Analysis of the NB-IoT technology towards massive Machine Type Communication

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Abstract

The Internet of Things (IoT) is going to redefine the way people interact with each other and with the objects that surround them, with the goal of creating a global network connecting everyone, and everything. IoT is expected to accommodate massive Machine Type Communication (mMTC), in which devices transmit and receive a small amount of data, with the goal of improving industrial and metering processes, health services, and transportation, to mention a few.

Low Power Wide Area (LPWA) radio technologies have emerged as a solution for the design of mMTC, satisfying the requirements of low power consumption, low data rates, scalability, and long range. Narrow Band (NB) approaches are being analyzed by research and standardization communities, and some candidates for the creation of LPWA networks have been proposed and deployed, towards a satisfying balance between the challenge of accommodating many devices and the optimal exploitation of the limited spectrum resources.

3GPP introduced in 2016 (Release 13), the Narrowband Internet of Things (NB-IoT), as a brand new cellular technology, thus going to be a step forward 5G based IoT implementation. NB-IoT is compatible with 4G Long Term Evolution system (LTE), and with 2G Global Systems for Mobile communication (GSM). This advantage, added to a higher spectral efficient usage, places the technology in a privileged position for the implementation of LPWA networks.

Late 2017 and 2018 will be the initial period where operators like Vodafone, Huawei, T-Mobile along with Qualcomm, Ericsson, Deutsche Telecom, or Telecom Italia, among others, will deploy their NB-IoT architectures on a country basis.

The aim of this work is to analyze the deployment of NB-IoT technology in a dense urban scenario, and the performance enhancement of NB-IoT devices thanks to signal repetition procedures. Furthermore, a preliminary analysis of an heterogenous architecture is presented, that embeds the traditional cellular outdoor architecture formed by macrocells, with indoor small cells, with the goal of increasing the overall system coverage.

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1 Introduction

1.1 Internet of Things

The Internet of Things (IoT) is a network composed by the interconnection of a plethora of elements.

One decade after the concept was firstly coined in 1999 by Kevin Ashton [1], a fast-paced technological development of multiple platforms, standards, applications and devices has turned the IoT into a world-renowned system. Due to the introduction of smart mobiles and tablets, among others, humans can constantly stay connected to the Internet in their daily lives. In fact, it is expected that the number of connected devices will grow constantly in the next decade [2], with tens of billions of connected devices by then [3]. From that perspective, it is practically impossible to avoid being part of the hyperconnected network that represents the Internet.

Thanks to the usage of embedded sensors, devices can extract information regarding the physical world and share different types of data. Data is processed, and then it can be used in several applications. IoT is expected to evolve and develop in many directions the next 5-10 years, and as the IoT involves lots of different knowledge and fields, many standardization bodies, companies, and researchers must work together to carry on this pharaonic system. Besides the new and fruitful opportunities around the IoT that will arise, the final aim of this technology is to improve human's life quality with practical applications. Thus, IoT can be used in different fields such as metering, health, transport, surveillance or industry, magnifying its impact on every part of the society.

Attached devices will grow in number during the next years, and others than common computers and smartphones will join, creating a more complex system of interconnected nodes. Also, the IoT network requires of some segmentation. Some parts of the network, will inevitably need different levels of security, data rates, or communication techniques. Consequently, scalability and heterogeneity are two key technological problems to address when facing the construction of the future IoT network.

Machines oversee obtaining, transmitting, and analyzing data without almost any human intervention, so IoT cannot be able to prosper without Machine Type Communications (MTC). More specifically, some applications and scenarios are ruled directly by machines capable to communicate and share knowledge between their peers. As stated above, IoT can be useful in many different scenarios, and they can be distinguished and classified by different characteristics.

A general taxonomy can be traced studying different types of smart environments and its different characteristics. We can classify cases by their communication enablers, network types, local area wireless standards, and so on. The most widespread technologies to provide communication across the Internet are Wi-Fi, GSM (3G), and LTE (4G), as reported in Table 1.1-1.

Technology	Frequency	Data rates	Range	Power Consume	Application
Bluetooth	2,4 GHz	25 Mb/s	10 m	Low	Smart home
DASH7	433 MHz (Europe)	55 kb/s, 200kb/s	1000m	Low	Smart cities, buildings, transport, health
ZigBee	868, 915, 2400 MHz	250 kb/s	Up to 100m	Low	Smart homes, health
Wi-Fi	2.4 GHz, 5 GHz	54 Mb/s, 6.75 Gb/s	140 m, 100 m	Medium	Smart cities, home, buildings, transport, industry, grid
3G	750 MHz	24.8 Mb/s	1-5 mi	High	Smart cities, transport, industry, grid
4G	700, 750, 800, 1900, 2500 MHz	800 Mb/s	1-6 mi	High	Smart cities, transport, industry, grid

Table 1.1-1 Main technologies involved in IoT

1.2 Machine Type Communications

Inside the IoT ecosystem, we found the MTC, also Machine to Machine Communications (M2M), that refers to the data generation, exchange, and actuation between interconnected machines, where end-to-end device communication is achieved with low or any human intervention. The topic involves mobile network operators, MTC companies, researchers, and standardization bodies. The major challenges in MTC are: scalable deployment, protocol flexibility, energy efficiency, and compatibility with actual cellular technologies and future 5G mobile communication networks.

In the device domain, an MTC system is mostly managed remotely and acts automatically. The monitoring and actuator devices can be mobile or fixed, and scalable up to an order of

10^{12}. After the data acquisition and exchange, the system processes and interprets the data.

The main institutions working on MTC are 3GPP and IEEE on the wireless access side, while ETSI on the architecture and components counterpart.

Inside MTC, it should be distinguished the massive MTC and the critical MTC, whose main characteristics are listed in Table 1.2-1.

Massive MTC	**Critical MTC**
Massive number of devices	Very reliable
Low device cost	Very low latency
Long battery life	High availability
Small data volumes per device	Short transmission times
Scalable and flexible access	Contention-based access
Pervasive networks	Device to device link

Table 1.2-1 mMTC and Critical MTC networks comparison

1.2.1 Scalability

It was predicted that by 2020, 50 billion of devices will be connected to the Internet [4]. Nowadays, even this prediction seems to be lower than stated, it is unavoidable to introduce the concept of massive Machine Type Communications (mMTC) networks. Those networks involve many power-constraint devices, that transmit a small volume of low-delay sensitive data.

Within the mMTC context, where systems tend to operate in narrow bandwidth, massive and simultaneous signaling attempts by many devices can congest the network, leading to a downgrade in the overall system performance.

There are some soft and rigid techniques that operators can apply to handle congestion, such as reducing signaling, minimizing the frequency of attempts of a process, assigning randomized guard times, rejecting a group of nodes to connect during a time, etc. Forbidden transmission times can be allocated, or even bulk signaling plus randomized methods to reduce the overload of the system [5].

1.2.2 Heterogeneity

Communication systems nowadays are mainly designed for human usage, and tend to be monolithic structures, without any interaction capabilities among each other. Clearly, it is a huge impediment when operators want to implement an MTC specific solution, that should be customizable, open and ubiquitous.

In 3GPP Release 10, a clear example of supporting different features per device is shown in the Subscription Control:

An MTC network can support different features to optimize the network efficiency depending on the use case. The MTC features are controlled and subscribed by a central unit, providing a database that contains subscription-related information. Based on operator policies, devices can activate or deactivate some features while the network operator can solve incompatibilities when features cannot be enabled. For example, a device made to measure the air pollution twice a day, can subscribe to some features like “low mobility”, “small data transmission”, or “infrequent transmission”, among others [6].

1.2.3 System Requirements

An MTC network should accomplish and provide lots of general requirements, principles, and services. It is possible to summarize some of them.

The system must be able to provide communication between applications in the network domain and devices, and devices must be able to communicate between peers. The network, should also be able to communicate with sleeping devices, and schedule the network access and path selection, notifying a failure if necessary. The communication must provide security and be trustable in terms of integrity, connectivity, authentication, logging, and failure robustness [7].

1.2.4 Architecture

A commonly adopted MTC system architecture consists in the device and gateway domain, the network domain, and MTC application domain, whose scheme is presented in Figure 1.2.4.1-1.

1.2.4.1 Device and Gateway

Devices are the actuators and sensors that own the embedded electronic computing and communication capabilities. The main utility of this layer is to collect information from the physical world and send it to the network. They support MTC applications and transmit or receive data as the use case requires.

There are two ways in which a device can transmit data to the network, depending if there is direct connectivity or a gateway as a network proxy.

1. In the case of direct connectivity, devices connect to the network domain via the access network. The devices itself manages the registration, authentication, provisioning, etc., with the network domain.
2. The other case is the one where a gateway acts as a network proxy. Then, the device connects to the network domain via the gateway. Indeed, devices connect to the gateway by the access network. The system can count on different multiple gateways.

The access network mentioned above allows connectivity between devices and gateways. Some examples of access network are the Personal Area Networks (PAN) (e.g. IEEE 802.15.1, ZigBee, Bluetooth, RFiD, etc.), Local Area Networks (e.g. PLC, Wireless M-BUS or KNX), or Wide Area Networks (WAN) (e.g. Wi-Max, UMTS, LTE).

1.2.4.2 Network and Application Domain

The network layer is the most complex layer in IoT. It oversees the transmission and routing of processed information to the IoT network, applications or third devices. The network layer can also provide various data services, like data aggregation or computing. Diverse devices such as hubs, switches, or gateways appear at this domain, and a range of communication technologies can be integrated.

A common type of MTC network is the Low Power Wide Area Networks (LPWAN), that enable wireless connection for many low-cost devices. LPWANs normally present high connectivity, low energy consumption, and compatibility with legacy architectures.

Network domain is composed by the following elements (see Figure 1.2.4.1-1):

- The access network that allows the device and/or the gateway to communicate with the core network. Some examples are xDSL, HFC, satellite, eUTRAN or WiMAX.
- The Core Network (CN) that provides IP connectivity, control functions, connection with other networks, roaming, etc. Each core network offers different features, and some examples of core networks could be 3GPP CN, ETSI TIPSAN CN or 3GPP2 CN.
- The MTC service capabilities provide functions that are shared by different applications, expose functions through a set of open interfaces, and simplifies and optimizes application development and deployment through hiding of network

specificities. The MTC applications run the service logic and use service capabilities by open interface.

- There are some network management functions that handle the access and core networks, in terms of provisioning, supervision, fault management, etc. The MTC management functions consist in the functions required to manage the service capabilities in the network domain. The management of devices and gateway uses a specific MTC service capability.

The application layer is the top one, in charge of receiving data from the network and provide required services. The application domain consists in the client application, and the MTC servers, under the control of a mobile operator or a third party.

An IoT network should provide confidentiality, integrity, availability, identification, authorization, and privacy guaranteed within all layers.

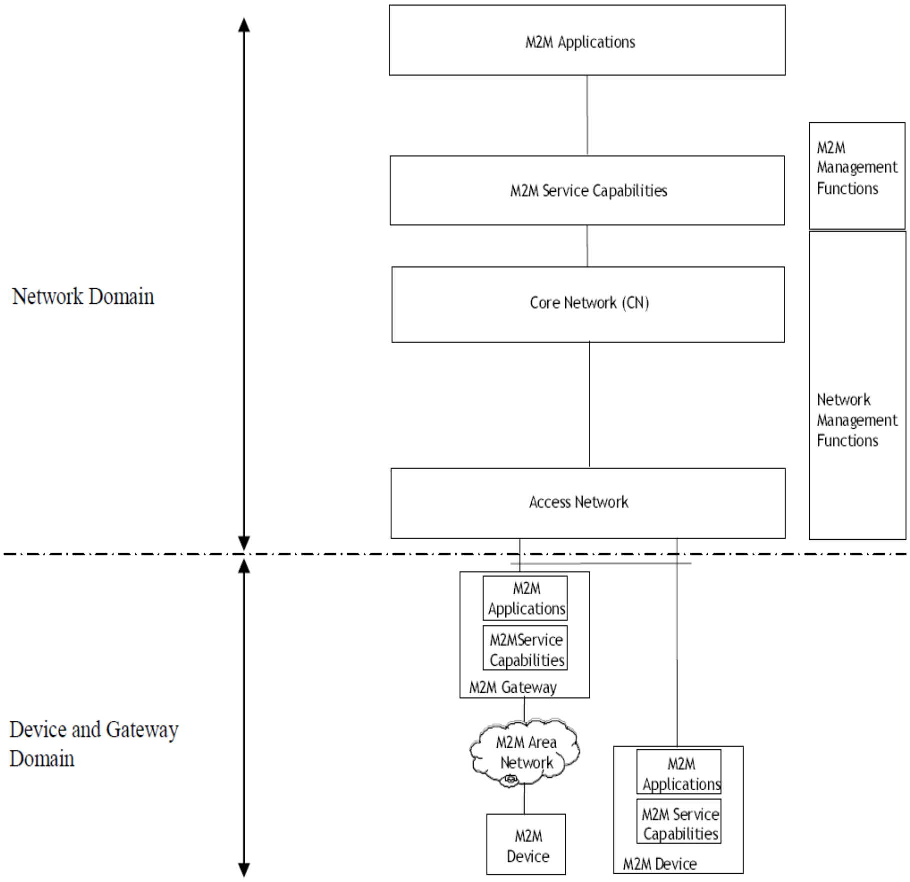


Figure 1.2.4.1-1 Architecture of an MTC network

1.3 Smart Environments

An IoT environment, or smart environment, is the one in which sensors, actuators and computational elements in general, are constantly connected to the physical world, collecting data and applying decisions. All those devices form an interlaced network that improves human lives.

Currently, smart environments are a reality, as small processors can be placed in all kind of objects. It is now possible thanks to the explosion and development of fields such as mobile communications, sensor networking, portable devices, and Ipv4/6 support.

A smart environment should ensure proper functionality, long battery life and energy efficiency, intelligent interactivity between elements, and an accurate response time in each use case. The actuation area and field where a smart environment is deployed, defines its final objective and its reason of existence, segmenting the market in sectors such as smart home, city, buildings, transport, grid, health or industry, among others.

- Smart home and buildings

A smart home is a complex entity with multiple systems that make more comfortable the life of the tenants. Systems rely on the information acquired from computing applications, and they must provide security and interoperability. Smart buildings shall count with the same functionalities than smart home, extending it to a wider area and complexity.

Detectors and actuators, such as fire alarms, security cameras, environmental control, energy management, etc., are involved [8].

- Smart transportation

Transportation relates to IoT through applications like smart ticketing, communication between vehicles, data related to goods and passengers, etc. IoT solutions can connect every public transport element, thanks to sensors, commonly referred as Electronic Control Units (ECU) [9], that monitor the network in real time. Traffic congestion negative effects can be countered with IoT smart solutions.

- Smart Industry

A smart industry can optimize all the processes that take place in the supply chain. Gains are seen in flexibility, intelligent decision making in mass consumption processes, customization, monitoring. Integrating energy consumption data in the production management decisions, can drive companies to be more environment friendly [10].

- Smart Health

Wearables and sensors can be used to monitor and preserve the health of users, like in hospitals or outdoor environments. Smart health applications can be developed and commercialized by a vast number of companies and subsectors, like pharmaceutical industry, smart pills, biosensors, healthcare buildings, insurance companies, etc. Special attention in user's health records privacy is demanded, and regional laws can be a stopper in smart health technology.

- Smart Cities

Smart cities are the most complex IoT cases, managing public affairs in wide areas. Smart city market is expected to reach hundreds of billion dollars by 2020, but nowadays it is still at its initial stage, mainly due to political, economic, and technical stoppers. On the one hand, it is difficult for administrations to select between stakeholders. Moreover, on the technical side, the non-interoperability between networks increases deployment costs. On the other hand, the economic context does not favor the development of solutions that do not jointly involve public service and direct economic gain.

As a use case, an experimental wireless sensor network testbed, with more than 300 nodes was deployed at the University of Padova [11]. The experiment, develops a smart city architecture and realize proof-of-concept demonstrations.

In the Padova Smart City project, nodes where installed in street lights. Each device has temperature, humidity, light, and benzene sensors to monitor the environment, forming all of them, an LWPA network. Thanks to gateways and proxies, the database server can store all the information, to be lately accessible through traditional web programming technologies. At the end, it was possible to determine that a quick storm reduced the levels of light and temperature, rising the humidity, while producing a congestion in the traffic flux, that triggered a peak in the levels of benzene.

- Smart Grid

Smart grid involves replacing the old-fashioned power grid with an intelligent system. By the installation of several smart meters, it is possible to obtain measures about the grid maintenance and the end user consumption and send it to the system operator. Beyond that, smart grids should allow two-way information flow, that can also allow consumers to control more accurately their habits.

The two basic types of communication technologies for smart metering are Radio Frequency (RF), and Power Line Carrier (PLC) [12]. Smart metering is imposing to old grids, primarily in Europe and Asia. Market for smart meters was valued approximately 4$ billion in 2011, and it is expected to grow to 20$ billion in 2018 [13].

Smart grid is an example of a mMTC system created to support large number of devices, with low data rates and no mobility, requirements that fit perfectly to the ones for which NB-IoT (that is technology studied in this thesis) was created to satisfy.

2 Enabling technologies for the IoT

This chapter gives an outline of the currently used technologies in LPWA networks and focuses on the NB-IoT one, that operates in the cellular licensed spectrum.

2.1 Low Power Wide Area Networks

Low Power Wide Area Networks (LPWAN) provide connectivity to low power devices in wide areas. This type of networks complements the traditional cellular networks and short range wireless technologies (WLAN, WPAN), when applied to smart environments and MTC applications. Roughly, LPWA networks try to reach a system range about 20km, where devices are provided with up to 10 years of battery life, and the cost per device is not superior than 10$.

The range of this technology is extended using a dense deployment of devices and gateways, connected using multi-hop mesh networking. There are some standards, design features, and techniques, that different LPWAN technologies exploit.

As explained before, LPWA networks present a tradeoff between the short-range wireless networks like ZigBee, Bluetooth, legacy WLANs, Wi-Fi, and the long range cellular networks, such as GSM or LTE, in terms of connection of low power devices in large areas. LPWANs are particularly efficient for delay-tolerant mMTC applications.

There are several technologies to enable LPWA networks in both unlicensed (e.g. SIGFOX, LoRa, Weightless) and licensed spectrum (e.g. LTE-M, NB-IoT), and all them tend to be narrowband in the spectrum, due to spectral efficiency requirements.

2.1.1 Standardization Efforts on LPWAN

Standardization efforts in LPWA networks are pursued by some Standards Developing Organizations (SDO) and Special Interest Groups (SIG). In the following, the most important standardization efforts are briefly reported:

3GPP unites seven telecommunications standard developer organizations and is evolving their cellular standards to reduce complexity and cost, while improving range and battery life. Their multiple licensed solutions (LTE, LTE-M, EC-GSM, NB-IoT) offer different tradeoffs [16]. They try to re-use their cellular infrastructure and spectrum.

ETSI from 3GPP, tries to standardize low data for bidirectional LPWA. They defined use cases, architectures, protocols, etc., and the interface of the Low Throughput Network (LTN) [17].

IEEE is extending range and reducing power consumption of 802.15.4 and 802.11 standards with some new specifications at PHY and MAC layers. IEEE have proposed two LPWA standards as amendments to 802.15.4 low rate WPAN, to enlarge the range of 802.11 standard for WLAN [18].

IETF aims to support LPWA of dominantly proprietary technologies by standardizing end-to-end IP-based connectivity for low power devices and applications [19].

Some of the most important SIG are LoRa Alliance, Weightless, SIGFOX, and Dash7.

- LoRa is a proprietary physical layer for LPWA connectivity. However, the upper layers and the system architecture are defined by LoRa Alliance and were released in July 2015.
- Weightless Special Interest Group proposed three open LPWA standards with different specifications, such as Weightless-W, N, and P.
- DASH7 Alliance is a consortium that defines a full vertical network stack for LPWA connectivity.
- SIGFOX is a proprietary wireless company, that has developed its own network to connect multiple devices with low data rates, pretending to extend worldwide in few years [20].

2.1.2 Main Challenges

As LPWA networks are so complex ecosystems, they should be upgraded and developed in real time, and present some challenges in the design, that must be faced by the engineering community. Also, there are several research lines inside the LPWAN topic, some of them in a state-of-the-art situation. We can summit some of them in the following section.

- Access

Most of the LPWA technologies are based on ALOHA or CSMA MAC access protocols, which are not good for scale many devices. Research directions to address that topic are channel diversity, opportunistic spectrum access, or adaptatively transmission strategies [21].

- Interference Control Mitigation

The interference varies depending on the time, frequency, and space, so devices should adapt properly to mitigate it, exploiting design diversity in the PHY and MAC layer. Devices operating in Industrial, Scientific, Medical (ISM) bands must mitigate lots of interference, produced by similar devices and other technologies. This can affect negatively the performance of LPWA networks.

- High data rates modulations

LPWA values more the link budget than high data rates, but there are some concrete applications where high data rates are meaningful. To support them, multiple modulation schemes should be implemented to allow system flexibility.

- Interoperability

Having mentioned before some of the current LPWA technologies, it is obvious that they must coexist. IP can connect short-range wireless devices using mesh network, and IoT middleware and virtualization techniques can help to connect LPWA devices, supporting multiple radio access technologies. Testbeds and open-source tool chains are not yet available to evaluate interoperability. Providing scientific instrumentation for public usage can be technology trigger.

2.2 LPWAN on Unlicensed Spectrum

There are several technologies to implement LPWAN in the unlicensed (e.g. SIGFOX, LoRa, Weightless) spectrum. The most used ones are summarized in this section.

2.2.1 SIGFOX

SIGFOX, created the Ultra-Narrow Band (UNB) technology in 2009 as a wide area wireless access technology, to support a massive number of low power IoT devices. The key features of UNB are: ultra-narrow band channels of the order of hundreds of Hz, supporting couple loss higher than 160 dB, with uplink triggered transmissions that follow a client-server model.

The transmissions are simple: UNB devices wake up only when uplink application data arrives, and then select a to send a fixed 96 bits packet, repeated 3 times to enhance coverage. Then, there is an opportunity window of 10 seconds to receive downlink answer. The clear drawback is that in UNB, it is not possible to transmit network-originated calls. This client-server model maximizes the battery life [22].

2.2.2 LoRa

LoRa was established in 2015 by Semtech. LoRA supports network-originated calls mode, deploying a wakeup period and sending a beacon signal by the gateway, like in LTE cellular networks. LoRa assigns a variable communication bandwidth for each device to improve battery life and system capacity. The minimum bandwidth is 125kHz, with coupling loss of 157dB. A LoRa chirp spread spectrum modulation is used to reduce interference effects [23].

2.2.3 Weightless

Weightless-N, by Weightless Special Interest Group (WSIG), supports device-originated transmission on 200Hz ultra-narrow band channels in the sub-GHz ISM band, like SIGFOX. Weightless-P, the latest technology by WSIG, supports bi-directional communications, in 12.5kHz narrowband channels, using frequency hopping and spread spectrum as in LoRa. Weightless-P provides flexible channel assignment and data rates, from 200b/s to 100kb/s [24].

2.2.4 Unlicensed Spectrum Considerations

Systems in the unlicensed spectrum are operator-less. Unlicensed spectrum presents interference and non-reliability problems. Moreover, constraints in duty cycle, limits on the transmitted power, or the need of frequency hopping, can further decrease the system performance in terms of coverage and capacity.

2.3 LPWAN On Licensed Spectrum

As mentioned before, working in the unlicensed spectrum has the drawback that the service availability is not guaranteed. Thus, there are some technologies that operate in the licensed spectrum and can be a real option to develop LPWANs.

Given that the cellular networks are mainly designed for human-type communication, while LPWAN is mainly for MTC, devices of both technologies are very different. LPWAN requires low power consumption, small data and infrequent transmissions, less mobility and cost, while opposite to that, cellular devices, such as an LTE User Equipment (UE), are complex, with rechargeable batteries and with high performance on data rates and mobility. To address this difference, LTE-M and NB-IoT were proposed [25]. This section provides a short review, as later they are compared with the unlicensed spectrum LPWA technologies.

2.3.1 LTE-M

3GPP started studying the supporting of MTC in 2009. In 2016 (Release 13), LTE-M was introduced to reduce power consumption in low peak rate, simple hardware, and narrow band operation, in 1.08MHz bandwidth.

The original LTE design is retained, including downlink OFDMA, uplink SC-FDMA, channel codding, etc. The reason to choose 1.08MHz bandwidth, that is six LTE resource blocks (RBs), is due to the minimum channel requirement of legacy system for channel acquisition and the random-access [26]. LTE-M provides a coverage extension of 15dB, for a Maximum Coupling Loss (MCL) of 155dB [27], enabling to reach devices located in areas with high penetration loss, thanks to temporal repetitions.

2.3.2 Narrowband IoT

3GPP started to standardize NB-IoT air interface in 2015 for LPWAN. NB-IoT operates on a 180kHz bandwidth that can be reduced. Contrary to LTE-M, this bandwidth can be provided by a 200kHz carrier GSM spectrum.

The MCL is extended 20dB over the 140dB of LTE, achieved through repetitions and BPSK modulation over a single subcarrier.

NB-IoT retains LTE transmission structure, and as it is the main technology studied in this thesis, it is deeply explained in section 3.

2.4. Technologies Comparison

As it has stated previously, all the systems being used and developed nowadays for IoT, tend to present a narrow band (NB) approach. The main reason is that LPWAN objective is to achieve a high spectral efficiency, to provide enhanced connexion reliability for a massive number of devices, without providing high data rates.

A fundamental topic in communications is to select the access method and how the capacity is modified when introducing multiple users. The key resources to transmit information are power, time, and frequency. Some multiple access methodologies like, TDMA, FDMA, OFDMA, CDMA, NOMA, and its combinations, are currently used.

- Capacity and coverage extension

The clearest benefit of a reduced transmission bandwidth is that, by considering the same amount of transmitted power, a higher Signal to Noise Ratio (SNR) can be obtained at the receiver, because of the reduction of the noise bandwidth, leading to a decreased noise power. Moreover, reduced bandwidth leads to save more spectrum, with the possibility to accommodate more devices.

It is possible to convert this gain in spectral efficiency not in data rates, but in a coverage extension. Doing so, device data rates are lower, but the sensitivity can be improved, enlarging the link budget.

- Power consumption

Battery life is a key factor in low-power massive IoT applications. Typical battery ranges vary from 300mAh (small devices like wearables) to 5000mAh (e.g. metering devices). The battery life should vary from days to years, but for low-power applications, up to 10 years are expected. The current power drawn for a single transmission for IoT devices range between few milliamps to more than 200mA.

The battery consumption is the product of the current drawn and the operation time. Consequently, battery life is directly related to the time that the device is not in standby.

- Transmission time

There are two main issues to mention regarding the transmission time in LPWA networks:

1. Because of the delay tolerant nature of many IoT applications, repeating the same transmit signal to furtherly enhance coverage is a commonly adopted technique.
2. From the Shannon-Hartley theorem, we can conclude that the minimum time to transmit a message is achieved when the transmission bandwidth is infinite, so there is a time penalty as the transmission bandwidth is always finite. Then, this transmission time penalty produces a power consumption penalty, affecting the battery life.

Although the mentioned time penalty always exists, it can be defined the concept of effective bandwidth, that provides a threshold. When the effective bandwidth threshold is exceeded, the effect of increasing the data rates, while spreading the transmission bandwidth, is lower each time, as it follows a logarithmic growth. If that happens, allocating more bandwidth is suboptimal for reducing the transmission time (see Figure 2.4-1).

Figure 2.4-1 Bandwidth trade-off

The effective bandwidth provides an optimal balance between transmission time and spectral efficiency. Then, it is preferable to allocate a bandwidth near to the effective bandwidth threshold to the device.

Technology	LTE-M	NB-IoT	LoRa	SIGFOX UNB
Sensitivity	-132dBm	-137dBm	-137dBm	-147dBm
Minimum bandwidth	180 kHz	3.75 kHz	125 kHz	100Hz or 600Hz
Effective bandwidth	10kHz	3 kHz	3 kHz	300Hz

Table 2.4-1 LPWAN technologies comparison

Table 2.4-1 compares the LPWA technologies in terms of minimum transmission and effective bandwidth [28].

As LTE-M is constrained to the resource block of 180kHz, NB-IoT offers a better performance in terms of effective bandwidth.

SIGFOX UNB has a much smaller bandwidth to match the enhanced coverage and stays close to the effective bandwidth. LoRa, has the same coverage than NB-IoT, but with greater bandwidth due to spread spectrum to deal with interference. Even though, NB-IoT is deployed in the licensed spectrum.

This thesis does not pretend to prove better any technology, as they may be useful in different applications and customers considerations, but to provide a technical comparison between the different LPWAN commonly used technologies. In the next section, NB-IoT legacy technology LTE is explained, as it is the precursor of NB-IoT.

3 NB-IoT

3.1 Primer on Long Term Evolution

Long Term Evolution (LTE), also known as 4G, is a wireless technology by 3GPP, an industry trade group. LTE is the evolution of UMTS (3G), which also evolved from the GSM (2G) technology [29] (see Table 3.1-1).

LTE investigation and research started at 2004 and standardized in the 3GPP Release8 in 2008, all based on the success of High-Speed Packet Access (HSPA). There is a growing need in capacity and enhancements in existing networks, mobile internet offerings, and new device types. LTE is accepted worldwide as the evolution of 3G.

1G	2G	3G	4G
Basic voice service	Designed for voice	Designed for voice with data consideration	Designed primarily for data
Analog based protocol	Improved coverage and capacity	Designed for voice with data consideration	IP-based protocols (LTE)
Initial development state	First digital standards (GSM, CDMA)	First mobile broadband	True mobile broadband
2.4 kbps	64 kbps	2000kbps	100000kbps

Table 3.1-1 Generation term evolution

The main characteristics that LTE improved are data rates, reduced latency, and scalable bandwidth.

Upper layers of LTE are based on TCP/IP, resulting in an all-IP network, like the ones in wired communications, and supports mixed data, voice, video, and messaging traffic, through Orthogonal Frequency Division Multiplexing (OFDM). It also supports Multiple Input Multiple Output (MIMO) antenna technology, providing an SNR improvement.

Some of the requirements, besides the mentioned data rates, are radio access network latency (user plane) below 5ms, support of scalable bandwidth (1,3,4,5,10,15,20MHz), support of paired and unpaired spectrum (FDD and TDD), support legacy networks interaction, and improved spectral efficiency.

Data rates that LTE could potentially achieve are 100Mbps and 30Mbps, downlink and uplink respectively. In the future, it is expected to reach close to the theoretical peak throughput of 300Mbps, using the 4x4 MIMO 20MHz bandwidth setup.

3.1.1 Frequency and Modulations

LTE allows flexibility in the channel bandwidth, with values of 1.4, 3,5, 10, 20MHz, where the smallest entity for resource assignment is the Resource Block (RB) of 180kHz, for both Uplink (UL) and Downlink (DL). Some modulation schemes available are QPSK, 16QAM, 64QAM. The multiple access is performed OFDMA in DL and SC-FDMA in UL.

LTE frequency bands are specified in 3GPP specifications.

3.1.2 Network Architecture

LTE network architecture is divided in 3 sections, the User Equipment (UE), the Evolved UMTS Terrestrial Radio Access Network (E-UTRAN), and the Evolved Packet Core (EPC) (see Figure 3.1.2-1).

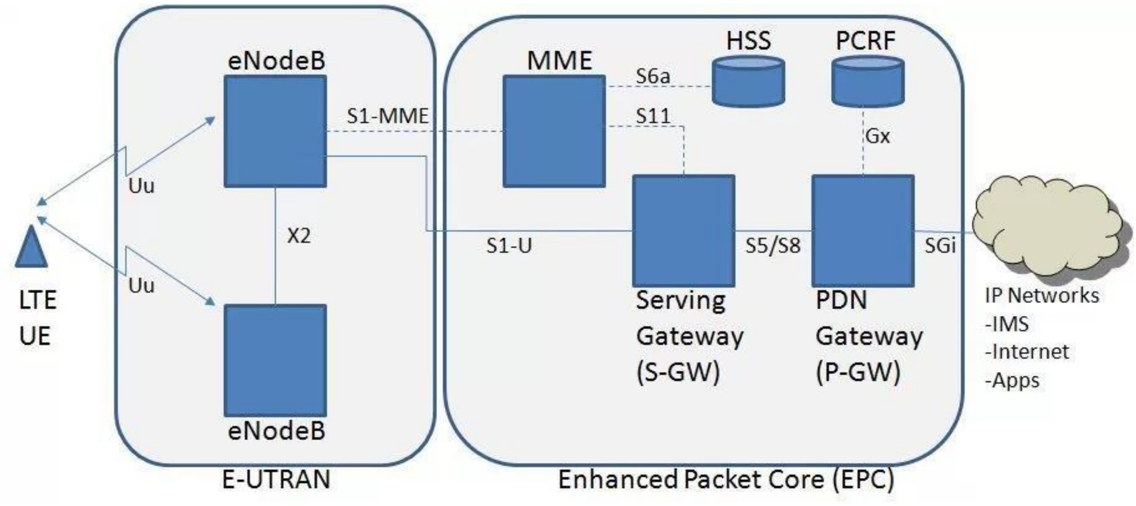


Figure 3.1.2-1 LTE network architecture

1) User Equipment:

The UE architecture in LTE is equivalent to the one used in UMTS and GSM, previously known as Mobile Equipment (ME), where each ME is comprised by the modules of:

Mobile Termination (MT), that handles communication functions, the Terminal Equipment (TE), that terminates data streams, and the Universal Integrated Circuit Card (UICC), known as the SIM card for LTE equipment. The Universal Subscriber Identity Module (USIM), stores user specific data like 3G SIM card, and keeps the information about security keys, home network identity and phone number.

2) E-UTRAN:

The E-UTRAN is the access network that handles the radio communications between the UE and the core and counts with several base stations known as eNodeB (eNB).

Figure 3.1.2-2 shows a common LTE eNodeB.

The function of the eNB, is to send and receive radio transmissions using the digital and analogue functions of the LTE air interface, controlling the power of the communication links sending signaling and handover messages.

Figure 3.1.2-2 LTE base station

Each eNB connects with the EPC by the S1 interface and with other base stations with the X2 interface.

3) Evolved Packet Core:

The EPC communicates with packet data networks in the outside world, like Internet, private corporate networks, IP multimedia subsystem, etc. There are lots of complex modules inside the EPC core network, that can be seen in [30].

- The Home Subscriber Server (HSS), that is a central database with information about all the network operator's subscribers.
- The Serving Gateway (SGW) acts like a router, enabling communication between base station and PGW.
- The Packet Data Network Gateway (PGW), communicates with the outside servers.
- The Mobility Management Entity (MME) controls high-level operation of the mobile with signaling messages and the HSS.

3.1.3 Protocol Stack

The LTE protocol stack is explained in this sub-section and can be observed in Figure 3.1.3-1. A IP packet encapsulation can be observed in Figure 3.1.3-2.

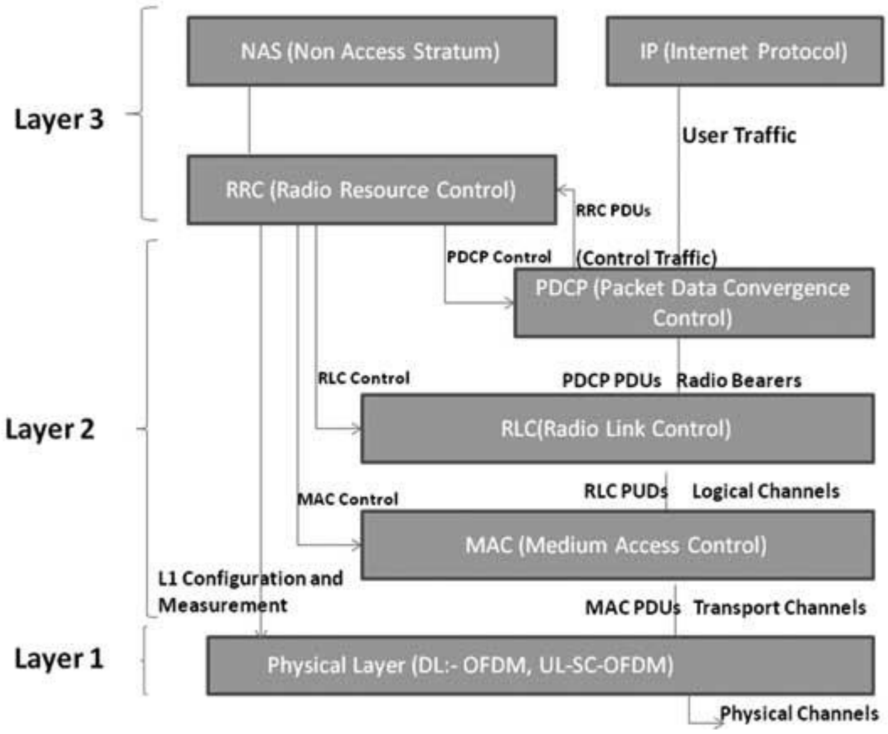


Figure 3.1.3-1 LTE Protocol Stack scheme

In LTE, packets received from a layer are called Service Data Unit (SDU), and the output of a layer packet is called Protocol Data Unit (PDU). The layers that conform the protocol stack are the following ones (see Figure 3.1.3-1):

- The Physical Layer (PHY), is the first one and the one that carries all the information from the MAC transport channels over the air interface. That layer oversees the link adaptation, the cell search, power control, and other measurements for the Radio Resource Control (RRC) layer.

- The Medium Access Layer (MAC), is the one that performs the mapping between the logical and transport channels. Main functions are multiplexing of MAC PDUs from one logical channel to Transport Blocks (TB), delivered from the PHY layer on transport channels, scheduling information reporting, error correction (HARQ), priority handling between UEs and logical channels, etc.

- The Radio Link Control (RLC), has three modes of operation (Transparent, Unacknowledged, and Acknowledged), and is responsible to transfer of upper layer

PDUs, error correcting (ARQ), and the segmentation and reassembly of RLC PDUs, among others.

- The Packet Data Convergence Control (PDCP), oversees header compression of IP data, transfer of data, maintenance of PDCP sequence numbers, delivery between layers, duplicate elimination, ciphering of user plane and control plane data, integrity protection and verification, etc.

- Radio Resource Control (RRC) protocol is used in UMTS and LTE on the air interface. It is a layer that exists between UE and eNB and exists at the IP level. This protocol is specified by 3GPP in TS 25.331 for UMTS and in TS 36.331 [31] for LTE. RRC messages are transported via the PDCP-Protocol. The Radio Resource Control (RRC) protocol, performs connection establishment and release functions, broadcast of system information, radio bearer setup and release, mobility procedures, paging notification, etc.

- The Non-Access Stratum (NAS) protocols form the highest layer of the control plane between the UE and the MME. They support the mobility of the UE and the session management procedures, to maintain IP connectivity between UE and PGW.

3.1.4 Channels Overview

The information flows between protocols using different types of logical, transport, and physical channels (see Figure 3.1.4-1), that are distinguished by the type of information.

- Logical channels, that define what type of information is transmitted over the air. Data and signaling messages are transmitted on logical channels between RLC and MAC.

- Transport channels, that define how and with what type of characteristics the data is transferred by the PHY layer. Data and signaling messages are carried between the MAC and the PHY layer.

- Physical channels, where data and signaling messages are exchanged in UL and DL. There are two types of physical channels, the data channels and the control channels, that are explained in their own section.

In thesis, we focus in the uplink physical transport channels, as are the ones that are going to be studied in the ns-3 simulations. More information about the different data and control channels in LTE can be found in [32].

3.1.5 Physical Layer

3.1.5.1 Downlink: OFDMA Modulation and Frame Structure

In OFDM, each available bandwidth is divided in multiple subcarriers, that can be independently modulated. Compared with the single carrier transmission (SC TX), since the multiple subcarriers transmit in parallel, the bandwidth is divided into narrower flat fading subchannels, improving the system robustness.

The signal generation chain flows in the subsequent manner (see Figure 3.1.5.1-1): operation produces an OFDM symbol through an Inverse Fast Fourier Transform (IFFT), and a Cyclic Prefix (CP), that protects from Inter Symbol Interference (ISI) is added finally. On the receiver part, there is an Fast Fourier Transform (FFT) to reverse the process. There is a lot of available literature regarding OFDM technique [33] (see Figure 3.1.5.1-1).

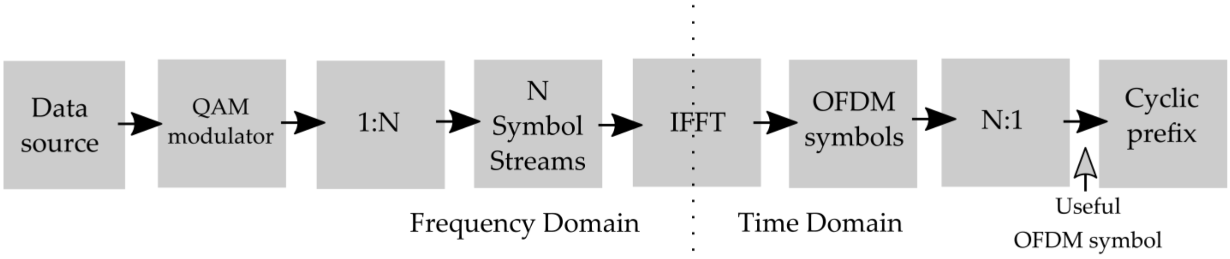


Figure 3.1.5.1-1 OFDM symbol generation

Normal CP with 5.2us for the first symbol and 4.7us for the others is used. The subcarriers have a typical spacing of 15kHz, and the bandwidth is scalable. To support transmission in paired and unpaired spectrum, two duplex modes are supported, Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD).

Radio frame structure type 1 is allocated in FDD, used in DL. It has duration of 10ms with 20 slots of 0.5 ms each (1 small slot of 0.5ms is considered a Resource Block (RB)) (see Figure 3.1.5.1-2). There are 6 or 7 OFDM symbols on each slot, depending if the CP is extended or normal (see Figure 3.1.5.1-2).

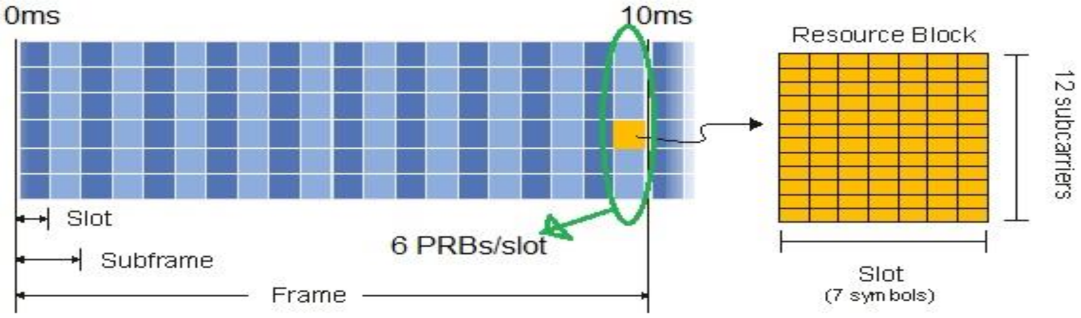


Figure 3.1.5.1-2 LTE FDD frame structure

Radio frame structure type 2 is transmitted in TDD, used in UL, and consists of two half frames of 5ms, that count each one with 5 subframes of 1ms. There are 7 uplink-downlink configurations for TDD (see Figure 3.1.5.1-3).

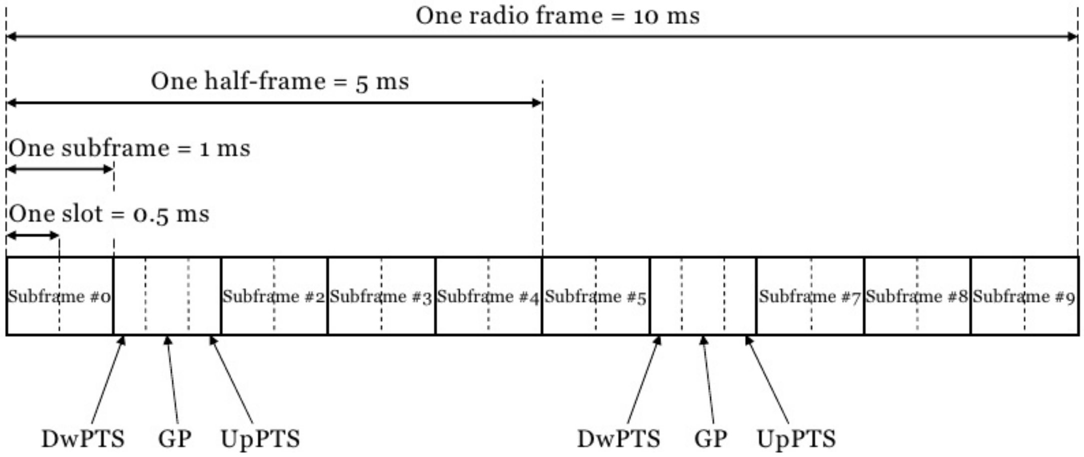


Figure 3.1.5.1-3 LTE TDD frame structure

1 subframe is of 1ms and represents 2 RBs. A PRB is defined as a pair of 12 consecutive subcarriers with one slot duration of 0.5ms. 12*6=72, are the OFDM symbols per time slot.

LTE physical layer supports any bandwidth from 1,4 to 20MHz in steps of 180kHz (RB). LTE supports a subset of 6 different system bandwidth. All UEs must support the maximum bandwidth of 20MHz.

3.1.5.2 Uplink: SC-FDMA Modulation

OFDMA has some disadvantages, the major one is the high Peak to Average Power Ratio (PAPR). As the transmitted signal is the sum of all modulated subcarriers, some of them are in phase. Then, high amplitudes are not avoidable. The high PAPR requires high AC/DC converter resolution and causes out of band spurious radiation. In DL it is not a problem, but it is impossible to manage in the UL (see Figure 3.1.5.2-1).

Discrete Fourier Transform (DFT) pre-coding is performed on modulated data symbols to transform them into frequency domain, then, a subcarrier mapping allows flexible allocation. Finally, the CP is inserted. This DFT pre-coding is the main difference between UL and DL modulations. In this UL method, each subcarrier has a portion of superposed symbols [34].

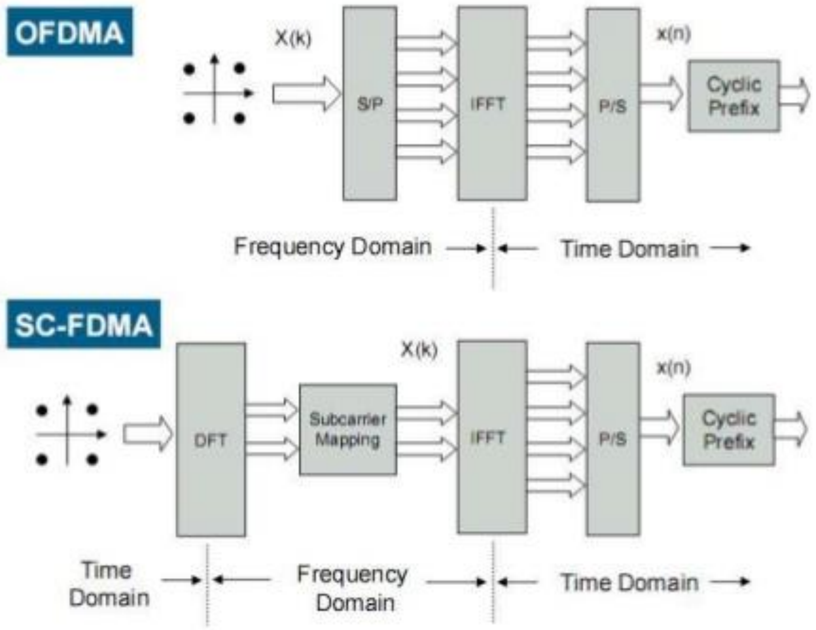


Figure 3.1.5.2-1 OFDMA and SC-FDMA pre-coding scheme comparison

So, each sub-carrier contains information of all transmitted symbols. The SC-FDMA mode fits better to the overall system requirements of LTE, as the goal is to lower the PAPR (see Figure 3.1.5.2-2).

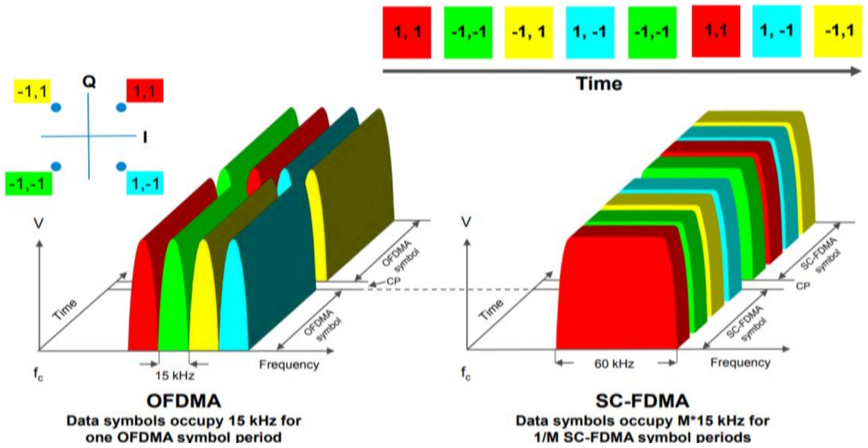


Figure 3.1.5.2-2 OFDMA and SC-FDMA carrier comparison with QPSK modulation

3.1.5.3 Uplink Physical Channels and Signals

There are some LTE Uplink Physical Channels:

- Physical Uplink Shared Channel (PUSCH) that carries user data.
- Physical Uplink Control Channel (PUCCH) that carries control information.

- Physical Random-Access Channel (PRACH), for preamble transmission for initial access.

Also, the LTE Uplink physical signals are two, the Demodulation Reference Signals (DRS), that enables channel estimation and data demodulation, and the Sounding Reference Signals (SRS) that enables uplink channel quality evaluation.

Demodulation Reference Signals (DRS) are transmitted in the UL, over the entire allocated bandwidth, and occupies a specific single carrier FDMA symbol. Sounding Reference Signals (SRS) are used to estimate uplink channel quality on other frequency areas.

Physical Uplink Control Channel (PUCCH) carries Uplink Control Information (UCI) when PUSCH is unavailable. If PUSCH is available, means that resources have been allocated to the UE for data transmission, UCI are multiplexed with user data.

Uplink Control Information (UCI) are Scheduling Requests (SR), ACK/NACK of DL data packets, CQI, Precoding Matrix Information (PMI) and Rank Indicator (RI) for MIMO. PUCCH is transmitted on reserved frequency regions configured by higher layers.

3.1.6 Attachment and Random-Access Procedures

Each UE must compile some cell information to complete a successful attachment:

- Cell ID (0 to 503)
- Cyclic Prefix (Normal or Extended)
- Multiplexing technique (FDD or TDD)
- Cell Bandwidth

In DL, LTE uses 2 types of signals, known as Primary and Secondary Synchronization Signals (PSS and SSS), that provide acquisition of cell timing and identity, and Downlink Reference Signal (DRS), for cell search, acquisition, demodulation and channel estimation.

LTE information transport is carried in Downlink Physical Channels (DPC). LTE radio cell is identified by the physical layer cell identity group. This information is transmitted by the PSS and SSS. SSS are transmitted in first and sixth subframe, so the repetition time between synchronization signals is 5ms.

Also, each UE must follow some further steps before transmitting data:

- Cell Search and Selection Procedure

- Random Access Procedure
- Derive System Information

Random Access Procedure consists in a Random-Access Preamble, Random Access Response, Scheduled Transmission, and Contention Resolution. After the procedure, UE can receive data, transmitted in the PDSCH. The device must know scheduling information, transmitted in PDCCH.

There is Hybrid Automatic Repeat Re-Quest (HARQ) in the LTE downlink. It is transmitted in the PUCCH or in PUSCH, depending if there is data transmission in parallel.

EPS Bearer Setup is a connection-oriented transmission network, that requires a virtual connection between UE and core network (EUTRAN) before any traffic can be sent. This virtual connection provides a transport service with a specific Quality of Service (QoS). It must cross multiple interfaces to achieve this connection, and a lot of produces and information are stablished.

3.1.7 Additional features

- Mobility

The way an UE changes the attached eNB is known as handover. This procedure proceeds as:

1. UE makes measurement reports, and source eNB takes a handover decision and communicates to another eNB (target eNB). Second eNB decides and sends ACK if handover is feasible.
2. First eNB sends to UE an RRC connection reconfiguration, to able UE access the target cell. The UE realizes the change, detaching from old, and delivering packets to the new eNB, using buffers.

In LTE there are only 2 protocol states defined in the Radio Resource Control (RRC), connected or idle. LTE can interwork with 2G and 3G. Mobility is not considered in NB-IoT.

- MIMO

Multiple Input Multiple Output (MIMO) is one important characteristic of LTE as it enables to reach the desired throughput and communication requirements. Multiple antennas are used in the radio channels to transmit and receive. As MIMO is not used in NB-IoT, there is a reference for the interested reader [35].

3.2 From LTE to LTE-Advanced

LTE Advanced (LTE-A) is an enhancement of the LTE standard. 3GPP, in late 2009, presented Release 10, this communication system to meet the requirements of the IMT-Advanced, also known as 4G. LTE-A is focused on achieve higher capacity, providing higher bit rates in a more efficient manner, and at the same time, fulfil the mentioned requirements set by ITU. The above-mentioned objectives differ from the ones in the LPWA network with low data rates that this thesis studies, so only the most important concepts introduced in LTE-A are mentioned. The interested reader can refer to [36] for a detailed overview.

The main new functionalities introduced by LTE-A are Carrier Aggregation (CA), the introduction of Relay Nodes (RN) to achieve more efficient heterogeneous network planning, Coordinated MultiPoint's (CoMP) to improve performance in cell edges, enhancements in MIMO and Inter-Cell Interference Coordination (eMIMO and eICIC), plus the evolution towards Self Organizing Networks or 256QAM.

3.3 NB-IoT Technology

NB-IoT is a narrowband radio technology introduced by 3GPP in Release 13, specifically tailored for providing wide-area coverage for ultra-low-end IoT and MTC applications. NB-IoT enables cost-efficient and flexible massive MTC deployments with LTE cellular system functionalities, achieving improved coverage to many low power devices, with low peak-data rates each one. The minimum system bandwidth required to operate is 180kHz, equal of the smallest LTE Physical Resource Block (PRB), that can be reduced in a so-called multi-tone configuration.

NB-IoT can enhance coverage up to 20 dB thanks to signal repetitions, compared to legacy LTE technology, allowing up to 52000 devices per channel per cell, each of those with up to 10 years of battery life. Moving apart from the reliability limitations and interferences in the unlicensed spectrum, NB-IoT offers a suitable solution in the licensed spectrum.

NB-IoT acquires almost all features of legacy LTE, including numerologies, downlink OFDMA and uplink SC-FDMA, channel coding, interleaving, etc. So on, the same infrastructure can usually be used, reducing significantly the time required to develop full specifications. If hardware recycling is not an option, NB-IoT can be supported with a software upgrade. Because of that, NB-IoT can be deployed partially with the pre-existing infrastructure and then be gradually implemented. Such facilitates in the deployment of the technology also reduce the costs severely.

Inside Release 13, the designers detailed targets for all deployment operations, including

[37]:

- Improved indoor coverage of 20dB compared to GPRS devices, that correspond to a maximum coupling loss (MCL) of 164dB. At application layer, with this MCL, data rates around 160bps should be achieved in both uplink and downlink. From those 20dB, 6dB are because the reduced bandwidth, and the other due to multiple repetitions. Discontinuous reception (DRX), enables battery saving allowing devices to sleep mode. NB-IoT new feature of extended DRX cycles reach up to 10s for UEs in connected state and about 3 hours for UEs in idle state.

- Up to 50000 devices that rarely send message to the network within a cell-site sector should be supported. The whole system should offer coverage to millions of devices.

- Reduced complexity devices with a battery of 10 years with a typical battery capacity of 5Wh at 164dB MCL.

- The latency requirements are very flexible as it is not usually a requirement for MMTC, but there is a fixed upper bound of 10 seconds for 99% of the devices.

All in all, main NB-IoT advantages are low power and consumption, low complexity in the UEs and low cost for the radio chip, plus a significant coverage enhancement.

3.3.1 Operation Modes

As stated before, NB-IoT can operate in three differentiated modes [38] (see Figure 3.3.1-1):

1. Standalone operation, when the carrier occupies one GSM carrier. This is an option when LTE is deployed in a higher band and GSM is still in use, providing coverage for basic services.

2. In-band operation, when one or more LTE PRBs are reserved for NB-IoT. In this mode, there are some scheduling restrictions, as some resources are restricted to LTE usage. Even though being different technologies, the same the eNBs power can be shared between LTE and NB-IoT efficiently.

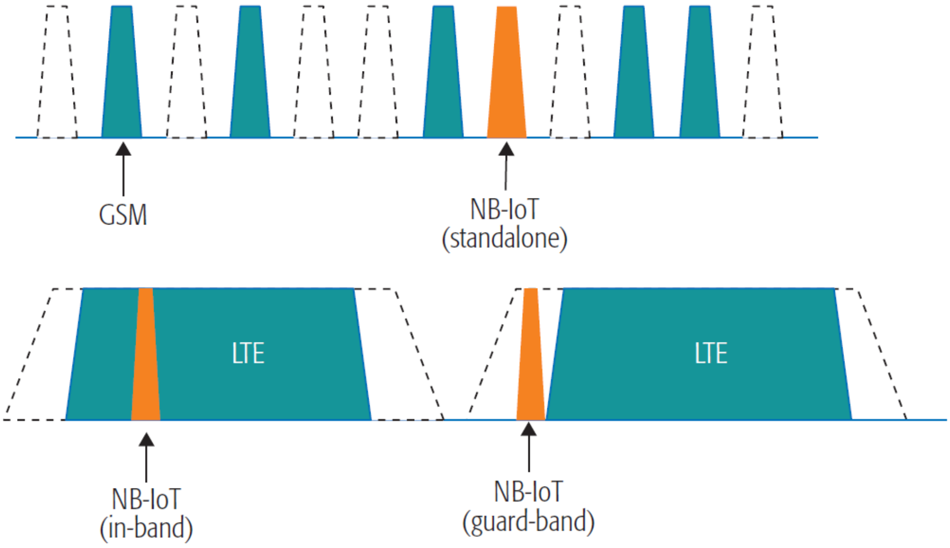


Figure 3.3.1-1 NB-IoT operation modes

3. Guard-band operation, when unused resource block in the LTE carrier's guard band are used. In this mode, the NB-IoT cell is served by the same base station, sharing the maximum base station transmission power. Usually, less interference is expected in this mode from legacy LTE due that it is operating in a guard band. Each NB-IoT carrier is within the guard-band and the center frequency is at most 7.5kHz offset from the 100kHz channel raster.

As the system operation bandwidth is reduced to 180kHz, much less compared to the one in LTE (1.08MHz), all the physical signals and channels have also to be adapted to fit properly. For added capacity, NB-IoT can operate in multi-PRB mode, where one anchor carrier is used to transmit at least common signals and channels, like synchronization or broadcast information, and secondary carriers where UEs are moved by higher-layer signaling to receive and transmit over data channels.

3.3.2 Physical Layer

The most important modifications are introduced in the new physical layer design:

- Downlink

As in past LTE, OFDM with 15kHz sub-carrier spacing is used in downlink. Slot, subframe, and frame durations are 0.5, 1, and 10ms like in LTE, and the slot cyclic prefix duration and number of OFDM symbols are also identical (see LTE section 3.1). NB-IoT carrier uses one LTE PRB in the frequency domain, as twelve 15kHz subcarriers occupy a total of 180kHz. Orthogonality and coexistence is then achieved at downlink because of the reuse of the same OFDM numerology than in LTE.

- Uplink

On the uplink, NB-IoT allows single and multi-tone operations. Single-tone operation mode can vary in bandwidth from 3.75kHz to 15kHz. Multi-tone transmission is according to SC-FDMA, with 15kHz of spacing, with 0.5ms slot and 1ms subframe like in LTE. In downlink and 15kHz version of uplink transmissions, one NB-IoT carrier has 12 sub-carriers. [39].

Operation Modes	In-band and Guard band in LTE, Standalone
MCL (Coverage)	164 dB
Downlink	OFDMA (15kHz subcarrier spacing), 1Rx, 2Txantenna
Uplink	SC-FDMA (15kHz subcarrier spacing), Turbo Code or Single Tone (15kHz and 3.5kHz spacing)
Bandwidth	180kHz (1 PRB), inside eNB assigned BW
Peak data rate	250kbps (20kbps UL single tone)
Duplex	FDD, TDD
Power class	23dBm
Power saving	PSM, ext. I-DRX, C-DRX

Table 3.3.2-1 NB-IoT main features

The subframe duration is of 1ms like in LTE. Hence, there is not enough frequency-domain space for the multiplexing of physical channel. All downlink channels are multiplexed in time, some of them spanning multiple subframes. Half-duplex operation is adopted to save battery and complexity, so an UE cannot transmit and monitor simultaneously.

3.3.3 Physical Channels and Signals

Less channels and signals are supported in NB-IoT than in LTE. It must be noticed that there is no uplink control channel in NB-IoT, so uplink acknowledgement must be transmitted in the NB-PUSCH later explained, while scheduling request must be indicated using random access procedure.

There are four physical layer downlink channels in line with LTE design, that are the Physical Broadcast Channel (NB-PBCH), the Physical Downlink Control Channel (NB-

PDCCH), the Physical Downlink Shared Channel (NB-PDSCH), and the Physical downlink synchronization channel for PSS and SSS signals (see Table 3.3.3-1) [40].

- NB-PBCH is the broadcast channel that carries the Master Information Block (MIB) of 34 bits, transmitted in the first subframe of each radio frame, with a periodicity of 10ms. MIB includes System Information Block (SIB) for scheduling, number of antenna ports and use mode.
- NB-PDCCH utility is to transmit Downlink Control Information (DCI) with scheduling information for both uplink and downlink data transmissions. Resources are grouped into control channel elements (CCE), that occupy six sub-carriers of a subframe, so there are 2 CCEs per subframe. This means that the control information, fixed at 23 bits, is encoded over 1 subframe. Coverage extension is achieved using repetition coding, with up to 2048 repetitions.
- NB-PDSCH allows downlink payload Transport Blocks (TB) transmission. Scheduling information about NB-PDSCH is sent over NB-PDCCH. The smallest Resource Unit (RU), is one carrier that occupies one subframe. The minimum size of each information block is 256 bits, and the maximum size of a TB is limited to 680 bits. It is important to notice that only QPSK is supported. The TB bits are encoded through Tail-Biting Convolutional Coding (TBCC).

Link	Physical Channels and Signals
Downlink	Narrowband Physical Downlink Control Channel (NB_PDCCH)
	Narrowband Physical Downlink Shared Channel (NB-PDSCH)
	Narrowband Physical Broadcast Channel (NB-PBCH)
	Narrowband Synchronization Signal (NB-PSS/NB-SSS)
Uplink	Narrowband Physical Uplink Shared Channel (NB-PUSCH)
	Narrowband Physical Random-Access Channel (NB-PRACH)

Table 3.3.3-1 NB-IoT physical channels

For the synchronization and Reference Signal (NB-RS), downlink is also used. In uplink, there are two channels, the physical uplink shared channel (NB-PUSCH), and the physical random-access channel (NB-PRACH).

- NB-PUSCH is the channel that carrier the UE TBs (NB-PUSCH Format 1) and uplink control information (UCI or NB_PUSCH Format 2). It involves that contrary to LTE, both data and control information are carried over the uplink shared channel, because that two different formats. The RU varies between 2 to 16 slots depending of the tones, that can be 1, 3, 6, or 12. The slot length is 0.5ms and 2ms for subcarrier spacing of 15kHz and 3,75kHz respectively. Then, and contrary to the LTE uplink, the 1ms time is not fixed at RU.

- NB-PRACH provides connexon between the user and the base station. The base uses the random-access preamble sent by a user terminal to estimate the uplink timing, to maintain uplink orthogonality between many users. NB-PRACH uses single-tone transmission and 3.75kHz sub-carrier spacing. The preamble transmission can be repeated to 128 times in contiguous subframes. The base station can configure to three NB-PRACH, each one with its coverage level. Each NB-PRACH is defined by periodicity, number of repetitions, and a set of sub-carriers.

Legacy LTE synchronization sequences occupy 6 PRBS, so new Synchronization Signals (SS), that are the primary (NB-PSS) and secondary (NB-SSS) synchronization signals have been introduced to handle the signaling. NB-PSS is transmitted in the fifth every 10ms, using the last 11 OFDM symbols in the subframe. The NB-PSS detection is one of the most demanding processes for the UE in terms of computation.

3.3.4 Signal Repetitions

Signal repetition technique is used in NB-IoT to enhance coverage, depending on the condition of the channel between the UE and the eNB. For transmissions on NB-PDCCH and NB-PDSCH, up to 2048 possible repetitions are allowed, and 128 in the NB-PUSCH. Repetitions can improve SNR up to 33dB and 20dB in both downlink and uplink. The channel estimation error is a factor to improve when working in bad SNR conditions [41].

3.3.5 Deployment Considerations

3.3.5.1 LTE Coexistence

Operators face the problem to integrate NB-IoT technology in fractions of their existent networks. A partial network deployment presents some deployment problems. One PRB used for NB-IoT in a cell, could be used for LTE in other close cells, compromising the system availability. Sparse deployment of NB-IoT results in a wider area to be covered by NB-IoT cells, so remote NB-IoT devices from the serving cell could be close to another LTE cell, causing destructive co-channel interference. To manage this coexistence problem, power boosting of the PRB can be used, stealing power from other PRBs, with limit 6 dB.

Resource mapping is also designed to ensure an efficient performance when NB-IoT is deployed inside LTE carrier, avoiding mapping NB-IoT signals to the resource elements used in LTE, ensuring orthogonality (see Figure 3.3.5.1-1).

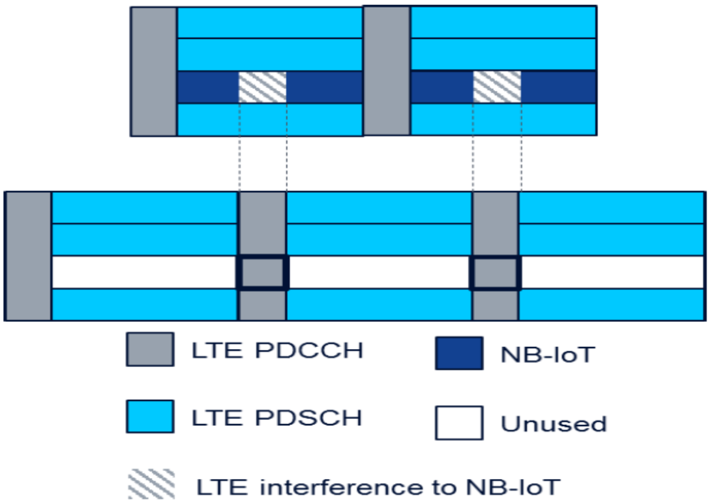


Figure 3.3.5.1-1 LTE and NB-IoT interference scheme

For the stand-alone and guard-band operation modes, no LTE resource must be protected, but for in-band operation, interference can occur. To mitigate that, NB-IoT UEs can learn the deployment mode and the cell identity through initial acquisition and notice which resource elements are used by LTE. Finally, the UE can map symbols to available resource elements. NB-PSS and NB-SSS need to be detected without knowing the deployment mode, but there are some common strategies to avoid this concrete problem, like avoiding the usage of the first three OFDM symbols in every subframe, that may be used by LTE PDCCH [42]. Nevertheless, de-synchronization can lead to interference.

3.3.5.2 Synchronization

When an UE is firstly attached to an eNB, the synchronization must be precise enough to distinguish the cell via NB-PCID, and to obtain the first subframe and frame reference number. NB-IoT UEs are designed with crystal oscillators that may introduce Carrier Frequency Offset (CFO), and some modes of operation (in-band and guard-band) can even introduce higher CFO. NB-IoT synchronization is designed very similarly to LTE synchronization, but with some variations to ensure that UEs in high pathloss and low SNR condition (e.g. UEs placed on basements) can correctly communicate.

As explained previously, synchronization is carried out by the usage of NPSS and NSSS signals. NPSS obtains the symbol timing and CFO, and NSSS obtains the NB-PCID.

3.3.5.3 Device Complexity

NB-IoT UEs are designed to be simple. With respect to LTE UEs, they only require a single antenna (no MIMO), single HARQ process, no need of complex coding, only mobility measurements in Idle mode, low sampling rate due to lower bandwidth, and only half-duplex frequency-division duplexing (FDD) operation. The coverage objective is achieved with a transmission power of 20 or 23 dBm [43].

3.3.6 Main Differences between NB-IoT and LTE

This section summarizes the main differences between both technologies, as NB-IoT will be performed in the network simulator, and some modifications in the LTE module will have to be applied, given the fact that NB-IoT module does not already exists.

3.3.6.1 Physical Layer

NB-IoT is a technology created for MTC with no need of mobility. There is no interaction with other radio technologies and most of the LTE-A features are not implemented: there is not interference avoidance for in-device coexistence, no Carrier Aggregation, no device-to-device services, the concept of QoS is missing, etc.

In the in-band operation mode, NB-IoT has available only some RBs. There are two coverage enhancement areas in NB-IoT, CE1 and CE2 to reach higher MCL of 154 and 163 dB.

Then, a UE that in LTE should be considered out of range, may transmit and receive in NB-IoT thanks to the signal repetitions in CE1 and CE2.

3.3.6.2 Full Duplex (Uplink vs. Downlink)

- Downlink

There are less channels in the DL, as there is not Multicast, Broadcast, Paging, or Shared Downlink Channels. In DL, only QPSK modulation is applied. Note that a detailed analysis is out of the scope of that thesis, that focuses on uplink performance.

- Uplink

In NB-IoT uplink, all signals are transmitted over the NB-Physical Uplink Shared Channel (NB-PUSCH), so there is no channel equivalent to the Control channel in LTE.

While in LTE the UL subframe structure is quite like the DL one, in NB-IoT they can be different. The subcarrier spacing may be 3.75kHz, instead of the 15kHz in DL. Then, this leads to a fourfold transmission time, from 0.5 to 2ms for each slot. The uplink maintains the SC-FDMA scheme as explained in LTE, with BPSK or QPSK modulations.

4 Network Simulator 3

NS-3 is a free software discrete-event network simulator, created primarily for research and development use. NS-3 have a simulation core, documented in its own website, and can provide flexibility in the design and configuration of the network. The simulator does not provide an IDE, so the simulation compiling, and execution are done by command line. The network simulator can collect traces and analyze them, and the principal technologies that are tested in ns-3 are Wi-Fi, WiMAX, and LTE, running wireless/IP simulation in layers PHY and MAC.

4.1 Simulation modules

Technically, ns-3 is a C++ library that provides network simulation models implemented as C++ objects. NS-3 provides a public API that includes a tutorial, a manual, and a model library with source code. Inside the model library, we can find some of the models that are going to be used, the most important ones in this work are:

- Antenna Module
- Buildings Module
- Flow monitor
- LTE Module
- Internet Models (IP, TCP, Routing, Applications)
- Mobility
- Network Module
- Propagation Module
- Antenna Module

The antenna module provides an interface to model the radiation of the antenna, and a set of classes with different radiation patterns that define each type of antenna. The antenna model, is defined in spherical coordinates and returns a value of the gain (in dB), only considering the angular direction. Inside the antenna module, we can find three antenna models, that are the isotropic antenna model (used in our indoor base station), the cosine antenna model (used in our outdoor base stations), and the parabolic antenna model.

- Buildings Module

The buildings module provides the building class that reproduces the presence of buildings in the simulation scenario, the mobility building info, that allows to specify the location, size, and characteristics of the buildings, plus some useful channel models like the hybrid buildings model bye ns-3, the ITUR1238, or the Okumura-Hata model.

If class, the building floors, area, separation, walls, and other parameters, are modified to fit with the desired scenario.

- Flow Monitor Module

The flow monitor provided by ns-3 provides a flexible system to make measurements of the network's performance. If the module is installed in the network nodes, it can track packet exchanges at IP level, dividing all the communications in work flows, that are organized in the tuple {protocol, source (IP, port), destination (IP, port)}. Statistics can be exported in XML format and analyzed in NetAnim.

The flow monitor has some limitations, and since the packets are tracked at IP level, any retransmission will be a new packet.

Important data provided by the flow monitor is the delay, transmitted and received bytes and packets, and the time of first and last reception or transmission. With that information, we can compute the bytes lost ratio and the throughput of each individual node.

- LTE Module

Inside the LTE module, ns-3 provides an LTE model that includes radio protocol stack (RRC, PDCP, RLC, MAC, and PHY), that reside entirely inside the UE and eNB nodes. Also, there is an EPC model, that includes core network interfaces, protocols and entities, including SGW, PGW, and MME nodes. The model has been designed for testing radio resource management, QoS, dynamic spectrum access and ICI, among others. The granularity is at least of one RB, and the module is designed to run for tens of eNBs and hundreds of UEs because of computational requirements. It is possible to manage different eNBs that work in different frequency bands.

The LTE model is used to simulate transmission of IP packets by upper layer, and it should be considered that in LTE the scheduling and radio resource management do not work in IP packets directly, but in RLC PDUs, which are obtained by segmentation and concatenation of IP packets by RLC entities.

The EPC model provides end-to-end IP connectivity over LTE model, and only supports IPv4 so far.

- Mobility Module

The mobility module allows the user to track the cartesian position and speed of each UE, with high level of flexibility as the mobility can course changes inside the simulation. Also, it provides some helpers used to place nodes and setup the mobility models. Inside mobility, we can find useful classes as rectangle, box, and functions as *GetPosition ()* or *GetDistanceFrom ()*. There are also position allocators used to set initial positions, but in our non-mobility case studio will suppose the final and static placement of the UEs.

- Propagation Module

The propagation module defines the interfaces of the propagation loss and delay. The most important is the propagation loss model, because thanks to it we can model the channel. There are some channels included in ns-3, like *Cost231*, *Friis*, *OkumuraHata*, *ThreeLogDistance*, etc.

The ones that we are going to use are the *ItuR1411NlosOverRooftop* and the *ItuInh* propagation models. They are deeply explained in the next channel model section.

4.2 Propagation Channel Models

The channel models used in the work are the ITU R1411 NLOS Over Rooftop, for the outdoor base stations, and the ITU Indoor Hotspot (ITU InH), for the indoor base stations.

4.2.1 Outdoor: ITUR1411NLOS Over Rooftop

This model is designed for Non-Line-of-Sight (NLOS) short range outdoor communication, and adequate for the frequency range between 300MHz and 100GHz. It includes some buildings parameters that can be modified manually.

The model includes some environments like urban, residential, and rural, and some vegetation loss. Reader can find full documentation of this outdoor channel model in [44].

4.2.2 Indoor: ITU-InH

The channel model applies a LOS or NLOS model regarding the distance. We can modify the distance between which the model applies LOS, NLOS, or no coverage.

If the distance d is larger than 37m, it applies NLOS or LOS with equal probability, but if d is less than 37m, it applies LOS with probability $e^{-(\frac{d-18}{27})}$.

The LOS pathloss formula is:

$$L = 16{,}9 * log10(d) + 32{,}8 + 20 * log10\left(\frac{freq}{1e9}\right) \qquad [dB].$$

The NLOS pathloss formula is:

$$L = 43 * log10(d) + 11{,}5 + 20 * log10\left(\frac{freq}{1e9}\right) \qquad [dB].$$

In our case, before 100m, the pathloss can be only NLOS, and before 150m the indoor base station losses coverage abruptly.

The ITU InH indoor channel model was introduced in ns-3 during Phase 3 of the License-Assisted Access (LAA)-Wi-Fi-Coexistence project by Wi-Fi Alliance. The aim of the project is to facilitate the studies about coexistence on the same channel of Wi-Fi and unlicensed variants of LTE.

4.3 Simulation parameters for NB-IoT

To characterize the system frequency, it is required to change the EUTRA Absolute Radio-Frequency Channel Number (EARFCN) to 23400 and 18300 values for outdoor and indoor base stations, to operate at LTE band 1 and 20, respectively.

As LTE module in ns-3 only allows usage of 6, 15, 25, 50, 75, or 100 PRB, different number of PRB can be allowed by modifying the lte-enb-net-device.cc and lte-ffr-algorithm.cc documents. As the minimum PRB that must be used in each transmission per UE is 6, ns-3 can be modified to work with 12 PRB, and then, it is possible to normalize the data flow by a factor of 12, as 12 times the bandwidth is being used. If less PRBs are implemented, the UE fails to complete the random-access procedure.

In LTE networks, eNBs use Sounding Reference Signals (SRS) to monitor the channel quality. The periodicities are 2, 5, 10, 20, 40, 80, 160, or 320ms. This value can be modified in *lte-phy.cc*, *lte-enb-rrc.cc* and *lte.phy.h*, but this will provoke abnormal simulation.

As the maximum modulation order in NB-IoT is QPSK, the lte-amc.cc document has been modified in order to constraint Channel Quality Indicator (CQI) to a maximum value of 6, forbidding the system to work in a higher modulation than QPSK.

4.4 Base Station Types and Attachment

The objective of this section is to explain the base stations introduced in this thesis and some attachment procedure considerations.

4.4.1 Indoor Base Station

An indoor base station (small cell) is composed by an isotropic antenna that radiates at 23dBm, providing a circular radiation pattern (see figure 4.5.1-1). The channel model adopted is the Hotspot model (see channel section 4.2), and the link budget of each indoor cell is of 150m, finishing abruptly (see Figure 4.4.1.1-1).

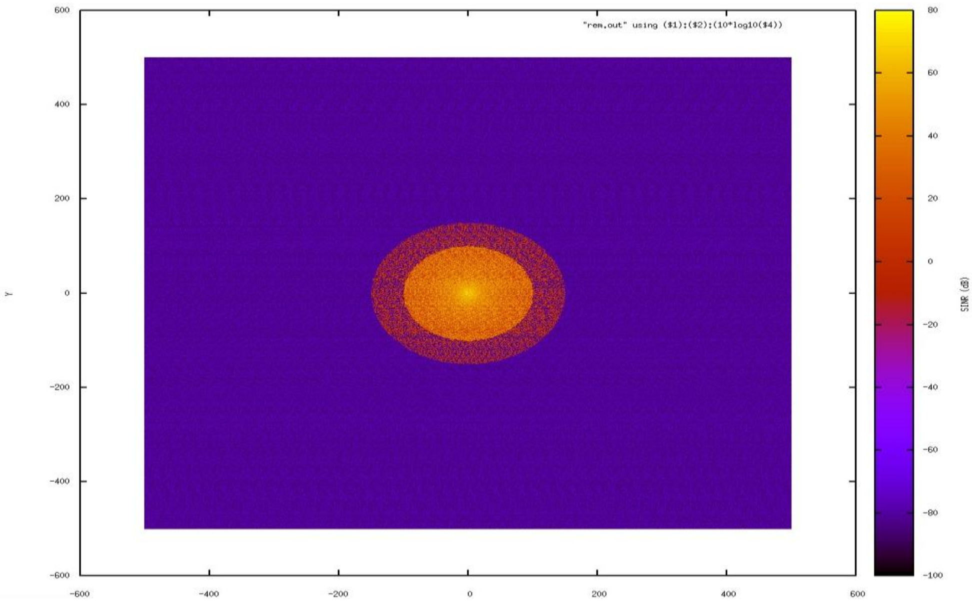


Figure 4.4.1-1 Indoor base station SNR

4.4.2 Outdoor Base Station

An outdoor base station has a tri-sectorial radiation pattern, composed by three cosine-model antennas, oriented at the same angular distance each other, with a radiation power of 43dBm. The channel model is the ITU model explained in the section 4.2.

The coverage of a single eNB has been studied and varies according to the UEs position. If the UE is placed along the beam with no deviation, the uplink transmission can be performed at a distance up to 1620m. If contrary, when the UE is placed in the area between two beams, the coverage can be less than 650m in this thesis simulations.

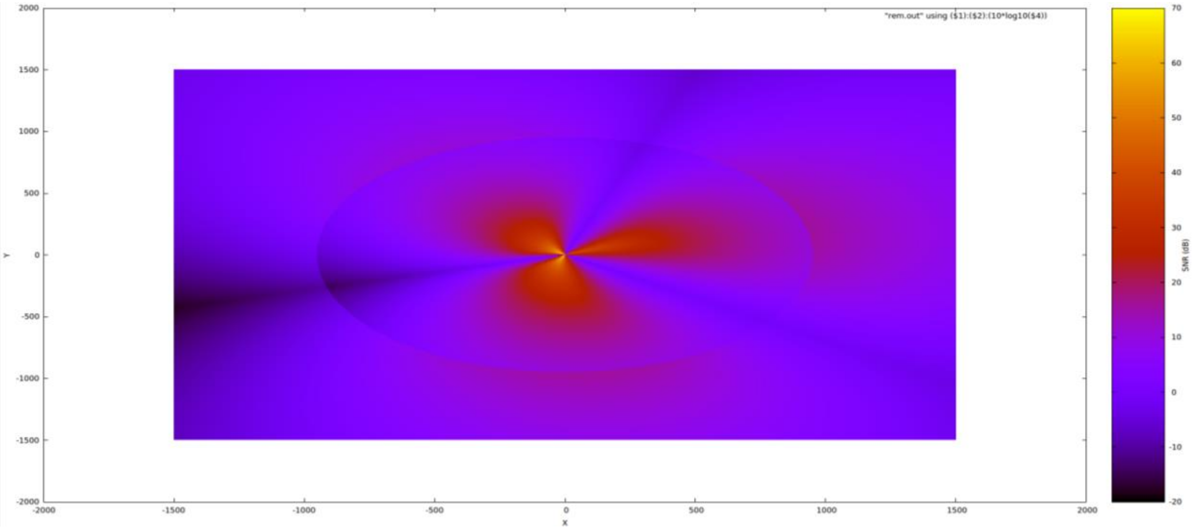


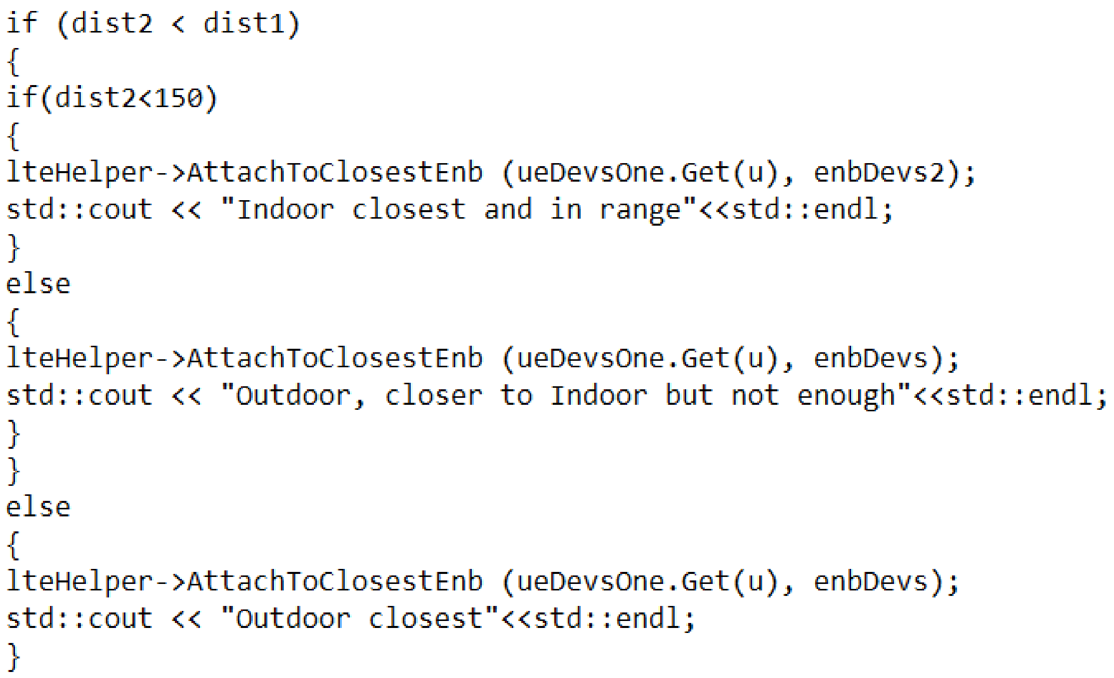
Figure 4.4.2-1 Outdoor base station SNR

4.4.3 Attachment

The attachment of a UE is defined as the following:

The UE should attach to the nearest base station, except when the closest base station is an indoor one situated further than 150m. In that case, the UE must attach to the closest outdoor tri-sectorial base station.

An attachment C++ code can be seen in Figure 4.4.3-1, being dist1 the distance to the closest outdoor eNB and dist2 the distance to the closest small cell. Variables enbDevs and enbDevs2 represents the complete set of base stations.



```
if (dist2 < dist1)
{
if(dist2<150)
{
lteHelper->AttachToClosestEnb (ueDevsOne.Get(u), enbDevs2);
std::cout << "Indoor closest and in range"<<std::endl;
}
else
{
lteHelper->AttachToClosestEnb (ueDevsOne.Get(u), enbDevs);
std::cout << "Outdoor, closer to Indoor but not enough"<<std::endl;
}
}
else
{
lteHelper->AttachToClosestEnb (ueDevsOne.Get(u), enbDevs);
std::cout << "Outdoor closest"<<std::endl;
}
```

Figure 4.4.3-1 C++ attachment code

5 Use Cases and Results

In this section, the use cases adopted for performance analysis are introduced first, and then discussed together with corresponding simulation results, from a simpler to a more complex case. The scenarios mainly differ in term of the following parameters:

- Number of UEs
- Packet size
- Number of repetitions
- Inter packet interval

The analysis has been performed studying the ns-3 flow monitor module and RLC traces. The performance in each scenario is obtained by computing a ratio between received and transmit bytes, after processing the results with a MATLAB script.

Two performance ratios are defined. The unweighted efficiency ratio as:

$$\beta = \left(\frac{ReceivedBytes}{TransmittedBytes}\right)$$

And the weighted efficiency ratio, that considers the connected devices:

$$\beta w = \left(\frac{ConnectedDevices}{TotalDevices}\right) * \left(\frac{ReceivedBytes}{TransmittedBytes}\right)$$

The efficiency is studied in different case scenarios, varying the four parameters reported at the beginning of this section.

Also, flow monitor module received/transmit bytes are considered for very simple cases.

Regarding the MATLAB post-processing of the uplink RLC traces, the following procedure is adopted:

- If an UE transmits less bytes than the packet size, transmit and received bytes in its data flow are put to 0, as the UE is not considered
- If an UE is repeating, and the received bytes are major than the packet size, they are equated to the transmitted bytes, since a successful transmission is considered.

5.1 Use Cases

5.1.1 Tri-sectorial Antenna

The first scenario evaluated is the tri-sectorial antenna. Up to 500 UEs are placed randomly inside a centered rectangular shape, whose extension is modified, from 2000x1700m, to the same size divided by 2 and 4. The bigger the area, the further the UEs are allocated.

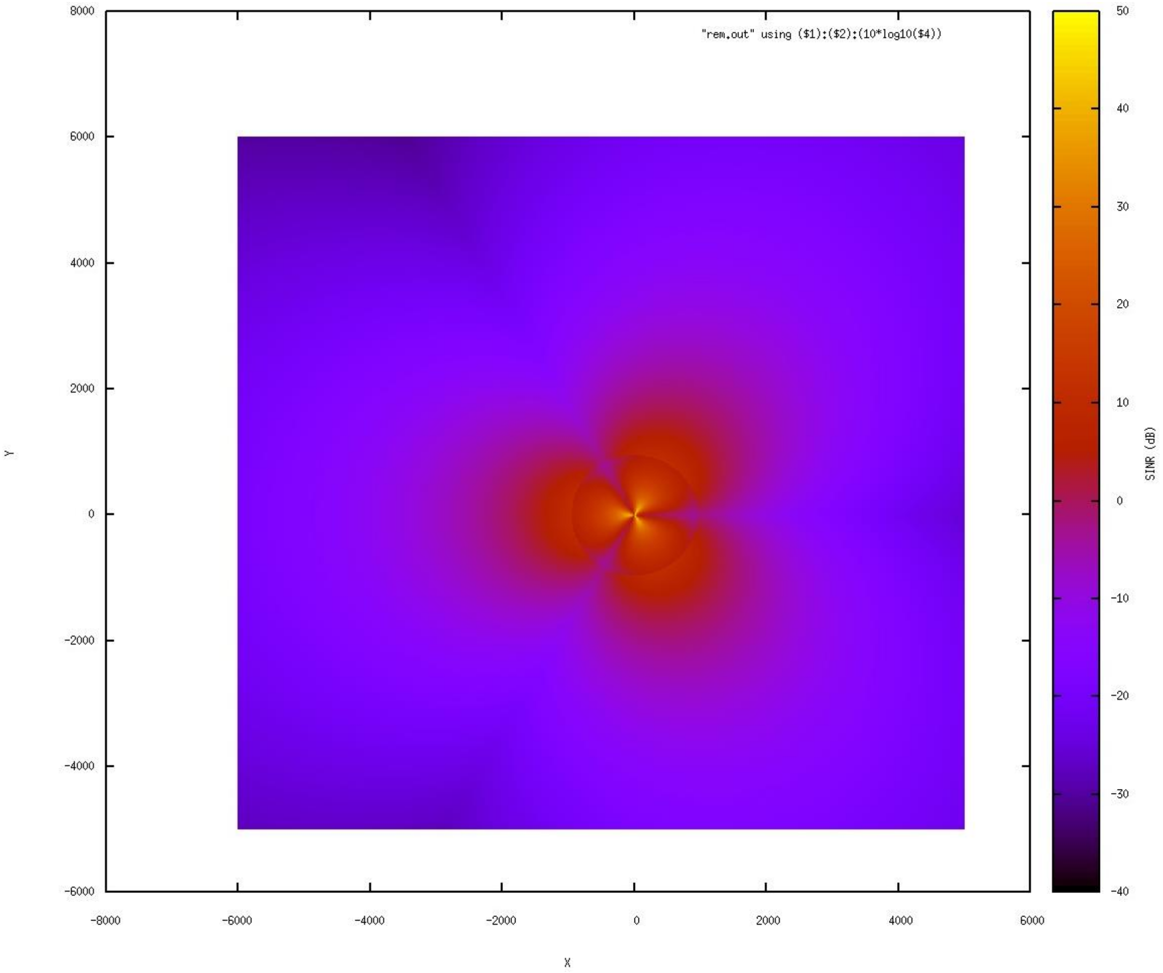


Figure 5.1.1-1 Tri-sectorial antenna SNR

The tri-sectorial antenna provides coverage in three sectors (see Figure 5.1.1-1), and it is possible to allocate around 500 UEs given the same SRS periodicity.

The NB-IoT UEs are expected to transmit few times a day, so the inter-packet interval is set to 30 minutes per day.

In this scenario, the flow monitor module is used to evaluate the performance.

5.1.2 Dense City Scenario

After this single antenna introductory case, a dense urban European city scenario is simulated (see Figure 5.1.2-1). 5 tri-sectorial antennas are deployed in an area of 2000x1700m, and given the SRS periodicity, around 2500 UEs can be placed.

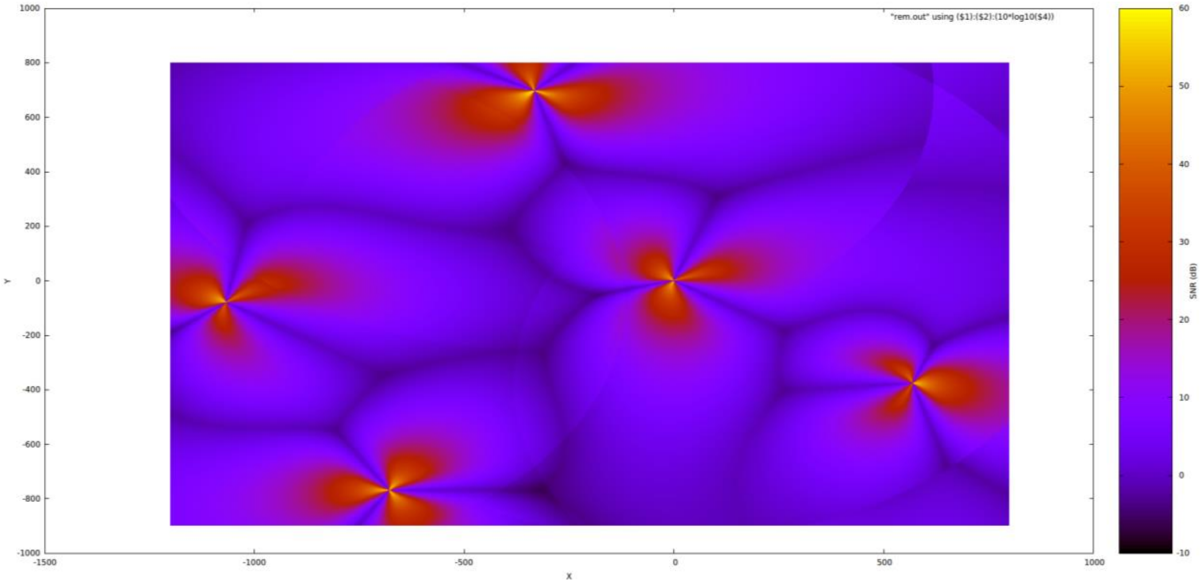


Figure 5.1.2-1 Dense city scenario SNR

This distribution corresponds to a scenario like the one observed in Figure 5.1.2-2.

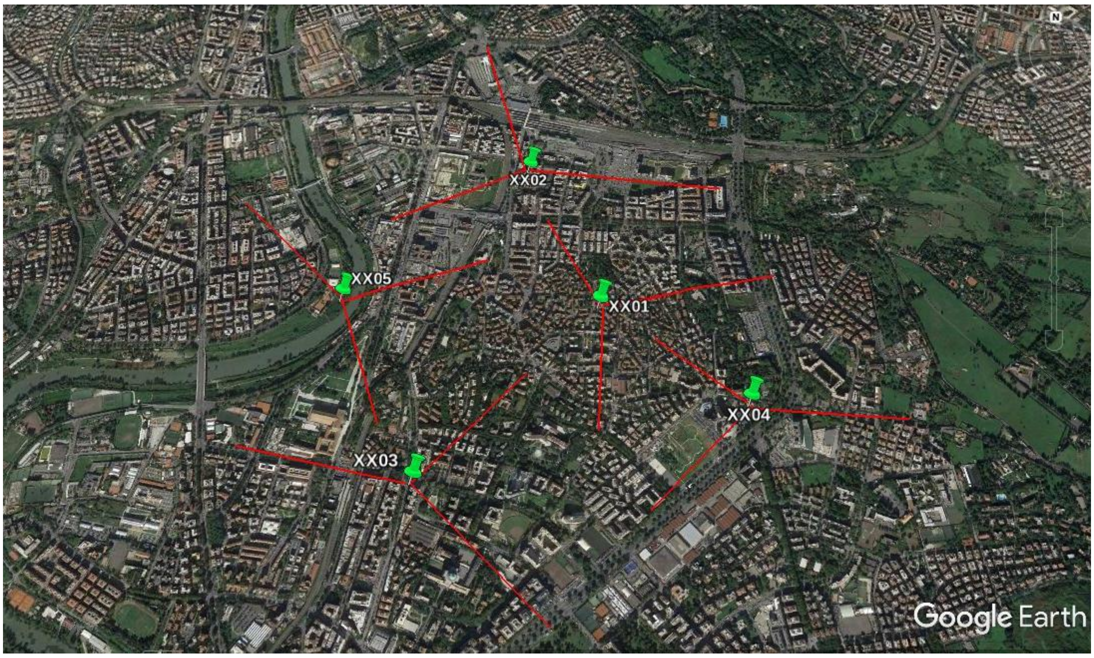


Figure 5.1.2-2 Dense city scenario in real life (Rome city)

Three types of UEs are implemented:

- Type A, with an inter-packet interval time of 24 hours.
- Type B, with an inter-packet interval time of 2 hours.
- Type C, with an inter-packet interval time of 1 hour.

Four UE types of distribution cases are considered:

- Fair Distribution with 30%-40%-30%
- Type A Predominance with 80%-10%-10%
- Type B Predominance with 10%-80%-10%
- Type C Predominance with 10%-10%-80%

As explained in the NB-IoT section, NB-IoT technology uses repetitions to enhance the coverage of the network. To analyze the impact of repetitions, the efficiency is computed after processing of the ns-3 UL RLC traces.

Two schemes have been adopted in order to select the UEs that repeat:

- Selecting the UEs by distance to eNB.
- Selecting the UEs by observing their initial efficiency.

In section 5.2, results of both cases are reported.

5.1.3 Heterogenous Scenario

The aggregation of small cells to a network is a feasible technique to widen the coverage area. These base stations introduce the heterogeneity concept to the system, being convenient when it comes to ensure connection on areas that deal with a high path loss [45].

Then, to improve the coverage of the whole system, it is possible to introduce some indoor base stations (small cells) in the simulation. The indoor base stations coverage and attachment have been already explained in their own sections.

- Small Cell Aggregation to a Tri-sectorial Antenna

Firstly, we develop a single antenna scenario, placing one single tri-sectorial antenna. 100 UEs are distributed randomly in a 1-kilometer area.

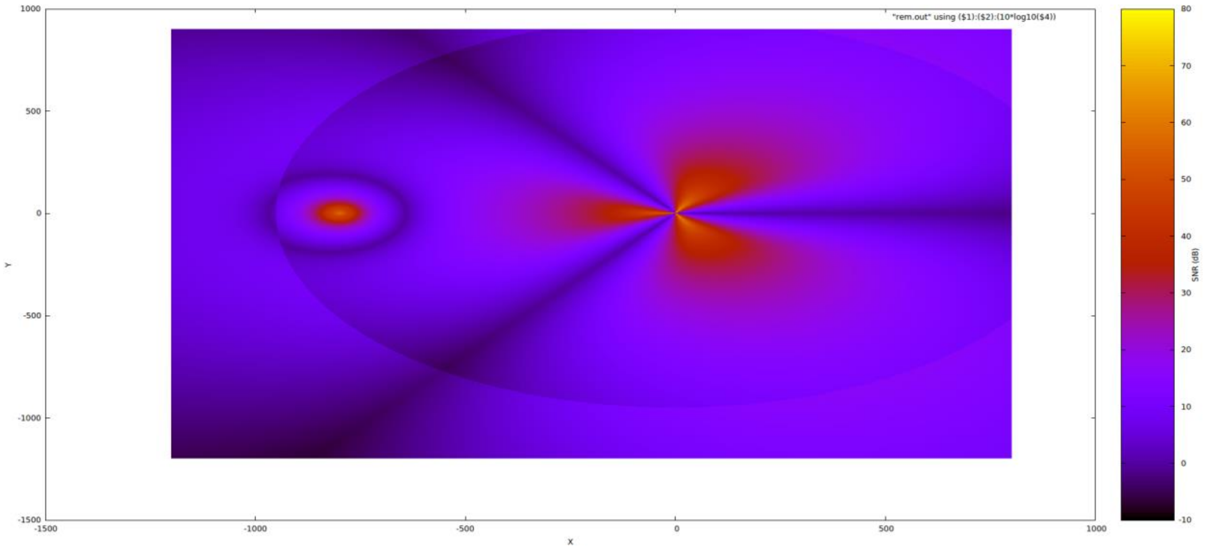


Figure 5.1.3-1 Small cell aggregation to a tri-sectorial antenna SNR

To analyze the effects of the indoor base station aggregation, 5 indoor base stations are placed to provide coverage to the UEs that where not attached.

- Small Cell Aggregation in a Dense City Scenario

Figure 5.1.3-2 shows a dense city aggregation scenario when small cells and outdoor base stations work in the same frequency. In the simulated cases, these different types of base stations work in different frequencies and do not interact with each other.

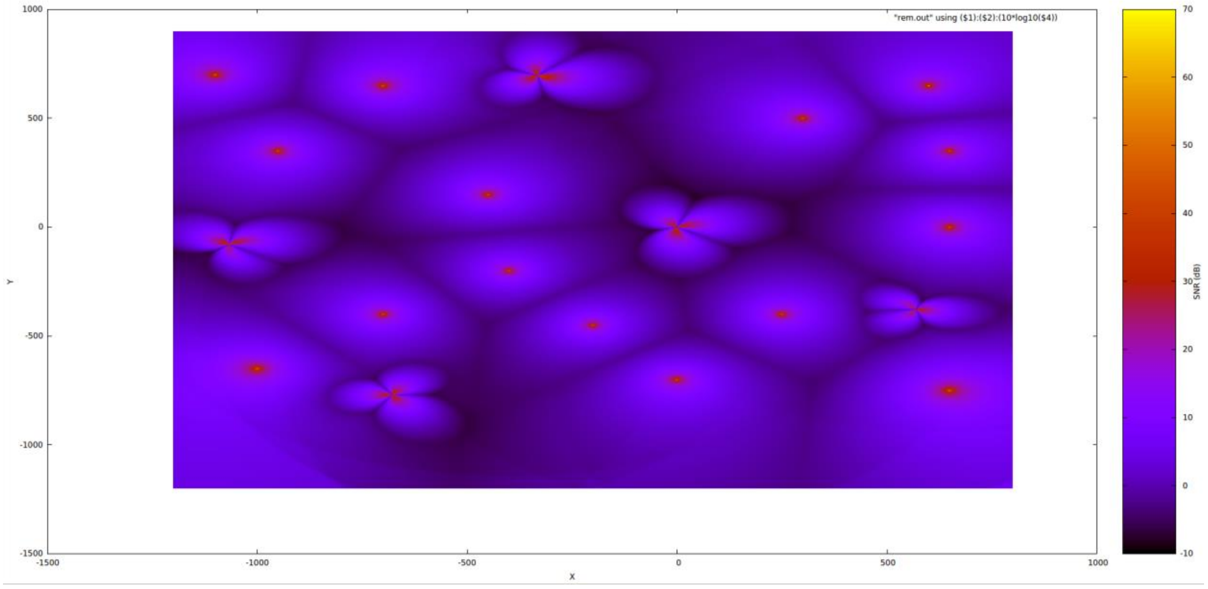


Figure 5.1.3-2 Small cell strategic aggregation case in dense city scenario SNR working at the same frequency bands

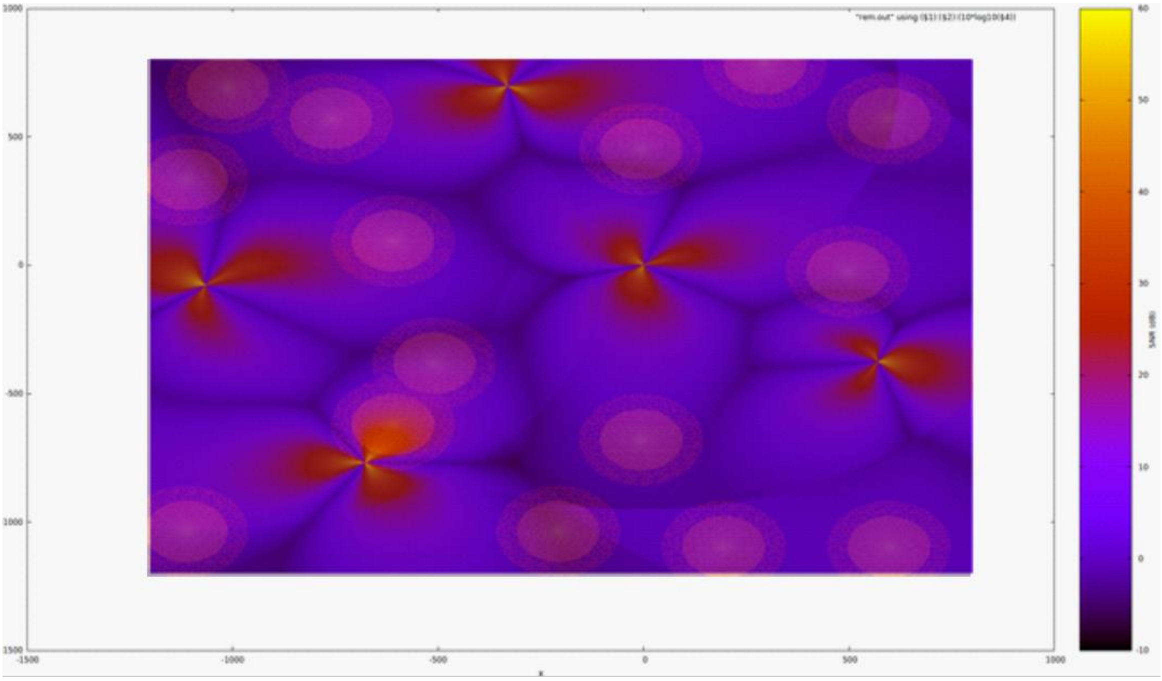


Figure 5.1.3-3 Small cell strategic aggregation case in dense city scenario SNR working at different frequency bands

5.2 Results

5.2.1 Tri-sectorial antenna

Firstly, the performance of a tri-sectorial antenna is evaluated with the ns-3 flow monitor module. Figure 5.2.1-1 presents the weighted efficiency in the presence of diverse number of UEs, by changing the area in which UEs are placed:

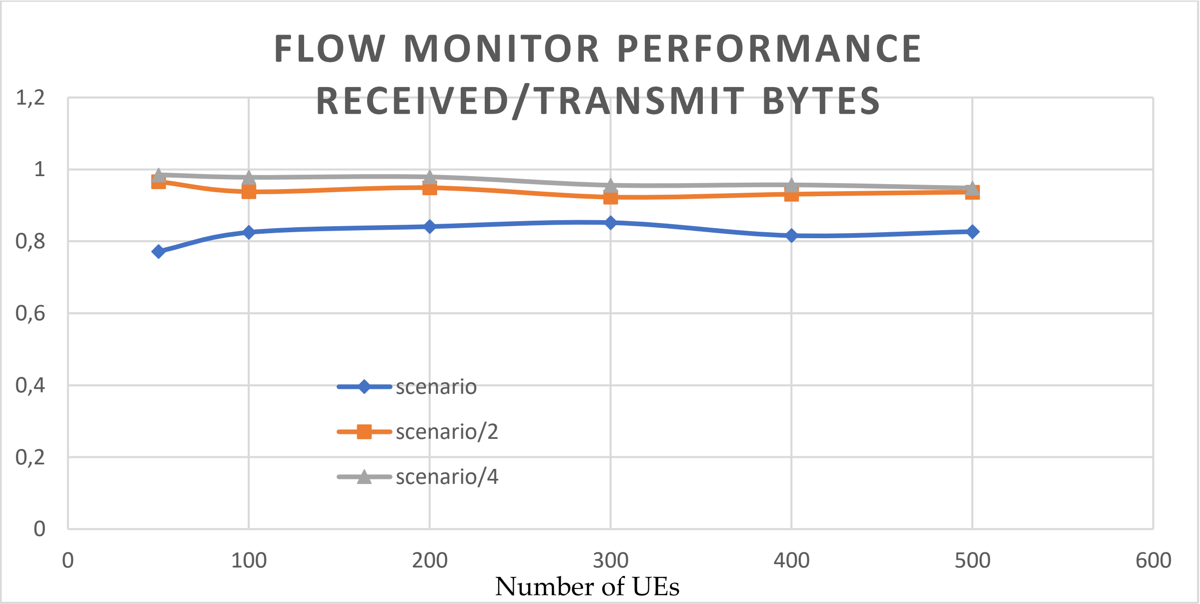


Figure 5.2.1-1 Tri-sectorial antenna weighted efficiency ratio

After the scenario was systematically reproduced with different number of UEs, it can be concluded that the wider the area, the less UEs are attached (see Table 5.2.1-1), diminishing the weighted efficiency ratio.

Area/4	478
Area/2	473
Area	416

Table 5.2.1-1 Attached UEs

In the smaller placement area, the efficiency ratio tends to decrease when placing more and more UEs. This tendency is not observed with the 2000x1700m full area, as the network is not congested.

5.2.2 Dense City Scenario

5.2.2.1 Selecting Repeating UEs by Distance

After this preliminary analysis with the flow monitor module, the RLC traces with MATLAB processing have been adopted.

With the three mentioned different types of UEs (A, B, and C), two types of distributions are studied, the Fair Case and the Predominance A one.

As NB-IoT implements repetitions, we arbitrarily define a Coverage Extension (CE) area of 640 meters. UEs having a distance larger than this threshold repeat. In this case, only class A devices can repeat.

Three study cases are presented, with different packet sizes and number of repetitions:

The first study case presents a packet size of 20 bytes and 32 repetitions.

In the second case, a larger packet size of 160 bytes is presented, with 4 repetitions.

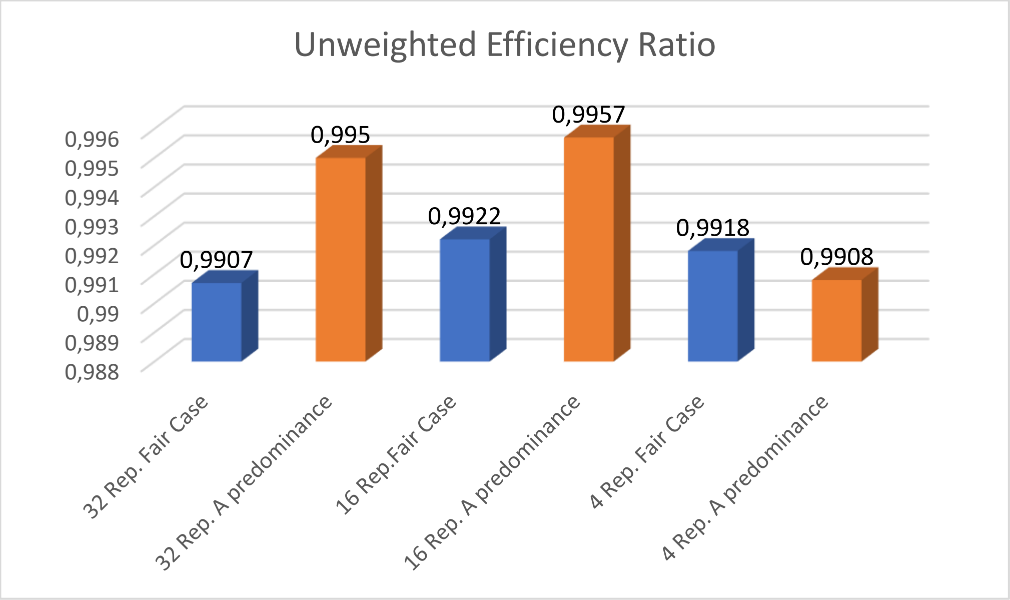


Figure 5.2.2.1-1 Unweighted efficiency ratios, selecting UEs by distance

In the small packet and high repetitions case, the unweighted efficiency of the Predominance A distribution is higher than in the Fair Case, as with a smaller packet size, UEs benefit from the repetitions in class A devices, that only transmit once a day.

On the contrary, in the second case, with big packets and small repetitions, the tendency varies: when the packet size is larger, too many class A repeating UEs leads to increase the congestion in the network, that does not benefit as much from signal repetitions as in the Fair Case.

5.2.2.2 Selection of Repeating UEs by Performance

The next case study focuses on the effect of repetitions on the efficiency.

To select the threshold of repeating UEs, a CDF graph, and arbitrary selected that UEs with an efficiency less than 95% repeat.

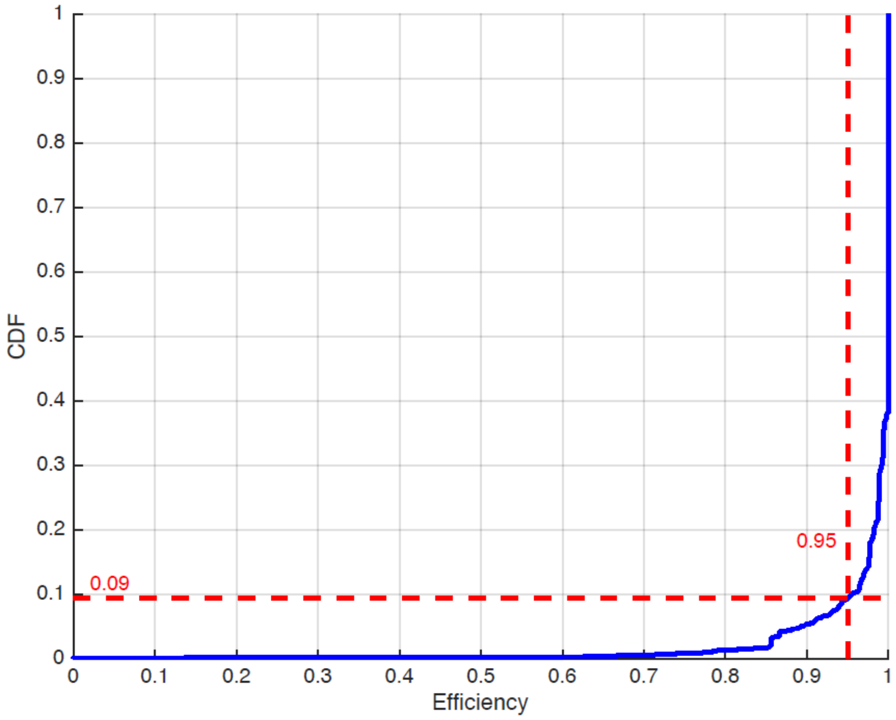


Figure 5.2.2.2-1 CDF of efficiency in case of Class Fairness distribution (no repetition)

The packet size is fixed to 20B, with 32 repetitions, and all four UEs distributions are simulated. In this case, UEs that repeat are selected between all types of UEs (A, B, C), among the ones that present a lower initial efficiency.

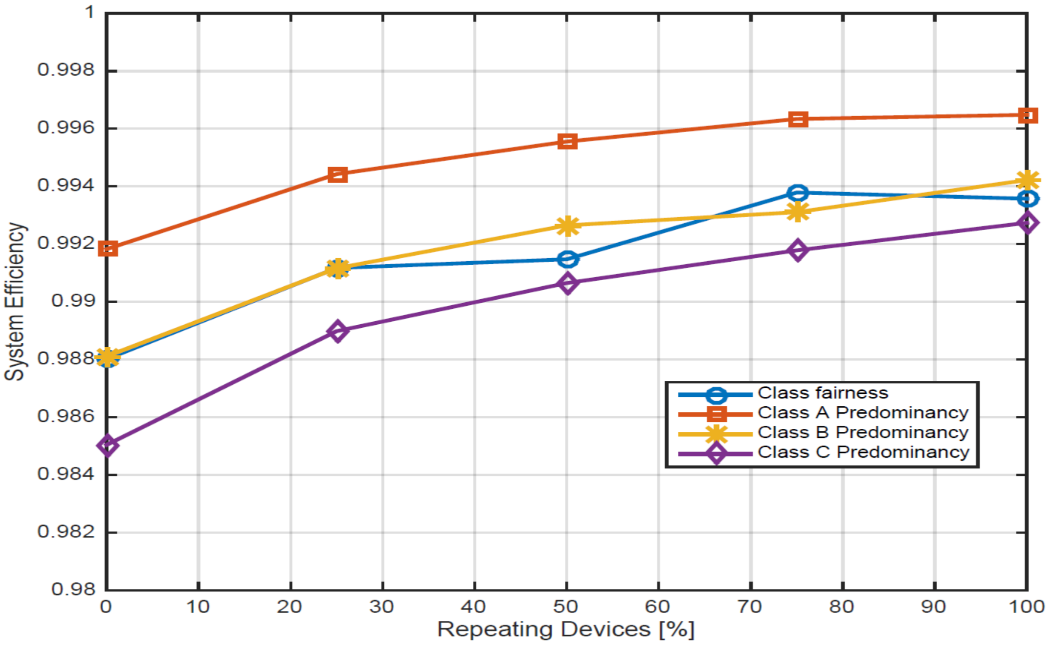


Figure 5.2.2.2-2 Manual selection of repeating UEs, with small packets and high number of repetitions unweighted efficiency ratio results

Varying the percentage of repeating UEs, the efficiency ratio is modified (see Figure 5.2.2.2-1).

Implementing repetitions, the efficiency improves. As can be observed in Figure 5.2.2.2-1, the Predominance A case has higher values than the others, as the network is less congested.

The network performance is also studied when the packet size is of 160B and the number of repetitions is reduced to 4.

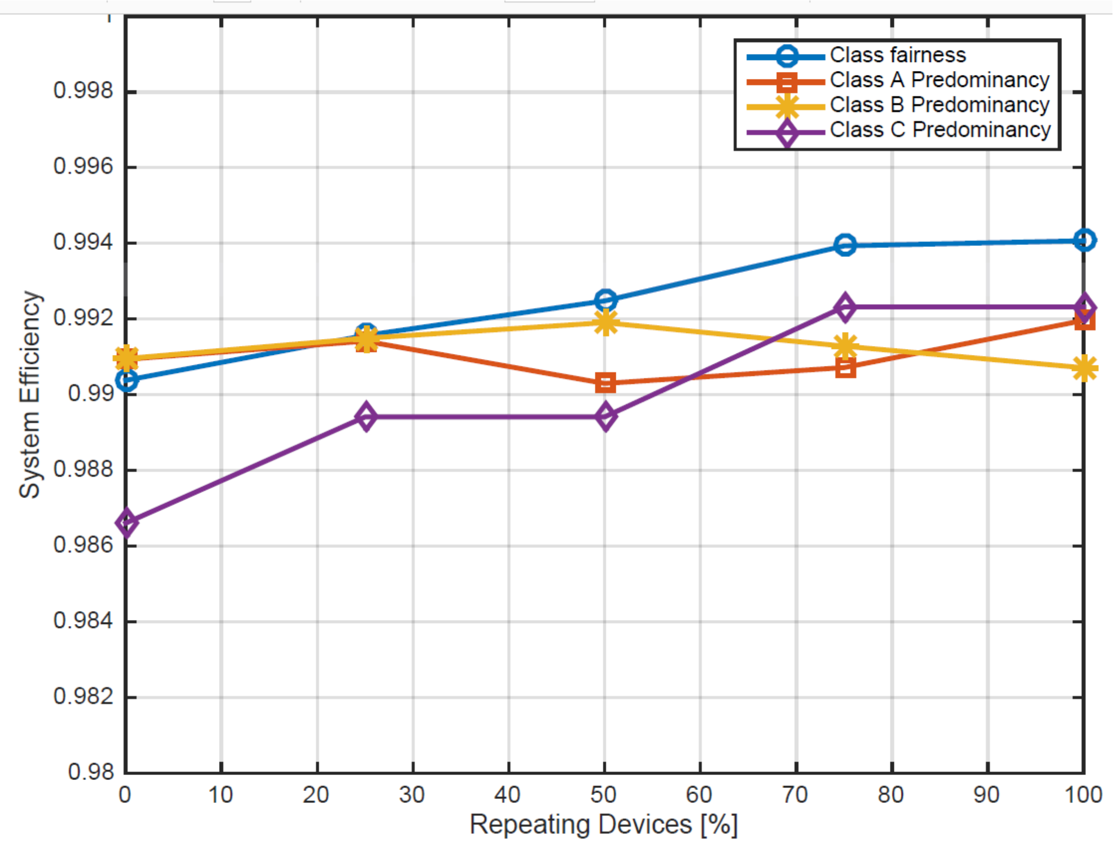


Figure 5.2.2.2-3 Manual selection of repeating UEs, with big packets with high number of repetitions, unweighted efficiency ratio results

The tendency in this big packet size and low number of repetitions is similar than the previous one but with Predominance A and Predominance B showing worse results.

In the case of class B Predominance, the bad performance can be explained because of the randomicity of the simulator, while on class A Predominance, the bad performance is explained because of too reduced simulation time. As the packets are big and class A only sends one packet, some class A UEs do not achieve the communication in the given time. This misleading result can be simply solved by running such scenario on a longer simulation time.

5.2.3 NB-IoT with Heterogenous Architecture

5.2.3.1 Small Cell Aggregation to a Tri-sectorial Antenna

Figure 5.2.3.1-1 show the effect of introducing small cells within the coverage of a single outdoor base station.

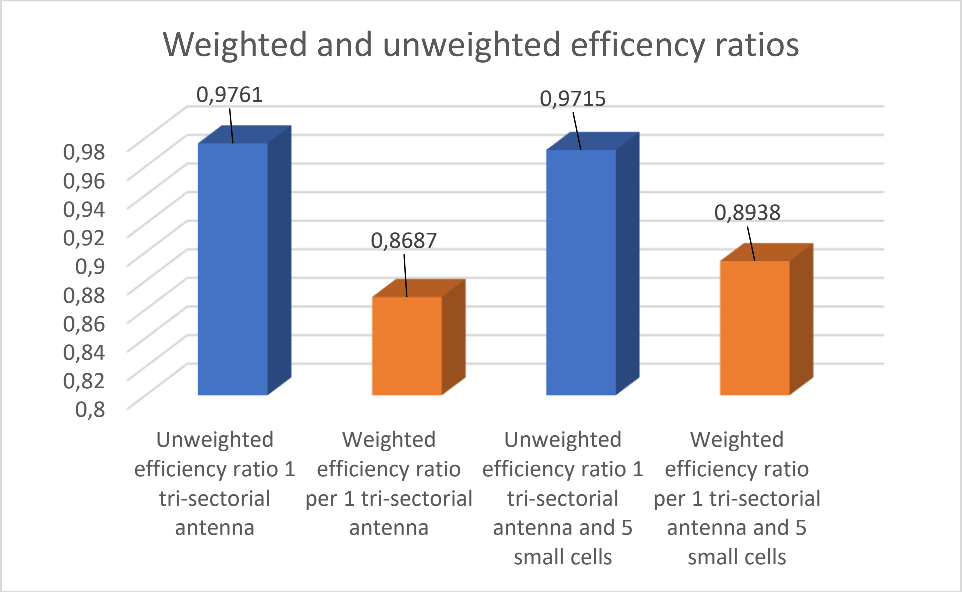


Figure 5.2.3.1-1 Efficiency ratios for small cell aggregation to a tri-sectorial antenna

By introducing 5 small cells, the unweighted efficiency is very similar, but a significant improved of the weighted efficiency can be observed. This is mainly due to the fact that the introduction of small cells allows a higher number of UEs to be connected.

As this area is too small, the introduction of more small cells produces an interference that should be avoided.

5.2.3.2 Small Cell Aggregation to a Dense City Scenario

Figure 5.2.3.2-1 shows the effect of introducing 15 small cells in a regular dense city scenario.

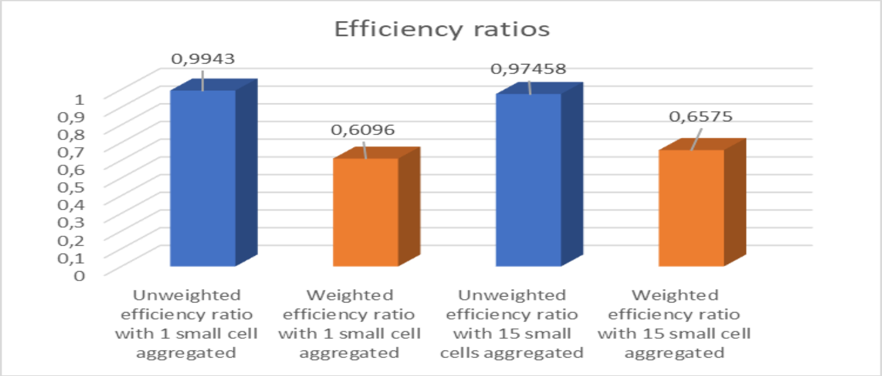


Figure 5.2.3.2-1 Efficiency ratios for small cell aggregation in a dense urban city scenario

It can be observed that as in the previous case, the unweighted efficiency tends to be similar, while weighted indicator significantly improves. This represents an enhancement in the coverage of the network, as when the number of aggregated antennas increases from one to fifteen, the number of attached UEs grow from 1533 to 1653.

It is worth mentioning that for poor coverage zones or even for critical applications, small cell aggregation can be very beneficial.

5 Conclusions and Future Works

This thesis presented an analysis on the recent NB-IoT technology and proposed a framework to evaluate its performance considering different networks and parameters.

The first chapter provided a brief overview of the IoT landscape, introducing the concepts of mMTC and smart environments. The architecture and requirements of an MTC network, and the plethora of smart environments have been emphasized.

The second chapter presented and compared commonly adopted solutions to tackle the demand of massive IoT connectivity. LPWAN networks were explained, and both unlicensed and licensed solutions were compared.

After studying the suitability of NB-IoT cellular technology, the third chapter expounds legacy NB-IoT technology LTE and LTE-A, as they are necessary to comprehend the NB-IoT standard. Then, NB-IoT is deeply explained.

The fourth chapter, regarding Network Simulator-3, summarizes the modules and modifications that have been used or introduced in ns-3 code, along with an explanation of the different channel models, base stations, and some attachment considerations.

The last chapter, presents and analyzes the results of different simulation scenarios, from simple deployments to a complex dense urban city case. The RLC layer traces post-processing and analysis is also detailed. It is exposed the trade-off between the number of repetitions in the uplink, and the performance of the network due to congestion, depending on the size of the packets, UEs interval of transmissions, and number of repetitions. The aggregation of small cells solution is also presented, with a proof-of-concept that this method can enhance the network coverage.

More advanced scenarios are under study and analysis, in particular regarding the small cell aggregation concept.

With a more general perspective, that exceeds the possibilities of this thesis, there is a lot of work to be done by researchers in the IoT topic. Because of the ns-3 open source project nature, the simulator must be extended and developed continuously. Coexistence projects like LAA-Wi-Fi-Coexistence should be tested and developed in the future. Even regarding NB-IoT is close to LTE, a specific NB-IoT module creation should is helpful to the technology testing, improving the reliability and standardization of the simulations.

Also, as cellular operators are already deploying their NB-IoT networks since early 2018, a fluent communication with these companies should be strongly pursued.

Budget

The software used in the project is open source, unless MATLAB, with a cost of 500 euros for educational institutions like Sapienza di Roma or Polytechnic University of Catalonia.

Author dedication to the project was around 25 hours per week, for approximately 20 weeks of project, resulting in 500 hours in total. Considering 10 euros per hour retribution, the authors total retribution for this project would be around 5000 euros. Thesis supervisor and co-supervisor retributions are not considered.

During the project, seven different computers have been used because of the thesis computational requirements. The cost of the computers is close to 10000 euros.

The total cost of the project considering the previous mentioned resources is approximately around 15500 euros.

Concerning the financial viability, the ACTS Laboratory at DIET, that is the research group laboratory where the project was carried out, is publicly funded by the Italian Ministry of Education for the University and Research (*Ministerio dell'Instruzione dell'Università e della Ricerca*). Furthermore, it is supported by a team of cooperating industrial partners.

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List of Abbreviations

2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
AC	Alternating Current
ACK	Acknowledgment
AM	Amplitude Modulation
AR	Augmented Reality
AWGN	Additive White Gaussian Noise
CA	Carrier Aggregation
CDD	Cyclic Delay Diversity
CDMA	Code Division Multiple Access
CE	Coverage Extension
CFO	Carrier Frequency Offset
CoMP	Coordinated Multi-Point
CP	Cyclic Prefix
CQI	Channel Quality Indicator
CSMA	Carrier Sense Multiple Access
DC	Direct Current
DCI	Downlink Control Information
DFT	Discrete Fourier Transform
DL	Downlink
DPC	Downlink Physical Channel
DRS	Demodulation Reference Signal
DRS	Downlink Reference Signal
DRX	Discontinuous Reception
EARFCN	EUTRA Absolute Radio-Frequency Channel Number
ECU	Electronic Control Units
eMIMO	enhanced Multiple Input Multiple Output
eMTC	enhanced Machine Type Communications
eNB	enhanced NodeB
EPC	Evolved Packet Core
ERP	Effective Radiated Power
EU	European Union
eUTRAN	Evolved Terrestrial Radio Access Network

FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
GSM	Global System for Mobile communications
HeNB	Home enhanced NodeB
HFC	Hybrid Fiber-Coaxial
HSPA	High-Speed Packet Access
HSS	Home Subscriber Service
ICIC	Inter-Cell Interference Coordination
ICT	Information and Communication Technology
IDE	Integrated Developer Environment
IEEE	Institute of Electric and Electronic Engineers
IoT	Internet of Things
IP	Internet Protocol
ISI	Inter Symbol Interference
ISM	Industrial, Scientific, Medical
ITU	International Telecommunication Union
IUI	Inter-User Interference
LOS	Line of Sight
LPWAN	Low Power Wide Area Network
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
LTN	Low Throughput Network
M2M	Machine-to-Machine Communications
MAC	Medium Access Control
MAN	Metropolitan Area Network
MCL	Maximum Coupling Loss
MIB	Master Information Block
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MMTC	Massive Machine Type Communications
MT	Mobile Termination
MTC	Machine Type Communications
NACK	Non-Acknowledgement
NB	Narrow Band
NB-IoT	Narrow-Band Internet of Things
NB-PBCH	Narrow-Band Physical Broadcast Channel
NB-PDCCH	Narrow-Band Physical Downlink Control Channel

NB-PDSCH	Narrow-Band Physical Downlink Shared Channel
NB-RS	Narrow-Band Reference Signal
NLOS	Non-Line of Sight
NOMA	Non-Orthogonal Multiple Access
NS	Network Simulator
OFDMA	Orthogonal Frequency Division Multiple Access
PAPR	Peak to Average Power Ratio
PDCP	Packet Data Convergence Protocol
PGW	Packet Data Network Gateway
PHICH	Physical Hybrid-ARQ Indicator Channel
PHY	Physical layer
PLC	Power Line Carrier
PRACH	Physical Random-Access Channel
PRB	Physical Resource Block
PRM	Precoding Matrix Information
PSD	Power Spectral Density
PSS	Primary Synchronization Signal
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QoS	Quality of Service
QPSK	Quaternary Phase Shift Keying
RAN	Radio Access Network
RB	Resource Block
RF	Radio Frequency
RLC	Radio Link Control
RN	Relay Nodes
RRC	Radio Resource Control
RRC	Radio Resource Control
RU	Resource Unit
RX	Reception
SC	Single Carrier
SC-FDMA	Single Carrier-Frequency Division Multiple Access
SDO	Standard Developing Organization
SGW	Serving Gateway
SIG	Special Interest Group
SIM	Subscriber Identity Module
SINR	Signal to Interferent-Noise Ratio
SM	Spatial Multiplexing

SNR	Signal to Noise Ratio
SR	Scheduling Requests
SRS	Sounding Reference Signal
SS	Spread Spectrum
SS	Synchronization Signal
SSS	Secondary Synchronization Signal
TB	Transport Block
TBCC	Tail-Biting Convolutional Coding
TC	Turbo Coding
TCP	Transmission Control Protocol
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TE	Terminal Equipment
TM	Transmission Modes
TX	Transmission
UCI	Uplink Control Information
UE	User Equipment
UICC	Universal Integrated Circuit Card
UL	Uplink
UMTS	Universal Mobile Telecommunication System
UNB	Ultra-Narrow Band
US	United States
USIM	Universal Subscriber Identity Module
UWB	Ultra-Wide Band
VR	Virtual Reality
WAN	Wide Area Network
WB	Wide Band
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WRAN	Wireless Regional Area Network
DSL	Digital Subscriber Line

List of Tables

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