejlgaard, N. Mangalvedhe and A. Ghosh, "NB-IoT system for M2M communication," 2016 IEEE Wireless Communications and Networking Conference, Doha, 2016, pp. 1-5.

[8] A. Adhikary, X. Lin and Y. P. E. Wang, "Performance Evaluation of NB-IoT Coverage," 2016 IEEE 84th Vehicular Technology Conference (VTC-Fall), Montreal, QC, 2016, pp. 1-5.

[9] Nokia white paper, "LTE evolution for IoT connectivity", 2017 Nokia Technology White Paper, Espoo, Finland

[10] R. Ratasuk, N. Mangalvedhe, Y. Zhang, M. Robert and J. Koskinen, "Overview of narrowband IoT in LTE Rel-13," 2016 IEEE Conference on Standards for Communications and Networking (CSCN), Berlin, 2016, pp. 1-7.

[11] X. Lin, A. Adhikary and Y. -. Eric Wang, "Random Access Preamble Design and Detection for 3GPP Narrowband IoT Systems," in IEEE Wireless Communications Letters, vol. 5, no. 6, pp. 640-643, Dec. 2016.

[12] K. Y. Lee, "A cellular technology connecting the Internet Of Things", Keysight Technologies 2016, California, United States

[13] Y. D. Beyene, R. Jantti, K. Ruttik and S. Iraji, "On the Performance of Narrow-Band Internet of Things (NB-IoT)," 2017 IEEE Wireless Communications and Networking Conference (WCNC), San Francisco, CA, 2017, pp. 1-6.

[14] 3GPP TS 36.213, "Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures (Release 13)", in Technical Specification 3rd Generation Partnership Project 2016, Valbonne, France

[15] J. HuaWu, "CAT-M & NB-IoT Design and Conformance Test", Keysight Technologies 2017, California, United States

[16] B. Schulz, "Narrowband Internet of Things Measurements", Rohde & Schwarz Application Note 2016, München, Germany

[17] C. Yu, L. Yu, Y. Wu, Y. He and Q. Lu, "Uplink Scheduling and Link Adaptation for Narrowband Internet of Things Systems," in IEEE Access, vol. 5, pp. 1724-1734, 2017.

[18] J. Schlienz, D. Raddino, "Narrowband Internet of Things", Rohde & Schwarz white paper 2016, München, Germany

[19] 3GPP TS 36.211, "Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation (Release 13)", in Technical Specification 3rd Generation Partnership Project 2016, Valbonne, France

[20] M. Lauridsen, I. Z. Kovacs, P. Mogensen, M. Sorensen and S. Holst, "Coverage and Capacity Analysis of LTE-M and NB-IoT in a Rural Area," 2016 IEEE 84th Vehicular Technology Conference (VTC-Fall), Montreal, QC, 2016, pp. 1-5.

[21] Y. -. E. Wang et al., "A Primer on 3GPP Narrowband Internet of Things," in IEEE Communications Magazine, vol. 55, no. 3, pp. 117-123, March 2017.

[22] J. Chen, K. Hu, Q. Wang, Y. Sun, Z. Shi and S. He, "Narrowband Internet of Things: Implementations and Applications," in IEEE Internet of Things Journal, vol. 4, no. 6, pp. 2309-2314, Dec. 2017.

[23] Y. Sun, F. Tong, Z. Zhang, and S. He, “Throughput Modeling and Analysis of Random Access in Narrow-band Internet of Things”, in IEEE Internet of Things Journal 2017, China

[24] S. K. Routray and S. Anand, "Narrowband IoT for healthcare," 2017 International Conference on Information Communication and Embedded Systems (ICICES), Chennai, 2017, pp. 1-4.

[25] A. Rakić, I. Popović, I. Petruševski, Đ. Begenišić, V. Spajić and M. Rakić, "Key aspects of narrow band internet of things communication technology driving future IoT applications," 2017 25th Telecommunication Forum (TELFOR), Belgrade, 2017, pp. 1-4.

[26] A. S. Petrenko, S. A. Petrenko, K. A. Makoveichuk and P. V. Chetyrbok, "The IIoT/IoT device control model based on narrow-band IoT (NB-IoT)," 2018 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus), Moscow, 2018, pp. 950-953.

[27] M. Chafii, F. Bader and J. Palicot, "Enhancing coverage in narrow band-IoT using machine learning," 2018 IEEE Wireless Communications and Networking Conference (WCNC), Barcelona, 2018, pp. 1-6.

[28] S. Ha, H. Seo, Y. Moon, D. Lee and J. Jeong, "A Novel Solution for NB-IoT Cell Coverage Expansion," 2018 Global Internet of Things Summit (GIoTS), Bilbao, 2018, pp. 1-5.

[29] S. Popli, R. K. Jha and S. Jain, "A Survey on Energy Efficient Narrowband Internet of Things (NBIoT): Architecture, Application and Challenges," in IEEE Access, vol. 7, pp. 16739-16776, 2019.

[30] N. Živic, "Improved Up-Link Repetition Procedure for Narrow Band Internet of Things," 2017 International Conference on Computational Science and Computational Intelligence (CSCI), Las Vegas, NV, 2017, pp. 1284-1289.

[31] B. Martinez, F. Adelantado, A. Bartoli and X. Vilajosana, "Exploring the Performance Boundaries of NB-IoT," in IEEE Internet of Things Journal, vol. 6, no. 3, pp. 5702-5712, June 2019.

[32] K. K. Nair, A. M. Abu-Mahfouz and S. Lefophane, "Analysis of the Narrow Band Internet of Things (NB-IoT) Technology," 2019 Conference on Information Communications Technology and Society (ICTAS), Durban, South Africa, 2019, pp. 1-6.