AN EFFICIENT INTERFERENCE AVOIDANCE SCHEME FOR DEVICE-TO-DEVICE ENABLED FIFTH GENERATION NARROWBAND INTERNET OF THINGS NETWOKS'

by

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Submitted in partial fulfilment of the requirements for the degree
Doctor of Philosophy (Electronic Engineering)

in the

Department of Electrical, Electronic and Computer Engineering
Faculty of Engineering, Built Environment and Information Technology

UNIVERSITY OF PRETORIA

June 2022

SUMMARY

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Keywords:	Cell-edge user, channel-gain factor, channel-to-interference-plus-noise ratio (CINR), device-device (D2D) communication, D2D relaying, 5G NB-IoT, interference-avoidance, interference-aware, max-max signal-to-interference-plus noise ratio (SINR), quality of service, resource allocation.

Narrowband Internet of Things (NB-IoT) is a low-power wide-area (LPWA) technology built on long-term evolution (LTE) functionalities and standardized by the 3rd-Generation Partnership Project (3GPP). Due to its support for massive machine-type communication (mMTC) and different IoT use cases with rigorous standards in terms of connection, energy efficiency, reachability, reliability, and latency, NB-IoT has attracted the research community. However, as the capacity needs for various IoT use cases expand, the LTE evolved packet core (EPC) system's numerous functionalities may become overburdened and suboptimal. Several research efforts are currently in progress to address these challenges. As a result, an overview of these efforts with a specific focus on the optimized

architecture of the LTE EPC functionalities, the 5G architectural design for NB-IoT integration, the enabling technologies necessary for 5G NB-IoT, 5G new radio (NR) coexistence with NB-IoT, and feasible architectural deployment schemes of NB-IoT with cellular networks is discussed. This thesis also presents cloud-assisted relay with backscatter communication as part of a detailed study of the technical performance attributes and channel communication characteristics from the physical (PHY) and medium access control (MAC) layers of the NB-IoT, with a focus on 5G. The numerous drawbacks that come with simulating these systems are explored. The enabling market for NB-IoT, the benefits for a few use cases, and the potential critical challenges associated with their deployment are all highlighted. Fortunately, the cyclic prefix orthogonal frequency division multiplexing (CP-OFDM) based waveform by 3GPP NR for improved mobile broadband (eMBB) services does not prohibit the use of other waveforms in other services, such as the NB-IoT service for mMTC. As a result, the coexistence of 5G NR and NB-IoT must be manageably orthogonal (or quasi-orthogonal) to minimize mutual interference that limits the form of freedom in the waveform's overall design. As a result, 5G coexistence with NB-IoT will introduce a new interference challenge, distinct from that of the legacy network, even though the NR's coexistence with NB-IoT is believed to improve network capacity and expand the coverage of the user data rate, as well as improves robust communication through frequency reuse. Interference challenges may make channel estimation difficult for NB-IoT devices, limiting the user performance and spectral efficiency. Various existing interference mitigation solutions either add to the network's overhead, computational complexity and delay or are hampered by low data rate and coverage. These algorithms are unsuitable for an NB-IoT network owing to the low-complexity nature. As a result, a D2D communication-based interference-control technique becomes an effective strategy for addressing this problem.

This thesis used D2D communication to decrease the network bottleneck in dense 5G NB-IoT networks prone to interference. For D2D-enabled 5G NB-IoT systems, the thesis presents an interference-avoidance resource allocation that considers the less favourable cell edge NUEs. To simplify the algorithm's computing complexity and reduce interference power, the system divides the optimization problem into three sub-problems. First, in an orthogonal deployment technique using channel state information (CSI), the channel gain factor is leveraged by selecting a probable reuse channel with higher QoS control. Second, a bisection search approach is used to find the best power control that maximizes the network sum rate, and third, the Hungarian algorithm is used to build a maximum bipartite matching strategy to choose the optimal pairing pattern between the sets of NUEs and the D2D pairs. The proposed approach improves the D2D sum rate and overall network SINR of the 5G NB-IoT system, according to the numerical data. The maximum power constraint of the D2D pair, D2D's location, Pico-base station (PBS) cell radius, number of potential reuse channels, and cluster distance impact the D2D pair's performance. The simulation results achieve 28.35%, 31.33%, and 39% SINR performance higher than the ARSAD, DCORA, and RRA algorithms when the number of NUEs is twice the number of D2D pairs, and 2.52%, 14.80%, and 39.89% SINR performance higher than the ARSAD, RRA, and DCORA when the number of NUEs and D2D pairs are equal. As a result, a D2D sum rate increase of 9.23%, 11.26%, and 13.92% higher than the ARSAD, DCORA, and RRA when the NUE’s number is twice the number of D2D pairs, and a D2D’s sum rate increase of 1.18%, 4.64% and 15.93% higher than the ARSAD, RRA and DCORA respectively, with an equal number of NUEs and D2D pairs is achieved. The results demonstrate the efficacy of the proposed scheme.

The thesis also addressed the problem where the cell-edge NUE's QoS is critical to challenges such as long-distance transmission, delays, low bandwidth utilization, and high system overhead that affect 5G NB-IoT network performance. In this case, most cell-edge NUEs boost their transmit power to maximize network throughput. Integrating cooperating D2D relaying technique into 5G NB-IoT heterogeneous network (HetNet) uplink spectrum sharing increases the system's spectral efficiency and interference power, further degrading the network. Using a max-max SINR (Max-SINR) approach, this thesis proposed an interference-aware D2D relaying strategy for 5G NB-IoT QoS improvement for a cell-edge NUE to achieve optimum system performance. The Lagrangian-dual technique is used to optimize the transmit power of the cell-edge NUE to the relay based on the average interference power constraint, while the relay to the NB-IoT base station (NBS) employs a fixed transmit power. To choose an optimal D2D relay node, the channel-to-interference plus noise ratio (CINR) of all available D2D relays is used to maximize the minimum cell-edge NUE's data rate while ensuring the cellular NUEs' QoS requirements are satisfied. Best harmonic mean, best-worst, half-duplex relay selection, and a D2D communication scheme were among the other relaying selection strategies studied. The simulation results reveal that the Max-SINR selection scheme outperforms all other selection schemes due to the high channel gain between the two communication devices except for the D2D communication scheme. The proposed algorithm achieves 21.27% SINR performance, which is nearly identical to the half-duplex scheme, but outperforms the best-worst and harmonic selection techniques by 81.27% and 40.29%, respectively. As a result, as the number of D2D relays increases, the capacity increases by 14.10% and 47.19%, respectively, over harmonic and half-duplex techniques.

Finally, the thesis presents future research works on interference control in addition with the open research directions on PHY and MAC properties and a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis presented in Chapter 2 to encourage further study on 5G NB-IoT.

DEDICATION

The thesis is dedicated to my late mother Mrs. Muyibat Gbadamosi, and my father, Alhaji Muh'd Nafiu Gbadamosi, and my wife, Mrs. Ganiyat Junaid Gbadamosi, my children, Muh'd Yasir Gbadamosi, Yumna Gbadamosi, Yusrah Gbadamosi and Yusuf Gbadamosi for their frequent prayers. Thank you all for your support and frequent calls.

ACKNOWLEDGEMENTS

I am grateful to God Almighty for bestowing His kindness, knowledge, understanding, and mental strength to pursue and accomplish my Ph.D. studies.

I would like appreciate my supervisors, Prof. Gerhard P. Hancke and Prof. Adnan M. Abu-Mahfouz, for their guidance, support, and supervision in bringing out the best in me. I recall my first contact with Prof. Gerhard P. Hancke as a prospective student seeking admission. Prof. Hancke responded quickly to my email and supported my application with documents, even though he had never met me in person. Sir, your fatherly role and prompt response to my mails have given me this opportunity, and Prof. Adnan M. Abu-Mahfouz keeps encouraging and refocusing our thoughts and minds in ensuring the research work is on-time through the progress meetings he took the time to set up every month. Though it was anxiety-inducing, it is the foundation and success of this work.

Also recognized are the staff of the Department of Electrical, Electronic and Computer Engineering, the head of the advanced sensor network research group, and staff members of the University of Pretoria for their consistent emails, advice, and support.

I would also like to thank the Federal Government of Nigeria through the TETFund program and the Federal University of Technology Minna, for the financial support and opportunity to study at the University of Pretoria, South Africa. Also, to acknowledge the University of Pretoria's Department of Research and Innovation for their financial assistance, workshops, seminars, and training during this study.

I also acknowledge the management of the Federal University of Technology, Minna, the Staff Training Unit, Bursary, Registry, the school of Electrical Engineering and Engineering Technology, and the Electrical and Electronics Engineering department staff for their assistance during my study fellowship. Prof. Tsado Jacob, the department's head, deserves special recognition for his constant calls, support, and prayers. Sir, thank you very much for your contribution and efforts in making this a success.

I am grateful to all of my colleagues at the University of Pretoria's advanced sensor network research group for their support and suggestions throughout this study.

Also, to acknowledge the support and sacrifice of my friends both in Nigeria and South Africa. To mention a few are Dr. A. J. Onumanyi, Dr. Henry Ohize, Dr. Godfrey Akpakwu, Dr. Martins Osifeko, Mrs. Rachel Kufakunesu, Dr. Stephen Oyewobi, and Dr. Owoicho Ijiga Emmanuel, and finally Mal. Ndafatima Abubakar.

I would also like to express my gratitude and appreciation to Dr. (Alhaji) Muhammad Dattijo Usman and his family for their role in my life. Sir, God Almighty will continue to uplift you beyond human imaginations. Also, to acknowledge Prof Jacob's family, Dr. A. B Usman, and my in-laws for their prayers at all times.

I would like to personally thank and appreciate my wife, Mrs. Ganiyat Junaid Gbadamosi for her support, love, prayers, and, most importantly, for being a pillar for the family while I was away. To my children, thank you for your love and sacrifice.

I would like to acknowledge my father, Alhaji Muh'd Nafiu Gbadamosi for his prayers, support, and calls. Thank you for your sacrifice, Sir. Daddy, you will continue to live longer, to enjoy the fruits of your labor.

Finally, my siblings, Engr Abdul-Hakeem Badamasi, Mrs. Sherifat Ogunbajo, Mr. Kayode Badamasi, Mrs. Laitan Gbadamosi, and Mrs. Latifah Gbadamosi and Mr. Suleiman Gbadamosi for their frequent calls, support, and prayers. Thank you all, and God bless every one of you. Amen.

LIST OF ABBREVIATIONS

2G	2nd Generation (cellular communications)
3GPP	3rd Generation Partnership Project
3GPP- LPWA	3rd Generation Partnership Project – Low-power wide area
4G	4th Generation (cellular communications)
5G	5th Generation (cellular communications)
5G-IoT	5th Generation Internet of Things
5G- MTC	5^{th} Generation machine type Communication
5G-NR	5th Generation New Radio
AS	Access Stratum
AUSF	Authentication Server Functions
BBU	Basebands Unit
BH	Backhaul
BLER	BLER Block Error Rate
BPSK	Binary Phase Shift Keying
BS	Base Station
CAT-M/LTE-M	Category M/Long-term Evolution M
CAGR	Compound Annual Growth Rate
CCH	Control Channel
CDMA	Code Division Multiple Access

CIoT	Cellular Internet of Things
CP-OFDM	CP-OFDM Cyclic Prefix Orthogonal Frequency Division Mod.
CRAN	Centralized/Cloud Radio Access Network
CSI	Channel State Information
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CU	Central Unit
DCI	Downlink Control Information
DL/UL	Downlink/Uplink
DU	Distributed Unit
E2E	End-to-End
eICIC	Enhanced Inter-Cell Interference Coordination
eMBB	Enhanced Mobile Broadband
eMTC	Enhanced Machine Type Communication
EPC	Enhanced Packet Core
EPS	Evolved Packet System
ETSI	European Telecommunications Standards Institute
EU	European Union
E-UTRA	Evolved-universal Mobile Telecommunications System (UMTS) Terrestrial Radio Access
FeICIC	Further enhanced Inter-Cell Interference Coordination
eGPRS	Enhanced General Packet Radio Service
EC-GSM IoT	Extended Coverage Global System for Mobile Communications

	Internet of Things
HARQ	Hybrid Automatic Repeat request
ICI	Inter-Carrier Interference
ICIC	Inter-Cell Interference Coordination
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IMT	International Mobile Telecommunications
IoT	Internet of Things
IQ	In phase and Quadrature Phase
ISM	Industrial, Scientific and Medical
ISO	International Organization for Standardization
ITU	International Telecommunication Union
ITU-R	ITU - Radiocommunication sector
LoRa	Long Range, low power technology
LPWA	Low Power Wide Area
LPWAN	Low Power Wide Area Network
MAC	Media Access Control
MIB	Master Information Block
MME	Mobility Management Entity
mMTC	Massive Machine-Type Communications
NACK	Negative Acknowledged
NAS	Non-Access Stratum

NB-IoT	Narrowband Internet of Things
NF	Network Function
NFV	Network Function Virtualization
NG	Next Generation
NR	New Radio
OFDM/A	Orthogonal Frequency Division Multiplex/Access
OOB	Out of Band
OPEX	Operational Expenditures
PCID	Physical Cell ID
NPDCCH	Narrowband Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
NPSS	Narrowband Primary Synchronization Signal
NSSS Signal	Narrowband Secondary Synchronization Signal
NPBCH	Narrowband Physical Broadcast Channel
NPUCCH	Narrowband Physical Uplink Control Channel
NPRACH	Narrowband Physical Random-Access Channel
NPUSCH	Narrowband Physical Uplink Shared Channel
NPDSCH	Narrowband Physical Downlink Shared Channel
NRACH	Narrowband Random-Access Channel
NUE	Narrowband User Equipment
PDU	Protocol Data Unit
PGW	Packet Data Network Gateway

PHY	PHY Physical layer
PLL	Phase-Locked Loop
PRB/PSM	Physical Resource Block/Power Saving Mode
RAN/RAT	Radio Access Network/Radio Access Technology
QoS	Quality of Service
RA	Random Access
RB/RBC	Resource Block/Resource Block Control
RE	Resource Element
RRM	Radio Resource Management
SC-FDMA	Single Carrier Frequency Division Multiple Access
SDN	Software-Defined Networking
SFBC	Spatial-Frequency Block Code
SGW	Serving Gateway
SIB	System Information Block
SINR	Signal to Interference plus Noise Ratio
SIMO	Single Input Multiple Output
SMF	Session Management Function
SPS	Semi-Persistent Scheduling
SPTP	Small Packet Transmit Procedure
SR	Scheduling Request
SSB	Synchronization Signal Block
SSS	Secondary Synchronization Signal

TBS	Transport Block Size
TDD	Time Division Duplex
TTI	Transmission Time Interval
UP	User Plane
UPF	User Plane Function
URLLC	Ultra-Reliable Low-Latency Communications
UTRA	Universal Mobile Telecommunications System (UMTS) Terrestrial Radio Access
V2X	Vehicle-to-Everything
WCDMA	Wideband Code Division Multiple Access
ZC	Zadoff-Chu
ZP-OFDM	Zero Padding OFDM

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CHAPTER 1 INTRODUCTION

NB-IoT is an open 3GPP standard optimized for machine-type communication (MTC) traffic to lower the energy consumption of IoT use cases. The narrowband radio technology was specifically designed for low-power wide-area (LPWA) applications to support low-data rate, very low-power consumption, scalability, and long-range coverage of cellular data. It promotes the creation and deployment of intelligent IoT. The NB-IoT protocol operates in three (3) modes; in-band, guard, and standalone mode, thus can be incorporated into the 5G new radio (5G-NR) networks to support the ultralow-end IoT applications, such as the intelligent meters, remote sensors, and smart health systems [1]. NB-IoT (also known as LTE-Cat-NB1) provides simplification and optimization of enterprise-grade technical specifications that reduce the radio overhead and deliver IP and non-IP data [2], being the practical choice for network carriers, device manufacturers, and enterprise users [3]. The NB-IoT integration into the 5G network promotes optimal coexistence by occupying a physical resource block (PRB) of 180kHz for both uplink (UL) and downlink (DL) operations or by replacing one GSM carrier of 200kHz without compromising the host network performance.

In the context of 5G NB-IoT, the interference is an intrinsic limitation of the NB-IoT network operating the frequency reuse of the 5G-NR wireless systems. Although frequency reuse mechanisms improve maximum spectrum utilization, it also limits spectral efficiency, network, and user performance. As a result, mitigating the co-channel interference is critical for the coexistence of harmonic and adaptability between NB-IoT and 5G systems. Most importantly, overcoming the interference will ensure high capacity and wide coverage of high end-user data rates, promoting efficient and robust communication. The channel interference occurs in two modes of NB-IoT deployment in the 5G NR spectrum, namely, the in-band and guard modes. The interference is referred to as narrowband interference

(NBI) because NB-IoT bandwidth is relatively small compared with the 5G-NR bandwidth. However, several reasons might cause interference as a result of NB-IoT reusing the 5G-NR spectrum, thus resulting in problems such as the mismatch of sampling rate, power leakage between NB-IoT and NR physical resource blocks (PRBs), and loss of orthogonality as described in [4] which leads to performance degradation. In standalone mode, an NB-IoT network can coexist with 5G networks in a heterogeneous manner, resulting in co-channel interference. The interference challenge in 5G NB-IoT is still an open issue and thus there is insufficient literature. There are various interference mitigating techniques used in modern wireless systems (cellular and wireless local area networks (WLAN)), such as intercell interference coordination (ICIC) [5], beamforming, and interference alignment (IA) [6], but none of these schemes can be used to solve the 5G NB-IoT network interference challenges due to the system's low-complexity. As a result, this thesis considers D2D communication as a novel technique for reducing the interference bottle-neck for a 5G NB-IoT networks to solve the problem of the co-channel interference issue by improving the resource allocation, spectrum utilization, and poor channel quality, limited coverage, low data rate, and network performance.

1.1 PROBLEM STATEMENT

Interference mitigation becomes a critical issue in most frequency reuse HetNets, with many schemes employing dynamic or static resource allocation techniques to improve spectral efficiency and network capacity. However, these techniques have poor optimal performance, resulting in low bandwidth and spectral efficiency[7], [8]. Some of the first interference mitigation schemes introduced in LTE release 8 were: the centralized scheduling, the ICIC to improve cell-edge SINR via frequency and power-allocation, coupled with changing levels of network coordination [9], the enhanced ICIC (eICIC) structured for HetNet in advanced LTE releases to mitigate interference on data and control channels in frequency and time domain [7],[10], the eICIC facilitated with almost blank subframes (ABS) to avoid overlapping through the scheduling of planned and interfered signals on other subframes [11], the further eICIC (FeICIC) for mitigating interference on UE via interference removal schemes [12] and finally, the carrier aggregation schemes for interference management in the control channels of macro-cells and small-cells on diverse carriers in the frequency domain [13]. The preceding approaches have high computational complexity and are unsuitable for low complex systems such as NB-IoT. As a result, minimizing channel interference in the 5G NB-IoT network depends on the use cases, deployment scenarios, and the size of the cooperative set, which differs from the commonly used long-term evolution (LTE) interference reduction strategy. As a result, an intelligent and flexible interference control method for resource planning in a standalone mode of NB-IoT solutions in the 5G NB-IoT HetNet needs to be developed. This thesis aimed to address the interference avoidance scheme by leveraging a low complexity D2D communication technique to improve spectrum efficiency and network capacity for optimal NB-IoT performance in 5G networks.

1.1.1 Context of the problem

Apart from the improved data rate and network capacity gained from NB-IoT carriers within the 5G network coexistence, an interference challenge within the network may hamper this benefit. The interference may create weak signals at the cell edge, increasing packet loss, limiting transmission performance, user performance, overall cell capacity, and network performance. Most interference elimination methods reviewed in works of literature are either marred by poor spectrum efficiency, poor estimation accuracy, high computational complexity, and poor elimination of NBI for the existing LTE systems [14], which results in delays and high iteration convergence rate [15], or results in the poor performance of low data rate, limited coverage, and loss of spectral efficiency in the case of frequency reuse networks in 5G network. As a result, to improve the 5G NB-IoT network performance, the Third-generation partnership project (3GPP) in 3GPP Rel-12 and Rel-13 time-frames [16] permits proximate services (Pro-Se) for devices in close range to engage in robust D2D communication without using the Base station. D2D communication can reduce network latency, improve a weak receive signal at the cell edge, increase the data rate, and extend the coverage area, thus, improving the network performance. However, the convectional D2D communication creates more interference to the existing cellular devices within the networks due to the frequency reuse mechanism, which might further degrade the network. Therefore, for efficient 5G NB-IoT systems, the interference avoidance scheme becomes significant to enhance the data rate, coverage area, and spectrum efficiency of the network.

1.1.2 Research gap

The permission of D2D communication in cellular networks has further created intelligent and innovative systems, stimulating diverse ideas from the research community to promote IoT use cases for future internet of things. Thus, to build on this trend and further promote the coexistence of NB-IoT carriers and cellular networks for the exponential growth of IoT applications, this research aims to leverage D2D communication schemes to develop an efficient interference avoidance scheme for D2D-enabled 5G NB-IoT systems for IoT-based applications. The D2D communication inclusion into 5G NB-IoT networks will create complexity and interference bottlenecks due to the frequency reuse mechanism [17]. Frequency reuse creates reuse interference to cellular reuse partners, causing deterioration to the cellular users and limiting the system's performance. As a result, to build an efficient resource allocation mechanism within the 5G NB-IoT system, the interference bottleneck would need to be avoided.

1.2 RESEARCH OBJECTIVE AND QUESTIONS

The objectives of this thesis are:

- To design an efficient interference avoidance scheme for device-device enabled fifth-generation narrowband internet of things (5G NB-IoT) HetNet that improves the network capacity and spectrum efficiency while addressing the interference constraints.

- To permit a D2D communication architecture and select cellular narrowband internet of things user equipment (NUEs) with high channel gain factor to improved quality of service (QoS) control that D2D users can reuse.

- To ensure that NUEs meet QoS requirements by eliminating the D2D pairing with increased interference power through the interference constraints.

- To develop a bipartite matching approach for selecting the optimal pairing pattern between the D2D pairs and the set of NUEs with a high channel gain factor.

- To evaluate the performance of the developed D2D-enabled 5G NB-IoT interference avoidance scheme to existing solutions.

- To develop an interference-aware 5G NB-IoT D2D relaying strategy for cell edge NUE QoS improvement and evaluate the performance with the above developed D2D-enabled 5G NB-IoT interference avoidance.

This thesis seeks to answer the following research questions:

- How can D2D communication be leveraged to develop an efficient interference avoidance scheme for 5G NB-IoT networks while considering the QoS requirement of the cellular NUEs?
- What interference avoidance scheme best suits 5G NB-IoT to ensure network performance that would translate to improved capacity, spectrum efficiency, and minimization of interference constraints?
- How does D2D communication reduce the interference bottleneck for 5G NB-IoT networks, given the radio resource constraints and the co-channel interference power within the NB-IoT physical resource block of 180kHz?
- What performance metric can be used to evaluate and validate the developed interference avoidance scheme for D2D-enabled 5G NB-IoT networks?

1.3 APPROACH

The implementation of 5G NB-IoT HetNet is feasible if the interference and other performance constraints are identified. NB-IoT technology is critical for the mass deployment of low-power machine-type communication. It has numerous applications in various systems, improving process efficiency and convenience in homes and industries. Thus, when all constraints are acknowledged for robust D2D-enabled 5G NB-IoT networks, the introduced D2D communication enhances system performance. As a result, this thesis takes a theoretical derivation, computation, and simulation approach to a D2D-enabled 5G NB-IoT interference avoidance scheme. As a result, the thesis is organized as follows:

- **Literature review:** An in-depth concept of the NB-IoT study was reviewed and studied, which details the overview of the 5G architecture design for NB-IoT integration and the enabling technologies for 5G NB-IoT improvement, 5G NR coexistence with NB-IoT, and the possible deployment schemes with cellular networks. An interference avoidance scheme for 5G NB-IoT HetNet is designed based on the research gap and using D2D communication enabling technology.

- **System Modelling:** The network and system models are required to obtain effective solutions to the designed engineering problems. To achieve optimal 5G NB-IoT networks, two different system models based on interference avoidance for D2D-enabled 5G NB-IoT HetNet and Interference-aware D2D relaying for 5G NB-IoT HetNet are developed for this thesis. Several identified interference constraints limit the realization of optimal solutions for both the interference avoidance for D2D-enabled and interference-aware 5G NB-IoT networks in the system models. The developed solution models use interference constraints to regulate interference power and allocate resources to D2D pairs while ensuring NUE QoS are satisfied. The interference constraints and the power optimization concepts of the two system models implemented achieve an increased D2D pair's sum-rate and interference power minimization within the network. The system model has been carefully analysed and implemented for efficient resource utilization in 5G NB-IoT networks. The results obtained are presented and discussed in the thesis's related chapters.

- **Simulation and Performance Analysis:** The system models designed were simulated in the MATLAB environment, and detailed numerical analysis are performed. The simulation results show an improved 5G NB-IoT performance in D2D sum rate and interference power minimization. The simulated results were validated using related research works from the literature and compared with the optimal D2D-enabled 5G NB-IoT using the cumulative distribution function and SINR value.

1.4 RESEARCH GOALS

The following are the thesis's research goals:

- leveraging a D2D communication within the 5G NB-IoT system to improve the quality of experience (QoE) of the cell-edge NUE and increase the network capacity and spectrum efficiency.
- developing an interference avoidance for the 5G NB-IoT system to regulates the interference power of the Pro-Se D2D pairs that can reuse the NUEs channel resources.
- developing an interference-aware D2D relaying strategy for 5G NB-IoT QoS improvement for cell-edge NUEs

1.5 RESEARCH CONTRIBUTION

The following are the main contributions of this thesis:

- A comprehensive literature review has been discussed, as well as a flowchart relating the 5G network to the emerging LPWA IoT, with a focus on NB-IoT carriers, to support the exponential growth of IoT. The new service requirements (such as mMTC, eMBB, and network operations), channel communication properties, and technical performance properties to promote efficient IoT use cases are among the properties detailed for the optimal coexistence of the 5G NR and NB-IoT numerologies to promote service delivery. The review explores the available connectivity landscape solutions for future IoT networks for 5G NB-IoT service requirements, market analysis, enabling technologies, and the strength, weaknesses, opportunities, and threats (SWOT). Also, present the interference limitations caused by their coexistence and open research directions on PHY/MAC properties that can assist NB-IoT carriers in operating seamlessly, to improve efficient and satisfactory QoS for 5G NB-IoT networks. The review appeared in IEEE Access Journal.

- The possibility of architectural design for cloud-assisted relay with ambient backscatter communication for the 5G NB-IoT network are also described to give an insight on how tremendous connectivity, resource pooling, spectral, and energy efficiency can be a supporting solution for practical roll-out for NB-IoT technology.

- The development of a new framework for uplink interference-avoidance resource allocation for D2D-enabled 5G NB-IoT network problems to maximize the D2D pair's sum rate underlying the NB-IoT network. Thus, to avoid any harmful interference on the NUE link, the maximum interference limit for the D2D users is identified and analysed.

- The formulated resource allocation problem is a mixed-integer non-linear problem (MINLP) for D2D-pair communication under the PBS control due to the combinatorial of resource allocation. As a result, it aids the designed system to regulate all the constraints that tend to inhibit the system's performance.

- The developed optimization problem is sectioned into three parts: the first is channel reuse selection, which determines the potential reuse channels for D2D pairs. The second part involves determining the optimal power allocation for each D2D user and its reuse partner to maximize overall network throughput and, finally, forming a bipartite graph to find an optimal pairing pattern between the set of NUEs and the D2D users using the Hungarian scheme [18].

- The research work was evaluated using extensive simulations, and when compared to other algorithms, the research's algorithm outperforms the other algorithms, significantly improving system performance in terms of sum-rate maximization and interference power minimization as shown in Chapter 3.

- The development of a new framework for interference-aware D2D relaying for 5G NB-IoT networks to improve cell-edge NUE QoS while meeting cellular NUE transmission requirements. Using the Max-max SINR approach, an optimal D2D relay to forward traffic from the cell-edge NUE to the NBS to improve QoE under co-channel interference constraints was identified and selected. Unlike the authors of [19] and [20], who considered co-tier interference from neighbouring sources, as well as spectrum utilization trade-off and fairness, respectively, the research studied metric reduces network overhead and interference power caused by signal relaying within the network by adaptively selecting a D2D relay candidate with the highest maximum CINR to maximize the D2D link data rate.

- The formulated optimization problem is to maximize the data rate of the cell-edge NUE based on the cellular NUEs' transmission rate and power allocation. The Lagrangian dual approach was used to derive a closed-form power allocation expression and, as a result, formulate optimization constraints such as interference power constraints and its minimum data rate to limit any D2D relay link power above the interference threshold and below the minimum data rate. As a result, existing cellular NUE communications are not disrupted.

- The investigation of additional relay selection policies, such as (a) best-worst selection scheme, (b) best harmonic relay selection scheme, and (c) Decode and Forward (DF) half-duplex relay selection scheme, in addition to the designed system above (i.e., D2D-enabled 5G NB-IoT in [21]. The data-rate maximization and interference power minimization of these schemes were compared. Because of the high channel gains between the two communicating pairs, the interference-aware scheme outperforms the other schemes except the designed system.

1.6 RESEARCH OUTPUTS

This research work's contributions have been published or are currently being considered for publication in peer-reviewed journals. A list of publications from the research works that contribute to the body of knowledge is provided as an output:

- S. A. Gbadamosi, G. P. Hancke, and A. M. Abu-Mahfouz, “Building upon NB-IoT networks: A roadmap towards 5G new radio networks”. *IEEE Access*, *8*, pp.188641-188672, 2020.

- S. A. Gbadamosi, G. P. Hancke, and A. M. Abu-Mahfouz, “Interference-Avoidance Resource-Allocation for D2D-enabled 5G Narrowband Internet of Things”. *IEEE Internet of Things Journal*. 9 (22), pp. 22752-22764, 2022. doi: 10.1109/JIOT.2022.3184959.

- S. A. Gbadamosi, G. P. Hancke, and A. M. Abu-Mahfouz, “Interference-Aware D2D Relaying Strategy for 5G NB-IoT QoS Improvement for Cell-edge User”. *IEEE Internet of Things Journal*, *(under review),* 2022.

1.7 OVERVIEW OF STUDY

Chapter 2 describes a comprehensive guideline for integrating NB-IoT into 5G networks. Based on the review, an analytical investigation of the NB-IoT environment for a 5G-IoT class of connectivity, cloud-assisted relay with ambient backscatter communication, as well as the limitation of the inseparable control and user planes of LTE EPC posing a challenge to the performance and acceptability of LTE NB-IoT, were presented to enhance the understanding of NB-IoT performance and problems. Furthermore, the possible 5G architectural design for NB-IoT integration, technical performance, enabling markets, use cases, application, and key challenges to all the use cases, as well as all the required enabling technologies needed for the optimal combination, has been introduced for the coexistence of NB-IoT with 5G NR. Finally, open research challenges and future research focus on the coexistence of 5G NR with NB-IoT have led to the SWOT analysis presented to foster research activities for future IoT. Some of the challenges involve channel scheduling, interference, random access procedures, heterogeneity, and interoperability, which need to be solved to promote successful NB-IoT systems. In Chapter 3, a novel interference avoidance framework that provides the solution to the co-channel interference in 5G NB-IoT HetNet, detailing the system model, network model, problem formulations, and the optimal resource allocation algorithm for the formulated problems is discussed. Chapter 4 outlines numerical and simulation results. In Chapter 5, the investigation into an interference aware D2D relaying strategy for 5G NB-IoT QoS improvement for a cell-edge user is presented, followed by the performance evaluation and results' discussion in chapter 6. Finally, Chapter 7 presents the thesis conclusion and research opportunities for future consideration.

CHAPTER 2 LITERATURE STUDY

2.1 CHAPTER OVERVIEW

The Narrowband Internet of Things (NB-IoT) is built on a platform of long-term evolution (LTE) functionalities and will continue to coexist and operate seamlessly with new 5G networks, thus supporting LTE-IoT deployment scenarios. The existing 4G LTE networks employed to test the implementation of different NB-IoT connectivity and applications [22] remain an ongoing effort, particularly as the capabilities of various existing low-power wide-area networks (LPWAN) technologies continues to grow [23]. Despite the attempt to optimize current LTE broadband systems, it remains unsuitable for much machine-type communication (MTC) applications. MTC plays an essential role in the core of NB-IoT connectivity between devices and the cloud. 5G networks are to create a horizontal transformation approach [24] to drive massive numbers of NB-IoT devices and applications to expand the operation of the cellular-IoT. 5G data infrastructure plays a vital role in LPWA-based IoT devices that need strong security, widespread availability, ultra-low latency, ultra-low power consumption, wide coverage area, low device cost, and high reliability [25] for streamlining and improving a variety of services and industries. According to the International Data Corporation (IDC) survey, billions of dollars spent by companies to drive 5G services requiring ubiquitous connectivity include mobile, nomadic, and stationary to the tens of billions of devices, objects, and machines [26]. The connected devices generate immense economic value across the world. To make NB-IoT a core component in achieving this dream, a roadmap of NB-IoT toward 5G networks is the focus of this chapter. The chapter examines the practical features and technical performance of NB-IoT carriers coexisting with 5G new radio (NR), the NB-IoT carriers and 5G NR numerologies, and open research challenges that may impede the NB-IoT carriers' operation within the NR network.

This chapter is structured as follows: Section 2.2 presents the background to the 5G-IoT class of connectivity. Section 2.3 discusses the overview of NB-IoT, highlights the technical differences between NB-IoT and other LPWA technologies, and summarizes the design objectives and benefits, modes of operation, and the physical channels and signals. Section 2.4 presents the OSI layer framework and optimized LTE NB-IoT architecture design and the 3GPP standardization and releases for NB-IoT. Section 2.5 details the 5G architecture design for NB-IoT integration, the list of NB-IoT and LTE-M1 commercial mobile-IoT networks available and the enabling technology needed for 5G NB-IoT network. Section 2.6 describes the possibility of architectural design of cloud-assisted relay with ambient backscatter communication for 5G NB-IoT. Section 2.7 highlights the 5G NR coexistence with NB-IoT, the similarity between the NR and NB-IoT, and the achievable architecture deployment schemes for asynchronous and synchronous network distribution structures. Section 2.8 discusses the technical performance properties of NB-IoT detailing the PHY/MAC challenges concerning various channel parameters and possible solutions. Section 2.9 describes the enabling market analysis for NB-IoT, applications and use cases with some potential problems affecting their deployment. Section 2.10 discusses the open research challenges and provides a SWOT analysis of NB-IoT in 5G NR carrier network and finally, section 2.11 summarizes the chapter.

2.2 BACKGROUND TO 5G-IOT CLASS OF CONNECTIVITY

The 5G networks utilize intelligent architectures of radio access technology (RAT), dynamic by nature, coherent, and flexible over multiple advanced technologies that can support NB-IoT and a wide variety of IoT applications. According to the new 3GPP releases 16 and 17, the adaptation of 5G-IoT services can create a link with high performance and low complexity to virtually everything around us [27]. The 5G-IoT can improve the spectral efficiency and data rate of NB-IoT, and thus promote the total addressable market of NB-IoT devices and 3GPP solutions for IoT use cases. In Figure 2.1, 5G-IoT has three classes of connectivity, namely; wired, wireless, and satellite [28], but wireless technologies will be reviewed. The 5G-IoT wireless technologies can be classified into two groups based on transmission distance as short-range MTC wireless technologies (e.g., WHAN, Wi-Fi, and WPAN, examples such as Bluetooth, Mi-Wi, ANT, 6lowpan, ZigBee, and Z-wave) [29] and long-range MTC wireless technologies (e.g., low-power, wide-area networks (LPWAN)), and finally, the MTC services [30].

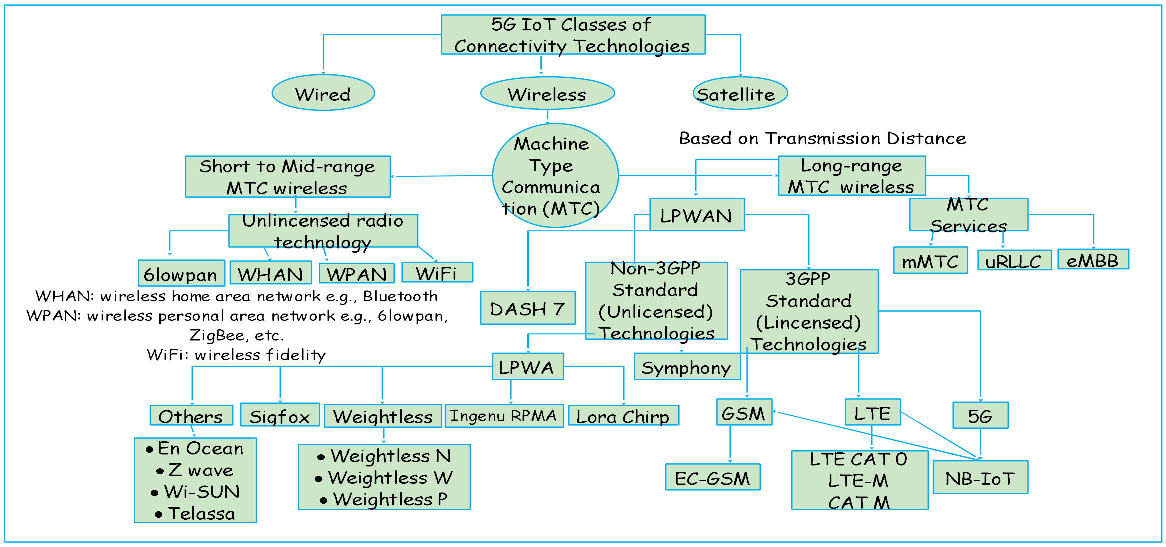


Figure 2.1. Classes of 5G-IoT connectivity Based on Transmission Distance

Considering the perspective of frequency spectrum licensing, LPWAN can be categorized into two classes, namely; the non-3GPP standards (unlicensed spectrum) and the 3GPP standards (licensed spectrum), [30]. The first category consists of LPWA technologies such as Sigfox LoRa, Weightless, Ingenu RPMA, Z-wave [1], etc. that are of custom and non-standard implementation. For instance, LoRa and Sigfox operate in the sub-Gigahertz unlicensed spectrum while RPMA operates in 2.4 GHz industrial, scientific and medical (ISM) bands. More importantly, this category has limited channel access due to the spectrum shared between different technologies. The transmission time has a limited duty cycle and a listen-before-talk or frequency-hopping scheme implemented to avoid interference with other coexisting systems. The second category is based on 2G/3G cellular technologies (such as the GSM, CDMA, WCDMA), LTE, and evolves LTE technology that supports different classes of terminals [31]. The standards for the second category (licensed spectrum) were developed by the 3GPP and 3GPP2 [32]. Unlike the unlicensed spectrum, the licensed spectrum does not suffer from the duty cycle and uncontrollable interference [33]. In general, MTC has limited power at the device side while the network can still benefit from the increased downlink link-budget due to the high base station (BS) transmitting power. Based on the modification, specific demands [34] and features of MTC services related to 3GPP set objectives of release 13, three (3) kinds of narrowband air interfaces were defined, namely, extended-coverage GSM internet of things (EC-GSM-IoT), enhanced machine-type communication (eMTC) known as LTE-M (LTE-Cat M1) or Cat M and the new NB-IoT technology.

The EC-GSM-IoT is a high-potential, long-range, low-energy, and low-complexity technology-based eGPRS system. The eMTC supports applications with higher data rate and mobility requirements designed for LTE enhancement, for the implementation of MTC and IoT. As regards the new NB-IoT technology, on the other hand, the focus of this thesis is intended for intelligent low-data rate applications for data perception and acquisition. NB-IoT is a highly efficient IoT solution that can significantly extend device battery life and has significant cost advantages for large-scale IoT device deployment.

The MTC service offers an optimized 3GPP network support to connected devices and services to the potential 5G-IoT as specified in Rel. 14 [35]. The 5G-IoT, is expected to connect more than 70 use cases cutting across a range of new services and markets from IoT to vehicular communications, applications, and control, industrial automation, tactile internet, drone control systems, remote maintenance, and monitoring systems [36], theft prevention and recovery, as well as smart cities [37], smart buildings and surveillance [38], intelligent health systems, smart metering [39], smart grid [40], smart parking, smart lighting, shared bicycle, connected cow [1],[41], and lots of other use cases. The use cases have inspired research issues related to the capacity and services of the deployed 5G communication systems.

The 5G-MTC services are: Enhanced mobile broadband (eMBB), Ultra-reliable and low-latency communication (uRLLC), and lastly, massive machine type communication (mMTC). The services offer enhanced localization support, multicast, mobility, high data rate, positioning update, new user equipment output class necessary for system throughput, and link adaptation to 5G NB-IoT and cellular IoT. To further bolster this point, two-step strategies are adopted by 3GPP to puzzle-out the technological challenges from the MTC services. The transition strategy is the first step taken. The first strategy optimizes the existing network and technologies to offer MTC services [42]. The second strategy, termed a long-term strategy, provides support to the rising large-scale MTC services based on the introduced new air interface of NB-IoT, and for maintaining core competitiveness to non-3GPP LPWA technology [43].

The diverse NB-IoT software and hardware solutions deployed from different vendors such as the Skyworks [44], Media Tek [45] Qualcomm [27], Sierra wireless [46], Neul (Huawei) [47], Intel [48] and so on, have made it possible for the Telecom operators across the globe to carry out practical feasibility studies of different NB-IoT use cases with real-life trials such as the smart city in Las Vegas, USA [49], smart metering and tracking in Brazil [50], NB-IoT at sea in Norway [51],[52] and so on, to mention a few. The products implemented from different vendors speed up the adopted NB-IoT technology.

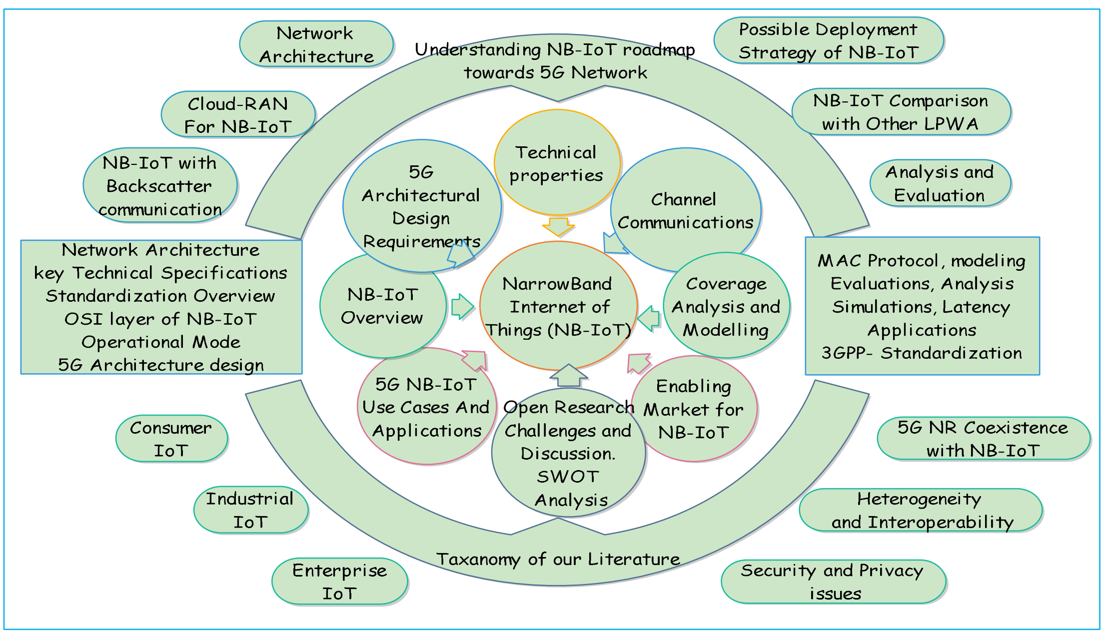


Figure 2.2. Brief Taxonomy of Literature

Numerous studies detailing the architecture design and OSI layer, coverage enhancement mechanism, theories, modelling, security challenges, channel estimation and limitations are highlighted in this survey. Figure 2.2 presents the taxonomy of the literature studies. The study classifies nine main sections, each section with a sub-branch as mentioned above.

2.3 AN OVERVIEW OF NARROWBAND INTERNET OF THINGS (NB-IOT)

NB-IoT is an open 3GPP standard optimized for MTC traffic to lower the energy consumption of IoT use cases. The narrowband radio technology was designed specifically for LPWA applications to support a low data rate, very low power consumption, scalability, and long-range coverage of cellular data. It promotes the development and implementation of intelligent IoT. NB-IoT can be integrated into the 5G new radio (5G-NR) networks, to bolster the ultralow-end IoT applications, including the intelligent meters, remote sensors and smart health systems [1]. NB-IoT (also known as LTE-Cat-NB1) provides simplification and optimization of enterprise-grade technical specifications that reduce the radio overhead and deliver IP and non-IP data [2], being the practical choice for carriers, device manufacturers and enterprise users [53]. The NB-IoT integrates into the existing network and promotes optimal coexistence by occupying a physical resource block of 180kHz for both uplink (UL) and downlink (DL) operations or by replacing one GSM carrier of 200kHz without compromising the host network's performance. According to [2], NB-IoT supports cell reselection in idle state but does not aid hand-over services in the connected state. Also, due to the features of employing power-saving mode (PSM), NB-IoT lacks provision for QoS. Table 2.1 tabulates the key technical specifications (KTS) of NB-IoT in comparison with other LPWA technologies.

The summary of the design objectives and benefits of NB-IoT [54],[33],[55],[56] is as follows:

- The complexity of the transceiver is lower.
- Energy consumption is lower.
- Radio-chirp is lower.
- It has a maximum-coupling loss of 164 dB for coverage improvement.

- It should provide multi–Physical Resource Block (PRB)/Carrier support.
- It adopts a HARQ process of adaptive and asynchronous for both UL and DL.
- FDD only and half-duplex User Equipment (UE)
- Employs 180kHz (1PRB) for narrowband physical DL channel.

TABLE 2.1. [57], [1], [3][58] The key technical specifications of NB-IoT in comparison with other LPWA technologies

KTS	**Sigfox**	**LoRa**	**NB-IoT**	**eMTC**	**EC-GSM-IoT**
Technology	Proprietary	Proprietary	Open LTE	Open LTE	Open
Coverage	160dB	157dB	20dB	15dB	20dB and 14dB
Spectrum	Unlicensed	Unlicensed	Licensed (LTE/any)	Licensed (LTE band)	Licensed GSM band
Duty cycle restriction	Yes (typically 1%)	Yes (typically 1%)	No	No	No
Downlink data rate	0.1 kbps	0.3-50 kbps	0.5- 200kbps	1MHz	74kbps
Uplink data rate	0.1 kbps	0.3-50 kbps	0.3-180kbps	1MHz	240 kbps
Battery life (200b/day)	10+ yrs	10+ yrs	15+ yrs	+10 yrs	+10 yrs
Module cost	< $10 (2016)	< $10 (2016)	$ 7 (2017) to $ 2 (2020)	< $ 10	$ 7
Security	KGME, MAC verification, Sequence	AES COM 128	NSA, AES 256	AES 256	AES 256
Frequency band	EU: 868MHz US: 90 MHz	EU: 868MHz US:433/ 915 MHz. AS: 430MHz	In-band, Guard & Stand-alone LTE Frequency	In-band LTE Frequency	GSM Frequency
Channel bandwidth	100 Hz	250 kHz and 2.16 MHz	180kHz (200kHz carrier)	1.08MHz (1.4MHz carrier bandwidth)	2.4MHz
3GPP release	Not supported	Not supported	13	12	13
Duplex mode	Half-duplex	Half-duplex	Half-duplex FDD only	Full and half duplex FDD/TDD	Half-duplex FDD only
MCL	3dB	3dB	+164dB	+155.7dB	+164dB & 154dB
Rx antenna	Single	Single Rx	Support single Rx	Support single Rx	Support single Rx
Max. transmit power	14dBm/ 22dBm	14dBm/27dBm	20dBm or 23dBm	20dBm or 23dBm	33dBm or 23dBm
PSM	Deployment driven	3 classes of device operation	PSM, eDRX	PSM, eDRX	PSM, eDRX
Reliability	Low reliable	Low reliability	Highly reliable	Reliable	Reliable
Interference/distance	High	Very high	Low	Low	Low
Network congestion under high load	High packet loss	Very high packet loss as throughput degrades	Low	Low	Low
Base station capacity	Millions of devices/ access point	1,000,000 devices	52,547	80,000	50,000
Supports	Sigfox alliance	LoRa alliance	By over 30 of world's largest operators such as AT&T, China-Unicom, etc	By over 30 of world's largest operators such as AT&T, China-Unicom, etc.	By over 30 of world's largest operators such as AT&T, China-Unicom, etc.
Latency	< 10s	< 10s	< 10s for 164dB	-5s for 155dB	< 10s
Mobility	40km/h	40km/h	Cell selection, re-selection only (80km/h) (Normadic)	Legacy support (120km/h)	GSM support ()
Coexistence	ISM band	ISM band	GSM standalone, LTE in-band, LTE guard band, 5G NR	LTE in band	LTE in band

Reduced complexity	High	High	Ultra-low cost (˜1$)	Similar to EGPRS modem cost	Similar to EGPRS modem cost
Standardization	A collaboration of ETSI and Sigfox alliance	LoRa alliance	3GPP	3GPP	3GPP
Topology	Star	Star of Star	Star	star	Star
Modulation	DBPSK (UL) GFSK (DL)	Chirp spread spectrum (CSS) CSS	QPSK/BPSK (DL) GFSK (UL)	OFDMA SC-FDMA	GMSK
Localization	Yes (RSSI))	Yes (TDOA)	Not (under specification)	No (under specification)	No (under specification)
Handover	No centralized base-station for end-devices.	No centralized bas -station for end-devices.	Centralized base-station provided for all devices	Centralized base-station provided for all devices	Centralized base-station provided for all devices
Allow private network	No	Yes	No	No	No
Adaptive data rate	No	Yes	No	No	No
Max. payload length	12 bytes (UL), 8 bytes (DL)	243 bytes	Network Deployment-driven	Network Deployment-driven	Network Deployment-driven.
Max. Message/day	140 (UL), 4 (DL)	Unlimited	Unlimited	Unlimited	Unlimited
Bi-directional	Yes	Yes	Yes	Yes	Yes
Phonetic Ability	Not supported	Not supported	Not supported	Limited capacity / Weaker than FDD for FDD/TDD	Limited
Output power Restriction	Yes (14dBm = 25mW)	Yes (14dBm = 25mW)	No (23dBm = 200mW)	No (23dBm)	No (23dBm)
Voice	No	No	No	No	Yes
Typical range	15Km LOS	5Km (Urban) 15Km LOS	Deployment-driven 20Km LOS	Deployment-driven ~5Km	Deployment driven 15Km
Transmission Techniques	UNB	FHSS (Aloha)	FDD	FDD/TDD	FDD/TDD

- Uses 3.75kHz random-access preambles (RAP).
- Can adopt a single tone (15 kHz/3.75 kHz) or multi-tone ($\mathcal{N}$*15 kHz, $\mathcal{N}$= (3,6,12)).
- Uses 680 bits and 1000 bits of the maximum transport block size (TBS) for DL and UL.
- NB-IoT offers support for up to 10s for UEs using eDRX when connected, but uses 3hrs for UEs in idle state.
- Has a power spectral boosting of 6dB relative to the LTE system, and the multiple repetitions method can aid in improving the received signal quality.
- NB-IoT provides 20dB improvement in coverage relative to LTE.
- An NB-IoT carrier can support the transmission of short messages to the network from more than a hundred thousand devices. Additional carriers to the system can scale the network connections to millions of devices.
- NB-IoT can be implemented on CRAN to facilitate IoT deployment in centralization and network-virtualization to operate the base band of a base station. Such

implementation will improve the performance by deploying a distributed antenna system (DAS) in large buildings or industries. It will also reduce the capital expenditures (CAPEX) by applying network function virtualization (NFV) to the radio-access network.

- The low processing power of the NB-IoT protocol stack and latency requirement enable the implementation of CRAN.
- NB-IoT aids optimization of the access-stratum (AS), also known as RRC, that minimizes the signaling required to discontinue or return the connection of the user plane [2].

2.3.1 Mode of Operation

NB-IoT system shares a frequency band with legacy LTE, hence uses three (3) operational modes of deployment, namely; in-band, guard band, and standalone in the GSM spectrum as illustrated in Figure 2.3.

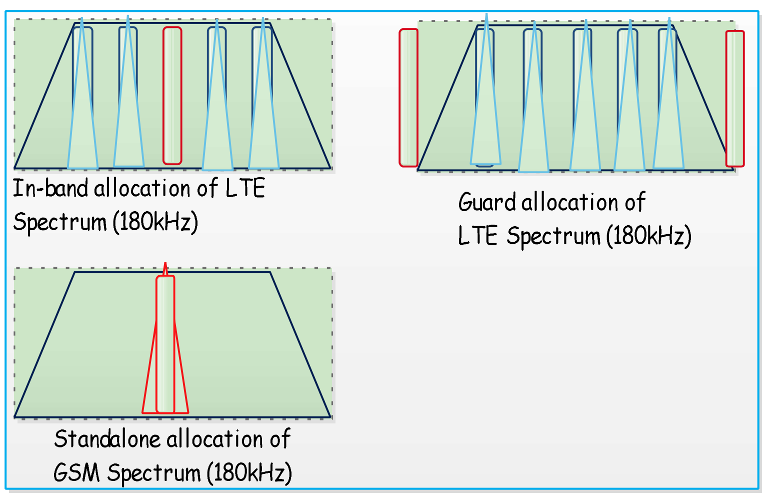


Figure 2.3. The Operational Mode of NB-IoT, Adapted from [59], © 2017, IEEE.

- The in-band operation uses the same PRB as the LTE but with some scheduling restrictions for LTE on physical DL control and reference signals. Also, share the same transmit power with legacy LTE.

- The guard band operation uses the unused PRB within LTE carrier and, share the same base station maximum transmit power. There is a little interference in the guard band relative to the in-band operation.

- The NB-IoT standalone operation mode uses all available transmit power of the base station. This approach enables the GSM carriers to be re-framed with NB-IoT in one or more active carriers [60].

Table 2.2 tabulates the NB-IoT deployable band for the 5G network defined by 3GPP TS 36.101 [61] in release 13 by regional usage. There is a minimum number of ten (10) bands required for NB-IoT coverage in all member countries, excluding the overlap bands for individual countries [62]. Detail explanation of the above features of NB-IoT is contained in [24], [63], [64], [32], [53], [65], [62], [59], [66]. NB-IoT employs LTE orthogonal Frequency division multiple access (OFDMA) structure in the DL with sub-carriers spacing of 15kHz while Single-carrier frequency division multiple access (SC-FDMA) was used in the UL with sub-carrier spacing at 3.75kHz [33]. There is a little difference between the frame structure of the LTE standard and NB-IoT for 3.75kHz spacing between subcarriers at the physical layer. Each LTE frame slot turns 2ms while the NB-IoT frame becomes a five (5) slots, totaling a period of 10ms. The increment in time-repetitions and (π/2) BPSK single sub-carrier transmission was achieved to provides a coverage radius of 15km [67].

TABLE 2.2. The supported deployment band of NB-IoT utilized in regions of the world [62], [66]

Regions	Bands	Downlink Freq. Range (MHz)	Uplink Freq. Range (MHz)
Europe	3, 8, 20	1805 – 1880, 925 – 960, 791 - 821	1710 – 1785, 880 – 915, 832 - 862
Commonwealth Independent States	3, 8, 20	1805 – 1880, 925 – 960, 791 - 821	1710 – 1785, 880 – 915, 832 - 862
North American	2, 4, 5, 12, 17, 26, 66, 71	1930 – 1990, 2110 -2155, 869 – 894, 729 – 746, 734 – 746, 859 – 894, 2110 – 2200, 617 – 783,	1850 – 1910, 1710 -1755, 824 – 849, 699 – 716, 704 - 716, 814 – 849, 1710 – 1780, 633 – 698,
Asia Pacific	1, 3, 5, 8, 18, 20, 26, 28	2110 – 2170, 1805 – 1880, 869 – 894, 925 – 960, 860 – 875, 791 – 821, 859 – 894, 758 – 803.	1920 – 1980, 1710 – 1785, 824 – 849, 880 – 915, 815 – 830, 832 – 862, 814 – 849, 703 - 748

Sub-Sahara Africa	3, 8	1805 – 1880, 925 – 960	1710 – 1785, 880 – 915
Middle East and North America	8, 20	925 – 960, 791 - 821	880 – 915, 832 - 862
Latin America	2, 3, 5, 28	1930 – 1990, 1805 – 1880, 869 – 894, 758 - 803	1850 – 1910, 1710 – 1785, 824 – 849, 703 - 748

2.3.2 Physical channels and Signals

There are three (3) types of DL channel, two synchronization signals and one reference signal that are common in the physical (PHY) layer DL channel of NB-IoT namely [33],[67]; as illustrated in Figure 2.4;

- Narrowband Physical Broadcast Channel (NP-BCH),
- Narrowband Physical Downlink Control Channel (NP-DCCH),
- Narrowband Physical Downlink Shared Channel (NP-DSCH),
- Narrowband Primary Synchronization Signal (NPSS),
- Narrowband Secondary Synchronization Signal (NSSS),
- Narrowband Reference Signal (NRS).

The space frequency block coding (SFBC) employed are for the support of transmitting modes of the single-port antenna and double-port antenna with transmission-diversity. In the UL channel, there are only two UL channels namely:

- Narrowband Physical Random-Access Channel (NP-RACH) and
- Narrowband Physical Uplink Shared Channel (NP-USCH).

Multiplexing of all synchronized signals and channels occurred at the physical layer. Further information on NB-IoT frame-structure and sub-frame for DL and UL with up-to-date supported multi-cast transmission, are contained in [61] for diverse physical signals and channels. Each NB-IoT sub-frame consists of a resource-block (RB) in the frequency-domain and 1ms in the time-domain.

The NB-IoT carrier has twelve (12) sub-carriers [33]. The synchronization signals (NPSS and NSSS) performed both time-frequency synchronization as well as cell-detection. NPSS utilizes subcarrier 11 in the sub-frame #5 of each radio-frame attracting 10 per cent of DL resources. NSSS provides cell-identity and information for additional clarification. The signal applies sub-frame #9 of each even radio-frame amounting to 5 per cent of DL resources [68]. The reference signal (NRS) applied for detecting phase reference in DL channels demodulation. NB-IoT maintains up to two NRS ports [69]. The NP-BCH loads

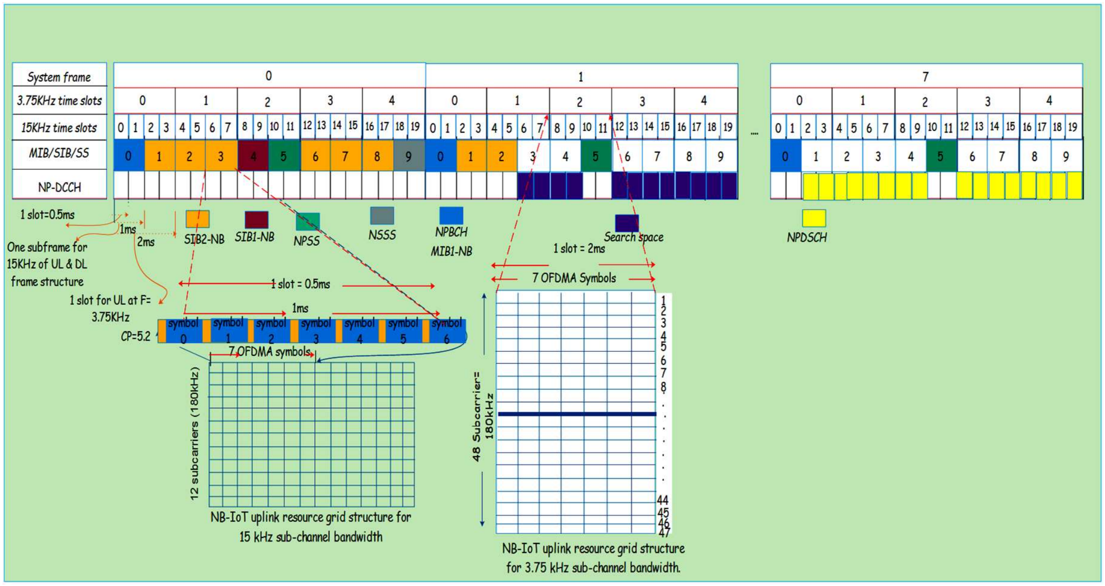


Figure 2.4. Frame Structure of Uplink NB-IoT, Adapted from [59], © 2017, IEEE.

the master information blocks (MIB) transmitted into the first subframe of every radio-frame. The information comprises of the system information blocks (SIB), scheduling information, number of antenna ports and deployment mode. NP-BCH uses 640ms of time transmission interval and occupies subframe #0 of every radio frame [68].

The NP-DCCH conveyed the DL control information (DCI) carrying scheduling information for both UL and DL data transmissions, paging and random access. The resources in this channel, grouped into control channels elements (CCEs) occupying six (6) sub-carriers in a sub-frame. This channel is similar to the LTE except for the forward scheduling used.
The NP-DSCH conveys higher layer data as well as paging messages, system-information and random-access response messages to a specific UE through the transport-blocks. The data is repeatedly transmitted several times using a coding scheme in the DCI and transport-block. The determined repetition number depends on the signal strength of the transmitting eNB to the UE.

The UL channel (i.e., the NP-USCH) carries both UL data signals from a specific UE using different formats. It has two formats namely; UE's transmission block size (TBs i.e., NPUSCH format-1) and UL control information (UCI i.e. format-2). The first format used; load UL data of a maximum transmission block size of 1000 bits smaller in size as compared to legacy LTE. The second format supports single tone transmission only and conveys 1bit UCI corresponding to hybrid automatic repeat request (HARQ) feedback for NP-USCH TBS. Note that Both NP-USCH format-1 and NP-DSCH uses single-process adaptive HARQ. UL HARQ retransmissions are asynchronous. This is another point-blank difference of NB-IoT from legacy LTE.

The NP-RACH employs the use of single-tone transmission scheme and sub-carrier spacing of 3.75kHz for the eNB to receive random-access preambles (RAP) from the UEs. The BS can be deployed to configure up to three NP-RACH resources with different coverage level, each defined by periodicity, number of repetition and a set of sub-carriers. The NP-RACH preamble transmission can be repeated up to 128 times over contiguous sub-frames [33]. The highlight on the physical layer design has made NB-IoT an excellent device, for the large-scale economically deployed IoT in different applications. We believe that most novel features of NB-IoT come from the study of the protocol stack (i.e. open system interconnection (OSI) reference model of NB-IoT. Therefore, taking a critical look at the OSI reference model of NB-IoT structure will offer a guide towards optimization, analysis, modelling, evaluations and better standardization of NB-IoT to ease a clear framework that describes the functions of its networking or telecommunication system.

2.4 THE OSI LAYER OF NB-IOT FRAMEWORK AND ARCHITECTURE

The NB-IoT OSI reference model, mostly referred to as the protocol stack, does not have a legacy of existence; however, its architectural design is highly rated to provide a connection to over five (5) billion devices through the platform of 5G. The features in the protocol stack that enhance the planning and development of NB-IoT as the most favored energy-efficient version of an IoT warrants studying. According to [70], the layers of the protocol are of the same types as those of the reference model of OSI, developed by the international standard organization (ISO), except for the five (5) upper layers. The layer architecture of NB-IoT is grouped into two planes, namely the data plane and the control plane. The data plane describes the user data flow between two nodes while the control plane describes the protocols that regulate the radio-access bearers and the link connecting the network and the UE. There are six (6) layers of the NB-IoT protocol stack defined by 3GPP as a value-added system for the cellular communication network. The six layers are the physical layer (PHY), media access control (MAC), radio link control (RLC), packet data convergence protocol (PDCP), radio resource control (RRC) and non-access stratum (NAS). The physical layer and the MAC are called the access stratum (AS). The access stratum and the air access methods are the only layers defined by the 3GPP protocol stack which are responsible for handling and processing the physical transmission or reception on the media. The other five upper layers are called the non-access stratum (NAS). The NAS has the same functions and protocols, unique and independent across different physical media. Figure 2.5 illustrates the difference between the 3GPP protocol stack and the OSI reference model. It is important to note that some of these layers such as the application, session and presentation layers in the OSI reference model might not exist in the control plane.

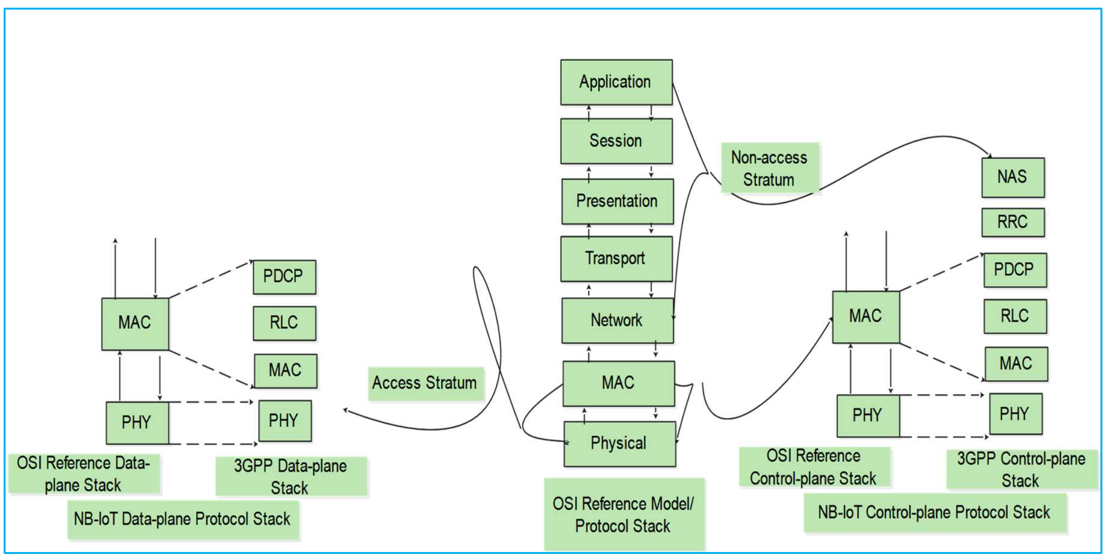


Figure 2.5. The NB-IoT Protocol Stack Architecture vs. OSI Reference Model

NB-IoT protocol stack uses two movements of exchange of data units, either within or between the protocol stacks. The data units are the service data unit (SDU) and protocol data unit (PDU). The service data unit moves the data unit within the layers. For example, each layer has its SDU appended by the header of each layer when exchanging the SDU to an upper or lower layer (i.e., intra-layer data unit). Also, for the PDU, each layer knows the size of its header. Therefore, when a PDU receives or transmits between the layers of data-plane protocol stacks, the layers either strip off the PDU or add up to the checksum of PDU to extract the SDU from the upper or lower layers respectively.

Understanding the protocol stack of NB-IoT would enhance a systematic architecture required for efficient planning, dimension, cost estimation, design, and network deployment. This will support the international telecommunication union (ITU) for international mobile telecommunication 2020 (IMT-2020). 3GPP has introduced the sublayers of the protocol stack of NB-IoT for 5G NR coexistence. Figure 2.6 illustrates the general network architecture of an optimized LTE NB-IoT. The figure simplifies the overall 3GPP LTE NB-IoT network connection to the NB-IoT user equipment (UE), eNodeB, and the core network (evolved packet core (EPC)) to address the IoT traffic model requirements [70], [2]. The LTE core network, known as EPC, has two interfaces with the eNodeB; the S1-MME protocol that conveys all signaling messages and the S1-U that sends all user or data messages. Data plane traffic flows from the UE to eNodeB through the S1-U interface to the serving-gateway (SGW), packet-gateway (PGW) and finally to the internet. Each eNodeB provides geographical coverage of the area. All NB-IoT devices equipped with a universal subscriber identity module (USIM) card are connected to these eNodeB services. Multiple eNodeBs are connected through the X2 interface and protocols. The traffic of the control plane from the UE to the eNodeB is directed through the S1-MME interface to the MME. The role of the MME is to ensure NAS signalling, select the SGW and PGW, provide authentication and authorization, and finally, to lawfully intercept a piggybacked signaling message or data plane message with the signaling messages. The eNodeBs connects to different MME to avoid overwhelming the MME. Each eNodeB can associate with over hundreds of thousands of NB-IoT devices within the MME region, thereby creating load balancing among the network nodes. Table 2.3 describes the functions of each feature in Figure 2.6.

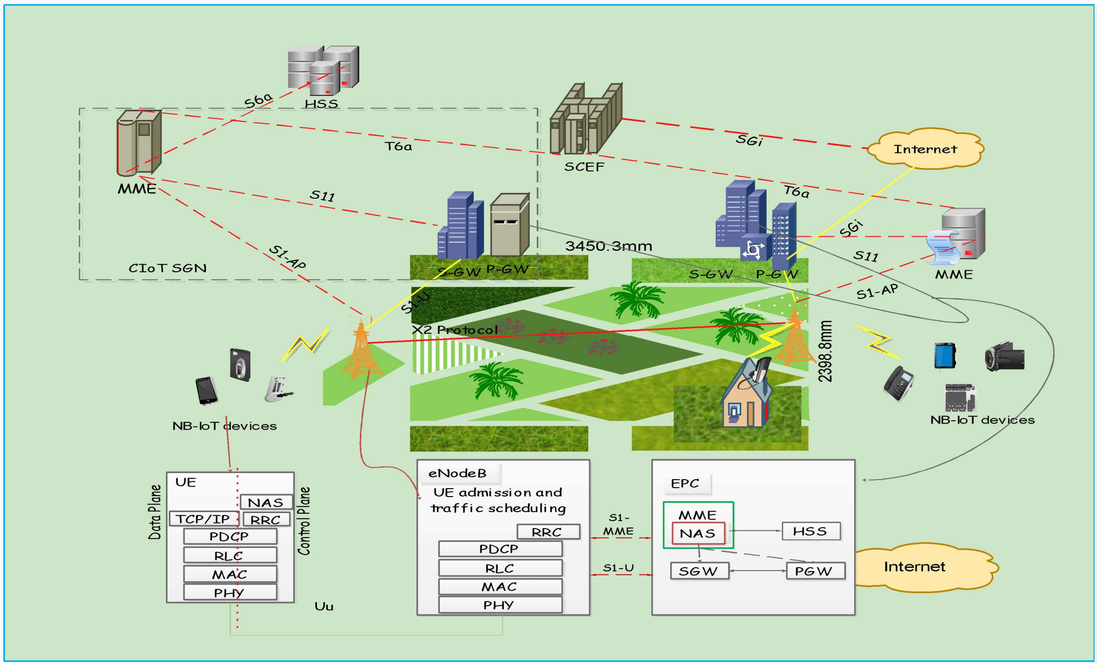


Figure 2.6. The general network architecture of an optimized LTE NB-IoT

TABLE 2.3. Functions of LTE NB-IoT network components

Features	Functions
Physical Layer (PHY)	This is the sublayer at the bottom of the NB-IoT protocol stack responsible for physical channels, transmissions, and receptions of MAC PDUs. It is defined as the air access channel of all NB-IoT devices by the 3GPP, [71]. The configuration parameters of this sublayer are contained in [70].
Media Access Control (MAC)	This is the sublayer interfacing directly with the PHY. It performs multiple functions ranging from multiplexes and demultiplexes of several RLC PDUs, random access and contention resolution procedures, DRX for battery power conservation, hybrid ARQ operation and so on, to mention but few [70], [67]
Radio Link Control (RLC)	In LTE NB-IoT, RLC is an essential sublayer responsible for the guaranteed transfer of control and data plane PDU to the receiver. The design objectives and configuration of this sublayer are presented in [70], [72].
Packet Data convergence Protocol (PDCP) Layer	The sublayer is responsible for providing integrity and security protection to both control plane and data plane PDUs. The architectural design and objectives of this sublayer are contained in [70], [73].
Radio Resource Control (RRC)	This sublayer keeps the UE complexity much lower, suitable for extremely low power consumption, low data speed, and lower cost. The identity of UE components is described in [70].
Non-access Stratum (NAS)	NAS is a signaling layer that establishes communication between UE and the core network. It has evolved and exists with other 3GPP protocol

	stacks. It manages authentication, mobility management, security control, and bearer management [71], [70].
Serving Gateway (SGW)	SGW receives the packets of the data plane from the UE through the S1-U interface. It is the first component in EPC. If the packets of the data plane from the UE are piggybacked with NAS signaling messages, then the packets are routed through another interface, except for the SGW. The main functions of SGW are contained in [70].
Packet Gateway (PGW)	PGW provides the second gateway to the packet data network (PDN) in EPC. It is an access point that provides connectivity to the UE through the internet, applications, and services [70].
Home Subscriber Server (HSS)	HSS is a component, contained in EPC, responsible for storing and updating UE subscription information, UE information about different security keys for identity and generated tracking encryption [70].

2.4.1 The 3GPP NB-IOT standardization

The NB-IoT standardization in release 13 by 3GPP technical specification group (TSG), for IoT and M2M (MTC) applications, connects many devices in a wide range, on the platform of IoT. The 3GPP is an open-based standard facilitating innovative consensus-based decision-making application of NB-IoT interoperability with cellular networks on the different technology-based systems. The standard creates unlimited technologies crucial for developing IoT applications over cellular technologies. However, much researches on the NB-IoT architecture, emerging technologies, deployment, and standardization are still ongoing. We hope that the collaborative effort to improve the efficiency and connectivity of NB-IoT will promote various enabling global technologies that guarantee security, interoperability, quality of service (QoS), and longevity of IoT applications. Two different data rates have been developed for NB-IoT by 3GPP standard, namely the data rates ranging from 10s of kbps in 180 kHz bandwidth (LTE Cat-NB1) to a few hundreds of kbps (LTE Cat-NB2) [74].

Several other standardization bodies such as IETF, IEEE, ITU, ETSI, etc. (as illustrated in Figure 2.7) on LPWA technologies projects have also provided a framework for standardized IoT deployment, but despite their efforts, there is still no standard reference for the IoT-platform [75]. The journey of in-depth research into NB-IoT by the 3GPP started in 2015 with release 13 to make MTC services an essential part of 5G networks. Possible problems such as congestion and overload on data and signaling planes, numbering and addressing of resource shortages during synchronous access of many terminals, time-control and so on that hampered its potential were highlighted, and led to the enhancement features implemented in release 14, the three (3) support services introduced such as; eMBB, uRLLC and mMTC

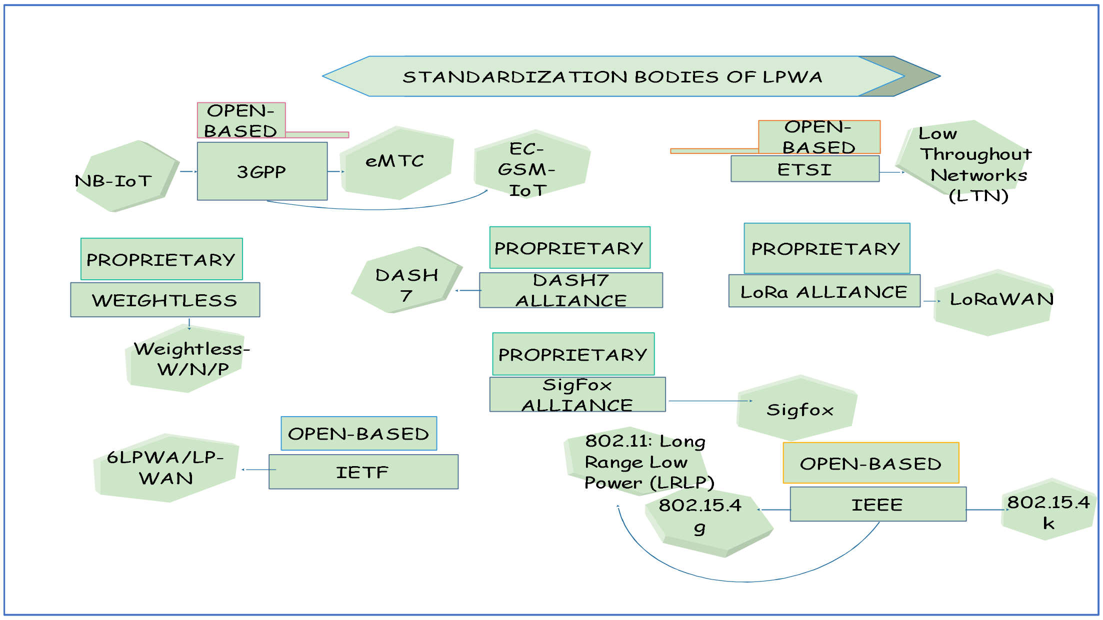


Figure 2.7. LPWA Standardization Bodies.

in Release 15, and to the focus on full support for the industrial internet of things (IIoT) for industry 4.0, including enhanced uRLLC and TSC, introduction of support for non-terrestrial networks (NPNs), unlicensed spectrum operation, and enhanced deployment by integrated access and backhauling (IAB) operation, mainly geared towards mmWave networks in Release 16, completed in March, 2020. The ongoing work is expected to include enhanced IIoT support and enhanced NPN support, enhanced wireless support and wire line convergence, multicast support and enhanced network automation support, including 5G New Radio-light (NR Light) which strives to facilitate light-weight communications for industrial sensors and related applications to be completed in mid-2021. Table 2.4 lists the features of all the 3GPP releases from Release13 to the current anticipated Release 17. More information about the features described in Table 2.4 are detailed in [28], [32], [76], [77]. The implementation of 5G NB-IoT will also feature some advanced attributes of massive IoT that include resource spread multiple access (RSMA) for IoT use cases requiring asynchronous and grant-less access, multi-hop mesh, PSM schemes, and eDRX for longer battery life. The benefits of 5G NB-IoT cannot be overemphasized, especially when considering the large-scale deployments and impressive prospects for widespread market success.

TABLE 2.4. Features of 3GPP standard release

Freezing time	Version	`Technologic fields of concern
2016	R13	Newly developed 180kHz physical-layer channels and signal, RF-bandwidth, half-duplex, 3 operational mode (Standalone, inband and guard band), multitone and single tone on the uplink, RRC connected/suspended, transmitted data through control plane, eDRX, mobility only idle mode [77].
2018	R14	Newly improved UE power class of the mission-critical (MC) aspects, such as the video and data MC-services. Introduction of vehicle-to-everything (V2X) communications, such as vehicle-to-vehicle (V2V), improved cellular internet of things (CIoT) by 2G, 3G, and 4G MTC support, improved radio interface for enhanced coordinated WLAN and unlicensed spectrum [78].
2019	R15	Power consumption reduction, reduced latency, improved accuracy, reliability of random access and enhanced range, small cell support, TDD support, enhanced access barring, enhanced eDRX, additional enhancement of critical communications for both uRLLC and high-reliable low-latency communication, MTC and IoT, vehicle-related communications (V2X), MC and WLAN-related features and unlicensed spectrum [79].
2020	R16	5G phase 2, due for June 2020 completion with a focus on multimedia priority service, application of vehicle-to-everything (V2X) services, 5G satellite-access, 5G local area network support, 5G wireline convergence, and wireless, terminal location and positioning, vertical-domain communications and network-automation, and novel radio technique. Additional items comprise security, codecs and streaming services, interworking of local area networks, network slicing and IoT, Inter RAT cell-selection, co-existence with NR, UE-group wake-up signal [80], [81].
2021	R17	The work addresses RAN 1, RAN 2, and RAN 3: physical layer, radio protocol, and enhanced radio architecture. Various characteristics of RAN 1, necessary for overall efficiency and 5G NR performance; MIMO, improved spectrum sharing, UE power saving and enhancement in coverage will be implemented. RAN 1 overview and specifications for improvement in the physical layer in support of frequency-bands beyond 52.6GHz up till 71GHz [82].

2.5 5G ARCHITECTURAL DESIGN FOR NB-IOT INTEGRATION

NB-IoT incorporated into the ongoing 3GPP 5G architectural design was possible by using wireless software-defined networking and the network function virtualization (NFV) paradigm [83], [84] through the relationship between the 5G radio access network (RAN) and the 5G architectural infrastructure. The introduced WSDN and NFV created cost-efficient service support for the NB-IoT model to facilitate communication between NB-IoT devices and applications. To buttress this point, we examined the limitations in EPC developed by 3GPP for LTE cellular network as illustrated in Figure 2.8. The limitation in EPC influences the latency of the overall system. One primary concern is inseparability of the control and data planes in the EPC. This has led to the coupling level between SGW and PGW that reduces the quality of service (QoS) of the network. Decoupling of the control plane and the data-plane becomes essential, since both control plane and data plane have different network QoS criteria to be met. The control plane requires low latency to process signaling messages, and the data plane needs a high throughput to process the data. Therefore, for efficient design of a plane, it is desirable to decouple the planes completely. Another limitation is the centralized implementation of the data plane of the LTE EPC. This limitation creates in-efficiency in system performance and a high latency that do not satisfy the 5G NB-IoT criteria [85]. The result of this limitation is witnessed when a user transmits traffic meant for local communication through a hierarchy system ending with a few numbers of centralized PGW. This effort increases the end-to-end (E2E) latency as illustrated in (2.1) [86].

$$T = \sum (T_{Radio} + T_{Backhaul} + T_{Core} + T_{Transport}) \qquad (2.1)$$

where T is the total one-way transmission time contributed by the RAN, Backhaul, Core network, and the data center (Internet). The T_{Radio} is the packet transmission time between the eNB and UE, which is due to the physical layer communication. $T_{Backhaul}$ is the time it takes to establish interaction (connections) between eNB and the Core network (i.e. EPC). T_{Core} is the time taken by the Core network to process the signal and finally, the $T_{Transport}$ is the communication delay between the core network and the cloud (internet).

Note that the centralized implementation of the network enhances the ease of managing and monitoring the system, but hindered the network QoS. The WSDN is an important pillar that separates the control plane and the data plane. Hence, support load balancing, reshapes enterprise network design, tackles the classes of complexity in the 3GPP 5G networks, and the IoT, and creates an excellent QoS for the network. The NFV, on the other hand, coordinates dynamic network resource sharing to promote the high-flexibility network.

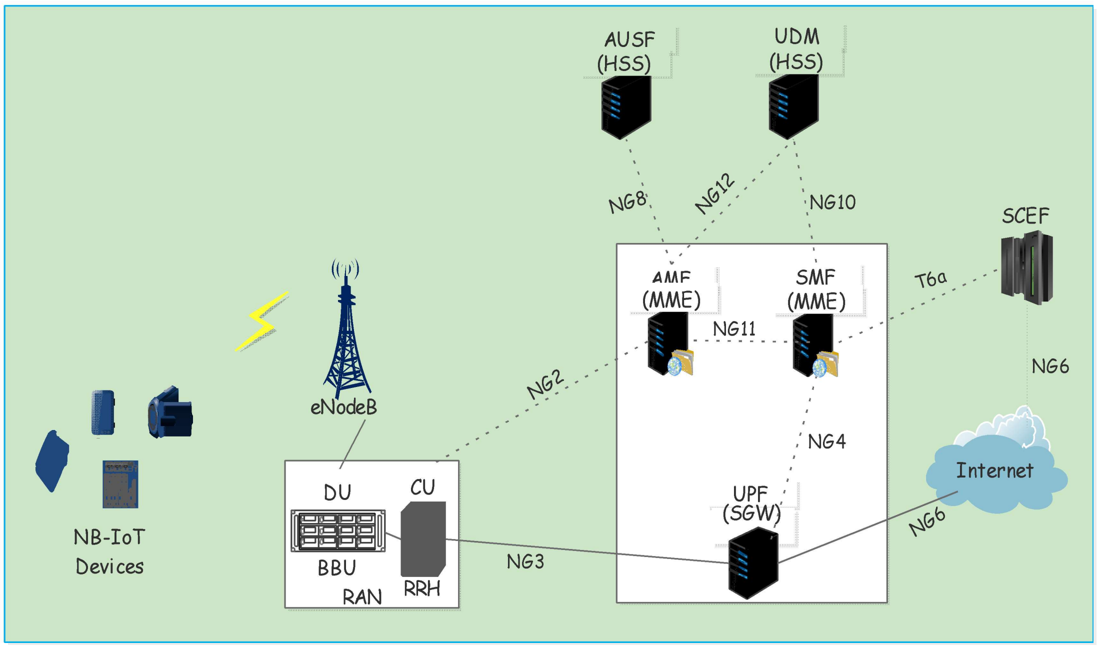


Figure 2.8. The proposed NB-IoT functional architecture for the on-going 3GPP 5G networks, Adapted from [83], [2].

The decoupling of the RAN promotes serviceable segregation of the broadband unit (BBU) from the remote radio head (RRH) that meets the condition of the interface of the 5G NB-IoT specifications [87]. Figure 2.8 describes the proposed NB-IoT functional architecture for the ongoing 3GPP 5G networks. The proposed NB-IoT architecture consists of network functions (NFs) and reference points (NG) connecting the NFs. Figure 6 comprises seven (7) NFs, namely the distribution unit (DU) and centralized unit (CU), and the access and mobility function (AMF), the session management function (SMF), the authentication severs function (AUSF), user data management (UDM), user plane forwarding (UPF) and service capability exposure function (SCEF). The RAN connects the UE as well as the AMF. The

RAN comprises two logical architectural components, namely the DU and CU. The DU and CU have the same functions as the existing LTE BBU and the RRH respectively. Both components support signaling exchange and data transmission between radio access interfaces (endpoints) of the NB-IoT specifications [88]. The remaining NFs are explained as follows [83], [2]:

- The primary task of AMF is to allow UE-based authentication, authorization, mobility management, connection management, and so on, including various functions related to security management. AMF performs the same features as the MME in the LTE network. It is independent of the access technologies. This can be seen when a UE with multiple access still upholds the connection to a single AMF.

- The SMF is accountable for the session management context with the UPF just as in the LTE MME, SGW-C, and PGW-C. Amongst the functions performed by the SMF are allocating IP addresses to UEs, NAS signaling for session management, sending QoS and information policy to RAN through the AMF, DL data notification, controlling, and selecting UPF for traffic routing. The UPF function selection facilitates the mobile edge computing (MEC) by selecting a UPF close to the edge of the network and so on, to mention but few.

- UDM stores UE subscription data.

- AUSF stores UE authentication data.

- UPF is the UE mobility anchor that promotes the UE traffic backwards and forwards into the internet.

- SCEF ensures the delivery of non-ip data over the control plane and provides an abstract interface for network services such as authentication, access control, or discovery.

The UPF is in the user plane and carries user traffic while the remaining NFs (AMF, SMF, AUSF, and UDM) are in the control plane. The user and control plane separation ensure that the resources in each plane scaled, will be independent. Also, the UPFs deployed will be distributed differently from the control plane functions. For example, UPF deployed, connect to the UEs to reduce the round-trip time (RTT) connecting UEs and data network for promoting applications with low latency [83].

The global acceleration of NB-IoT design in the 5G NR air interface standard was aimed at providing smooth transition and continuity of large-scale mMTC to 5G networks. More importantly, for ensuring technical guarantee for the operators, equipment vendors, chip manufacturers, and vertical industries in creating R&D and business model exploration [81]. The human user experience is expected to be enhanced by various 5G-enabled machine-related use cases through the 5G NB-IoT transformation. According to GSMA, altogether 129 NB-IoT and LTE-M commercial mobile-IoT networks have already been launched from January 2020 [89] (as depicted in Table 2.5) with coverage of approximately 93% of the world's largest IoT market in Q2 2019 [56]. The total number of NB-IoT (and IoT in general) connections expected is to rise to 25 billion by 2025 with a growth in application platforms and services to the tune of 68% of IoT-revenue of $1.1 trillion [89]. The transformation will provide a matured industrial-chain from a developed policy-driven to service-driven NB-IoT growth in the future when fully commercialized. The service-driven will, in turn, drive unquantified satisfaction and pleasant experience in human activities and industries through its deployment to various aspects of life activities. However, the challenges and related issues of NB-IoT implementation need to be considered from multiple perspectives such as enabling technologies, service and applications, business models, environmental and social impacts [90]. The enabling technologies necessary to address the required 5G NB-IoT can be grouped into the spectrum and network-enabling technologies [91], [25].

Table 2.5. NB-IoT and LTE-M Commercial Mobile-IoT Network

OPERATORS	COUNTRY/REGION	TECHNOLOGY
3	Hong Kong, SAR China	NB-IoT
A1	Austria, Belarus, Croatia, Slovenia	NB-IoT
AIS	Thailand	LTE-M and NB-IoT
American Movil	Mexico	LTE-M
APTG	Taiwan, Province of China	LTE-M and NB-IoT
Altice	Portugal	NB-IoT

AT&T	Mexico, & United States	LTE-M and NB-IoT
BASE (Telenet)	Belgium	NB-IoT
Bell	Canada	LTE-M
China Mobile	Hong-Kong SAR china and China	NB-IoT
China Telecom	China	NB-IoT
China Unicom	China	NB-IoT
Chunghwa Telecom	Taiwan	LTE-M and NB-IoT
Dialog Axiata	Sri Lanka	LTE-M and NB-IoT
DNA	Finland	LTE-M and NB-IoT
DU	UAE	NB-IoT
Elisa	Estonia and Finland	LTE-M and NB-IoT
Etisalat	UAE	LTE-M and NB-IoT
Far Eas Tone	Taiwan, Province of China	NB-IoT
Grameenphone	Bangladesh	NB-IoT
KDDI Corporation	Japan	LTE-M
Kcell	Kazakstan	NB-IoT
Korea Telecom	South Korea	LTE-M and NB-IoT
KPN	The Neitherlands	LTE-M
Kyvistar	Ukraine	NB-IoT
LGU+	South Korea	NB-IoT
LMT	Latvia	NB-IoT
M1 Singapore	Singapore	NB-IoT
Maxis	Malaysia	NB-IoT
Megafon	Russia	NB-IoT
Mobitel	Sri Lanka	NB-IoT
MTS	Russia	NB-IoT
NOS	Portugal	NB-IoT
NTT Docomo	Japan	LTE-M
Orange	France, Spain, Romania	LTE-M
Proximus	Belgium	NB-IoT
Reliance Jo	India	NB-IoT
Rogers	Canada	LTE-M and NB-IoT
SFR	France	NB-IoT
SingTel	Singapore	LTE-M and NB-IoT
Smartone	Hong-Kong, SAR, China	NB-IoT
Softbank	Japan	LTE-M and NB-IoT
Spark	New Zealand	LTE-M
Sprint	North American	LTE-M
StarHub	Singapore	NB-IoT
STC	Saudi Arabia	NB-IoT

Swisscom	Switzerland	LTE-M and NB-IoT
Taiwan Mobile	Taiwan, Province of China	NB-IoT
TDC	Denmark	NB-IoT
TIM	Brazil and Italy	NB-IoT
Telefonica	Germany, Brazil. Argentina, Colombia, Spain	LTE-M and NB-IoT
Telenor	Denmark, Norway	LTE-M and NB-IoT
Telia	Norway, Denmark, Estonia, Finland, Sweden	NB-IoT
Telkomsel	Indonesia	NB-IoT
Telstra	Australia	LTE-M and NB-IoT
Telus	Canada	LTE-M
True corporation	Thailand	NB-IoT
T-Mobile	Austria, Germany, Greece, Croatia, Hungary, Poland, Slovakia, The Netherlands, United States	NB-IoT
Turkcell	Turkey	LTE-M and NB-IoT
Viettel	Vietnam	NB-IoT
Verizon	North American	LTE-M and NB-IoT
	New Zealand, Hungary, Greece, Germany, Czech Republic, Ireland, Italy, Malta, Spain, Portugal, South Africa, Australia, United Kingdom, Ukraine, Turkey	NB-IoT
XL Axiata	Indonesia	NB-IoT

2.5.1 The enabling technologies required for 5G NB-IOT

The network-enabling technologies are:

- Network densification through small cells
- Cognitive radio (CR)
- Device-Device (D2D) communication
- Massive multiple-input multiple-output (MIMO) antennas (beam forming)
- Distributed network
- Cloud-based radius access network (CRAN)
- Wireless network function virtualization (WNFV)
- Wireless software-defined networking (WSDN)
- Edge computing to support low-latency application

- Control and user plane separation
- Network slicing (network as a service) to support application specific QoS
- Real-time machine learning/artificial intelligence
- New fronthaul, mid-haul, backhaul solutions and the spectrum-enabling technologies which are:
- New band (3.5GHz mm wave)
- Efficient use of spectrum through spectrum-sharing techniques such as licensed shared access (LSA)
- Large bandwidth to support the required data flow
- Using unlicensed band to offload the traffic

The key technology enablers for realizing 5G NB-IoT networks are the two wireless SDN and NFV, as stated earlier. Both software technologies define the methods of the deployed and operated network services. The two technologies enable network slicing to provide customized QoS and specific functions required for different vertical markets. The CRAN cut down the total cost of operational expenditure (OpEx) to facilitate efficient resource allocation. The improvement in spectrum reuse and network capacity was achieved through the deployment of small cells. The new backhaul solutions assist both the traditional and distributed RAN networks to ensure user connectivity. The edge computing employed for local analysis and data processing enhances the users' quality of experience (QoE) with improved visual, audio and haptic interfaces. The implemented MIMO increases the user data speed and system capacity for 5G NB-IoT requirements. Data transmission and reception over the same radio channel are enhanced through highly focused beams by exploring multipath propagation and spatial multiplexing. The CR techniques employed can identify available free spectrum (spectrum sensing), detect licensed users, select (spectrum management) and vacate the best possible spectrum on the arrival of the primary user (spectrum mobility) [92].

Since 5G NB-IoT-operated systems will be in NR of a higher frequency band than LTE, the bandwidth offers a high-frequency band of much wider channels and high speeds beyond 1GHz. The use of technologies such as MIMO, D2D communication, macro-assisted small-cells, and super-dense meshed cells supports the varying requirements of all use cases.

Spectrum-sharing techniques, such as licensed shared access (LSA), enhance spectrum utilization, while unlicensed spectrum, coupled with licensed spectrum, increases the access to network capacity and improves users' wireless experience.

2.6 THE CLOUD-ASSISTED RELAY WITH AMBIENT BACKSCATTER COMMUNICATION FOR 5G NB-IOT NETWORKS

Before the implementation of CRAN, the interaction among base stations (BSs), radio access network (RAN) and a core network, as well as the direct X2 interface between RANs operating in separate cells, was based on Internet protocol (IP) (as in the case of flat architecture of core network in LTE) [93]. This, however, restrained handing-over procedures for mobility management, increased inter-cell coordination for interference management, and joint transmission of baseband signals through coordinated multipoint (CoMP) [87]. With the multitude of RATs and HetNet configurations to be deployed in 5G NB-IoT, managing and deploying large networks can be challenging and expensive without the implementation of CRAN. The adoption of CRAN provides a solution to the above challenges and also allows tremendous connectivity, resource pooling, spectral, and energy efficiency for supporting the practical roll-out of NB-IoT, as well as the centralization of baseband (BB) processing functions of BS demanding architectural changes to RAN components. The RAN protocol stack of NB-IoT has to be flexible to adapt complex signal-processing and radio resource management (RRM) functions [94]. Though NB-IoT deployment can be a software upgrade to an existing LTE network, it can also be accomplished in a 5G-enabled cloud-RAN due to its simplified baseband processing and signaling protocol. The simplified baseband processing and signaling protocol provide cost-effectiveness in deploying and executing NB-IoT on a general cloud computing infrastructure or virtual machine (VM) using software-defined radio (SDR) [33]. The virtualization of RAN has been possible in NB-IoT due to the narrow bandwidth that requires an off-the-shelf network router for its modest fronthaul link capacity. Another feature of NB-IoT suitability for CRAN was the relaxed-latency requirement. The relax latency permits the BS to operate in very restricted computational power conditions due to the asynchronous HARQ design when compared to the legacy LTE. In such a situation, NB-IoT can profit from the deployed processing delay flexibility caused by multiple hops in cloud infrastructure. This implies that the remote radio units (RRUs) can be located further away. Therefore, the baseband unit (BBU) server can traverse a larger area [87].

The enhanced coverage area of cloud NB-IoT BS also creates the possibility of NB-IoT femtocell deployments for large buildings and industrial sites due to the signal repetitions and increased power performance gain. However, the repetition is constrained by channel estimation accuracy that depends on the received signal-to-noise ratio (SNR) and the channel coherence time [33]. Also, the efficient realization of CRAN is challenged by factors such as the scalability, latency requirement, and fronthaul capacity constraints as well as the network resource slicing between IoT applications and other broadband services [33]. The fronthaul link between the BBU and remote radio head (RRH) reduces the amount of processing time available for the BBU before the HARQ feedback time expires. Further information about CRAN implementation can be found in [87]. The reports on ambient backscatter [95], data compression [96], and power-saving [97] mechanisms have been highlighted to meet the challenges of fronthaul capacity, latency problems, and co-channel direct-link interference (DLI).

Ambient backscatter paradigm is an emerging technology that can harvest energy from external sources to extend the lifetime of wireless NB-IoT devices with the exclusion of strict battery constraints involving any type of power-consuming active components or other signal-conditioning units. Ambient backscatter can be designed to use wireless information and power transfer (SWIPT) mechanism [98],[99] through the exploitation of existing or legacy RF signals (such as cellular, TV, Wi-Fi, or radio systems) [100] for effective deployment of cloud NB-IoT network. The incorporation of ambient backscatter relay technology into the cloud NB-IoT network will increase communication distance, channel capacity, and diversity, as well as link reliability [95], [101], [102]. The research work from [95], [98] provides a guide to effective implementation of a cloud-assisted relay with ambient backscatter communication for 5G NB-IoT networks. Figure 2.9 illustrates the conceived architectural design of the cloud-assisted relay for 5G NB-IoT networks. In Figure 2.9a, the edge node provides bi-directional radio functionalities for transmitted/received signals to/from the UEs within and outside the coverage area of the network. Each UE is provided with a dedicated channel (i.e. UL/DL channel) to interact with the edge node, including the relay node E placed on the same channel. It can be assumed that OFDMA has been employed by the edge node to allocate resources to the UEs and the relay node E respectively. Also, the following assumptions can be made to achieve an effective system [102]:

1. All UEs should be equipped and powered by a battery, single antenna, and operated in half-duplex mode.
2. The relay node E should be equipped with energy-harvesting capacity for its operation. Moreover, node E should be allowed to relay information through either active radio or passive ambient backscatter, termed Active-relaying and Passive-relaying.
3. The node UE_j is located far apart from the edge node coverage and transmit power budget. Hence the information from the edge node passes through the relay node E to reach the node UE_j.
4. The relay node E has a power-splitting (PS) based receiver architectural design [103] for conducting simultaneous information decoding and energy harvesting. The relay node E should function as energy harvester to charge the on-board capacitor of the adopted circuit components.

Once the circuit is fully charged and powered-on successfully, the excess harvested energy is reserved in energy storage for intended active communication. The relay node E adopts decoding and forward protocol procedure by using the time slot model to perform mode selection as depicted in Figure 2.9b. During the edge-to-relay transmission, a portion of the aggregated RF signal collected from both the energy sources and interferers (i.e. co-channel interference) is utilized for harvesting and the overflow is used for information decoding to transmit preamble signals from the E to the node UE_j in the first half of the time slot. The process is termed active relaying mode (i.e. the energy harvesting rate of E $\geq$ twice the circuit power dissipation in the active state). Otherwise, node E chooses a passive relaying mode. At the node UE_j, feedback of the received signal-to-interference plus noise ratio (SINR)

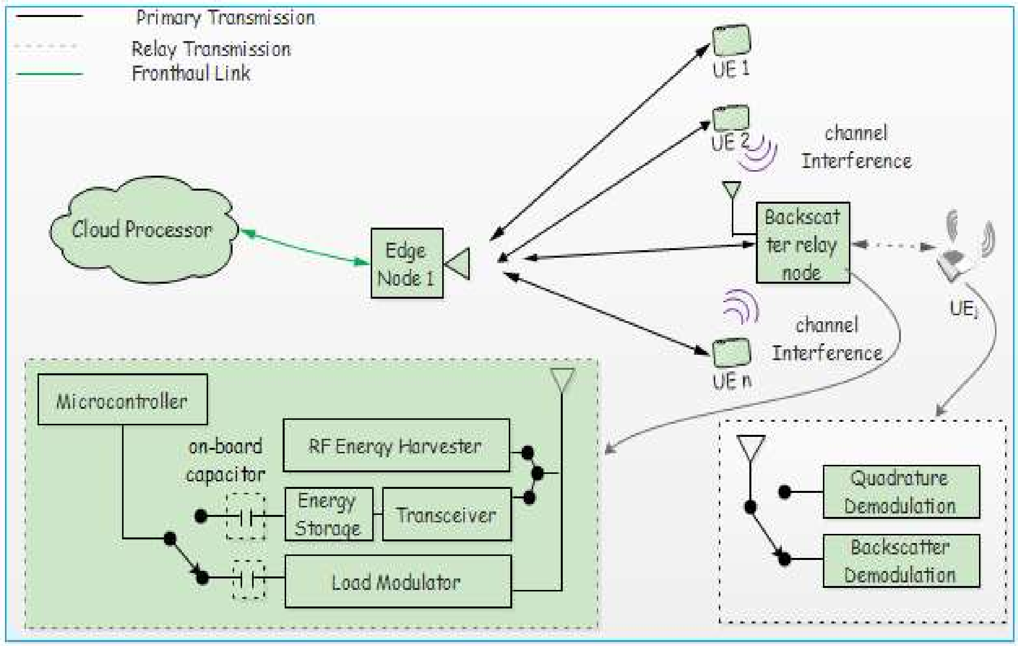


Figure 2.9a. The conceived architectural design of the cloud-assisted relay for 5G NB-IoT networks, Adapted from [98], [102], © 2018 & 2019, IEEE.

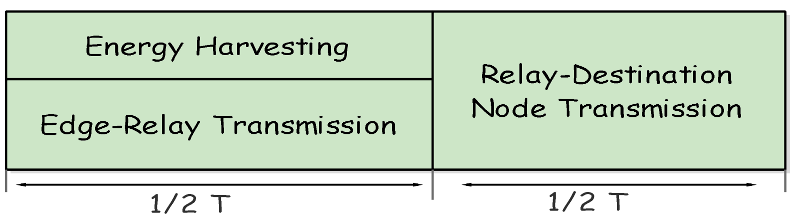


Figure 2.9b. Time Slots Model of Power Splitting based relaying protocol for performing mode selection, Adapted from [102], © 2018.

through the signaling is granted depending on the relay transmission ratio of the active and passive relay modes. If the received SINR at the node is greater than the active time slot, node E chooses active relaying mode and the nodes work with the quadrature demodulation. Otherwise, node E chooses the passive relay mode and the nodes work with the backscatter demodulation. This proposed process can estimate channel parameters by using a standard technique for all the UEs associated with the cloud. Also, the interference contribution can be subtracted from the received BB signal, thereby solving the challenge of interference instead of applying complex multiple antenna techniques as discussed in [103]. It is worthwhile to mention that the performance of the backscatter relay node E neither suffer the latency from the edge node nor be affected by the performance of the UEs appreciably [104].

2.7 5G NR AND NB-IoT COEXISTENCE

NR specifications were approved in March 2017 by 3GPP as part of release 15 [105] and release 16. Since then, many operators (both existing and new) have commenced migration from LTE to NR, with the United States leading in 2019, due to the flexible deployment of NR. NR key features are contained in [106], [105]. The NR coexistence with NB-IoT can enhance resource efficiency and avoid mutual interference between the two networks, though, NR channel bandwidth flexibility has some numerology similar to that of LTE and NB-IoT as tabulated in Table 2.6. The subcarrier orthogonality between NR and NB-IoT can be obtained by examining specific design limitations that need to be overcome, for example interference, scheduling, and resource utilization. The resource utilization through the aligned resource blocks (RBs) between the NR and NB-IoT can be improved. The feature of FDD bands as listed in Table 2.6 enables NR tractability to examine effectively deployed NB-IoT within the NR carrier. For instance, the deployed in-band NB-IoT within the NR carrier requires the guard band reserved to forestall interference between the NR and NB-IoT. The listed parameters to be exploited [107] are:

1. NR resource reservation in the time domain (symbol level) and frequency domain (RB-level) configuration using a flexible method.

2. System bandwidth choices, as well as raster steps requirements.

3. Placement of synchronization signal block (SSB) in an NR carrier.

Generally, the air interface of NR is flexible and can meet the general requirements of several NB-IoT use cases and deployments by adapting the scalable cyclic prefix orthogonal frequency division multiplexing (CP-OFDM) waveform of NR. The scaling factor 2^{μ} helps to align the slots and symbols of different numerologies in the time domain to secure TDD networks. However, for NB-IoT to sustain use cases with diverse requirements simultaneously on the same NR carrier, two options have been suggested [108];

Table 2.6. The Similarities between the Numerologies of NR and NB-IoT [105], [107], [109]

Features	New Radio (NR)	NB-IoT
Frame structure	Consists of 10 subframes, each of 1ms duration. The sub-frame consists of 2^{μ} slots of 14 OFDMA symbols each	Consists of 10 subframes, each of 1ms duration. Each subframe has 2 slots of 14 OFDMA symbols each
Subcarrier spacing	Has adjustable sub-carrier spacing of 2^{μ} *15kHz, where μ =0, 1….,4. This identical property (when μ=0) facilitates coexistence between NR and NB-IoT.	Has subcarrier spacing of 15kHz in DL and 3.75kHz in UL
Resource block (RB)	RB contains 12 subcarriers in the frequency domain and has one dimension. The bandwidth of RB relies on the subcarrier spacing. For example, with 30kHz subcarrier spacing, each NR RB has 360kHz and 180kHz for 15kHz subcarrier spacing.	RB is two-dimensional in the time and frequency-domain. It also has 12 subcarriers. The bandwidth of the 15kHz subcarrier spacing is 180kHz.
Raster grid	Describes a subset of RF reference frequency employed to distinguish the RF channel region in DL & UL. The raster step relies on the carrier frequency. The reference frequency of the RF channel is related to the resource element on the carrier. Therefore, for initial access, the UE explores its carrier across the raster grid.	Raster designates the center of the carriers. Hence, the NB-IoT raster is midway between two subcarriers in the NB-IoT RB.
FDD Frequency bands for NR and NB-IoT deployment	Bands (1,2,5,8,20.25.28.66) have NR channel bandwidth for 15kHz subcarrier spacing (MHz) of 5,10,15, & 20. Band (3) has (5,10,15,20,25, & 30), Band (12) has 5,10 & 15 and Band (77) has 5,10,15,20, and 25, respectively. The channel raster of 100kHz is used for them all.	This is the possible NB-IoT carrier's center locations relative to NR

1. The use of mini-slots between regular slots, to enhance low latency and avoid extended CP overhead. The use of mini-slots can also expeditiously enable transmissions in an unlicensed spectrum, as well as schedule users on a short time scale.
2. Frequency domain multiplexing (FDM) of numerologies is another option. The use of FDM results in inter-numerology interference. Therefore, spectral confinement of waveform becomes essential. The low-complexity windowing/filtering and slight guard band overhead can be adopted to reduce inter-numerology interference. The windowing method can also be adapted to enhance asynchronous access to mMTC applications.

For instance, the author in [110], employs 700MHz wireless band standards of which 10MHz bandwidth was shared between 5G NR, LTE-A and three (3) NB-IoT DL carriers. The three (3) NB-IoT carriers have different operational mode of two (2) guard band mode and one autonomous mode located at the center of the spectrum. This scenario is termed as dynamic Spectrum sharing (DSS) as specified in 3GPP rel. 15. To achieve an effective coexistence and avoid collisions, 5G NR must be configured with 15kHz subcarrier spacing to ensure the synchronism signals out of band of LTE signals. Again, since the maximum delay spread of NB-IoT guard band is the LTE-A cyclic prefix (CP) length (i.e., 4.7 μs), precaution is critical in the planning of the network to avoid interference for the first OFDM subcarrier of LTE-A.

The fundamental abstract above about coexistence of NR and NB-IoT will form the foundation of prospective NB-IoT design supports for diverse use cases and applications on NR carrier, based on the choice of the parameter μ (μ depends on several factors, including deployment types, service requirements, hardware impairments, mobility, performance, and implementation complexity) [108].

2.7.1 Potential architectural development scheme of NB-IoT with cellular networks

5G networks and the currently deployed LTE networks consist of macro-cell and small-cell infrastructures of heterogeneous networks. The overlaying of small cells on macro-cells results in interference, which affects small-cell edge users and NB-IoT UEs towards obtaining adequate QoS in the NB-IoT network. In order to enhance the NB-IoT performance in a small-cell network, based on spectral efficiency, coverage and capacity over the heterogeneous infrastructures (macro-cell and small cells), four categories of possible support for NB-IoT coexistence with the legacy LTE and the ongoing 5G networks listed in [32], [111] are:

- Synchronous distribution of NB-IoT in all small cells
- Asynchronous distribution of NB-IoT in all small cells
- Synchronous distribution of NB-IoT in small cells and macro-cells
- Asynchronous distribution of NB-IoT in small cells and macro-cells.

2.7.1.1 Synchronous Distribution of NB-IoT in all small cells

In this scenario, all synchronized small cells appear in a mode to make use of the same PRB. All NB-IoT UEs configured should apply an identical transmit power despite the highest transmitted power capacity, to limit the creation of co-channel interference to many UEs on similar radio resources. The power restriction requires a practicable innovation that ensures satisfactory performance. Despite this, cell edge UEs may still experience interference difficulty due to the associated low quality of channel estimation of NB-IoT UEs to reduce computational complexity.

2.7.1.2 Asynchronous Distribution of NB-IoT in all Small-cells

This scenario involves a precise frequency plan, as well as a specific-power configuration for NB-IoT UEs. NB-IoT enabled is devised in all the small-cells utilizing unique PRBs. This strategy prevents interference among NB-IoT UEs of diverse small cells but may cause co-channel interference within the NB-IoT and 5G NR/LTE UEs employing similar radio resources. Several techniques proffered to mitigate this co-channel interference need further enhancement. Conventional methods are blanking and frequency hopping. The blanking technique referred to as a wasteful technique will be avoided.

2.7.1.3 Synchronous Distribution of NB-IoT in Small Cells and Macro-cells

The approach facilitates NB-IoT in both the small cells and macro-cells with different transmit powers on a similar PRBs. The macro-cell UEs configured should use higher transmitted power than the small-cell UEs. The remaining PRBs configured are used for 5G NR/LTE. Co-channel interference may arise on small-cell edge UEs if the UEs scheduled are on identical resource units. The effect of the interference may increase on UEs requiring handing-over from one serving cell to another. Frequency reuse, power control, frequency hopping, and geographical planning may be needed urgently for low-complexity NB-IoT to improve the coverage range of NB-IoT.

2.7.1.4 Asynchronous Distribution of NB-IoT in Small-cells and NR/LTE in Macro-cells

The approach estimates various variables such as the use case specifications, environmental limitations, equipment status, and so on to guarantee improved spectral efficiency, performance, and extensive NB-IoT distribution with other technologies. The approach employs separate PRBs for NB-IoT among small cells and macro-cells intending different PRBs for small cells and macro-cells. The strategy requires effective PRBs planning to avoid interference from an adjacent cell of NB-IoT users with identical resource units. It is also likely that NR/LTE users with similar resource elements might conflict with the small cell or macro-cell UEs. Different transmitting power control configurations are applied to prevent interference.

2.8 TECHNICAL PERFORMANCE PROPERTIES OF NB-IOT

The technical properties of NB-IoT can be grouped under two layers i.e. the PHY and the MAC layers. Features such as coverage area, scalability, transmission data rate, physical channel estimations, and MAC PDU reception applicability are referred to as PHY properties while the design and enhancement of protocols that support energy management, link adaptations, resource allocation, security, and coverage enhancement are referred to as the MAC properties. The PHY layer has been called a layer that accommodates most of the innovation and novel inventions of the NB-IoT features. The study of both layers (PHY and MAC) was necessary to discover the plethora of research gaps and proposals for future research into NB-IoT stack optimization towards 5G mMTC requirements. However, NB-IoT employs a similar protocol stack as the legacy LTE, with design modifications in PHY/MAC layers, which has introduced an added +20dB MCL support.

At the MAC/PHY interface, the transport channels are mapped to physical channels and vice-versa at the transmission and reception [70], which allows multiple interactions within one LTE PRB of NB-IoT. The data channels, control, broadcast, and random access are all multiplexed on the same radio resource. This relates to when and how the radio resources shared among the NP-RACH, NP-USCH, NP-DCCH, and NP-DSCH can significantly affect the services rendered and the device performance. The effect of these parameters has prompted researches on downlink control information (DCI) search space under a different set of coverage classes as they relate to control channel allocation and data scheduling. The scheduling process allocates radio resources to UEs in every transmission time interval (TTI) through the DCI in NP-DCCH. The NB-IoT scheduling process is located in the lower MAC and upper PHY layers [59], [68]. The DCI specifies the scheduling information for uplink and downlink transmission in every base station of NB-IoT. The UE specific DCI for procedures such as paging, random access, and data transmission carried by the NP-DCCH are to deliver scheduling command. The DCI defined occurs in three (3) formats, namely the DCI format N0 has a payload of 23 bits and is responsible for carrying NP-USCH scheduling grants. The NP-USCH scheduling grants comprises the repetition number, modulation and coding scheme (MCS), resource assignment, scheduling delay and subcarrier sign. The DCI format N1 has a payload of 23 bits and carries NP-DSCH scheduling control and the NPRACH contention-free procedure preamble which consists of DCI format N0, including ACK resource index of the HARQ process. The last DCI format N2 has a payload of 15 bits and carries both paging and direct sign messages for NPDSCH.

For the UE to discover the DCI messages, the UE tracks the search spaces of the predefined NP-DCCH within the boundary of the subframes allowed for NP-DCCH. The distance between two successive NP-DCCH (NP-DCCH period) is referred to as the $R_{max} \times G$ subframes long, where R_{max} is the maximum repetition number of DCI and G is a system parameter. Since the NPDCCH allocation determines the scheduling opportunities, the combination (R_{max}, G) is also critical for resource scheduling [68].

The resource scheduling issue has prompted state-of-the-art research into data transmission towards scheduling parameter selection and DCI search space allocation. To study the effect of extensive resource consumption per data transmission, a large amount of energy is consumed during the implemented coverage enhancement (CE) features, latency, co-channel interference, design optimization, channel estimation and error correction, among others, on NB-IoT channel communication and resource management. Therefore, we present a brief reviewed works of the literature on the above-listed topics listed to identify the research gaps with a view to enhance the 5G NB-IoT system's performance.

2.8.1 NB-IoT Channel Communication

This section explains the connectivity procedure of a UE in an NB-IoT network and goes further to review the research gaps in every step of the established connectivity between the UE and the eNBs. The first operation executed by the UE in DL is the acquisition and synchronization of system information. The UE retrieves the cell and access configurations. The synchronized time required ranges from 24ms to 2604ms for high-grade and poor propagation conditions. To communicate with the UE in idle state, the network transmits paging information to the UE through the NP-DSCH by using Format N2. The paging information can be either a request to set up a remote radio-control (RRC) link or it may be due to a variation in the system parameters. After the process of paging (i.e., UE connection status), data acquisition can commence. The DCI Format N1 shows the resources allocated, the DL transmission span, the subframe number, and the ACK/NACK resources applied. The conferred repetition number allows the eNB to transmit identical copies of the data in continuous DL sub-frames without the adopted S1 message subframe through one interleaving subframe. If no repetitions apply, the transmission is outlined in a consecutive DL subframe [112]. The designated repetition number depends on the strength of the signal transmitted from the eNB to the UE [68].

For the UL procedure, access is usually random (RA). There are two methods of initiating the RA. The first method is by a response to a paging message while the second method is by a UE-initiated operation during data transmission. In triggering the RA, the UE demands the system configurations. In the idle state, the UE already has the system information, but for the PSM mode, the UE reacquires the master information block (MIB), system information (SIB1 and SIB2). The RA procedure is always contention-based, and there are four procedures as demonstrated in Figure 2.10. The first step begins with the preamble signal transmission (Msg1) to the eNB to initiate the RA [113]. If there are multiple UEs with the same subscriber sending preamble signals, the preamble sequences will collide, and the eNB is yet to be aware of the situation. After the transmitted Msg1, the eNB schedules a DL transmission for the random-access response (RAR, Msg2) through the NP-DCCH and NP-DSCH.

This lasts for about 2-10 times the NP-DCCH period. At this time, the RAR responds to the preamble and grants the next message. The maximum amount of preamble considered per RAR is network-specific and frequently utilized to regulate the load. The UEs without Msg2 in the RAR window, set up a different RA request. At this stage, the colluded UEs experience an identical RAR without being aware that a conflict has occurred. After Msg2, the UE

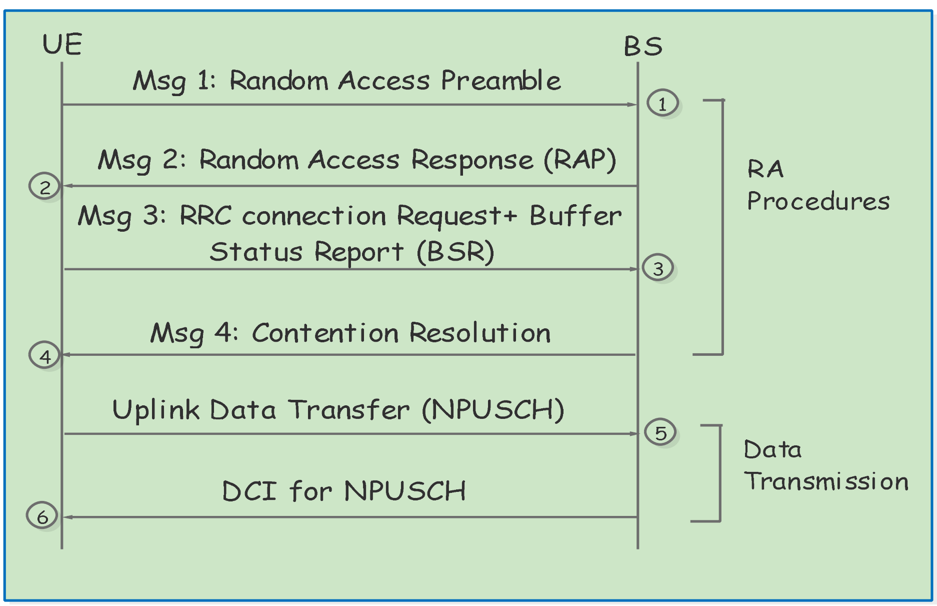


Figure 2.10. RA procedures and data transmission for UL transmission in NB-IoT, Taking from [113], © 2018, IEEE.

forwards a link request via the UL by utilizing resources pre-allocated in RAR (Msg3). Msg3 conveys a message such as the UE-identity and the buffer size report (BSR).

The UE also commences a contention resolution timer (1-64 times of NP-DCCH period) to wait for the Msg4 on the NP-DSCH. After reception of the link request (Msg4), the eNB schedules the set-up information in the DL to end the RA processes. The UL message (Msg5) from the UE sets the RRC link known as the NAS service request. If any of the procedures of RA fails in the listed steps, the UE will set up a new request after a back-off time of up to ~ 9 minutes. If the UE has exhausted all the trials as configured by the network and up to 10, the UE will have to try in a different coverage class. The UE can attempt for the relatively configured number of 200 before declaring the RA failure. After the RRC link has been secured, the core network commences the transmission of DL information, also known as NAS service data for mobile terminated (MT) DL data-packet communication [113], [112].

2.8.2 Cell Synchronization and Acquisition

NB-IoT UE performs cell synchronization and acquisition by using PSS/SSS to obtain the system configurations as mentioned earlier. This information consists of cell ID, scheduling information, number of a subframe, and allocated system bandwidth. Poor cell synchronization and acquisition performance occur when there is a low complexity of devices caused by poor channel estimation capacity and carrier frequency offsets. Usually, the PSS/SSS is located at the center of the carrier in NB-IoT, and all UEs must search all possible carrier positions. This retards the acquisition of system information for any UE without prior knowledge of the position of the carrier frequency. Therefore, for an effective 5G NB-IoT system, there is a need for a fast cell search to be adopted. Many types of research have tried to proffer solutions to optimize the initial cell synchronization and acquisition procedure. The research work in [114] proposes a comprehensive synchronization signal structure design for low-cost NB-IoT in a broad frequency offset scenario for DL synchronization signal design. The synchronization signal with a conjugated Zadoff-Chu (ZC) couple of sequences has been used to eliminate timing issues caused by the large frequency offset. The ZC sequence witnesses a small loss of energy detection due to the insensitivity to the frequency offset. The result of the simulation illustrates a timing detection performance loss of approximately 2dB under large frequency offset in the range of -40kHz to 40kHz when compared with NPSS. The limitation of this model is the fact that there are no records of the number of samples per symbol employed to obtain the simulated results. The research of [115] proposes frequency diversity (FD) reception for narrowband NPSS and NSSS at a UE to enhance the PHY cell identity (PCID) detection probability for NB-IoT deployed in multiple resources blocks (RBs). The reception of NPSS and NSSS by the UE in the time domain transmitted from different RBs within the same frequency band demonstrates link-level simulation results of approximately 16% improvement for PCID detection probability using FD reception, compared to without FD reception of the four RBs with single antenna transmission. Besides, the simulation results of 90% and 97% of PCID detection, probabilities using FD reception are achieved with precoding vector switching (PVS) diversity transmission at an average received SNR power of 0dB for both maximum frequency offset of 70kHz, and without frequency offset respectively. The results of the simulation prove the efficiency of the proposed FD reception towards improving the NPSS detection probability without changing the NB-IoT radio interface.

2.8.3 Random Access Procedure (RAP)

For the 5G NB-IoT system, RAP is employed for uplink transmissions between UEs and eNB to achieve system configurations. However, during the multiple UEs transmission of preamble signals with the same subscriber, there is performance degradation resulting from a collision in the network. This is due to the fact that RA is a contention-based mechanism that is not synchronous with the LTE nature at every cell change. Therefore, several investigations and solutions have been proposed in the literature. The author in [116] has emphasized the power consumption challenge faced when the eNB received superimposes NPRACH preambles from massive connectivity of multiple users [117] and the different repetitions of preambles for different coverage areas [118] per transmission over channel probabilities due to collision. The authors have analyzed the increment in the average energy consumed, compared to the increase in the number of repetitions, and they propose a novel power-efficient RAP (PE-RAP) to reduce the power consumed by NB-IoT devices in a highly congested environment. The research of [119] has presented two solutions for RA. The first solution is an approximate performance metrics of an analytical model of access success-probability and average access delay of RA in NB-IoT. The second solution is a joint optimization of multiple parameters such as the maximum number of preamble transmissions, size of back-off windows, and the number of subcarriers per coverage enhancement level of RA to maximize the probability of successful access under a delay constraint. The accuracy of the optimization validated in computer simulations has been benchmarked in exhaustive search. However, the authors have not considered the limit of the feasibility of the thorough search method in a real-world system. But instead, they have used a proficient simulation tool to benchmark their work to promote the findings of their research work towards improving the NB-IoT RAP technology. Besides, RA performance in the higher CE level has not been considered. The research work of [120] presents an efficient 3GPP open-source simulator tool capable of investigating and modeling the behavior of RAP in NB-IoT technology. The authors explain three aspects of the usefulness of the simulation tool as: i) for analytical modeling of RAP in estimating the number of users operating RAP and an extensive study of the average end-to-end delay, ii) achieving both collision and success-probabilities incorporated into the RAP and finally, for cross-validation of the analytical model and simulation tool taking into consideration the enabling periodic report of the device referencing application networks. The research work enhances RAP optimization in the simulation tool for the standard procedure. The result achieved from the simulation tool proves the accuracy and usefulness of the calibrated tool for future activities. In summary, since the focus of all the research works is either on access delay, detection of RA preambles or optimization of resource allocation, a proficient simulation tool that captures all the limits will aid a novel NB-IoT RAP technology development.

2.8.4 Channel Estimation and Error Correction

The NB-IoT system depends on the cell-specific reference signals for channel estimation. Therefore, fast synchronization time depends on the complexity ability of the UE to assess the quality of the channel estimation. Also, the coverage enhancement of signal repetitions in exceedingly poor radio conditions, and adequate receiver performance depends on the quality of the channel estimation. The effect of poor channel estimation on NB-IoT systems can lead to passive inter-modulation, signal misdetection, carrier frequency offset, phase noise, IQ-imbalance, increased power use, and so on, to mention few. Hence, for an effective 5G NB-IoT system, the quality of channel estimation should solely depend on the user-specific demodulation reference signals [121]. Some of the solutions to poor channel estimation, as well as the error correction in the NB-IoT system in the literature are reviewed below.

In [122], the authors use a simple DFT-based low-complexity cell ID estimator to prove the estimated maximum likelihood (ML) of the cell ID in the NB-IoT system. The likelihood function was further introduced to estimate the channel leading to the maximized concentrated-likelihood function. The simulation results show a lossless performance of the exhaustive ML cell ID search as compared to the exhaustive search. Furthermore, other series of simulations have revealed a robust residual frequency offset of ≤ 0.5dB loss of up to 200Hz offset and a mean square error (MSE) of channel estimation of Cramer-Rao bound (CRB). However, the study has increased the computational complexity of the ML estimator which might take time and more resources to execute since NB-IoT operating SNR is expected to be less than or equal to zero. Therefore, any channel estimation and error correction algorithm should be computationally efficient at extremely low SNR. In [123], a modified linear minimum mean square error (LMMSE) channel estimation for the NB-IoT downlink system is proposed. Both singular value decomposition (SVD) and overlap banded technique have been used to reduce the LMMSE estimation complexity from the partition of the channel autocorrelation matrix into small submatrices. The performance and complexity of the LMMSE estimator have been compared with the traditional LMMSE and its counterparts. The result shows that the LMMSE estimator is useful for NB-IoT downlink systems with a dint performance of negligible degradation. However, the model is only efficient for linear data but not suitable for noisy or nonlinear data. In [124], two efficient narrowband demodulation reference signal (NDMRS)-assisted channel estimation algorithms have been proposed. The NDMRS algorithms are based on the conventional least-squared (LS) [125], and minimum means square error (MMSE) [126] methods. The results of the theoretical analysis and link-level performance illustrate that the proposed algorithms perform much better than the traditional LS and MMSE methods in low SNR conditions. Besides, analyses of raised cosine (RC) and square root raised cosine (RRC) pulse shaping for peak-to-average power ratio (PAPR) reduction have been evaluated for both single-tone and multitone transmissions for the uplink filter. The result illustrates that RRC pulse shaping with lower PAPR values can achieve a practical NB-IoT uplink transmitter design with increased power efficiency. However, the algorithms have not considered carrier frequency offset which may affect system performance.

2.8.5 Channel Interference

In the context of 5G NB-IoT, the interference is an intrinsic limitation of the NB-IoT network operating frequency reuse of the new 5G NR and 4G LTE wireless systems, although the concept of frequency reuse improves maximum spectrum utilization but at the same time limits the spectral efficiency, network and user performance. Therefore, mitigating the co-channel interference is obviously needed for the coexistence of harmonic and adaptability among NB-IoT and 5G systems. Most importantly, overcoming the interference will ensure high capacity and wide coverage of high end-user data rates as well as efficient and robust communication. The channel interference occurs in two modes of NB-IoT deployment in the 5G NR/LTE spectrum, namely, the in-band and the guard modes. The interference is termed narrowband interference (NBI) because NB-IoT bandwidth is relatively small compared with the 5G NR/LTE bandwidth. However, several factors might cause interference as a result of NB-IoT reusing NR/LTE spectrum, thus leading to problems such as the mismatch of sampling rate, power leakage between NB-IoT and NR/LTE PRBs. Loss of orthogonality is proposed in [4] which leads to performance degradation. The interference issue in 5G NB-IoT is still an open issue as adequate literature is not yet available. Most interference elimination (mitigation) methods reviewed in the literature are as follows. In [127], the authors propose a new sparse machine learning-based probabilistic structure and a sparse combinatorial optimization problem for the reliable restoration of NBI for harmonious coexistence of NB-IoT and LTE systems. The proposed algorithms are referred to as sparse cross-entropy minimization (SCEM). Further enhancement of the recovery accuracy and convergence rate has resulted in regularization in the loss function of the algorithms to produce a regularized SCEM. The simulated results outperform the state-of-the-art compressed sensing theory-based methods [14] in spectrum efficiency, estimation accuracy, computational complexity and effective elimination of NBI from the LTE systems. However, there is a tradeoff between the computational complexity and the total number of iterations which results in delays and less convergence. In [15], the block sparse Bayesian learning (BSBL) is proposed to estimate the NBI in the LTE-A systems. The estimation is aided with the use of intra-block correlation (IBC) which facilitates the recovery. Furthermore, the accuracy of the approximation technique has improved with the exploitation of the informative BSBL (I-BSBL) method using the inherent structure of the identical IBC matrix. The I-BSBL does not require prior estimation knowledge of the block partition to improve the technical performance, irrespective of the frequency offset value. The results achieved illustrate that the proposed BSBL-based algorithms achieve much more robust and accurate recovery in terms of computational and time complexity when analyzed in comparison with other counterpart techniques. However, the authors have been unable to establish the theoretical relationship between the total iteration number and the sparsity level. More importantly, the research work did not highlight the defect of the technique when the halting condition of BSBL iterations goes beyond the set threshold of the iterations. Table 2.7 tabulates the other common interference mitigation schemes and their objectives. In general, since NB-IoT is part of the 5G RAN technology, the design, and implementation of an effective channel interference mitigation scheme will depend on the use cases, the scenario of its deployment and size of the cooperative set, unlike the LTE interference mitigation scheme, while sustaining an intelligent level of flexibility for the resource planning.

Table 2.7. Common Interference mitigation schemes and their objectives

Ref.	Techniques	Objectives
E. Pateromic helakis *et al.* [9]	Centralized scheduling, as well as inter-cell interference coordination (ICIC), introduced in LTE Release 8	Enhance cell-edge SINR via frequency and power-allocation, coupled with changing levels of network coordination
E. Hossain *et al.*[7], R. Madan *et al.* [11]	Enhanced ICIC (eICIC) structure for heterogeneous networks for later LTE Releases	Providing the capacity to mitigate interference on data and control channels in frequency-domain or time-domain

3GPP TS 36.300 [12]	Further enhanced ICIC (FeICIC) from Release 11	Focuses on mitigating interference on UE via interference removal schemes.
3GPP TR 36.819 [128]	Carrier aggregation methods	Creating a degree of freedom exploited for interference management by partly avoiding interference through control-channel. scheduling of macro-cells and small cells on diverse carriers in the frequency-domain.

2.8.6 Radio Resource Management (RRM)

For NB-IoT to coexist within the 5G NR, the RRM strategy demands an extra degree of flexibility to introduce new functionalities, thereby enhancing QoS requirements and classifications. The allocation of radio transmission resources is among the most vital tasks of RRM to ensure massive connectivity in NB-IoT cells. Radio resources such as tone allocation, power configuration, OFDMA symbols, slots (subframes) in the time domain, the control of assignment of UL and DL resources in terms of PRBs in the frequency domain, and so on, are scheduled to support the diverse traffic and latency requirements of different use cases, to ensure flexibility and maximum performance in the timing of scheduled resources. One prime challenge faced is to balance these resources among different transmission types such as unicast, multicast and broadcast, as well as scheduled and non-scheduled UL access, UE categories and related constraints such as the maximum supported data rate and supported format types. To support the traffic from both UL and DL, review of existing literature has shown a tradeoff between scheduling users, to maximize their spectral efficiency, coverage, latency or reliability [129]. This prompts the demand for a flexible and functional scheduler capable of scheduling each user to their desired optimized target. The current opinion to solve this problem is to set up a flexible design frame structure of NB-IoT in 5G NR with different transmission time intervals (TTI) and size configurations per user to aid scheduling requests. 5G NR can support single or multiple scheduling request configurations that provide gNB with information about the data and data type awaiting transmission in the device [130], [84]. The research work of [131], understands the in-applicability of the existing RRM after the introduction of the concepts of time offset and repetition to reduce the computational complexity and to provide coverage extension in NB-

IoT. The authors, therefore, have proposed a theoretical structure for the upper-bound to realize a maximum data rate of 89.2kbps and 92kbps for DL and UL respectively in the proximity of a repetition factor and control channel. Secondly, a formulated interference-aware resource allocation for the maximum puzzle, studying the overhead of control channels, repetition factor and time offset has been proposed for NB-IoT using a suboptimal clarification with an iterative algorithm based on cooperative methods. The evaluation of the algorithms based on the influence of the time offset, repetition factor and intercell interference (ICI) on the NB-IoT data rate, and the energy dissipated has been studied and compared to noncooperative and optimal designs. The simulated result of the algorithm shows an 8% growth rate in the cooperative scheme and a 17% decrease in energy expended as correlated to the non-cooperative scheme. The authors in [132] have highlighted some major RRM issues affecting maximization of spectral efficiency and device connectivity between UL and DL which result in underutilization of resources, particularly for asymmetric traffic distribution. Concern has also been raised about NB-IoT performance due to interference from multi-tier 5G HetNets. The issues raised in this article have been addressed by the presence of a novel RRM framework designed specifically for an NB-IoT-efficient resource allocation scheme through exploited cooperative interference prediction (CIP) and flexible duplexing techniques. The simulated results illustrate that the intended structure extenuates the ICI effect considerably, decreases retransmissions, supports asymmetric traffic, and enhances the overall spectrum resource utilization by up to 14% data rate, and decreases resource wastage by 58%. However, most of the RRM schemes presented in the literature have not taken into consideration the dynamism of 5G NR scheduling strategies. Therefore, for efficient NB-IoT network operability within the NR, every feature of the 5G radio access technology (RAT) needs to be evaluated for efficient adoption of NB-IoT within the networks. In addition, the preceding research works are limited by high computation complexity, low data rate and high overhead signaling. As a result, not suitable for low-complexity NB-IoT systems.

2.8.7 Coverage Enhancement

The 5G NB-IoT design supports coverage extension of up to 164dB MCL, by enhancing cellular IoT services, most in the very hard-to-reach areas. This coverage extension demands more resources to send a data packet. For instance, data packets of 190,000 and more transmitted are in the normal CE (i.e. CE 0), while 2,606 packets transmitted are in the extreme CE (i.e. CE 2) [68]. The variation in transmitted packets creates an imbalanced use of resources in the downlink and uplink that leads to wasted resources in the uplink (i.e. in NPUSCH) and an increased latency in data transmission. To meet the coverage enhancement, three (3) solutions are proposed for NB-IoT in the literature, namely: tones (subcarriers) to minimize the bandwidth and to allocate resources instead of resource-blocks (RBs). A considerable tone number facilitates the UE to send in a narrower bandwidth. The second extract employs *repetition,* a technique used in re-transmitting data repeatedly for multiple times. The last selection is the *modulation and coding scheme,* commonly used in LTE for better coverage enhancement as considered in many research works reviewed.

The research of [133] proposes a coverage class adaptation scheme to improve the efficiency of the NB-IoT network by changing the coverage class dynamically according to the location or the state of the device channel. The result of the simulation shows a decrease in both the overhead signalling and the decoding error rate of the PDCCH, compared with the conventional coverage class adaptation scheme in the 3GPP standard. The author in [134] has employed a satellite network (i.e. LEO constellation) to study the coverage enhancement through the proposed specific unidirectional system. The model derivations demonstrate that NB-IoT can still operate within the 3GPP release 13 standard and reach 20dB MCL more than the LTE. The result shows the distortion in the packet error rate (PER) of the transmitting signal by Doppler spread. The shortcoming lies in the absence of synchronization between the NB-IoT device and the satellite which results in performance degradation. More importantly, the author has not included the study of the maximum achievable throughput of the proposed system when compared with the terrestrially deployed NB-IoT. In [135], the author suggests an optimal hybrid link adaptation strategy based on repetition, bandwidth, and modulation and the coding scheme to enhance the coverage capacity of NB-IoT by using an NS-3 simulator. The implementation involves optimized problem formulation with an objective function based on the latency, and constrained-based signal-to-noise ratio (SNR). The best optimized latency algorithm with accuracy and speed deployed has been implemented for the hybrid link adaption. The numerical results show that the hybrid link adaptation is eight times faster than the exhaustive search approach with the same latency. The coverage range of 40km for open areas with better scalability is also achieved. The weakness of the research work is shown in urban areas where the reduction achieved in the packet error rate occurs at a coverage range of 2km.

In summary, signal repetition is an essential concept in NB-IoT coverage analysis that improves the coverage area but reduces the operational bandwidth. This method also reduces the amount of battery power used and the user's throughput. As a result, it is not an efficient approach for NB-IoT network's lifespan.

2.8.8 Link Adaptation

The link adaptation is an essential technology for the 5G NB-IoT system, employed for securing the reliability of transmission, coverage enhancement, peak data rate, and throughput enhancement. At NP-USCH transmission, there is an intimate relationship between power control and link adaptation (rate control), since the required received power is directly dependent on the data rate. Therefore, the proper determination of channel state information by the device and the modeling of different degrees of control channel (CCH) overhead (such as aggregation levels or several resource element dedications to CCH) based on the UE radio conditions depends on the use of scheduling grant and link adaptation [136]. Link adaptation is implemented in at least two areas, namely selection of MCS and determination of repetition. The combination of both parameters is crucial in a specific channel status. However, the sequence of both parameters can be defaced with reduced spectral efficiency and broader consumption of power if the packet size is large, notably, for inner-loop link adaptation designed to contend with block-error rate (BLER) variation and the outer loop link adaptation for regulating the selection of MCS and determination of repetition. A lot of solutions have been proffered in the literature to address these issues as compiled below.

In [137], a modest and effective link-adaptation scheme for the combination of the MCS level and the number of resource units (RU) is proposed for selecting a large transport block per packet size. The process is aimed at reducing the NP-USCH and NP-DCCH transmissions and at satisfying the BLER condition for the selected repetition number per channel status. The results demonstrate a decrease of 27% in power consumption and improvement of 69% in spectral efficiency as compared with the straightforward method. However, the authors do not define the method used for the selection of MCS and the number of repetitions for coverage enhancement. In [138], an innovative UL adaptation design with a focus on the number of repetitions is achieved by using the inner-loop link adaptation and the outer-loop link adaptation respectively. Apart from the key technologies of UL scheduling, power control and transmission gap are interpreted and a modest single-tone scheduling scheme is proposed. The link level simulation results show that the proposed UL link adaptation system exceeds the repetition-dominated approach and the straightforward approach, most notably for vigorous channel conditions and more substantial packet sizes. The proposed method preserves more than 14% and 46% of the active time and resource consumption as compared with the repetition-dominated method and straightforward method, respectively. However, the author's conclusion has not estimated the performance of the algorithms when the empirical value of the threshold exceeds the set values.

2.8.9 Energy Management

For NB-IoT, one of the enablers for rapid data traffic growth is the increase in energy efficiency. There are two energy-saving mechanisms in the NB-IoT network for decreasing the energy used by UE, namely the power-saving mode (PSM) and extended discontinuous reception (eDRX). Both mechanisms turn off their radio modules to conserve battery power, but the inability to reach these UEs while asleep may impede the use of these two mechanisms in some applications, depending on the device reachability and power consumption [62]. However, due to the latency and energy efficiency specifications of different IoT devices, new demand in 5G NB-IoT might raise the need for diverse and more efficient approaches. In the literature, different possible solutions have been proffered to solve this problem. [139] propose an enhanced energy-efficient NB-IoT system using a framework of joint optimized power ramping and preamble picking. The algorithm examines the drawback of the random-access procedure by establishing an energy estimation model that shows the impacts of the framework (power ramping and preamble picking) on energy efficiency. Besides, to reduce the complexity of the algorithm, a proposed distributed multi-agent reinforcement learning (MARL) algorithm based on "Win and Learn" fast policy hill-climbing (WoLF-PHC) has been used to search for optimal policies for the formulated joint optimization. The result confirms that the high energy efficiency is appropriate and convergent. However, the algorithm adaptability is not guaranteed as it takes a long time to execute and converge due to the state of parameters used in the algorithms. More importantly, the power ramping in the algorithm can be wasteful for sparse traffic. In [140], a stochastic resonance (SR) with a comparatively weak sensitivity has been merged with the Okumura-Hata model to enhance the coverage of NB-IoT base station, as well as reduce the power consumed at the terminal without modifying the cell coverage area. The proposed model validates the theoretical analysis and simulation results by efficiently diminishing the power dissipated at the terminal and improving the base station coverage area. However, the effect of different geographic (both location and environment) has a striking impact on the accuracy of the result achieved from the proposed model. In [141], a cooperative relaying paradigm is proposed to express an optimal relay selection algorithm to minimize the overall quantity of energy dissipated in NB-IoT cells. The simulation result demonstrates an energy saving of up to 30% for conventional communication techniques. Also, a greedy approach has been implemented to assist in solving the high computational effort which achieved a 10% energy consumption compared to the optimal strategy. However, the approach does not consider the impact of data rate on the algorithm since the power received is directly dependent on the data rate.

2.8.10 Modelling and Analysis approach of NB-IoT

The primary challenge of NB-IoT development is the realized network complexity and PHY-MAC layer in its system architecture. The NB-IoT network interface, radio technologies, and the modes deployed for various applications have led to the modelling issue faced. At present, there is no available methodology pattern for modelling NB-IoT complex systems.

Therefore, modelling of NB-IoT systems for the three modes is a very challenging issue. These models vary from the UE differentiation performance by adjusting the physical channel deportments and network procedures in accordance with the deployment conditions, the repetition exploitation and narrowband transmission to the access of the devices in a challenging situation, to the enhanced power-saving mechanisms to increase the battery lifespan, the hardware and procedure simplification to scale down the UE complexity [142], [112].

A fascinating addition to theoretical modelling of NB-IoT based on UE's buffer has been presented as a First-In-First-Out (FIFO) queue in [143]. The research work uses a Markov-chain to model the re-transmission created by the collisions and the period of the queue and explores the three probabilities in the steady-state distribution characteristics. The analysis of the model based on the random-access performance calculated, shows the system throughput in terms of UE number, packet generation rate, retransmission number, and the period of the queue. In [144], QoS metrics such as the packet delivery ratio (PDR), throughput, and transmission time, as well as the UE configuration are proposed to meet strict NB-IoT requirements using the NB-IoT deterministic link adaptation model (NB-DLAM). The analysis of the result shows that NB-DLAM estimation on PDR is the most accurate when compared to NS-3 simulations. The NB-IoT design is aimed at reducing cost and gain power efficiency through the battery as the network scalability accommodates a large volume of NB-IoT devices with low data transmission. Again, some other model on coverage enhancement has also been reviewed. The research work of [143], models the channel estimator for two extreme channel conditions in a weak coverage environment. The signal repetitions boosting the received signal quality are affected by the quality of the channel estimation, and are limited by the channel coherence time. The author analyses the impact of channel coherence time on the uplink coverage. The result of this model illustrates that a short channel coherence time significantly reduces the amount of coverage improvement expected from the signal repetitions. All the above models did not offer a robust model that employed t*ones, repetition and MCS implemented to* support QoS performance, as well as reduce resource consumption and cost. These parameters have a direct impact on QoS metrics, including packet delivery ratio (PDR), throughput and transmission time. Therefore, these models do not represent the ideal network operation of the NB-IoT network.

2.8.11 Simulation and Evaluation

Simulation approaches are essential for robust implementation and effective deployment of the NB-IoT system [145]. Since the introduction of NB-IoT in 3GPP rel. 13, NB-IoT has become a focus of research by industries and academia. The advantages of NB-IoT in the development and implementation of IoT are numerous. The NB-IoT deployed, from the field of industrial, consumer, and enterprise IoT such as maritime, healthcare, smart environment [146], and so on have made it possible to manage an entire lifecycle of manufactured household appliances, logistics, warehousing, industrial equipment and environment for retailing applications and maintenance [41]. However, the challenges of running simulation models that bring optimization of NB-IoT superiority in the areas of long battery life, low cost, large capacity, and wide coverage into a single reality are still mostly unresolved. Several research algorithms and protocols have been implemented in the literature to improve NB-IoT performance, but none have been able to address all the listed challenges in a single model. The research work of [147], has a receiver algorithm for NB-IoT NP-RACH detection and the arrival time of estimation. The result of the simulation highlighted the potentials of NB-IoT in detection rate, false alarm, and estimated arrival time accuracy. This result does not provide an insight into ways of achieving the low-cost characteristics of NB-IoT. Another algorithm proposes the use of agent-based modeling and simulation [148] to analyze the performance of IoT systems. The algorithm uses an agent-based cooperative smart object (ACOSO) framework and OMNeT++ simulator for driving IoT systems design and deployment. The limitation of the approach lies in its unsuitability for NB-IoT modeling as it does not deal with device density, physical network design and coverage overlap. The recent simulation tools such as OPNET, NS-3, OMNeT and MATLAB are employed in [144], [135], [149], and [145] to understand and model the NB-IoT network. However, simulation tools that would validate design choices and disclose unexpected behaviors before actual system deployment are still missing. Therefore, there is no suitable simulator capable of exploring the complex evolution of NB-IoT. Table 2.8 tabulates the other simulation tools and modelling techniques used for LPWAN-IoT.

Table 2.8. Simulation tools used in Modeling IoT Networks

Ref.	Uses	Limitation
MASON [150]	Allows simulating moving entities	Does not allow consideration of high levels of details due to its nature.
SUMO [151]	Allows simulating moving entities	Requires a large amount of hardware memory.
Cooperative differential game theory [152] and Evolutionary-game theory.	Adopted for efficient energy and optimal regulation of other resources.	It is time-consuming, and the complexity and heterogeneity of IoT scenarios were not captured
IoTSim [153]	Supports and enables simulation of batch-processing activity in IoT systems limiting themselves to the MR model	Insufficient in the context of modeling and simulating the behavior of IoT complex system, which requires multiple big data programming models and diverse resources.
CloudSim [154]	Provides computing, storage, and software for hosting infrastructure-based application systems.	Creates inadequate links between datacenters, resulting in lack of exchange of shared communication

Summary: This section has highlighted the technical part of PHY/MAC performance properties of NB-IoT with the focus on improving these properties towards 5G NR compatibility with NB-IoT. Besides, we hope the anticipated 5G NB-IoT will be scalable and configurable to sustain a considerable set of distinct use cases with the following listed standards in mind.

1. Creating integrated different radio access technologies (RATs), most notably for NB-IoT and 5G coexistence to offer broad IoT services to different use cases.

2. A flexible and versatile 5G NB-IoT satisfying the required substantial heterogeneity of IoT services in different deployment modes, link requirement characteristics, and within the different carrier frequency operations.

3. Deploying QoS satisfactorily to all IoT use cases and without all interference limitations such as phase noise and channel errors.

4. Providing efficiency and robustness in energy consumption, resource utilization, cost reduction (both of hardware and software), spectral usage, and support of any future compatibility of new services and functionalities without calling for restructuring of the air interface.

2.9 ENABLING MARKET FOR NB-IOT

The NB-IoT market size is valued globally at USD 578.0 million in 2018, with an expected increase of compound annual growth rate (CAGR) of 34.9% from 2019 to 2025 [155]. NB-IoT has been found to be more desirable than other LPWA technologies in the current IoT market due to its features such as the ubiquitous wide coverage area, low power usage with a promise of ten (10) years battery life, maximum coupling, low cost, high reliability, with specific carrier network security, an integrated business control platform that allows accelerated network upgrade and minimizes operational and maintenance (O&M) costs. These features have catered for the deficiencies of poor reliability, hapless security, high cost of O&M, and limited coverage area plaquing the LPWA market for over 10 years. The NB-IoT use cases and applications have controlled the IoT market due to the dramatic growth in the scope of internet usage from people-operated computers to autonomous smart devices. Thereby promoting industry players' participation in NB-IoT exploitation. The increase in internet usage has created innovative IoT services and hardware that generate revenue through the possible diagnostics, control and monitoring of connected devices in remote areas (or far from the reach of the cellular base station) by saving the cost of operation and maintenance [156]. The NB-IoT global market is segmented into five sections to dissect the grand-view research analysis of the market. The segmented parts are; NB-IoT component, deployment, device type, applications (end-uses) and regions [157]. These analyses will expatiate the targeted niche markets of NB-IoT and its competitive landscape for market leaders.

The segmentation by component can further be sectioned into the network and the module sections. The network section promotes cost-effective services that increase the number of IoT deployments while the module section is predicted to rise the demand of NB-IoT modules for specific consumer-oriented applications. The NB-IoT deployment segment defines the modes (i.e. in-band, guard band, and standalone) that have been adopted the most. The most adopted mode in 2018 was the guard band, owing to its deployment in the existing cellular network, including radio frequency (RF) and antenna without any spectrum cost appended. It is predicted to be the driving factor behind the growth of NB-IoT in the guard band section.

The segmentation by device type sectioned the market further into devices that measure specific parameters such as smart meter, alarm and detector, wearables, and many others. The wearable-device categories controlled the market in 2018 due to the rapid increase in demand for personal care devices and diagnostics such as the sport, healthcare, and fitness devices.

The application section deals with the sectors of the industries that employ NB-IoT technology, for example the automobile, and agricultural industries, healthcare, infrastructures, energy and utilities, manufacturing, consumer electronics, and many others. The consumer electronics section is expected to control the market due to the NB-IoT module’s integration into consumer products such as wearables, phones, home electronics, and so on. An example is a case in Germany, where Vodafone and Panasonic Corporation collaborated to manufacture an electronic device for home-based appliances that will enable consumers to store data related to all electronic devices on the cloud.

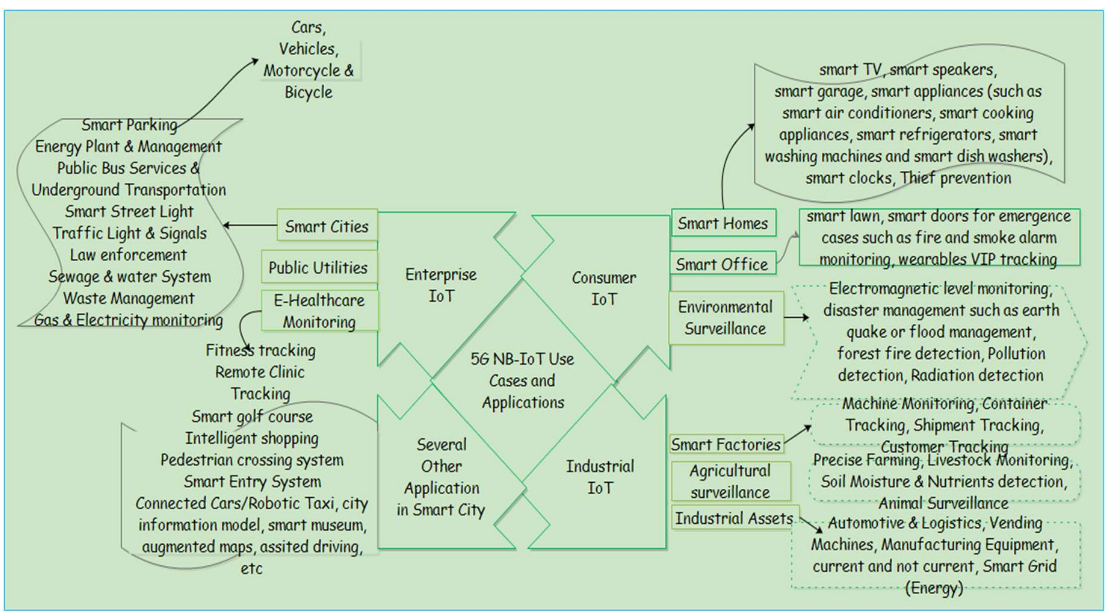


Figure 2.11. Classification of 5G NB-IoT Use Cases.

And finally, the region section represents the largest market of NB-IoT technology. North America's reported domination of the market in 2018 was due to the presence of leading device manufacturing companies and network service providers such as Qualcomm Inc., AT&T, Cell-co partnership, MediaTek, and so on. These companies focus on testing and commercially deploying NB-IoT solutions for both consumer and industrial applications. [155].

2.9.1 5G NB-IoT Use Cases and Applications

NB-IoT supports the achievement and aspirations of diverse use cases and applications without human intervention. These applications enhance lives and daily activities. The three groups of use-cases of NB-IoT are the consumer IoT, industrial IoT, and enterprise IoT, as sketched in Figure 2.11. The consumer IoT involves smart homes, environmental surveillance and smart offices and many others. The industrial IoT involves smart factories, agricultural surveillance (e.g., animal tracking, and so on). The last group is the enterprise IoT consisting of the smart city and all public utilities (such as energy plant and management, and so on). Table 2.9 tabulates the benefits of NB-IoT in each use case and the possible key challenges to be addressed in 5G NB-IoT.

The objective of 5G NB-IoT is to offer an integrated experience for users deploying the different use cases listed above. Each of the use cases is anticipated to have a comprehensive specification from the network operations. However, the successful deployment of these use cases on the 5G NB-IoT network using sensors will support the growth and improvement of IoT services in the vertical industries, and for social-economic benefits. The improvement in IoT services will provide more business opportunities for NB-IoT network operators.

2.10 OPEN RESEARCH CHALLENGES AND DISCUSSION

This section summaries the open challenges on NB-IoT system interoperability and coexistence within 5G NR carriers. The open research challenges need to be resolved to support multiple use cases that are coexisting with the 5G NR air interface.

Table 2.9. The Benefit of NB-IoT in each Use Cases and possible critical challenges related to their deployment

Classification	Applications	Benefits	Challenges
	Smart Homes	-Promote the growth of the use of voice-assisted devices in our homes. -Provide a centralized platform for solving many challenges related to home appliances [70].	1. Might be prone to a series of attacks due to a single layer of management level, i.e. the centralized system adopted. Therefore, formalized encryption mechanism is needed to secure the NB-IoT communication Network.
Consumer IoT	Smart Offices	-Help in organizing office calendars, utilities billing and consumption, entry, and security systems through the data collated. -Aid the use of cognitive NB-IoT for personalized and tailored home and office environments for advice about office activities such as workout, weather control, traffic conditions, predictive maintenance, alerts, etc [70].	
	Environmental surveillance	-It helps to create an enabling environment that saves time and cost thereby increasing the productivity. - Can be used for detecting natural disasters such as earthquake, landslides, etc. -Use for tracking ambient temperature, humidity, rainfall, and air quality through NB-IoT sensors [158]. -Help in monitoring public waterways, parks, and green spaces in order to identify spaces that require clean-up or projection [70].	2. Accuracy and reliability of data collection might be greatly affected due to interference and the kind of sensors deployed. Also, the inadequacy of manpower and training can hinder the effectiveness of the system.
Industrial IoT	Smart Factories	-The use of networked NB-IoT sensors on smart machines and analytical data can enhance the day-to-day business across a wide range of market sector and activities from manufacturing to public services. -it can be used for application monitoring, monitoring of chemical production plant processes, monitoring of vehicle fleet, etc. thereby enhancing optimal planning and flexibility in manufacturing and maintenance. - can be used to create industrial automation by providing a model for connection of industrial IoT devices to the critical industrial systems. This will minimize factory downtime and create scheduling maintenance [58].	3. Fault identification and possible repairs can be a serious issue in large NB-IoT network. Since there can be limitation in IoT devices and also, environmental factors are inevitable. Interoperability issues, positioning accuracy, and management of open

	Agricultural surveillance	-For surveillance monitoring of domestic animals and Livestock. - For monitoring of weather conditions such as temperature, humidity, soil moisture and nutrients, etc - Can be used for smart green houses and for enhancing the sales of agricultural products. - can ensure consistent conditions of the grower and improve productivity. - Can be used in Geo-fencing and Chrono-fencing of livestock [159]. - Can be used to provide information about certain parameters when they exceed the threshold while maintaining the trend of data analysis [58], [158].	data can also be a problem. 4. The limitation in the UE complexity, positioning accuracy, and calibration of hospital wearable devices can lead to misinformation and wrong diagnosis in inpatient treatment. 5. Several cyber-attacks might be
	Industrial Assets	- The combination of NB-IoT network and AI can be used to create an alert for automatic monitoring machine conditions. - Can be used for logistic and industrial assets tracking - can be used for monitoring equipment status, control processes, and safety in the factory [58].	launched on the NB-IoT Industrial assets networks due to the signal traveled distance, correlated related-critical areas and low complexity
Enterprise IoT	Smart City:	-Promote the implementation of smart applications. - Assist fostering of a data-driven economy - Benefit the government/tourists/residents with a huge amount of structured and un-structured data that can be used for automation, decision-making and analysis. - Promotes cognitive computing in citizen centric - Provides cross-collaborations and application opportunities to citizens to engage with LG, communicate requests, feedback or reports faults with utilities and infrastructures [70].	of NB-IoT devices which cannot be used to run complex algorithms. 6. The security and privacy protection of data generated from the NB-IoT use cases is not guaranteed as some of these data might be life
	Smart Parking	-It improves efficiency, cost, effort and fuel consumption and time in trying to search for parking space near/at any destination. - can use NB-IoT devices with Ultrasonic sensors detecting the availability of a parking space - Helps the driver to book for a parking spot upfront or proceed directly to the vacant spot. - Provides parking information on the driver dashboard, guiding the driver to park at the exact location of the vacant spot at his destination. - Generates income for the government based on the charge calculated for amount of time spent on the reservation. - Helps parking officers to use the parking information to manage and handle billing information better and also offers discounts	threatened to the organization that adopted the NB-IoT networks if proper authentication is not implemented. Example is the medical data related to the security of patient's life. 7. Poor and inefficient NB-IoT network design can lead to huge amount of energy consumption

	based on the parking utilization and several other analytic tasks [70].	by the sensors, data overload, and
Smart Street Light	-It can be used to enhance energy utilization and improve the management of the large-scale deployment of streetlights, thereby reducing the difficulty in their maintenance. -It can foster the adoption of an intelligent energy consumption model for massive urban street light control and real-time status monitoring of the streetlights. - Fosters onward upgrading and performance optimization by analyzing the data collected from streetlight information [160].	heterogeneity of data during communication, if the implemented protocols are not energy efficient. Also, the lack of data fusion suitable for NB-IoT can lead to more consumption of energy. Therefore, a
Waste Management	-Notifies and reports the level of the waste to the waste management authority [161]. - Promotes cost-effectiveness in waste collection management through fuel saving of the collection vehicle. - Ensures smart routes and is sustainability complacent [70].	data fusion algorithm is needed to compressed the data or generated data to reduce the energy consumed.
Gas & Electricity Metering	-Ensures more efficient electricity and gas delivery by applying analytic data to the data gathered from the smart electricity grid. - Enhances plans, project demand, and capacity by using data gathered from the grid operators. - It can be used to provide an intelligent inter-connection and cooperation between the electric Vehicles, Batteries, and Charging stations under the control of the Power supply Grid-management System (PGMS). -It can offer low-cost energy and power consumption in hardware [70], [162].	8. To support QoS and customization of 5G NB-IoT in various use cases, the limitation in the functionality of the EPC architecture of LTE network needs to be overcome by exploiting the network enabler such as SDN, NFV, mobile edge computing and so on.
Public Bus services and Underground Transportation	-Help in monitoring the position of trains on routes. -Monitors the health of the tracks, bus arrivals, and departures or bus emergencies or breakdowns for effective fault detection. -Enhances the saving of lives and properties, minimizes delays and optimizes the operations [70].	9. To avoid the plummeting of the NB-IoT modules and service solutions in 5G network, a deployment
Energy Plant & Management	-Promotes a load-balancing system -Provides healthy monitoring of energy plant -Ensures adequate maintenance and fault detection.	assessment detailing the sincere traffic forecast with estimated revenue,
Sewage and Water System	-NB-IoT can be used for monitoring public sewage, waterways leakages within society.	and techno-economic analysis should be documented to
Shipment Tracking	-It can be used for tracking goods, rentals, cargo locations, Storage capability etc.	positioned the NB-

Smart Clinic/Hospital	-It can be used to collect data in real-time of various health conditions of patients ranging from heart rate, body temperature, etc. through wearable devices. -It can provide comprehensive information about outpatient medical records to the doctors based on the data collated from the wearable devices. -It can be applied to supervised a discharged Patient's health condition (PHC) through wearable devices [163].	IoT market over other LPWA devices. 10. Different access control level should be provided to users to avoid data sharing.

2.10.1 Physical Design Challenges for NB-IoT in 5G NR

2.10.1.1 Hybrid automatic repeat request (HARQ)

Fading causes variation of signal strength at the receiver, leading to a data loss in most wireless channels. To increase the reliability of the data transmission link in NB-IoT, the HARQ mechanism is used as one of the potent technologies to achieve super coverage with low complexity. NB-IoT adopted a single-process adaptive and asynchronous HARQ for both UL and DL just as in the 5G NR wireless system. NB-IoT uses the HARQ type II due to its soft sequence increment at the receiver to raise error corrections. This mechanism consumes more transmit power during the process of retransmission, rises packet drop probability, doubles the cost of processing effort, and overhead that increases the latency. Therefore, for an effective 5G NB-IoT system to generate a degree of flexibility in serving various use cases and also meet the stringent latency condition for uRLLC services, a versatile air interface design and optimal resource utilization of channel resources during the transmission are desirable. The air interface should involve a flexible link layer design that creates an adaptation of every single link in logical terms with its QoS requirements and the received radio considerations. Also, the advancement in the HARQ mechanism should enhance the timing design for scheduling over asymmetric DL and UL transmission in 5G NB-IoT cell scenarios depending on the TTI size used for diverse use cases. As proposed by [164], enhanced HARQ feedback can be used for improved network-based interference coordination to improve the success rate of HARQ retransmission.

2.10.1.2 Orthogonal Frequency Division Multiplexing (OFDM) Waveform Limitation

The most salient multicarrier waveform representation in NB-IoT is OFDM. This allows high spectra efficiency due to the maximum usage of the bandwidth by the subcarrier signals. Though the orthogonal design of these spectra ensures free interference reconstruction at the receiver. However, there are some drawbacks to this waveform. One major drawback is the lack of secure synchronization in time and frequency to support the signal orthogonality, as well as vulnerability to doppler distortions in highly mobile channels. The reason for this drawback is the *sinc-shape* of the subcarrier spectra that results in the poor localization of the signal power in the frequency domain due to the high side lobes. The limitation of OFDM leads to the adoption of cyclic prefix OFDM (CP-OFDM) [165] in the NR system. The CP-OFDM was created to keep the guard interval overhead small to prevent degradation of spectral efficiency However, the limitation of CP-OFDM in peak-average power ratio (PAPR), out-of-bound emission to minimize power back-off, lower frequency localization, and slacken synchronization requirements [84] renders the usage of CP-OFDM unfavorable. Moreover, other proposed waveforms of different variation of CP-OFDM (such as filter bank multicarrier (FBMC), generalized frequency division multiplexing (GFDM)) that outperform more than the CP-OFDM comes at the cost of high transceiver complexity and incompatibility with the MIMO techniques. This poses a challenge to NB-IoT due to its low complexity. Again, because of the advantages of high spectral efficiency, compatibility with MIMO and low-complexity implementation, 3GPP adopted the CP-OFDM and mitigated its challenges with well-established techniques such as filtering, clipping, and windowing. However, for better coexistence between NB-IoT and NR, a multi-carrier waveform with spectral containment of signal power, flexible and capable of asynchronous UL access and able to be evaluated with the following key performance index (KPI) (spectral efficiency, PAPR, phase noise robustness, robustness to frequency/time selective channels, MIMO compatibility, time localization, OOB (with and without PA), complexity and flexibility) is desirable.

2.10.1.3 Phase Noise

The major challenge to designing the OFDM waveform is the demonstration of imperfections in the function of the transceiver hardware used in its implementation. The variation in phases between the receiver and transmitter oscillators due to the discontinuously received coded repetition transmit data blocks, causes the presence of random phase noises in the signals received. The imperfections become more disturbing in the higher-level carrier frequencies. The most common hardware impairment is the oscillator phase noise, and nonlinear characteristics of the power amplifier. The most prominent of all is the phase noise phase locked-based oscillator that contains three (3) sources of noise namely; the reference oscillator, the phase frequency detector along the loop filter, as well as the voltage-controlled oscillator (VCO). Each of the sources of noise contains both thermal noise (white noise) and flicker noise (colored noise). The defamatory consequence of phase noise increases with the carrier frequency function. The effect of phase noise causes common phase errors and intercarrier interference (ICI) that result in an increment of error vector magnitude (EVM) of the desired signal.

2.10.1.4 Coexistence Issue

Since the adoption of CP-OFDM based waveform for eMBB services [165] by 3GPP NR, other waveforms for other services such as the NB-IoT service for mMTC have not been precluded. Therefore, the 5G NR coexistence with NB-IoT must be manageably orthogonal (or quasi-orthogonal) to reduce the mutual interference that can restrict the form of freedom in the general design of the waveform. Another constraint of 5G NR coexistence with NB-IoT is the structural design of the frame of NB-IoT. The NB-IoT NP-DCCH resides in three consecutive OFDM symbols across the whole band. Also, the relationship of cell-specific reference symbols derived from the narrowband cell identity in a specific in-band deployment is not permitted to be subdued, when NB-IoT is internetworked with the 5G NR but rather, the 5G signals are restrained at a unique location in the time-frequency grid due to their adaptability. The introduction of mini-slots in 5G NR can resolve the above challenge. The choice of frame design in the UL is not restricted, as the placement of both the control channel and the reference symbol is frequency-localized to avoid overlap of NR with the NB-IoT.

2.10.1.5 Cell search and Initial Synchronization

There is a significant difference in the cell search and initial synchronization of 5G NR and the NB-IoT system. The difference poses a severe challenge to the 5G NR’s coexistence with the NB-IoT due to the latency and signaling overhead detection. For instance, the NB-IoT cells use ungrouped NPSS and NSSS for cell search discovery. Also, NPSS does not contain physical cell identity (PCI) information as compared with the SSB block of NR that depends on the PCI. Again, the PSS and SSS in the SSB are the same and cannot determine the relative device location. Besides, NR SSB uses different m-root sequences with 20ms periodicity, which is four times higher than the 5ms frequency domain of Zadoff-chu (ZC) sequence of both NPSS and NSSS in NB-IoT. The lengthy SSB period accepts the ultra-lean design paradigm and supports the efficiency of the energy consumption rate of the NR network that alleviates the provision of massive access to higher loads. Therefore, to foster NR coexistence with NB-IoT, a flexible cell search discovery that would achieve a reduction in signaling overhead and latency should be proposed.

2.10.1.6 Contention-based/Grant-free access

The previous contention-based access protocol has been marred by high signaling overhead and high latency, which hampered the performance of the NB-IoT network due to the massive rise in the number of devices per cell. The introduction of NB-IoT technology for mMTC service support for the 5G NR technology has made 3GPP agree to extend the contention-based access used by the UEs for the initial connection to the network to RRC connected-inactive to compliment RRC-idle and RRC-connected state. The added state will support grant-free, semipersistent scheduling, and UL transmission with a grant [165]. The access scheme is required for mMTC services to maintain the large number of active UEs concurrently striving to access the network. The RRC connected-inactive will support various UE services, battery life, latency, and mobility. According to [166], three types of contention- based access protocol have been proposed to complement the RRC-idle and RRC-connected namely;

a) the multistage access scheme; b) the two-stage (double) access scheme, and c). one-stage (single) access scheme.

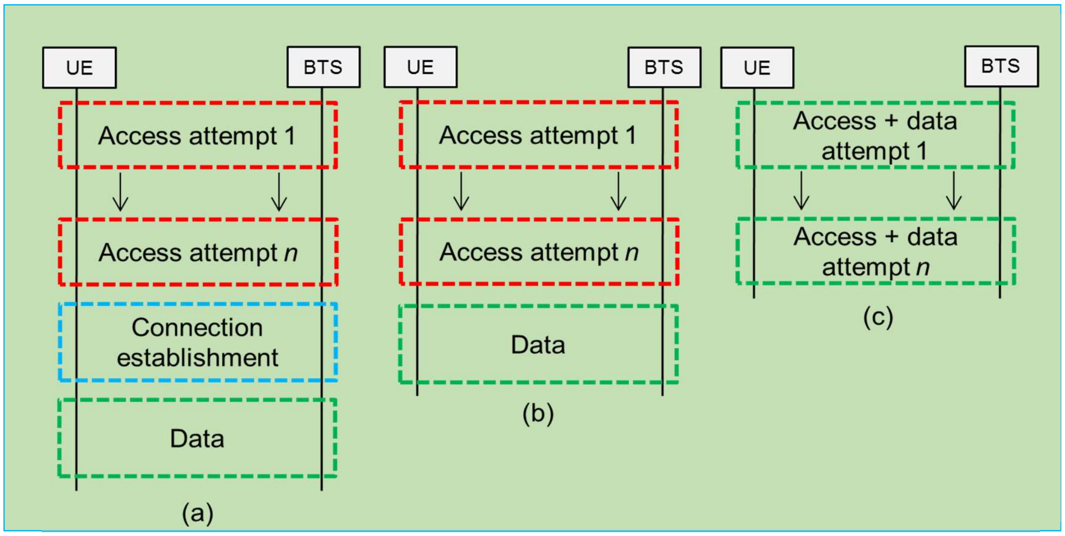


Figure 2.12. The considered contention-based access-protocol, Taking from [84].

The multistage access is similar to the tropical NB-IoT link establishment which comprises three stages, namely access, link establishment (inclusion of security and authentication), and finally the data phase. The double (two-stage) access permits the UE to isolate the access-notification phase from its data delivery phase while the one-stage access uses both access notification and data delivery in one transmission as depicted in Figure 2.12. For both the single and the double-access schemes, contention may occur only in the initial step of the protocol. Inventing this kind of access scheme is a mutual interaction between the physical design (to enhance discovery and to manage collisions through high-level signal processing) and the higher layers (to manage network entries of the PHY capacities).

2.10.1.7 Semi-Persistent Scheduling (SPS)

The NB-IoT scheduling study of channels and signals in the literature is centered around dynamic downlink and uplink scheduling. However, most of the scheduling techniques adopted have high overhead as compared to SPS with minimal control signaling overhead suitable for traffic with periodic features such as the NB-IoT. However, SPS has few built-in inefficiencies, such as the empty transmissions for implicit release. The implementation of SPS in 5G NB-IoT would need further improvements to configuration/activation split and sharing of SPS resources to support the effective operation of NB-IoT in the 5G NR systems.

2.10.1.8 Random Access Procedure (RAP)

The challenge of an insufficient number of preambles in NB-IoT RAP results in collision problems, a low random access (RA) success rate, high network congestion, and access delay if massive devices attempt to access the radio channel resources simultaneously for UL data transmission. The challenge further complicates the network so that it consumes more power, has high packet loss and excessive use of radio resources, thereby overloading the NPRACH. Many approaches proposed can be classified into two broad groups, namely the pull-based and push-based procedures. Both procedures try to solve the challenge of collision and latency requirements based on the method of groups prioritization and small-data transmission (SDT), respectively [84], [167]. However, none of the schemes is effective in meeting the challenges mentioned above. Therefore, grand-winning research is required to propose priority level-specific RACH-preambles, that permit an improvement in the success probability of the initial access of high-priority services, without decreasing the initial access of other functions [31].

2.10.1.9 Radio Resources Management (RRM)

The radio resource allocation is an essential task for RRM for varying signaling patterns amongst diverse transmission types (such as broadcast, unicast and multicast, as well as scheduled and nonscheduled UL access) in NB-IoT network. The critical issue is partitioning the available resources between the network infrastructure and UEs without resulting to intercell interference. It is predicted that the deployed NB-IoT in 5G NR carriers may lead to a new challenge of intercell interference and resource scheduling that needs to be overcome to secure flexibility, high network capacity, and broad coverage in the network.

2.10.1.10 Interference Mitigation

The deployment of NB-IoT carriers within the 5G NR carriers will result in a new interference challenge that is different from that of the legacy network, although the NR's coexistence with NB-IoT is considered to improve network capacity and expand the coverage of the user data rate, as well as improve robust communication through the process of frequency reuse. The interference challenges may hamper the channel estimation for NB-IoT devices which cripple the achievable energy performance, as well as the spectral efficiency. Therefore, an interference-mitigating scheme becomes an essential strategy in curbing this challenge. The design of 5G NR ultra-lean was implemented to improve the performance of energy, and to minimize the interference in the network, but the design alone is not enough to curb the threat of channel interference.

2.10.1.11 Latency

Low-latency support is an essential strategy for coexistence between the NR and NB-IoT systems. The latency in the NB-IoT network remains 10s, and the latency for NR is 1ms for improving the signal-to-interference-plus-noise ratio distribution among users. The increase in repetition for a device that experiences path loss, coverage class, exchange of messages for RA, control and data channels, contributes to the latency of the system. The extent of the challenge depends on the scheduling strategy of the UL and DL channels. Many approaches proposed to reduce the timing request of NB-IoT transmitting devices in LTE carriers and for minimizing the transmission latency have been suggested in the literature. However, the idea of NB-IoT deployment in NR carrier needs a different approach, considering the essentials of mini-slot (as the smallest slot) that can be scheduled to reduce latency in 5G NR.

2.10.1.12 Energy Saving

The eDRX and PSM are the two energy-saving mechanisms employed in the NB-IoT network to extend the device battery life. Similarly, there is an inefficiency in the two popular RRC schemes adopted (i.e., RRC idle and RRC connected). The schemes result in high protocol overhead due to the transition of UE from the RRC idle to RRC connected for a device enduring bad channel conditions. The situation can worsen for a network with a massive number of devices transmitting low data frequently. Moreover, it is not cost-efficient to keep the device in the RRC connected state without any active data transmission due to the extensive consumption of battery power, high usage of dedicated resources, high measurement reports, and handovers. However, with the proposed deployment of NB-IoT in 5G NR, a new scheme has been proposed to enhance the RRC scheme. The 3GPP adopted a lightweight signaling transition from RRC connected to RRC-connected inactive [165]. The RRC-connected inactive should benefit low data transmission optimization for devices operating for a short period. The UE transmitting UL data can use the small-packet transmit procedure (SPTP) to communicate, depending on the contention-based processes adopted. The method might be a single contention-based (one step) or prefaced by a contention-based scheduling request and grant (two-step) [166]. The RRC connected-inactive has the support of the configurable DRX in the frequent monitoring of the system control channels by some devices and for others in low-activity state for many hours that could also continue connection quickly after their low-active state. Furthermore, there is still a need for further research into the proposed RRC connected-inactive due to some overhead and latency issues that may be encountered in the network. Moreover, the emerging ambient backscatter with relay cooperation technology can be incorporated into NB-IoT design to perform simultaneous wireless information and power transfer (SWIPT) mechanisms. This design can prolong the lifetime of NB-IoT devices, expand communication distances and channel capacity, and improve link reliabilities.

2.10.1.13 Heterogeneity and Interoperability

The interoperability of NB-IoT products from multi-vendor is one way to standardize the future IoT-platform and applications towards mMTC services. Various NB-IoT products from leading Telecom companies such as Qualcomm, Ericsson, Nokia, Huawei, and Affirmed Networks have all pass-through interoperability development testing (IODT) carried out globally by Vodafone networks and its partners [168]. Currently, Vodafone and GSMA are preparing a roadmap for the NB-IoT scale and flexibility required to achieve numerous applications. We hope that proper documentation on usage type, product number, deployment types, adaptability and duration of the device will be specified. However, the device complexity should be upgraded to include improved latency, the accuracy of measured data, further enhanced NPRACH, improved power and some programmable chips for light algorithm support to be implemented and managed over the air (OTA) to satisfy further use cases. Also, there should be a reference standard that would serve as a guide for all the IoT platforms.

2.10.1.14 Security and Privacy

The integration of NB-IoT into the 5G NR networks will provide assumed security and privacy. The NB-IoT operation does not have any practical access-authentication scheme in 5G networks due to its low complexity as related to the 3GPP standard. NB-IoT adopts the conventional access-authentication methods to achieve mutual authentication with the network which may result in massive signaling overhead. However, this poses a severe challenge to securing NB-IoT devices. A solution from [169] guarantees the application of lattice-based homomorphic encryption technology access authentication in NB-IoT.

2.10.1.15 Channel Modelling

The emergence of 5G NR has brought new challenges to the data rate for shared channels at diverse configurations, link reliability, end-end (E2E) latency, to the modeling of NB-IoT channel for different use cases and service types, inadequately supported by the current channel models. Channel models such as the updated 3GPP NR channel model and IMT-2020 channel model with a wide range of frequency of 0.5MHz-100GHz [170] mmWave propagation characters such as modeling of blockage and atmospheric attenuation, high mobility, space-time-frequency consistency, dual connectivity and beam-tracking simulations, have not been tested to predict the accuracy and peculiarity of the NB-IoT propagation channel. However, the evaluation of these models has shown a deficiency in the estimation of loss in deep shadowing zones, spatial consistency procedure in the channel modeling for evaluation of user mobility, multiuser-multi-node communications and beam-tracking design for 5G communication, a unification of path loss model from 0.5MHz-100GHz, link-specific outdoor-to-indoor penetration, UE-specific outdoor-to-indoor penetration, and the frequency inconsistency within the channels below and above 6GHz for dual connectivity of multiple frequency bands between the separation of the control plane and the user plane for throughput enhancement in mmWave band.

Therefore, to develop efficient 5G NB-IoT channel models to support the massive devices, channel features such as the time variability of scattering clusters, deep shadowing, dynamic blockage or movement in the dual-mobility scenarios, aerial scenarios, carrier frequency, system bandwidth, transmit power for eNB and UE, propagation model, doppler spread (for denoting speed of UE for the base station and also, due to the significant impact it has on the CP length of the OFDM symbols), antenna configuration and noise figure for UL and DL should be studied [58], [84].

2.10.2 SWOT analysis of NB-IoT technology

This segment presents a strength, weakness, opportunities, and threat (SWOT) analysis of NB-IoT technology. The main strengths of NB-IoT are low-cost devices, the mass connection of devices, ultra-low power consumption, in-depth coverage, stability, safety, and reliability to support a large number of diverse use cases. These features have made NB-IoT the choice of many organizations.

The primary weakness of NB-IoT is the inaccessibility of the downlink channel (due to the usage of PSM and eDRX), security, and scalability. However, various modifications are on-going to introduce an additional feature that would meet these challenges.

The low-power transmission synchronization and the possible multifold services are parts of the great opportunities that can be provided by NB-IoT for future IoT deployment and access to the 5G networks.

The greatest threat to NB-IoT technology is the signal interference induced by long communication distance, which is a key design challenge for the fabrication, integration, and implementation of NB-IoT devices. Poor scheduling of resource allocation can also result in interference; and large consumption of power raises the latency and increases proneness to attack by adversaries. Details of all the challenges affecting the deployment of NB-IoT have been elucidated in section 2.10. Table 2.10 presents a summary of all the SWOT analyses of NB-IoT technology.

Table. 2.10. Summary of SWOT analyses for NB-IoT Technology

Strengths	Weakness
▪ 20dB Deep-coverage area, ▪ low-cost device, ▪ ultra-low power consumption, ▪ easy to implement, ▪ cost-efficient to deploy, ▪ can be implemented on a general-purpose computing platform,	▪ Capacity requirement ▪ Latency can be high for a massive connection ▪ Scheduling delay might be high

▪ Attractive to cloud computing platforms (CCP), CCP offers scalability, ▪ efficiency and possible reduction in cost for various use cases. ▪ Massive connection of devices, ▪ safe, reliable and stable for large-scale connection, ▪ licensed and secure spectrum, ▪ open standard technology, ▪ low-complexity, ▪ easy coexistence with other technologies, supported by more than 30 of the largest Telecom operators, and support access stratum optimization	▪ Signaling overhead can be high ▪ Increased operational cost for massive dense IoT application deployment due to subscription fee application. ▪ Scalability

Opportunities	**Threat**
▪ Reduction in low-power consumption, ▪ Growing market demand for various use cases, ▪ Enabling intelligent and smart economy, environments, cities, that can be used to create jobs and increase income. ▪ The inclusion of tone, repetition, modulation, and coding, for coverage enhancement, efficient scheduling resource allocation, use of artificial intelligence, etc.	▪ Signal attenuation induced ▪ Security and privacy ▪ Out-of-bound emission (OOB) ▪ High price

2.10.2.1 Strength

NB-IoT uses three (3) solutions for coverage enhancement, namely: tones (subcarriers) to minimize the bandwidth and to allocate resources, repetition, and the third, is modulation and coding scheme used in LTE for better coverage enhancement. The NB-IoT coverage enhancement depends on the device's location, environment, as well as the device's channel state condition, which can support up to 164 MCL of coverage extension, providing a 20dB coverage improvement over LTE. Because it has a life span of more than ten years, NB-IoT is a low-cost device that helps to reduce maintenance costs. NB-IoT consumes ultra-low power via eDRX and has a power spectral boosting of 6dB when connected.

2.10.2.2 Weakness

The signal overhead increases as more NB-IoT devices are connected, increasing packet loss, consuming a large amount of bandwidth, and limiting system performance. As a result, the average power consumed per device rises, reducing battery life span and increasing operational costs while making devices more vulnerable to security threats.

2.10.2.3 Opportunities

Increased internet usage has resulted in the development of innovative Internet of Things (IoT) services and hardware that generate revenue by enabling the diagnostics, control, and monitoring of connected devices in remote areas (or far from the reach of a cellular base station) while saving on operating and maintenance costs [156]. As new technology advances, these opportunities have expanded to applications in the economy and environment, creating jobs and expanding applications (e.g., smart meters, smart agriculture, and so on) and platforms that generate income for the populace.

2.10.2.4 Threats

As mentioned in section 2.10.2, the greatest threat is signal attenuation i.e., signal interference and security as NB-IoT continue to operates within the licensed bands.

2.11 CHAPTER SUMMARY

Most of the previous reviews explicitly based their study of NB-IoT on the LTE system's limitations and simulations. The findings and solutions proposed by these reviews cannot be implemented for the ongoing 5G NB-IoT system. However, it has been observed that the most potent mechanisms (such as the Interference, HARQ, contention-based, radio resource management, etc.), required by the NB-IoT system to operate seamlessly, are limited in capacity and unsuitable for coexistence with the 5G NR carrier network. To build a robust, efficient and satisfactory service quality for 5G NB-IoT networks, the mechanisms of NB-IoT systems need to be researched further and enhanced. Therefore, this review provides detailed guidelines for integrating NB-IoT into 5G networks. This is the first study of the challenges and operation of NB-IoT technology for 5G NR coexistence. Based on this thesis, an analytical investigation of the NB-IoT environment for a 5G-IoT class of connectivity, cloud-assisted relay with ambient backscatter communication, as well as the limitation of the inseparable control and user planes of LTE EPC posing a challenge to the performance and acceptability of LTE NB-IoT, were presented to enhance the understanding of NB-IoT performance and problems. Furthermore, the possible 5G architectural design for NB-IoT integration, technical performance, enabling markets, use cases, application and key challenges to all the use cases, as well as all the required enabling technologies needed for the optimal combination, has been introduced for the coexistence of NB-IoT with 5G NR. Finally, open research challenges and future research focus on the coexistence of 5G NR with NB-IoT have led to this SWOT analysis which is presented to foster research activities for future IoT. Some of the challenges involve channel scheduling, interference, random access procedures, heterogeneity, and interoperability, which need to be solved to promote successful NB-IoT systems. In summary, 5G NB-IoT flexibility can be achieved if all the mechanisms of 5G NR can be adapted to suit the coexistence with NB-IoT and other cellular technologies' air interface variants (AIVs), to promote the versatility of the 5G NR protocol stack as compared with that of the 4G networks. To begin with, this thesis focused on the interference generated within the 5G NB-IoT network as a result of their coexistence. The following chapters will be focused on improving data rate, SINR, spectrum efficiency, and system performance through the interference avoidance scheme and interference-aware scheme present in chapter three and chapter five.

CHAPTER 3 INTERFERENCE-AVOIDANCE RESOURCE-ALLOCATION FOR D2D-ENABLED FIFTH GENERATION NARROWBAND INTERNET OF THINGS

3.1 CHAPTER OBJECTIVES

This Chapter describes an interference-avoidance resource allocation scheme for the D2D-enabled 5G NB-IoT system to improve the NB-IoT operations within the 5G networks. The objective is to enhance the NB-IoT's limitation of insufficient data, poor coverage, poor spectral efficiency, reduce overhead signaling, and increase energy efficiency. The rest of the chapter is organized as follows: Section 3.2 introduces the framework of the interference avoidance concept. Section 3.3 presents the related works. Section 3.4 describes the system, network model, and the problem formulation of the proposed system. Section 3.5 discusses the optimal resource allocation procedure, and Section 3.6 concludes the Chapter.

3.2 INTRODUCTION

As the internet of things (IoT) services continue to have promising and strategic values, increasing productivity and process efficiency in a wide range of applications, supporting digitalization and asset utilization, Narrowband IoT (NB-IoT) has steadily gained popularity. NB-IoT, a long-term evolution (LTE)-based technology, critical for mass connection of low-power machine-type communication, has multiple applications in different systems such as intelligent vehicle systems, healthcare systems, and industries that promote effective and convenient life. However, due to the inefficiency of the LTE eNodeB, which influences the overall system latency, 5G networks was proposed to serve a range of these exponentially growing NB-IoT devices to give higher productivity [171].

Co-channel and orthogonal approaches are used to coexist 5G and NB-IoT technologies as heterogeneous networks (HetNet). An orthogonal deployment approach is used in this paper to provide coverage for the standalone NB-IoT device solution. The advantage of this approach is that it reduces interference at the expense of assigned frequency resources while maintaining NB-IoT small cell coverage [172]. The architectural distribution of NB-IoT pico-base stations (PBSs) on 5G macro-cells causes co-tier interference among the PBSs, affecting cell edge NB-IoT user equipment (NUE). The cell edge NUE receives a weak signal, limiting transmission performance, overall cell capacity, spectral efficiency, network performance, and user performance [171]. In addition, to improve coverage and reliability, traditional NB-IoT relies on repeated transmission as a foundation solution. If the direct link to the base station has poor channel quality, the technique may not be optimal, resulting in excessive interference, spectrum waste, and decreased system throughput. Besides, packet loss has an impact on uplink retransmission rates, which are larger for cell edge NUEs. As a result, to improve the performance of 5G NB- IoT networks, researchers in [173], [174], [175], [127], [15], [176] referred to the interference as narrowband interference (NBI) and, in some cases, narrowband noise [173], [127]. NBI, in contrast to additive white Gaussian noise (AWGN) [173], has limitations in its power spectrum density. This explains why some reviews, such as [174], [175], decided to reduce the interference from this perspective. Iterative sparse learning algorithm [127], block sparse Bayesian learning (BSBL) [15], and multiple NBIs suppression algorithm joined time-frequency domain for orthogonal frequency division multiplexing (OFDM) system [176] were the solutions proposed by [127], [15], [176]. However, the previous research findings did not support a solution to the combined challenges of NB-IoT networks' low data rate, poor channel quality, spectral efficiency, and limited coverage.

Several other conventional approaches, such as cooperative transmission, resource partitioning, intercell interference coordination (ICIC) [5], beamforming, and interference alignment (IA) [6], have been researched and applied to modern wireless systems, such as cellular and wireless local area networks (WLAN). These methods control interference in rare cases, and due to their high complexity, they may not be optimum in 5G NB-IoT network configurations. As a result, an efficient method of spectrum resources usage should be promoted. A robust localized D2D communication between proximal edge NUEs, as proposed by the Third-generation partnership project (3GPP) in 3GPP Rel-12 and Rel-13 time-frames [16], can be permitted to enhance the cell edge NUE experiences as well as guaranteed QoS for the existing cellular NUEs. The D2D pair and the cellular NUEs can coexist in the same channel through a frequency reuse mechanism. As a result, the devices can communicate directly without using Pico-base station (PBS). Hence, edge NUEs can have less path loss attenuation, reduced latency and a stronger received signal that promote faithful services.

Despite the benefits of D2D communication, the feasibility of D2D communication sharing the same resources as the cellular users depends on the distance restriction between the D2D pairs (i.e., the D2D transmitter and its receiver) and interference control between the cellular users in the same or different tier. This paper proposes an interference avoidance resource allocation (RA) for D2D-enabled 5G NB-IoT to maximize spectrum utilization and achieve a higher network sum-rate under QoS constraints. The satisfaction of QoS between the D2D pair and the cellular NUEs within the 180kHz physical resource block (RB) is a critical issue in the NB-IoT's resource allocation. Resource allocation tends to be more difficult due to the low complexity of the NB-IoT's RB. To implement an interference avoidance strategy for D2D-enabled 5G NB-IoT, the transmit power, data rate, or both, as well as the reuse channel selection, can all be adjusted in tandem to minimize reuse interference. Therefore, given the complexity, interference characteristics, and time-varying nature of the 5G NB-IoT wireless channel, the relationship between data rate and channel reuse selection are interdependent. The reason is that channel reuse selection affects the sets of interfering links and thus influences the optimal link rate selection. Typically, maximizing the minimal data rate under interference constraints will increase the spatial reuse and capacity [177]. As such, for the 5G NB-IoT system, the statistical channel link feature with a high priority gain is selected to obtain a channel with interference power below the interference threshold.

To the best of our knowledge, the selection of the optimal reuse channel allocation based on the channel gain's fraction has not been considered in the literature for balancing performance optimality and practicality for D2D-enabled 5G NB-IoT systems. The metric seeks to reduce the link loss probability of a channel with a higher gain due to the degree of interference and avoid costly computation of each D2D user on its predetermined channel sets as compared to the initial number of assigned channels. The process also avoids retransmission at the source which improves the signal-to-interference-plus noise ratio (SINR) and the network's sum-rate. In addition, the feature of an optimal resource allocation algorithm for D2D-enabled systems should have the following [178] a) an effective frequency reuse mechanism, b) flexible power control for D2D pairs, and c) a feasible complexity to leverage on the gain acquired from D2D communication underlaying cellular networks. Realizing these features will maximize the cellular network spectrum and increase system throughput. Many approaches in D2D communication for selecting reuse channels among candidate sets involve maximum achievable throughput as proposed in [179], admission control and power allocation [180], social-aware selection [181], joint subcarrier assignment and power allocation [182], and CSI and delay constraint [183]. Our proposed work is similar to [178], [180] but takes a different approach to obtaining reuse candidate sets and power allocation. Unlike our proposed method, [178] used the product of the channel gain's fraction of the D2D pair to the reuse partners and the channel gain's fraction of reuse partner to the D2D pair. [180] used QoS-awareness and admission control to assign a reuse partner. The proposed algorithm is also suitable for large-scale NB-IoT networks in which D2D users reuse an adjacent cell's uplink network resources based on their interaction with the environment. Consider the cognitive D2D communication system, where devices connect to various base stations linked by backbone networks via hopping [184]. This type of work can be found in [185] where cognitive radio (CR)-assisted D2D communications in a cellular network was proposed as a viable solution for D2D communication with mixed overlay–underlay spectrum sharing. The proposed algorithm could also be used for D2D communication handover in network system, when two D2D communications devices enter the same cell at the same time. They both go through a joint handover, as described in the speed-aware joint handover approach for D2D Clusters [186]. The preceding D2D communication features revealed the number cases in which the algorithm might be quite useful in improving the utility of D2D communications. The main contribution of this chapter is as follows.

- A new framework for uplink interference-avoidance resource allocation for D2D-enabled 5G NB-IoT network problems to maximize the sum rate of the D2D pair underlying the NB-IoT network is proposed. To avoid any harmful interference on the NUE link, we identify and analyse the maximum interference limit for the D2D users.
- Due to the combinatorial of resource allocation, the resource allocation problem is formulated as a mixed-integer non-linear problem (MINLP) for D2D-pair communication under the PBS control.
- The optimization problem is section into three parts: the first is channel reuse selection, in which potential reuse channels for D2D pairs are determined. The second part involves the optimal power allocation for each D2D user and its reuse partner to maximize overall network throughput and, finally, a bipartite graph to find an optimal pairing pattern between the set of NUEs and the D2D users is formed using the Hungarian scheme [18].
- Based on the proposed scheme, the network performance through extensive simulations is evaluated. When compared to other algorithms, the algorithm significantly improves system performance in terms of sum-rate maximization and interference power minimization.

3.3 RELATED WORK

Few studies on NB-IoT D2D communication have been conducted based on the vision of opportunistic crowdsensing applications involving traffic from battery-constrained IoT sensors [187], increasing the efficiency of resource allocation for D2D communication in NB-IoT [188], achieving the best-expected delivery ratio (EDR) and expected two-hop delay

[189], and improving trust and security enhancement for opportunistic hop-hop forwarding schemes [190]. None of these studies considers the interference control between the underlay D2D pair and the cellular NUEs in three-tier NB-IoT HetNets.

However, most research has attempted to balance resource allocation to boost network spectrum utilization to address interference control between the D2D underlay and the cellular NUE. Recent solutions, for example, include resource pooling [191], non-cooperative game or bargaining game [192], admission control and power allocation [180], clustering partitioning, greedy heuristic algorithms [193], and convex optimization-based methods [172]. These techniques presume perfect knowledge of the channel state information (CSI) and may necessitate a high level of computational complexity. They may also increase feedback channel overhead, which may be impractical in dense 5G NB-IoT networks.

By applying D2D communication, [172] investigated a transmit power restriction and distance between two pairs to find the best reuse candidates for each D2D device. In addition, [194] proposed a local awareness scheme for effectively controlling interference between multi-user diversity in the cellular network. Based on the Hungarian algorithm, the work in [195] investigated optimal channel reuse selection and interference coordination for D2D communication. In [196], a simulation based on an architecture and open source was developed to study the physical layer, application layer and queuing model for D2D NB-IoT uplink and downlink performance. The results reduce the power consumption, malicious attack and minimizes queuing delay in D2D NB-IoT networks. All the above researches motivated our proposed contributions.

3.4 SYSTEM MODEL AND PROBLEM FORMULATION

This section introduces the system model, network model, and resource's problem formulation for interference-avoidance D2D-enabled 5G NB-IoT networks.

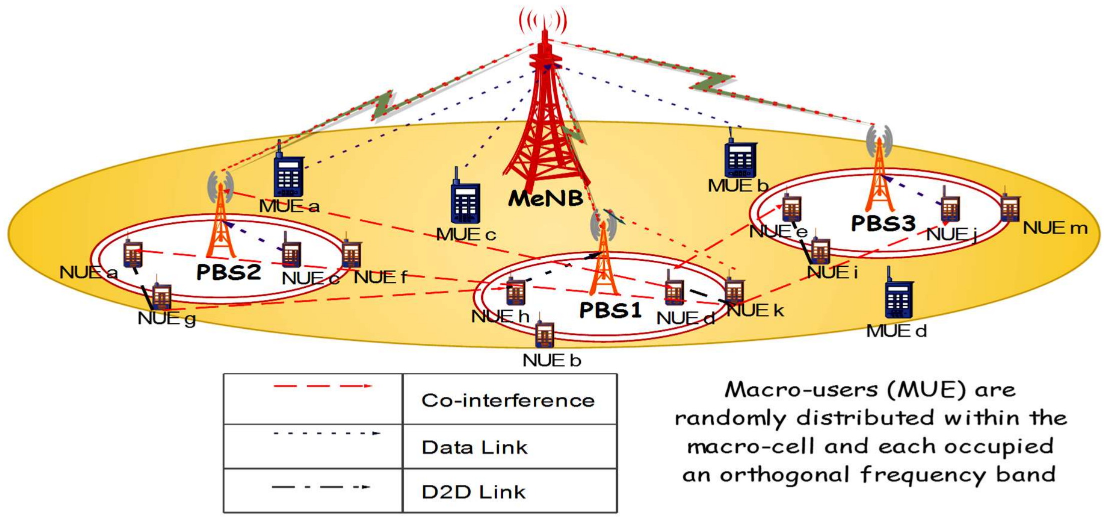


Figure 3.1. System model

3.4.1 System model

Consider an uplink channel in a 5G HetNet where an NB-IoT network architecture is deployed as an access environment, as shown in Figure 3.1. The PBSs are configured with NB-IoT networks and linked to the central macro-eNodeB (MeNB) via the X2 interface for control information sharing. The total frequency bandwidth of the MeNB is B1. Assume that each PBS channel is used up, with a frequency bandwidth B2 and an equivalent resource value of $\boldsymbol{\mathcal{M}}$kHz. The use of bandwidth B1 is orthogonal to the use of bandwidth B2 (i.e., no co-channel interference between the macro-cell and the PBSs). However, co-tier interference, on the other hand, emanates among the PBSs, affecting the channel condition of the cell edge NUE. Let ℓ denotes the PBS, where $\ell = \{1,2,..\mathrm{L}\}$. Assume that each PBS serves z orthogonal cellular NUEs and there are n D2D pairs[1]. Denote the corresponding sets by $\mathcal{Z}$= {1,2…, z} and $\mathcal{N}$={1,2,..n}, respectively.

3.4.2 Network model

In 5G NB-IoT systems, NUEs upload data to the PBS using single carrier frequency division multiple access (SC-FDMA) [171], [197][2]. To support D2D communication, $\mathcal{N}$ ($\mathcal{N}$< $\mathcal{Z}$) orthogonal channels can be reused by the D2D pair links, increasing spectrum utilization but incurring reuse interference to the reuse partners. To be more specific, the PBS serves the NUEs with an equivalent resource value of $\dot{M}\ kHz$ divided into $\mathcal{K}$ sub-channels, where $\mathcal{K} = \{1, 2\ldots\acute{k}\}$. When allocating resources for each D2D pair, there are two types of interference. The first is reuse interference, which occurs when NUEs and D2D pairs share the same channels. The second type of interference is co-tier interference, which occurs when different PBSs share the same resources. We assume that the scheme proposed in [10], [198], [199], [200] can effectively mitigate the latter, as a result, it was not considered in this thesis. Thus, the interference analysis will only consider the reuse interference between D2D pairs and cellular NUEs.

D2D communication in uplink resource sharing only affect the PBS's operation, and incurred interference can be managed by the PBSs appropriately. To lower complex reuse interference between NUEs and D2D pairs, each PBS RB can only be shared by one D2D user and that each D2D pair can only reuse one PBS-channel. Assume that the distance between the D2D pair transmitter and receiver is smaller to $\mathcal{D}_{max}$, and that the PBS is completely aware of the CSI of all network links and responsible for resource allocation. Therefore, all network links are statistically obtained based on the long-term channel observation. In practice, the PBS obtain the CSI of all users based on classic channel estimation through the training sequence[3]. However, the instantaneous CSI of all network links consumes high signaling overhead for frequent CSI updates and resource allocation which might not be suitable for 5G NB-IoT networks. Furthermore, assume that both the D2D pair and the NUE satisfied the minimum QoS requirement of the signal-to-interference-plus-noise ratio (SINR). For the sake of simplicity and mathematical tractability, consider only one of the PBS and assume a general solution for the others.

The research employs 3GPP TR 38.901 pathloss model [201] and consider the fast fading due to multipath propagation and slow fading due to shadowing. Therefore, the channel gain, $g_{i\ell}$ between the NUE i and the PBS ℓ can be modelled as;

$$g_{i,\ell} = J h_{i,\ell} B_{i,\ell} D_{i,\ell}^{-a} \qquad (3.1)$$

[1]The D2D pair consist of transmitter and receiver.

[2]SC_FDMA has the advantage of a single carrier multiplexing and a lower Peak-to-average Power Ratio when compared to OFDMA [197].

where J is a pathloss constant, $h_{i,\ell}$ is the fast-fading gain with exponentially distributed unit mean, $\mathfrak{B}_{i,\ell}$ is the slow fading gain with log-normal distribution, a is the pathloss exponent, and $\mathcal{D}_{i,\ell}$ is the distance between the NUE i and the PBS. Similarly, we denote the channel links $g_{i,j}$, $g_{j,\ell}$ and g_j as the channel from the NUE i to the D2D pair j, the D2D pair j to the PBS, and from the D2D pair's transmitter to its receiver respectively. The σ^2 is assumed to be the power of the additive white gaussian noise for each link.

3.4.3 Problem formulation

The D2D pair must satisfy the minimum SINR requirement, and the incurred interference from the D2D user to the cellular NUEs must be less than the interference threshold I_0 for every pair link and frequency reuse. The SINR of both the NUE and the D2D pair can be express as:

$$\gamma_i^c = \frac{P_i^c g_{i,\ell}}{\sigma_n^2 + \rho_{i,j} P_j^d g_{j,\ell}} \qquad (3.2)$$

$$\gamma_j^d = \frac{P_j^d g_j}{\sigma_n^2 + \rho_{i,j} P_i^c g_{i,j}} \qquad (3.3)$$

where γ_i^c, γ_j^d, P_i^c and P_j^d are the SINR, transmit power of the NUE i and the D2D pair j respectively. Note that D2D communication was set up under two conditions: (i) if the NUE's link reliability (i.e., the wireless path between the NUE-to-PBS, $g_{i,\ell}$) is poor to ensure transmission quality, and (ii) when the NUE's transmit power incurred severe interference, resulting in a degradation of individual SINR and a lower total system throughput. As a result, the optimization problem $\mathcal{P}1$ due to resources sharing can be as follows to maximize the D2D pair's sum-rate;

$$p1 = \max_{\rho_{i,j}, P_i^c, P_j^d} \left\{ \sum_{j \in N} \left[\log_2 \left(1 + \gamma_j^d \right) \right] \right\} \qquad (3.4)$$

$$\text{subject to } \gamma_i^c = \frac{P_i^c g_{i,\ell}}{\sigma_n^2 + \rho_{i,j} P_j^d g_{j,\ell}} \geq \gamma_{imin}^c \ \forall \imath \in Z \qquad (3.5a)$$

$$\gamma_j^d = \frac{P_j^d g_j}{\sigma_n^2 + \rho_{i,j} P_i^c g_{i,j}} \geq \gamma_{jmin}^d \ \forall j \in N \qquad (3.5b)$$

$$\sum_j P_j^d g_{j,\ell} \leq \sum_z I_o \qquad (3.5c)$$

$$\sum_i \rho_{i,j} \leq 1 \quad \rho_{i,j} \in \{0,1\}, \forall i \in Z \quad (3.5d)$$

$$\sum_j \rho_{i,j} \leq 1 \quad \rho_{i,j} \in \{0,1\}, \forall j \in N \quad (3.5e)$$

$$P_i^c \leq P_{max}^c \quad \forall i \in Z \qquad (3.5f)$$

$$P_j^d \leq P_{max}^d \quad \forall j \in N \qquad (3.5g)$$

where $\rho_{i,j}$ is the binary decision variable for the resources reuse indicator for the NUE i and D2D pair j as expressed in (5). P_{max}^d, P_{max}^c, γ_{imin}^c and γ_{jmin}^{d} denote the maximum transmit powers of the transmitter of the D2D pair j, NUE i, minimum SINR requirement of the NUE i, and the D2D pair j respectively. I_o is computed as given in (3.7).

$$\rho_{i,j} = \begin{cases} 1 & \text{when DUE } j \text{ reuses the resource of NUE} \\ 0 & \text{otherwise} \end{cases} \qquad (3.6)$$

$$I_o = \frac{P_i^c g_{i,\ell}}{\gamma_{i.\min}^c} - \sigma_n^2 \qquad (3.7)$$

The interference threshold I_o is calculated for each NUE based on the minimum acceptable SINR received at the PBS. The computation in (3.7) allowed resources to be allocated to D2D pairs since the NUEs have equal transmit powers P_i^c. Constraints (3.5a) and (3.5b) defined the QoS requirement for each NUE i and D2D pair j respectively. Constraints (3.5c) restrict the aggregated interference between the D2D pair and the PBS to the tolerable interference estimated in constraint (3.7). (3.5d) and (3.5e) ensures that the NUE's channel resource can only be reused by one D2D pair j and that each channel can only be used by one D2D pair j. The constraint is used in the D2D-enabled 5G NB-IoT communications to reduce the complexity of the interference scenarios. Constraint (3.5f) and (3.5g) ensures that the NUE and D2D pair transmit power is within the maximum power threshold.

The optimization problem $\mathcal{P}1$ is combinatorial, non-linear, and NP-hard due to resource sharing and the use of binary variables. As a result, in polynomial time, it is impossible. The resource allocation problem is segmented into three subproblems in order to find an efficient solution.

3.5 OPTIMAL RESOURCE ALLOCATION

The optimization problem is section as follows: (i) reuse channel selection and QoS control of D2D pairs, of which NUE's CSI (i.e., channel gain factor) is used to determine the potential reuse channel that can maximize the sum rate of each D2D pair. (ii) The optimal power control strategy of each NUE-D2D reuse pair is then applied, considering constraint (3.5d) and (3.5e) that shows that interference also exists within the reuse pair. The optimal power allocation to maximize the sum rate of multiple D2D users while ensuring the reliability of the reuse NUE partners was also investigated against the interference threshold requirement for the PBS and annihilating infeasible pairs.

3.5.1 Reuse Channel Selection (RCS) and QoS Control for D2D Pairs

Since the goal is to maximize the sum rate of the uplink D2D pair, the set of D2D pairs with the highest throughput compared to other D2D users is prioritized for NUE channel reuse[4]. Assume the jth D2D pair's channel gain factor β, on the kth channel is defined as;

$$\beta = \frac{g_j^k}{g_{i,j}^k} \qquad (3.8)$$

For a given transmit power constraint of NUEs and D2D pairs, the jth D2D user with the highest value of β can achieve high throughput compared to other D2D users as verified by [178]. Therefore, these set of D2D users with the highest value of β allowed to reuse the kth channel can be grouped as ($\widetilde{D_k} \subseteq \mathcal{N}$). In addition, the set of potential reuse channel by the jth D2D user can be derived as ($\mathcal{R}_j^k \subseteq Z$), $\forall j \in \widetilde{D_k}$ and $\forall i \in \mathcal{R}_j^k$.

[3]Note that the PBS only have the statistical information of $g_{j,\ell}$ and g_j $channel$ gain. Since the D2D pair is not directly connected to it. The statistical CSI is assumed to be more accurate and less costly than Instantaneous CSI [202], [203].

The selection of the reuse candidate channel on the kth channel reduces the computational cost for each jth D2D user on its pre-determined channel sets compared to the number of channels initially assigned to each D2D pair. Thus, the algorithm's complexity is further reduced as the number of reusable channels decreases.

To obtain an effective optimization in (3.4), the constraints in (3.5a), (3.5b), (3.5f), and (3.5g) must also be satisfied. i.e.

$$\begin{cases} \gamma_i^c = \dfrac{P_i^c g_{i,\ell}}{\sigma_n^2 + P_j^d g_{j,\ell}} \geq \gamma_{imin}^c & (3.9a) \\ \gamma_j^d = \dfrac{P_j^d g_j}{\sigma_n^2 + P_i^c g_{i,j}} \geq \gamma_{jmin}^d & (3.9b) \\ P_j^d \leq P_{max}^d, \; P_i^c \leq P_{max}^c & (3.9c) \end{cases}$$

To this end, if the constraint (3.9c) is ignored, the minimum transmit power for the $j \in \widetilde{D_k}$ and $i \in \mathcal{R}_j^k$ can be computed as (3.10), to satisfy the minimum SINR requirement taken at a coordinate point $\boldsymbol{\mathcal{X}}$, [180] and proved in the Appendix A1.

$$\begin{cases} P_{j,X}^d = \dfrac{\left(\gamma_{jmin}^d g_{i,\ell} + \gamma_{imin}^c \gamma_{jmin}^d g_{i,j}\right)\sigma_n^2}{g_j g_{i,\ell} - g_{j,\ell} g_{i,j} \gamma_{jmin}^d \gamma_{imin}^c} \\ P_{i,X}^c = \dfrac{\left(\gamma_{imin}^c g_j + \gamma_{imin}^c \gamma_{jmin}^d g_{j,\ell}\right)\sigma_n^2}{g_j g_{i,\ell} - g_{j,\ell} g_{i,j} \gamma_{jmin}^d \gamma_{imin}^c} \end{cases} \quad (3.10)$$

Hence, the transmission link reliability condition for QoS control is summarized as;

$$\begin{cases} 0 < \dfrac{\left(\gamma_{jmin}^d g_{i,\ell} + \gamma_{imin}^c \gamma_{jmin}^d g_{i,j}\right)\sigma_n^2}{g_j g_{i,\ell} - g_{j,\ell} g_{i,j} \gamma_{jmin}^d \gamma_{imin}^c} \leq P_{max}^d \\ 0 < \dfrac{\left(\gamma_{imin}^c g_j + \gamma_{imin}^c \gamma_{jmin}^d g_{j,\ell}\right)\sigma_n^2}{g_j g_{i,\ell} - g_{j,\ell} g_{i,j} \gamma_{jmin}^d \gamma_{imin}^c} \leq P_{max}^c \end{cases} \quad (3.11)$$

[4] Note that the channel gain between the NUE-to-D2D links and the D2D links is used to determine the reuse partners, as we assume the D2D links are near the cell edges to avoid interference to the PBS.

3.5.2 Optimal Power Control for Single D2D Pair

In this section, the optimal power allocation for each D2D pair ($\widetilde{D_k} \subseteq \mathcal{N}$) over the predetermined set $\mathcal{R}_j^k$ in sub-section 3.5.1 is computed to maximize the sum rate of the D2D users. The optimization problem can be formulated as;

$$\left(P_i^{c*}, P_j^{d*}\right) = \max_{\rho_{i,j}, P_i^c, P_j^d} \left\{ \sum_{j \in \tilde{D}} \left(1 + \gamma_j^d\right) \right\} \quad (3.12)$$

$$\text{subject to} \begin{cases} \gamma_i^c = \dfrac{P_i^c g_{i,\ell}}{\sigma_n^2 + \rho_{i,j} P_j^d g_{j,\ell}} \geq \gamma_{imin}^c & (3.12a) \\ \gamma_j^d = \dfrac{P_j^d g_j}{\sigma_n^2 + \rho_{i,j} P_i^c g_{i,j}} \geq \gamma_{jmin}^d & (3.12b) \\ P_j^d \leq P_{max}^d,\ P_i^c \leq P_{max}^c & (3.12c) \end{cases}$$

Define $P_{1\max}^d = \dfrac{\gamma_{j\min}^d \left(\sigma_n^2 + P_{max}^c g_{i,j}\right)}{g_j}$, $\quad P_{1\max}^c = \dfrac{\left(P_j^d g_j - \gamma_{j\min}^d \sigma_n^2\right)}{\gamma_{j\min}^d g_{i,j}}$

$P_{2\max}^c = \dfrac{\gamma_{i\min}^c \left(\sigma_n^2 + P_{max}^d g_{j,\ell}\right)}{g_{i,\ell}}$ and $P_{2\max}^d = \dfrac{\left(P_{max}^c g_{i,\ell} - \gamma_{i.min}^c \sigma_n^2\right)}{\gamma_{i\min}^c g_{j,\ell}}$

To solve the optimization problem in (3.12), we introduce the following preposition to illustrate the observation on the property of the sum-rate of the D2D pair proved in the Appendix B.

Preposition 1. Represent the $f\,(P_i^c, P_j^d) \triangleq (1 + \gamma_j^d)$, the optimal power vector (P_i^{c*}, P_j^{d*}) in (3.12) can be expressed as;

$$\left(P_i^{c^*}, P_j^{d^*}\right) = \begin{cases} \max\limits_{\left(P_i^{r^*}, P_j^{d^*}\right) \in \Omega} f\left(P_i^c, P_j^d\right) \\ when \;\; \gamma_i^c > \gamma_{i\min}^c \;\; \text{and} \;\; \gamma_j^d \geq \gamma_{j\min}^d \quad (3.13) \\ when \;\; \gamma_i^c > \gamma_{i\min}^c \;\; \text{and} \;\; \gamma_j^d < \gamma_{j\min}^d \end{cases}$$

Based on the preposition, we have the closed form solution of the power allocation to (3.12) in the following theorem.

Theorem 1: The solution of the optimal power allocation to (3.12) is

$$P_j^{d*} = \begin{cases} min\left\{P_{max}^d, P_{1max}^d\right\}, if\ P_{max}^d \leq P_{j,X}^d, \\ min\left\{P_{max}^d, P_{2max}^d\right\}, if\ P_{max}^d > P_{j,X}^d,\ and\ P_{max}^c > P_{i,X}^c \\ P_{1max}^d, \qquad otherwise \end{cases}$$

and

$$P_i^{c*} = \begin{cases} min\left\{P_{max}^c, P_{1max}^c\right\}, if\ P_{max}^d \leq P_{j,X}^d, \\ min\left\{P_{max}^c, P_{2max}^c\right\}, if\ P_{max}^d > P_{j,X}^d,\ and\ P_{max}^c > P_{i,X}^c \\ P_{max}^c, \qquad otherwise \end{cases} \tag{3.14}$$

P_{1max}^c and P_{1ma}^d , and P_{2max}^c and P_{2max}^d, are obtained from implicit functions of (3.13), hence $f_1(P_{1max}^d, P_{max}^c) = 0$ and $f_1(P_{max}^d, P_{1ma}^c\ ) = 0$. Also, $f_2(P_{2max}^d, P_{max}^c) = 0$ and $f_2(P_{max}^d, P_{2m}^c\ \ ) = 0$. By adopting bisection search method and taken advantage of the monotonic relation between the P_i^c, and P_j^d in the implicit functions.

$$f_1\left(P_j^d, P_i^c\right) = \gamma_j^d - \gamma_{j\min}^d = 0, \text{ when } P_j^d \in \left(P_{1max}^d, P_{j,X}^d\right) \text{ and}$$

$$f_2\left(P_j^d, P_i^c\right) = \gamma_i^c - \gamma_{i\min}^c = 0, \text{ when } P_j^d \in \left(P_{j,X}^d, +\infty\right) \tag{3.15}$$

Remark: Based on the preposition above, the optimal power vector is divided into two parts, depending on whether $\gamma_j^d \geq \gamma_{jmin}^d$ or not. According to (3.10), the analysis of the two region's upper boundaries (as further shown by the implicit functions $f_1(P_j^d, P_i^c) = 0$ and $f_2(P_j^d, P_i^c) = 0$, respectively) intersect at $(P_{j,X}^d, P_{i,X}^c)$ which lies on the separating line $\gamma_j^d = \gamma_{jmin}^d$. Again, the two functions ($f_1(P_j^d, P_i^c) = 0$ and $f_2(P_j^d, P_i^c) = 0$) maintain a monotonically increasing relation between P_i^c and P_j^d in the range $(P_{1max}^d, P_{j,X}^d)$ and $(P_{j,X}^d,\ P_{2max}^d)$ respectively [204] to ascertain that at least one device is transmitting at the peak power to maximize the overall sum rate. It Was deduced from the constraint (3.12a) that the γ_i^c, increases with P_i^c and decreases with P_j^d. Therefore, the optimal solution must be located at the upper limit of the feasible region, which is jointly determined by the continuous line of $f_1(P_j^d, P_i^c) = 0$ and $f_2(P_j^d, P_i^c) = 0$. Additionally, investigation reveals that γ_i^c improves as P_j^d along the boundary line increases. As a result, the solution to the optimal power allocation for single NUE-D2D pair is determined by the relative magnitudes of P_{max}^c and P_{max}^d as well as their intersections with the boundary line, as summarized in the theorem 1. Following the solution to the optimal power allocation for each single pair, the next step is to find the optimal reuse partner for a D2D pair when more than one partner user is available.

3.5.3 Pair Matching for multiple D2D pairs

The optimal power allocation for a single NUE-D2D pair yields the D2D pair's sum rate and guarantees QoS for the reusing NUE partners. However, even after applying the optimal power allocation scheme in (3.14), it is necessary to eliminate those combinations of NUE-D2D pairs that do not satisfy the QoS constraints for the D2D pair in (3.5). To that end, the NUE-D2D pairs was evaluated and those that do not meet the interference threshold I_o constraint while satisfying the NUEs' minimum QoS requirement were discarded. As a result, such a NUE-D2D pair is not feasible, and the channel power gain was set to negative infinity. i.e.

$$f^*\left(P_i^{c^*}, P_j^{d^*}\right) = \begin{cases} f\left(P_i^{c^*}, P_j^{d^*}\right), & if \;\; P_j^{d^*} g_{j,\ell} \leq I_0 \\ -\infty, & otherwise \end{cases} \quad (3.16)$$

With the satisfaction of constraint (3.16), P_j^d becomes a critical tuning parameter used to adjust the algorithm's power gain complexity. As a result, it can be determined dynamically based on network conditions and the number of NUEs and D2D users.

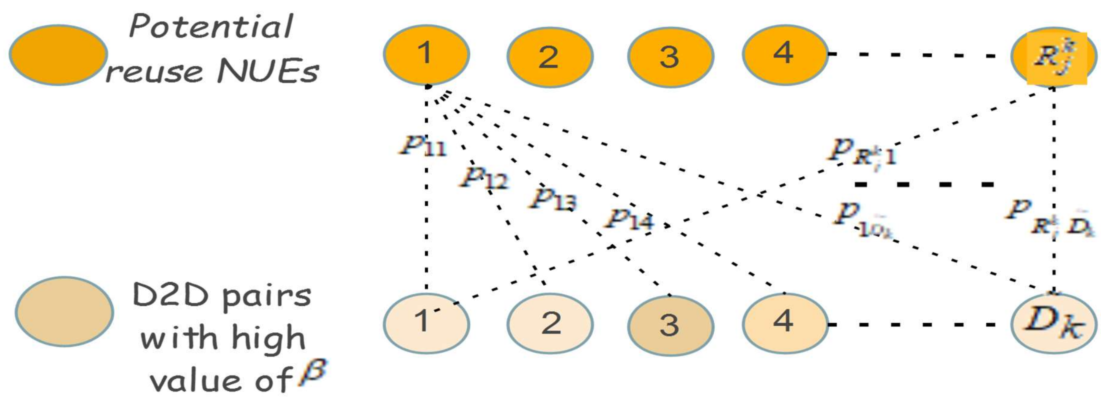


Figure 3.2. Bipartite graph for potential reuse NUEs and D2D pair with the higher value of β matching problem.

When compared to other algorithms that either set a static value for the interference threshold or do not consider the interference threshold, the proposed algorithm has the advantage of flexibility and dynamism, as well as lower complexity which creates fairness for indiscriminating services among all the users. After this evaluation for all possible NUE-D2D pair combinations, the resource allocation problem reduces to;

$$\max_{\rho_{i,j}} \sum_{i \in R_j^k} \sum_{j \in \tilde{D}} \rho_{i,j} f^* \left(P_i^{c*}, P_j^{d*} \right)$$

$$\text{s.t} \quad \sum_i \rho_{i,j} \leq 1, \quad \rho_{i,j} \in \{0,1\}, \ \forall i \in R_j^k \quad (3.17a)$$

$$\sum_j \rho_{i,j} \leq 1, \quad \rho_{i,j} \in \{0,1\}, \ \forall j \in \hat{D} \quad (3.17b)$$

which turn out to be a maximum weight bipartite matching problem and can be efficiently solved by the Hungarian method in polynomial time [18]. The bipartite matching problem in (3.17) is illustrated in Figure 3.2, where the problem of resources utilization between the set $\widetilde{D_k}$ of D2D pairs with the higher value of β and the set $\mathcal{R}_j^k$ of potential reuse channels of the NUEs is considered as two groups of vertices in bipartite graph (i.e., $\mathcal{R}_j^k \cap \widetilde{D_k} = \emptyset$). Vertex i is joined with vertex j by an edge ij. Thus, the Kuhn-Munkres technique is used to solve the optimization objective in (3.17). Table 3.1 summarizes the optimal solution to the RA problem in (3.17) for the interference avoidance RA of D2D-enabled 5G NB-IoT networks.

Table 3.1. Optimal Resource Allocation in D2D-enabled 5G NB-IoT Networks

Algorithm1. Optimal Resource Allocation with RCS

1. Initialize $\forall i \in Z$, $\forall j \in \mathcal{N}$, $k \in \mathcal{K}$, $i \in \mathcal{R}_j^k$ & $j \in \widetilde{D}_k$,
2. for $i \in Z$ and $j \in \mathcal{N}$, do
3. Compute β from (3.5)
4. end for
5. for $j \in \widetilde{D}_k$
6. sort β ($i \in Z$) in a descending order and store in $\mathcal{R}_j$
7. set $\mathcal{R}_j = arg\max_{i \in Z} \beta \quad \forall j \in \widetilde{D}_k$
8. set $\mathcal{R}_j^k = \mathcal{R}_j \quad \forall i \in \mathcal{R}_j^k$ & $\forall j \in \widetilde{D}_k$
9. end for
10. for $i \in \mathcal{R}_j^k$ and $j \in \widetilde{D}_k$, do
11. compute (P_j^{d*}, P_i^{c*}) from (3.11) for the single NUE-D2D pair.
12. Compute the sum-rate $f^*(P_j^{d*}, P_i^{c*})$ from (3.14)
13. If $P_j^d g_j \leq I_o$
14. $f^*(P_j^{d*}, P_i^{c*}) = -\infty$
15. end if
16. end for
17. Apply Hungarian Algorithm (Douglas B. West, 2002) to obtain the optimal reuse pair based on $f^*(P_j^{d*}, P_i^{c*})$
18. Output the reuse pair ($\rho_{i,j}$) and the corresponding power allocation (P_j^{d*}, P_i^{c*})

The computational complexity of the proposed algorithm is expressed in terms of big O notation. The algorithm is sectioned into three steps. The first step selects the reuse partner for the $\mathcal{N}$ D2D links iterations, and the complexity is O$|Z\mathcal{N}|$. The second step generate the sum-rate $f^*(P_j^{d*}, P_i^{c*})$ with a complexity of O$|(Z\text{-}\mathcal{N})\ \mathcal{N}\log((Z\text{-}\mathcal{N})\ \mathcal{N})\ |$ where the bisection search method complexity is given as O$|\log(Z\text{-}\mathcal{N})|$. The complexity of the third step as regards to the Hungarian method is O$|(Z\text{-}\mathcal{N})^3|$ if $Z \geq \mathcal{N}$. The overall complexity can be expressed as O$|\ Z\mathcal{N} + (Z\text{-}\mathcal{N})\ \mathcal{N}\log((Z\text{-}\mathcal{N})\ \mathcal{N}) + (Z\text{-}\mathcal{N})^3|$.

3.6 CHAPTER SUMMARY

Interference is a barrier to throughput improvement in HetNet (or for two coexisting carriers such as 5G NB-IoT networks). As a result, the research community is working hard to achieve reliable and effective communication. This Chapter implements an interference-avoidance scheme to improve the spectrum efficiency, cell coverage, cell-edge data rate, and SINR, all of which enhance the network performance. Previous approaches only increase the network overhead, reduce the data rate, and reduces the spectral efficiency, as well as, have high computations that are not suitable for the 5G NB-IoT networks due to their low complexity. As a result, to meet NUE's SINR requirement, a D2D communication scheme is used to reduce the interference bottleneck, and an interference constraint was developed to eliminate D2D pairs with high interference power. In contrast to several other approaches from the literature, the interference avoidance scheme is evaluated and validated.

CHAPTER 4 PERFORMANCE ANALYSIS AND EVALUATION

4.1 CHAPTER OUTLINE

This Chapter describes the evaluation and performance of the proposed system as the results are compared to three (3) other schemes from the literature. Section 4.2 describes the system configuration and parameters. Section 4.3 presents the simulation results of the proposed system with the three (3) approaches using two performance metrics: cumulative distribution functions and sum data rate. Section 4.4 discusses the obtained results in detail, and Section 4.5 summarizes the Chapter.

4.2 SYSTEM CONFIGURATION AND PARAMETERS

In this section, the performance of the proposed system is evaluated and the simulation parameters is presented. Consider a single PBS with a radio R = 100m, randomly and uniformly distributed NUEs and D2D pairs, as shown in Figure 3.1. The PBS provides a stand-alone NB-IoT solution to the growing number of IoT devices in a heterogeneous cell where the MeNB and PBSs are orthogonal in terms of bandwidth usage. A D2D pair is established between neighboring cell edge NUEs to improve network throughput and avoid interference from a disadvantageous cell edge NUE. The NUEs are assumed to share the whole bandwidth equally. The system simulation was carried out in matrix laboratory (MATLAB R.2021a) environment and the results in each figure for the CDF are obtained by averaging a minimum of 10,000 iterations. Table 3.2 summarizes the simulation parameters used.

Table 4.1. Simulation Parameters

Parameter	Value
Carrier Frequency	2GHz
Bandwidth	180kHz
Cell radius	100m
SINR Threshold	25dB
Number of NUEs, Z	20
Number of D2D pairs, $\mathcal{N}$	10, 20
Max. D2D distance	20m
Max. NUE Transmit Power	17, 23dBm
Max. D2D pair Transmit Power	17, 23dBm
Noise Power σ^2	-114
Pathloss Model	3GPP TR 38.901 [201]
Multipath fading	Rayleigh fading
Shadowing for NUE link	Log-normal distribution with standard deviation of 8dB
Shadowing for D2D link	Log-normal distribution with standard deviation of 3dB
Bisection Accuracy	10^{-6}

The performance of the proposed scheme is validated with three other approaches as references:

1. DCORA algorithm, a device-device communication optimal resource allocation algorithm used in [180].

2. ARSAD algorithm used in [178] is an adaptive resource sharing algorithm for Device-Device underlying cellular networks.

3. The RRA algorithm is a device-to-device communication resource sharing allocation method that uses a random selection of reuse partners irrespective of the interference situations within the network. The reuse channel is selected at random from the

potential reuse candidate sets. The first two algorithms are nearly identical to the one proposed here, with a difference in the channel selection strategy. To better understand the effectiveness of our proposed algorithm, we referred to the RRA performance scheme as the proposed scheme without channel reuse selection.

4.3 SYSTEM RESULTS

This section presents the performance evaluation of the proposed scheme with respect to the three other approaches referenced above using two performance metrics: the cumulative distribution function (CDF) and sum-rate.

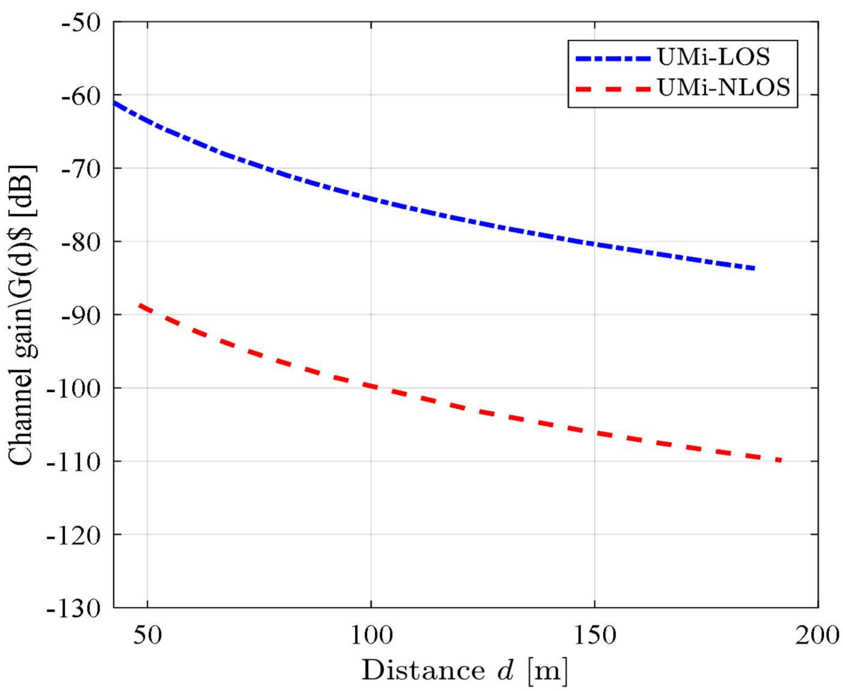
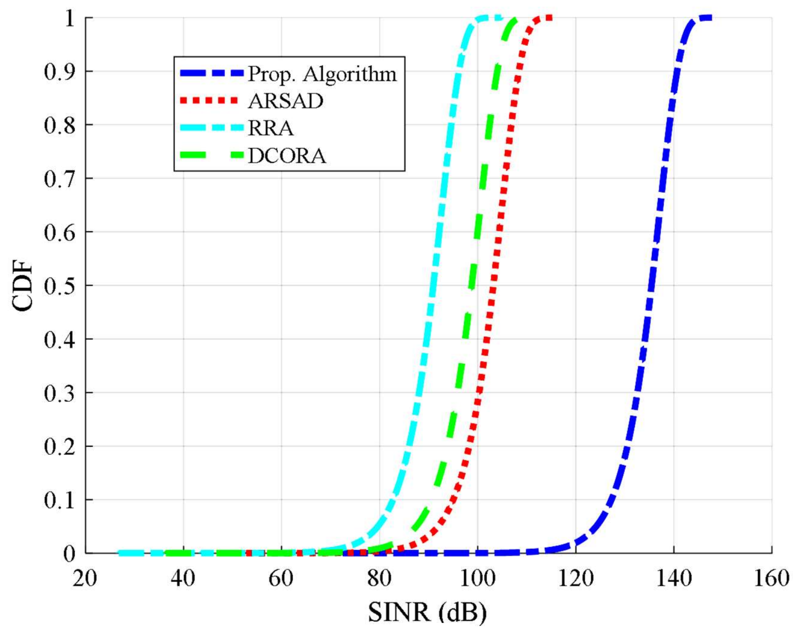
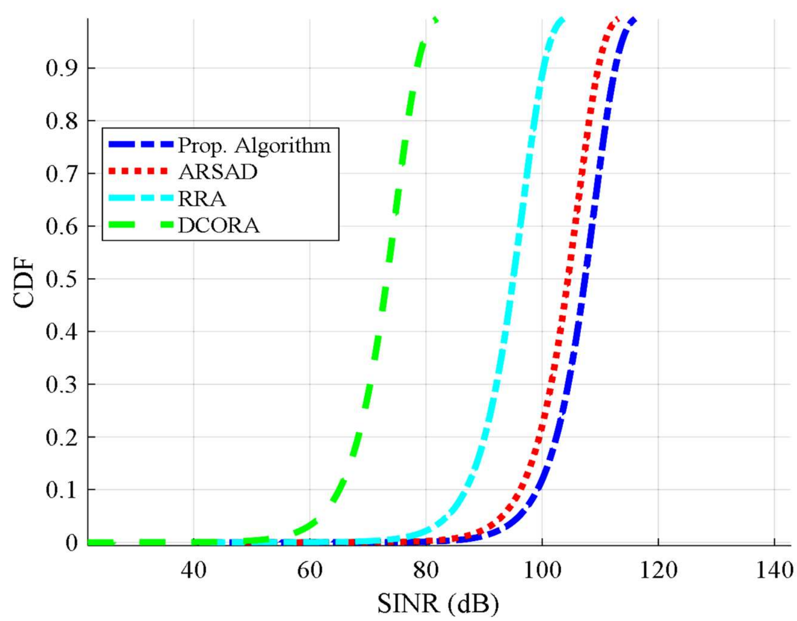


Figure 4.1. Channel gain Vs Distance

****Please note that the text "scheme" and "algorithm" will be interchangeably used in the thesis. ****

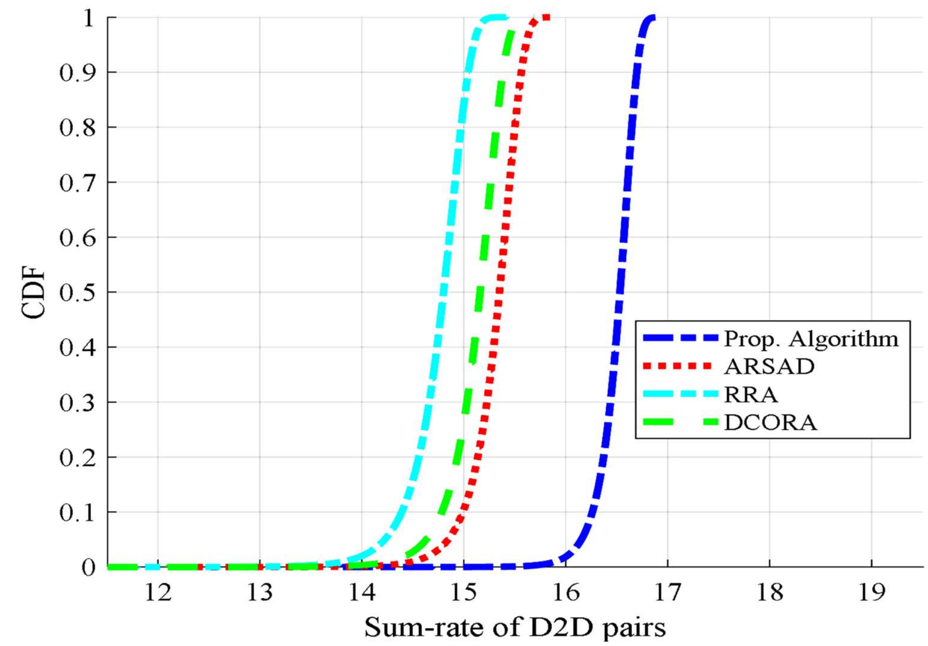


(a)

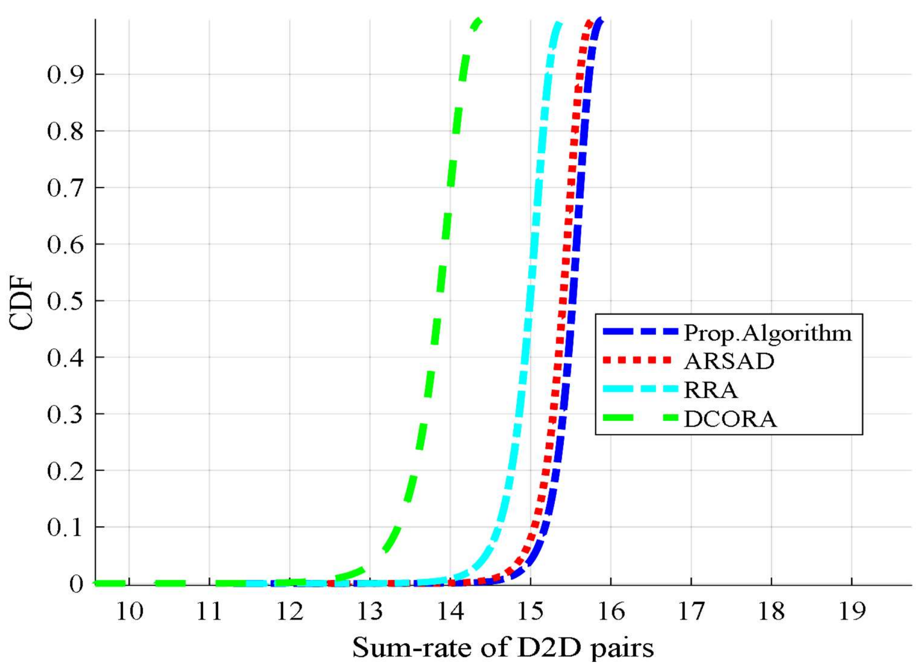


(b)

Figure 4.2. The SINR of D2D pairs of the proposed algorithm with three other approaches when (a) Z=20 and $\mathcal{N}$= 10, (b) Z=20 and $\mathcal{N}$= 20 and $P^{d}_{2max} = P^{c}_{max}$=23dBm.

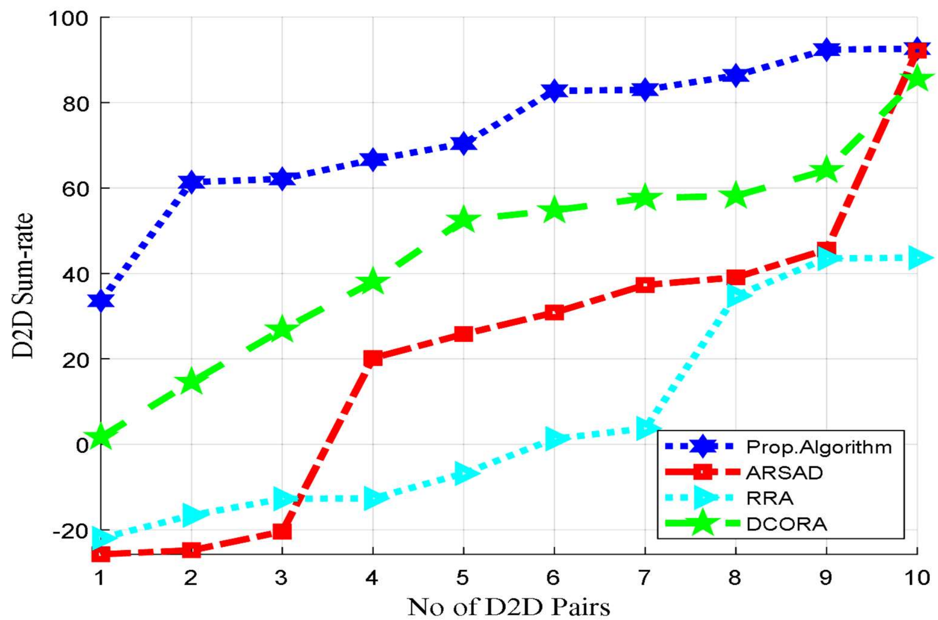


(a)

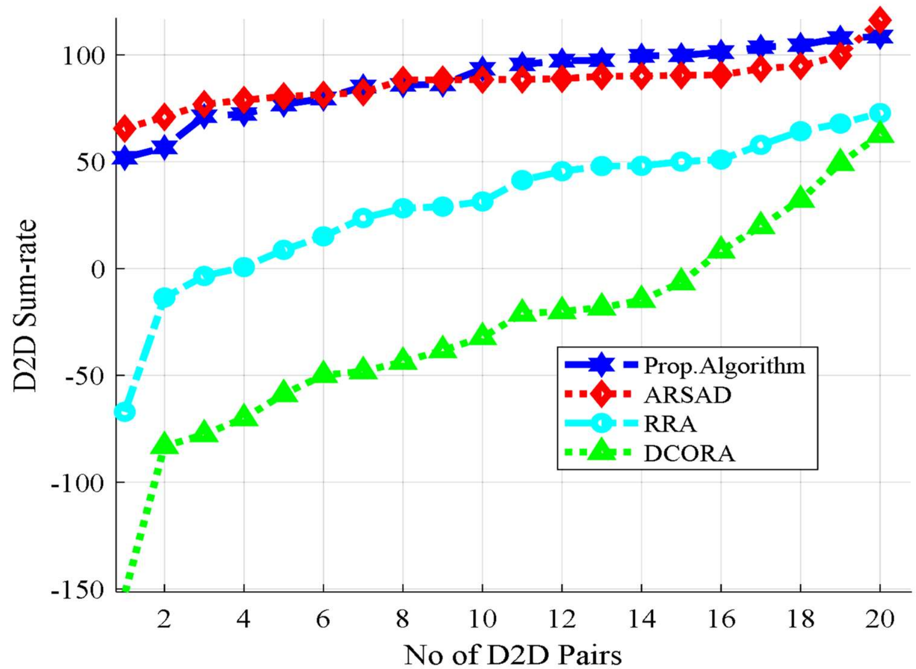


(b)

Figure 4.3. The cumulative distribution of D2D Sum-rate with three other approaches when (a) Z=20 and $\mathcal{N}$= 10, (b) Z=20 and $\mathcal{N}$=20 and $P_{2max}^{d} = P_{max}^{c}$=23dBm.

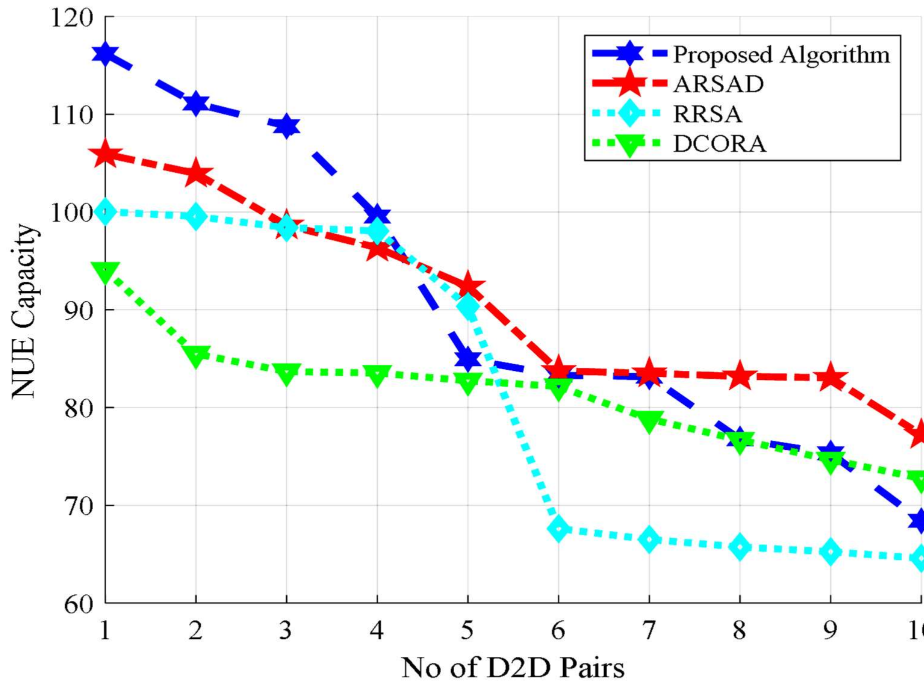


(a)

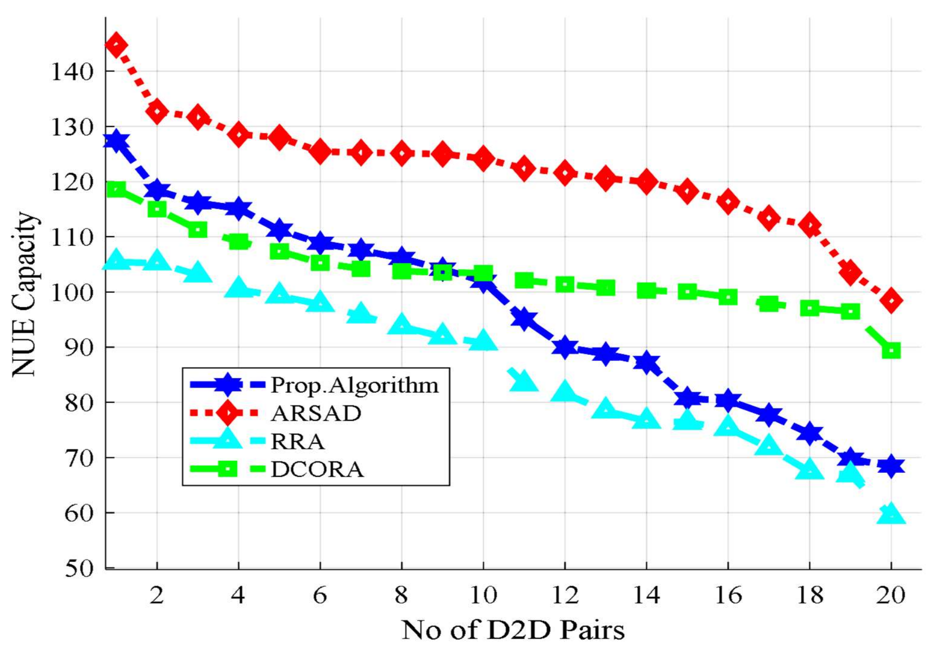


(b)

Figure 4.4. D2D pair's Sum-rate against the number of D2D pairs for the different approaches when (a) Z=20 and $\mathcal{N}$= 10, (b) Z=20 and $\mathcal{N}$=20 and $P_{2max}^{d} = P_{max}^{c}$=23dBm.

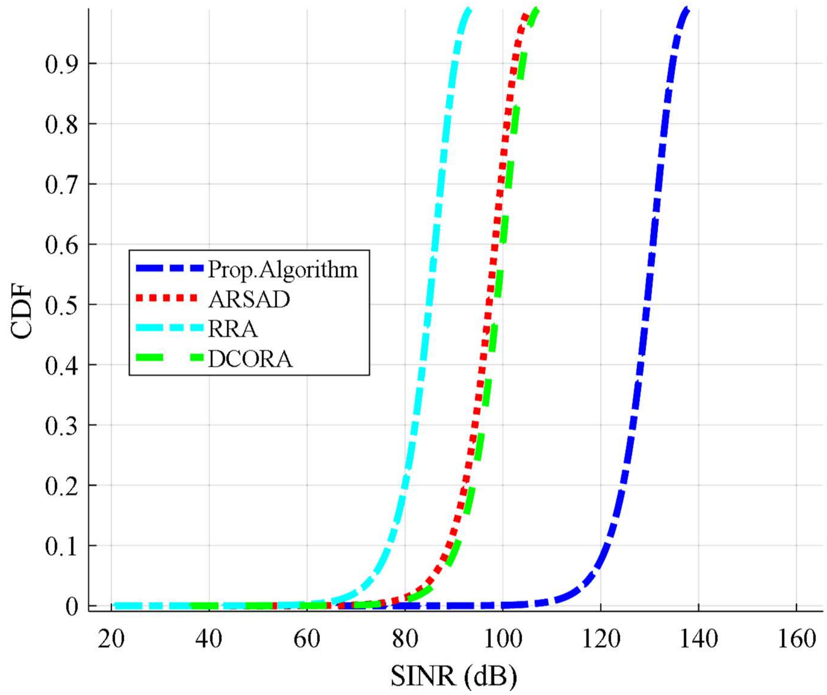


(a)

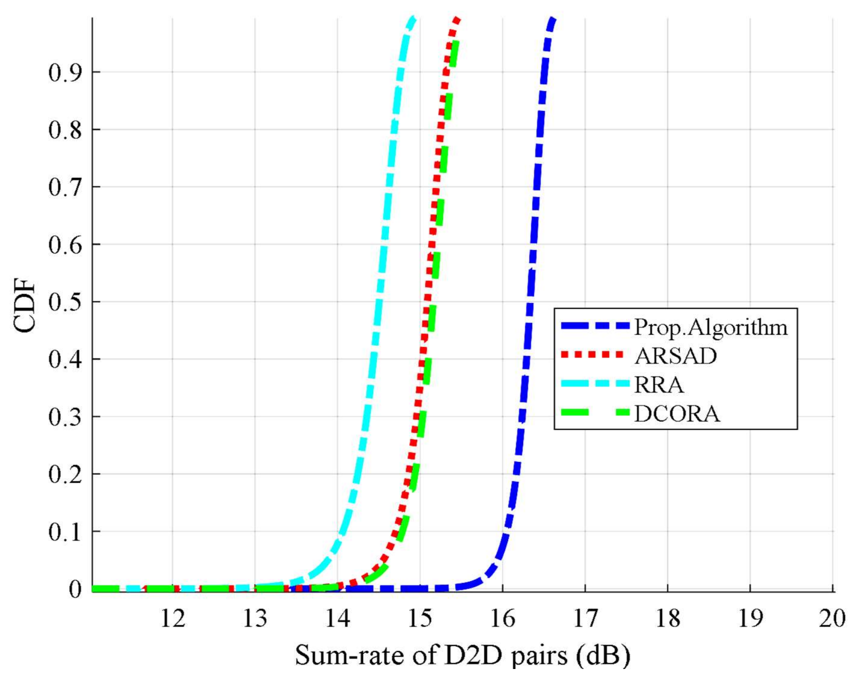


(b)

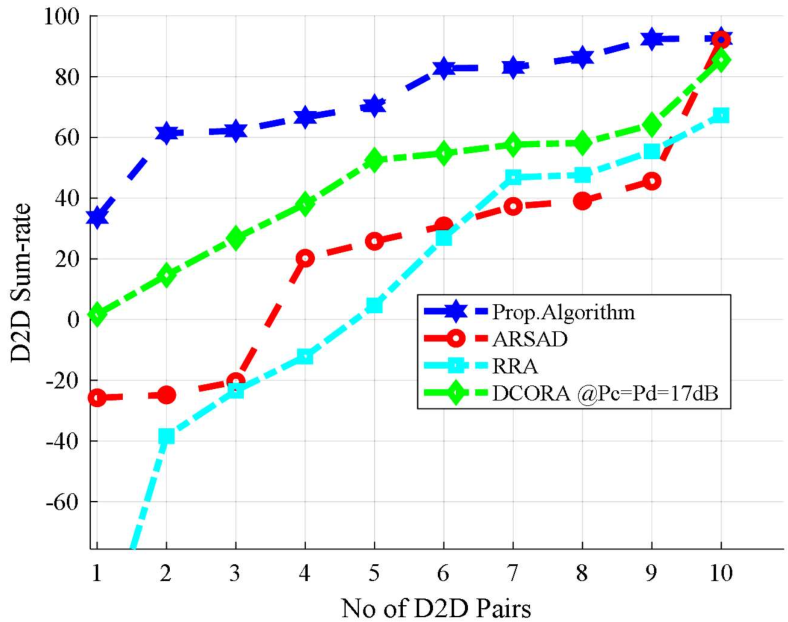
Figure 4.5. NUE's capacity against the number of D2D pairs with three other approaches when (a) Z=20 and $\mathcal{N}$= 10, (b) Z=20 and $\mathcal{N}$=20 and $P_{2max}^{d} = P_{max}^{c}$=23dBm.


CDF
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
20 40 60 80 100 120 140 160
SINR (dB)
Prop.Algorithm
ARSAD
RRA
DCORA

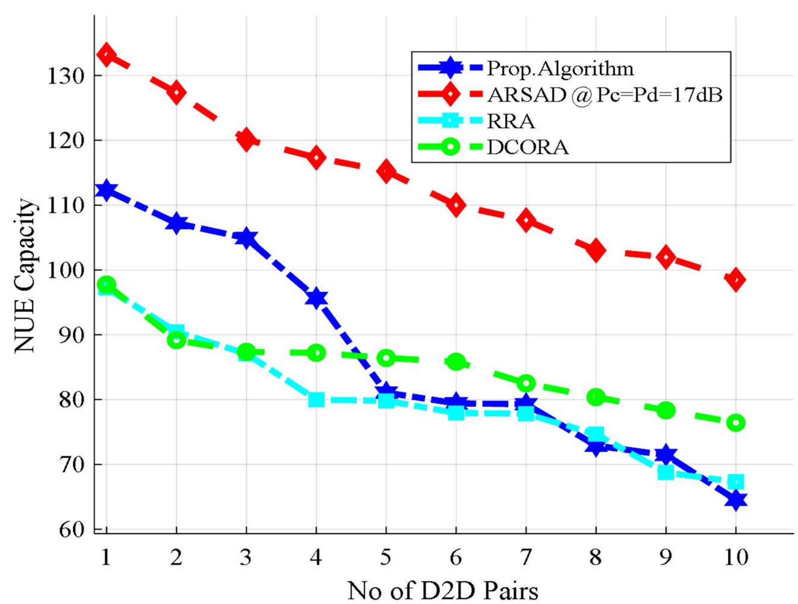
(a)


CDF
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
12 13 14 15 16 17 18 19 20
Sum-rate of D2D pairs (dB)
Prop.Algorithm
ARSAD
RRA
DCORA

(b)

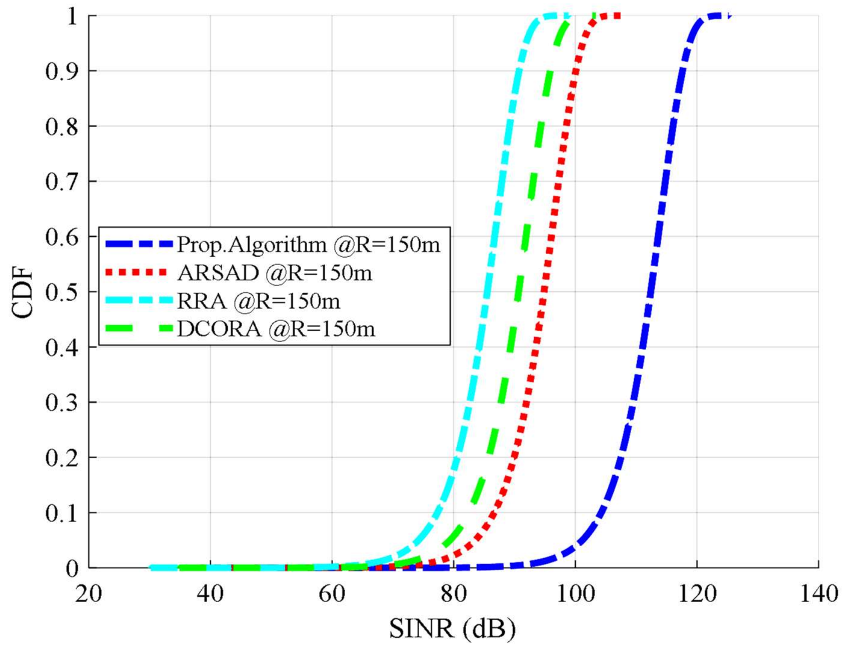


(c)

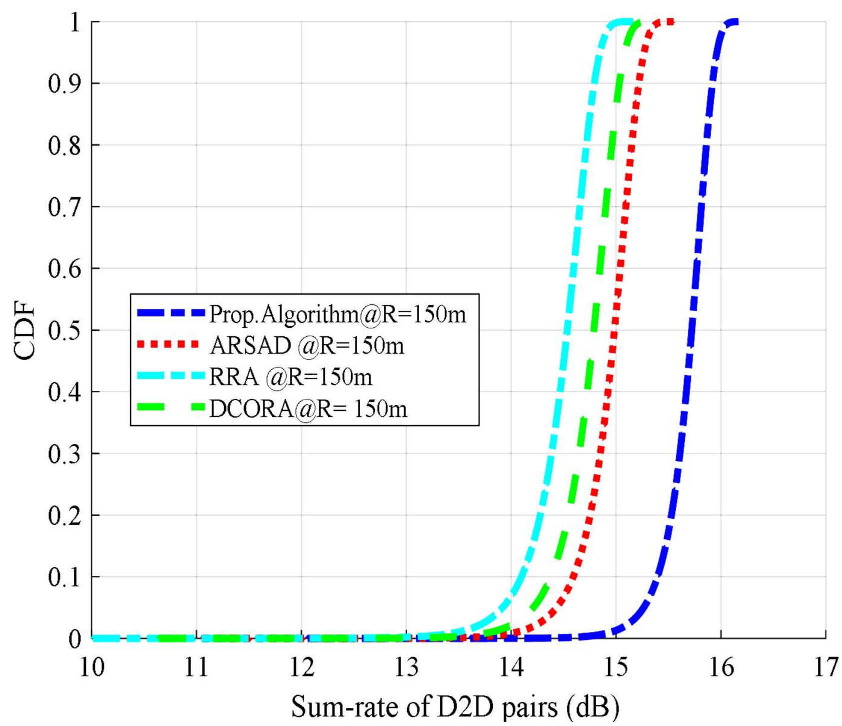


(d)

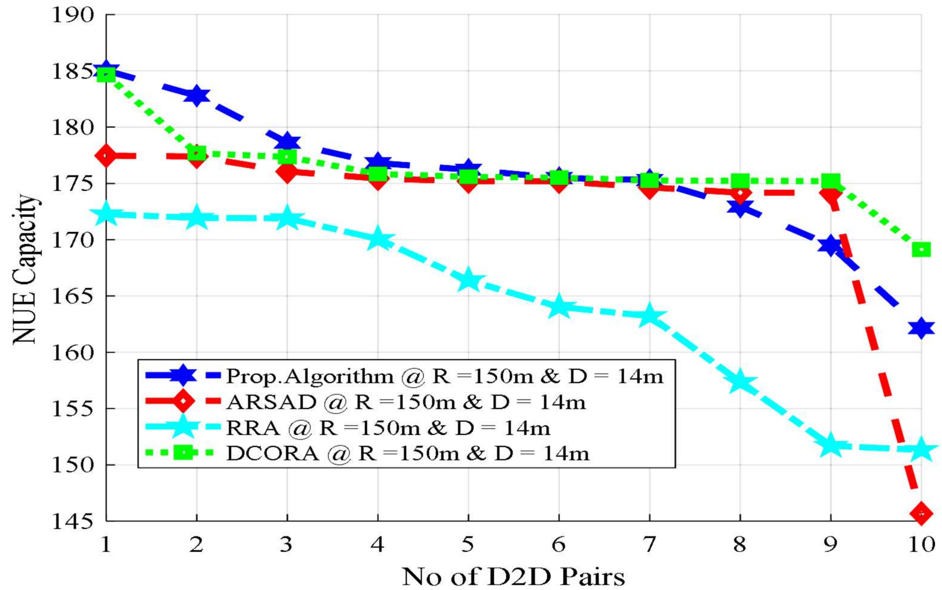
Figure 4.6. (a) CDF of D2D's SINR, (b) CDF of D2D's Sum-rate, (c) D2D's Sum-rate against the number of D2D pairs and (d) NUE's Capacity against number of D2D pairs when $P_{2max}^{d} = P_{max}^{c}$= 17dBm for Z=20 and $\mathcal{N}$= 10.


CDF
SINR (dB)
Prop.Algorithm @R=150m
ARSAD @R=150m
RRA @R=150m
DCORA @R=150m
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
20
40
60
80
100
120
140

(a)

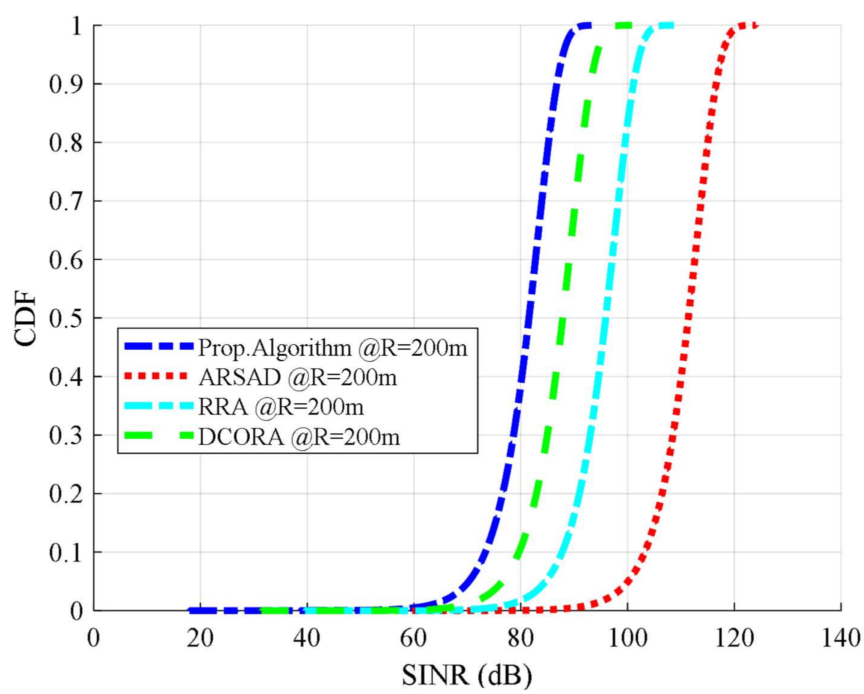

CDF
Sum-rate of D2D pairs (dB)
Prop.Algorithm@R=150m
ARSAD @R=150m
RRA @R=150m
DCORA@R= 150m
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10
11
12
13
14
15
16
17

(b)

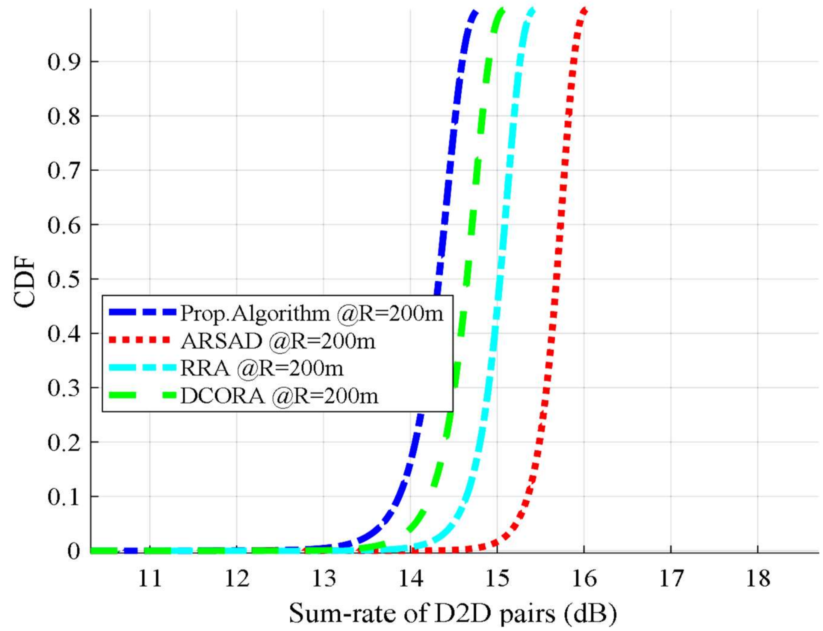


(c)

Figure 4.7. (a) The SINR, (b) Sum-Rate and the (c) NUE capacity against number of D2D pairs When R=150m and D2D pair's cluster distance = 14m for Z=20 and $\mathcal{N}$= 10.



(a)



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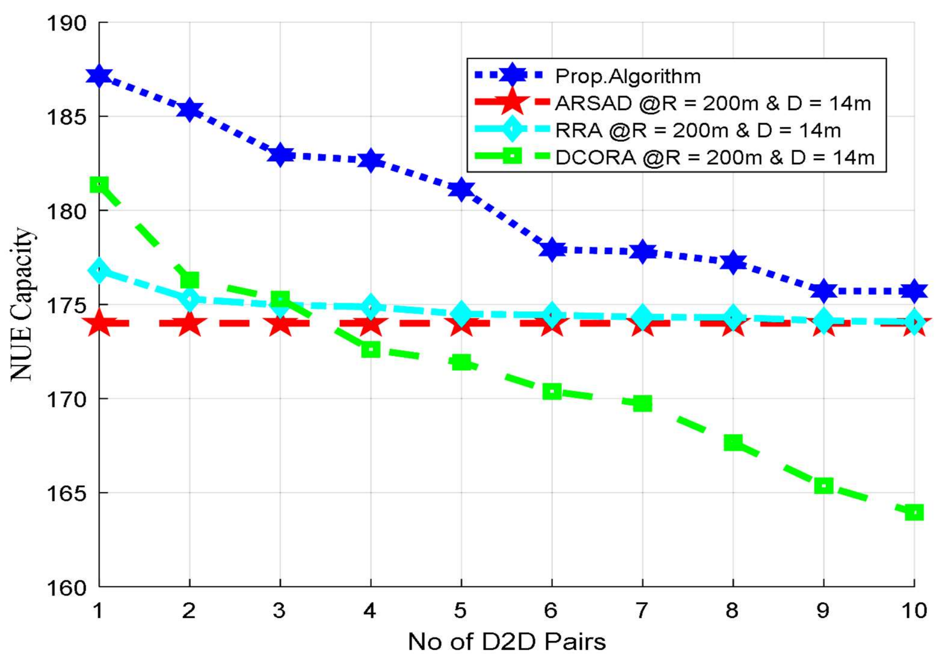
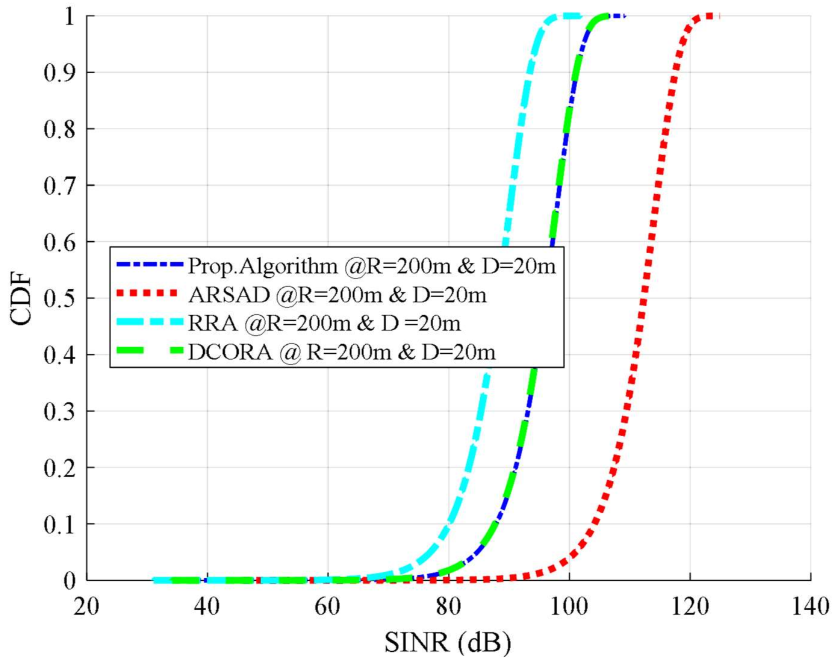
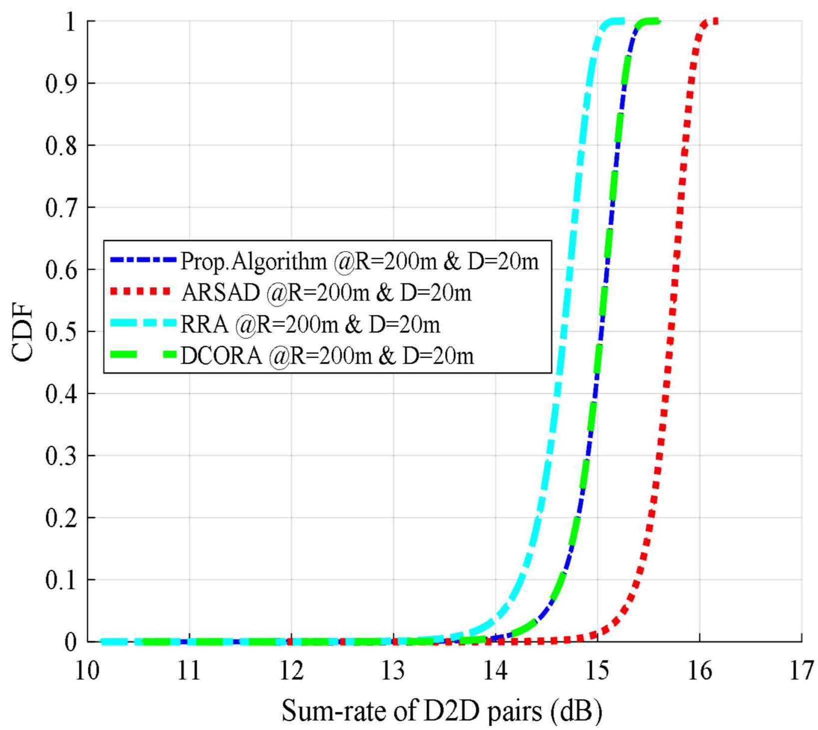


(c)

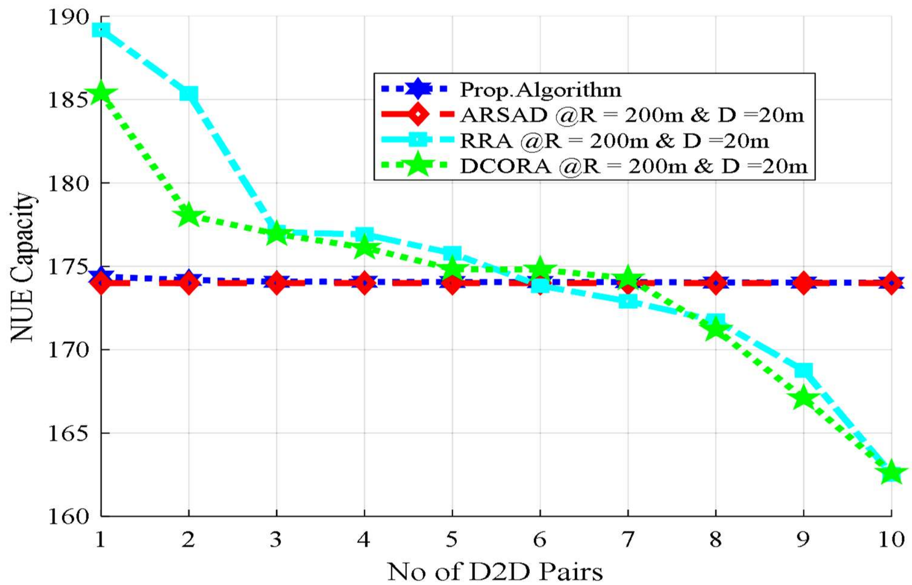
Figure 4.8. (a) The SINR, (b) Sum-Rate and (c) the NUE capacity against number of D2D pairs when R=200m and a Distance between D2D pairs = 14m.


CDF
SINR (dB)
Prop.Algorithm @R=200m & D=20m
ARSAD @R=200m & D=20m
RRA @R=200m & D =20m
DCORA @ R=200m & D=20m
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
20
40
60
80
100
120
140

(a)


CDF
Sum-rate of D2D pairs (dB)
Prop.Algorithm @R=200m & D=20m
ARSAD @R=200m & D=20m
RRA @R=200m & D=20m
DCORA @R=200m & D=20m
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10
11
12
13
14
15
16
17

(b)



(c)

Figure 4.9. (a) The SINR's CDF, (b) Sum-Rate's CDF and (c) the NUE's capacity against number of D2D pairs when R=200m and Max. D2D's cluster Distance = 20m.

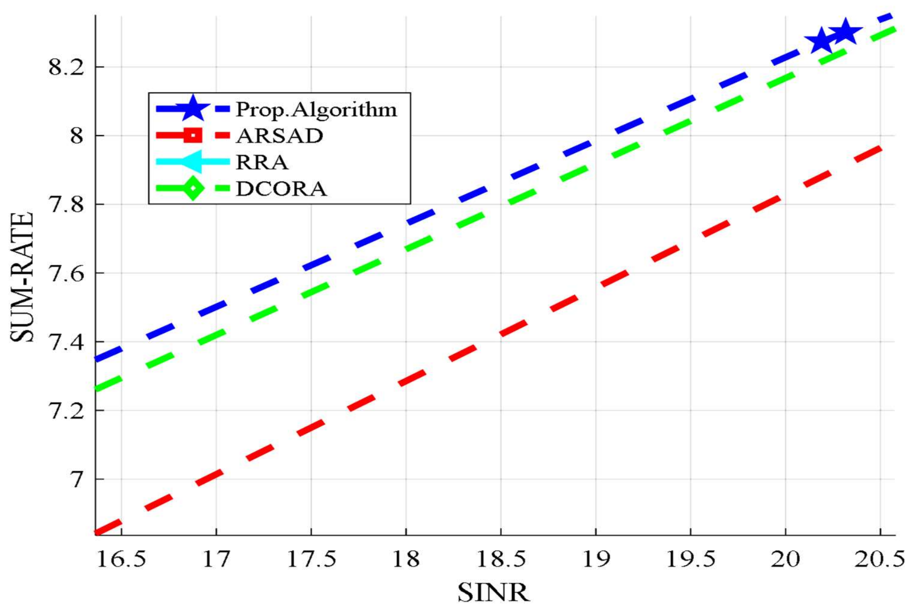


Figure 4.10. The Sum-rate against the SINR of the proposed algorithm with three other approaches when Z=20 and $\mathcal{N}$= 10, and $P^{d}_{2max} = P^{c}_{max}$=23dBm

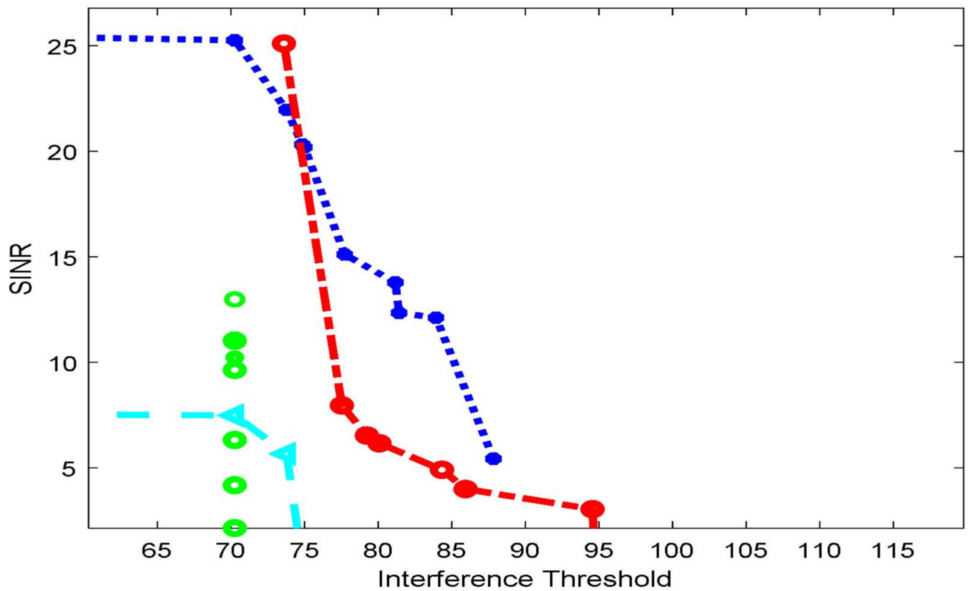


Figure 4.11. The SINR against the Interference threshold of the proposed algorithm with three other approaches when Z=20 and $\mathcal{N}$= 10, and $P_{2max}^{d} = P_{max}^{c}$=23dBm.

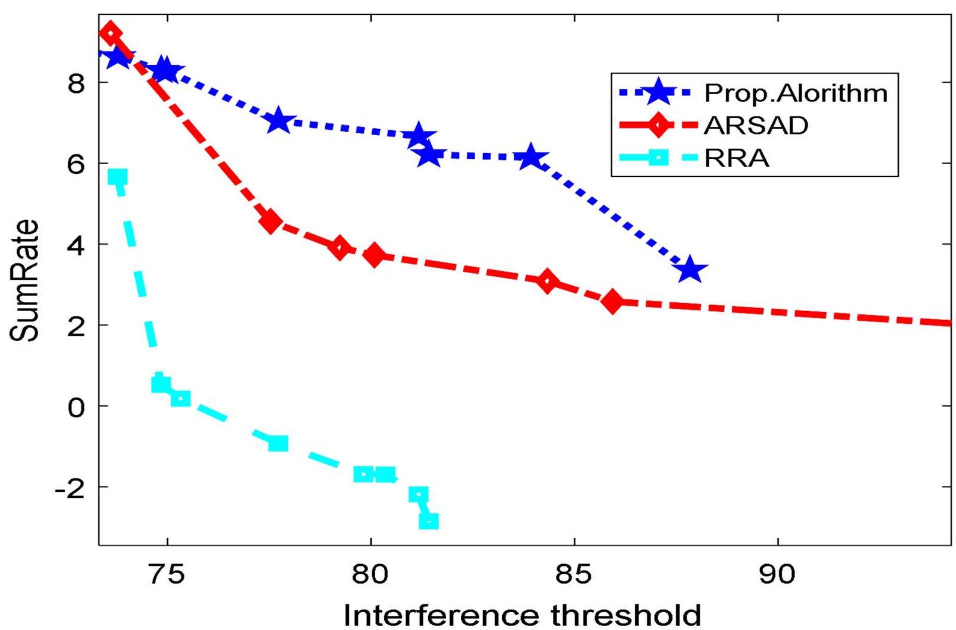


Figure 4.12. The Sum-rate against the Interference threshold of the proposed algorithm with three other approaches when Z=20 and $\mathcal{N}$= 10, and $P_{2max}^{d} = P_{max}^{c}$=23dBm.

4.4 DISCUSSION OF RESULTS

This section discusses the performance evaluation of the results obtained by the proposed scheme with the three other approaches mentioned earlier using the CDF and sum-rate performance metrics. Therefore, the discussion of each figure will follow in sequential order.

To get an understanding of channel deterioration at the cell edge, the channel gains between the PBS and the cellular NUEs is modelled using the 3GPP TR 38.901 [201] line of sight (LOS) and Non-LOS (NLOS) versions of Urban Microcell (UMi) for distances greater than 10m. The shadowing is included to get the LOS and NLOS variation and show channel gain g as a function of distance d in Figure 4.1. Figure 4.1 depicts a very large channel gain for the NUEs, whereas a typical value generally ranges from -70 to 110dB [205].

Figure 4.2 illustrates the SINR obtained by the proposed scheme compared to the other three approaches mentioned earlier. Intuitively, the SINR achieved by the proposed scheme in this thesis is higher than that of ARSAD, DCORA, and RRA. Note that the SINR of the D2D pair is closely related to the interference from the PBS, even with the PBS's transmit power remaining constant. As a result, there would not be much difference in the RA algorithms' computation. The proposed scheme tends to adjust the transmit power of the D2D pairs to minimize network interference rather than focusing on individual NUE interference. The proposed scheme selects the NUE with the highest gain and allocates resources to the best NUE and D2D pairs to minimize reuse interference. Furthermore, the optimal power control allows D2D users to increase their transmit power without significantly degrading the transmission of the existing NUE, resulting in improved D2D pair performance. By contrast to the RRA scheme and the other two algorithms, the adopted channel reuse application results in an SINR performance trade-off. Figure 4.2 (a) is the SINR performance when the number of D2D pairs is less than the number of NUEs (i.e., Z=20 and $\mathcal{N}$= 10), the proposed scheme (algorithm) achieves 28.35%, 31.33% and 39% performance than the ARSAD, DCORA and RRA respectively. In Figure 4.2 (b), the performance of the proposed algorithm was tested for equal numbers of both NUEs and D2D pairs. The result was very close to that of the ARSAD, achieving 2.52%, 14.80% and 39.89% for ARSAD, RRA and DCORA accordingly. As seen from Figure 4.2 (b), it was surprising to observe that the RRA scheme performs better than the DCORA scheme. The reason could be the introduction of more D2D pairs that creates intense interference to the NUEs within the network. However, it brings more diversities in channel selection and increases the chances of running into a better channel than the DCORA scheme that only select reuse candidate based on admission control. In summary, our proposed algorithm performs far better than the other three approaches due to a better choice of reuse channel candidate for the D2D pairs even as the D2D number increases.

Figure 4.3 depicts the CDF of the D2D's sum rate of the proposed algorithm with three different approaches as observed from Figure 4.3 (a) when Z=20 and $\mathcal{N}$= 10. The proposed algorithm improves the sum rate of the D2D pair compared to the ARSAD, DCORA and RRA, which impact the overall network sum rate. The proposed algorithm achieves 9.23%, 11.26% and 13.92% higher than the ARSAD, DCORA and RRA. Figure 4.3 (b) is the results of the D2D's sum rate when Z=20 and $\mathcal{N}$= 20 which achieves 1.18%, 4.64% and 15.93% higher than the ARSAD, RRA and DCORA respectively. Just as observed in Figure 4.2 (b), there was a close gap between the proposed algorithm and the ARSAD scheme due to a better choice of reuse channel candidate for the D2D pairs even as the D2D number increases. However, the performance of all the schemes decreases generally as the number of D2D pairs increases.

Figure 4.4 depicts the sum-rate of the D2D pair with three other approaches when (a) Z=20 and $\mathcal{N}$= 10, and (b) Z=20 and $\mathcal{N}$=20 respectively. Figures 4.4 (a) and (b) show a linear increase in proportion to the number of D2D pairs, indicating an increase in the D2D sum rate for all three algorithms, including the proposed algorithm. However, in both figures, the proposed algorithm outperformed the three other approaches, except for the ARSAD scheme, which has a relatively close performance to the proposed algorithm when the NUE and the D2D pair are equal in number. As a result, Figure 4.4 (b) implies that as the number of D2D pairs increases, the network becomes saturated and cannot serve more upcoming D2D pairs. Hence the diversity of multi-D2D users can only result in a lesser sum-rate gain. In summary, as the number of D2D pairs exceeds the number of NUEs, SINR deterioration of the NUEs may occur, limiting transmission performance, overall cell capacity, spectrum efficiency, network performance, and user performance of the 5G NB-IoT system. As a result, given the same amount of NUEs and D2D pairs, the proposed algorithm still outperforms the other three schemes.

In Figure 4.5, the NUE's capacity was plotted against the number of D2D pairs when (a) Z=20 and $\mathcal{N}$= 10, and (b) Z=20 and $\mathcal{N}$=20. As shown in Figure 4.5 (a), the proposed algorithm maximizes the reuse resources of the NUE, causing minimal reuse interference on average as the number of D2D pairs grows compared to the ARSAD and DCORA schemes. The reason for this is that the proposed algorithm shares resources with a distant D2D user to reduce reuse interference using a combination of channel reuse selection and a power control mechanism. If the D2D pair's power and interference constraint do not exceed the maximum allowable threshold, the D2D pair's transmitter will maintain a high transmit power to maximize its sum rate while ensuring the NUEs' QoS according to constraints (3.5c) and (3.5g). Comparing the ARSAD and DCORA schemes to the proposed algorithm, the level of interference appears to be slightly higher than the proposed algorithm, but RRA produced an average rate of interference. Compared to Figure 4.5 (a), the result of Figure 4.5 (b) demonstrates a comparatively high degree of resource maximizing as the number of D2D pairs grows. However, as the number of D2D users increases, so does the interference generated inside the network, and the NUEs' link quality suffers. The proposed algorithm outperformed the other two algorithms (ARSAD and DCORA), which tend to increase their transmit power regardless of the number of D2D pairs. Given the proposed algorithm's optimal power control, the D2D transmitter will always reduce its' transmit power when there is a high level of interference to ensure the NUEs' QoS.

Figure 4.6 shows the evaluation of the proposed algorithm when the transmit power of both the D2D pair and the NUE was reduced to 17dBm. The performance of the proposed algorithm is still significantly superior, as seen in Fig. 4.6 (a) and (b). The DCORA scheme outperforms the ARSAD scheme in terms of performance. This is because the DCORA scheme continues to transmit at high power to meet the D2D pairs' channel gain and SINR constraints while ignoring the NUEs' minimum SINR requirement. In comparison to Figure 4.2 (a) and Figure 4.3 (a), the performance of the proposed algorithm, ARSAD, and RRA in terms of the required SINR and the sum-rate achieved reduces, as seen in Figure 4.6 (c) vs Figure 4.4 (a). As the D2D cluster radius grows, this decline accelerates, lowering the D2D pairs' chances of access. Furthermore, reducing the D2D user's transmit power will lessen interference to the NUE, aiding in satisfying the NUEs' minimal QoS criteria, as demonstrated in Figure 4.6 (d) versus Figure 4.5 (a).

Figure 4.7 shows the simulation results when the cell radius is raised from 100m to 150m while maintaining the same D2D cluster distance of 14m. Within the cell, the density of NUEs and D2D pairs remains constant (i.e. =20 and N=10). As observed from Figure 4.7 (a) & (b), the performance of the proposed algorithm continues to outperform the other three schemes as the cell radius grows. However, in contrast to Figure 4.3 (a), the performance of the proposed algorithm and the three approaches decreases when the distance between the NUE and D2D pair, as well as the PBS and the NUEs, increases. As a result, the channel power gain diminishes, which reduces the number of potential reuse partners who could provide reuse access. Furthermore, as shown in Figure 4.7 (c), the interference between the NUEs and the D2D pairs will rise, contradicting [180]. Interestingly, the ARSAD scheme flattened out, suggesting that it had achieved saturation and could no longer support the D2D pairs. In contrast to the ARSAD scheme, the proposed algorithm, DCORA and RRA, increased their transmit power in response to a bigger cell radius to grant access to the D2D pairs.

Figure 4.8 confirms the findings of Figure 4.7 that the overall performance of all the schemes declines as the cell radius grows under the same D2D cluster distance. Close inspection of Figure 4.7 (a, b, and c) reveals that the value achieved by any of the schemes in terms of SINR’s CDF, Sum-rate’s CDF and the level of generated interference are 98.22, 15 and 165.7 better than Figure 4.8 (a, b, and c) 96.45, 14.89 and 176.12 for the same CDF of SINR, Sum-rate’s CDF and the level of generated interference. When compared to other schemes, the ARSAD and RRA schemes perform remarkably as the cell radius grows. The proposed algorithm and the DCORA scheme perform poorly as the radius of the cell increases, as shown in Figure 4.8 (a, b, and c). The reason for this is that the proposed algorithm could not locate any reuse candidate within the cell radius despite the increase in the transmit power of the D2D pairs. Furthermore, the maximum cell radius of the Pico-base station theoretically is less or equal to 200m, which could mean that the cell is out of coverage considering the cell's practicality. ARSAD and RRA schemes, on the other hand, were able to find a reuse candidate for each D2D user and deliver optimal power for each D2D pair and its reuse partner.

In Figure 4.9, the performance of the proposed algorithm and DCORA improves slightly for SINR's CDF and Sum-rate's CDF as seen in Figure 4.9 (a, b, and c) when the D2D cluster distance is raised from 14m to 20m. This is due to an increase in a channel power gain of the reuse channel selection of the NUEs to the PBS. As a result, the number of potential reuse channels for D2D pairs that provide access opportunities has increased. The interference power from D2D users to NUEs at the PBS is uniform for the proposed algorithm and the ARSAD scheme, as shown in Fig. 4.9 (c), which also guaranteed the NUE's QoS requirements.

The sum rate was plotted against the SINR for three schemes, including the proposed algorithm, in Figure 4.10. The proposed algorithm outperforms the ARSAD and DCORA schemes by 2.86% and 7.14%, respectively. Every SINR improvement in the network results in a direct increase in the sum rate of the D2D pairs. This means that as the network dynamicity changes for each NUE's SINR requirement, the SINR conditions of the D2D users improve, increasing the D2D's sum rate. However, as the interference threshold rises, the SINR and sum rate of the D2D pairs decline, as shown in Figures 4.11 and 4.12, respectively. In comparison to ARSAD, DCORA, and RRA in Figure 4.11, the proposed algorithm adjusts to changes in the interference threshold appropriately. While Figure 4.12 shows a decrease in the sum rate of the proposed algorithm, ARSAD and RRA. RRA has a significantly lower sum rate when compared to the proposed algorithm and the ARSAD scheme.

4.5 CHAPTER SUMMARY

This chapter compares the proposed scheme's performance to three (3) other approaches in the literature. The CDF of the SINR and sum-rate, as well as the Sum-rate plot against the interference threshold, were assessed. The proposed scheme outperforms the other three approaches from the literature. The proposed scheme's ability to adapt to interference changes by adjusting its transmit power accordingly to ensure NUE's SINR requirement was a unique feature. The proposed approach is a novel framework that differs from the traditional approach to interference mitigation in cellular networks. The framework can address interference issues in networks with multiple carriers and control the amount of interference generated as the networks grow. The proposed interference approach in this chapter computes the number of resources allocated to the D2D communicating devices to adjust the D2D pair power gain complexity. As a result, the scheme creates flexibility, dynamism, and fairness that promote indiscriminating services among all users with varying QoS requirements compared to the approaches in the literature. In summary, the proposed scheme's performance evaluation has improved the SINR and sum rate of D2D pairs as the interference power within the network increases.

CHAPTER 5 INTERFERENCE-AWARE D2D RELAYING STRATEGY FOR 5G NB-IOT QOS IMPROVEMENT FOR CELL EDGE USER

5.1 CHAPTER OBJECTIVE

In the quest to further explore the benefits of D2D communication schemes, a D2D relay strategy that differs from the previous chapter was researched. The preceding chapter describes the application of proximate D2D pairs to improve the quality of experience (QoE) of the cell edge user when the interference affects signal reception within the network. This chapter, however, investigates D2D relay selection strategies to address the challenges of long-distance transmission, delays, low bandwidth utilization, and high system overhead to improve the network performance. This chapter's work is currently being evaluated as a contribution to the general body of knowledge. The chapter is organized as follows: Section 5.2 presents the introduction and the related work of the chapter. Section 5.3 describes the system and network model. Section 5.4 presents the problem formulation. Section 5.5 describes the relay selection strategy with interference and Section 5.6 present the chapter summary.

5.2 INTRODUCTION

With the rapid proliferation of the Internet of Things (IoT) devices and data applications for NB-IoT systems, increasing capacity, improving quality of service (QoS), and achieving seamless coverage of NB-IoT networks have become pressing issues. NB-IoT is an LTE-based technology that supports a wide range of applications in systems such as smart agriculture [158], [161], intelligent vehicle systems, smart healthcare systems, and smart industries, to promote a more effective and convenient way of life [171]. To achieve these standards, 5G networks were develop for a horizontal transformation approach to promote the process efficiency of the exponential growth of NB-IoT devices due to their higher bandwidth and processing power than existing LTE-based technology. However, when NB-IoT technology coexists with 5G networks as a HetNet, cell size is reduced and aggressive frequency reuse occur. As a result, fading and interference between base stations have become the major performance bottlenecks of throughput improvement, and techniques such as coordinated multipoint (CoMP) [206], cooperative networks [20], power control [207], multiple-input, multiple-output (MIMO) [208] and scheduling [209] were propose to ensure link performance and reliability. However, recent findings in the field of cooperative networks show that relay-assisted techniques have a higher impact on sets of fading and interfering links, influencing optimal link rate selection [210] in low-complexity networks than CoMP and MIMO techniques that exploit space diversity to mitigate channel fading and extend the transmission range. As a result, given the 5G NB-IoT HetNet complexity and time-varying nature, co-channel interference challenges exist, resulting in poor coverage and poor user performance for cell-edge NB-IoT users (NUEs). The system generates a lot of interference, which complicates the problem of allocating resources to different users with varying quality of service (QoS) requirements.

This chapter proposes an interference-aware D2D relaying strategy for 5G NB-IoT systems to improve cell-edge NUE's QoS. Using idle NUEs with perfect coverage, the cell edge NUE data is transmitted to the NBS via the D2D relaying strategy. The D2D relay strategy, also known as opportunistic D2D communication, can help improve the network coverage and throughput and reduce interference constraints on the cell edge NUEs. D2D relaying, as opposed to traditional relays, provides much greater networking flexibility by responding to user pairing and traffic through dynamic deployment and resource allocation [211]. However, the performance of the technology greatly depends on the optimal selection method of the D2D relay and interference control produced by the signal relaying strategy. Few existing solutions are channel capacity analysis [212], user pairing stability, and user acceptability to discover a positive correlation between the proposed metric and system performance [211]. In a HetNet, two-stage D2D relay selection to offload the unevenly distributed load [179], coverage analysis [213], power allocation design algorithms [214], and resource allocation [215] are applied. Although the studies demonstrated the effectiveness of using cooperative networks in an isolated wireless network, none of them included interference control as part of the D2D relaying strategy.

To the best of our knowledge, no research has been conducted on the performance of D2D relaying in 5G NB-IoT systems based on the D2D relay selection strategy and the average interference power constraint. The study aims to improve the quality of experience (QoE) of cell-edge NUE with poor link quality by selecting links with low interference and delay to avoid costly retransmission at the source. Increase spatial reuse and capacity under interference constraints by maximizing the D2D relay link's minimal data rate while ensuring the cellular NUE's transmission requirement. In most cases, influences the sets of interfering links and, as a result, the optimal link rate selection. The research work in [19] and [20] studied the impact of interference on two-hop relay networks with multiple source-destination pairs and collaborative relays, which is different from our proposed approach. The main contributions of this paper are as follows:

- A standalone NB-IoT access mode in a two-tier HetNet was investigated and a new framework for interference-aware D2D relaying is proposed for 5G NB-IoT networks to improve cell-edge NUE QoS while meeting cellular NUE transmission requirements. Using the Max-max SINR approach, an optimal D2D relay was identified and selected to forward traffic from the cell-edge NUE to the NBS to improve its QoE under the co-channel interference constraints. Unlike the authors of [19] and [20], who considered co-tier interference from neighbouring sources, as well as spectrum utilization trade-off and fairness, respectively, the proposed metric reduces network overhead and interference power caused by signal relaying within the network by adaptively selecting a D2D relay candidate with the highest maximum CINR to maximize the D2D link data rate.

- To maximize the data rate of the cell-edge NUE, an optimization problem was formulated based on the cellular NUEs' transmission rate and power allocation. The Lagrangian dual approach was used to derive a closed-form power allocation expression and, as a result, formulate optimization constraints such as interference power constraints and its minimum data rate to limit any D2D relay link power above the interference threshold and below the minimum data rate. As a result, there is little interference with existing cellular NUE communications.
- Other relay selection policies were investigated, including the (a) best-worst selection scheme, (b) best harmonic relay selection scheme, and (c) Decode and Forward (DF) half-duplex relay selection scheme, as well as the D2D communication scheme in [21]. These schemes were compared in terms of data-rate maximization and interference power minimization. The proposed scheme outperforms the other relay schemes except for the D2D communication scheme owing to the high channel gains between the two communicating pairs.

5.3 RELATED WORK

Due to the variances in the degree of interference and path loss of each D2D link, matching users for optimal resource usage becomes a significant issue when using a D2D relaying network. Transmission delays may occur if the best D2D relay link is not selected under interference conditions because D2D relaying channel conditions differ for each D2D relay link. The following is some recent research on NB-IoT D2D relay networks. Using a set of D2D relays operating on a duty cycle, the researchers [189] devised two optimization problems to achieve the best-expected delivery ratio (EDR) and expected two-hop delay. [187] envisions an opportunistic crowdsensing application that uses vehicle-mounted mobile relays to provide reliable connection, transmission latency, and energy efficiency for low-cost and battery-constrained IoT sensors. The study promotes network operations throughout the human-aware IoT ecosystem. The work in [188] achieves a 10% to 15% rate improvement for investigating the potential impact of multi-user diversity of allocation strategy in the context of mutual interference between D2D NB-IoT terminals and cellular terminals transmitting in the same resource block (RB). The study [141] investigated the extension of the NB-IoT architecture to develop an optimal relay selection algorithm that minimizes the overall energy consumed within NB-IoT cells. The author employs a greedy algorithm to achieve the same result with less computational complexity. [216] proposes a novel mechanism for relay selection and optimal relay scheduling with the goal of cell edge user repetition to save energy while maintaining system performance and QoS. [217] propose a theoretical derivation and an experimental simulation to address the identified D2D relay network coverage issue using stochastic geometry. Simulation results that exclude the D2D relay validate the theoretical solution, demonstrating optimal coverage in an irregular shape. The best relay locations and performance improvements are recorded over existing schemes. None of the current research works for NB-IoT technology have considered two-tier cellular networks with D2D relaying to solve the interference problem in 5G NB-IoT networks.

Prior interference research in the NB-IoT network, on the other hand, includes studies [173], [174], [175], [127], [15], and [176] that referred to the interference as narrowband interference (NBI) and, in some cases, narrowband noise [173]. Unlike additive white Gaussian noise (AWGN), NBI has power spectrum density constraints [173]. This explains why some reviews, like [174], and [175], chose to reduce interference from this viewpoint. [127] proposed iterative sparse learning algorithms, block sparse Bayesian learning (BSBL) [15], and time-frequency domain solutions for multiple NBIs suppression algorithms for orthogonal frequency division multiplexing (OFDM) systems [176], respectively. However, the research findings did not support solutions to the challenges of low data rate, poor channel quality, spectral efficiency, and limited coverage in NB-IoT networks.

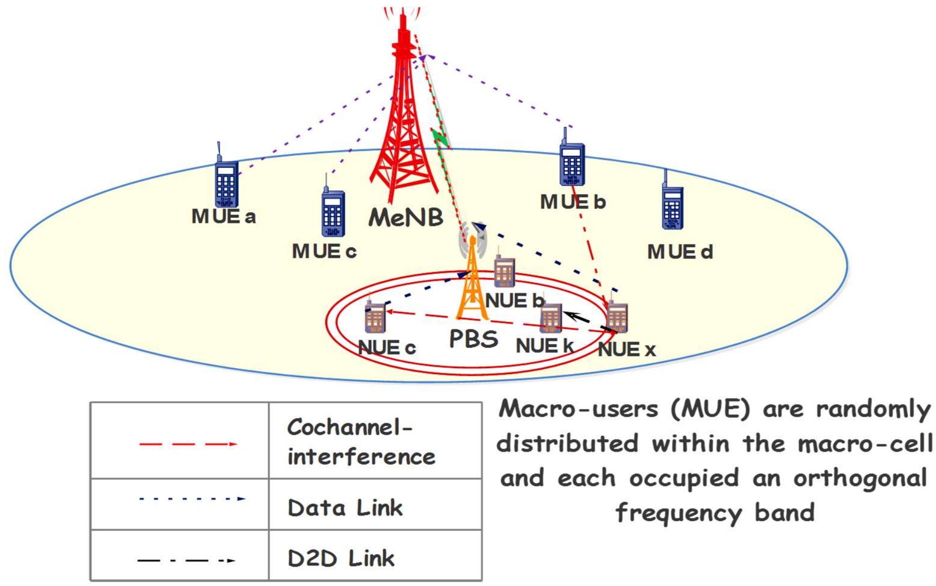


Figure 5.1. System Model.

5.4 SYSTEM MODEL

Figure 5.1 depicts an uplink channel in a 5G HeterNet with an NB-IoT network architecture deployed as an accessible environment. The NBS[1] is a pico-base station (PBS) equipped with NB-IoT technology and linked to the central macro-eNodeB (MeNB) via the X2 interface to share control information. To provide indoor/outdoor coverage for NB-IoT devices, the NBS reuses the MeNB frequency with a bandwidth of $\mathcal{W}$Hz. As a result, co-channel interference exists, which influences the channel condition of the cell edge NUE. Let M, ℓ denote the MeNB and NBS, respectively. Assume the MeNB serves n orthogonal macro-users (MUEs), while the NBS serves z orthogonal active cellular NUEs and r idle NUEs acting as D2D relays, respectively. Let $\mathcal{N}$= {1, 2,.., m}, $\mathcal{Z}$= {1,2…, z}, and $\boldsymbol{\mathcal{R}}$ ={1,2,...., r} denote corresponding sets of MUEs, active NUEs and relays (idle NUEs). We denote the selected D2D relay as κ and assume that each NUE is equip with a single antenna. To concentrate our efforts on the D2D relaying process, we assume that there is no cell-edge NUE direct link to the NBS (i.e., the source-to-destination channel is in deep fade) and that communication can only be established via D2D (two-hop) relaying by allowing proximity services. This assumption is made to buttress on the interference from D2D relays during the relaying process, whereas relay selections do not affect direct links. Furthermore, most relays in real-world systems, such as LTE-A, use two-hop transmission without a direct link [218].

5.4.1 Network model

As shown in Figure 5.1, the cellular NUEs communicate with the NBS via cellular mode. The cell-edge NUE-$\varkappa$ communicates with the NBS via relay NUE-κ (D2D communication, also known as D2D relaying), reusing the existing cellular users' uplink resources. As a result, each communication link receives interference from cellular users accessing the channel simultaneously. However, due to different channel patterns at the relay node and the NBS, the D2D communication link may differs in channel gains in separate-hops, which defines the relay node's heterogeneous environment. To avoid complex resource reuse, each D2D pair is assumed to reuse only one channel and that a channel can be reused at most by one D2D user. In addition, accommodating all transmission requests without causing significant interference is impossible. As a result, when the level of interference exceeds a certain threshold, spectral efficiency suffers and QoS requirements for individual communications are affected. Therefore, it is desirable to implement an interference control for the D2D relay underlay cellular NUEs in HetNet to achieve the desired system performance while ensuring cellular NUE QoS. The proposed two-hop D2D communication operates in two separate phases simultaneously. The cell-edge NUE-$\varkappa$ sends its data to the selected relay (NUE-κ) in the transmission phase 1, reusing the cellular NUE-c uplink resources, and will be interfered with by the cellular NUE-c as the relay node retransmit the data to the NBS in the transmission phase 2. The SINR, $\boldsymbol{\gamma_{i,j}}$ **fr**om NUE-$\varkappa$ to the relay NUE-κ and from the relay NUE-κ to the NBS, can be expressed as follows;

$$\gamma_{xk} = \frac{P_x g_{xk}}{P_c g_{cx} + I_m + \sigma^2} \text{ and } \gamma_{k\ell} = \frac{P_k g_{k\ell}}{I_m + \sigma^2} \qquad (5.1)$$

$where\ \mathrm{I}_m = \sum_n P_m g_{mx}$, is the co-channel interference generated from the MUEs as a result of resource reuse. $\mathbf{P_c}$ and $\boldsymbol{P_m}$ are the transmit power of the cellular NUEs, and MUEs respectively. Assuming all the wireless channels exhibit Rayleigh fading, the channel models for all links employ 3GPP TR 38.901 pathloss model [201] and consider the large-scale and small-scale fading effects of the terminal i to terminal j. Therefore, the channel coefficient, $\boldsymbol{g}_{\varkappa,\kappa}$ between the cell-edge NUE-$\varkappa$ and the relay NUE-κ can be modelled as;

$$g_{x,k} = Jh_{x,k}B_{x,k}D_{x,k}^{-a} \quad (5.2)$$

where J is a pathloss constant, $\boldsymbol{h}_{\varkappa,\kappa}$ is the large-scale-fading gain with exponentially distributed unit mean, $\boldsymbol{\mathfrak{B}}_{\varkappa,\kappa}$ is the small-scale fading gain with log-normal distribution, a is the pathloss exponent and $\boldsymbol{\mathcal{D}}_{\varkappa,\kappa}$ is the distance between the cell-edge NUE-$\varkappa$ and the relay NUE-κ. Similarly, we denote the channel links, $\boldsymbol{g}_{\kappa,\ell}$, $\boldsymbol{g}_{c,x}$ and $\boldsymbol{g}_{m,x}$ as the channel from the relay NUE-κ to the PBS ℓ, the cellular NUE-c to the cell-edge NUE-$\varkappa$, and from the MUEs to the cell-edge NUE-$\varkappa$, respectively. The $\boldsymbol{\sigma^2}$ is assumed to be the additive white Gaussian noise (AWGN) in different channels (i.e., as circularly symmetric complex Gaussian noise and subject to $\boldsymbol{\mathcal{C}\sigma^2}(0,\boldsymbol{\sigma^2})$). Throughout the relay selection process, the channels are assumed to be static and precisely estimated. The source transmit power is assumed to be controlled while the transmit power at the relay to NBS is fixed. The reason for this is to conserve NUE-$\varkappa$ energy while minimizing interference. The proposed system model in this chapter differs significantly from the single-cell studies in [19], [20]. The Decode and forward (DF) protocol is used. Assuming that the relay NUE-κ correctly decodes the information and that the NBS only receives information in transmission phase 2 of each transmission cycle, the joint SINR, $\boldsymbol{\gamma_{x\kappa\ell}}$, at the NBS can be expressed as follows:

$$\gamma_{xk\ell} = min\{\gamma_{xk}, \gamma_{k\ell}\} \quad (5.3)$$

Thus, the D2D relaying link's instantaneous data rate, $\boldsymbol{\mathcal{R}_{\varkappa\kappa\ell}}$, can be expressed as;

$$R_{xk\ell} = \sum_{z}^{Z}\sum_{r}^{R} \log_2\left(1+\gamma_{xk\ell}\right) \quad (5.4)$$

Due to the HetNet nature of the system, co-channel interference is experienced by both

[1]NBS uses single-carrier frequency division multiple access (SC-FDMA) as uplink and downlink transmission schemes, thus impose no intra-cell interference nor near-far effects. SC-FDMA has the advantage of a single carrier multiplexing and a lower Peak-to-average Power Ratio when compared to OFDMA [219], [220].

MUEs and NUEs, as well as interference to the cellular NUE due to spectrum resource sharing with the D2D relay link when receiving its expected signals caused by NUE-$\varkappa$. The magnitude of the interference, however, varies depending on the transmission phase. The NUE-$\varkappa$ will cause additional interference to the cellular NUEs in the first transmission phase, from the NUE-$\varkappa$ to the relay NUE-κ, in addition to the co-channel interference within the system, whereas in the second transmission phase, from the relay NUE-κ to the NBS, there is only the co-channel interference. As a result, the SINR received by the cellular NUEs at the NBS will be

$$\gamma_{c\ell} = \begin{cases} \dfrac{P_c g_{c\ell}}{P_x g_{cx} + I_m + \sigma^2}, \; \textit{first phase} \\ \dfrac{P_c g_{c\ell}}{I_m + \sigma^2}, \; \textit{second phase} \end{cases} \tag{5.5}$$

The cellular link's instantaneous data rate from NUE-c to the NBS, $\boldsymbol{\mathcal{R}_{c\ell}}$, can be expressed as:

$$R_{c\ell} = \log_2\left(1 + \gamma_{c\ell}\right) \tag{5.6}$$

5.5 PROBLEM FORMULATION

Given the transmission priority of NUEs under interference control, the QoS satisfaction of the D2D relaying link can be maximized by obtaining the optimal transmit power at which the source (NUE-$\varkappa$) can transmit. As a result, the power optimization model can be express based on the data-rate as follows:

$$P1: \max_{P_x^{opt}} \left(R_{xk\ell}\right) \tag{5.7}$$

$$s.t. \begin{cases} P_x \le P_{\max} \\ R_{c\ell} \ge R_{c-min} \\ I_t \ge \sum\limits_{z \in Z} P_x^{opt} g_{cx} \\ R_{xk\ell} \ge R_{min} \end{cases} \tag{5.8}$$

$$where \; I_t = \sum_{z} \left(P_c g_{cx} + I_m\right)$$

where $\boldsymbol{P}_{\mathbf{max}}$ is the maximum transmit power at the source, $\boldsymbol{\mathcal{R}}_{\boldsymbol{c-min}}$ is the minimum data-rate allowed for the cellular uplinks, $\boldsymbol{P}_{\boldsymbol{\varkappa}}\boldsymbol{g}_{\boldsymbol{c\kappa}}$ is the interference power at the source that should not be greater than the total generated interference, $\boldsymbol{I}_{\boldsymbol{t}}$, within the HetNet and $\boldsymbol{\mathcal{R}}_{\boldsymbol{min}}$ is the minimum achievable data-rate by the relay to successfully decode the signal. The total generated interference, $\boldsymbol{I}_{\boldsymbol{t}}$, is calculated for each NUE based on the minimum acceptable SINR received at the PBS. The computation allowed resources to be allocated to the D2D link since the NUEs have equal transmit powers, $\mathbf{P}_{\boldsymbol{c}}$.

5.5.1 Cellular User Transmit Power

Deducing the optimization problem P1, the objective function was discovered to be a reducing function with respect to P_c. Because the D2D relaying strategy has a greater impact in the first phase. As a result, to obtain the maximum $\mathcal{R}_{\varkappa\kappa\ell}$, P_c need to be minimized, i.e.

$$R_{c-\min} = \sum_{z}^{Z} \log_2\left(1 + \frac{P_c^z g_{c\ell}}{P_x g_{cx} + I_m + \sigma^2}\right) \qquad (5.9)$$

However, equation (5.9) includes variables P_m and P_x in addition to variable P_c. To simplify power control on the NUE-c, the potential maximum interference to the BS caused by NUE-$\varkappa$ and I_m is considered to justifies the resources reuse scheme, when calculating the P_{c-opt}. As a result, the expression (5.8) can be rewritten as follows:

$$R_{c-\min} = \sum_{z}^{Z} \log_2\left(1 + \frac{P_{c-opt}^z g_{c\ell}}{max\left\{P_{max} g_{xc} + I_m\right\} + \sigma^2}\right) \qquad (5.10)$$

The optimal transmit power at NUE-c can be solve from (5.9) as;

$$P_{c-opt}^z = \left(\frac{2^{R_{c-\min}} - 1}{g_{c\ell}}\right)\left(max\left\{\sum_z P_x g_{xc} + I_m\right\} + \sigma^2\right) \quad (5.11)$$

For the purpose of further analysis, the following is expressed as;

$$\eta_{xk} = \frac{g_{xk}}{P_{c-opt}^z g_{cx} + I_m + \sigma^2} \text{ and } \eta_{k\ell} = \frac{g_{k\ell}}{\mathrm{I}_m + \sigma^2} \quad (5.12)$$

where $\eta_{\varkappa\kappa}$ and $\eta_{\kappa\ell}$ are the channel-to-interference plus noise ratio from the NUEs to the relay and from the relay to the NBS, respectively.

5.5.2 Optimization Problem Transformation

The transmit power of the cellular NUEs is calculated in (5.11). As a result, the optimal transmit power $\mathbf{P}_{\boldsymbol{\kappa}}^{\mathbf{opt}}$, at the cell-edge NUR-$\varkappa$ must be determined. The optimization problem P1 can be described following the preposition below based on the analyses in section 5.4.1.

Preposition 1: $\gamma_{xk\ell} = \min(\gamma_{xk}, \gamma_{k\ell}) = \gamma_{xk}$. Assuming that $P_{\varkappa}\eta_{\varkappa\kappa} \leq P_{\kappa}\eta_{\kappa\ell}$, the objective function in P1 can be rewritten as P2.

The relay optimization problem $\mathcal{P}2$ is combinatorial, non-linear, and NP-hard due to resource sharing. As a result, it cannot be determined in polynomial time. From 5.13 (b), the interference generated by the D2D link is solved by the NUE's previous power allocation and the interference channel gain between the cellular NUE and the cell-edge NUE. Based on this information, the MeNB computes the correlation between the interference generated

$$P2 : \max_{P_x^{opt}} (R_{xk\ell}) \qquad (5.13)$$

$$s.t. \begin{cases} P_x \leq P_{\max} & (5.13a) \\ I_t \geq \sum_{z \in Z} P_x g_{cx} & (5.13b) \\ R_{xk\ell} \geq R_{min} & (5.13c) \\ P_x \geq 0 & (5.13d) \end{cases}$$

$$where\ I_t = \sum_{z} \left(P_{c-opt}^{z} g_{cx} + I_m \right)$$

within the NBS and the total generated interference I_t, in the system. The NBS used the correlated results for power optimization at the cell-edge NUE. The interference power constraint in 5.13 (b) is to control the interference generated by the D2D relaying within the NBS network.

Preposition 2: The optimization problem $\mathcal{P}2$ is a concave problem as proofed in the appendix C.

The dual problem of P2 can be solve using the optimization structure resulting from the concave maximization problem because the difference between the optimal solution to P2 and the solution to the dual problem is zero according to the principle of strong duality [221], [222]. As a result, we apply the Lagrangian function to P2 in the following manner:

$$L(\lambda,\mu,\phi,P_x) = \sum_{z\in Z}\sum_{r\in R}\log_2\left(1+\frac{P_x g_{xk}}{P^z_{c-opt} g_{cx} + I_m + \sigma^2}\right)$$
$$+\lambda\left(I_t - \sum_{z\in Z} P_x g_{xc}\right) + \mu\left(P_{max} - P_x\right) + \sum_{r\in R_i}\phi P_{x_i} \qquad (5.14)$$

$$= \sum_{z\in Z}\sum_{r\in R}\left[\log_2\left(\beta + P_x\right) + \alpha\right] + \lambda\left(I_t - \sum_{r\in R}\varsigma P_x\right) +$$
$$\mu\left(P_{max} - \sum_{r\in R} P_x\right) + \sum_{r\in R}\phi P_x \qquad (5.15)$$

where $\alpha = \log_2\left(\frac{\mathrm{g_{xk}}}{\mathrm{I_t} + \sigma^2}\right)$, $\beta = \frac{\mathrm{I_t} + \sigma^2}{\mathrm{g_{xk}}}$, $\varsigma = \sum_{z\in Z}\mathrm{g_{xc}}$ & $\mathrm{I_t} = \left(\sum_{z\in Z}\mathrm{P^z_{c-opt}g_{cx}} + \mathrm{I_m}\right)$. Also, λ, μ, ϕ are the Lagrangian multipliers. To solve (5.15), the KKT conditions is applied. The first-order partial derivative of P_x is expressed as;

$$\frac{\partial L(\lambda,\mu,\phi,P_x)}{\partial P_x} = \frac{1}{\ln 2}\frac{1}{\beta + P_x} - \lambda\varsigma - \mu + \phi \qquad (5.16)$$

It is clear from (5.16) that ϕ is a slack variable vector that can be discarded [223]. Thus, P3 can be obtained by substituting (5.16) into (5.14) as;

$$\frac{\partial L(\lambda,\mu,\phi,P_x)}{\partial P_x} = 0, \;\therefore\; \mathrm{P}_x = \frac{1}{\ln 2}\frac{1}{\lambda\varsigma + \mu} - \beta \qquad (5.17)$$

$$\begin{aligned} P3: min\ \Psi(\lambda,\mu) &= min \max_{P_x} L(\lambda,\mu,P_x) \\ &= \min_{\lambda,\mu} \sum_{z\in Z}\sum_{r\in R}\left[-\log_2(\mu+\lambda\varsigma)+\beta(\mu+\lambda\varsigma)\right]+\lambda I_t+\mu P_{max} \\ &+\sum_{z\in Z}\left[\log_2\left(\frac{1}{\ln 2}\right)-\left(\frac{1}{\ln 2}\right)+\alpha\right] \\ &\text{s.t. } \lambda\ge 0,\ \mu\ge 0 \end{aligned} \quad (5.18)$$

Due to the properties of the objective function, P3 is identify as a convex optimization problem (i.e., concave minimization function with convex constraints). The KKT conditions, can be used to solve P3 while ignoring the constraints of (5.18). At the same, the minimization function in (5.18) can be used to validate the obtained solution. The newton Raphson method [224] is one method for solving an objective function with no constraints.

Therefore, the optimal solution to (5.18) can be considered under the partial derivative of (5.18) in two cases namely; $\boldsymbol{\mu = 0}$ $\boldsymbol{or}$ $\boldsymbol{\lambda = 0}$.

Case 1: when $\boldsymbol{\lambda = 0}$, then $\boldsymbol{\psi(\lambda,\mu) = \psi(0,\mu)}$. Hence, solving $\frac{\delta\boldsymbol{\psi(0,\mu)}}{\delta\boldsymbol{\mu}} = \boldsymbol{0}$ and Optimal $\boldsymbol{\mu}^*$ is obtained as;

$$\mu^* = \frac{1}{\ln 2}\frac{1}{\sum_{z\in Z}\sum_{r\in R}\beta+\mathrm{P}_{\max}} \quad (5.19)$$

Case 2: when $\boldsymbol{\mu = 0}$, then $\boldsymbol{\psi(\lambda,\mu) = \psi(\lambda,0)}$. Hence, solving $\frac{\delta\boldsymbol{\psi(\lambda,0)}}{\delta\boldsymbol{\lambda}} = \boldsymbol{0}$ and Optimal $\boldsymbol{\lambda}^*$ is obtained as;

$$\lambda^* = \frac{1}{\ln 2}\frac{1}{\mathrm{I}_t+\sum_{z\in Z}\sum_{r\in R}\beta\varsigma} \quad (5.20)$$

To obtain the optimal power $P_{\varkappa}^{opt}$, [200] substitute the optimal μ^* and λ^* values into (17). Because ϕ was discarded, there is need to ensure that the optimal power for all D2D links is greater than zero (i.e. $P_x^{opt^*} \ge 0, \forall r \in R$). As a result, if $P_x^{opt^*} \ge 0, \forall r \in R$, the optimal power is the solution to P2, otherwise we must discard those $P_{\varkappa}^{opt} < 0$ values and solve P3 again until a solution for $P_{x}^{opt^*} \geq 0, \forall r \in R$ is obtain. Table 5.1 present the power optimization algorithm.

Table 5.1. Optimal Power Optimization Algorithm for D2D relaying scheme

Algorithm 1: *Optimal power allocation for cell-edge NUE*

1. *Initialize:* $\boldsymbol{\lambda = 1, \mu = 1}$,
2. *Obtain* $\boldsymbol{P_x}$ *using equation (5.17)*
3. *If* $\boldsymbol{P_x \geq 0}, \forall \boldsymbol{r} \in \boldsymbol{R}, \forall \boldsymbol{z} \in \boldsymbol{Z}$, *then*
4. $\boldsymbol{P_{\varkappa}^{opt} = P_x}$
5. $\boldsymbol{else}$
6. *While* $\boldsymbol{P_x \leq 0, do}$
7. *Solve for P3 (dual Problem) using Newton Raphson Method (NM) with no constraint in eqtn (5.18)*
8. *Consider the two cases scenario in eqtn (5.19) & (5.20)*
9. *If* $\boldsymbol{\lambda = 0}$, *obtain* $\boldsymbol{\mu}^*$ *in eqtn (5.19)*
10. *end*
11. *If* $\boldsymbol{\mu = 0}$, *obtain* $\boldsymbol{\lambda}^*$ *in eqtn (5.20)*
12. *end*
13. *Update* $\boldsymbol{P_x}$ *in eqtn (5.17) using the value of* $\boldsymbol{\mu}^*$ & $\boldsymbol{\lambda}^*$
14. *If* $\boldsymbol{P_x \geq 0}, \forall \boldsymbol{r} \in \boldsymbol{R}, \forall \boldsymbol{z} \in \boldsymbol{Z}$,
15. *Break*
16. *else*
17. *Find the D2D relay* $\boldsymbol{r_{\varkappa}^*}$ *with minimum Power*
18. $\boldsymbol{P_{\varkappa}^{r_{\varkappa}^*} = min(P_x)}$
19. *end*

5.6 RELAY SELECTION STRATEGY WITH INTERFERENCE

This section describes the proposed relay selection scheme and some single relay selection schemes from the literature. The relay node is assumed to uses a fixed allocated transmit power from the NBS and only optimizes the transmit power at the source to achieve full diversity under interference power control. The following are the relaying schemes:

5.6.1 Max-max SINR Best Relay Selection

In dual-hop network, each relay has two channels; the channel from the source-to-relay and the channel from the relay-to-base station. In this chapter, this scheme is adopted to relay the source NUE-$\varkappa$ information to the NBS via the selected relay NUE-κ. In [225], [226], the relay with the maximum signal-to-noise-ratio (SNR) is selected. i.e., $\boldsymbol{SNR_{x,k} = \max(\gamma_{xk})}$,

$\boldsymbol{SNR_{k\ell}} = \boldsymbol{max(\gamma_{k\ell})}$ for both source NUE-$\varkappa$ to relay and relay to NBS. However, we slightly modify the selection scheme to suit our model as;

$$\kappa = argmax\left(\gamma_{xk_i}, \gamma_{k\ell_i}\right), \text{ i} \in \Re \qquad (5.21)$$

$$where\ \gamma_{xk_i} = max\left(P_{x_i}^{opt}\eta_{xk,i}\right) \text{ and } \gamma_{k\ell_i} = max\left(P_k\eta_{k\ell,i}\right)$$

5.6.2 Harmonic Mean Selection

According to [227], [228], the relay with the largest harmonic mean is selected. i.e., $\left(|\boldsymbol{h_i}|^{-2} + |\boldsymbol{g_j}|^{-2}\right)$. Therefore, the selection scheme is modified and assumes all the nodes within the NBS have equal transmit power (i.e., $\boldsymbol{P_\kappa} = \boldsymbol{P_\varkappa} = \boldsymbol{P}$) as follows;

$$\kappa = argmax\left\{P\left(\frac{\eta_{xk,i} + \eta_{k\ell,i}}{\eta_{xk,i} * \eta_{k\ell,i}}\right)\right\}, \text{ i} \in \Re \quad (5.22)$$

5.6.3 Best Worse channel Approach

In [227], the selected relay is the best worse channel given as; $\min\left(|h_i|^2, |g_j|^2\right)$. But here, the selection function is slightly modified to suit the purpose of this work as;

$$\kappa = \max\left\{\min\left(P_{x_i}\eta_{xk,i}, P_k\eta_{k\ell,i}\right)\right\}, \text{ i} \in \Re \qquad (5.23)$$

5.6.4 Half-duplex Relay Selection Scheme

Half-duplex (HD) relaying is used to compare the performance of the other relaying schemes discussed above. However, any self-interference is eliminated, and the resources used are only half that of the Full Duplex transmission mode. As a result, except for co-channel interference from the MeNB as a result of resource sharing, no interference exists within NBS. The goal here is to maximize the throughput of the cell edge NUE while satisfying MeNB's reuse interference constraint. As a result, the relay selection scheme is as follows:

$$\kappa_i = \min\left(P_{x_i}^{opt}\eta_{xk,i^*} + P_k\eta_{k\ell,i^*}\right),\ \mathrm{i} \in \Re \qquad (5.24)$$

$$\kappa^* = \max\left(\kappa_i\right),\ \mathrm{i} \in \Re$$

$$where \quad \eta_{xki^*} = \frac{g_{xki}}{I_m + \sigma^2} \text{ and } \eta_{k\ell i^*} = \frac{g_{k\ell i}}{\mathrm{I}_m + \sigma^2}$$

The data rate of the D2D link is obtained under the interference power constraint after selecting the optimal relay based on the schemes presented above. The interference constraint is used to create flexibility and dynamism, and to redistribute the total generated interference across all paired D2D links to achieve fairness, reduce complexity, and avoid discriminating services among all users with different QoS. Because all of the NUEs are distributed at random within the NBS, the interference constraint becomes necessary. The transmit power from the source varies depending on the location and position of the relays, influencing the data rate of the D2D link. Table 5.2 presents the algorithm of the interference-aware D2D relaying strategy for 5G NB-IoT network QoS improvement for cell-edge NUE.

Table 5.2. Algorithm for Interference-aware D2D relaying strategy for 5G NB-IoT network QoS improvement for cell edge NUE

Algorithm 2: *Optimal D2D Relaying Strategy for cell-edge NUE Improvement in 5NB-IoT Network*

1. *initialize* $\boldsymbol{x}, \boldsymbol{\mathcal{N}}, \boldsymbol{\mathcal{Z}}, \boldsymbol{\mathcal{R}}, \boldsymbol{P_{max}}, \boldsymbol{I_m}$
2. *for* $\boldsymbol{a} = \mathbf{1}{:}\,\boldsymbol{x}$
3. *for* $\boldsymbol{i} = \mathbf{1}{:}\,\boldsymbol{\mathcal{Z}}$ $\forall \boldsymbol{z} \epsilon \boldsymbol{\mathcal{Z}}$ *do*
4. *Calculate* $\boldsymbol{P_{c-opt}^{z}}$ $\forall \boldsymbol{z} \epsilon \boldsymbol{\mathcal{Z}}$ *using eqtn (5.11)*
5. *end*
6. *for* $\boldsymbol{\ell} = \mathbf{1}{:}\,\boldsymbol{\mathcal{R}}$ $\forall \boldsymbol{r} \epsilon \boldsymbol{\mathcal{R}}$ *do*
7. *Compute* $\boldsymbol{\eta_{xk}}$ *and* $\boldsymbol{\eta_{k\ell}}$ $\forall \boldsymbol{r} \epsilon \boldsymbol{\mathcal{R}}$ *using eqtn (5.12)*
8. *solve the power allocation problem in (5.17) using algorithm 1 in Table 1.*
9. *Solve the relay selection problem using the schemes in section IV.*
10. *end*
11. *Compute the interference Threshold in (5.13a)*
12. *Calculate* $\boldsymbol{\mathcal{R}_{xk\ell}}$ *using eqtn (5.4)*
13. *If* $\boldsymbol{P_x^{opt}} \boldsymbol{g_{xc}} \geq \boldsymbol{I_t}$ *and* $\boldsymbol{\mathcal{R}_{xk\ell}} \leq \boldsymbol{\mathcal{R}_{min}}$
14. $\boldsymbol{\mathcal{R}_{xk\ell}} = \mathbf{0}$
15. *end if*
16. *end.*

The proposed algorithm's complexity is expressed in big O notation. The algorithm has three steps. The first step calculates the transmit power of cellular NUEs, P_{c-op}^{z} as well as the channel-to-interference-plus-noise ratio (CINR) for the cell-edge NUE, x, iterations, and the complexity is $O|x\mathcal{Z}|$. The transmit power of the cell-edge NUE x to the relays, $\mathcal{R}$ is calculated in the second step. Though the complexity of the power computation cannot be expressed directly due to first and second-order partial differentiation, however the Newton-Raphson method iteration times can be expressed as $O|x\mathcal{Z}\mathcal{R}|$. The third step is the sum-rate complexity, which is expressed as $O|x\mathcal{R}|$. The overall complexity can be expressed as $O|x\mathcal{Z} + x\mathcal{Z}\mathcal{R} + x\mathcal{R}|$.

5.7 CHAPTER SUMMARY

This chapter describes an interference-aware D2D relaying strategy for 5G NB-IoT network QoS improvement for cell edge users to address the issues of long-distance transmission, delay, poor spectral efficiency, and low data rate. As a result, network performance is improved by increasing spectrum efficiency and network data rate. The proposed scheme is unique and incorporates a Max-max SINR scheme to select the best D2D relay to forward the cell edge NUE to the NBS. During relaying, network-generated interference increases in addition to the generated co-channel interference by the NBS's frequency reuse. Interference can reduce individual SINR of cellular NUEs, limiting the performance of the 5G NB-IoT system. A source transmit power (cell-edge NUE) is optimized using Lagrange method, and an interference power constraint that regulates the D2D link interference power was considered with a fixed D2D relay's transmit power to achieve an efficient system. The best D2D relay with the highest channel-to-interference plus noise ratio (CINR) from the source to the NBS is selected to forward the source information. The proposed solution is flexible and dynamic, adapting to every network change to ensure fairness and indiscriminate service within the network. The proposed scheme's computation is simple, requiring little energy and time.

CHAPTER 6 PERFORMANCE ANALYSIS AND EVALUATION

6.1 CHAPTER OUTLINE

This chapter evaluates and analyses the network performance of the proposed interference-aware D2D relaying strategy for 5G NB-IoT networks to improve the QoS of the cell edge user. As described in Chapter 5, the performance of the proposed scheme is evaluated based on the relay selection scheme mentioned and the proposed scheme discussed in Chapter 3. The performance metrics considered were data rate and the CDF, as utilized in Chapter 4. This chapter's work is currently submitted to a journal and under peer review. The Chapter is organized as follows: Section 6.2 presents the system configuration and parameters. Section 6.3 presents the simulation results of the proposed system with the four (4) other schemes including the D2D communication scheme proposed in Chapter. Section 6.4 discusses the obtained results in detail, and Section 6.5 summarizes the Chapter.

6.2 SYSTEM CONFIGURATION AND PARAMETERS

In this section, consider a single NBS with a radio R = 100m, randomly and uniformly distributed NUEs (active and idle NUES), and a randomly placed NUE at the cell edge at a distance slightly beyond 100m, as shown in Figure 5.1. The NBS provides a stand-alone NB-IoT solution to the growing number of IoT devices in a heterogeneous cell where the MeNB and NBSs share resources, resulting in co-channel interference that affects signal reception at the cell edge. A D2D relay strategy is established between the cell-edge NUE and the NBS to improve network data rate while ensuring the cellular NUEs QoS under interference power constraints. The simulation parameters used are summarized in Table 6.1.

TABLE 6.1. Simulation Parameters Used

Parameter	Value
Carrier frequency	2GHz
Bandwidth	180kHz
NBS Cell Radius	100m
Number of Active NUEs, $\mathcal{Z}$	30
Number of idle NUEs, $\boldsymbol{\mathcal{R}}$	30
Number of Active MUEs, $\mathcal{N}$	5
Minimum Throughput, $\mathcal{R}_{min}$	1
Noise Power, σ^2	-112
NUE Antenna Gain	5dBi
Distance between MeNB and NBS	350m
Max. NUE Transmit Power	20dBm
Max. MUE Transmit Power	23dBm
Pathloss Model	3GPP TR. 38.901
Reference Distance	10m
Reference Power	30dB
Path loss exponent	2
Multipath fading	Rayleigh fading
Shadowing for NUE link	Log normal distr. with standard

6.3 SYSTEM RESULTS

This section presents the performance evaluation of the proposed algorithm for interference-aware D2D relaying strategy of 5G NB-IoT network QoS improvement at the cell edge and the simulation results.

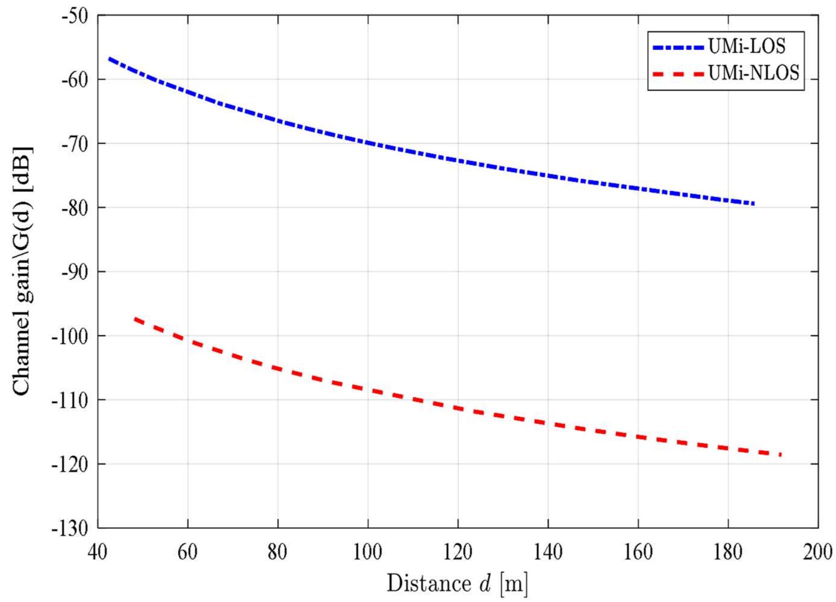


Figure 6.1. Channel gain Vs Distance

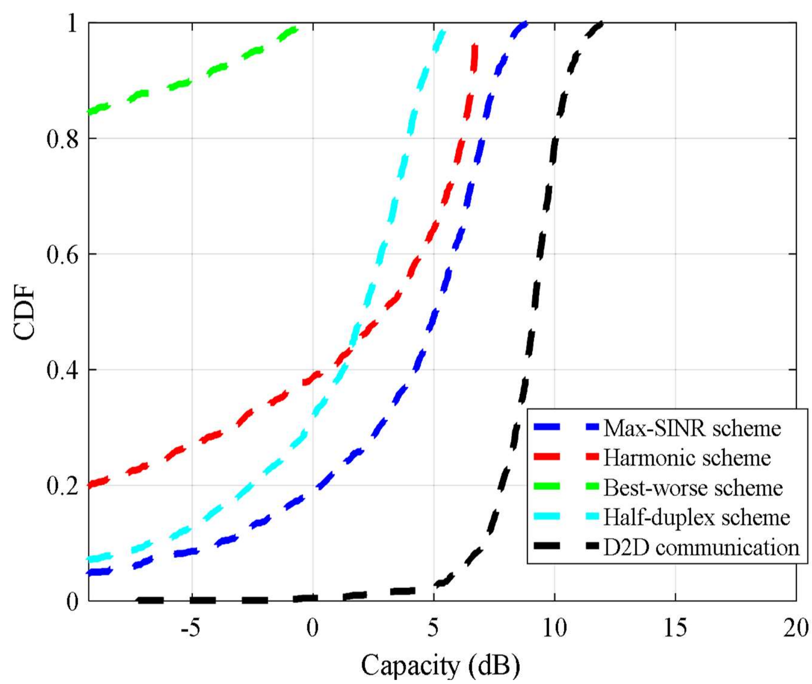


Figure 6.2. The CDF of Cell-edge NUE's capacity with four other schemes including the D2D communications.

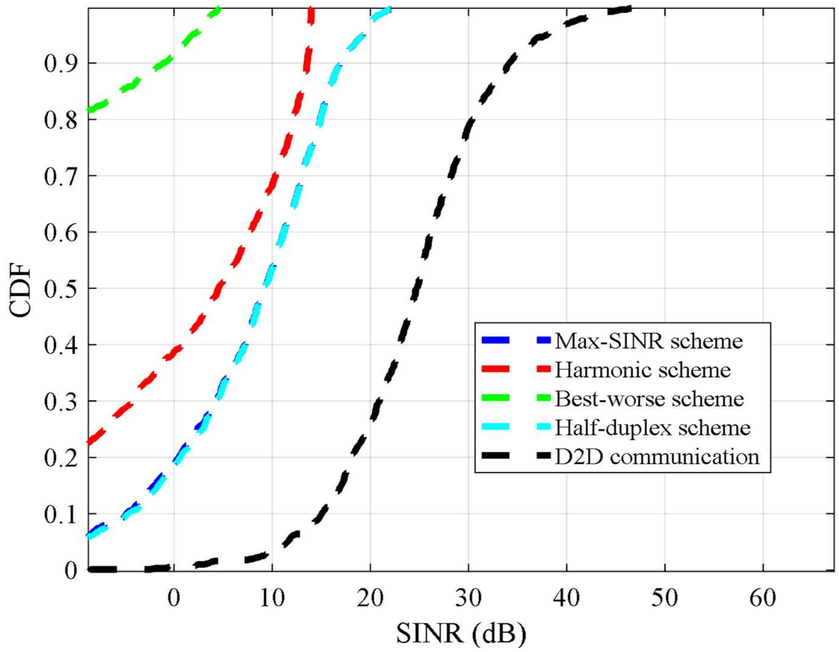


Figure 6.3. The SINR's CDF of the proposed algorithm and the four (4) other schemes including the D2D communications.

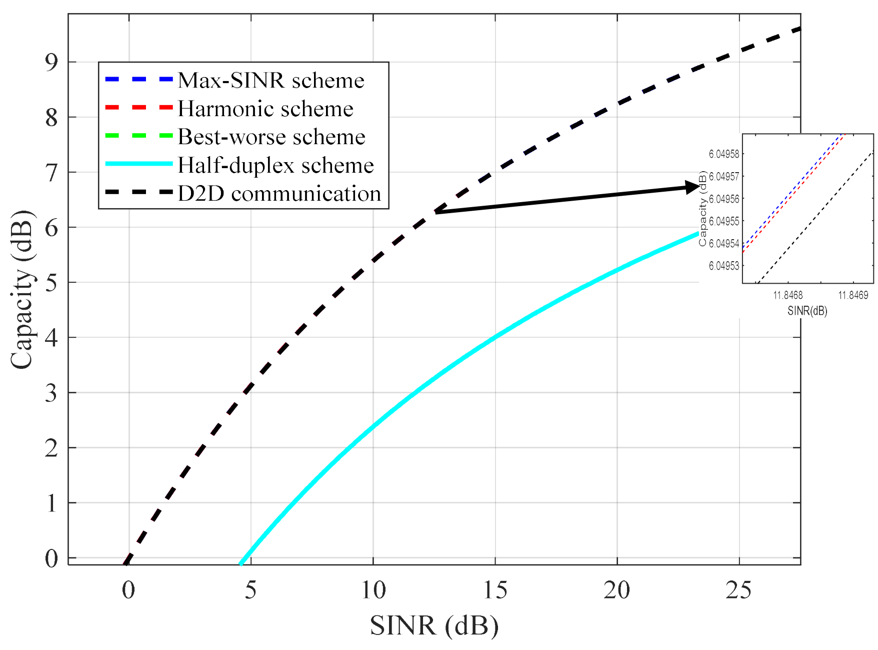


Figure 6.4. The Capacity against SINR for the proposed algorithm and the four other schemes including the D2D communication scheme.

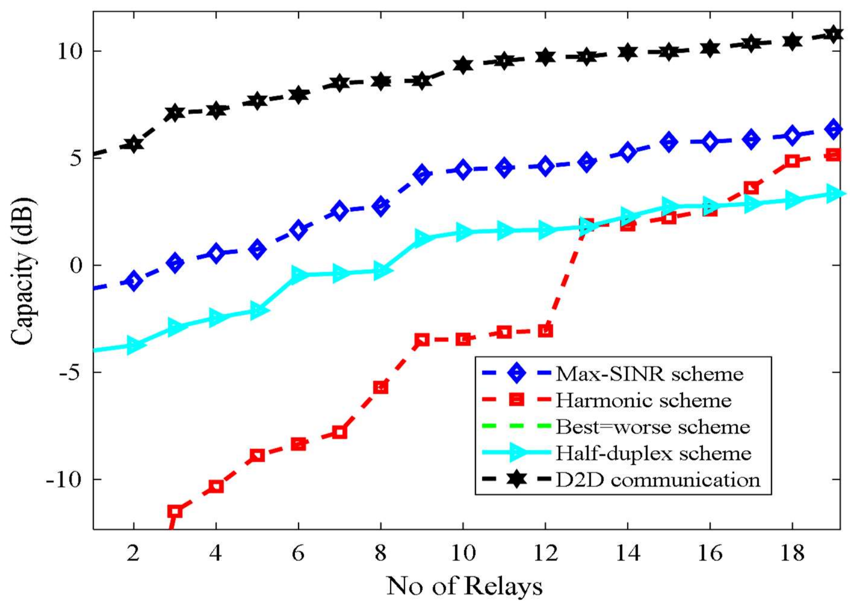
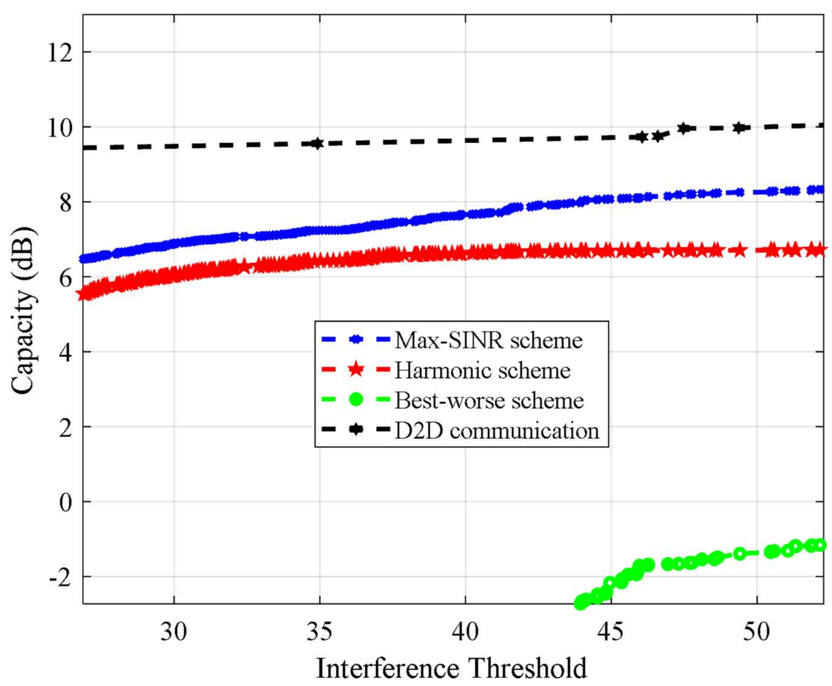
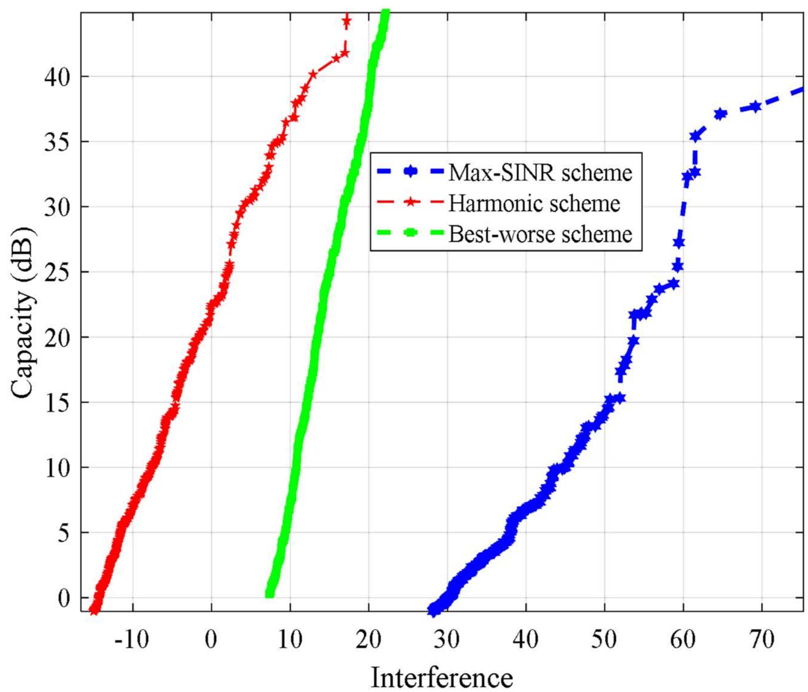


Figure 6.5. Capacity performance against the number of relays.

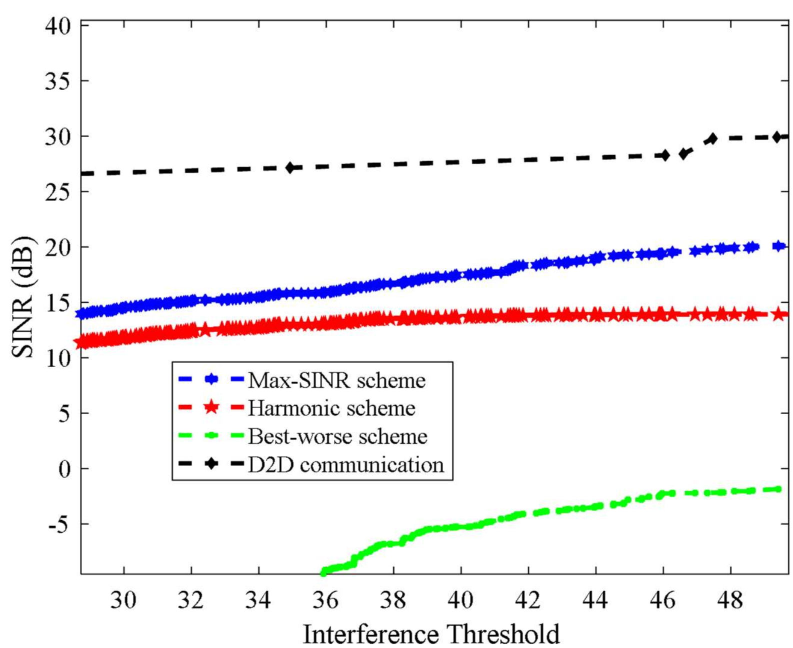


(a)



(b)

Figure 6.6. The Capacity against the (a) Interference Threshold and (b) the interference Power.



(a)

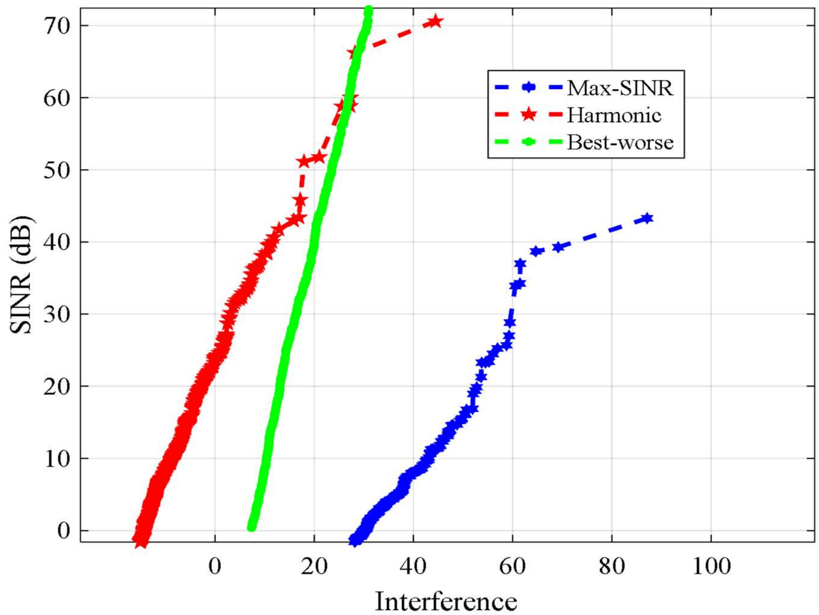


Figure 6.7. The SINR against the (a) Interference Threshold and (b) Interference Power.

6.3.1 DISCUSSION OF RESULTS

The performance of the proposed algorithm is validated using the mentioned relay schemes and the algorithm proposed in [21], which compares the performance of a D2D communication scheme underlaying cellular networks to that of the D2D relaying technique. Figure 6.1 depicts the line of sight (LOS) and non-light of sight (NLOS) signal reception of cellular NUEs with the NBS using 3GPP TR. 38.901 [201] version of Urban Microcell (UMi) for distances greater than 10m. To better understand the signal variation within the NBS, we include shadowing to show the channel gain g as a function of distance d. The typical signal reception value for LOS and NLOS generally ranges from -70 to 110dB [205].

Two metrics are used: the cumulative distribution function (CDF) and the data rate (and will interchangeably be referred to as the capacity in some instances) to evaluate the performance of the proposed algorithm. Figure 6.2 depicts the capacity CDF of the proposed algorithm (max-SINR scheme) alongside four (4) other techniques, including the D2D communication scheme. The proposed algorithm outperforms the other three (3) relay schemes (i.e., best-worst, harmonic, and the half-duplex scheme), except for the D2D communication scheme. When compared to the 19.45% harmonic scheme, and the 17.26% half-duplex scheme, the proposed algorithm improves the capacity of the cell-edge NUE by 27.51%. On the other hand, D2D communication outperforms the proposed technique by 23%. Furthermore, at zero capacity, both the half-duplex and the harmonic scheme lost 40% of the D2D relay links to interference as against the 20% of D2D relay links lost in the proposed technique. The CDF plots in Figure 6.2 have proven the efficacy of our proposed algorithm.

In Figure 6.3, the SINR's CDF of the proposed algorithm and four other schemes, including the D2D communication strategy, are illustrated. The proposed algorithm outperforms the harmonic and the best-worst schemes while maintaining an SINR value that is approximately equal to the half-duplex technique. However, as shown in Figure 6.2, the D2D communication scheme outperforms the proposed algorithm. The proposed algorithm achieves 21.27%, almost identical to the half-duplex scheme's 21.23%. The proposed algorithm outperforms the best-worst and harmonic techniques by 81.27% and 40.29%, respectively. The D2D communication scheme, on the other hand, outperforms all the D2D relay schemes. The reason for the D2D communication's performance could be that the relay schemes are optimal in interference-free isolated networks but perform poorly in interference-limited networks. The system SINR improved when an interference power constraint was implemented to decouple the signal from the induced interference.

Figure 6.4 illustrates the plot of the four (4) D2D relay schemes' capacities and the D2D communication scheme against the SINR. On the indication point, the proposed algorithm outperforms the harmonic scheme, best-worst scheme, half-duplex scheme, and the D2D communication scheme. However, as observed in the open window of the indication point, both the proposed algorithm, the harmonic technique, and the D2D communication scheme have an approximate equal performance and outperform the half-duplex scheme's performance. The plot shows a corresponding increase in capacity as the SINR of all the techniques increases.

In Figure 6.5, the D2D relay's capacity is plotted against the number of relays for the four schemes, and the D2D communication scheme. As the number of relays increases, the proposed algorithm (max-SINR technique) outperforms the other three schemes (i.e., harmonic, half-duplex, and the best-worst scheme), which improves the link capacity. However, the D2D communication achieved 41.40% higher than the proposed algorithm, while the proposed algorithm achieved 14.10% and 47.19% higher than the harmonic and half-duplex techniques, respectively. The reason for the D2D communication scheme's performance could be that there is a high channel gain between the two D2D communicating sets, as opposed to the D2D relaying scheme, where signals may be delayed or dropped depending on the condition of the relay device. Again, in two-hop communication, the first-hop is always the bottleneck. As a result, the difference between the first-hop channel gain and the second-hop channel gain will always have influence on the system capacity.

Figure 6.6 (a and b) show the capacity versus the interference threshold and the interference power for the proposed algorithm, two other relaying schemes (i.e., harmonic and Best-worse scheme), and the D2D communication scheme, respectively. In Figure 6.6 (a), the D2D communication scheme outperforms the proposed scheme by 20.46%, whereas the proposed scheme outperforms the harmonic scheme by 22.27% when an interference threshold is applied. However, as the interference threshold increases, the capacity of both the D2D relay link and the D2D pair link increases at a constant rate except for the best-worst relaying scheme, which degrades. It implies that as the network dynamicity changed, the cell-edge NUE was able to find a D2D relay with a higher SINR requirement, which leads to full diversity benefit, thereby increasing the D2D relay link's capacity. In Figure 6.6 (b), as the capacity increases, so does the interference power. Due to poor channel quality and the desire achieve a data rate higher than the minimum data rate, the best-worst scheme transmits with more interference power than the other deployed schemes. This explains why the best-worst scheme's signal was lost when the interference threshold was applied. The proposed scheme, the harmonic scheme, and the D2D communication scheme, on the other hand, adjust their transmit power as the SINR changes to achieve a data rate higher than the minimum data-rate while meeting the NUE's SINR.

Figure 6.7 (a and b) show the plot of SINR versus the interference threshold and interference power for the proposed algorithm, two other schemes (i.e., harmonic and Best-worse scheme), and the D2D communication scheme. In Figure 6.7 (a), the D2D communication scheme outperforms the proposed algorithm by 32.86%, whereas the proposed algorithm outperforms the harmonic by 30.67% as the best-worst technique retrogresses with the application of an interference threshold. Furthermore, as the interference threshold rises, the capacity of both the D2D relay link and the D2D pair link increases steadily, except for the best-worst scheme, which regresses. The reason is that the network dynamicity changes as the capacity of the D2D relaying link increase for every SINR improvement within the NBS. Similarly, in Figure 6.7 (b), as the network's SINR increases, so does the interference power within the NBS, reducing the SINR of individual NUEs and limiting network capacity. The best-worst scheme's poor performance can be related to the fact that the technique is transmitting at a higher power to meet the D2D relaying link's minimum data-rate requirement, even when the channel gain, $\boldsymbol{g_{xk}}(\boldsymbol{SINR})$, has a small positive value that does not translate to suitable performance. For D2D relay networks, a large positive channel gain $\boldsymbol{g_{xk}}(\boldsymbol{SINR})$, corresponds to system performance. As a result, most of the signals of the best-worst technique corrupted by interference were not recovered due to the high probability of decoding error.

6.4 CHAPTER SUMMARY

This chapter discusses the performance evaluation and analysis of the proposed scheme against four (4) other approaches, including the D2D communication scheme presented in Chapter 3. The simulation results confirmed that the proposed approach outperforms the best mean-harmonic, best-worst, and half-duplex techniques except for the D2D communication scheme. The D2D communication scheme's performance was due to the high channel gain advantage between the two communicating D2D pairs over the D2D relaying strategy. In addition, the D2D relay strategy impacted by the strong presence of interference power results in a delay and poor channel estimation compared to the direct communication among the D2D pairs. Furthermore, the proposed algorithm's performance over the other schemes is strongly influenced by the available number of link quality which depends not only on the number of D2D relays but also on the selection scheme.

CHAPTER 7 CONCLUSION AND FUTURE WORK

7.1 CONCLUSIONS

The rapid proliferation of the Internet of Things (IoT) devices and data applications has prompted the invention of Narrowband Internet of Things (NB-IoT) technology. NB-IoT is an open 3GPP standard optimized for machine-type communication (MTC) and built on the platform of Long-term Evolution (LTE) functionalities. NB-IoT technology was designed specifically for IoT traffic to lower energy consumption and support low data rate, scalability, and long-range cellular data coverage. However, the integration of NB-IoT into the LTE cellular network is limited by evolved packet core (EPC) which leads to latency in the overall system. The inseparable of the control plane and data plane in EPC led to a coupling level between the serving gateway and the packet gateway that reduces the quality of service (QoS) of the network. As a result, the adaptation of 5G NB-IoT brings a wide variety of IoT applications and use cases that create links with high performance and low complexity to virtually everything around us.

However, the coexistence of 5G and NB-IoT is mar by several factors ranging from interference as a result of frequency reuse, radio resource management (RRM), latency, and so on. This thesis focused on one of the factors and carry out in-depth research on the coexistence of 5G and NB-IoT technology to understudy the research gap of operating NB-IoT seamlessly in 5G networks with a focus on mitigating interference. Interference is a limiting factor that impacts the network performance of any coexisting or heterogeneous network that becomes the bottleneck of throughput improvement of the network. As a result, mitigating interference for 5G NB-IoT networks becomes non-trivial for seamless operation of NB-IoT carriers within 5G network for efficient and effective resource utilization. To come up with a solution, a review of previous research works on interference for NB-IoT coexisting with LTE was studied, and a research gap was identified. One limitation of the previous solution was: high computation complexity, high signal overhead, low data rate, poor spectral efficiency, poor channel estimation, and poor coverage that do not promote the usage of NB-IoT carriers in IoT use cases. Several techniques proposed in the literature are Coordinated multipoint (CoMP), Multiple-input multiple-output (MIMO) technology, and scheduling which are either marred by the high cost of additional equipment or by high signal overhead that may not be suitable and compatible with NB-IoT low-complexity nature. As a result, the D2D communication scheme permitted by the 3GPP solved the challenges mentioned above. But the application of D2D communication in a 5G NB-IoT system can further increase the interference power within the network and thus propose interference avoidance resource allocation for 5G NB-IoT networks.

In this thesis, interference avoidance resource allocation for D2D-enabled 5G NB-IoT networks, where an optimization problem was designed and addressed through three sub-optimal solutions: reuse channel selection and QoS management for D2D pairs, optimal power control for the D2D user and its reuse partner, and maximum weighted matching to locate the optimal reuse partner for each pairing D2D user. When compared to other well-known schemes, simulation results demonstrate that the proposed approach performs better in terms of D2D sum rate and D2D SINR. However, the D2D SINR and D2D sum rate decrease as the interference threshold increases. As a result, the network functions better when interference is minimized at a value lower than the interference threshold to benefit networks.

Furthermore, this thesis proposes an interference-aware D2D relay strategy to improve the QoS of cell edge users for 5G NB-IoT networks. The study used the Max-SINR approach to implement a D2D relay selection strategy for 5G NB-IoT interference-limited networks. The optimization problem was devised to select the channel-to-interference-plus-noise ratio (CINR) of an optimal D2D relay that maximizes the data rate among all available D2D relays while ensuring the QoS of cellular NUEs. The research used a Lagrangian-dual approach to optimize the transmit power of the source (cell-edge NUE) to the relay while keeping the transmit power from the D2D relay to the NBS fixed to minimize interference within the NBS. An interference threshold constraint is used to control and eliminate improper relays with high interference power above the interference threshold. Except for the D2D communication scheme in Chapter 3, the simulation results confirmed that the proposed approach outperforms the best mean-harmonic, best-worst, and half-duplex techniques. The D2D communication scheme's performance was due to the high channel gain advantage between the two communicating D2D pairs over the D2D relaying strategy. In addition, the proposed approach's performance over the other schemes was influenced by the available number of link quality which depends not only on the number of D2D relays but also on the selection scheme.

7.2 RESEARCH CONTRIBUTIONS

This research work has contributed to the general scientific body of knowledge and can be summarized as follows:

- A comprehensive survey on the 5G and NB-IoT coexisting detailing the available connectivity landscape solutions for future IoT networks for 5G NB-IoT service requirements, market analysis, enabling technologies, and the strength, weaknesses, opportunities, and threats (SWOT) has been presented. Also, included were different factors that may limit the NB-IoT seamless operations within the 5G networks such as the interference limitations caused by their coexistence and open research directions on PHY/MAC properties, to improve efficient and satisfactory QoS for 5G NB-IoT networks. In addition, the survey also describes the architectural design for cloud-assisted relay with ambient backscatter communication possibilities to improve the energy consumption of IoT use cases. The survey has been published as a journal article.
- A design and implementation of an interference avoidance scheme for resource utilization for D2D-enabled 5G NB-IoT networks that improve the data rate and D2D

user's SINR of the 5G NB-IoT networks. The approach adopts an interference constraint to regulate the interference power within the network and ensures the cellular NUEs SINR is satisfied. The outcome of this work has been published as a journal article.

- An interference-aware D2D relaying strategy was designed and implemented to solve the QoS of the cell edge users in the scenario of long-distance transmission, delay, low bandwidth utilization, and high system overhead that affects the performance of the 5G NB-IoT networks. The scheme adopts a different approach to relay the cell edge information to the Base station via a selected D2D relay using the Max-SINR technique. The scheme's performance was superior to the popular mean-harmonic, best-worst, and half-duplex approaches except for the previous D2D-enabled 5G NB-IoT approach implemented in the second point above. This contribution is submitted and currently under peer review.

7.3 FUTURE RESEARCH WORK

Several future research works has been investigated and presented in the literature review in Chapter 2. However, there is still a lot more that can be explore in the 5G NB-IoT research area. The following are some of the possible recommendations for future consideration.

7.3.1 Application of Multi-cell Cooperation using Multiple-input Multiple-output approach for 5G NB-IoT Network Base stations.

Multicell cooperation can significantly improve system performance in dense 5G NB-IoT networks where interference is the primary bottleneck for throughput improvement by exploiting inter-cell interference via jointly processing the user data by several interfering base stations, thus simulating the benefits of a large virtual MIMO array. The study can assess Multicell MIMO cooperation concepts from different angles.

7.3.2 Application of Cognitive D2D Communication for large-scale 5G NB-IoT networks.

Cognitive communication can significantly improve the spectrum efficiency of 5G NB-IoT heterogeneous networks by allowing secondary users to use vacant bands without interfering with primary users. The cognitive D2D adoption in 5G NB-IoT networks eases the operator burden of frequency allocation. In addition, cognitive D2D allows for the sensing and reusing of NB-IoT band resources, resulting in more efficient resource utilization and interference management.

7.3.3 Application of reinforcement learning for interference control in 5G NB-IoT networks.

Due to the NB-IoT specific function of low-power device mass connectivity, an intelligent network is required for the processes and analyses of the massively connected devices to promote effective and efficient resource utilization for efficient applications across the industry and society. As a result, future NB-IoT research work requires investigating the use of reinforcement learning for interference control in NB-IoT networks for intelligent network resource usage. Thus, the implementation will aid the performance of NB-IoT systems by allowing for more effective interference management.

APPENDIX

PROOF OF QOS CONTROL IN CHAPTER 3

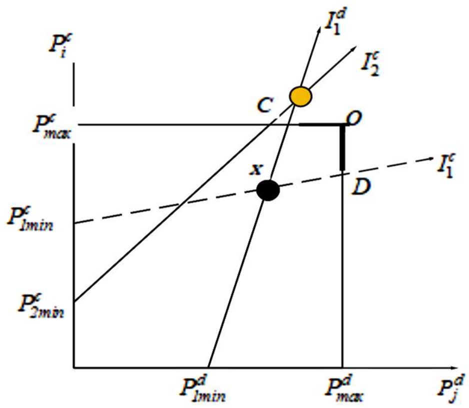
Assume both NUE i and D2D pair j employs orthogonal resources (i.e., no interference between NUE i and D2D pair j). The SINR requirement for both NUE i and D2D pair j can be expressed as;

$$\begin{cases} \gamma_i^c = \dfrac{P_i^c g_{i,\ell}}{\sigma_n^2} \geq \gamma_{imin}^c \\ \gamma_j^d = \dfrac{P_j^d g_j}{\sigma_n^2} \geq \gamma_{jmin}^d \end{cases} \tag{A1}$$

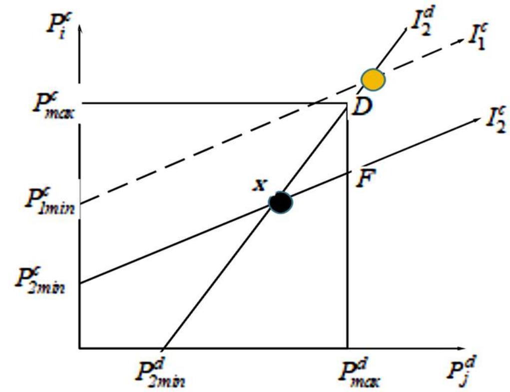
A D2D pair j can reuse NUE i only when (A1) holds which can be expressed as two inequalities in (A1.1).

$$\begin{cases} \gamma_j^d - \gamma_{j\min}^d > 0 \text{ i.e. } \mathrm{P}_{max}^d g_j - \gamma_{j\min}^d \sigma_n^2 > 0 \\ \gamma_i^c - \gamma_{i\min}^c > 0 \text{ i.e. } \mathrm{P}_{max}^c g_{i,\ell} - \gamma_{i\min}^c \sigma_n^2 > 0 \end{cases} \tag{A1.1}$$

The QoS constraint in (3.9) can be depicted as in Figure A1, where lines l_i^c and I_j^d represent constraints (3.9a) and (3.9b) with equality respectively. The square area denotes the maximum transmit power constraint in (3.9c) for both NUE i and D2D pair j.



(a)



(b)

Figure A.1. The feasible region of optimal power Control for NUE and D2D user based on the magnitude of the (P_{max}^c, P_{max}^d), (a) depicts Power perspective of the reuse of D2D pair 1 with NUEs (1 and 2), and (b) depicts Power perspective of the reuse of D2D pair 2 with NUEs (1 and 2).

The intersection at $\mathcal{X}$ of I_i^c and I_j^d in both Figure A1 (a) and A1 (b) is below the maximum transmit power satisfying constraint (3.9c). Thus, D2D pair j can reuse the NUE's resource. Therefore, the transmit power at $\mathcal{X}$ in (3.9) that satisfy the SINR condition is obtained from the following (A1.2);

$$\begin{cases} \gamma_{i\min}^{c} = \dfrac{P_i^c g_{i,\ell}}{\sigma_n^2 + P_j^d g_{j,\ell}} \\ \gamma_{j\min}^{d} = \dfrac{P_j^d g_j}{\sigma_n^2 + P_i^c g_{i,j}} \end{cases} \qquad (A1.2)$$

When the SINR constraint is not met, the D2D pair is not allowed to reuse the NUE's resource. As a result, the algorithm eliminates such D2D pair. When no NUE is available or all D2D pairs have been tested, the process ends. It is also necessary that the intersection slope in Figure A1 (a & b) satisfies the following;

$$\frac{g_j}{\gamma_{j\min}^{d} g_{i,j}} > \frac{\gamma_{i\min}^{c} g_{j,\ell}}{g_{i,\ell}} \qquad (A1.3)$$

Which can be transformed into the following inequality

$$g_j g_{i,\ell} - \gamma_{j\min}^{d} \gamma_{i\min}^{c} g_{j,\ell} g_{i,j} > 0 \qquad (A1.4)$$

APPENDIX B

PROOF OF PREPOSITION 1 IN CHAPTER 3

According to [229], for any given power pair in the interior of the feasible region, there always exist another power pair $(\lambda \mathrm{P}_i^c, \lambda \mathrm{P}_j^d)(\lambda > 1)$ in the feasible region such that;

$$f\left(\lambda P_i^c, \lambda P_j^d\right) > f\left(P_i^c, P_j^d\right) \qquad (B1)$$

where $$f\left(P_i^c, P_j^d\right) \triangleq \log_2\left(1 + \gamma_j^d\right) \qquad (B2)$$

This means that the peak power constraint will limit at least one power in the optimal power combination $(\mathrm{P}_i^{c*}, \mathrm{P}_j^{d*})$. Consider the two cases illustrated in Figure A1 (a & b);

For case 1: $\gamma_i^c > \gamma_{i\min}^c$ and $\gamma_j^d \geq \gamma_{j\min}^d$, Figure A1 (a) shows the feasible zone. Line CO or OD will have the highest power. When the optimal power is on line CO, it is at point C or O. When the optimal power is on line OD, the optimal power pair is at point O or D. As a result, the optimal power allocation in this case can be expressed as;

$$\left(P_i^{c*}, P_j^{d*}\right) = \underset{\left(P_i^c, P_j^d\right) \in \Omega}{argmax}\ f\left(P_i^c, P_j^d\right) \qquad (B3)$$

where
$$\Omega = \left\{ \begin{array}{l} \left(P_{\max}^{c}, \left(\dfrac{P_{\max}^{c} g_{i,j} + \sigma_n^2}{g_j} \right) \gamma_{j\min}^{d} \right), \ \left(P_{\max}^{c}, P_{\max}^{d} \right), \\ \left(\left(\dfrac{P_{\max}^{d} g_{j,\ell} + \sigma_n^2}{g_{i,\ell}} \right) \gamma_{i\min}^{c}, P_{\max}^{d} \right. \end{array} \right\}$$

For case 2: $\gamma_i^c > \gamma_{i\min}^c$ and $\gamma_j^d < \gamma_{j\min}^d$, Figure A1 (b) depicts the feasible region. The optimal power pair will reside on line DF. On the line DF, $P_j^d = P_{max}^d$, and $f(P_i^c, P_{max}^d)$ is a convex function on Pc, hence the optimal power pair can be obtained at the corner point D or F. This means

$$\left(P_i^{c*}, P_j^{d*} \right) = \underset{\left(P_i^c, P_j^d \right) \in \Omega}{argmax} \ f\left(P_i^c, P_j^d \right) \qquad (B4)$$

$$\Omega = \left\{ \left(\left(\frac{P_{\max}^{d} g_j - \gamma_{j\min}^{d} \sigma_n^2}{\gamma_{j\min}^{d} g_{i,j}} \right), P_{\max}^{d} \right), \left(\frac{P_{\max}^{d} g_{j,\ell} + \sigma_n^2}{g_{i,\ell}} \right) \gamma_{i\min}^{c}, P_{\max}^{d} \right\}$$

From Figure A1 (a & b), the assumptions of fixed P_{min}^d, and vary P_{min}^c was used and vice-versa to calculate the sum-rate of the D2D pair. The observation reveals that the optimal solution of (3.9a) and (3.9b) can only reside at the upper boundary line of the feasible region defined by the two functions $f_1(P_j^d, P_i^c)$ and $f_2(P_j^d, P_i^c)$ that maintain a monotonically increasing relation between P_i^c and P_j^d in the range $(P_{1max}^d, P_{j,X}^d)$ and $(P_{j,X}^d, P_{2max}^d)$ respectively [204] to ensure that at least one device is transmitting at the peak power.

PROOF OF CONCAVITY IN CHAPTER 5

Given the first-order derivative of P2 with respect to $\boldsymbol{P_{x}}$, (5.16) is obtained, which satisfies the constraints 5.13 (a), 5.13 (b), and 5.13(d) (i.e., the constraints are convex sets) respectively. The Hessian matrix of P2 can be expressed in diagonal matrix as;

$$\nabla\theta = \begin{bmatrix} \partial_{xk_1} & & & \\ & \partial_{xk_2} & & \\ & & \ddots & \\ & & & \partial_{xk_i} \end{bmatrix} \forall r \in R \quad (C1)$$

where $\partial_{xk_i} = \frac{1}{\ln 2} \frac{-1}{\left(P_{x_i} + \left(\frac{\sigma^2 + I_{t_i}}{g_{ck_i}}\right)\right)^2}, \forall i \in R$

We express the total co-channel interference $\boldsymbol{I_t}$, on each D2D relay channel as a constant. From (C1), it can be observed that the $\boldsymbol{\nabla\theta}$ is a diagonal and negative semi-definite matrix due to its first-order minor. However, because of the second-order conditions [200], [224], it can be concluded that the function P2 is a concave function.

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