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INTERFERENCE MANAGEMENT IN NB-IOT FOR HETEROGENEOUS WIRELESS NETWORK

Master's thesis

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NB-IOT MÜRA HALDAMINE HETEROGEENSETES JUHTMEVABADES VÕRKUDES

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Author’s declaration of originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

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Abstract

The third-generation partnership project (3GPP) introduces in release 13 the new radio access technology called narrowband internet of things (NB-IoT), which arouses in different operation modes with the idea to re-use the same LTE spectrum. These modes are stand-alone, guard band, and in-band. Consequently, the interference between these two technologies will affect the service to the end users to some extent within a heterogeneous network (HetNet) scenario. There are some studies which show that in-band mode causes more interference due to the use of the same resource block by NB-IoT and LTE technology. Therefore, in this master thesis, an extensive investigation of interference caused by the new NB-IoT devices, in different HetNet deployment strategies is presented together with a cooperative power management approach. Those scenarios include the presence of NB-IoT either in Macro or in Small cell and considering if both technologies are synchronous or asynchronous. From the simulations is demonstrated that scenario 4 (Macro and Small Cells with NB-IoT) introduces more interference because both cells enable the power boosting of 6 dB [1]. Additionally, the cooperative method is implemented and studied, as a result, the method increases the performance of edges users approximately 14% to 70%.

This thesis is written in English and is 59 pages long, including 6 chapters, 36 figures, and 10 tables.

Key Words: NB-IoT, LTE, small cells, macro cells, interference, HetNet.

Annotatsioon

[Thesis title in Estonian]

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Lõputöö on kirjutatud [mis keeles] keeles ning sisaldab teksti [lehekülgede arv] leheküljel, [peatükkide arv] peatükki, [jooniste arv] joonist, [tabelite arv] tabelit.

List of abbreviations and terms

3GPP	Third Generation Partnership Project
ABS	Almost blank subframe
BPSK	Binary Phase-shift Keying
BS	Base-station
CAPEX	Capital expenditures
CDF	Cumulative distribution function
CRC	Cyclic Redundancy Check
DCI	Downlink Control Information
DL	Downlink
DRX	Discontinuous Reception.
ECG	Electrocardiography
eDRX	Extended DRX
eICIC	Enhanced Intercell Interference Coordination.
eNB	Evolve Node Base-station
EPC	Evolve Packet Core
FDMA	Frequency Division Multiple Access
GSM	Global System for Mobile Communications
HARQ	Hybrid Automatic Repeat Request
HetNet	Heterogeneous Network
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IP	Internet Protocol
ITU	International Telecommunication Union
KPI	Key Performance Indicator
LoRa	Long Range
LPWAN	Low-power Wide Area Network
LTE	Long Term Evolution
M2M	Machine to Machine

MCL	Maximum Coupling Loss
MME	Mobility Management Entity
MTC	Machine type communication
NB	Narrowband
NB-IoT	Narrowband internet of things
NPBCH	NB Physical Broadcast Channel
NPDCCH	NB Physical Downlink Control Channel
NPDSCH	NB Physical Downlink Shared Channel
NPRACH	NB Physical Random Access Channel
NPSS/NPSS	NB Synchronization Signal
NPUSCH	NB Physical Uplink Shared Channel
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational Expenditure
ORA	Optimal Resource Allocation
PDCCH	Physical Downlink Control Channel
PDN	Public Data Network
PGW	PDN Gateway
PRB	Physical Resource Block
PSM	Power Saving Mode
QoS	Quality of Service
QPSK	Quadrature phase-shift keying
RAN	Radio Access Network
RRC	Radio Resource Control
RU	Resource Unit
SBS	Signaling Radio Bearer
SC-FDMA	Single Carrier Frequency Division Multiple Access
SGW	Serving Gateway
SINR	Signal to Interference Plus Noise Ration
SMS	Short Message Service
SNR	Signal to Noise Ratio
Taltech	Tallinn University of Technology
TB	Transport Block
TBS	Transport Block Size
UE	User Equipment

UL	Uplink
VUE	Victim UE

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1 Introduction

Communication systems have evolved rapidly over the past two decades allowing to develop new technologies to guarantee connectivity to end users, which are either people using wearables or devices deployed in the industrial or rural sector, constantly monitoring crucial data for their proper operation (e.g. environmental measurement) and sending the data through the internet. By 2023 Ericsson has predicted that there will be more than 3.5 billion cellular internet of things (IoT) connections[2]. Much of those connections will be wearable sensors located indoor doing machine type communication (MTC) either MTC device to MTC server or machine-to-machine communication (M2M). MTC technology requirements are low-cost devices, ubiquitous coverage, and ultra-low battery life to achieve 10 years durability [3]; long term evolution-MTC (LTE-MTC) was launch in LTE release 11 [3] aiming to use the cellular network to support the massive IoT. Few examples of IoT devices and applications are electricity meter; smart watches; biomedical electrocardiography (ECG) wearable; temperature, gas, and water meter sensors [4], smart farm, smart cities, smart grids, smart supply chain, etc. These devices generate a huge amount of data exhibiting a saturation for cellular operator, subsequently, the capacity of the network requires to be increased obliging telecom operators to deploy new technologies; and small cells which its implementation becomes easier diminishing operational cost compared to macro cell offering the advantage of increasing the capacity of the network and indoor coverage.

To fulfil above mention requirement, high efficiency energy, low data rate, and support to massive IoT; a wireless connectivity technology which supports low power transmission, low bandwidth, long coverage is narrowband internet of thing (NB-IoT) launched by 3rd generation partnership project (3GPP) in long term evolution (LTE) release 13. NB-IoT offers more advantages than his predecessor LTE-MTC, offering higher energy efficiency and reduce bandwidth. However, by deploying new base stations either macro or small cell utilizing NB-IoT technology to satisfy the network capacity (massive IoT) and low-power devices requirements, raises a new question; how the interference in different deployment strategies in a heterogeneous network, with NB-IoT, affects the performance of the cellular network.

1.1 Background

Low-power wide area network (LPWAN) technology is characterized for offering connectivity to low-power devices with low data rate. It fits in applications when long-distance connection reliability, long battery life, high-density population of devices, and a small amount of data rate are highly required. This is achieved by reducing the modulation scheme and using new protocol designs to reduce the packet size increase by headers and error-correction.

NB-IoT technology is considered LPWAN. It offers the advantage of a low power communication system in which the devices can have a battery lifetime of approximately 10 years, increases the coverage area, reduces overhead and power consumption; in addition, implementing this technology in the existing LTE standard facilitates the time to market, reduces the capital expenditures (CAPEX) and operating expense (OPEX). By only upgrading their base station with new software which includes the capabilities of NB-IoT, no investment must be done in hardware or the evolved packet core (EPC). This is a great advantage compared with competitor technology long rage (LoRa).

Additionally, NB-IoT comes with three different modes of operations stand-alone, guard-band, and in-band. Each of the modes affects differently the performance of NB-IoT and LTE co-existence. For stand-alone, narrowband IoT is deployed in the GMS technology with a bandwidth of 180 kHz. For guard-band, the LTE guard band is used for the deployment of narrowband IoT, these two modes produce and overcome the interference issue better compare to in-band due to the separation in frequency with LTE. However, in-band which is deployed inside the LTE bands generates questions regarding interference due to the use of the same physical resource blocks between neighboring cells. The focus of this thesis is to evaluate and present the results of such deployment scenarios in a HetNet architecture.

1.2 Problem Statement

By having this new technology deployed in a production network brings new challenges to engineers, which are constantly monitoring the performance of the network to provide the best service to end users. Massive interference is expected in full-scale deployments scenarios.

NB-IoT over LTE functions in three different modes, which are standalone, guard-band, and in-band, each mode is affected differently by users which are attached to a neighboring cell and transmitting in the same frequency allocation or time slot. As a first step, new deployment scenarios need to be proposed and performance must be evaluated. Such a scenario can represent future 5G heterogeneous network (HetNet) environment between macro and small cell and NB-IoT deployment in those setups. Further interference management should be implemented and evaluated.

1.3 Motivation and Research Contribution

Therefore, this is a motivation for researchers to re-produce those challenges in simulations to illustrate how this new technology affects the service, with the goal to become a tool for engineers to properly deploy NB-IoT in their network without a negative impact over the former perception user already possess.

In this thesis, two main key performance indicators (KPIs) are evaluated, signal to interference plus noise ratio (SINR) and throughput. Different deployment scenarios present or experiment higher interference than others. Consequently, five scenarios are simulated, and their results are compared. In some of the eNBs, narrowband IoT will be enabled or disabled, as in a real environment is, depending on, if the zone covered by the eNB has NB-IoT users. Also, it could be found that the technology is in synchronous or asynchronous mode. The descriptions of those scenarios are in Chapter 3. The simulation is performed in MATLAB.

Many of the previous work, does not include this deployment scenarios analysis, they only cover one scenario without the incursion of HetNet. In addition to the comparison of the different scenarios, there are other studies which present a new algorithm or method to avoid interference between the technologies. One of them is the almost blank subframe (ABS) [5] in which some specific subframes are reserved for small cells, this could be used also for NB-IoT; another approach is a hybrid transmission [6] by checking the SNR the transmission is either LTE or NB-IoT. And cooperative method, which is already patented [7] and studied in paper [8], is evaluated in this thesis to visualized how the SINR improves, hence the throughput.

Overall, the main concern is the interference, in this thesis, the evaluation of inter-cell interference is presented for 5 different scenarios which generate important data for real environment deployment strategies; subsequently, a cooperative method is adopted and evaluated to manage or reduce or cancel the inter-cell interference in a HetNet environment with the purpose of increasing the overall throughput for downlink and uplink.

Furthermore, part of the activities from this thesis has resulted in two publications [9], [10], and few are under preparation:

1.4 Chapter Review

The structure of this thesis as follows:

Chapter 2 presents a review of LTE and NB technology. It starts with the explanation of LTE network architecture, functionalities, bandwidth parameters, and the resource blocks which is the most important part that needs to be understood to comprehend how NB-IoT functions. Then, the specifications, performance, new features, and channels of NB-IoT are presented. At last, an explanation of the different modes of the technology operation. Overall, here is the overview of the technology offering an understanding of how it works and presenting what can be achieved.

In Chapter 3, the state of the art or previous works related to the evaluation of the different modes regarding the deployment of NB-IoT are presented; for instance, guard-band and in-band evaluation of interference, the results are shown in a cumulative distribution function (CDF) graph. Besides, some methods that were proposed with the aim of solving the interference caused by frequency reuse method for spectrum efficiency, are explained. In addition, some studies associated with scheduling to improve the performance concerning the interference introduces by NB-IoT are reported too. This chapter gives the idea of what has been accomplished and what could be implemented to evaluate the new scenarios involve in a HetNet environment with NB-IoT enabled.

In Chapter 4, the descriptions of the five deployment strategies scenarios are described in detail explaining which technology is enabled and from where the interference is expected. In each sub-session, which corresponds to each scenario, there is a figure and SINR formula that shows which assumptions are taken for the simulation. This shows the possible deployment scenarios telecom operators can have in their network, and in Chapter 5 the evaluation is presented in terms of throughput, energy, and SINR.

In Chapter 5, All information regarding the simulation such as RF parameters, bandwidth, path loss models, maximum coupling loss (MCL), noise floor, throughput and code rate selection is specified. Then, the simulation method and process are described. Finally, results and analysis are presented with the goal of concluding which strategy is more convenience to deploy in a real HetNet environment.

In Chapter 6, the cooperative approach is explained and studied for all the scenarios, the result and analysis are shown giving the conclusion of how the cooperative method implemented in a HetNet environment improve the experience of the end user, in this case, higher throughput and lower energy consumption.

In Chapter 7, finally, the conclusion is presented and some open questions are raised and new investigation opportunities are presented; for instance, interference prediction. If the prediction is used the cooperative method will be more helpful due to reducing the delay of the communication between neighbors, also artificial intelligent can be used for this prediction process.

2 NB-IoT Overview

This chapter describes in detail how NB-IoT technology works plus how the bandwidth 180 kHz is distributed, channels such as narrowband physical downlink control and shared channel (NPDCCH and NPDSCH), and different mode of operations descriptions. The NB-IoT technology is independent of the LTE but both run in the same spectrum, in-band, and guard-band mode; additionally, this technology inherits many of LTE features, though, it is necessary to describe the LTE Network before moving on details with NB-IoT.

2.1 LTE Network

LTE network consists of the radio access network (RNA), and the evolved packet network (EPC), see Figure 1. The enhance node base-station eNB, which is part of the RNA, is the one in charge of managing and scheduling the resource to the end users. The EPC is the joined of three main nodes which are mobility management entity (MME), serving gateway (SGW), and public data network (PDN) gateway (PGW).

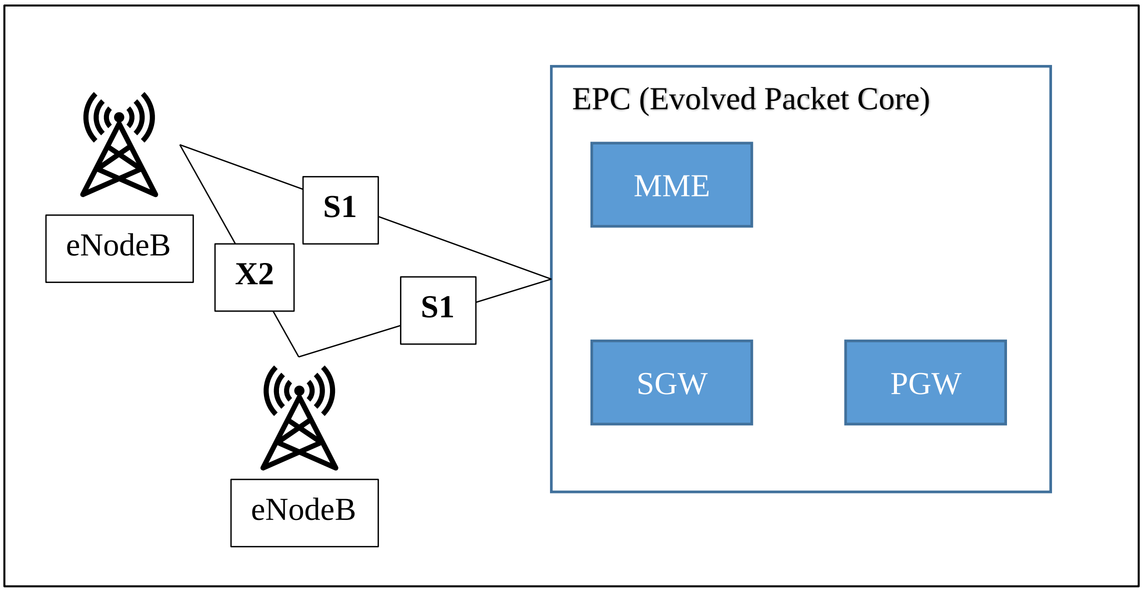


Figure 1. LTE Network Diagram.

The entity MME manages the signaling known as control plane. The signaling is related to security and mobility for the evolve universal mobile telecommunication system

(UTMS) terrestrial radio access (E-UTRAN) being the air interface. Besides, it is responsible for carrying or handling the tracking and paging of user equipment (UE) in idle-mode [11].

The SGW and PGW control the user data known as user plane, they transport the IP data between the external network and UE. The serving gateway is the interconnection between the eNB and EPC and it is known as the anchor [11].

LTE is based on Orthogonal Frequency Division Multiple Access OFDMA in downlink and single carrier frequency division multiple access SC-FDMA in the uplink.

LTE can work on different bandwidth from 1.4 MHz to 100 MHz. LTE advance can use more bandwidth and multi-carrier set up to improve the data rate. Below a table with the specification for each of the bandwidth option [12].

Bandwidth (MHz)	1.4	3.0	5.0	10	15	20
Sub-frame duration	1 ms					
Sub-carrier spacing	15 kHz					
FFT length	128	256	512	1024	1536	2048
Sub-Carriers	72	180	300	600	900	1200
Symbols per slot	7 with Short CP and 6 with Long CP					
Cycle prefix (CP)	5.210 us with Short CP and 16.67 us with Long CP					

Table 1. LTE physical layer bandwidth options and bandwidth specific parameters [12].

2.1.1 Radio Resource Organization

For uplink and downlink, the 180 kHz in 1ms of the sub-frame corresponds to one single LTE Physical Resource Block (PRB), this is equal to 12 subcarriers [12], [13] of 15 kHz, and one subcarrier and one symbol is a resource element (RE), see Figure 2.

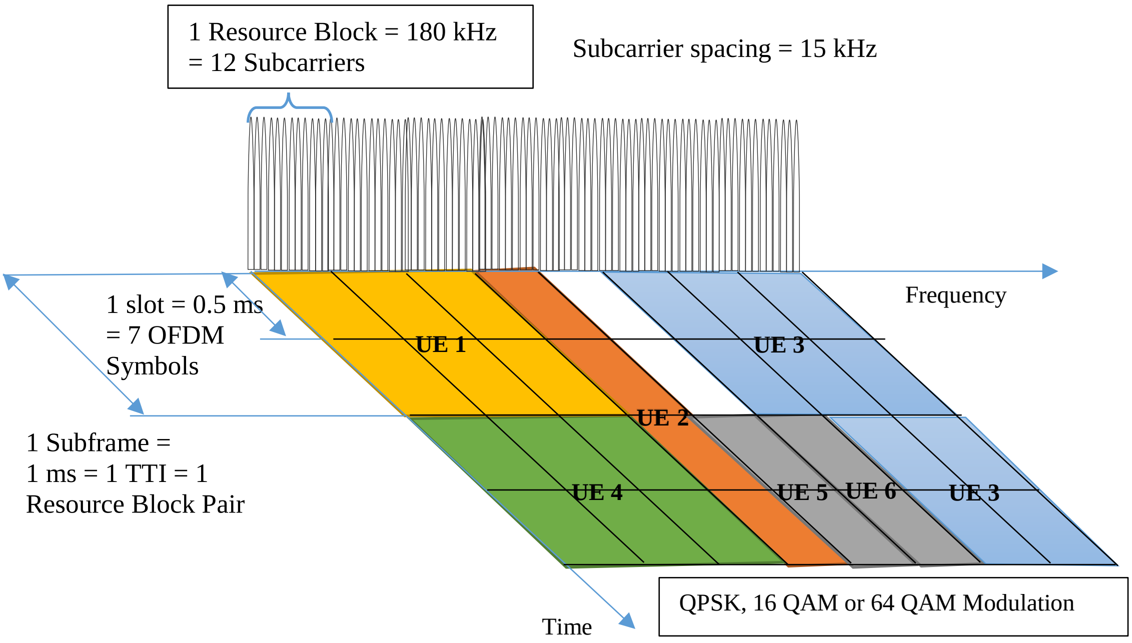


Figure 2. Physical Resource Block equivalent to twelve subcarriers. One slot equivalent to 0.5 ms and 7 OFDM symbols, and one subframe of 1 ms equal to a resource block pair [13].

The UEs are allocated in resource blocks by the eNB depending on many criteria such as traffic demand, channel conditions, and quality of service QoS [12]. For instance, if the user has a low signal to noise ratio SNR the eNB assigns less RB, low modulation scheme to guarantee the transfer of the data with translate in a low throughput or the use of diversity.

2.1.2 Interfaces

Another important characteristic of LTE is the interfaces between the nodes.

- S1, this interface connects the eNB to the EPC, it carries control and data plane information.
- X2, this interface provides connectivity between eNBs allowing them to perform a new task such as handover without involving the core and releasing the core of tasks to avoid signaling overload.

2.2 NB-IoT standard, specifications, and performance

NB-IoT uses the same frequencies used in LTE and can be deployed in all the bandwidth options, except for bandwidth 1.4MHz [4]. It minimizes the signal overhead, especially over the radio interface, improve battery life, support delivery of IP and non-IP data, and SMS support. In spite of this, it does not support all the feature built-in in LTE, for instance, multiple radio access technology (Multi-RAT) and handover [4]. However, inherited many of them that are crucial such as idle mode, power saving mode, paging, and access control [14].

In the data transmission, includes new optimization, one of them is the ability to transmit a small amount of data in the control plane via signaling radio bearer (SBS). Another one is the ability to suspend and resume the radio resource control (RRC), which eliminate the need of having a new connection at each reporting instance [14].

2.2.1 Performance

As stated at the beginning of this section, NB-IoT offers advantages as follow, these descriptions are taken from [14], [15], [16], and [17]:

a. Coverage: enhance coverage by 20 dB [16] corresponding to a Maximum Coupling Loss (MCL) of 164 dB. NB-IoT supports three different coverage levels: 0, 1, and 2. Repetition is an important key performance indicator (KPI) of coverage, less or more repetitions describe the coverage level. For 0 to 10 dB few repetitions or none are needed to reach a high data rate, where 20 dB the coverage can be maintained by sending more repetitions but low data rate.

b. Capacity: The target is to support 52K at least [17]; however, the system-level simulation result given in [14], it could support 250K devices in a cell sector per carrier. With narrowband physical downlink shared channel (NPDSCH) peak data rate of 226.7 Kbps layer1 and narrowband physical uplink shared channel (NPUSCH) peak data rate of 250 Kbps layer 1 [17]. However, when the time offsets between downlink control information (DCI), NPDSCH/NPUSCH, and hybrid automatic repeat request (HARQ) acknowledgment are taken into account [17] the data rate for downlink and uplink are lower than the ones stated above.

c. Energy efficiency: The target is to achieve a battery life of more than 10 years at the maximum coverage level using a battery capacity of 5 Wh [15]. For this NB-IoT keeps the same power saving mechanisms but extending the timer values to achieve a longer battery lifetime. Those methods are Discontinuous Reception (DRX) and power saving mode (PSM).

- eDRX: This is extended DRX is required for NB-IoT UE to save power consumption. Ant the DRX cycle maximum value of 10485.76s [14].

- PSM: *“In this mode, the UE remains registered to but not reachable by the network. The UE is in the power-off or sleep mode and will wake up only when there is data to send after timer expiration”* [14].

d. Latency: Target of a maximum latency of 10 seconds. Which indicates that this technology should be utilized for the situation where higher latency is acceptable [14].

2.2.2 Resource grid for NB-IoT

NB-IoT uses two different carrier spacing in uplink i.e., 3.75 kHz, and 15kHz, for downlink the spacing is only 15kHz. However, in the uplink the spacing could be either 3.75 kHz or 15 kHz and it can have single-tone or multi-tone transmission. The 3.75 kHz spacing is for single-tone only, and 15 kHz can be utilized for both single and multi-tone, see Table 2. Below figures Figure 3, Figure 4, and Figure 5 (PRB DL and UL) showing the distribution of RB [14]. For NB-IoT the resource unit is introduced as the smallest amount of time-frequency resource [14].

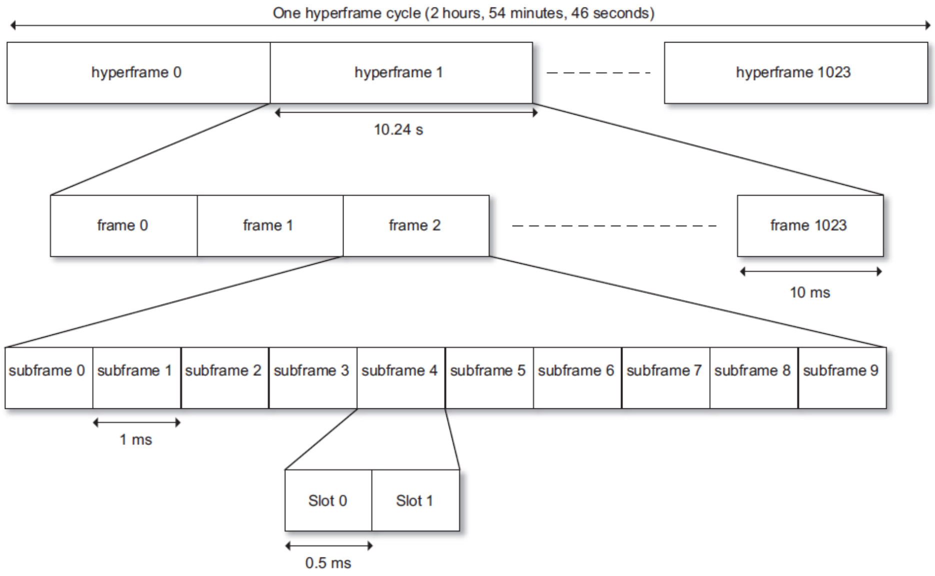


Figure 3. NB-IoT Frame for 15 kHz spacing [18].

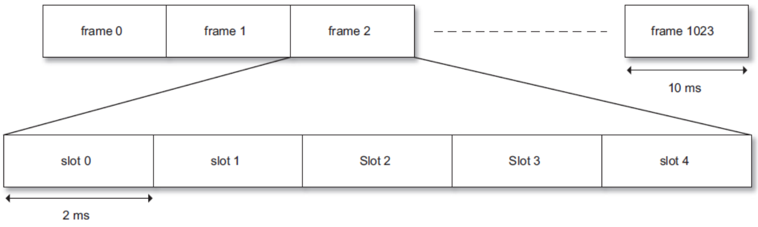
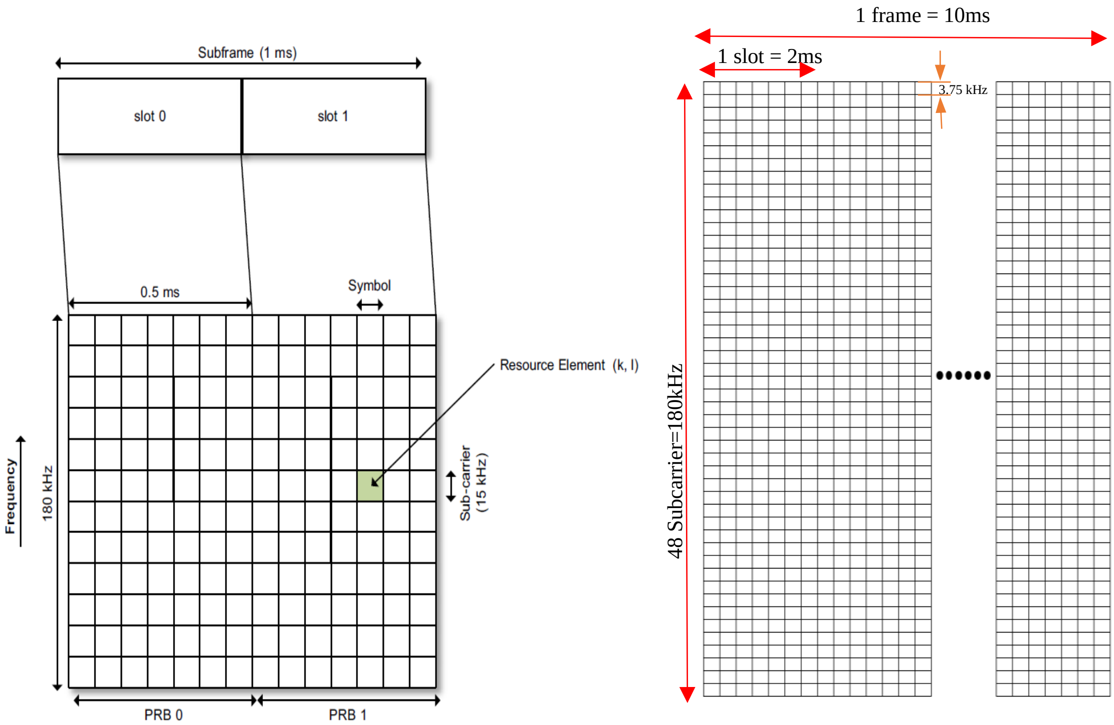


Figure 4. NB-IoT Frame for 3.75 kHz spacing [18].



a) b)

Figure 5. Physical Resource Block NB-IoT a) Downlink [18] 15kHz and b) Uplink [19].

Physical Channel	Transmission Mode	Subcarrier Spacing	The # of Subcarriers	Duration
NPUSCH	Single-Tone	3.75 kHz	1	32ms
		15 kHz	1	8ms
	Multi-Tone	15 kHz	3	4ms
		15 kHz	6	2ms
		15 kHz	12	1ms

Table 2. The time-frequency size of RU in NPUSCH [20].

2.2.3 NB-IoT Physical channels and Subframe

As mentioned before the NB-IoT occupies a bandwidth of 180 kHz that correspond to one PRB of LTE as described in Figure 2; on the other hand, the number of channels is different. Table 2 contains usage information of the different channels and signals, nevertheless they are explained in more detail in [14]. See in Figure 6 [15], the NB-IoT subframe with the allocation of the channels and signals stated in Table 3.

Channels/Signals		Usage
DL	Narrowband Physical Downlink Control Channel (NPDDCH)	Uplink and Downlink scheduling information
	Narrowband Physical Downlink Shared Channel (NPDSCH)	Downlink dedicated and common data
	Narrowband Physical Broadcast Channel (NPBCH)	Master information for system access
	Narrowband Synchronization Signal (NPSS/NSSS)	Time and frequency synchronization
UL	Narrowband Physical Uplink Shared Channel (NPUSCH)	Uplink dedicated data
	Narrowband Physical Random-Access Channel (NPRACH)	Random access

Table 3. NB-IoT channels and Signals [14].

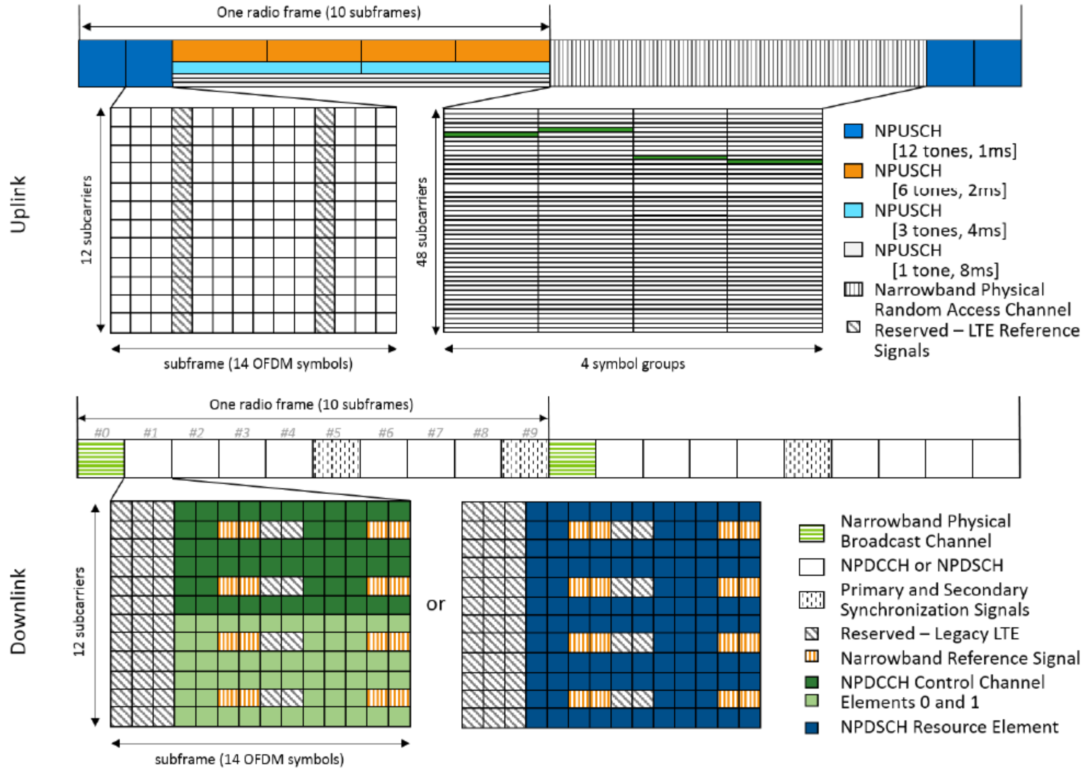


Figure 6. Channels of NB-IoT plotted on the subframe [15]. In the uplink, it is described as single and multi-tone the channel PUSCH. The multi-tone is shown in the radio frame on the top left of the figure with a different color; on the top left, it is shown the single tone for 3.75 kHz subcarrier spacing. On the bottom, it is described the downlink radio frame RB with the channels and signals distributions.

2.2.4 Signals and Channels in Downlink

Part of the description of these signals and channels are extracted from [8], [14]:

a) **Narrowband reference signal (NRS):** To provide phase reference, the signal NRS is transmitted in subframes that are dedicated to broadcast or downlink transmission.

b) **Narrowband primary and secondary synchronization signal (NPSS/NSSS):** This signal is transmitted every 10 ms, and 20 ms, respectively; these signals are used for cell searching by using time and frequency synchronization and cell detection.

c) Narrowband physical broadcast channel (NPBCH): The NB master information block size is 50 bits, similar to LTE MIB supplies the UE with the system frame number (SFN), operation mode, channel raster (depending on the operation mode) and LTE cell-specific reference signal (CRS), system information block (SIB).

d) Narrowband physical downlink control channel (NPDCCH): It carries the most important information paging, downlink/uplink assignment, random access channel response, type of modulation, and power control. The size is fixed to 23 bits in one subframe. For extended coverage, it supports 2048 repetitions. For NB-IoT, three new DCI format are defined: N0 for NPUSCH scheduling, N1 for NPDSCH scheduling and NPDCCH order, and N2 for paging and direct indication.

e) Narrowband physical downlink shared channel (NPDSCH): It is scheduled by NPDCCH and transmitted after the transmission of NPDCCH, this delay is 4 ms. The maximum transport block size (TBS) is 680 bits and can be mapped in a maximum of 10 subframes, the set is {1, 2, 3, 4, 5, 6, 8, 10}. Error detection CRC of 24 bits.

2.2.5 Signals and channels in the uplink

a) Demodulation reference signal (DMRS):

It is transmitted only in RUs which contains data.

b) **Narrowband physical random access channel (NPRACH)**:

It is based in a single-tone transmission. The NPRACH resource configuration is divided into three different levels of coverage. It used by the UE to camp on the base station (BS). The resource configuration is performed by the estimation of the uplink timing with the aim of maintaining orthogonality. For extended coverage, the maximum repetition is 128.

c) Narrowband uplink shared channel (NPUSCH):

This channel support single and multi-tone as aforementioned in section 2.1.1 Radio Resource Organization. The largest transport block is 10 resource units. It provides the extended coverage by the time-domain repetition, and low peak-to-average-power ratio modulation schemes BPSJ and QPSK. For this channel, two formats exist, the first format is for carrying uplink data and error correction, the second format is for the hybrid automatic repeat request (HARQ) acknowledgment for downlink data. The maximum number of repetitions is 128. The maximum TBS is 1000 bits and can be mapped in {1, 2, 3, 4, 5, 6, 8, 10] resource units in time.

2.2.6 Narrow Band IoT modes

NB-IoT can be implemented in three different modes, GSM-standalone (**Global System for Mobile communications**), in-band, and guard band. See Figure 7.

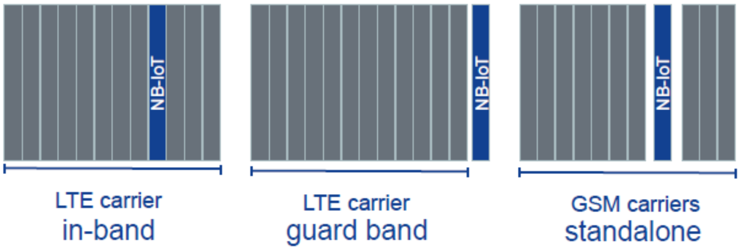


Figure 7. NB-IoT Operational Modes [21].

For standalone mode, the GSM technology is used by the replacement of one or more GSM carrier. This allows efficient re-framing of GSM carriers for IoT [21].

Over in-band operation, some of the LTE PRB are reserved to NB-IoT which indicates none LTE PRB will be transmitted where the NB-IoT PRB is allocated and vice-versa. The use of this operation mode increases the spectrum efficiency because of the reuse of the LTE spectrum. The total power is shared between both technologies with the possibility to use it in advantage for power boosting on NB-IoT [21]. Additionally, by deploying NB-IoT in this operational mode increases the interference between neighbors for both technology either being the victim LTE or NB-IoT PRB. The interference problematic is seen in more scale when single-tone in uplink with 3.75 kHz spacing is used. Nevertheless, *"this interference can be reduced by scheduling users with similar*

SNR requirements in NB-IoT nearby LTE PRBs. On the other hand, if 15kHz subcarrier spacing is used, LTE and NB-IoT orthogonality are maintained'' [21] which guarantee more stability in the system.

The guard-band mode offers a good co-existence between LTE and NB-IoT technology because the PRB assigned to NB-IoT are the ones in the LTE guard-band. *''Each carrier is within the guard-band and the center frequency is at a most 7.5kHz offset from the 100kHz channel raster. In addition, the orthogonality with LTE is maintained''* [21].

3 State of The Art

This chapter includes the overview of some of the research published in the evaluation of NB-IoT modes (guard-band and in-band modes), interference management and cancellation either in NB-IoT technology or HetNet environment.

3.1 Evaluation of NB-IoT guard-band mode

Guard-band mode offers good protection against interference in either technology, LTE or NB-IoT. In [22], it is presented the study of the interference experienced by LTE or NB-IoT as a victim. The biggest impact of interference is LTE over NB-IoT in the uplink; however, the interference caused by the LTE user is not significant to deteriorate the performance of narrowband IoT. In Figure 8, and Figure 9, it is shown the SINR when LTE and NB-IoT are the victim respectively. The evaluation was performed under the condition that the separation of 0 Hz between technologies.

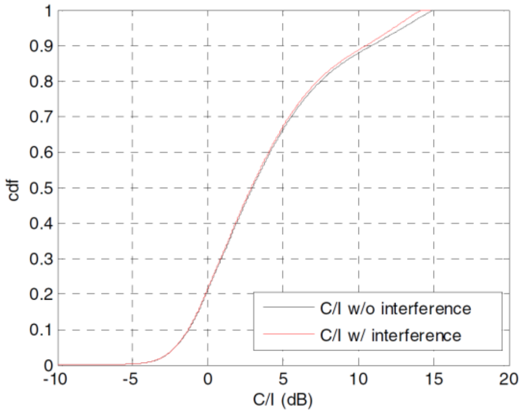


Figure 8. SINR when LTE is the victim [22]. C/I means carrier over interference, w/o without, and w with. This graph shows the uplink evaluation of interference over LTE when NB-IoT is considered the aggressor technology.

In the paper describes the first scenario when NB-IoT interferes LTE name it also as NB-IoT the aggressor and LTE the victim. As seen in Figure 8, the CDF graph shows a small change of carrier over interference (C/I) between 5 to 15 dB, the degradation was of 0.7 dB at 95% SNR, this is interpreted in throughput loss of 4.7% [22].

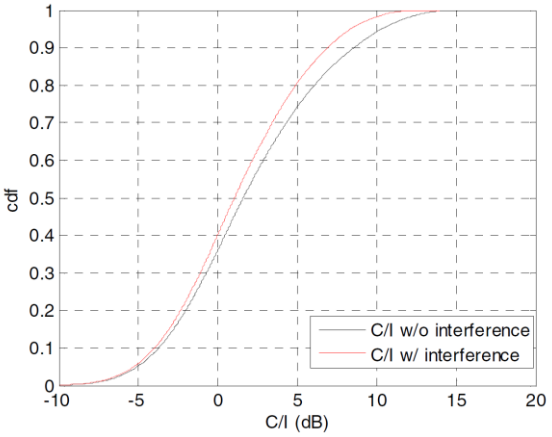


Figure 9. SINR when NB-IoT is the victim [22]. C/I means carrier over interference, w/o without, and w with. This graph shows the uplink evaluation of interference over NB-IoT when LTE is considered the aggressor technology.

When NB-IoT is considered the victim, the interference increases as shown in Figure 9. The SNR loss was of 2 dB approximately. Overall, mutual interference exists, when LTE is the victim the interference is relatively low due to the higher bandwidth (10 MHz) compare to NB-IoT 200 kHz bandwidth. The simulation assumptions or parameter can be found in [22].

3.1.1 Evaluation of NB-IoT in-band mode

In [21] the evaluation involves a number of cells in which NB-IoT technology is activated with the aim of measuring the interference caused by the neighboring cells. It is mentioned that the impact is shown in two-folds:

- The relative sparse deployment of NB-IoT results in a larger area that needs to be covered by each NB-IoT cell.

- The NB-IoT devices that are on the edge coverage or remote from the serving cell could potentially be covered by an LTE cell, resulting in strong co-channel interference.

Hence, if an NB-IoT device with the second condition stated above would have a low SINR, because of the near LTE cell which is transmitting in the same PRB. This can be improved by power boosting, NB-IoT standard limits it to 6 dB [21].

The simulation assumption can be found in [21]. The simulation is run for three different NB-IoT deployment densities of 50%, 75%, and 100%, and in synchronous mode and asynchronous mode between cells. Figure 10 illustrates the co-channel interference when the cells are not synchronized. Nonetheless, When the "*cells are synchronized the LTE subcarriers from adjacent PRBs of the second cell are orthogonal to the NB-IoT subcarriers in the first cell*" [21], and when they are not synchronized this orthogonality is lost and adjacent PRBs of the neighboring cell could potentially introduce interference.

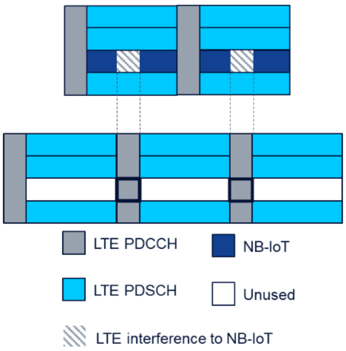


Figure 10. Co-channel interference in an asynchronous network. On top of the figure, it is the resource usage of a cell with NB-IoT, on the bottom, it is the resource usage of a cell with only LTE [21].

To solve the problem of co-channel interference it is proposed blanking the PRB used for NB-IoT on the LTE cell. This can be seen in Figure 10, where the unused (blank) PRBs on the resource usage on the bottom of the figure (LTE only) are not utilized for transmission. Moreover, the cells should be synchronous which guarantee orthogonality.

3.2 Resource Management in Cellular Network

In HetNet, the macro and small-cell operate in different channels or co-channel. The advantage of using different channels or dedicated channel is the interference is not an issue and reduce the complexity of deployment, but this implies the operators should own a license for each frequency band utilized which translates in new investment or partition of their spectrum in few parts to assign one channel for each type of cell indicating a decrement in their network capacity.

Therefore, it is necessary to introduce a system that shares the spectrum efficiently. By sharing the spectrum, the interference becomes the problem to solve by having an efficient allocation or scheduling process. The interference affects negatively the performance of the small cell due to the higher transmission power of the macro cells. One of the approaches to overcome this problem is the use of OFDMA systems. Even though, there should be a good scheduling algorithm along the OFDMA system to mitigate the interference in some extends to improve the performance of the network.

3.2.1 Conventional Frequency Reuse

The frequency reuse factor 1 or reuse-1 scheme is known as the simplest frequency reuse method where the complete bandwidth is reused in each cell [23]. In this scheme, all the cells use the same frequency band and without any power limitation, resulting in the maximum throughput [24]. Nevertheless, reuse-1 introduces high interference. Though, the reuse-3 or frequency reuse factor 3 divides the total bandwidth into three equals and orthogonal sub-bands [23]. The sub-bands are assigned to adjacent cells which the condition of not repetition. The resue-3 reduces or divides the bandwidth to avoid interference. However, it decreases the throughput due to the use of a third of the bandwidth. Reuse-3 becomes the first or simplest form of static interference coordination [24]. The illustration of both frequency reuse factors are in the figure below,

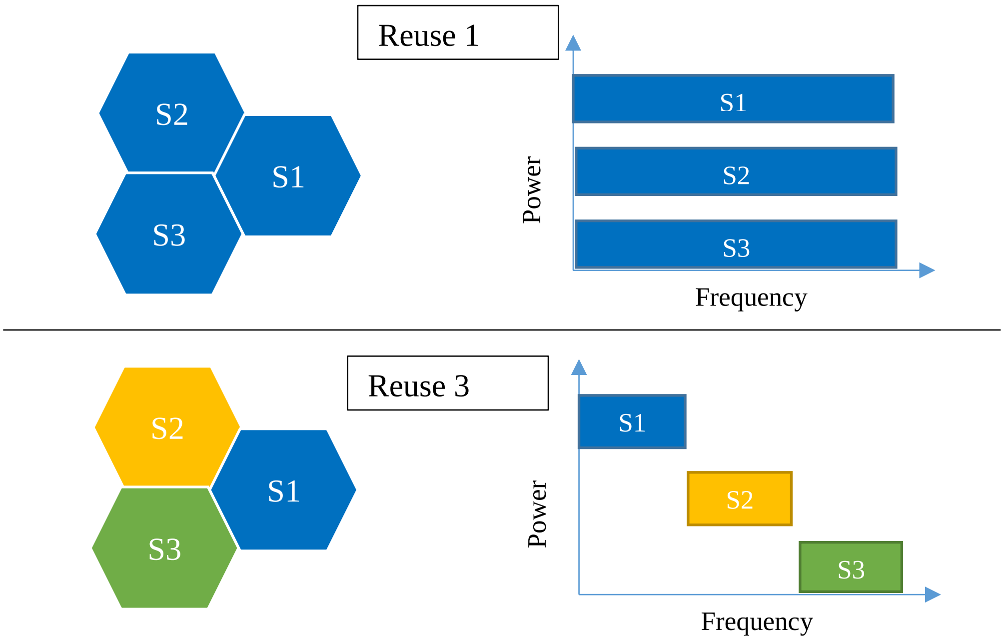


Figure 11.Frequency Reuse factor 1 and 3 (reuse-1 and reuse-3). In reuse-1, the three sectors (S) use the same band, therefore, the whole bandwidth. For reuse-3, each sector uses a different sub-band dividing the total bandwidth into three parts [24].

3.2.2 Almost blank subframe (ABS)

This method allows the mobile user to ensure resources free of interference by muting one of the transmitters. In [5] ABS has been studied in a HetNet environment, showing the essence of using ABS in LTE cellular network to mitigate the high interference seeing by the small cell due to the macro cell. It is considered two types of users, victim user (VUE), and non-victim user (NVUE). The authors specify the victim users are those which camps on the edge of the pico-cell, also macro cell users that are affected by picocell users should be considered as a victim user (VUE). Consequently, both macro and pico-cell should cooperate to reduce the inter-cell interference by introducing ABS method into picocell besides macro-cell. In the next figure, it can be seen in the proposed frame.

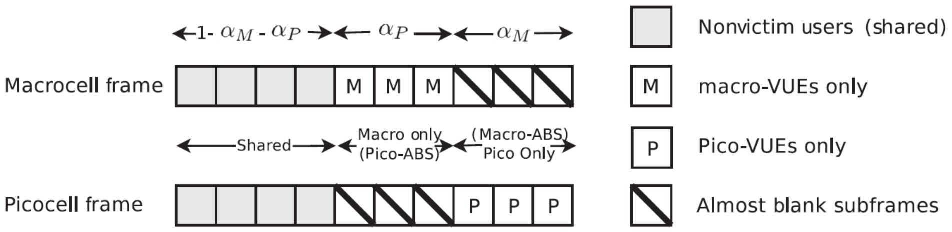


Figure 12. ABS propose frame [5]. This frame displays the ABS implemented in the picocell frame. $\propto_{\mathrm{p}}$ is the number of pico − VUE, and $\propto_{\mathrm{M}}$ is the number of macro − VUE.

It is proposed two solutions, based on dynamic enhanced intercell interference coordination (eICIC). First, product-rate utility function based on [25] which maximizes the product of bitrates of all UEs, and second, physical resource block allocation ratio-based method. In Figure 13Figure 12, it is shown the scenario of VUE and non-VUE.

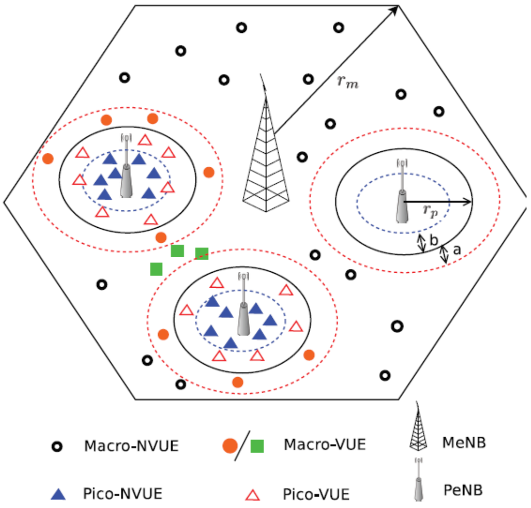


Figure 13. The scenario of the victim and non-victim UEs (VUE and NVUE) [5]. As illustrated the VUE are located on the edge of the coverage of picocells.

In paper [26] the same idea of muting the PRB on the femtocell is used, for those macro users considered as the victim, the authors proposed an optimal resource allocation (ORA) approach to guarantee the data rate demanded by the UE. This approach produces good results; in the below CDF graph can be observed that the ORA keeps the user data rate demand nearly 50% and 90% of the achieved it. However, the method loses some resources which limit the number of simultaneous users connected to the Network.

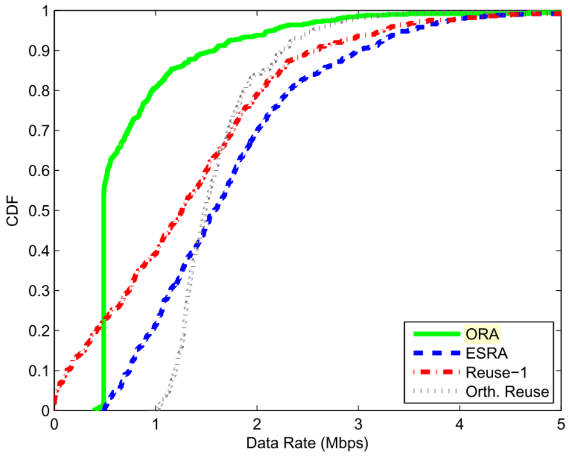


Figure 14. CDF of macro UE data rates for the demand of 0.5Mbps. Optimal Resource Allocation (ORA), Efficient Suboptimal RB Allocation (ESRA), reuse-1 (the simplest frequency reuse factor), Orthogonal Reuse [26].

3.2.3 Uplink Resource Scheduling for NB-IoT and LTE Hybrid Transmission

In [6], a novel uplink resource scheduling is proposed. The idea of using a hybrid transmission to enhance the uplink throughput by categorizing the users. See the establishment hybrid strategy in Figure 15. For those users with low SINR, LTE technology is utilized to provide service and achieve the highest throughput feasible. On the contrary, when the SINR is high the service is delivered by NB-IoT. Having this scheme becomes useful when the base station supports both technologies; nonetheless, in a massive deployment in HetNet, the interference affects the user in a higher amount, though this approach needs to be evaluated in a dense environment. Moreover, NB-IoT devices usually do not support LTE.

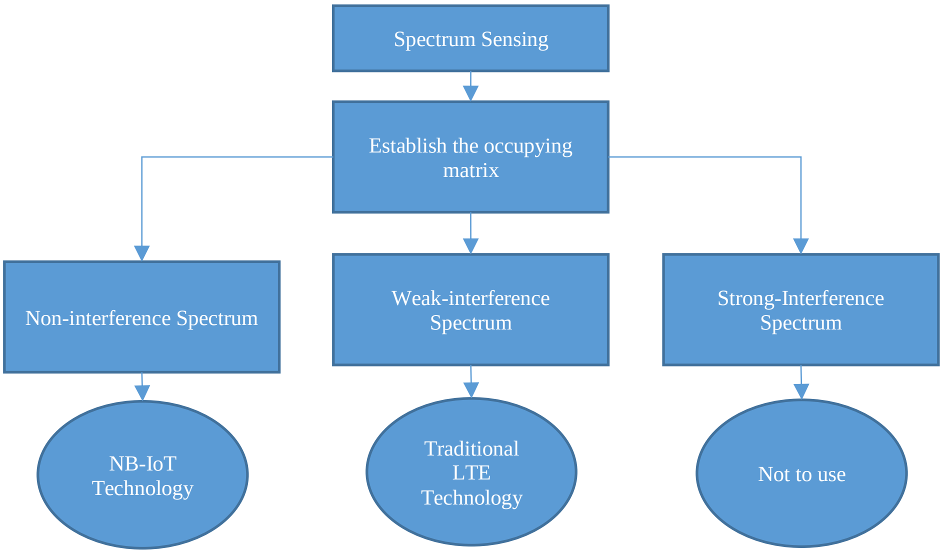
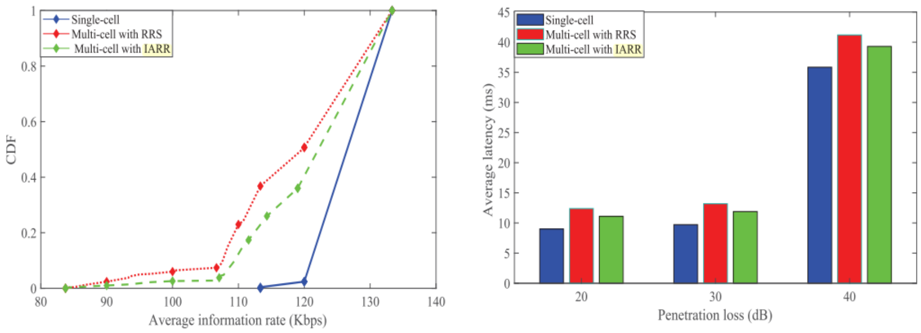


Figure 15. Establishment of a hybrid transmission strategy [6]. The occupying matrix corresponds to the SINR matrix for each of the RB allocations.

3.2.4 Interference awareness

In paper [27], interference aware radio resource has been proposed with the aim of reducing the retransmission and latency. Each user is assigned RB based on the data rate and SINR requirements. This information regarding which RBs are occupied by a certain user is shared to neighbors via the interface X2. This helps to restrict each user to a certain transmission power to achieve the required data rate. Having shared afore-mentioned information, in case the data rate conditions are not accomplished, the RBs for those users would be reassigned accordingly. The authors proposed an interference-aware radio resource (IARR) approach. Figure 16 shows that by using this method of awareness, the average rate and latency improve by 7% and 10% compare to round-robin scheduling (RRS).



a) b)

Figure 16. Graph Results: a) Average information rate comparison. b) Average latency vs penetration loss [27].

3.2.5 Cooperative Approach

The cooperative approach consists of cooperation between neighbor cells. This method aims to improve the interference by reducing the transmission power of the neighboring cell or user. There is a patent [7] which provide this solution for scheduling cell-edge user. It consists of retrieving interference information and reporting it to the neighboring cell for the usage of resource allocation. Then the edge users are scheduled depending on the interference reported data. There are three procedure described as follow,

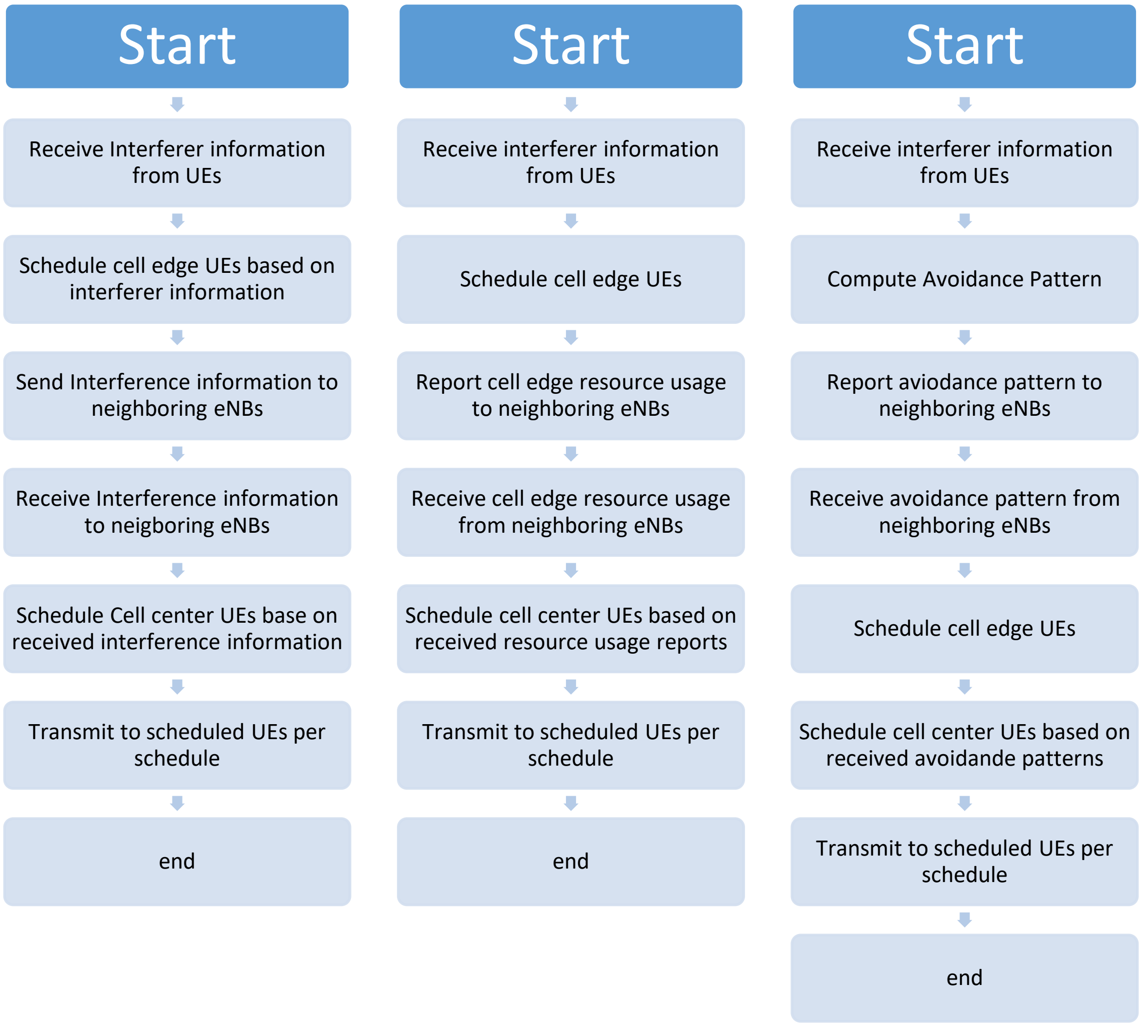


Figure 17. Three procedure described on patent [7]. In each of the three procedures include the interfere share information action; however, the procedure two (middle) shares the resource usage, and procedure three reports the avoidance pattern.

In addition, in paper [8], this method is implemented and showed an improvement in throughput of 9%, see Figure 18. The simulation is run by allocating the slots by using the maximum data rate achievable this is for non-cooperative. On the other hand, for cooperative, this is improved by optimizing the transmission power of the BS (DL) or UE (UL) using the water-filling and considering the interference threshold. The simulation parameters and algorithm proposed can be found in [8]. Nevertheless, the author considered the synchronous network, thri-sector sites with an inter-site distance of 500m (adjacent to each other).

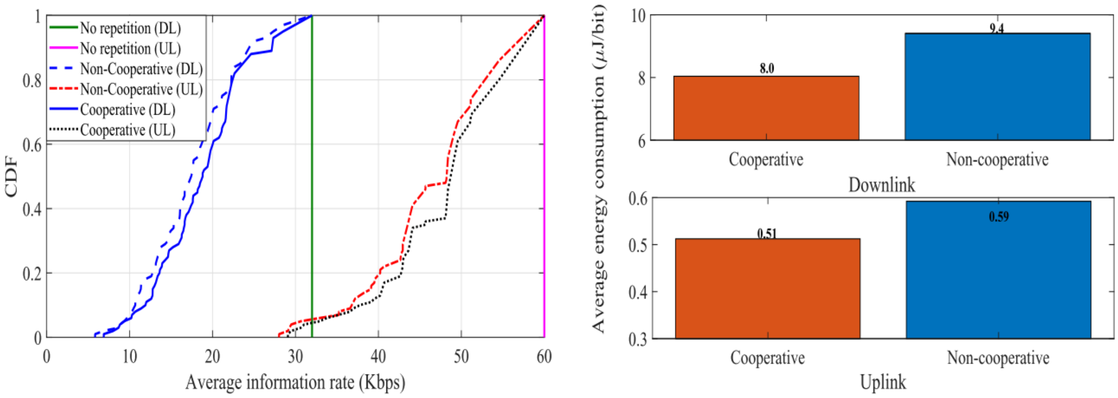


Figure 18. CDF average information rate and Average Energy consumption [8].

However, this paper does not evaluate HetNet scenarios. Another point is that cells are not deployed randomly within a radius coverage, instead, they are deployed adjacent to each other. which in this thesis I will cover it giving a more realistic experiment in HetNet environment.

4 Different Deployment Strategies in an HetNet Environment

As known, the growth of data transfer increases in huge steps every year, and small cells are now the best approach to fulfill that requirement of end user because of their easier implementation in infrastructure and operational cost compare to macro cells. Moreover, they increase the capacity of the network and improves indoor coverage. Mentioned the advantage of having small cells, still, it is needed to evaluate the performance of the NB-IoT in a HetNet environment. Consequently, in this chapter, five scenarios involving the deployment of NB-IoT, which could be seen in a real environment, are described. For instance, scenario one only involves small cell with NB-IoT, hence the inter-cell interference is only caused by the neighboring small cells. Below, it is the general formula for SINR calculation used for all the scenarios. Afterward in the next sessions, it will be modified depending on the scenario; besides, the simulations procedures and results will be explained in detail i.e. the parameter and conditions stated for the calculation and evaluation of the deployment strategies.

$$SINR\ UE_{NB_{ij}} = \frac{P_{tx}^{j} G_{i}^{j}}{PL + I_{Macro} + I_{Small} + \sigma} \tag{1}$$

Where, $I_{Macro} = \sum_{k \in \{\Omega_{MNB}\} k \neq j} P_{tx}^{k} G_{i}^{k} + \sum_{k \in \{\Omega_{MLTE}\} k \neq j} P_{tx}^{k} G_{i}^{k}$, and

$I_{Small} = \sum_{k \in \{\Omega_{SNB}\} k \neq j} P_{tx}^{k} G_{i}^{k} + \sum_{k \in \{\Omega_{SLTE}\} k \neq j} P_{tx}^{k} G_{i}^{k}$

PL = Pathloss
σ = Noise floor
P_{tx} = Trnasmission power.
G = Gain.
I_{small} = Interference within small cells.

Domains:
Ω_{MLTE} − Macro Cell LTE
Ω_{SLTE} − Small Cell LTE
Ω_{MNB} − Macro Cell NB
Ω_{SNB} − Small Cell NB
i → UE, j → BS, k → neighbour cells

There are two terminologies that need to be explained before continuing with the description of the scenarios, synchronous and asynchronous. When the cells are synchronized the dedicated NB-IoT PRBs are the same in all cells, and when they are not synchronized the neighboring PRBs could be potentially an LTE PRB or NB-IoT PRB due to the no synchronization between the cells [8].

4.1.1 Scenario 1 – Small cell coverage only with NB-IoT enabled

This is the scenario (Figure 19Figure 19), in which macro cells are not involved, gives us the first result for comparison with the rest of the scenarios that are HetNet. It can illustrate the normal interference behavior when none HetNet scenario is evaluated. In this particular scenario, the small cells have NB-IoT enabled and are synchronous This states that the same RB use for transmission in NB-IoT over the small cells are the same for the whole network and the interference is coming only from narrowband IoT technology. Therefore, interference is evaluated with the following formulas,

$$SINR\ UE_{NB_{ij}} = \frac{P_{tx}^{j} G_{i}^{j}}{PL + I_{Small} + \sigma}\ ; \qquad (2)$$

Where , $I_{Small} = \sum_{k \in \{\Omega_{SNB}\} k \neq j} P_{tx}^{k} G_{i}^{k}$

Above formula is used to calculate the SINR for downlink and uplink, the only consideration that needs to be taken into account is that the transmission power should be changed accordingly to get the proper calculation.

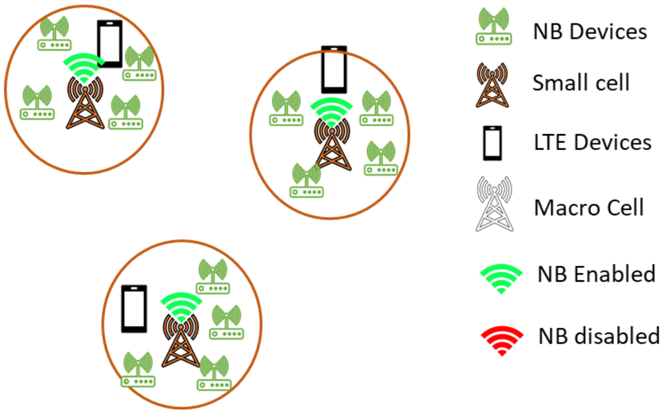


Figure 19. First Scenario – Only Small Cell with NB-IoT Enabled.

4.1.2 Scenario 2- Macro Cell LTE and Small Cell NB-IoT

In this second scenario (Figure 20), now macro cells are taken into account. The macro cell has NB-IoT disabled, and the small cells are deployed with NB-IoT. Those Macro cell users that are assigned with the same physical resource block (PRB) interferes the small cell NB-IoT users and vice versa. From this, the interference expected on the NB-IoT small cell should be higher, due to the neighboring macro cell involved, compare with the former scenario described in 4.1.1

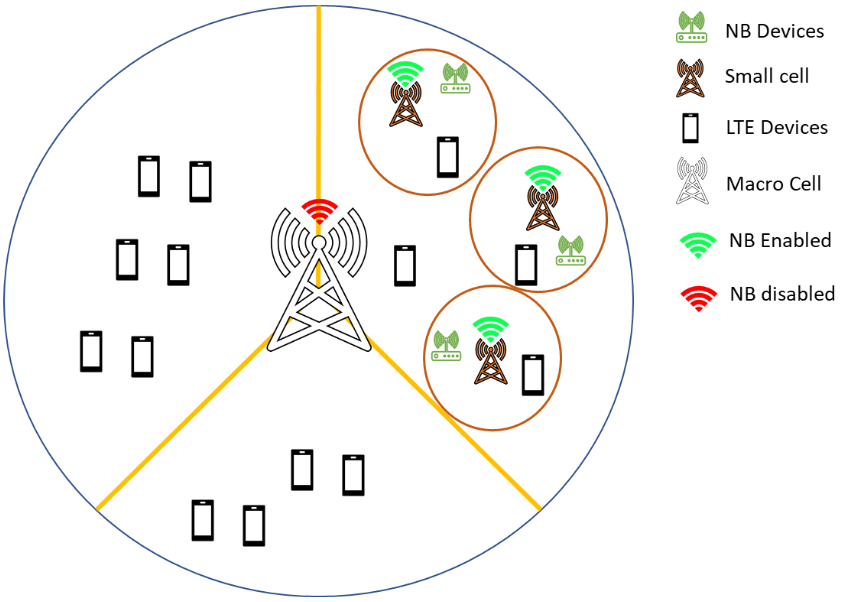


Figure 20. Second Scenario – Macro Cell with NB-IoT disabled, and Small Cell with NB-IoT Enabled.

For this scenario, because the macro cell does not have NB-IoT enabled the SINR formula only considers two domains macro cell with LTE (MLTE) and small cell with narrowband (SNB),

$$SINR\ UE_{NB_{ij}} = \frac{P_{tx}^{j} G_{i}^{j}}{PL + I_{Macro} + I_{Small} + \sigma}; \qquad (3)$$

Where, $I_{Macro} = \sum_{k \in \{\Omega_{MLTE}\} k \neq j} P_{tx}^{k} G_{i}^{k}$; $I_{Small} = \sum_{k \in \{\Omega_{SNB}\} k \neq j} P_{tx}^{k} G_{i}^{k}$

As mentioned in the previous section, the power needs to be considered at the moment to calculate the SINR either for downlink or uplink direction. For instance, the transmission power in the small cells is boosted by 6 dB.

4.1.3 Scenario 3- Macro Cell NB-IoT and Small Cell LTE

In this scenario, the macro cell supports NB-IoT technology, and the small cell only supports LTE (Figure 21). The NB-IoT users allocated in the macro cell are affected by those LTE users attached to the small cell which share the same PRB. The main difference between scenario two is that in this scenario the Tx power of the small cell does not have the 6dB boosting power, for the contrary Tx power of the macro cell is boosted.

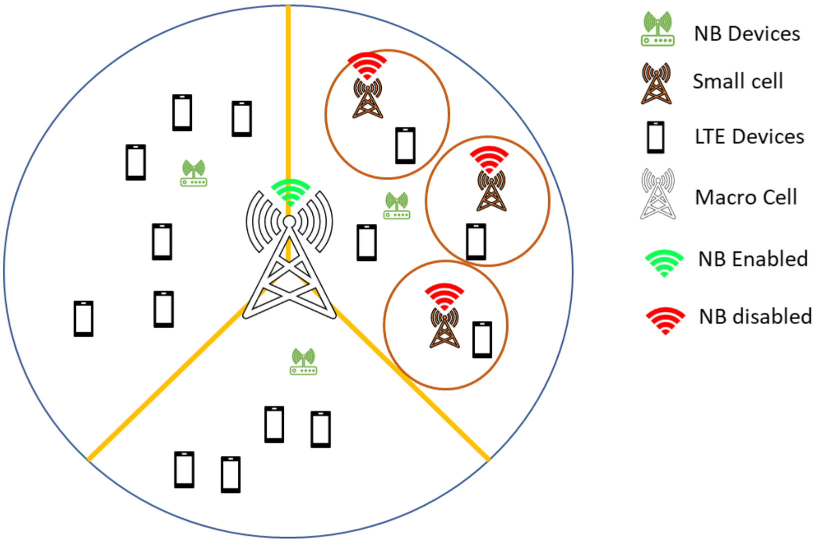


Figure 21. Third Scenario – Macro Cell with NB-IoT enabled, and Small Cell with NB-IoT disabled.

Thus, it is expected that the interference of those NB-IoT users over the macro cell will be lower than the interference experienced by the NB-IoT user on the previous scenario. Below the formulas,

$$SINR\ UE_{NB_{ij}} = \frac{P_{tx}^{j} G_{i}^{j}}{PL + I_{Macro} + I_{Small} + \sigma}; \tag{4}$$

$$I_{Macro} = \sum_{k\in\{\Omega_{MNB}\}k\neq j} P_{tx}^{k} G_{i}^{k}\ ;\ I_{Small} = \sum_{k\in\{\Omega_{SLTE}\}k\neq j} P_{tx}^{k} G_{i}^{k}$$

4.1.4 Scenario 4 – Macro and Small Cell NB-IoT

In this scenario (Figure 22), both macro and small cell support NB-IoT. It also emerges two new sub-scenarios, one when the technologies are synchronous, and the other one when they are asynchronous. When synchronous is used, all cells reserve the same PRB for NB-IoT making easier the evaluation of this case and avoiding interference from LTE users. Nevertheless, in asynchronous, a combination of interference takes place, LTE or NB-IoT users from neighboring cells could simultaneously affect NB-IoT users.

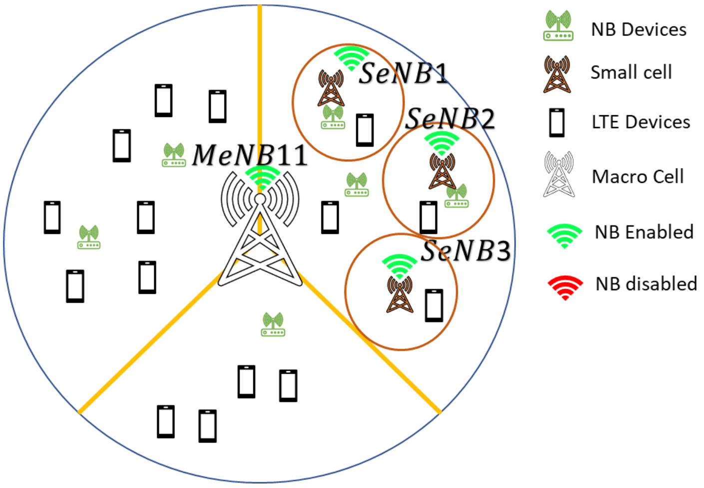


Figure 22. Fourth Scenario – Macro and Small Cell with NB-IoT Enabled.

Therefore, it is expected to see a result very close or similar to the second scenario; though they are slightly different due to the fact, that scenario two differs by having the same transmission power compared to an asynchronous mode where the PRB is either LTE or NB-IoT meaning two different transmission power. Below the formula, for this scenario, all the domains are included due to the synchronous and asynchronous mode.

$$SINR\ UE_{NB_{ij}} = \frac{P_{tx}^{j} G_{i}^{j}}{PL + I_{Macro} + I_{Small} + \sigma}; \qquad (5)$$

4.1.5 Scenario 5- Macro cell LTE and Small cell randomly assign NB-IoT

In this scenario (Figure 23), macro and small cells are deployed with both technologies; however, not all of them will radiate or support NB-IoT, the selection of which cell supports NB-IoT is random. As the fourth scenario, the fifth scenario raises two sub-scnarios which are synchronous and asynchronous.

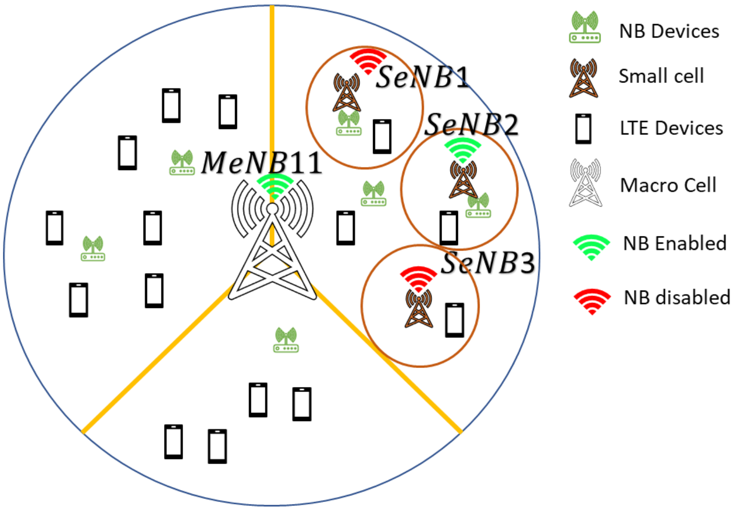


Figure 23. Fifth Scenario- Macro Cell and Small Cell with NB-IoT enabled randomly.

It is expected that the result of both sub-scenarios will be similar, because even if the cells are synchronous some of them will have NB-IoT disabled translating in an LTE RB. Below the formula, for this scenario, all the domains are included due to the synchronous and asynchronous mode

$$SINR\ UE_{NB_{ij}} = \frac{P^{j}_{tx} G^{j}_{i}}{PL + I_{Macro} + I_{Small} + \sigma} \tag{6}$$

5 Performance Evaluation of NB-IoT in HetNet Scenario

Each of the scenarios and simulations varies in the transmission power used either for the macro, small cell or in the uplink by the UE. In addition, when NB-IoT technology is enabled, a power boosting of 6 dB is injected to help in the performance against LTE users, that also incurs in interference due to closed neighboring cells. The simulation includes the calculation of the path loss with the Hata model, SINR, MCL, and downlink (DL) and uplink (UL) throughput. In the following subsections parameters, the software selected for the simulations, formulas, and models are documented.

5.1 Simulation Setup

The parameters were taken from the papers [8], [26], [28] and International Telecommunication Union (ITU) recommendation [29]. The radius coverage was selected regarding a small city and following the range stated in [29].

5.1.1 Simulation Software and Parameters

For the simulation of presented scenarios, MATLAB software is used, and the parameters utilized are in Table 4, Table 5, and Table 6.

Parameter	**Value**
Tx Power (Macro Cell)	46dBm (LTE) Max Power 29dBm +6dB Boosting (NB-IoT RB)
Tx Power (Small Cell)	40dBm (LTE) Max 23dBm +6dB Boosting (NB-IoT RB)
UE Tx Power	23 dBm
Radius Coverage	1 Km (Macro Cell) 200 meters (Small Cell)
Frequency	900 MHz
LTE Bandwidth	10 MHz
NB-IoT Bandwidth	180 kHz
Pathloss Model – Small Cells	$L = 120.9 + 37.6\log_{10}(R)$ [8] , R in kilometers
Pathloss Model – Macro Cells	Hata Model [30] Described below.
Macro cell height (BS)	20 meters
Mobile antenna height (UE)	2 meters

Shawoding	8 dB
Correlated Shadowing	0.5 dB
BS antenna gain	18 dBi
UE antenna gain	-4 dBi
BS cable loss	3 dB
Building penetration loss	40 dB
Noise figure BS	5 dB
Noise figure UE	3 dB
Noise power spectral density	-174 dBm/Hz

Table 4. RF Parameters for Simulation [8].

MCL (dB)	Repetition
Below 145	1
145 – 148	2
149 – 151	4
152 – 154	8
155 – 157	16
158 – 160	32
161 – 163	64
Above 164	128

Table 5. MCL vs Repetitions [8].

Parameter	Value
Transport Block size (TB)	680 bits (Downlink) 1000 bits (Uplink)
Resource Element (RE)	100 (Downlink) 148 (Uplink)
CRC	24 bits
Header	65 Bytes= 520bits
Time Subframe	1ms (Downlink) 1ms (1 RU, 12 sub-tones, Uplink)
Code Rate	See Sub-section 3.2.5
# bits per Modulation	2 bits QPSK

Table 6. Parameters for Throughput Calculation. The total resource element for DL and UL is [8].

5.1.2 Models and Formulas

For the calculation of pathloss for macro cell, the Hata model [30] is selected because it includes the height of the BS and UE antenna giving a more realistic model, see Table 4, the formula used is,

$$L = 69.55 + 26.16\log_{10}(f) - 13.82\log_{10}(h_B) - C_H + [44.9 - 6.55\log_{10}(h_B)]\log_{10}(d) \quad (7)$$

$$C_H = 0.8 + (1.1\log_{10}(f) - 0.7)h_M - 1.56\log_{10}(f)\ , where$$

L: Pathloss in urban areas. Unit in decibel.

$\mathrm{h_B}$: Height of base station antenna. In meter.
$\mathrm{h_M}$: Height of mobile Station antenna. In meter.
f: Frequency of transmission. In Megahertz.
$\mathrm{C_H}$: Antenna height correction factor.
d: Distance between the base and mobile stations. In kilometer.

For the noise floor, the following formula is used,

$$P = kTB, that\ for\ room\ tempeture\ of\ 290\ degree\ kelvin\ is\ equal\ to\ -174\ dBm/Hz$$

$$\text{Noise floor} = -174 + \text{NF} + 10\log_{10}(\text{Bandwidth}) \quad (8)$$

$\text{NF} = \text{Noise Figure};\ \text{P} = \text{Power in watts}$
$\text{K} = \text{Boltzmann's constant} = 1.380649 * 10^{-23}\text{J/K}$
$\text{B} = \text{Bandwidth in Hz}$

The maximum coupling loss formula is,

$$MCL = P_{tx} - Noise\ Figure - Noise\ Floor - 10 * \log_{10}(B) - SINR \text{ [8]} \quad (9)$$

For the throughput calculation, the formula is gathered from [8]

$$Thr = \frac{TB}{TT} \quad (10)$$

Where,

$$TT = \left(\frac{(TB + CRC + header)\left(\frac{1}{CR}\right)}{\#bits * RE}\right) * Rep * T_{SF}$$

TT = Transmission time.
CR = Code Rate.
Thr = Throughput.
Rep= number of Repetitions.
Tsf= Subframe time

Code Rate:

For the code rate, first, the MCS needs to be stipulated. To gather the correct MCS, the SINR is essential. By having the SINR, the MCS is extracted from Table 7 and Table 8 depending on which channel is utilized. These tables are extracted from the standard [31], [32] and master's thesis [33]. After the MCS is declared, the code rate should be calculated by using Table 9 and Table 10. The table contains the number of TBS that can be transmitted depending on the MCS and how many RU needs to be used to transmit certain TBS or the number of bits. For PDSCH the maximum TB size is 680 bits and 1000 bits for PUSCH. For instance, if 600 bits need to be transmitted with an MCS of 5, then 8 RUs allocated in scheduling.

From the book [18], the code rate is calculated as follow, *"First, a 24-bit CRC is calculated and attached to the TB. The CRC-attached TB is encoded using the TBCC encoder and rate-matched according to the code-word length determined jointly by the number of NPDSCH subframes allocated to the TB and the number of REs per subframe. Thus, the combination of TB size and the number of NPDSCH subframes allocated to the TB determines the coding rate."* [18]

SINR	**MCS**
-3	0
-2	1
-1	2
0	3
1	4
2	5
3	6
4	8
5	9
6	10

Table 7. MCS vs SINR for PDSCH [33].

SINR	**MCS**
-4	0
-3	1
-2	2
-1	3
0	4
1	5
2	6
3	7
4	8
5	9
6	10
7	11
8	12

Table 8. MCS vs SINR for PUSCH multi-tone [33].

Therefore, by having the correspondent TBS and number of RUs, the code rate is,

$$CR = \frac{TBS+24}{Mod*RU*RE} \tag{11}$$

Mod: number of bits for the modulation in use (2 bits for QPSK).
RU: number of resource units.
RE: number of resource elements.

MCS	Number of Resource Units							
	1	**2**	**3**	**4**	**5**	**6**	**8**	**10**
0	16	32	56	88	120	152	208	256
1	24	56	88	144	176	208	256	344
2	32	72	144	176	208	256	328	424
3	40	104	176	208	256	328	440	568
4	56	120	208	256	328	408	552	680
5	72	144	224	328	408	504	680	-
6	88	176	256	392	504	600	-	-
7	104	224	328	472	600	680	-	-
8	120	256	392	536	680	-	-	-
9	136	296	456	616	-	-	-	-
10	144	328	504	680	-	-	-	-

Table 9. Mapping Between MCS, RUs, and TBS for PDSCH [32].

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

Table 10. Mapping Between MCS, RUs, and TBS for PUSCH [31].

5.2 Simulation Process

The superlative simulation method used is the Monte Carlo method with 1000 samples to get enough information to obtain the correct behavior of the interference for different radio conditions. The simulation is run first for all the scenarios without any scheduling optimization algorithm, after having this result the next step is to run the simulation with the cooperative approach to evaluate and see how the scheduling by cooperative method improves the performance of the cells in an HetNet environment.

5.2.1 Scheduling of None Optimization Algorithm Implemented

In Figure 29, a flow diagram illustrates all the simulation steps. The simulation **starts** by creating a macro cell within 1 Km radius coverage which is common in an urban environment. **Second**, the small cells are created randomly inside the macro cell coverage with the conditions of being inside the macro cell without touching the edges, and a radius of 200 meters coverage. Another restriction is that the small cells cannot overlap with each other.

Third, the UEs are randomly allocated in the macro cell, and then into the small cells. In the MATLAB script, the number of users can be easily changed. The macro cell is populated with 100 users, seven small cells, and 25 users per small cell (The macro cells are created as a structure variable).

Fourth, the SNR is calculated for each of the users for macro cell and small cell. This is used for the scheduling process. For the SNR calculation, it is taking into consideration the white Gaussian noise, and the model path loss described in above section 5.1.2. For macro cell coverage, the Hata model is used to consider the height of the antenna. And for small cell the model stated in Table 4 [8] is used.

The **fifth step** is the execution of the scheduling by using the maximum rate by measuring the SNR.

The SNR is sort and user’s allocation or scheduling is performed, see algorithm I (Figure 24). The interference is calculated as follow; for SINR downlink calculation relate to algorithm II (See Figure 25), the simulation is performed by calculating the contribution of all the base station within the coverage area with respect to the evaluated UE, see Figure 27. The uplink SINR is calculated (Algorithm III, Figure 26) by calculating the contribution of the other UEs allocated in the same resource unit (RU) with respect to the evaluated cell, see Figure 28. The procedure is executed 100 times to get the average of path loss which takes into account the shadowing and co-shadowing of 8 dB.

```
Algorithm I: Scheduling of None Optimization Algorithm Implemented
Initialization:
Set RB Ptx;
Set cell coordinates x, y
Set Lt; total lost (cables and penetration)
Set GainBS and GainUE
Set TS; # of time slot available
Start:
for all TS do
    dist=calculate distance (cell and UE coordinates)
    PL=calculate path loss (dist, Lt);path loss model
    SNR(i)=calculate SNR(PL)
end for
Scheduling:
index = sort(SNR)
New TS allocation (index)
```

Figure 24. Algorithm I, scheduling of None Optimization Algorithm Implemented.

```
Algorithm II: SINR DL
Initialization:
Set RB Ptx;
Set UE coordinates x, y
Set Lt; total lost (cables and penetration)
Set GainBS and GainUE
Set TS; # of time slot available
Set Noise=Noise_down; (calculate with Noise floor formula)
Start:
for all UE do
    for all Scells do ; # of small cells
        dist=calculate distance (neigboring cell and UE coordinates)
        for j=1 to 100 do
            pl(j)=calculate path loss (dist, Lt); path loss model
        end for
        PL=average(pl);
        Int += Calculate interference (Ptx, PL, GainBS, GainUE) ; Interference
    end for
    SINR(UE)=calculate SINR(Ptx, PLi, GainBS, GainUE, Noise, Int)
end for
```

Figure 25. Algorithm II, Calculation of SINR DL.

```
Algorithm III: SINR UL
Initialization:
Set UE Ptx;
Set Cell coordinates x, y
Set Lt; total lost (cables and penetration loss)
Set GainBS and GainUE
Set TS; # of time slot available
Set Noise=Noise_up; (calculate with Noise floor formula)
Start:
for all UE do
    for all Scells do; # of small cells
        dist=calculate distance neighboring UE and Cell coordinates)
        for j=1 to 100 do
            pl(j)=calculate path loss (dist, Lt) ;path loss model
        end for
        PL=average(pl);
        Int += Calculate interference (Ptx, PL, GainBS, GainUE) ; Interference
    end for
    SINR(UE)=calculate SINR(Ptx, PLi, GainBS, GainUE, Noise, Int)
end for
```

Figure 26. Algorithm III, Calculation of SINR UL.

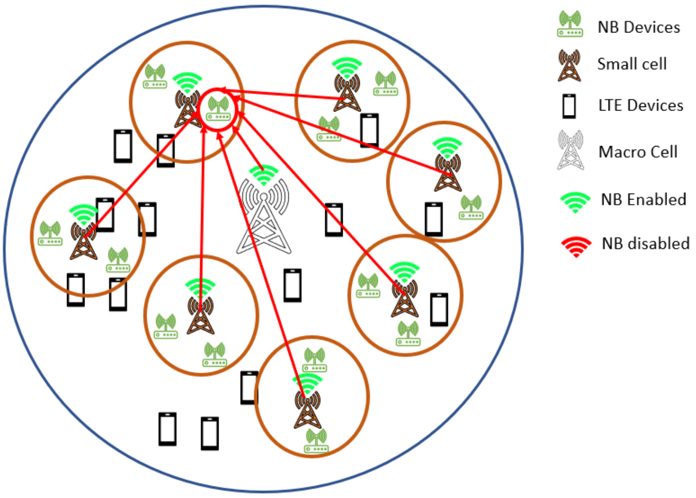


Figure 27. MATLAB Downlink SINR with respect to BS.

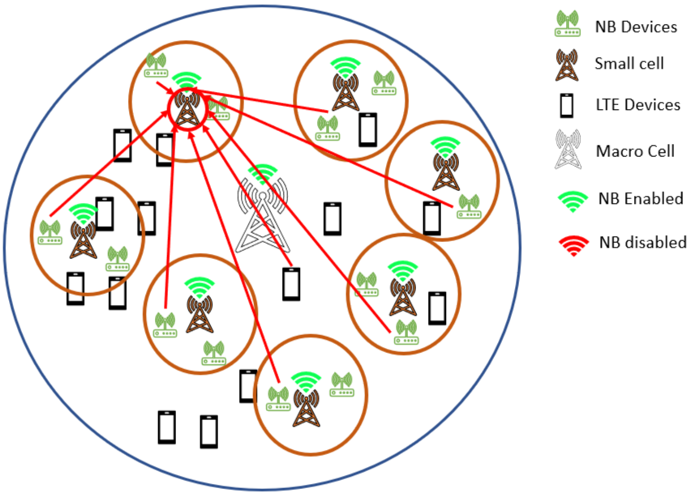


Figure 28. MATLAB Uplink SINR with respect to UE.

Subsequently, the throughput is calculated which is the main KPI of evaluation for the scenarios in this thesis. To calculate the throughput, the next procedures state the steps to get a reliable calculation:

I. With the calculated SINR, the MCL is calculated to get the number of repetitions that need to be added to the transmission by following the formula presented in section 5.1.2 and Table 5.

II. The code rate is calculated as stated in section 5.1.2, the MCS is extracted from Table 7 or Table 8 by using the SINR, after obtaining the value of MCS, in the table the number of RUs and TBS are selected and the throughput formula is applied.

III. By having followed I, II, and III steps, the throughput is calculated by using the formula in section 5.1.2 where the TB size is chosen as the maximum, 680 bits and 1000 bits for PDSCH and PUSCH, respectively.

Above procedure or methodology is described for one UE. However, the evaluation is performed on the cell; therefore; the SINR and throughput are averaged per cell as shown in the above flow diagram.

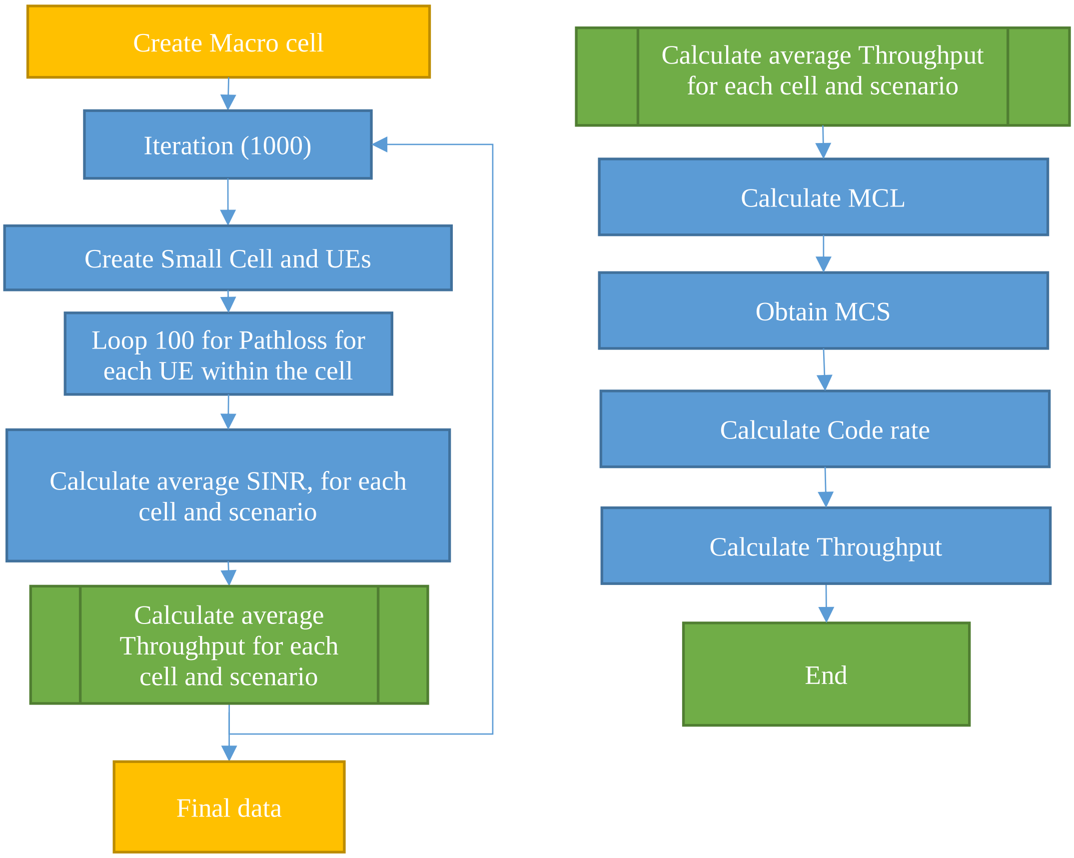


Figure 29. Flow Diagram of the simulation for the throughput calculation. The throughput is calculated overall cell; therefore, the throughput is averaged of all the users within the small cell.

5.2.2 Scheduling of Cooperative Algorithm (Optimized)

Figure 31 shows the flow diagram of the cooperative algorithm. The cooperative method is implemented with the aim of reducing the interference caused by neighboring cells or user by communicating between them. This means that the macro and small cells are communicating with each other the current interference status in every time slot; this communication is performed via the interface X2. Consequently, for the simulation, all the procedures stated on sub-section 5.2.1 are followed until the fifth step allocation by SNR.

In this part, the process differs. The interference is calculated for each user or timeslot occupied. An SINR or interference threshold is set. Before calculating the throughput or assigning the resource, the interference is measured as explained in the sub-section 5.2.1 depending on DL or UL.

```
Algorithm IV: Cooperative Algorithm
Initialization:
Set UE Ptx;
Set Cell coordinates x, y
Set Lt; total lost (cables and penetration loss)
Set GainBS and GainUE
Set TS; # of time slot available
Set Noise=Noise_up; (calculate with Noise floor formula)
Set SINR threshold;
Start:
for all UE do
    for all Scells do; # of small cells
        dist=calculate distance (neighboring UE and Cell coordinates)
      for j=1 to 100 do
        pl(j)=calculate path loss (dist, Lt) ; using the corresponding path loss model
      end for
      PL=average(i);
      Int += Calculate highest interference (Ptx, PL, GainBS, GainUE) ; Interference
  end for
      SINR(UE)=calculate SINR(Ptx, PLi, GainBS, GainUE, Noise, Int)
    if SINR < threshold
    I=calculate interference (threshold);  min interference to aim the threshold
    Pngh = calculate power (I); power that neighbor should transmit.
    SINRngh= calculate SINR(Ptx, PLi, GainBS, GainUE, Noise, Int); neighbor SINR
       if SINRngh<threshold
            Pngh= calculate power(threshold); reduce the power is possible
       else
            Next UE for scheduling
            sch=0; whether the UE is schedule (1) or not (0).
       break
       end if
       Int = Calculate interference (Pngh, PL, GainBS, GainUE)
        SINR(UE)= calculate SINR(Ptx, PLi, GainBS, GainUE, Noise, Int); again considering new Pngh
      sch=1; whether the UE is schedule (1) or not (0).
    else
      Next UE for scheduling
      sch=0; whether the UE is schedule (1) or not (0).
    end if ; end for
```

Figure 30. Algorithm IV, Cooperative Method.

When the interference is calculated is compared with the threshold, see algorithm IV (Figure 30), if this interference is higher than the set value. The cell communicates with the neighboring cell requesting to reduce the Tx power either of itself or UE. If it is possible to reduce the power and keep the interference of the neighbor above the threshold, the neighbor will agree to reduce the power. But if unfortunately, it is not possible to reduce the power requested, the neighboring cell or UE will reduce its power to the minimum taking into account the interference threshold limit.

This procedure is followed in every UE allocation either UL or DL. After the allocation is concluded the throughput is calculated as former sub-section 5.2.1.

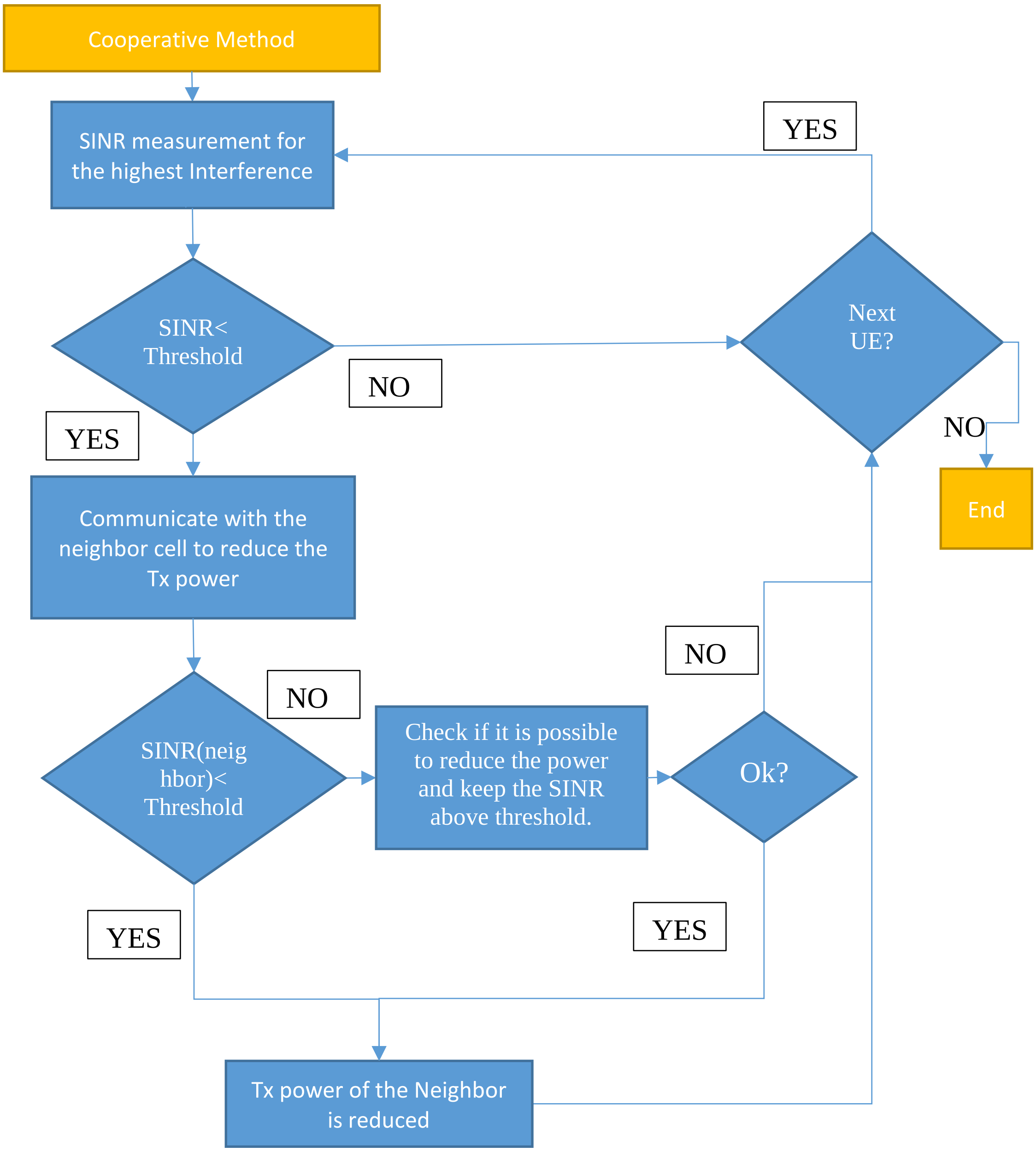


Figure 31. Flow Diagram of Cooperative Algorithm.

5.3 Simulation Results

It is important to mention that all the results are shown in a cumulative distribution function (CDF) graph. Furthermore, all the measurements are considered for NB-IoT technology. As explained in section 5.2.1, and illustrated in Figure 27 and Figure 28; for downlink, the interference measurement is performed over the UE which is listening to the signals coming from the neighboring cells; and for uplink, the interference measurement is performed over the cell that is now listening to the UEs. In section 4, the description of each of the scenarios explains that some of them produce a similar result, consequently, the analysis is focused on those which present a more significant difference.

5.3.1 None Cooperative Case (DL)

Figure 32 shows the result of the simulation for each of the scenarios and illustrates that a few of the scenarios present similar behaviors or SINR conditions.

Therefore, only the following four scenarios are considered for analysis:

- Scenario 1 (SC1 Only Scell(NB))
- Scenario 2 (SC2 MCell(LTE)-SCell(NB))
- Scenario 4 synchronous mode (SC4 Synch MCell(NB)-SCell(NB)),
- Scenario 5 synchronous mode (SC5 Synch MCell(LTE or NB)-SCell(LTE or NB))

Figure 32 shows the result of the achievable downlink throughput and SINR. Where the third scenario excels having exceptionally SINR condition than the rest of the scenarios. Consequently, the achievable throughput results are 60% better than the other scenarios. This is because the interference coming from the small cells is lower due to the no boosting in the transmission power considering that none of the small cells have NB-IoT enabled.

It is noted that the maximum throughput does not match the one on [17] 226.7 kbps because of the CRC and header inclusion in our calculation, plus the repetitions. From the results, the throughput range is between 2.5 and 57 kbps approximately. The minimum throughput of 2.5 kbps correspondent to SC5, 3.28 kbps to SC4, and 5.98 kbps to SC2.

As expected the first scenario which does not involve macro cells, offers a higher throughput compared to the other scenarios, and this is because the interference is lower. And the most affected scenario is SC2 where macro cells and small cells support NB-IoT. In this particular scenario, the SINR is higher than the other scenarios due to the power boosting of 6 dB used, besides the power used over the macro cell is 6 dB higher than the small which incurs in a higher interference from small cells.

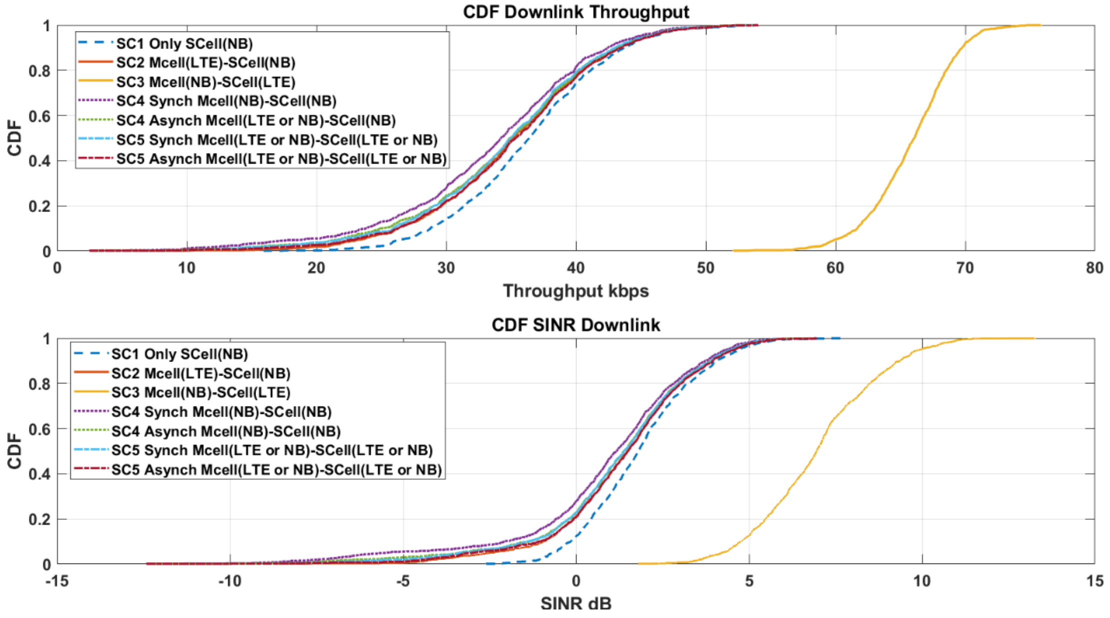


Figure 32. Downlink throughput and SINR results for all scenarios. SC stands for the scenario, SCell for Small cell, MCell for macro cell. When LTE or NB is stated, it means that the cells could or not have NB-IoT enabled during each iteration in the simulation, and this was selected randomly. Synch and Asynch states for synchronous and Asynchronous respectively. For synch, it means that the two technologies are synchronous and works in the same PRB. For Asynch, the technologies utilize different PRB.

From Figure 32, The gap between the scenarios is small. For instance, between SC1 and SC4 the gap is 3.49 kbps which indicates that SC1 offers 11% higher information rate; SC1 is 5.5% and 7.5% better than SC2, and SC5 respectively.

5.3.2 None Cooperative Case (UL)

With respect to uplink there are only two scenarios possible without and with the presence of macro cell:

- Scenario 1 only small cells (SC1 Only SCell (NB))
- Scenario 2 HetNet (SC2 MCell(LTE or NB)-SCell(LTE or NB))

The reason for having above-mentioned uplink scenarios is because the uplink power (23 dBm) is the same when evaluating the rest of the scenarios, the UE transmission power does not vary.

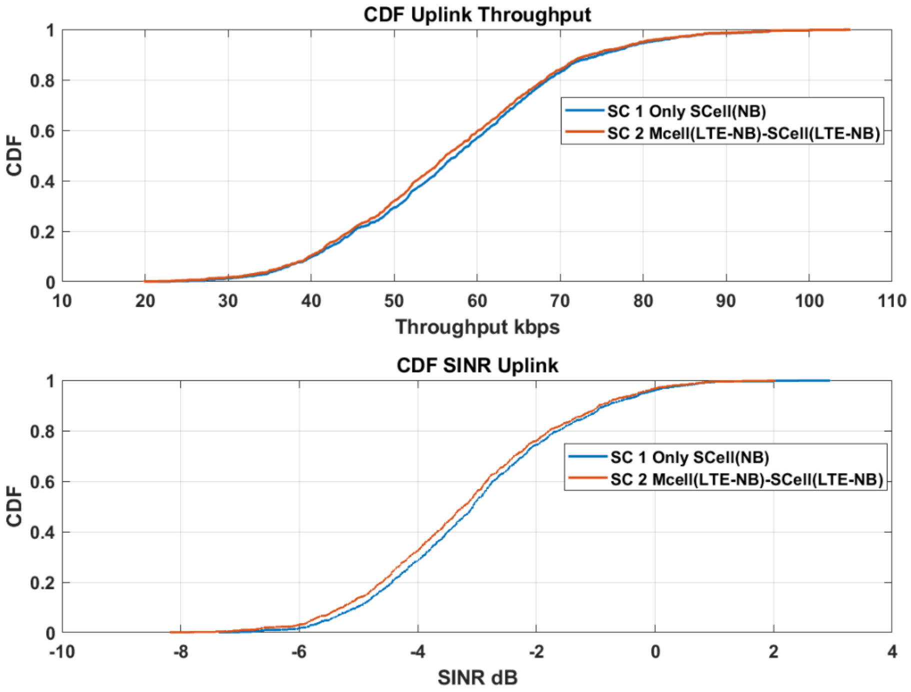


Figure 33. Uplink throughput and SINR results for uplink scenarios. SC stands for the scenario, SCell for Small cell, MCell for macro cell. When LTE or NB is stated, it means that the cells could or not have NB-IoT enabled during each iteration in the simulation, and this was selected randomly.

Figure 33 shows the result of achievable uplink throughput and SINR. From the results, the maximum achievable throughput was 100.4 kbps, and 105 kbps for SC1 and SC2 correspondingly. The minimum uplink throughput for SC1 was 19.89 kbps and SC2 21.57 kbps. This implies or corroborates that the presence of macro cells users collaborates negatively in the SINR hence obtaining in low throughput. Between SC1 and SC2, the gap is just 2.3%.

The simulation was also run with different penetration loss to evaluate diverse indoor coverage, those penetration loss values utilized were 20 dB and 30 dB. It is clear from the results that throughput improves due to lower interference. For instance, the SINR for SC1 in uplink and downlink never dropped below zero. See Appendix A – Simulation with different penetration loss.

5.3.3 Cooperative Case (DL)

As stated in section 5.3, the results and analysis selected are four, refer to that section. Firstly, it seen that the maximum through reached by cooperative approach is higher compared to former results with none optimization methods; however, this is caused due to the fact that in this result only the users, which are using cooperative method or in which time slot the method is applied, are considered; hence an increase in the average throughput. Additionally, the throughput seen in the graphs is only for those users and not for the overall cell. Secondly, Throughput and energy consumption are used as KPIs in this analysis. Figure 34 presents the result of achievable throughput, SINR, and energy consumption.

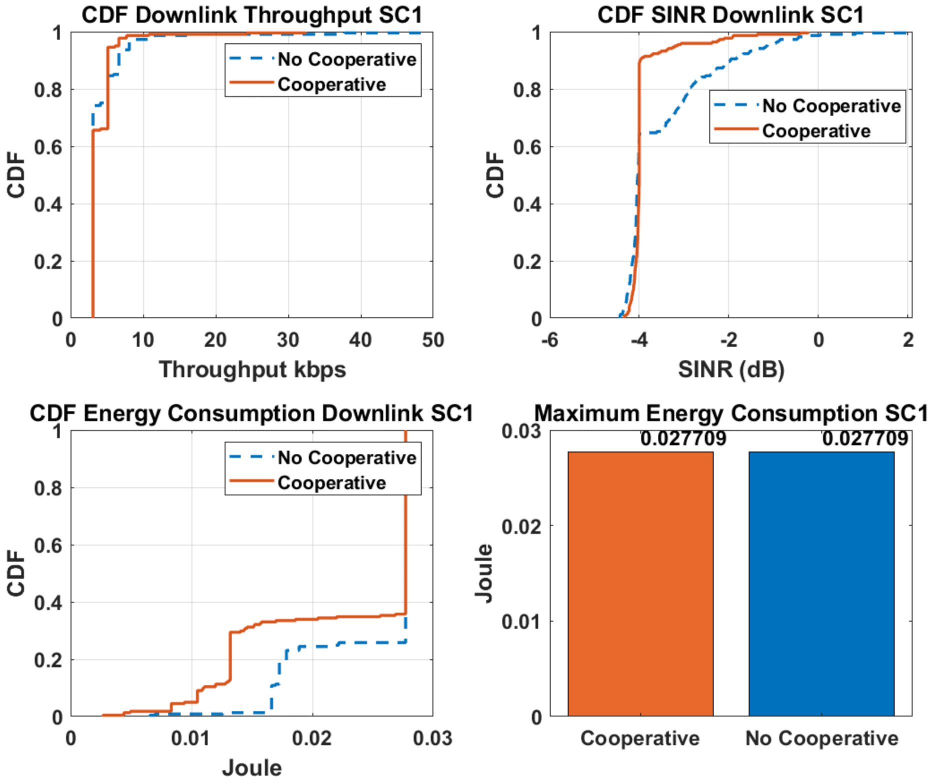
Figure 34 (a) illustrates the cooperative result for the first scenario. As expected the gap between no cooperative and cooperative results is not significant. Nevertheless, it improves the energy consumption as seen in the third graph in Figure 34 (a), even though, both cooperative and none cooperative achieve the same maximum energy consumption.

The gap percentage between cooperative and no cooperative are 14% increment and 23% decrement for throughput and energy consumption, respectively. However, the maximum throughput in cooperative is lower than no cooperative. Which indicates that the cooperative approach improves the interference for some user by decreasing the SINR to others.

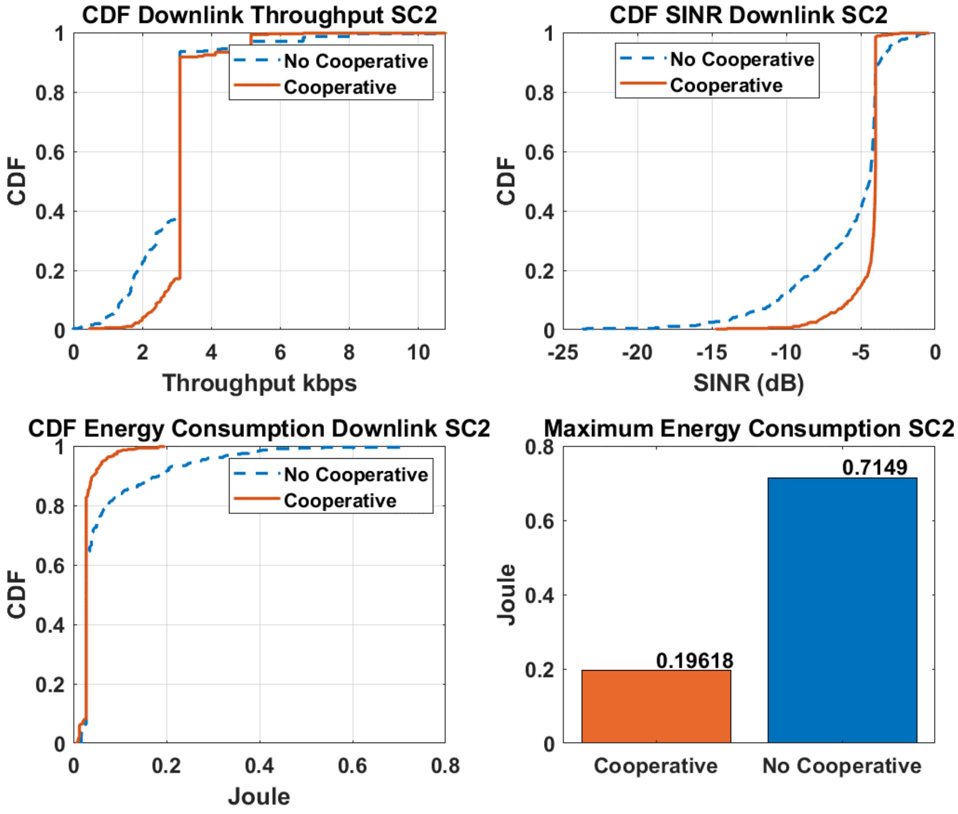
The straight line, seen in the graph for all scenarios, corresponds to the SINR threshold, as many of the cells reduce its power to achieve the threshold, the CDF shows a rapidly change to 1.

Figure 34 (b), (c), and (d) shows that the cooperative approach presents an enhancement when it is utilized in an HetNet environment.

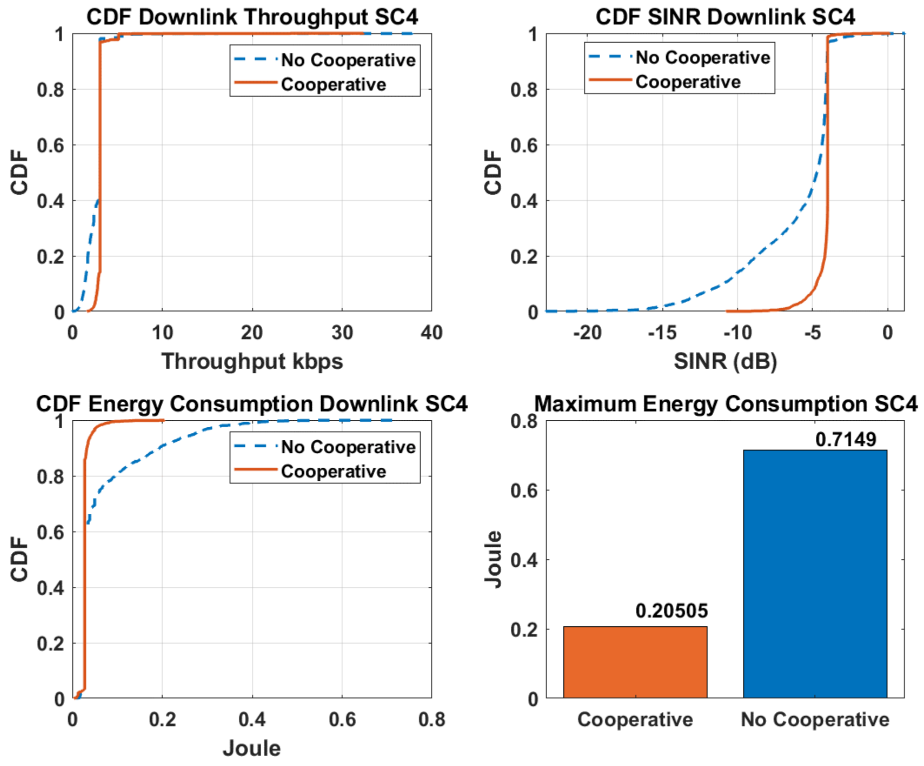
In Figure 34 (b), the second scenario shows an improvement in throughput of 78% and a reduction of 64% of energy consumption, and the maximum energy consumption for cooperative is 71% reduced.


CDF Downlink Throughput SC1
CDF
Throughput kbps
0
10
20
30
40
50
0
0.2
0.4
0.6
0.8
1
No Cooperative
Cooperative
CDF SINR Downlink SC1
CDF
SINR (dB)
-6
-4
-2
0
2
No Cooperative
Cooperative
CDF Energy Consumption Downlink SC1
CDF
Joule
0
0.01
0.02
0.03
No Cooperative
Cooperative
Maximum Energy Consumption SC1
Joule
0
0.01
0.02
0.03
0.027709
0.027709
Cooperative
No Cooperative

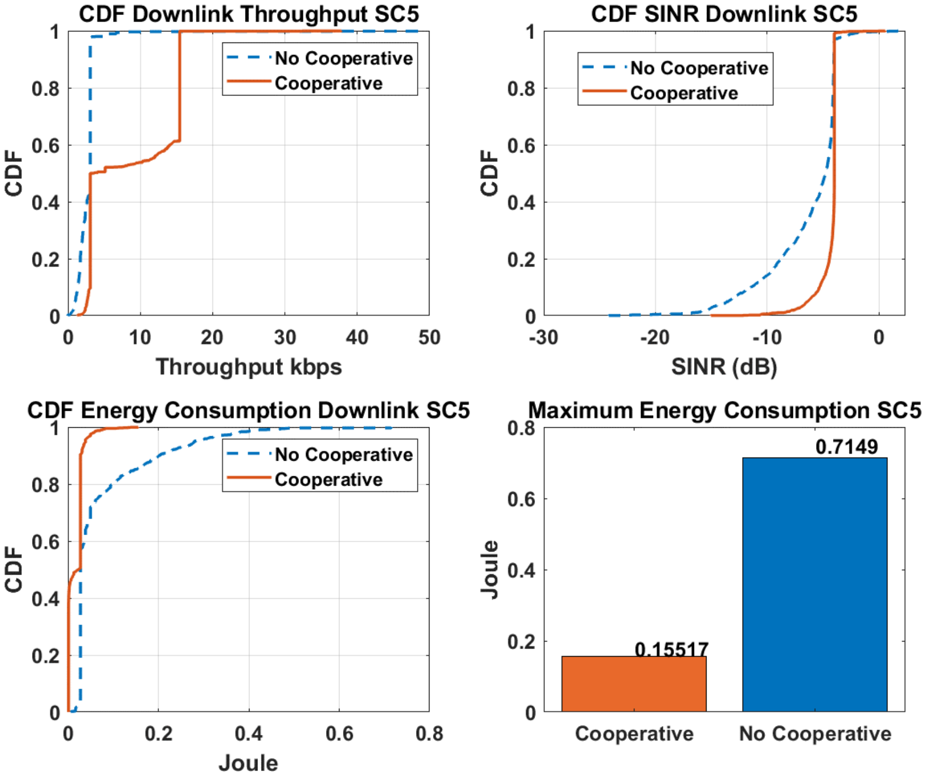
a)


CDF Downlink Throughput SC2
CDF
Throughput kbps
0
2
4
6
8
10
0
0.2
0.4
0.6
0.8
1
No Cooperative
Cooperative
CDF SINR Downlink SC2
CDF
SINR (dB)
-25
-20
-15
-10
-5
0
No Cooperative
Cooperative
CDF Energy Consumption Downlink SC2
CDF
Joule
0
0.2
0.4
0.6
0.8
No Cooperative
Cooperative
Maximum Energy Consumption SC2
Joule
0
0.2
0.4
0.6
0.8
0.19618
0.7149
Cooperative
No Cooperative

b)



c)



d)

Figure 34. Downlink scenario comparison between no cooperative and cooperative. (a) Scenario 1 (Only small cell environment). (b) Scenario 2 (Macro cell NB-IoT disabled and Small cell NB-IoT enabled). (c) Scenario 4 comparison between no cooperative and cooperative. (d) Scenario 5 comparison between no cooperative and cooperative. The evaluation is shown for throughput, SINR, and energy consumption. SC: scenarios.

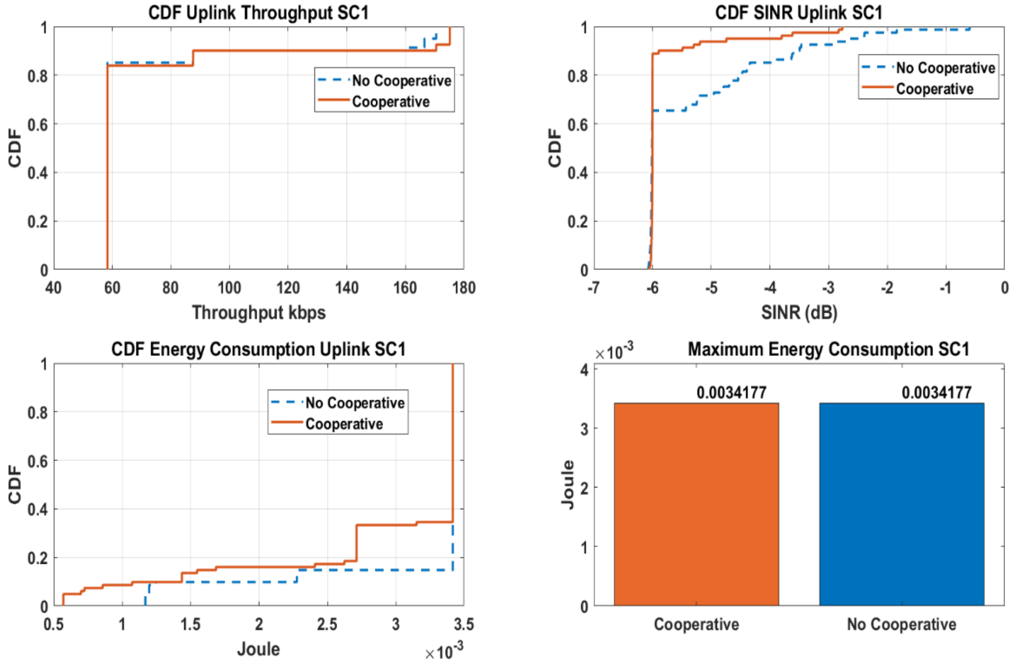
Figure 34 (c) shows that the fourth scenario the improvement in throughput is 80% and a reduction of 73% in energy consumption. In Figure 34 (d), the fifth scenario presents a gap of 80% and 68% for throughput and energy consumption, respectively. By comparing the cooperative method applied to the different scenarios, it points out that the best result in cooperative approach is when the HetNet strategy deployment both macro and small cells (scenario 4 and 5) have NB-IoT enabled.

For Scenario 4 and 5 with a cooperative approach, the maximum energy consumption for cooperative is 71% and 78% reduced respectively.

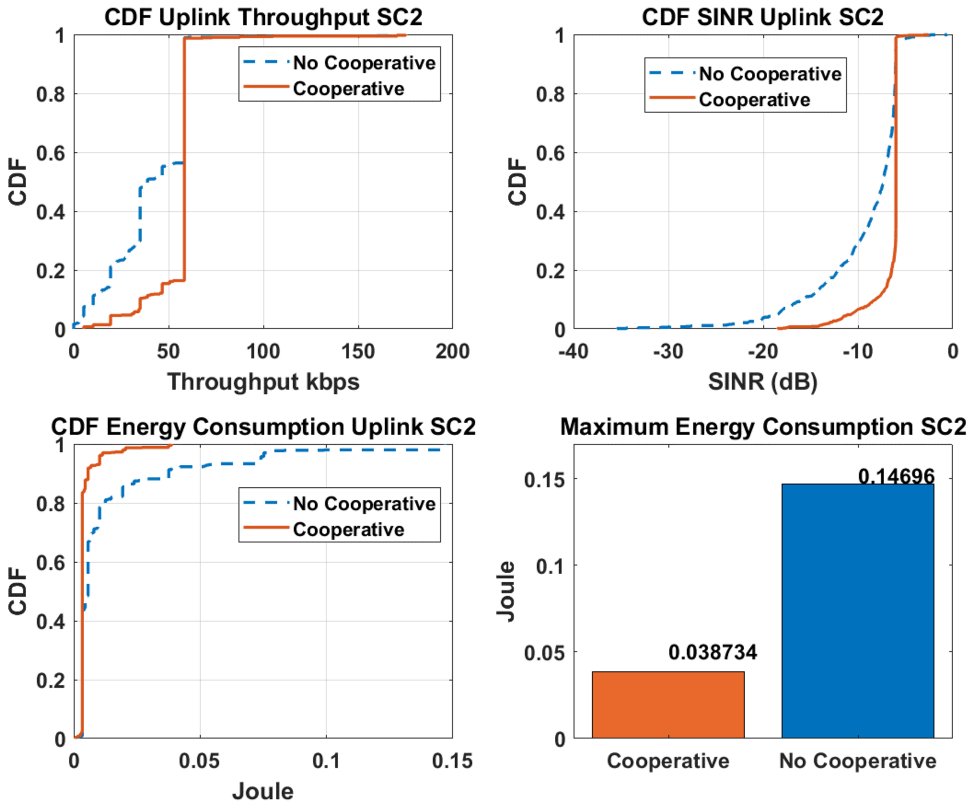
5.3.4 Cooperative Case (UL)

Figure 35 presents the result of achievable throughout, SINR, and energy consumption.

Figure 35 (a) exposes the same behavior seen in the downlink. For the first uplink scenario, the cooperative method does not improve the throughput significantly. However, in the uplink, the average power consumption was reduced; still for both cooperative and no cooperative the maximum achievable power consumption are equal.



(a)



(b)

Figure 35. Scenario 1 and 2 Uplink comparison between no cooperative and cooperative (a) Scenario 1 (b) Scenario 2. The evaluation is shown for throughput and energy consumption.

Figure 35 (b) illustrates how the cooperative approach performs better in a HetNet environment. As expected, it reduces the interference which leads to an improvement in the throughput and energy consumption, the gaps between no cooperative and cooperative are 66% and 67% correspondingly. The maximum energy consumption for cooperative is 73% reduced.

Figure 36 shows in a more qualitative and descriptive view of how the cooperative method enhances the performance of the cell in each of the scenarios. The measured indicators are minimum power, average throughput, minimum SINR, the maximum number of repetitions, and maximum energy consumptions.

The values go from 0 to 1. This scale is taken as a qualitative measurement which 0 means the worst case and 1 the best. For instance, in scenario 2 (HetNet Macro with NB-IoT disabled and Small with NB-IoT enabled), in absent of cooperative approach there is more energy consumption, the SINR and throughput are lower compared to the cooperative. Because the average throughput is very close it cannot be seen the improvement on a big scale. As dictated before, the SC1 DL and SC1 UL there is not a big difference between cooperative and none cooperative approach.

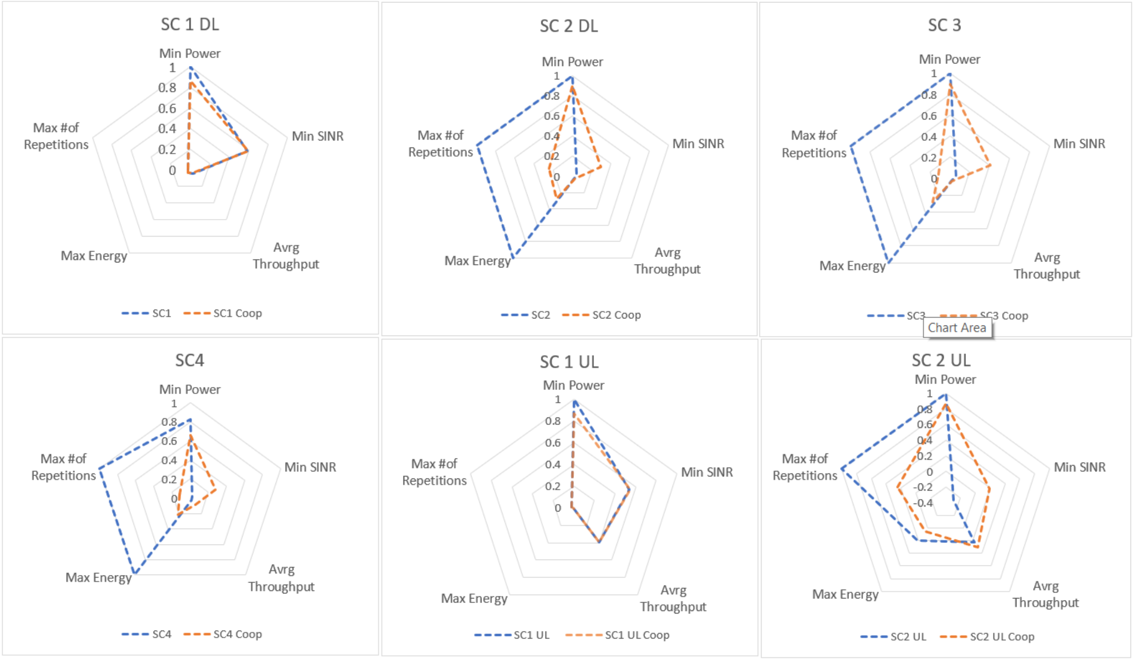


Figure 36. Radar Graph for each of the scenarios. As all the parameters have a different unit, each of those parameters is shown in the rank between 0 to 1 to have a better comparison. Thus, those values represented are not the real values obtained in the simulation. For each parameter, it was selected minimum, maximum or average to show the improvement. For instance, the minimum power is chosen because the cooperative approach reduces the power of the interference cell or user.

6 Conclusion

This study presents the interference concern of the different deployment strategies of NB-IoT technology in an HetNet environment and an interference management method to improve the performance of the cells or the overall network. Different scenarios which involve enabling and disabling NB-IoT were evaluated; the results prove that the best-case scenarios, which present a lower interference hence higher throughput, are scenarios 2 and 5, macro cell without NB-IoT and small cell with NB-IoT, and Macro cell and small cell with either LTE and NB-IoT in synchronous mode, respectively. These two scenarios are characterized in controlling a mix LTE and NB-IoT activation, which gives the advantage of having some cells transmitting with a lower power which corresponds to LTE that has not boosted power. All these results are shown in a CDF graph of 1000 samples using the Monte Carlo method.

By having performed this simulation gives us a perspective of how a real HetNet environment behaves when NB-IoT technology is deployed. Moreover, it helps to understand the root of the interference and opens the door to implement an interference management method with the aim of enhancing the performance of the cells. For the cooperative, the idea was to have communication between neighbors before scheduling the user. Results have proved that the interference management works as expected showing better throughput and lower energy consumption which contributes to having a longer battery lifetime.

This thesis produces an extensive study of how the performance of the new technology will perform in 5 possible deployment strategies. This offers crucial information to the researcher to see how the technology could perform in a real environment, more than that, the study is helpful to telecom engineer which are working in maintaining high standards performance to end user. For instance, before implementing or deploying this technology in a certain region or zone, the engineers can verify what kind of user and how many are covered by macro or small cells. After, they can utilize the above results of the scenarios and choose one accordingly. In addition, they can see the cooperative results over that specific scenario and decide if this method should be activated. However, the cooperative approach showed a good result in all the scenarios. It is important to mention that this thesis covers the gaps of previous work which did not include any HetNet scenario involving NB-IoT.

There are more open research fields after this work, for example, how the cooperative method could be improved by implementing a sort of prediction either in the cell or devices. It could be enough to get a model or a simple prediction algorithm or it is necessary to involve artificial intelligent or learning machine to predict the interference and act accordingly without asking to measure the inference continuously and employ the cooperative method.

Another future research is the cancellation of interference in hardware, diversity implementation in NB-IoT. Besides, the investigation of device 2 device communication could be implemented to guarantee reliability and zero outage to those users which are presenting bad RF conditions.

Nevertheless, a limitation in this research was the absence of a simulation tool for NB-IoT, for instance, a MATLAB tools that allows to the researcher to set certain parameters such as a number of users, packet size, etc... and this could accelerate the research. Thus, I recommend for further research on this field to build a complete NB-IoT communication system which can guarantee better progress in this field and giving more time for proposing solution or method to guarantee a better service.

As this thesis was funded by one of the telecom operators in Tallinn, which has already deployed NB-IoT technology in their network. This result will give them the advantage of sharing this data to their engineer to run some optimization in their network.

Overall, the thesis offers a conclusive result that cooperative approach guarantees a lower energy consumption, and high throughput by reducing the interference generated by neighboring cells or UEs. New challenges are raised related to prediction either by modeling or implementation of artificial intelligence. And finally, extends the knowledge of NB-IoT deployment in a HetNet environment which could help telecom engineer in their daily work.

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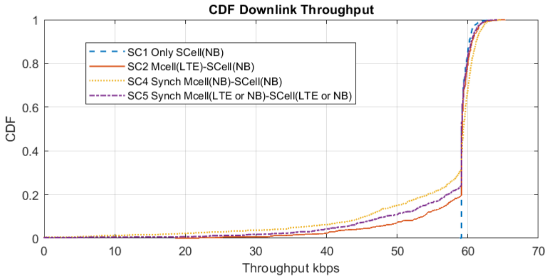
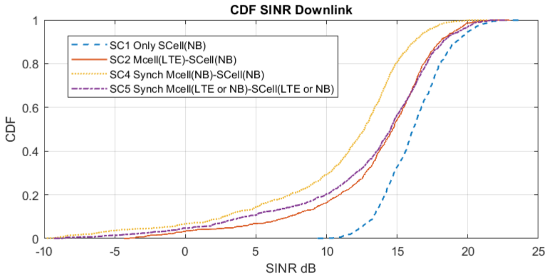
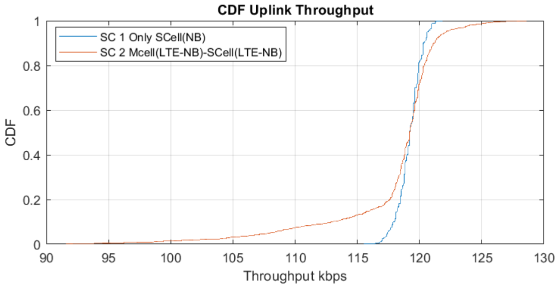
Appendix A – Simulation with different penetration loss

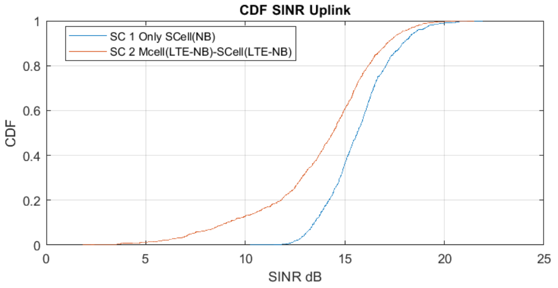
Here the result for different penetration loss.

Penetration loss of 20 dB









Penetration loss of 30 dB