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# Use of unlicensed bands for indoor ultra-broadband mobile networks: performance evaluation of LTE Licensed-Assisted Access


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# Abstract

The continuous growth of worldwide mobile subscriptions and the progress of mobile devices and telecommunications in the last few years have led to a tremendous increase of demand for high data rate. The scarcity of licensed spectrum and the high costs of this resource have encouraged mobile operators to move towards the unlicensed spectrum. LTE Licensed-Assisted Access is the technology proposed by 3rd Generation Partnership Project (3GPP) in Release 13, that allows to work on the 5 GHz unlicensed band. To operate on these frequencies already occupied by Wi-Fi and radar systems, LTE must fairly coexist with the above using a Listen Before Talk mechanism.

Thereby, LTE-LAA is the solution to provide more capacity, better user experience and higher quality of service, overcoming the limits of LTE-Advanced. Utilizing high-order modulation (256QAM) and adding up to four MIMO layers, LAA globalizes the Gigabit LTE opportunity. For those reasons, it is also named LTE-Advanced Pro.

The aim of this thesis is to present and describe LTE Licensed-Assisted Access outlining the evolution of the LTE standard. And then, to analyse the downlink performance improvements, offered by the aggregation of unlicensed bands, in terms of user throughput. Therefore, through extensive simulations based on ns-3 simulator, this work presents a comparison between the throughput results of LTE-LAA and the data-rates offered by LTE in licensed bands.

# Abstract

Il continuo aumento del numero mondiale di abbonati mobili ed il progresso degli apparecchi mobili e delle telecomunicazioni nel corso degli ultimi anni hanno portato ad un incredibile incremento della domanda di data-rate elevato. La ristretta disponibilità dello spettro licenziato e gli alti costi di tale risorsa hanno dunque incoraggiato gli operatori mobili verso l'uso dello spettro non licenziato.

La tecnologia proposta in questo senso dall'ente 3GPP (3rd Generation Partnership Project) all'interno della Release 13 è chiamata LTE Licensed-Assisted Access: essa consente per l'appunto di lavorare nella banda di frequenze non licenziate a 5 GHz. Per poter operare in queste range di frequenze, già occupate dai preesistenti sistemi radar e Wi-Fi, LTE deve garantire una coesistenza corretta e per fare ciò impiega il meccanismo denominato Listen Before Talk.

Perciò, LTE-LAA si configura come soluzione atta a fornire una maggiore capacità ed una migliore qualità del servizio, andando così a superare i limiti del LTE-Advanced.

Attraverso l'uso di ordini di modulazione elevati (come ad esempio 256QAM) e l'aggiunta di un numero massimo di quattro strati MIMO, LAA consente di globalizzare l'opportunità di quello che è definito Gigabit LTE – per via dell'elevato valore di throughput raggiunto. Proprio per tale ragione si fa riferimento a LTE-LAA con il nome di LTE-Advanced Pro.

Obiettivo di questa tesi è quello di presentare e descrivere la tecnologia LTE Licensed-Assisted Access ripercorrendo anche l'evoluzione dell'intero standard LTE che ne costituisce poi la base. Tale lavoro si propone in aggiunta lo scopo di analizzare i miglioramenti sulle prestazioni in downlink in termini di throughput di utente, apportati dalla tecnologia in esame grazie all'aggregazione di bande non licenziate.

Attraverso l'ampio uso di simulazioni basate sull'ambiente open source ns-3, questa tesi presenta dunque un confronto dei risultati di throughput ottenuti usando LTE-LAA con i risultati delle prestazioni offerte usando invece LTE esclusivamente in bande licenziate.

# Table of Contents

## List of the Abbreviations

| | |
|---|---|
| 1G | First Generation |
| 2G | Second Generation |
| 3G | Third Generation |
| 3GPP | Third Generation Partnership Project |
| 4G | Fourth Generation |
| ABS | Almost Blank Subframes |
| AM | Acknowledged Mode |
| AMC | Adaptive Modulation and Coding |
| BER | Bit Error Rate |
| BLER | Block Error Rate |
| BS | Base Station |
| CA | Carrier Aggregation |
| CB | Coordinated Beamforming |
| CCA | Clear Channel Assessment |
| CCS | Cross-Carrier Scheduling |
| CDF | Cumulative Density Function |
| CDMA | Code Division Multiple Access |
| CL | Closed Loop |
| CoMP | Coordinated Multi Point |
| CP | Cyclic Prefix |
| CQI | Channel Quality Indicator |
| CS | Coordinated Scheduling |
| CSMA | Carrier Sense Multiple Access |
| DL | DownLink |
| DRB | Data Radio Bearer |
| eICIC | Enhanced Inter-Cell Interference Coordination |
| eNB | eNodeB |
| EPC | Evolved Packet Core |
| EPS | Evolved Packet System |
| ESM | EPS Session Management |
| E-UTRA | Evolved Universal Terrestrial Access |
| E-UTRAN | Evolved Universal Terrestrial Access Network |
| FBE | Frame Based Equipment |
| FDD | Frequency Division Duplexing |
| HARQ | Hybrid Automatic ReQuest |
| HetNet | Heterogeneous Networks |
| HSPA | High Speed Packet Access |
| IP | Internet Protocol |
| ITU | International Telecommunication Union |

| | |
|---|---|
| JP | Joint Processing |
| LAA | Licensed-Assisted Access |
| LBE | Load Based Equipment |
| LBT | Listen Before Talk |
| LoS | Line of Sight |
| LTE | Long Term Evolution |
| LTE-A | LTE-Advanced |
| LTE-U | LTE-Unlicensed |
| MAC | Medium Access Control |
| MCS | Modulation and Coding Scheme |
| MIMO | Multiple Input Multiple Output |
| MME | Mobility Management Entity |
| MU-MIMO | Multi-User MIMO |
| NAS | Non-Access Stratum |
| NLoS | Non-Line of Sight |
| NPRB | Number of PRB |
| OFDM | Orthogonal Frequency Division Multiplexing |
| OFDMA | Orthogonal Frequency Division Multiple Access |
| OL | Open Loop |
| PAPR | Peak-to-Average Power Ratio |
| PCC | Principal Component Carrier |
| PDF | Probability Density Function |
| PDN | Packet Data Network |
| PDPC | Packet Data Convergence Protocol |
| PDU | Protocol Data Unit |
| PF | Proportional Fair |
| PGW | Packet GateWay |
| PHY | Physical Layer |
| PRB | Physical Resource Block |
| PS | Packet Switch |
| PSC | Primary Serving Cell |
| QAM | Quadrature Amplitude Modulation |
| QoS | Quality of Service |
| QPSK | Quadrature Phase-Shift Keying |
| QXDM | Qualcomm eXtensible Diagnostic Monitor |
| RAT | Radio Access Technology |
| RBG | Resource Block Group |
| RBS | Radio Base Station |
| RE | Resource Element |
| RLC | Radio Link Control |

| | |
|---|---|
| RNC | Radio Network Controller |
| RNTI | Radio Network Temporary Identifier |
| ROHC | Robust Header Compression |
| RRC | Radio Resource Control |
| RSRP | Reference Signal Received Power |
| SAE | System Architecture Evolution |
| SCC | Secondary Component Carrier |
| SC-FDMA | Single Carrier Frequency Division Multiple Access |
| SGW | Serving Gateway |
| SINR | Signal-to-Noise Ratio |
| SISO | Single Input Single Output |
| SON | Self-Organizing Networks |
| SRB | Signaling Radio Bearer |
| SRS | Sounding Reference Signal |
| TBS | Transport Block Size |
| TCP | Transmission Control Protocol |
| TDD | Time Division Duplexing |
| TL | Threshold |
| TM | Transmission Mode |
| TP | Throughput |
| TR | Technical Report |
| TS | Technical Specification |
| TTI | Transmission Time Interval |
| UDP | User Datagram Protocol |
| UE | User Equipment |
| UL | UpLink |
| UM | Unacknowledged Mode |
| UMTS | Universal Mobile Telecommunications System |
| UPT | User Perceived Throughput |

# 1 Introduction

## 1.1 Context and Motivation

Since the introduction of the first generation of mobile telecommunications – the analog 1G - in the 1980s, the wireless telephone technology has experienced an incredibly fast process of growth. Arriving to 4G - the fourth generation - has meant a continuous improvement of the standards, switching to the digital, enhancing the quality of the service and multiplying the possibilities offered, step by step, by the new technologies.

In parallel to this, the invention of new devices like smartphones and tablets has contributed in the same direction to the progress, allowing the always increasing number of subscribers to use new services and, in this way, giving a boost to the upgrade of the standards. The worldwide mobile subscriptions in 2014 were 7,1 billion and for 2021 the forecast [1] says that they will be 9 billion. In this context, the new subscribers concern is not anymore limited in voice services.

Multimedia applications, online gaming and above all video streaming have become more and more important for the users. Video content is the major factor of the growth in data traffic: mobile video traffic is forecast to grow by around 50% annually [2].

Between the first quarter of 2015 and the first quarter of 2016 the traffic due to data grew of the 60% [1].

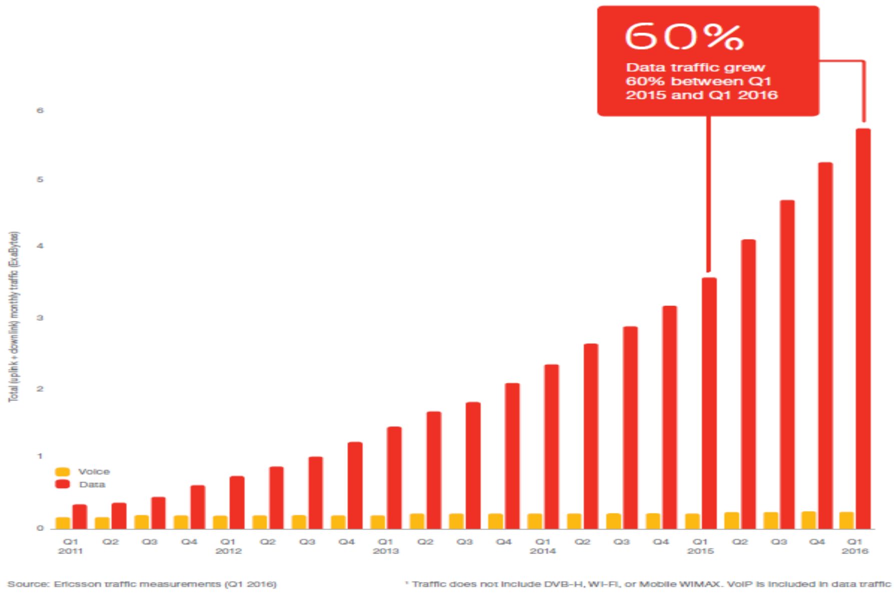



Figure 1.1 Data growth (Ericsson Mobility Report, November 2016)

The resulting increase of demand for high data rate is the principal engine that is driving the latest innovations. Hence the adoption of the LTE as new standard of telecommunication, a new solution to meet the requisites of high speed in downlink.

The ways for obtaining this increase of data rate are several: new coding and modulation schemes, higher number of antennas, flat system architecture, carrier aggregation in order to allocate more spectrum; all these are some of the main approaches.

Thanks to these and others novel aspects LTE makes it possible to overcome the throughput limits of previous generations and allows subscribers to enjoy network services with enhanced quality.

In this continuous race for higher capacity, the use of major amount of spectrum - taking advantage of the carrier aggregation - is the key technique to achieve good results in terms of throughput and keep on guaranteeing always higher speed in downlink. In this viewpoint, finding new available spectrum is not easy for mobile operators because of the limited nature of the resource and the great costs of licensed frequency bands. Therefore, this obstacle has encouraged the industries to look for availability in the unlicensed spectrum, especially at high frequencies. The most attractive unlicensed band is the 5 GHz band, which is not as crowded as the 2.4 GHz ISM band and has a good portion of continuous spectrum globally available.

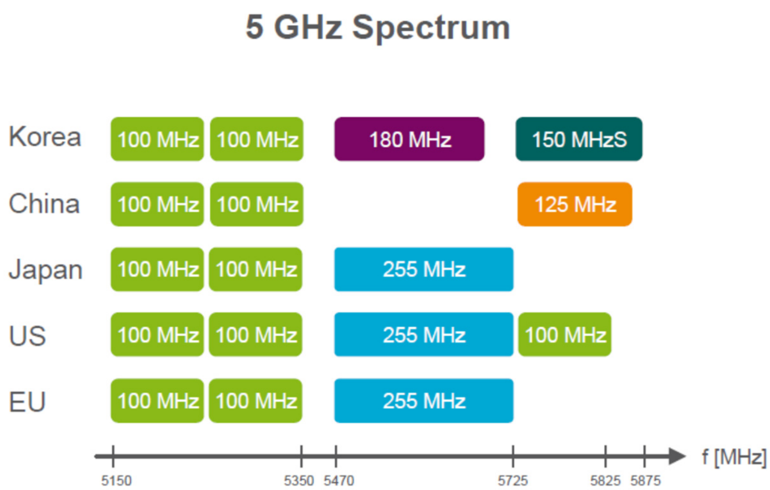



Figure 1.2 5 GHz band regional availability

However, it is important to consider that both Wi-Fi and radar systems already work in this band.

The investigation for new spectrum at high frequencies is a common element with the new generation 5G specified in [3], which will use higher frequencies for commercial deployments (e.g. 24.25-27.5 GHz in Europe but also millimetre-wave frequencies greater than 30 GHz in other countries as China and USA). So, LTE Licensed Assisted Access with its combination of licensed and unlicensed spectrum, working at high frequency band and based on a small cell architecture is a significant milestone toward the $5^{th}$ generation.

Aim of this thesis indeed is to study the LTE-LAA techniques working in the 5GHz unlicensed band and to prove experimental results about the performances in downlink focusing on the parameter of throughput. In doing that, it is important to verify the behaviour of LAA in indoor scenarios where it has to satisfies the requirement of fair coexistence with Wi-Fi and other technologies working on 5GHz band. Among several coexistence mechanisms already proposed, the LBT (Listen Before Talk) technique based on energy detection guarantees good results.

## 1.2 Aim and Contribution

Considering the context described above, the aim of this thesis is to contribute with an investigation on the potential of LTE-LAA presenting a direct comparison between the downlink throughput obtained using unlicensed spectrum and the one offered entirely by licensed bands. To do this, such an evaluation of performance will be carried out through the utilization of ns-3 simulator for the specific case of indoor environment. In addition to these simulation results, there will be presented laboratory recent tests on upcoming commercial devices capable of exploiting Licensed-Assisted Access operations.

## 1.3 Thesis Outline

This first chapter gives an overall introduction of the topics and issues that will be addressed in this thesis. An overall overview of the organization of this work is the following:

- Chapter 2 presents the Long Term Evolution technology and all the features and novel aspects introduced with it.
- Chapter 3 describes a further step in LTE evolution, represented by LTE-Advanced. In this section, they are explained those techniques that allow a boost in performances.
- Chapter 4 is focused on LTE in the unlicensed spectrum. Here, it is presented in detail the LTE Licensed-Assisted Access technology and its features. It is described the Listen Before Talk mechanism for a fair coexistence of LAA and Wi-Fi.
- Chapter 5 deals with simulations and scenarios of interest. The results obtained using ns-3 simulator are reported and analysed in this chapter.
- Chapter 6 summarizes the conclusions drawn in this document and outlines direction for future research.

# 2 Long Term Evolution

## 2.1 Background and novel aspects

The growth of the demand for high data rate in the first decade of 2000 proved that third generation was no longer able to satisfy user requirements. The performances of UMTS, described in 3GPP Release 5 and 6, dealt with downlink and uplink speed of 14.4 Mbps using High Speed Packet Access (HSPA) technology. The need for low latency and high data rate brought 3GPP to the creation of a new work item and to the standardization of the fourth-generation technology as Release 8, in 2008. The new release contained several novel aspects that differentiated 4G from its predecessors: use in downlink of Orthogonal Frequency Division Multiple Access (OFDMA) instead of Code Division Multiple Access (CDMA), as it happened for 3G; support for multiple-antenna technique (MIMO); duplexing operation in frequency (FDD) or in time (TDD); adaptive modulation and coding scheme up to 64 QAM; spectrum flexibility between 1.4 MHz and 20 MHz (instead of the previous fixed 5 MHz). Also the system architecture described in Release 8 was different since the implementation of the Evolution Packet System.

The introduction of all these features characterises the technology known as Long Term Evolution (LTE).

## 2.2 Multiple Access Techniques

The transition from 3G to 4G has meant a different multiple access technique utilisation: from CDMA for HSPA to OFDMA for LTE in Downlink (DL) and Single Carrier Frequency Division Multiple Access (SC-FDMA) in Uplink (UL). The choice of OFDM as form of transmission is due to its resilience to interference and multipath fading. These medium access techniques are presented in the following subsections.

### 2.2.1 OFDMA

This technique is based on orthogonal frequency division multiplexing (OFDM), where the digital data is encoded on multiple carrier frequencies and the carrier signals are orthogonal to each other. According to the meaning of frequency division, the usable bandwidth is split into several subcarriers closely spaced to each other with no interference. In order to have orthogonality, the subcarrier spacing (Δf) has to be the reciprocal of the useful symbol duration (T). In LTE, the spacing value is 15 kHz so symbol duration is about 66.7 μs.

High data stream is divided into parallel low data rate sub-streams on the different subcarriers: the total data rate is the same but on each subcarrier data rate is lower, therefore symbol duration is longer and the inter symbol interference (ISI) is reduced.

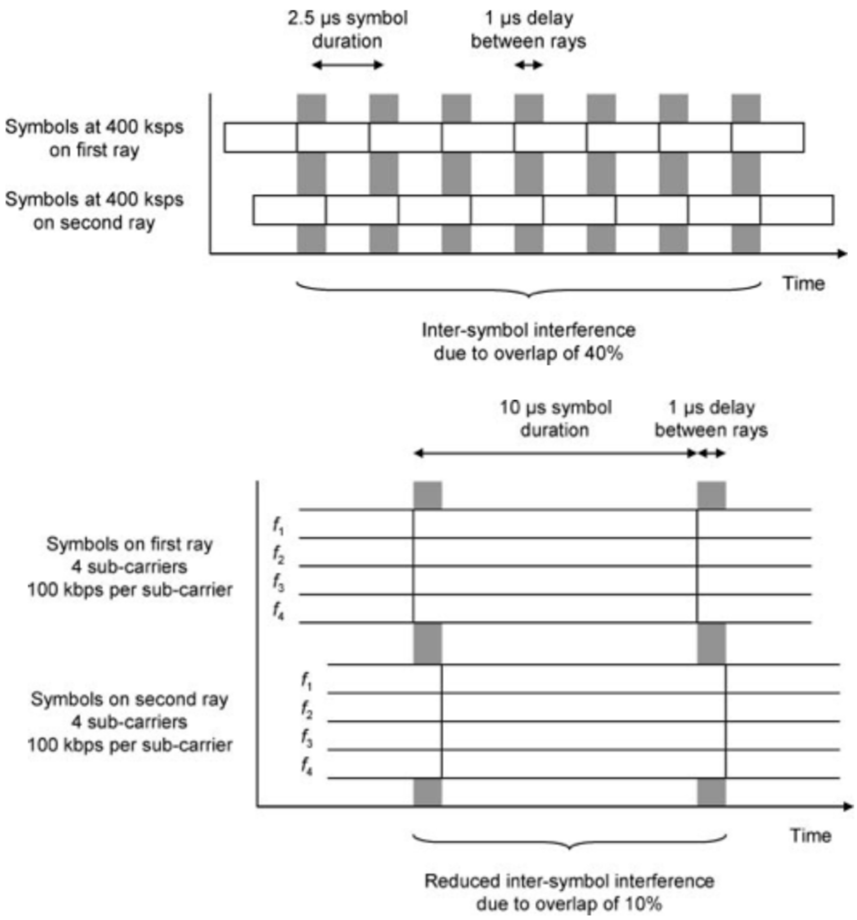



Figure 2.1 Subcarriers in OFDM

In OFDM each subcarrier can have a different modulation scheme, depending on the SNR level, giving a different speed. First 3GPP Release for LTE allows to use quadrature phase-shift keying (QPSK), 16-phase quadrature amplitude modulation (16QAM) or 64-state quadrature amplitude modulation (64QAM). In each of these modulation orders it changes the number of bits per symbol, from 2 bits/symbol (in QPSK) to 6 bits/symbol (in 64QAM). The higher the modulation order, the higher the spectral efficiency (hence the data rate). Higher orders are less robust to noise, thereby the choice of the modulation scheme to use depends on the channel condition.

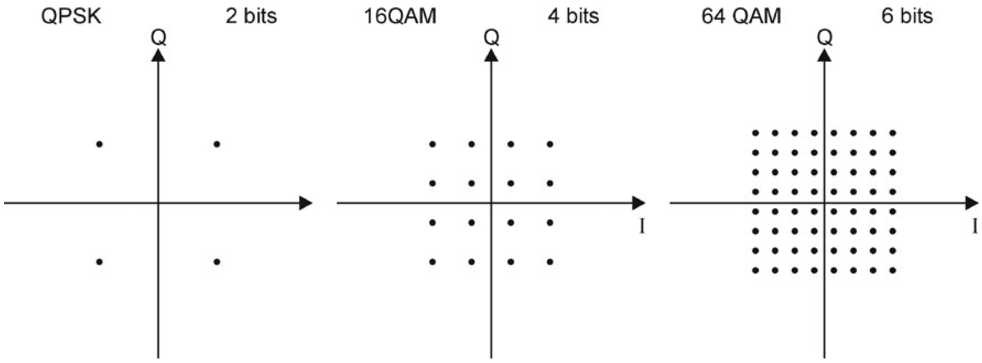



Figure 2.2 LTE modulation schemes

Advantages of OFDM are high spectral efficiency and robustness to interference and fading caused by multipath because the equalization process is no longer done on a single wide carrier but on different subcarriers. In order to reduce the percentage of ISI, in LTE it is used a cyclic prefix of the duration of about 4.7 μs: the price to pay for having it, is a reduction of the data rate.

OFDMA extends the feature of subcarrier division: in fact, the subcarriers are in turn divided into sub-channel. A sub-channel is indeed a group of subcarriers. So OFDMA is a multi-user OFDM: it assigns these sub-channels to individual users so that simultaneous transmission for several users are supported – while OFDM only support a single user at each moment. In OFDMA user can be allocated not only by time but also by frequency.

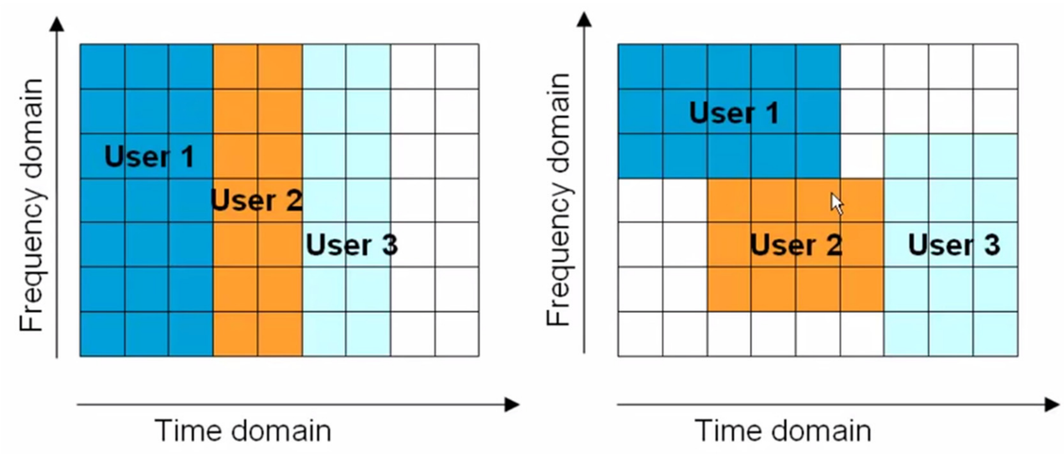



Figure 2.3 User allocation in OFDMA

### 2.2.2 SC-FDMA

One disadvantage of OFDM is the high peak-to-average power ratio. Because of this high value OFDMA requires power amplifier consuming great power to keep on working in linear area. It is not a problem in downlink since the eNodeB is connected to the energy grid, but it is a problematic in uplink for the power consumption of mobiles devices (e.g. smartphones). Then the choice of the Single Carrier FDMA. Differently from OFDMA, data transmission is serial so there are no parallel waveforms transmission and the diversity is lower. All subcarriers in uplink are modulated by the same data (in Fig 2.2.2.1 first group has same green colour).

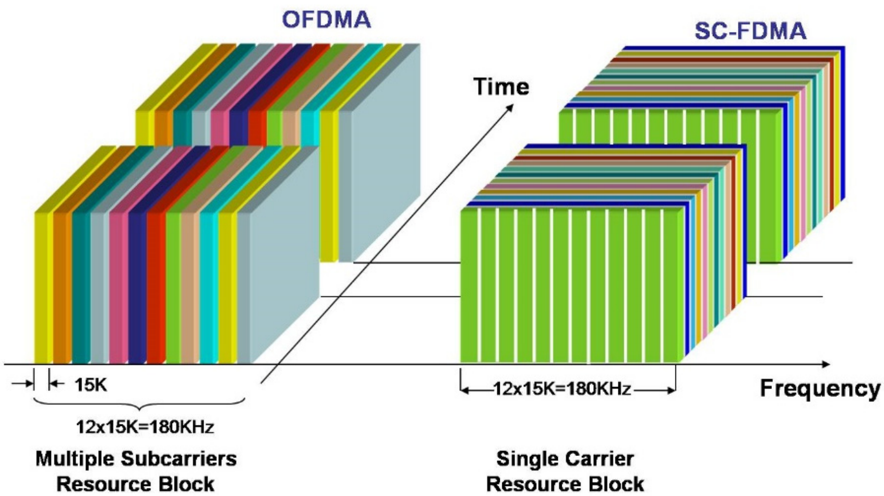



Figure 2.4 OFDMA and SC-FDMA

So, SC-FDMA has both the advantage of single carrier systems to have low peak to average ratio and resilience to multipath interference and subcarriers division offered by OFDM.

## 2.3 Multiple Input Multiple Output

MIMO is another key technique to achieve further improvements in spectral efficiency and data rate. It consists in the use of multiple transmit and receive antennas for sending signal on the same frequency, exploiting scattering and multipath propagation.

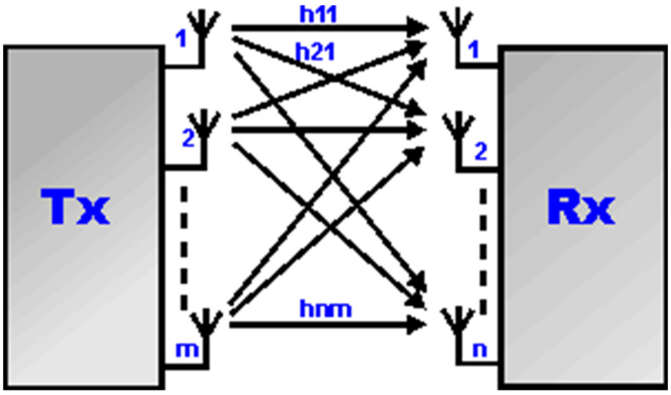
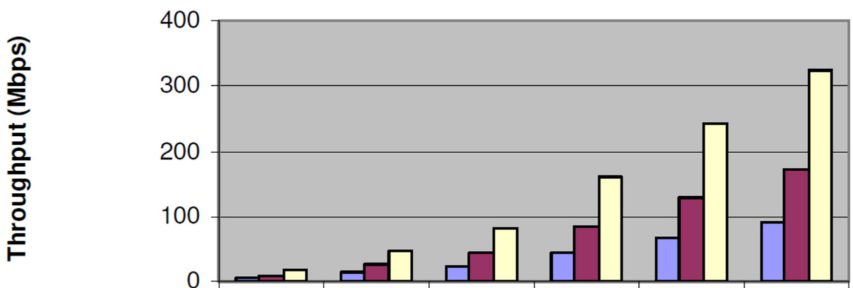



Figure 2.5 MIMO

This system can achieve higher values of SNR useful for working with high order of modulation scheme. MIMO can exploit different techniques such as spatial diversity, precoding and spatial multiplexing.

To transmit parallel independent streams, MIMO utilises spatial multiplexing that allows each transmit antenna to send a different data stream to multiple receive antennas. Each amount of data transmitted with spatial multiplexing is called layer. Then it implies in theory that LTE throughput can be almost multiplied by the number of layers using spatial multiplexing.




| | 1.4 MHz | 3 MHz | 5.0 MHz | 10 MHz | 15 MHz | 20 MHz |
|---|---|---|---|---|---|---|
| 1 Data Stream | 4.6 | 13.2 | 22.2 | 44.7 | 67.2 | 89.7 |
| 2 Data Streams | 8.8 | 25.3 | 42.5 | 85.7 | 128.9 | 172.1 |
| 4 Data Streams | 16.6 | 47.7 | 80.3 | 161.9 | 243.5 | 325.1 |

Bandwidth

Figure 2.6 Throughput values for different bandwidth and number of layers

Due to this multiplicative effect, it is clear that MIMO is one of the most important novel aspects introduced in Release 8 in terms of maximization of data rate. This first release of LTE supported 2X2 MIMO and no further, because of the difficulties of implementation on devices of a high number of antennas in terms of dimension and power consumption.

In LTE downlink operations, there are several MIMO techniques available. In 3GPP Release 8, seven transmission modes have been designed in order to make the most of the benefits in different conditions of channel and multipath, as well as UE capabilities and mobility.

| Transmission Mode | Downlink Transmission Scheme |
|---|---|
| Mode 1 | Single Antenna Port |
| Mode 2 | Transmit Diversity |
| Mode 3 | Open-Loop Spatial Multiplexing |
| Mode 3 | Closed-Loop Spatial Multiplexing |
| Mode 5 | Multi-User MIMO |
| Mode 6 | Closed-Loop Rank-1 Spatial Multiplexing |
| Mode 7 | Single Antenna Port Beamforming |

Table 2.1 LTE Transmission Modes (*3GPP*)

First mode, TM 1, uses only one transmit antenna; modes 2, 3, 4 and 6 are Single User MIMO (SU-MIMO). The choice of the best SU-MIMO mode depends on several aspects as channel conditions, mobility, SNR: each of these four modes offer a different potential throughput for different SNRs at low channel correlation.

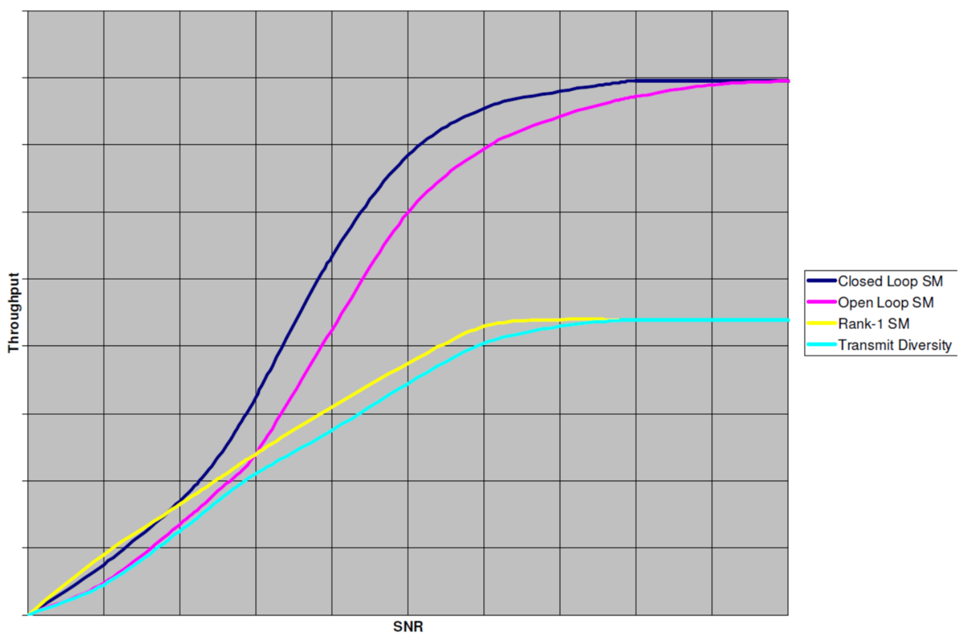



Figure 2.7 Potential throughput in different transmission modes

The difference between Open and Closed Loop Spatial Multiplexing is the presence of feedback from the UE used in the decision of the precoding matrix; thereby TM3 has also an overhead.

In open loop, the UE sends to the eNB minimal information, i.e. a Rank Indicator (RI) and a Channel Quality Indicator (CQI). The former indicates the number of layers supportable, the latter gives an index of channel conditions in the current transmission mode. For the selection of the correct modulation and coding scheme (MCS), the eNB uses the CQI: then given a CQI and a RI the eNB chooses the transmission mode and the resources to assign to the UE.

In closed loop, the UE evaluates and analyses also the multipath conditions and provides an RI and a Precoding Matrix Indicator. The UE provide the eNB with a CQI basing on RI and PMI and not on the current operation mode, so that eNB can adapt the transmission to the channel condition.

TM 5 instead is a Multi-User MIMO (MU-MIMO) technique: multiple antennas in transmission send data to receiving antennas located at different and separated UEs. Mode 7 – such as TM 1 – does not represent a real MIMO based antenna technique. The list of transmission modes has been updated in 3GPP releases subsequent to the eighth, adding other possible choices.

## 2.4 Duplexing Modes

Mobile networks are characterized by two-way communication, and then a full duplex communication is used. There are two different methods of duplexing: Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) and according to its standardization LTE can support both. The former mode requires a paired spectrum since the communication utilises two different frequencies for transmitting and receiving data at the same time. The latter uses only one frequency band because it alternates time slots for transmission and reception in the same channel.

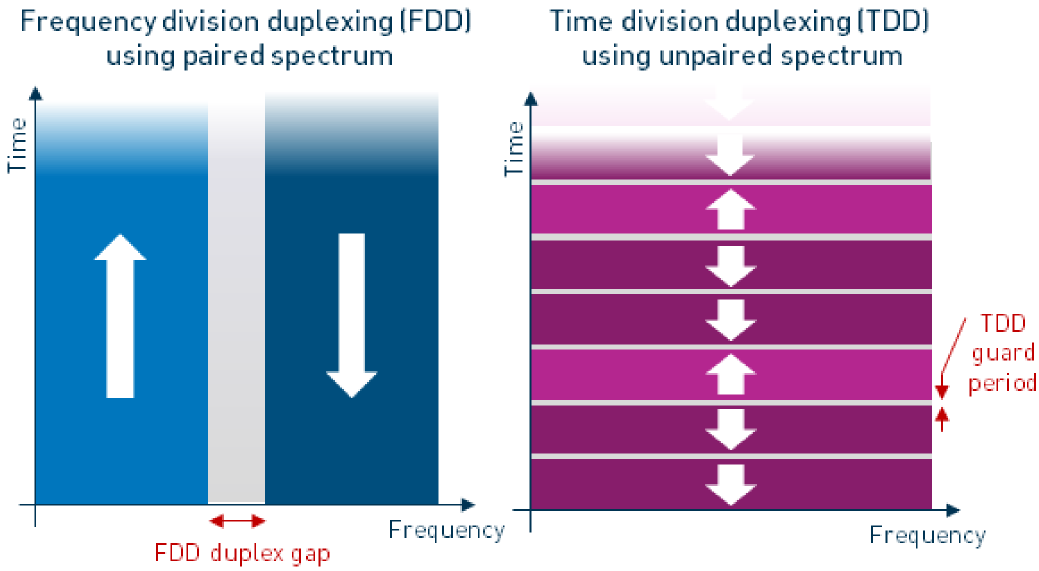



Figure 2.8 FDD and TDD duplexing modes

TDD does not require pair spectrum and it is convenient in cases where uplink and downlink are not symmetrical and typically in mobile broadband era the ratio between UL and DL show a major weight of the second one. Furthermore, TDD does not entail waste of spectrum guard bands for separation of channels as it happens in FDD. With no need for a diplex for the isolation of transmission and reception and TDD is cheaper to implement. Working in a single frequency band it needs guard times between different time slots.

In cellular systems FDD is more implemented as duplexing mode and it is also due to prior frequencies assignments for earlier technologies. However, the possibility to support also TDD affords to use other frequency bands that are not paired. In [4] are defined the frequency bands dedicated to FD-LTE and TD-LTE.

| Band | Duplex Mode | Uplink (MHz) | Downlink (MHz) |
|---|---|---|---|
| 1 | FDD | 1920 – 1980 | 2110 – 2170 |
| 2 | FDD | 1850 – 1910 | 1930 – 1990 |
| 3 | FDD | 1710 – 1785 | 1805 – 1880 |
| 4 | FDD | 1710 – 1755 | 2100 – 2155 |
| 5 | FDD | 824 – 849 | 869 – 894 |
| 6 | FDD | 830 – 840 | 875 – 885 |
| 7 | FDD | 2500 – 2570 | 2620 – 2690 |
| 8 | FDD | 880 – 915 | 925 – 960 |
| 9 | FDD | 1749.9 – 1784.9 | 1844.9 – 1879.9 |
| 10 | FDD | 1710 – 1770 | 2100 – 2170 |

| | | | |
|---|---|---|---|
| 11 | FDD | 1427.9 – 1447.9 | 1475.9 – 1495.9 |
| 12 | FDD | 699 – 716 | 729 – 746 |
| 13 | FDD | 777 – 787 | 746 – 756 |
| 14 | FDD | 788 – 798 | 758 – 768 |
| 17 | FDD | 704 – 716 | 734 – 746 |
| 18 | FDD | 815 – 830 | 860 – 875 |
| 19 | FDD | 830 – 845 | 875 – 890 |
| 20 | FDD | 832 – 862 | 791 – 821 |
| 21 | FDD | 1477.9 – 1462.9 | 1495.9 – 1510.9 |
| 22 | FDD | 3410 – 3490 | 3510 – 3590 |
| 23 | FDD | 2000 – 2020 | 2180 – 2200 |
| 24 | FDD | 1626.5 – 1660.5 | 1525 – 1559 |
| 25 | FDD | 1850 – 1915 | 1930 – 1995 |
| 26 | FDD | 814 – 849 | 859 – 894 |
| 27 | FDD | 807 – 824 | 852 – 869 |
| 28 | FDD | 703 – 748 | 758 – 803 |
| 29 | FDD / CA | | 717 – 728 |
| 30 | FDD | 2305 – 2315 | 2350 – 2360 |
| 31 | FDD | 452.5 – 457.5 | 462.5 – 467.5 |
| 32 | FDD / CA | | 1452 – 1496 |
| 33 | TDD | 1900 – 1920 | 1900 – 1920 |
| 34 | TDD | 2010 – 2025 | 2010 – 2025 |
| 35 | TDD | 1850 – 1910 | |
| 36 | TDD | | 1930 – 1990 |
| 37 | TDD | 1910 – 1930 | 1910 – 1930 |
| 38 | TDD | 2570 – 2620 | 2570 – 2620 |
| 39 | TDD | 1880 – 1920 | 1880 – 1920 |
| 40 | TDD | 2300 – 2400 | 2300 – 2400 |
| 41 | TDD | 2496 – 2690 | 2496 – 2690 |
| 42 | TDD | 3400 – 3600 | 3400 – 3600 |
| 43 | TDD | 3600 – 3800 | 3600 – 3800 |
| 44 | TDD | 703 – 803 | 703 – 803 |
| 45 | TDD | 1447 – 1467 | 1447 – 1467 |
| 46 | TDD | 5150 – 5925 | 5150 – 5925 |
| 65 | FDD | 1920 – 2010 | 2110 – 2200 |
| 66 | FDD | 1710 – 1780 | 2110 – 2200 |
| 67 | FDD / CA | | 738 – 758 |
| 68 | FDD | 698 – 729 | 753 – 758 |
| 69 | FDD / CA | | 2570 – 2620 |
| 70 | FDD | 1695 – 1710 | 1995 – 2020 |

Table 2.2 LTE frequency bands (source 3GPP TS 36.104)

## 2.5 Network Architecture in LTE

In previous generations, the network was based on circuit-switching services. In the fourth generation, instead, a new kind of network architecture has been proposed in order to offer seamless Internet Protocol (IP) connectivity between user and packet data network (PDN). The need for higher data rates and lower latencies – a need generated by applications like video streaming and online gaming with low latency tolerance - encouraged 3GPP to introduce the Evolved Packet System (EPS) in Release 8. As described in [5], this new system consists of Evolved Packet Core (EPC) and Evolved UMTS Terrestrial Radio Access Network (E-UTRAN).

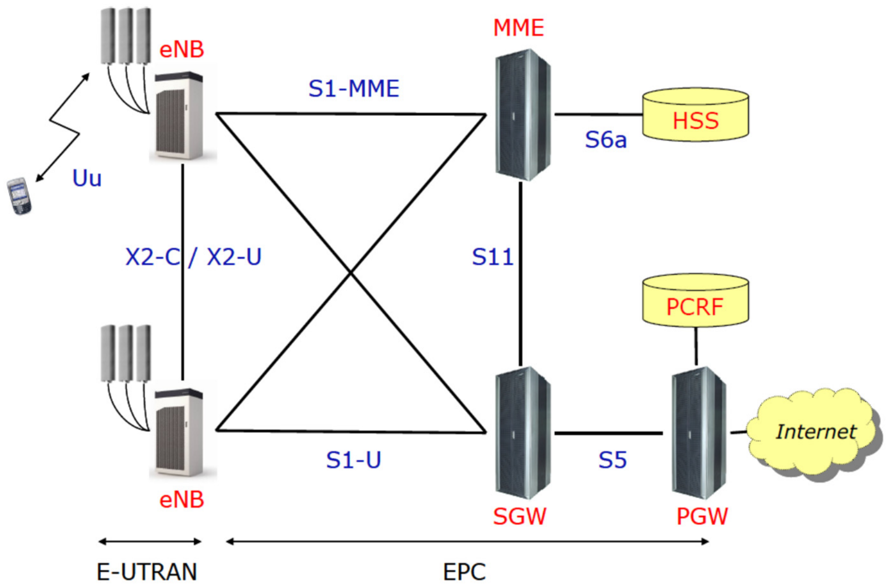



Figure 2.9 Evolved Packet System

EPC is the evolution of the Core Network, also called System Architecture Evolution (SAE), and it controls the UE and establishes the bearers. It is mainly composed of:

- Packed Data Network Gateway (PGW);
- Serving Gateway (SGW);
- Mobility Management Entity (MME).

The E-UTRAN is composed of the Evolved NodeB (eNB) that is responsible of all the radio procedures from/to the User Equipment (UE), and also of the signalling and data transfer towards the Core Network and others adjacent eNBs.

The main radio-related functions handled by the E_UTRAN are:

- Radio Resource Management (RRM): functions related to radio bearers, scheduling and allocation of resources to the UEs;
- Header Compression: procedure for facilitating the use of radio interfaces.
- Encryption of data sent over the radio interface;
- Connection to the Evolved Packet Core.

A great difference respect to UMTS and GSM is the absence of the radio network controller (RNC). The eNB can be seen as a combination – in terms of functionalities – of the previous NodeB and the RNC. This integration of features in the eNB brings advantages in terms of delay and it is a key element for the creation of a flat architecture such as the E-UTRAN.

The eNBs are interconnected by means of the "X2" interface in its two components: User Plane and Control Plane. This interface handles the handover mechanism between two eNBs without any data loss.

The connection between the radio side (eNB) and the Core Network (EPC) is represented by "S1" interface with the same previous distinction between Control Plane (S1-MME) and User Plane (S1-U). The interface S11 ensures the connection between SGW and MME, while S5 connects the SGW and the PGW.

## 2.6 LTE Protocol Architecture

The following image illustrates how radio protocol architecture is composed of control plane and user plane.

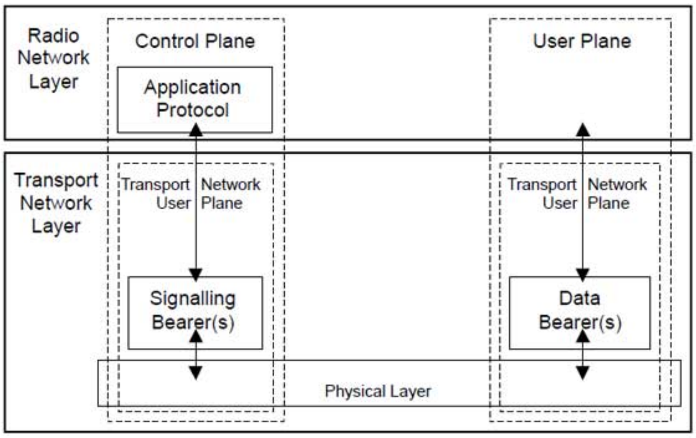



Figure 2.10 Radio protocol architecture

The exchange of signalling messages takes place in the control plane, where is active the Radio Resource Control (RRC) protocol – not present in the other plane. At the user plane instead, the data packets are created and then processed. Both planes have similar protocol stacks.

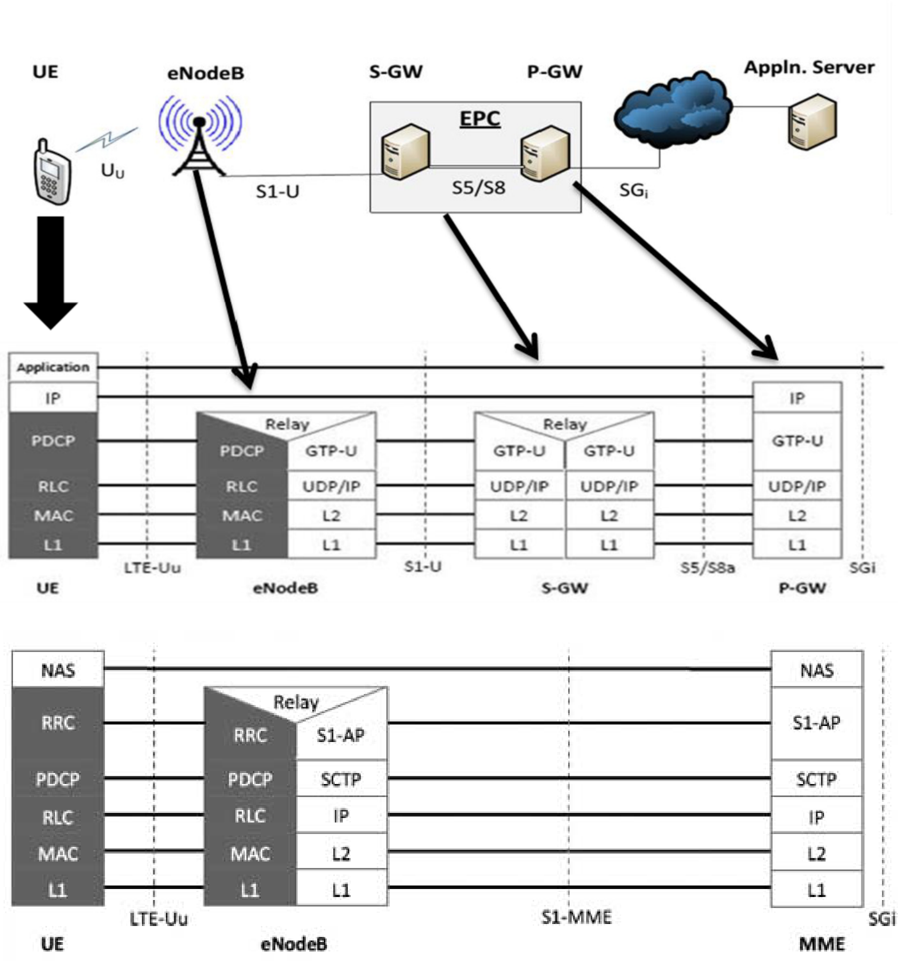



Figure 2.11 User Plane and Control Plane Protocol Stack

On the EU side, in addition to radio protocols, there are others completely transparent to the eNB, such as NAS (Non-Access Stratum) that allows the direct exchange of messages between UE and Core Network (e.g. the Service Request).

A substantial difference between the LTE system and the previous one is that in UMTS both RRC and PDCP protocols belonged to RNC while MAC level was distributed between RNC and NodeB. Instead in LTE all these protocols are included inside the unique access node, the eNB.

As in the case with UMTS, *Radio Resource Control* (RRC) protocol is responsible for Level 3 signalling between the EU and the eNB and it is mainly used to manage radio resources, to configure lower protocollary levels (PDCP-RLC-MAC-PHY) and also as a "container" of NAS-type messages that allow direct communication between the EU and Core Network. Although RRC uses the same language used in WCDMA, LTE has made a significant simplification of this protocol, reducing the number of possible messages. In fact, while in UMTS the RRC states where the mobile can be found are 4, in E-UTRAN the number drops to 2: RRC_IDLE and RRC_CONNECTED.

*Packet Data Convergence Protocol* (PDCP) provides the upper levels with the so-called Radio Bearer such as Signalling Radio Bearer (SRB) and Data Radio Bearer (DRB). The main functions of the PDCP protocol are:

- Numbering of the Packet Data Unit (PDU);
- Header compression;
- Ciphering and integrity protection.

*Radio Link Protocol* (RLC) is the one responsible for error detection, correction and recovery. It can be configured in three modes:

- Acknowledge Mode (AM): In this mode, RLC assures higher levels of delivery of PDUs in error-free mode using ACK/NACK at RLC sent by the receiver to the transmitter.
- Unacknowledged Mode (UM): Unlike AM, this mode does not send ACK / NACK and consequently no retransmission is provided. The PDU is always forwarded to the upper level and in case it has been transmitted with an error, an indication of the erroneous packet is transmitted too.
- Transparent Mode (TM): This mode, unlike the other two, does not have overhead, so there is neither retransmission nor error detection; thereby its only function is to buffer the PDUs to be transmitted.

Another mechanism of retransmission is used on the *Medium Access Control* (MAC) level, by means of the Hybrid Automatic Repeat Request (HARQ) mechanism. This protocol belongs to the Layer 2 and its most important operations are:

- Multiplexing and demultiplexing of RLC PDU;
- Dynamic scheduling of the radio resources: MAC scheduler establishes which UEs can be served basing on the instant quality of the radio channel, expressed through Channel Quality Indication (CQI);
- HARQ protocol for error correction.

On the bottom, the *Physical* (PHY) layer carries out the frame formation, the modulation and coding of control and traffic channels. It is also responsible for cell search and handover triggering. Data is transferred by this layer: with the name Transport Block (TB) is indicated the data exchanged per transmission time interval (TTI) of 1 ms between MAC on layer 2 and PHY layer 1.

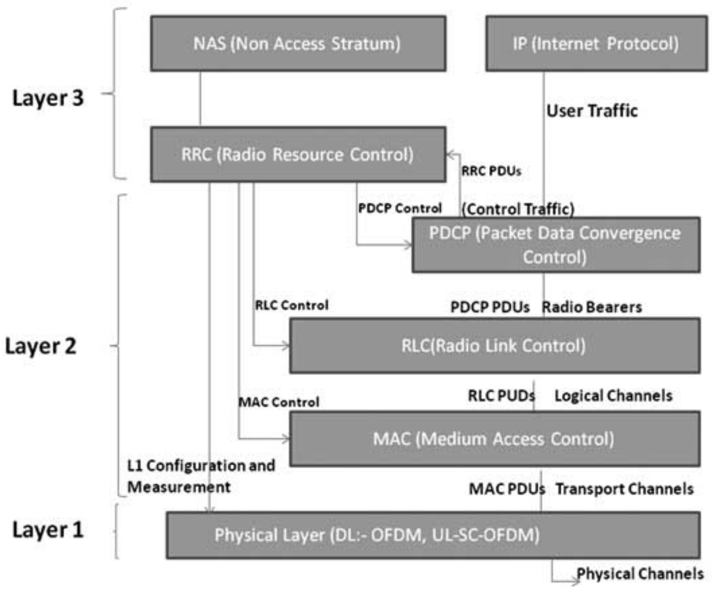



Figure 2.12 Layers overview

For the communication between UEs and eNBs, LTE Physical layer utilises OFDMA in downlink and SC-FDMA in uplink – as already seen – and during the transmission signals can be divided in two kinds of frames: FDD or TDD.

## 2.7 Frame Structure

In the above sections, the concepts of *OFDM symbol*, *subcarriers* and *duplexing modes* have been presented. On the physical layer, the transmission over the air is structured as it follows. According to the duplexing mode used there are two frame structure types for E-UTRA: with FDD it is used the frame structure type 1 while frame structure type 2 is for TDD mode.

The FDD frame has a duration of 10 ms, is divided in 10 subframes both for downlink and for uplink. Each subframe is 1 ms long and it is further divided into two slots of 0.5 ms duration each one. Slots are composed of either 6 or 7 OFDM symbols according to the type of cyclic prefix used (normal or extended).

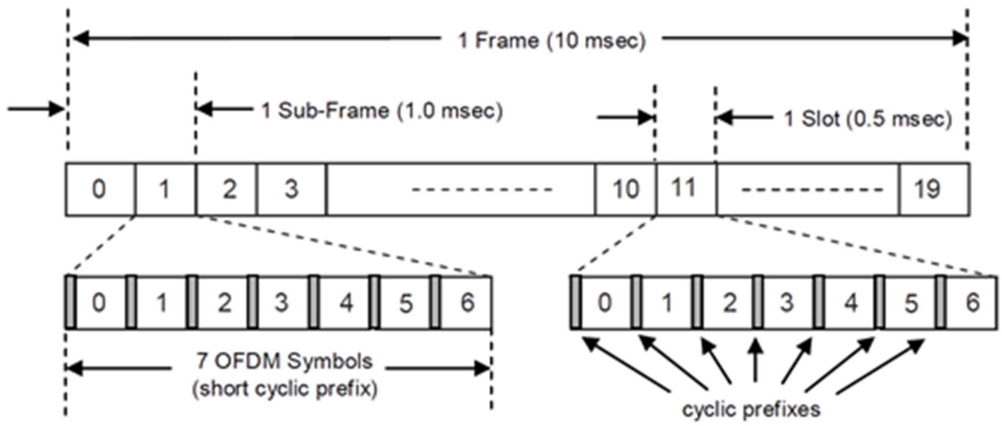



Figure 2.13 FDD frame structure

Therefore, in each FDD frame there are 20 slots. A Physical Resource Block (PRB) is the smallest element that a base station scheduler can assign in the resource allocation. A PRB consists of 12 consecutive sub-carriers in frequency domain (12*15MHz = 180 MHz) in a one-time slot of 0.5 ms (with 6 or 7 OFDM symbols). According to the System Bandwidth, the number of PRBs allocable per UE varies – as shown in the following table.

| **Bandwidth [MHz]** | 1.4 | 3 | 5 | 10 | 15 | 20 |
|---|---|---|---|---|---|---|
| **Number of PRB** | 6 | 15 | 25 | 50 | 75 | 100 |

Table 2.3 Number of PRB correspondence to system bandwidth

The i-th component of one of the symbols is called Resource Element (RE). So, in case of Normal Cyclic Prefix, the number of symbols is 7 and inside a PRB there is a number of Res equal to 12x7=84.

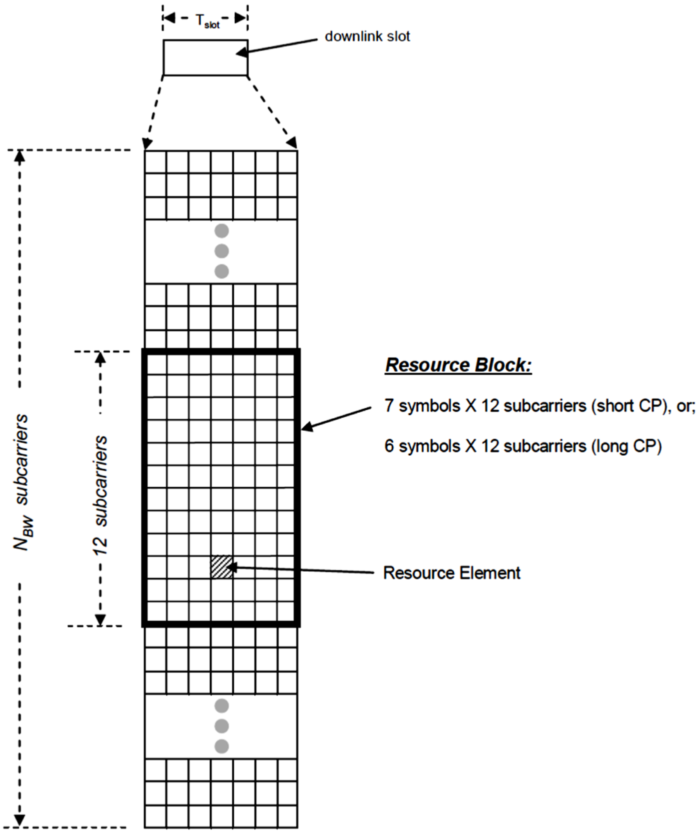



Figure 2.14 Resource Block and Resource Element

Each RE has information content corresponding to that of a QPSK / 16QAM / 64QAM modulation symbol, that is 2, 4 or 6 bits. The composition of one of the seven symbols in a time-slot, for the Normal Cyclic Prefix, is shown in the following figure.

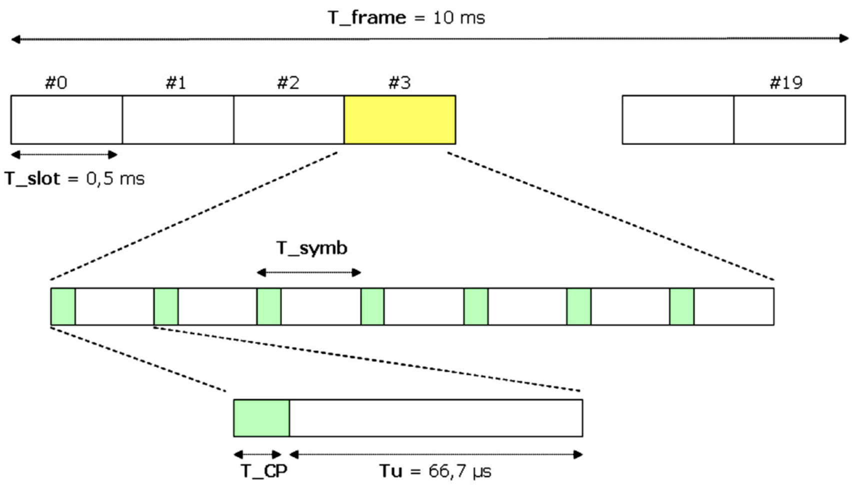



Figure 2.15 Symbol composition in a time-slot

Each symbol has a duration of 66.7 μs – as already seen – and this is due to the subcarrier spacing value of 15 kHz. The length of the CP is variable: it is about 5.2 μs for the first symbol and about 4.7 μs for the other six symbols. Therefore, the overall duration is (5.2+66.7)+(4.7*66.7)*6 = 71.9 + 428.4 = 0.5 ms.

TDD mode works in a paired spectrum and uplink and downlink are separated in time. The frame structure Type 2 used for this mode has a duration of 10 ms and consists of two half-frames long 5 ms. A half-frame is composed of five subframes of 1 ms each one.

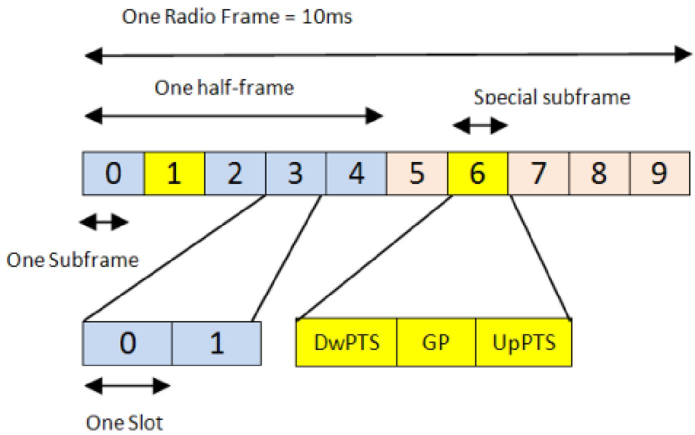



Figure 2.16 TDD frame structure

There are standard and special subframes. The special subframes are compose of three fields: Downlink Pilot Time Slot (DWPTS), Guard Period (GP) and Uplink Pilot Time Slot (UPTS). Seven different configurations are possible for either 5 ms or 10 ms downlink to uplink switch periodicity.

| Uplink / Downlink Configuration | Downlink to Uplink Switch Periodicity | Sub-Frame Number | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 0 | 5ms | D | S | U | U | U | D | S | U | U | U |
| 1 | 5ms | D | S | U | U | D | D | S | U | U | D |
| 2 | 5ms | D | S | U | D | D | D | S | U | D | D |
| 3 | 10ms | D | S | U | U | U | D | D | D | D | D |
| 4 | 10ms | D | S | U | U | D | D | D | D | D | D |
| 5 | 10ms | D | S | U | D | D | D | D | D | D | D |
| 6 | 5ms | D | S | U | U | U | D | S | U | U | D |

Figure 2.16 Possible configurations for frame structure Type 2

The advantage of TDD is the possibility to use the same channel both for uplink and downlink, dynamically adapting the balance between the two transmissions according to the traffic condition.

### 2.7.1 Resource Scheduling

The eNB is the entity responsible for the scheduling of the time/frequency resources: the allocation of these resources is performed basing on the channel quality (CQI) sensed by the UE. The scheduling is based on TTI (1 ms): the eNB assigns an integer number $K$ of PRBs corresponding to $K$*12 sub-carriers, that is equal to $K$*180 kHz in the frequency domain. The indication of which PRBs are assigned in a certain TTI to the UE is contained in the Physical Downlink Control Channel (PDCCH).

In LTE, there is a variety of scheduling algorithms, some of the most important are:

- *Round Robin* (RR) Scheduler: it divides the available resources among the active flows and if the number of resources is greater than the number of flows, then all the flows is allocated in the same subframe. Otherwise, the allocation is divided in different subframe, starting from the last flow not allocated in the precedent subframe. Each UE receive a MCS value based on the received CQI. This scheduler provides user a fair redistribution of the shared resources.
- *Proportional Fair* (PF) Scheduler: it schedules a user when its instantaneous CQI is high compared to its average channel condition over time. It represents a trade-off between the maximum throughput and the user fairness.
- Best CQI Scheduler: it assigns resource blocks to the user that has the best radio conditions so to the UE with the highest CQI. Thereby, this algorithm offers higher throughput to the users nearer the Base Station (BS).

# 3 LTE-Advanced

## 3.1 Introduction

After the standardization process in 2008, LTE first commercial networks were deployed by end 2009 as evolution of the previous systems like UMTS and CDMA2000. In the same period, in order to meet IMT-Advanced requirements - identifying mobile systems with features beyond the ones of IMT 2000 - 3GPP presented to the International Telecommunication Union (ITU) the Release 10, also known as LTE-Advanced. This further evolution of LTE was approved by ITU-R in October 2010, proving to largely fulfil IMT-Advanced targets such as enhanced peak data rates (1 Gbps and 100 Mbps respectively for low and high mobility) to ensure the support for advanced mobile services.

| Item | Sub-category | LTE target | LTE-Advanced (4G) target | IMT-Advanced (4G) requirement |
|---|---|---|---|---|
| Peak spectral efficiency (b/s/Hz) | Downlink | 16.3 (4x4 MIMO) | 30 (up to 8x8 MIMO) | 15 (4x4 MIMO) |
| | Uplink | 4.32 (64QAM SISO) | 15 (up to 4x4 MIMO) | 6.75 (2x4 MIMO) |
| Downlink cell spectral efficiency b/s/Hz/user Microcellular 3 km/h, 500 m ISD | (2x2 MIMO) | 1.69 | 2.4 | |
| | (4x2 MIMO) | 1.87 | 2.6 | 2.6 |
| | (4x4 MIMO) | 2.67 | 3.7 | |
| Downlink cell-edge user spectral efficiency (b/s/Hz/user) (5 percentile, 10 users), 500m ISD | (2x2 MIMO) | 0.05 | 0.07 | |
| | (4x2 MIMO) | 0.06 | 0.09 | 0.075 |
| | (4x4 MIMO) | 0.08 | 0.12 | |

Figure 3.1 Performance targets

Some of the most important features of LTE-Advanced formalized in 3GPP Release 10-11-12 are: introduction of *Carrier Aggregation* (CA) for the use of multiple carriers providing high data rates; enhancement of *multiple antenna* technologies for the improvement of spectral efficiency; deployment of *Heterogeneous Networks* (HetNet) to increase capacity with *Enhanced Inter-cell Interference Coordination* (eICIC) and *Coordinated Multi Point* (CoMP) technique; evolution towards *Self Organizing Networks* (SON); higher order modulation such as *256QAM*.

## 3.2 Carrier Aggregation

The aggregation of band is a key technique that allows to increase peak data rate and to handle flexibly the frequency bands available in heterogeneous scenarios. Because of its possibilities the aggregation of bands is crucial for overcoming the downlink throughput limits in standard LTE, but it also represents the base for a further evolution of LTE technology towards the use of unlicensed spectrum (as will be seen further on).

In LTE-A, CA makes it possible to concatenate different bandwidths even if they are allocated to different ranges. The implementation of this important technological step requires the sharing of baseband between pairs of nodes that work on the selected frequency bands. Two or more component carriers (CC) are aggregated: on the primary component carrier (PCC) takes place the registration of the UE with the network while the secondary component carriers (SCCs) offer additional bandwidth. The PCC is served by the primary cell, that is responsible for the RRC connection as well as NAS information. The PCC can be changed only at handover while the SCCs can be added and removed depending on the needs.

In this band aggregation process suitable for both FDD and TDD, each CC has a maximum of 110 resource blocks (20 MHz) as in LTE standard to keep backward compatibility with Releases 8 and 9. Initially in 3GPP Release 10, it was specified a limited number of maximum four SCCs for an overall bandwidth of 100 MHz. In FDD usually the number of component carriers in uplink is equal to or lower than the CCs in downlink and the single CCs can be allocated to different bandwidths. In TDD instead the number of CCs is the same for downlink and uplink.

Because of the diverse availability of frequency bands for each operator, the allocation can be either within the same operating band using contiguous or not component carriers (intra-band), or inter-band using carriers from different operating frequency band as explained in [6] and [7]. So, there are three possible alternatives.

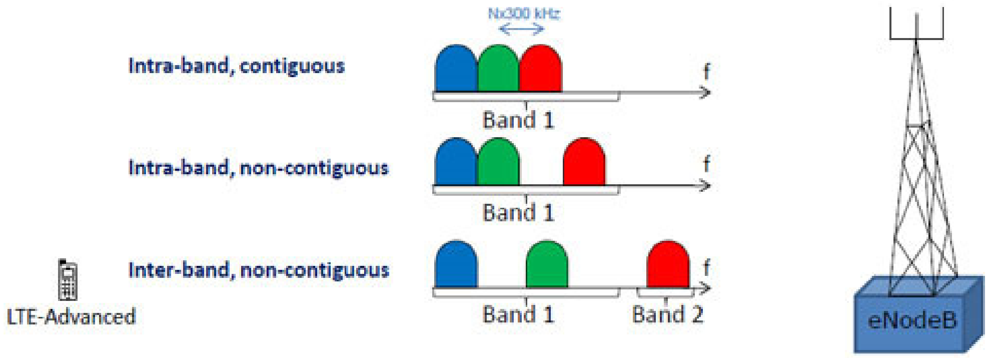



Figure 3.2 Carrier Aggregation alternatives (3GPP)

The implementation of contiguous aggregation it is easier because it does not require many changes to the physical layer. Continuous CA can be performed using a fast Fourier transform (FTT) module RF components.

However, since the difficulty in allocating wide continuous licensed spectrum, non-contiguous carrier aggregation allows mobile operators to fully exploit their spectrum resources.

## 3.3 Enhanced MIMO

One of the main aspects of LTE-Advanced to make a technological leap forward is represented by the enhancement of MIMO techniques. The standard LTE of 3GPP Release 8, with a maximum 4x4 MIMO scheme, provides peak spectral efficiency of 15 bit/s/Hz in downlink and 3.75 bit/s/Hz in uplink.

To be recognised as a real fourth generation technology, LTE-Advanced offers peak spectral efficiencies even higher than 15 bit/s/Hz for DL and 6.75 bit/s/Hz required by IMT-Advanced. This has been achieved by the adoption of 8x8 MIMO model in DL and 4x4 in UL that guarantees 30 bit/s/Hz and 15 bit/s/Hz spectral efficiency respectively.

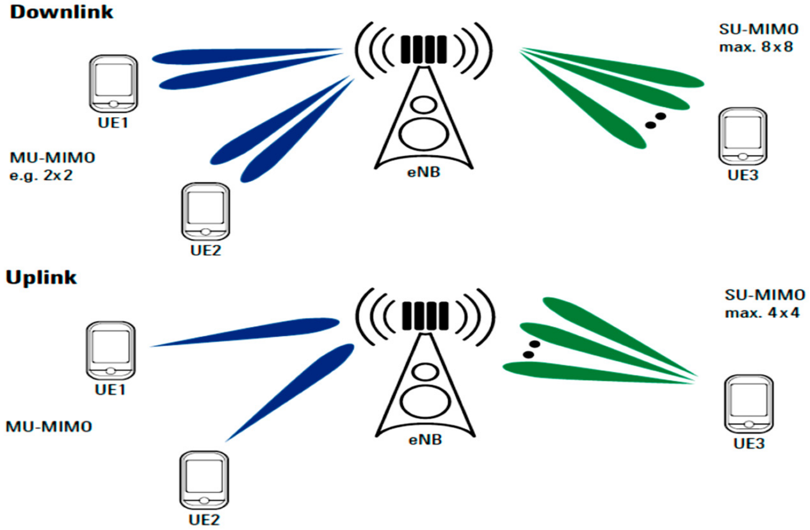



Figure 3.2 Enhanced MIMO

Therefore, 3GPP Release 10 has introduced a higher order MIMO, up to 8x8: the increase of the antenna array size to 8 provides double peak data rate compared to the value achieved in Releases 8 and 9. Other novel aspects of LTE-Advanced are the introduction of new transmission modes and the possibility of dynamic switching between SU-MIMO and MU-MIMO.

## 3.3 Heterogeneous Networks

One of the goals of LTE-Advanced is to provide a uniform experience to UEs in every place inside a cell. To do this it is needed a change in terms of topology of the traditional network usually deployed homogeneously, consisting of a system of base stations all with similar transmit powers. The growth of mobile broadband data subscriptions and services using intensively the bandwidth has encouraged the operators to face the challenge of increasing capacity. However, the introduction of spectrum aggregation, enhanced multi-antenna techniques and more efficient modulation schemes cannot entirely meet the needs and demands of crowded environments. Hence, the deployment of a different cellular system becomes necessary. Because of costs and difficulties of the acquisition of new sites for macro base stations in dense urban zones, it is required to expand the network in a more flexible manner in order to grant high user experience everywhere. So, the operator's choice is to bring the network closer to the UEs, building up an advanced heterogenous topology of network.

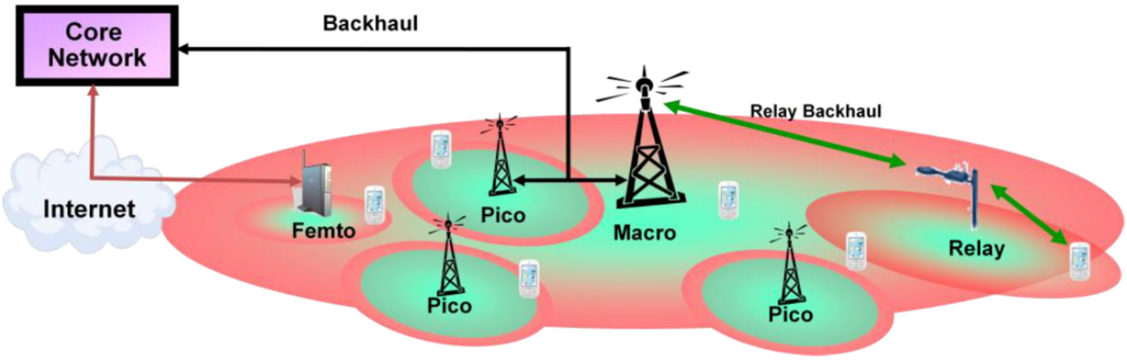



Figure 3.3 Heterogeneous Network

The network becomes heterogeneous with the utilization of diverse kind of base station introducing low power small cells (micro-, pico-, femto-cells, relay nodes) that can solve problems of coverage holes in areas covered only by macro eNBs and increase capacity in hot spots.  The Relay Node (RN), introduced in 3GPP Release 10, is a low-power cell connected to a donor eNB via the air interface; this technological solution it is used where wireline backhaul is not possible, to enhanced coverage and capacity.

The placement of the small cells with low transmit power it is easier than that of macro base station, and it makes it possible to offload from the macro cells. The introduction of small cells in the network has not only good effects, because it also generates interference. In heterogeneous networks (HetNets), advanced strategies and techniques are needed for coordination among base stations and interference management in order to get gains in throughput, increased bitrates per unit area and improvements of user experience. In fact, the expansion of the range in HetNets is supported by key features such as eICIC and Interference Cancellation (IC), from the network and device side respectively.

## 3.4 Enhanced Inter-cell Interference Coordination

In 3GPP Release 8 was presented ICIC to mitigate the inter-cell interference for the users, from the cell side. With the increasing density of cells in HetNets - characterized by the coexistence of macro and pico cells using the same frequencies - in LTE-

Advanced releases an evolution of this interference management technique has been introduced. The enhanced ICIC, in fact, uses the Almost Blank Subframes (ABS) with the aim of minimizing the interference of the macro cells on the UEs served by the micro/pico cells. ABS do not contain user data but only control channels and cell-specific reference signals.

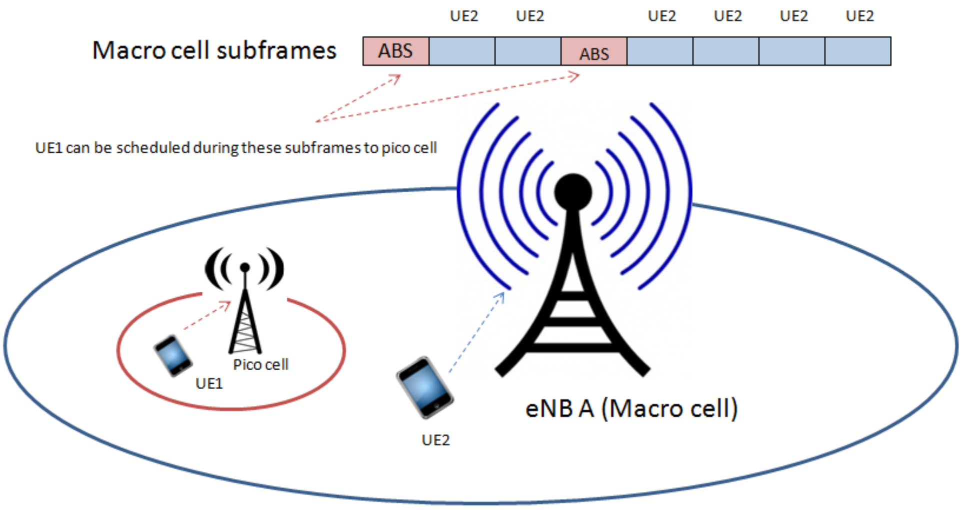



Figure 3.4 eICIC using ABS

Then the pico cells can exploit this opportunity to serve the UEs at the edge region that suffer of high interferences while macro does not send data.

## 3.5 Coordinated Multi Point

The problem of cell edge coverage in LTE-A is addressed by a technique such as CoMP, introduced in 3GPP Release 11 [8]. In CoMP the signal is transmitted and received by multiple coordinating points, increasing the useful signal level and decreasing the interference. As explained in [9], the CoMP technologies provided by 3GPP are:

- CS (Coordinated Scheduling) or CB (Coordinated Beamforming): the transmission points are coordinated to maximize the useful signal received by the user and reduce the interference to the other users;
- DPS (Dynamic Point Selection): for each user the most suitable transmission point is instantly selected for optimizing performance in the system;
- JP (Joint Processing): in DL the device receives from multiple transmitting points (Joint Transmission), in UL the transmitted signal is received in multiple receiving points

(Joint Reception). In either case the signal recombination to the receiver increases the quality of the signal.

CoMP mechanisms require that the eNBs are strictly synchronized.

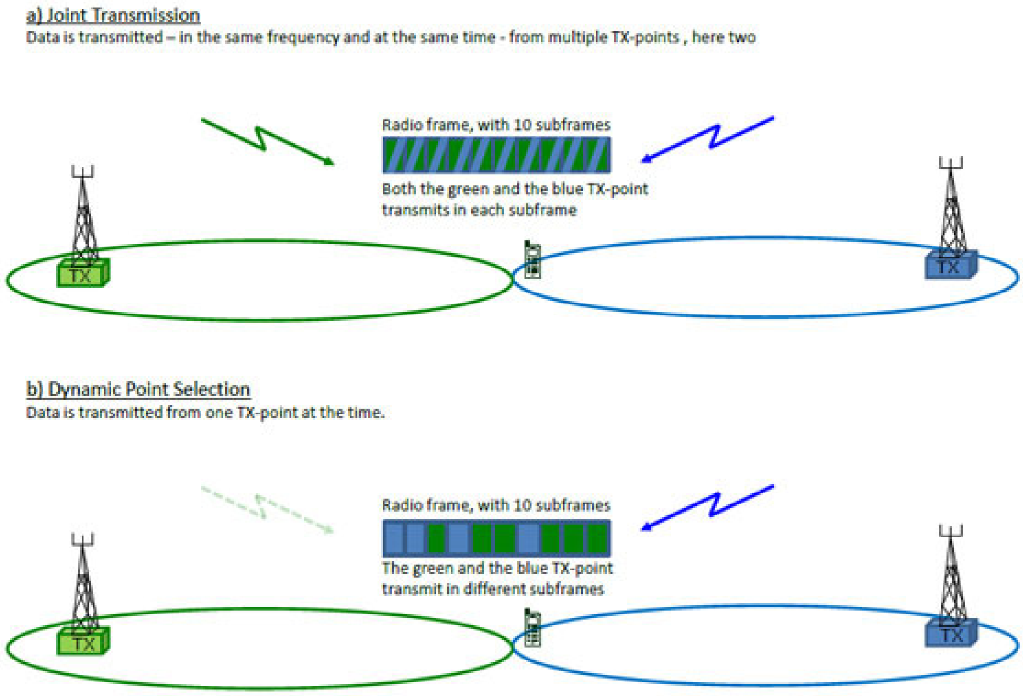



Figure 3.5 CoMP techniques (3GPP)

## 3.6 UE Categories

The information about UE's category is important for the eNB for an effective communication with the devices attached to it. The UE Category specifies uplink and downlink capability. Starting from 3GPP Release 8, the definition of these categories is presented in the [10]. In first LTE release, there were five different categories:

| UE Category | Maximum number of DL-SCH transport block bits received within a TTI | Maximum number of bits of a DL-SCH transport block received within a TTI | Total number of soft channel bits | Maximum number of supported layers for spatial multiplexing in DL |
|---|---|---|---|---|
| Category 1 | 10296 | 10296 | 250368 | 1 |
| Category 2 | 51024 | 51024 | 1237248 | 2 |
| Category 3 | 102048 | 75376 | 1237248 | 2 |
| Category 4 | 150752 | 75376 | 1827072 | 2 |
| Category 5 | 302752 | 151376 | 3667200 | 4 |

Table 3.1 UE Categories (3GPP TS 36.306 V8.3.0)

In LTE-A, from 3GPP Release 10, new UE Categories have been added to support the technological enhancements introduced. In latest version of 3GPP Release 12, there are up to 12 Categories described.

| UE Category | Maximum number of DL-SCH transport block bits received within a TTI (Note 1) | Maximum number of bits of a DL-SCH transport block received within a TTI | Total number of soft channel bits | Maximum number of supported layers for spatial multiplexing in DL |
|---|---|---|---|---|
| Category 1 | 10296 | 10296 | 250368 | 1 |
| Category 2 | 51024 | 51024 | 1237248 | 2 |
| Category 3 | 102048 | 75376 | 1237248 | 2 |
| Category 4 | 150752 | 75376 | 1827072 | 2 |
| Category 5 | 299552 | 149776 | 3667200 | 4 |
| Category 6 | 301504 | 149776 (4 layers, 64QAM)<br>75376 (2 layers, 64QAM) | 3654144 | 2 or 4 |
| Category 7 | 301504 | 149776 (4 layers, 64QAM)<br>75376 (2 layers, 64QAM) | 3654144 | 2 or 4 |
| Category 8 | 2998560 | 299856 | 35982720 | 8 |
| Category 9 | 452256 | 149776 (4 layers, 64QAM)<br>75376 (2 layers, 64QAM) | 5481216 | 2 or 4 |
| Category 10 | 452256 | 149776 (4 layers, 64QAM)<br>75376 (2 layers, 64QAM) | 5481216 | 2 or 4 |
| Category 11 | 603008 | 149776 (4 layers, 64QAM)<br>195816 (4 layers, 256QAM)<br>75376 (2 layers, 64QAM)<br>97896 (2 layers, 256QAM) | 7308288 | 2 or 4 |
| Category 12 | 603008 | 149776 (4 layers, 64QAM)<br>195816 (4 layers, 256QAM)<br>75376 (2 layers, 64QAM)<br>97896 (2 layers, 256QAM) | 7308288 | 2 or 4 |
| NOTE 1: In carrier aggregation operation, the DL-SCH processing capability can be shared by the UE with that of MCH received from a serving cell. If the total eNB scheduling for DL-SCH and an MCH in one serving cell at a given TTI is larger than the defined processing capability, the prioritization between DL-SCH and MCH is left up to UE implementation. | | | | |

Table 3.2 LTE-A UE Categories (3GPP TS 36.306 v12.11.0)

From this last table, it is possible to observe the added capabilities of the devices to support enhanced MIMO, carrier aggregation and high order modulation scheme (256 QAM).

A further step into the evolution of the UE-Categories it has been introduced with the latest 3GPP Release 13, the one of major interest for this thesis since the introduction of the possibility to work in the unlicensed spectrum. Therefore, it is worth to anticipate in this section the addition of those categories that support enhanced capabilities.

| UE DL Category | Maximum number of DL-SCH transport block bits received within a TTI (Note 1) | Maximum number of bits of a DL-SCH transport block received within a TTI | Total number of soft channel bits | Maximum number of supported layers for spatial multiplexing in DL |
|---|---|---|---|---|
| DL Category M1 | 1000 | 1000 | 25344 | 1 |
| DL Category 0 (Note 2) | 1000 | 1000 | 25344 | 1 |
| DL Category 1bis | 10296 | 10296 | 250368 | 1 |
| DL Category 4 | 150752 | 75376 | 1827072 | 2 |
| DL Category 6 | 301504 | 149776 (4 layers, 64QAM)<br>75376 (2 layers, 64QAM) | 3654144 | 2 or 4 |
| DL Category 7 | 301504 | 149776 (4 layers, 64QAM)<br>75376 (2 layers, 64QAM) | 3654144 | 2 or 4 |
| DL Category 9 | 452256 | 149776 (4 layers, 64QAM)<br>75376 (2 layers, 64QAM) | 5481216 | 2 or 4 |
| DL Category 10 | 452256 | 149776 (4 layers, 64QAM)<br>75376 (2 layers, 64QAM) | 5481216 | 2 or 4 |
| DL Category 11 | 603008 | 149776 (4 layers, 64QAM)<br>195816 (4 layers, 256QAM)<br>75376 (2 layers, 64QAM)<br>97896 (2 layers, 256QAM) | 7308288 | 2 or 4 |
| DL Category 12 | 603008 | 149776 (4 layers, 64QAM)<br>195816 (4 layers, 256QAM)<br>75376 (2 layers, 64QAM)<br>97896 (2 layers, 256QAM) | 7308288 | 2 or 4 |
| DL Category 13 | 391632 | 195816 (4 layers, 256QAM)<br>97896 (2 layers, 256QAM) | 3654144 | 2 or 4 |
| DL Category 14 | 3916560 | 391656 (8 layers, 256QAM) | 47431680 | 8 |
| DL Category 15 | 749856-798800 (Note 3) | 149776 (4 layers, 64QAM)<br>195816 (4 layers, 256QAM)<br>75376 (2 layers, 64QAM)<br>97896 (2 layers, 256QAM) | 9744384 | 2 or 4 |
| DL Category 16 | 978960 -1051360 (Note 3) | 149776 (4 layers, 64QAM)<br>195816 (4 layers, 256QAM)<br>75376 (2 layers, 64QAM)<br>97896 (2 layers, 256QAM) | 12789504 | 2 or 4 |
| DL Category 17 | 25065984 | 391656 (8 layers, 256QAM) | 303562752 | 8 |
| DL Category 18 | 1174752-1206016 | [299856 (8 layers, | 14616576 | 2 or 4 [or 8] |

| | | | | |
|---|---|---|---|---|
| | (Note 3) | 64QAM)<br>391656 (8 layers, 256QAM)]<br>149776 (4 layers, 64QAM)<br>195816 (4 layers, 256QAM)<br>75376 (2 layers, 64QAM)<br>97896 (2 layers, 256QAM) | | |
| DL Category 19 | 1566336 -1658272 (Note 3) | [299856 (8 layers, 64QAM)<br>391656 (8 layers, 256QAM)]<br>149776 (4 layers, 64QAM)<br>195816 (4 layers, 256QAM)<br>75376 (2 layers, 64QAM)<br>97896 (2 layers, 256QAM) | 19488768 | 2 or 4 [or 8] |
| NOTE 1: In carrier aggregation operation, the DL-SCH processing capability can be shared by the UE with that of MCH received from a serving cell. If the total eNB scheduling for DL-SCH and an MCH in one serving cell at a given TTI is larger than the defined processing capability, the prioritization between DL-SCH and MCH is left up to UE implementation.<br>NOTE 2: Within one TTI, a UE indicating category 0 shall be able to receive up to 1000 bits for a transport block associated with C-RNTI/Semi-Persistent Scheduling C-RNTI/P-RNTI/SI-RNTI/RA-RNTI and up to 2216 bits for another transport block associated with P-RNTI/SI-RNTI/RA-RNTI.<br>NOTE 3: The UE indicating category x shall reach the value within the defined range indicated by "Maximum number of DL-SCH transport block bits received within a TTI" of category x. The UE shall determine the required value within the defined range indicated by "Maximum number of DL-SCH transport block bits received within a TTI" of the corresponding category, based on its capabilities (i.e. CA band combination, MIMO, Modulation scheme). If the UE capability of CA band combination, MIMO and modulation scheme supported can exceed the upper limit of the defined range, the UE shall support the maximum value of the defined range indicated by "Maximum number of DL-SCH transport block bits received within a TTI" of the corresponding category. | | | | |

Table 3. UE Categories (3GPP TS 36.306 v13.6.0)

As it will be explained in the following sections, the specification of these new categories – in 3GPP Release 12 there were maximum 12 categories – it is of paramount importance to achieve higher data rate by making the most of techniques such as carrier aggregation and MIMO and exploiting higher order of modulation schemes.

# 4 LTE Licensed-Assisted Access

## 4.1 LTE in Unlicensed Spectrum

The continuous evolution process of LTE, started from its first standardization in 2008, has provided a successful mobile technology enhanced and improved through several releases. With LTE-Advanced, high performance levels have been reached thanks to the combined use of key features such as MIMO, 256 QAM and Carrier Aggregation. Current commercial deployment allows devices of the highest UE categories to achieve downlink throughput values of about 700-800 Mbps.

As LTE development itself reveals, the study researches for better solutions and performances did not have stopped with the last release of LTE-A. The ever-growing demand for high data rate and real-time services and the scarcity of the available spectrum resources have encouraged mobile operators to go further. Hence, in 3GPP Release 13 it has been proposed a new solution based on one of the most important techniques of the LTE-A, i.e. the aggregation of spectrum. In fact, in this release it has been introduced the possibility to aggregate the licensed and the unlicensed spectrum: a primary cell in licensed spectrum, delivering critical information and guaranteeing LTE quality of service, is aggregated with secondary cells in unlicensed spectrum to offer a boost data rate. Then, operators are interested in the use of unlicensed spectrum as a complementary tool for increasing capacity of mobile networks. This further step of LTE technology is known as LTE-Advanced Pro.

Licensed spectrum deployment of cellular systems takes places mainly in the frequency range from 700 MHz to 2.6 GHz; the amount of unlicensed spectrum available is wider than the licensed one. In dense HetNets scenarios characterized by large quantity of small cells, one of the main problems is indeed the congestion of licensed spectrum.

In the last few years several bands have been released for unlicensed commercial use starting from the 2.4 GHz Industrial, Scientific and Medical (ISM) band, then the 5 GHz band and lately also the millimetre wave band (e.g. 28 GHz and 60 GHz bands). The 5 GHz band is less congested than 2.4 GHz band that is used not only by Wi-Fi but also by cordless phone, Bluetooth and ZigBee.

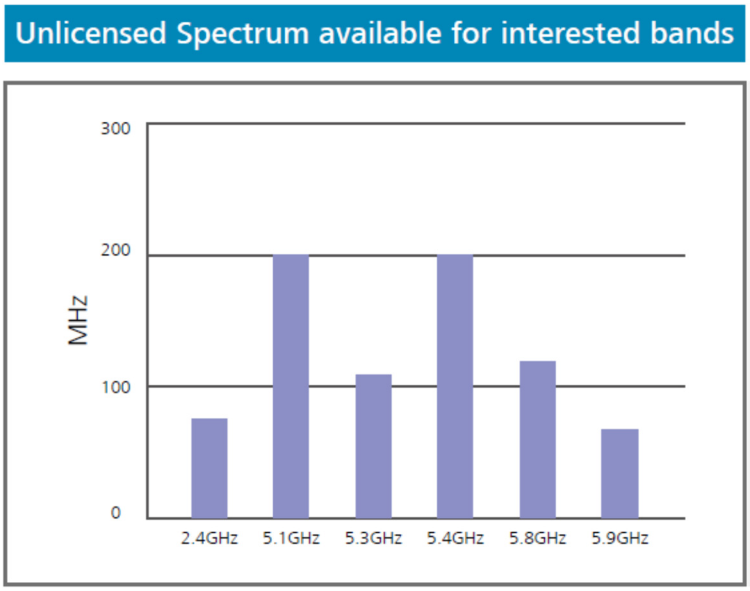



Figure 4.1 Unlicensed Spectrum availability

For this reason, LTE in unlicensed spectrum is focused on the 5 GHz bands.

The design principles of the use of LTE in the unlicensed spectrum include the integration with the licensed bands with a change of the LTE air-interface as minimum as possible, and of paramount importance the co-existence with all those system that work on such a portion of spectrum. Above all the respect of incumbent systems, in particular Wi-Fi, imposes strict regulations in terms of transmission power and coexistence mechanisms as described in [11].

## 4.2 Unlicensed solutions

There are several proposals for LTE deployment in unlicensed spectrum, the main three are: LTE Licensed-Assisted Access (LAA), LTE-Unlicensed (LTE-U) and MulteFire.

- LTE LAA: it is the developed by 3GPP, presented and specified in Release 13 published in 2016 where the downlink aspects are addressed. 3GPP Release 14, that has not been frozen yet, deals with Uplink specification.

  LAA is built on LTE-A CA technique, extended for the aggregation between licensed and unlicensed bands to offer a supplemental downlink (SDL), with an operating range between 5150 MHz and 5925 MHz. The primary cell (PCell) is anchored in the licensed band granting the quality of service and reliability typical of LTE, while the secondary cells (SCells) in unlicensed spectrum supply with more bandwidth to get a performance boost in throughput. The aim of 3GPP standardization process is to present a global solution that works with any regional regulatory requirements. To respect the pre-existing technologies that operate in the same unlicensed bands, 3GPP has properly defined LAA as a solution designed for fair and effective coexistence [12]: *"The LAA design should target fair coexistence with existing Wi-Fi networks to not impact Wi-Fi services more than an additional Wi-Fi network on the same carrier, with respect to throughput and latency"*.

Therefore, these design targets imply for LAA system the use of functionalities such as discontinuous transmission, *listen-before-talk* (LBT) mechanism, dynamic frequency selection to avoid radar, and carrier selection.

The LAA characteristics for the PHY layer imply the support for at least 20 MHz system bandwidth in the 5 GHz band.

The deployment scenarios for LAA, as described in [12], can be with or without macro coverage, both outdoor and indoor.

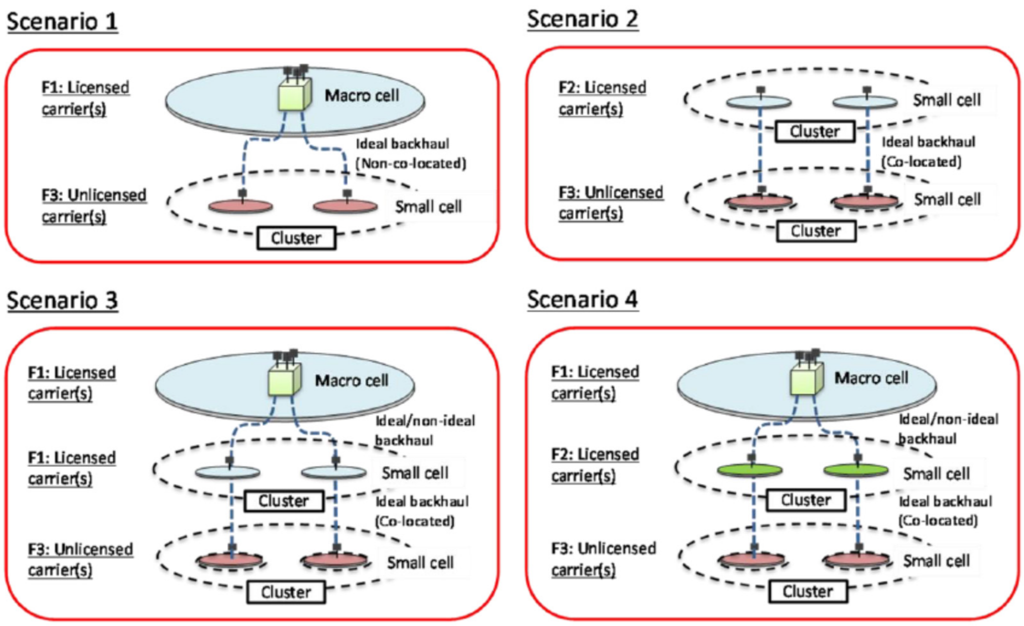



Figure 4.2 LAA deployment scenarios (3GPP TR 36.889)

*Scenario 1*: CA between licensed macro cell (F1) and unlicensed small cell (F3).

*Scenario 2*: CA between licensed small cell (F2) and unlicensed small cell (F3).

*Scenario 3*: aggregation of licensed macro and small cell (F1) with unlicensed small cell (F3).

*Scenario 4*: Licensed macro cell (F1), licensed small cell (F2) and unlicensed small cell (F3). CA between licensed small cell (F2) and unlicensed small cell (F3). CA between macro cell (F1), licensed small cell (F2) and unlicensed small cell (F3) if there is ideal backhaul between macro cell and small cell. If dual connectivity is enabled, there can be dual connectivity between macro cell and small cell.

- LTE-U is the proposal developed by the LTE-U Forum, that is a private group composed in 2014 by Verizon, Ericsson, Qualcomm, Alcatel-Lucent and Samsung. The aim of LTE-U Forum is to ensure as soon as possible a commercial deployment for those markets - China, Korea and US - where it is not required the use of LBT procedure. Hence, this is not a global solution being primarily planned for US. At the same way of LAA, LTE-U exploits CA for a Supplemental Downlink (SDL) using an anchor in licensed band.

  The coexistence with Wi-Fi and other LTE-U operators is an important aspect but it is addressed with approaches different from the 3GPP ones. LTE-U is based on carrier-sensing adaptive transmission (CSAT) mechanism where a duty cycle is defined according to the number of networks for the establishment of media access. In the duty cycle period, the small cells send LTE-U Discovery Signals (LDS) and switch the transmission on and off thus defining a SCell ON-state and a SCell OFF-state. According to the channel activity perceived in the SCell OFF-state, the ratio of on/off period can be modified adaptively. The SCell OFF-state, with a minimum duration of 1ms, is due to the presence of other nodes (Wi-Fi or LTE-U) overcoming the energy threshold of -62 dBm.

- MulteFire is the solution developed by the MulteFire Alliance composed by Qualcomm, Nokia, Ericsson and Intel. Unlike LAA and LTE-U, MulteFire represents a stand-alone deployment of the LTE in the unlicensed spectrum, i.e. it does not need the use of an anchor in licensed band. For such a reason, it offers great opportunities of deployment also to small companies and operators that do not have licensed bands. MulteFire aims to provide a technology characterized by the robustness of LTE in radio link performance combined with the advantages of Wi-Fi. This solution, primarily designed for indoor and dense environments, appears on the one hand as a possibility for new players and on the other hand as a threat for those mobile operators who have spent lots of economic resources for licenses.

This thesis focuses on the LAA solution proposed by 3GPP, since it is the only one globally available and completely respectful of Wi-Fi - as it will be demonstrated later. Therefore, the following sections present the detailed features that ensure LTE-LAA operations and fair coexistence.

## 4.3 Fair Coexistence

It has been stressed the importance of coexistence issue since the non-exclusive utilization of unlicensed spectrum. Thereby, for LAA a crucial challenge is to grant a friendly coexistence in unlicensed bands with other radio access technologies (RATs) and mobile operators. In particularly Wi-Fi can suffer for an unfair coexistence showing a resulting degradation of performance because of the presence of LTE system operating in the same bands with any respectful mechanism. This is due to the fact that Wi-Fi uses a carrier sense multiple access with collision avoidance (CSMA/CA). Unlike LTE, Wi-Fi is based on a decentralized scheduling of transmissions from different devices: there is not a centralized controller in this medium access scheme named Distributed Coordination Function (DCF). It uses a listen before talk mechanism to sense the availability of the channel and in case of collision in the access request there is a random time before another attempt to access. So, a Wi-Fi UE senses the medium performing a clear channel assessment (CCA) check, and if the detection reveals a free channel for a Distributed Inter-Frame Space (DIFS) period, then the transmission takes place. In case of busy channel, it is activated a random counter (between 0 16 or 32 in 802.11b/g) and then a back-off procedure of the transmission in this busy period. For failure of the transmission (no ACK from the receiver), the random back-off is repeated increasing the value of the counter – as reported in [13].

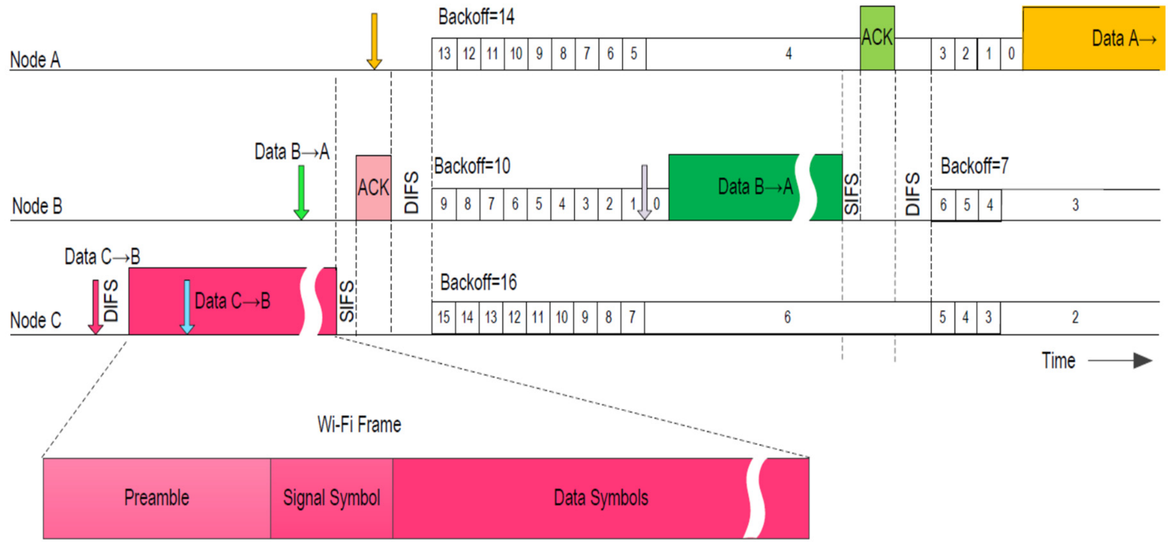



Figure 4.3 Wi-Fi transmission pattern using DCF

LTE instead is characterized by a different access mechanism: its channel access is synchronous and centralized, designed for a very efficient use in licensed bands. The radio resources are optimally distributed to all the synchronized UEs of a same cell by the eNB scheduler in a centralized way. Hence, in its standard configuration LTE appears to be more aggressive than Wi-Fi – designed for contention based access – in accessing to the channel.

### 4.3.1 LBT Mechanism and Trial Results

For the reasons explained above, it appears fundamental to study the procedures for complying coexistence regulations. The method chosen by 3GPP to address concerns from Wi-Fi stakeholders (e.g. Wi-Fi Alliance), is listen-before-talk (LBT) with clear channel assessment (CCA); the Channel Access Mechanism is entirely described in [14]. Enabling such a mechanism, already use by Wi-Fi as seen above, the devices in the network perform a scanning of channel, during the listening time called CCA period. They base on energy detection to sense the availability of the medium: if the energy level in the channel is below the prefixed threshold then they can transmit for a duration equal to the Channel Occupation Time (between 1 ms and 10 ms).

There is possibility for multiple transmission within a COT without repeating CCA if the gap inter-transmission is minor than 16 μs; otherwise it is required an addition CCA check for continuing the transmissions.

The CCA *Threshold Level* (TL) it is proportional to the maximum transmit power (PH expressed in dBm) according to:

TL = Min (-75 dBm/MHz, Max (-85 dBm/MHz, -85 dBm/MHz + (23 dBm - PH)))

This listen before talk mechanism indeed, complies with regulations of markets such as Europe, Japan and India, following the ETSI requirements for LBT for frame based equipment.

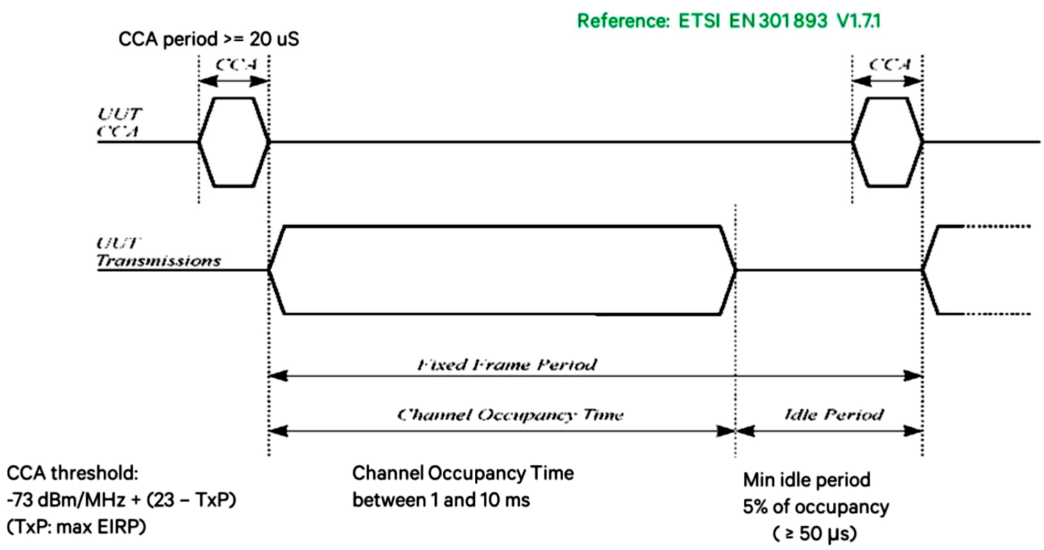



Figure 4.4 FBE LBT

In [14] two different approaches of LBT are specified:

- Frame Based Equipment (FBE)
- Load Based Equipment (LBE)

In LBE-LBT during the CCA procedure, if the channel is occupied the successive attempt to transmit is performed after back-off during the extended CCA (eCCA). The presence of a back-off makes LBE similar to Wi-Fi procedure characterized by an exponential back-off. As suggested in [15], an important improvement of average UPT can be achieved if using a partial subframe in the transmission subsequent to the decrementing the back-off to zero.

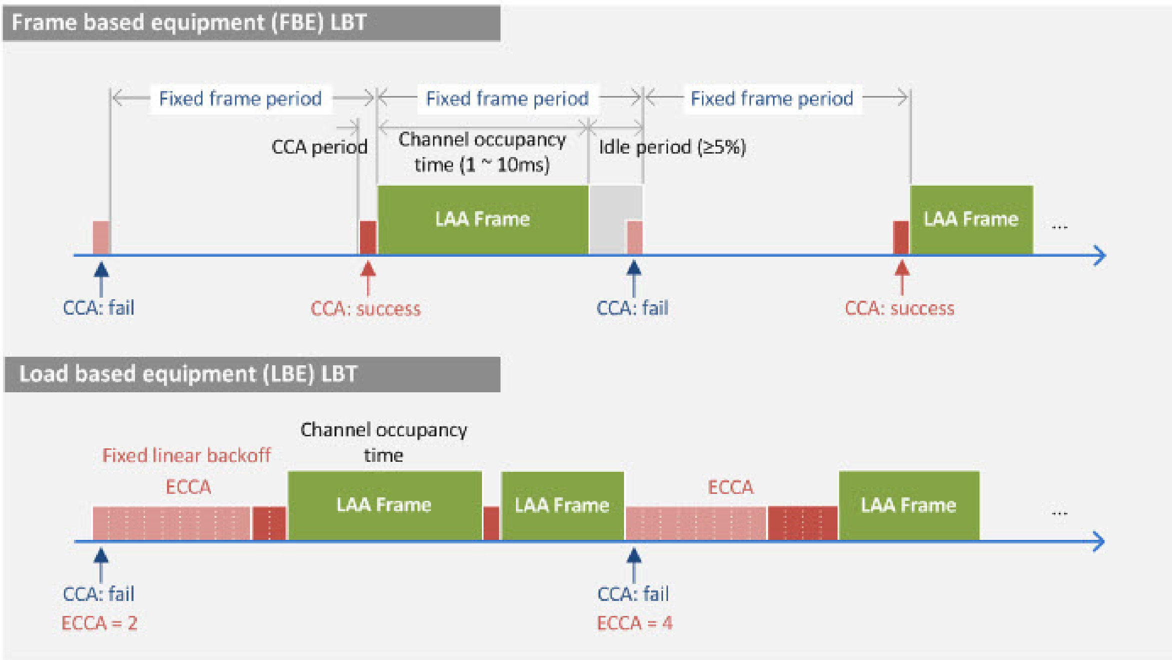



Figure 4.5 Types of LBT described by ETSI

As explained in [16] LTE needs some modification in order to adopt the LBT and meet regulatory requirements. It is necessary that mobile devices acquire the capability of detection in the unlicensed bands; in addition, it occurs to modify HARQ protocol.

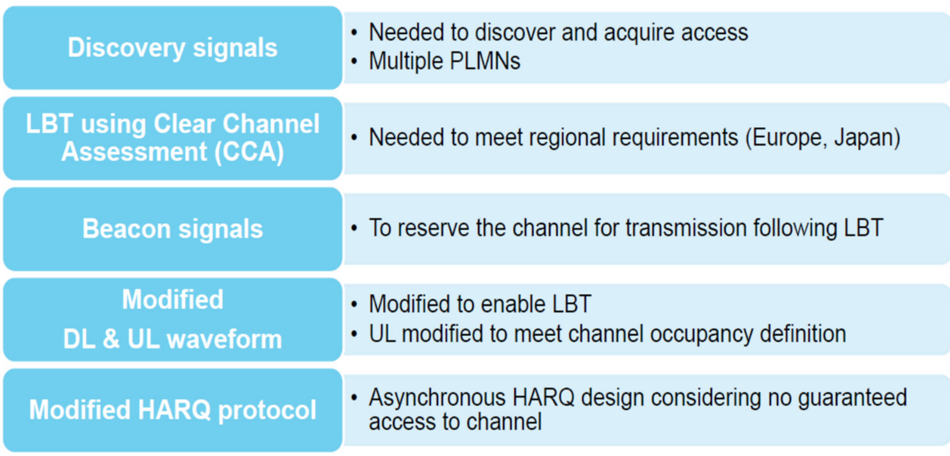



Figure 4.6 Modifications to LTE PHY and MAC layers (source Qualcomm)

In Sec. 7.2.1.6 and Sec. 8.2 of [12] four categories of channel access scheme are presented.

- Category 1: No LBT procedure is performed by the transmitting entity.
- Category 2: LBT without random back-off: The duration of time that the channel is sensed to be idle before the transmitting entity transmits is deterministic.
- Category 3- LBT with random back-off with a contention window of fixed size: The transmitter draws a random number N within a contention window. The

size of the contention window is specified by the minimum and maximum value of N. The size of the contention window is fixed. The random number N determines the duration of time that the channel is sensed to be idle before beginning transmission on the channel.

- Category 4- LBT with random back-off with a contention window of variable size: The transmitter draws a random number N within a contention window. The size of contention window is specified by the minimum and maximum value of N. The transmitting entity can vary the size of the contention window when drawing the random number N. The random number N determines the duration of time that the channel is sensed to be idle before beginning transmission on the channel.

The LBT category 4 has common features with IEEE 802.11 DCF: if it is not possible to transmit there is a binary exponential back-off, otherwise the contention window size is reset. It has an initial CCA (iCCA) for sensing the channel free and then an extended CCA (eCCA). This category may not be optimal in situations of saturated network since LAA users keep on transmitting even if Wi-Fi nodes are waiting for the channel to be free. Therefore, there are proposal like [17] for an enhancement of this functionality using an optimal constant contention window.

An important confirmation of the effectiveness of LBT mechanism for a fair coexistence is provided by LAA over-the-air trial in Nuremberg conducted by Deutsche Telekom and Qualcomm Technologies, Inc [18] and [19]. These tests for outdoor and indoor have been performed using equipment complying with 3GPP Release 13 development and using LBT with extended CCA.

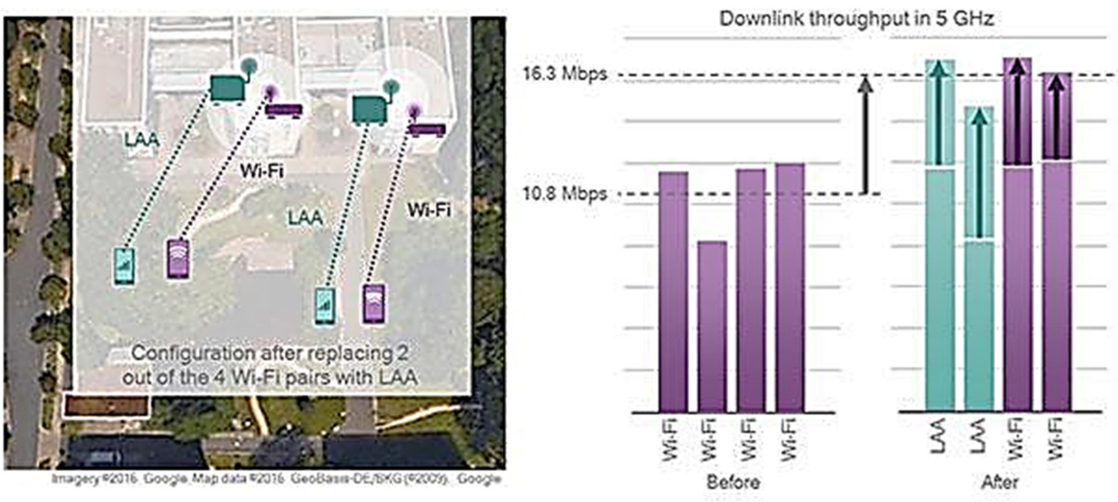



Figure 4.7 Outdoor LAA performance in OTA trial in Nuremberg (source Qualcomm)

The most important results from these trials is that LAA fair coexistence can improve the performance of Wi-Fi too. In fact, LAA proves to be an excellent neighbour to Wi-Fi: introducing two LAA small cells also Wi-Fi users experience higher data-rates. Besides LAA has coverage benefits compared to Wi-Fi outdoors: switching a Wi-Fi AP with a LAA small-cell produce an increase of capacity for the network and higher data-rates for the UEs.

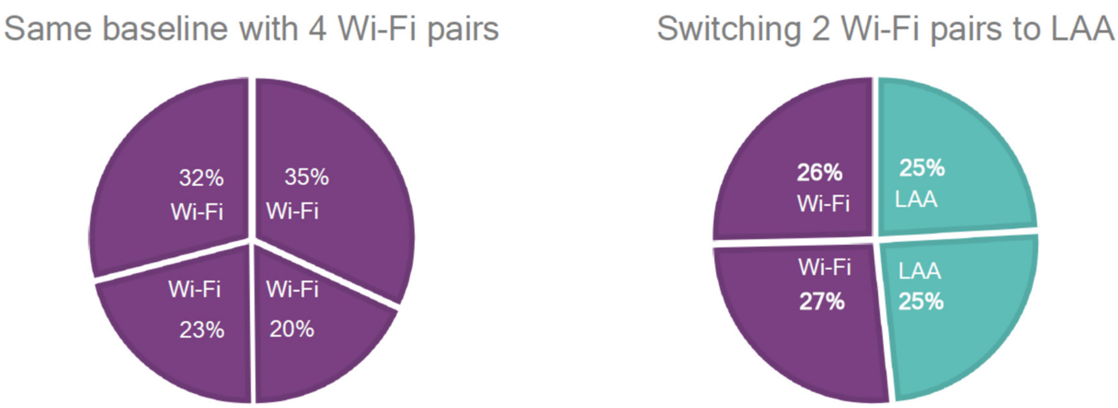



Figure 4.8 Channel occupancy: the total is not 100% due to over utilization (source Qualcomm)

LBT ensures a fair sharing of the channel with Wi-Fi system, as it can be observed from the figure above.

Trials in Nuremberg provide interesting results also for the behaviour of LAA in indoor environment, demonstrating that such technology offers more gain in high traffic load scenarios and improves neighbour Wi-Fi performances too.

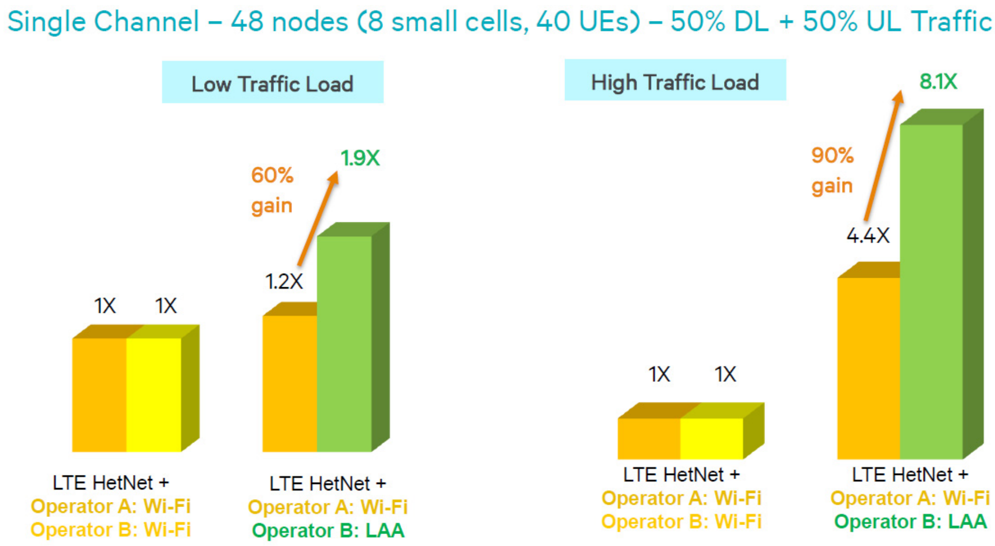



Figure 4.8 Downlink media user data rate in indoor deployment (source Qualcomm)

The scenario for the tests realized is a single-floor building with two operators (A, B), 4 small cells per operator; 3GPP traffic model 3 with 1MB file; DL 2x2 MIMO for LTE, LAA and Wi-Fi; Tx power 24dBm + 3 dB at LAA SC or Wi-Fi AP; LBE-based eCCA procedure for LBT.

The results are fundamental for a commercial deployment of LTE-LAA since they validate the potential benefits in terms of throughput and the respect of the other systems sharing the same channel.

## 4.4 Throughput Computation and Testbeds

This thesis focuses on the evaluation of LTE Licensed-Assisted Access analysing the performance in downlink mainly in terms of throughput. Hence, a correct estimation of the maximum theoretical throughput achievable by LAA it is of paramount important. When using the unlicensed spectrum, the computation is different from the licensed case already seen. This is due to the use of LBT mechanism that implies the CCA period: in ETSI BRAN EN 301.893 the duration established for this period is equal to 20 μs. Because of the features of LTE PHY layer and the functionalities of the scheduler, this period has to be mapped within one subframe (1ms) or at least within half-subframe (0.5 ms). After the CCA period the LTE node can transmit in DL for 8 ms or 10 ms, according to the Channel Access Priority Class defined in Table 5.1.1-1 [20].

| Channel Access Priority Class ( $p$ ) | $m_p$ | $CW_{\min,p}$ | $CW_{\max,p}$ | $T_{m\cot,p}$ | allowed $CW_p$ sizes |
|---|---|---|---|---|---|
| 1 | 1 | 3 | 7 | 2 ms | {3,7} |
| 2 | 1 | 7 | 15 | 3 ms | {7,15} |
| 3 | 3 | 15 | 63 | 8 or 10 ms | {15,31,63} |
| 4 | 7 | 15 | 1023 | 8 or 10 ms | {15,31,63,127,255,511,1023} |

Table 4.1 Channel Access Priority Class (source 3GPP TS 36.213)

Thereby, choosing a common and conservative case with *class p* equal to 4, $T_{mcot,p}$ = 8 ms and CCA period of 1 ms, the scheduling rate is 8/) – 8 subframes for transmission and 1 subframe for CCA – the throughput on the physical layer is:

$$391632 + 3 * \frac{8}{9} * 195792 = 913744 \ {}^{bits}/_{TTI} = 913.7 \ Mbps \tag{4.4.1}$$

Otherwise, if the eNB transmits for 10 ms and the CCA is performed in half-subframe:

$$391632 + 3 * \frac{10}{10.5} * 195792 = 951037 \ {}^{bits}/_{TTI} = 951.04 \ Mbps \tag{4.4.2}$$

Hence, the maximum theoretical throughput for LAA using 60 MHz in the unlicensed spectrum is about 950 Mbps. This results it is obtained in a configuration consisting of 20MHz, MIMO 4x4, in licensed band with 60MHz, MIMO 2x2, in unlicensed 5GHz band; all the carriers used 256QAM.

The aim for the commercial deployment indeed is to aggregate 60 MHz contiguous in the unlicensed spectrum as supplemental downlink to add to the licensed one. Currently are not designed configuration with MIMO 4x4 in the unlicensed band.

At the moment of writing, tests on the LAA performance are conducted by TIM using pre-commercial smartphone – based on Qualcomm downlink category 16 modem - with the capabilities to support operations in unlicensed spectrum and precommercial network equipment. Thanks to these tests it is possible to observe how a LAA device practically works and performs. In particular, for the results exposed further the configuration used consists of one PCC FDD 20 MHz, MIMO 4x4 (licensed) plus two SCCs LAA MIMO 2x2 20MHz per carrier. Even though it is not yet the maximal configuration exploiting "just" 40MHz unlicensed and not 60 MHz, it is really helpful to understand the potential of LAA technology.

Using LBT category 4, with a percentage of data transmission equal to the 87.5% of the overall time, the maximum theoretical throughput is:

$$390\ Mbps + 0.875 * (195 + 195) Mbps = 731\ Mbps \tag{4.4.1}$$

From the following figure, it is possible to observe the results of throughput performance offered by MIMO 4x4 256QAM compared with MIMO 4x4 64QAM.

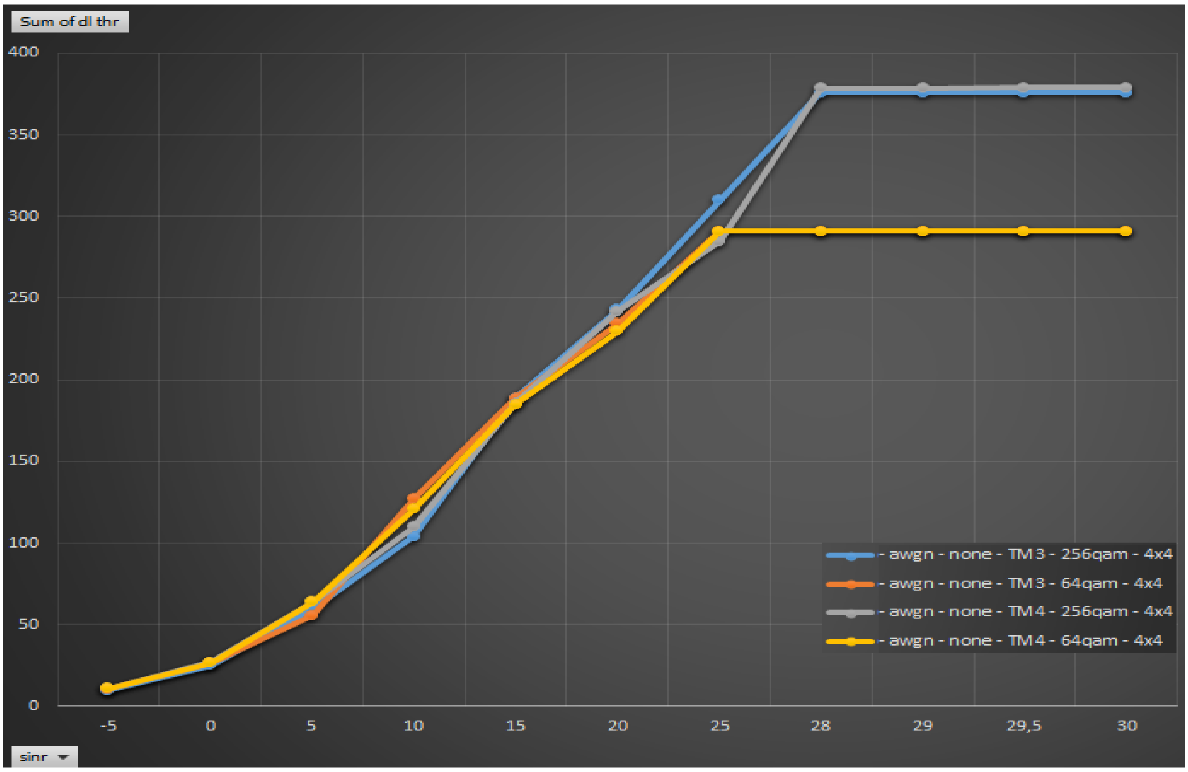



Figure 4.9 MIMO 4x4 – 256 QAM vs 64 QAM + TM3 vs TM4, no correlation, awgn fading (source TIM)

The curves above confirm the throughput value of about 390 Mbps in MIMO 4x4 and 256QAM, in licensed band for optimal value of SINR.

Then, with the tested LAA configuration already described the values of throughput obtained are presented through the following figures.

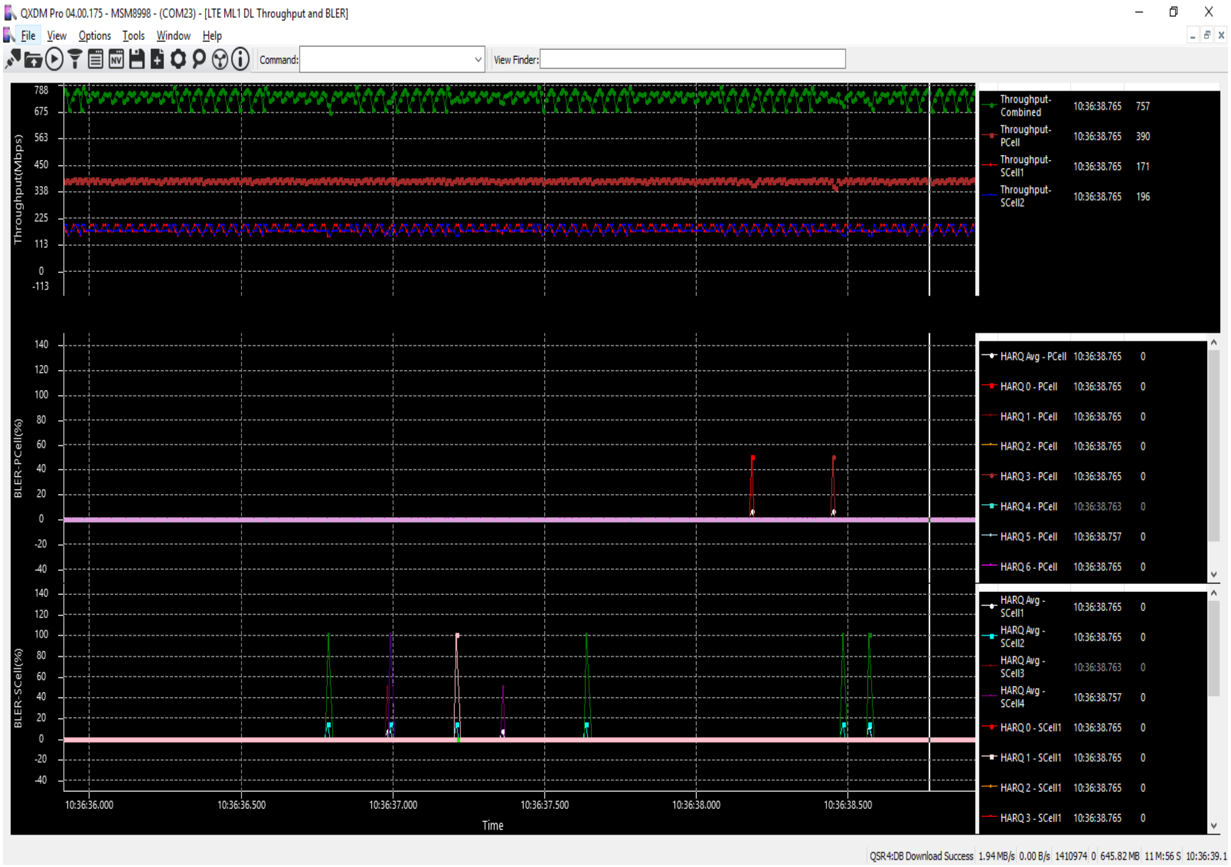


Figure 4.10 LAA throughput and BLER (source TIM)

This first figure reports the performances obtained when using LBT only for one SCC. In fact, it can be seen that the throughput of the SCell1 is equal to 171 Mbps due to the presence of LBT for the 87.5% of the time; the SCell2 instead has a higher throughput as expected from the theory. An excerpt of this situation is presented below.

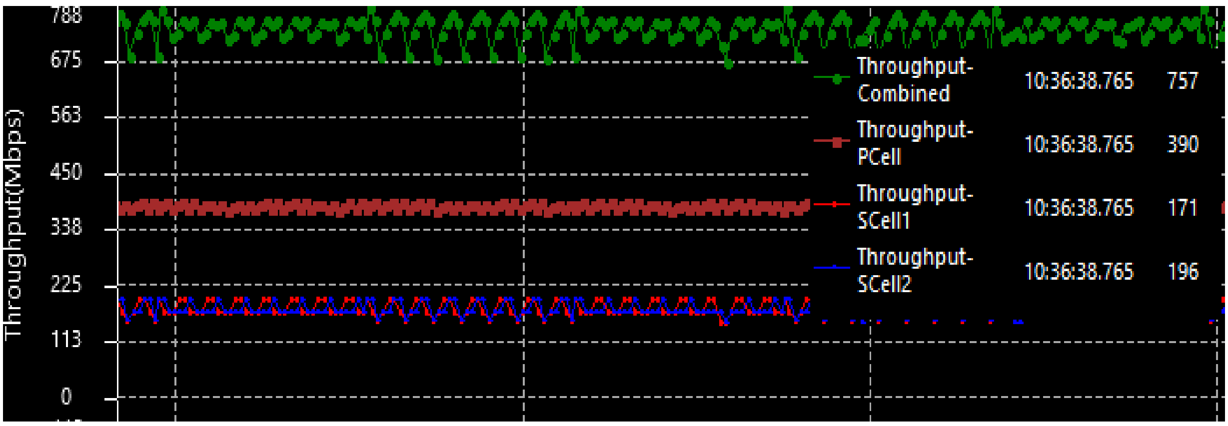



Figure 4.11 Excerpt of LAA throughput results (source TIM)

Another situation analysed in the test section consists of the evaluation of LAA performance with no LBT mechanism: it is clearly only a test situation because in commercial deployment LAA will have to respect the regulatory requirements already exposed.

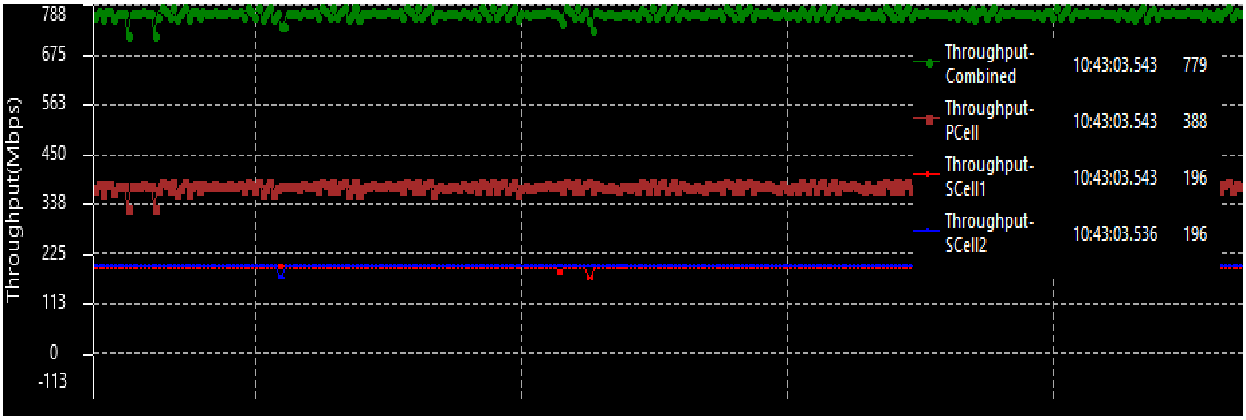



Figure 4.12 Excerpt of LAA with no LBT throughput results: (source TIM)

The results from the laboratory confirm high values of throughput achieved thanks to the combination of the three carriers. In particular, it has been achieved the value foreseen of about 780 Mbps without LBT mechanism.

All these results are fundamental for this work in the evaluation of the possibilities offered by LTE Licensed-Assisted Access. Such an evaluation it will be extended and further analysed through the simulation results presented in the next section. It is worth to note that in the simulation there will not be the 256QAM due to current limitation of ns-3 simulator. Thereby the achieved levels of throughput will be lower to those presented in the previous tests, anyway there will be provided other interesting results such as the possibilities offered by the use of MIMO 4x4 in unlicensed carriers.

# 5 Simulation and Results

## 5.1 Scenarios

The aim of this work is to study the effects that LTE-LAA has on the downlink performances of the user. It means that such investigation wants to observe if the adoption of this new technology offers real improvements to the data rate of the devices capable of using it, with respect to comparable LTE deployment scenarios based on licensed bands only. Then the key parameter is the user throughput in downlink.

In particular, this thesis will deal with LTE-LAA in indoor scenarios. In an office environment, a single floor building of 120m x 50m, there will be the compresence of two different operators, Wi-Fi Base Stations and LAA eNodeBs, with several UEs per each one. Two different deployment cases will be analysed:

- *LAA*: 3 eNBs, 20 UEs;
  *Wi-Fi*: 2 base stations (BS) and 16 clients (STAs);
- *LAA*: 3 eNBs, 20 UEs;
  *Wi-Fi*: 6 base stations (BS) and 60 clients (STAs).

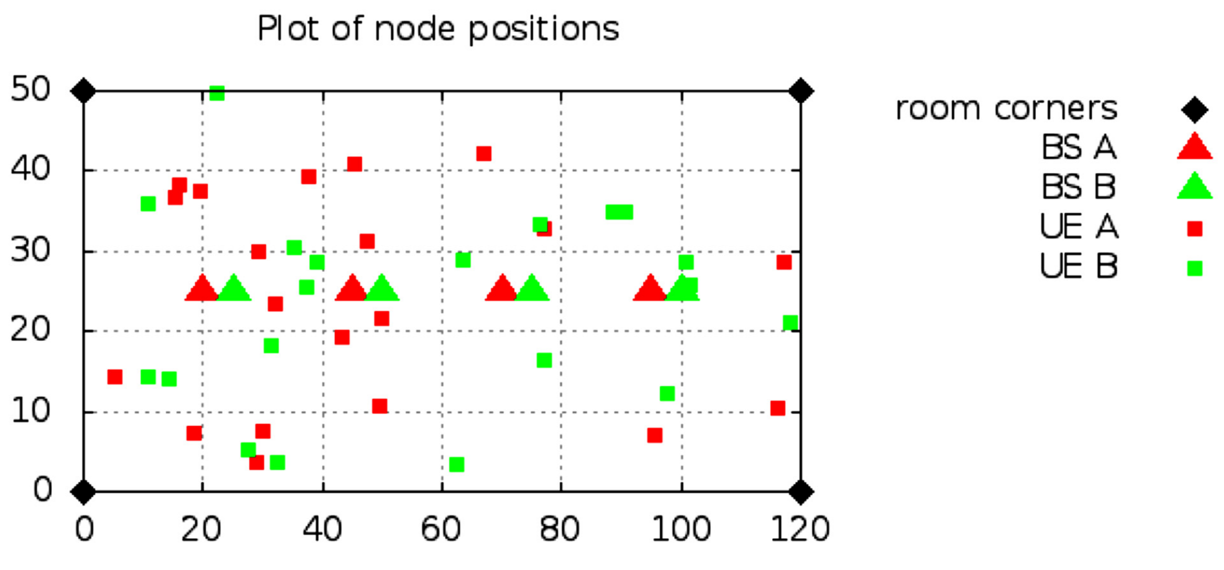



Figure 5.1 Indoor scenario in ns-3 simulator

The purpose of this differentiation is to analyse the behaviour of LTE-LAA technology in various conditions of interference and the effects on downlink performances.

There will be always the coexistence of the two different technologies that will be managed through the Listen Before Talk (LBT) mechanism. The throughput values that will be obtained in the different simulations will be a useful instrument to understand the potential for LTE-LAA.

In the implementation on the simulator the propagation model is the ITU Indoor Hotspot (InH) [21], that will be described in detail in the next section. Both Wi-Fi and LTE-LAA use the same traffic model: main part of the simulations is based on FTP model 1 – that will be presented further -with transmissions of files of size 512KB in packets of 1448B. The duration of simulation is configured proportionally to the parameter $\lambda$, representing the arrival time of the Poisson distribution.

An important parameter for simulation results is the Energy Detection Threshold adopted in the LBT mechanism: it can assume values of -62 dBm, -72 dBm and -82 dBm representing the energy level above which LTE devices sense the medium as occupied.

Several cases, entirely in indoor, will be studied: the first cases will provide an analysis of the coexistence between Wi-Fi system and LTE-LAA technology - both of them working on the same channel at 5180 MHz - varying some parameters such as the energy detection threshold and the traffic intensity.

Then, it will be presented an effective comparison between the performances using the assistance of unlicensed spectrum at 5 GHz and the performances obtained using only licensed bands.

Therefore, the test-cases of interest will be:

1) Indoor environment with small cells, 35 MHz of spectrum bandwidth: 20 MHz in unlicensed at 5180 MHz and 15 MHz in licensed spectrum at 2600 MHz;
2) Indoor environment with small cells, 35 MHz bandwidth entirely in licensed bands: 20 MHz at 2100 MHz and 15 MHz at 2600 MHz;
3) Indoor environment with small cells, 40 MHz of spectrum bandwidth: 20 MHz in unlicensed at 5180 MHz and 20 MHz in licensed spectrum at 2100 MHz;
4) Indoor environment with small cells, 40 MHz of spectrum bandwidth entirely in licensed bands: 20 MHz at 2100 MHz and 20 MHz at 2600 MHz.

For each of these cases, it will be done an analysis in different conditions and using several configurations of multiple antenna techniques and traffic models.

In fact, it will be tested the behaviour of these technologies in the following configurations:

- SISO, 64 QAM;
- MIMO 2x2, 64 QAM;
- MIMO 4x4, 64 QAM;

Besides, there will be presented the reasons for the choice of FTP Model 1 traffic model, among the three available models implemented, as the main one for the simulation scenarios. In setting the traffic model, particular interest is addressed to the presence of packet loss and the percentage of it, trying to present a comparison of performances between the different technologies in conditions of zero packet loss.

For these simulations, it will be assumed that the UEs of the two different operators are equipped with capabilities such as to grant they can fully exploit all the enhanced techniques presented in 3GPP Release 13.

## 5.2 Analytical Model and Assumptions

These are the cases that will be implemented through the NS-3 simulator to achieve results for the evaluation of eventual benefits brought by LTE-LAA.

Before the use of the simulator, it is necessary to analyse the key performance indicator of interest – the throughput – from an analytical and theoretical point of view.

The throughput indeed depends on several parameters that can affect its computation. Among these parameters, some of the most important are: number of antennas (MIMO); number of physical resource blocks (PRB) and so the spectrum bandwidth depending also on the carrier aggregation (CA); modulation and coding scheme (MCS).

The first two capabilities of MIMO and Carrier Aggregation depend on the device technology, on its category that reveals the maximum throughput achievable but not exactly the number of antennas and component carriers employed.

The last term influences the computation of the throughput because the MCS value expresses the quality of the channel and establishes the number of bits that can be carried by a single Resource Element (RE). It is clear, therefore, that the estimation of the channel is crucial to understanding the possibility for a user to achieve a certain value of throughput. In fact, the MCS, reflecting the channel quality, is an indicator based on SINR that in turn is connected to the value of power received according to:

$$SINR = \frac{P_R}{I + N} \tag{5.2.1}$$

So, the analytical study has to start from the correct choice of a channel model that influences the value of received power with its characteristic attenuation or path loss. In fact, from the link budget equation:

$$P_R = P_T + G_T + G_R - PL \tag{5.2.2}$$

In the specific indoor case of an office environment, the ITU-InH (Indoor Hotspot) is one of the suitable model. It provides the values of the path loss (PL) in the two different situations of line of sight (LoS) and no line of sight (NLoS).

| Scenario | | Path loss (dB)<br>Note: fc is given in GHz and distance in m! | Shadow fading std (dB) | Applicability range, antenna height default values |
|---|---|---|---|---|
| Indoor Hotspot (InH) | LoS | $PL = 16.9 \log_{10}(d) + 32.8 + 20 \log_{10}(f_c)$ | σ = 3 | 3 m < $d$ < 100 m<br>$h_{BS}$ = 3-6 m<br>$h_{UT}$ = 1-2.5 m |
| | NLoS | $PL = 43.3 \log_{10}(d) + 11.5 + 20 \log_{10}(f_c)$ | σ = 4 | 10 m < $d$ < 150 m<br>$h_{BS}$ = 3-6 m<br>$h_{UT}$ = 1-2.5 m |

Table 5.1 Indoor Hotspot model (ITU)

So, in the case of NLoS, given a determined frequency, the path loss only depends on the distance of the user from the eNB; it means PL depends on the position of the UE.

The throughput of the i-th user is expressible as a function of the coordinates of its position at the time instant *t*:

$$throughput_i = f\left(x_i(t), y_i(t)\right) \tag{5.2.4}$$

The distance is a random variable. Then it is possible to observe the behaviour of the attenuation in a statistical way, in order to find the probability to have a certain path loss that will affect the computation of the received power, the SINR, and therefore the MCS value of the UE.

To introduce this statistical computation, it is helpful to remind some theoretical basis. Given a random variable $x$, with density function $f_X(x)$, let $y=g(x)$ be its correspondence. The goal is to find the probability distribution. In case g is both a monotonical and differentiable function, it can be written:

$$f_y(y)dy = f_x(x)dx \tag{5.2.5}$$

and for differentiability hypothesis:

$$dy = g'(x)dx \tag{5.2.6}$$

Combining these two it is possible to get a new expression of $f_Y(y)$:

$$f_y(y)g'(x)dx = f_x(x)dx \tag{5.2.7}$$

$$f_y(y) = \frac{f_x(x)}{g'(x)} \tag{5.2.8}$$

Turning back to the case of interest with this background, the first assumption to do is that the distance has a uniform probability density function. So, each user has the same possibility to be in one of the possible position inside the office.

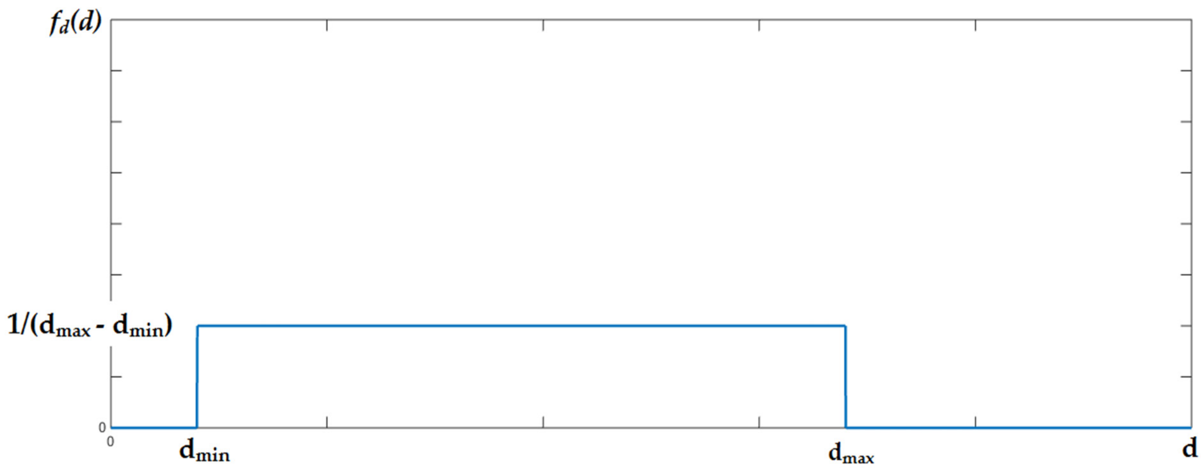



Figure 5.2 Probability distribution along the radius

Therefore, the density function $f_X(x)$ is known and it is as it follows.

$$f_x(x) = \frac{1}{(d_{max} - d_{min})} \tag{5.2.9}$$

The path loss equation, initially expressed in dB:

$$PL = 43.3\ \log_{10}(d) + 11.5 + 20\log_{10}(f_c) \tag{5.2.10}$$

It can be rewritten linearly:

$$PL = d^{4.33} * (10^{1,15} * f_c^2) = \ d^{4.33} * k \tag{5.2.11}$$

The relation between distance and path loss is:

$$d = \left(\frac{PL}{k}\right)^{0.23} \tag{5.2.12}$$

Now, deriving it:

$$g'(x) = 4.33 * k * d^{3.33} \tag{5.2.13}$$

It is possible to get to the wanted probability density function (pdf):

$$f_y(y) = f_{PL}(PL) = \frac{1}{(d_{max} - d_{min}) * 4.33 * k * \left(\frac{PL}{k}\right)^{0.77}} \tag{5.2.14}$$

The integral of this pdf has to be equal to 1:

$$\int_{PL_{min}}^{PL\,max} f_{PL}(PL)\, dPL = 1 \tag{5.2.15}$$

$$\frac{1}{(d_{max} - d_{min}) * 4.33 * k^{0.23}} \int_{PL_{min}}^{PL\,max} PL^{-0.77} dPL \tag{5.2.16}$$

$$\frac{1}{(d_{max} - d_{min}) * 0.23 * 4.33 * k^{0.23}} [PL^{0.23}]_{PL_{min}}^{PL_{max}} = \frac{k^{0.23}(d_{max} - d_{min})}{(d_{max} - d_{min}) * k^{0.23}} = 1 \tag{5.2.17}$$

So, there is no need to use any normalization constant to make the pdf integral equal to 1, because as demonstrated the pdf is already normalized.

Once the probability density function of the path loss has been studied, it can be applied directly to the SINR computation through (5.2.2), in the assumption that in (5.2.1) both the interference $I$ and the noise $N$ are constant.

Based on the SINR of each user, a certain value of MCS is assigned next to the computation of the spectral efficiency. Let $\gamma_i$ be the SINR of i-th user, the spectral efficiency $\eta_i$ is:

$$\eta_i = \log_2\left(1 + \frac{\gamma_i}{\Gamma}\right) \tag{5.2.15}$$

Where Γ is:

$$\Gamma = \frac{-\ln(5 * BER)}{1.5} \tag{5.2.16}$$

And:

$$BER = 0.00005 \tag{5.2.17}$$

Rewriting the SINR expression:

$$\mathrm{SINR} = \gamma_i = \frac{P_T}{(I + N) * PL} \tag{5.2.18}$$

The spectral efficiency can be seen in function of the path loss:

$$\eta_i = \log_2\left(1 + \frac{P_T}{\Gamma * (\mathrm{I} + \mathrm{N}) * \mathrm{PL}}\right) \tag{5.2.19}$$

At this point, the spectral efficiency depends on the path loss whose pdf has already been found. Then the (5.2.6) can be again applied to find the pdf of the spectral efficiency:

$$g'(x) = -\frac{P_T}{\mathrm{PL} * \ln(2)[P_T + \Gamma * (\mathrm{I} + \mathrm{N}) * PL]} \tag{5.2.20}$$

So:

$$f_{\eta_i}(\eta_i) = f_Y(y) = \frac{f(x)}{g'(x)} = \frac{PL^{0.23} * \ln(2)[P_T + \Gamma * (\mathrm{I} + \mathrm{N}) * PL]}{(d_{max} - d_{min}) * 4.33 * k^{0.23} * P_T} \tag{5.2.21}$$

Then it is possible to rewrite the pdf in function of $\eta_i$, knowing the relation with the path loss:

$$PL = \frac{P_T}{\Gamma * (\mathrm{I} + \mathrm{N}) * (2^{\eta_i} - 1)} \tag{5.2.22}$$

And finally:

$$f_{\eta_i}(\eta_i) = \left(\frac{P_T}{\Gamma * (\mathrm{I} + \mathrm{N}) * (2^{\eta_i} - 1)}\right)^{0.23} * \frac{\ln(2)[P_T + \Gamma * (\mathrm{I} + \mathrm{N}) * PL]}{(d_{max} - d_{min}) * 4.33 * k^{0.23} * P_T} \tag{5.2.23}$$

Thereby, an analytical observation brings to a closed form of the spectral efficiency.

In 3GPP TS 36.213 the spectral efficiency is quantized based on the channel quality indicator (CQI) and then a corresponding MCS scheme is assigned.

| CQI index | CQI index in previous table | Modulation | Code rate x 1024 | Spectral efficiency |
|---|---|---|---|---|
| 0 | 0 | out of range | | |
| 1 | 1 | QPSK | 78 | 0,1523 |
| 2 | 2 | QPSK | 120 | 0,2344 |
| 3 | 4 | QPSK | 308 | 0,6016 |
| 4 | 6 | QPSK | 602 | 1,1758 |
| 5 | 8 | 16QAM | 490 | 1,9141 |
| 6 | 9 | 16QAM | 616 | 2,4063 |
| 7 | 10 | 64QAM | 466 | 2,7305 |
| 8 | 11 | 64QAM | 567 | 3,3223 |
| 9 | 12 | 64QAM | 666 | 3,9023 |
| 10 | 13 | 64QAM | 772 | 4,5234 |
| 11 | 14 | 64QAM | 873 | 5,1152 |
| 12 | 15 | 256QAM | 711 | 5,5547 |
| 13 | - | 256QAM | 790 | 6,1719 |
| 14 | - | 256QAM | 869 | 6,7891 |
| 15 | - | 256QAM | 948 | 7,4063 |

Table 5.2 CQI vs. Spectral Efficiency (3GPP TS 36.213)

The MCS assignation can also depend on the single vendor proposal.

In summary, the function for a single user throughput has inputs as its position and spectral efficiency:

$$throughput_i = f\ (x_i(t), y_i(t), \eta_i\ ) \tag{5.2.24}$$

So, the average user perceived throughput of the scenario is given by the average of the throughput of the N users.

$$Average\ Throughput = \sum_{i=1}^{N} \frac{throughput_i}{N} \quad (5.2.25)$$

Another aspect that has to be managed for throughput analysis, working with the unlicensed spectrum at 5 GHz, is traffic model of Wi-Fi. In fact, given the adoption of the LBT as a fair coexistence technique, the possibility to use that portion of spectrum for LTE-LAA depends on the use of those 20 MHz by the Wi-Fi. Both technologies work at same frequency band: LTE operating on EARFCN 255444 (5.180 GHz), and Wi-Fi 802.11n on channel 36 (5.180 GHz). The traffic model can be either TCP or UDP. For the UDP application the parameters that characterise the transmission are the *packet size* and the *data rate*. For Wi-Fi transmission, it is worth taking into account the Wi-Fi *queue max delay* and *queue max size*.

Depending on the traffic model, the throughput evaluation has to consider a certain percentage of overhead in the transmission.

A theoretical computation of the maximum throughput achievable - for a user whose position, MCS, and capabilities are known - it is as it follows. Basing on the MCS table, for a certain value of PRB it corresponds a defined Transport Block Size (TBS).

For example, in the case of a device of category 16, with capabilities of 256 QAM, using 5 carriers and in good conditions of channel quality – high CQI – the features to compute the throughput are:

- MCS = 27 and 100 PRB → TBS=97896;
- MIMO 4x4;
- 5 Carrier Aggregation

$$Throughput = TBS * MIMO * C.A = 97896 * 4 * 5 = 1.96\ Gbps \quad (5.2.26)$$

Finally, the computation of the overall system throughput can be seen through the following block diagram.

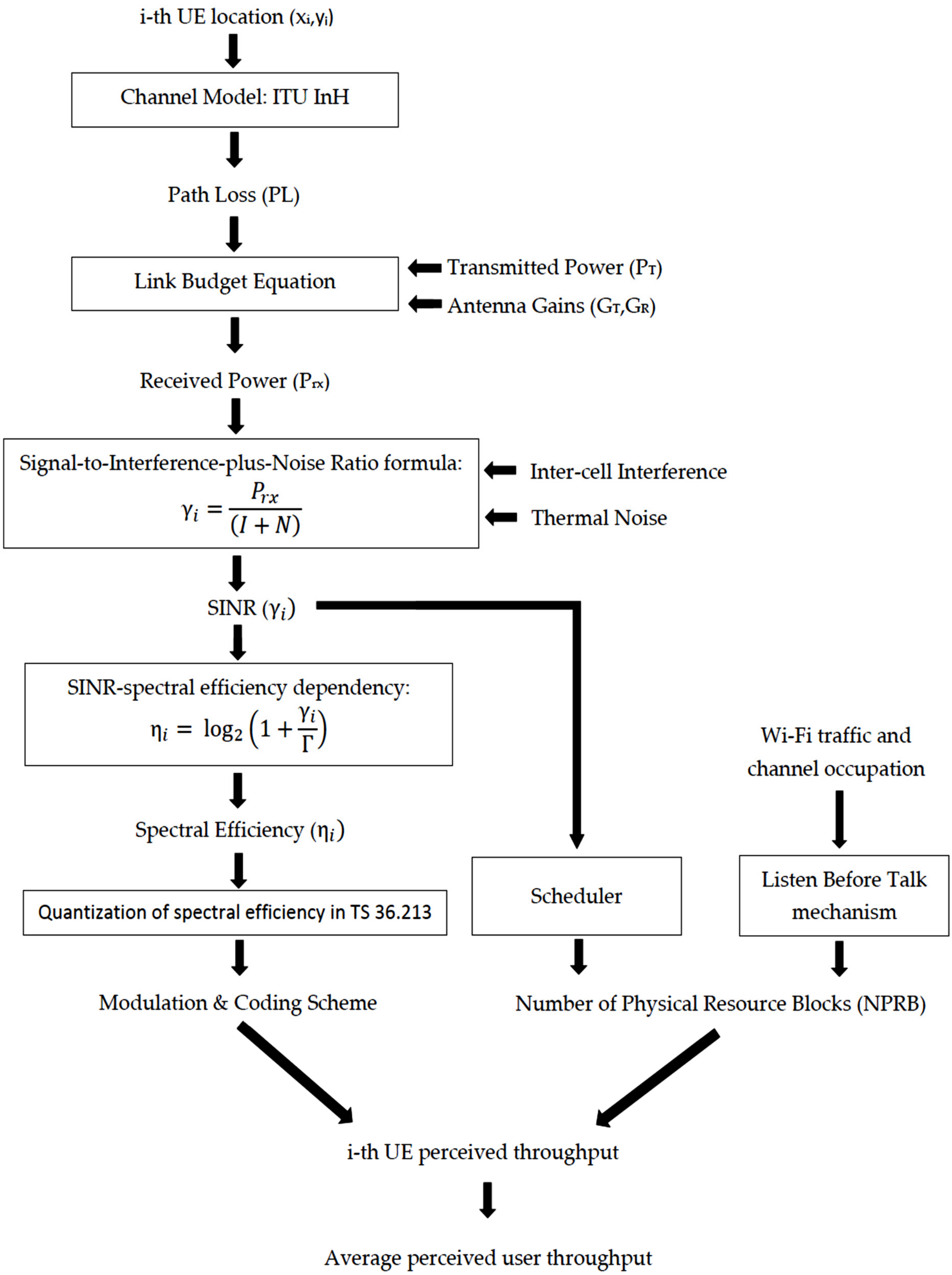



Figure 5.3 Flow chart for the evaluation of the average perceived user throughput

## 5.3 NS-3 Simulator

The ns-3 simulation framework is the discrete event (DE) network simulator used for the LTE-LAA performance evaluation of this thesis. The software architecture presented in detail in [22] is built on C++ and it is, at the moment of writing, the only open source simulator for coexistence study. Hence the choice of ns-3 as a tool for this work on LTE in unlicensed spectrum.

The simulator is based mainly on the following concepts:

- Event
- Node
- NetDevice
- Channel
- Protocol
- Application

An *event* is something scheduled to happen at a certain time instant. It is characterized by a target function and parameters. A simulation-wide scheduler is responsible for the ordering and the sequential execution of them.

A *node* is an object that takes care of the aggregation of other objects like protocols and applications. It represents a device connected to a network.

A *NetDevice* is the logical representation of a L2 communication interface.

*Channels* connect NetDevices and they are abstract representations of the effect experienced by a signal in its transmission over a certain medium. The most advanced channel models are based on the *propagation* module.

*Protocols* represent specific high-level protocols like IPv5, IPv6, ICMP, routing protocols and others.

*Applications* are traffic generators or data sinks and they are used for the generation of data traffic according to specific statistical distributions.

The configuration of ns-3 elements can be done through *Attributes*, used to change the properties of an object. They can modify the default behaviour of a class or the properties of a single instance.

The code organization of the simulator consists of modules that provide a single functionality or layer. The most interesting modules for the thesis are:

- Propagation
- Wi-Fi
- LTE
- Internet
- Flow Monitor
- Laa-Wifi-Coexistence

Special attention will be given to the last module that has been recently added in a separated version of the simulator called *ns-3-lbt*. This module has not been integrated in the main release yet, but it offers the possibility to analyse the coexistence problem when using LTE in unlicensed spectrum.

### 5.3.1 Propagation Module

This module contains the propagation and error models designed for wireless signals. According to the propagation condition, the parameters of the antennas and channel models, it can be calculated the delay and the attenuation of the transmission power.
There is the possibility to apply different channel models, e.g. Friis, Okamaura-Hata, etc…depending on the simulation scenario. For the scenario of interest in this thesis, the chosen channel model is the *Indoor Hotspot* (InH), proposed by ITU; a detailed description of this model will be given in the following sections.

### 5.3.2 Wi-Fi Module

The Wi-Fi module in ns-3 is consolidated module and it is still actively maintained and open to updates and expansions. Currently it presents features such as MIMO support, channel aggregation, 802.11ac.

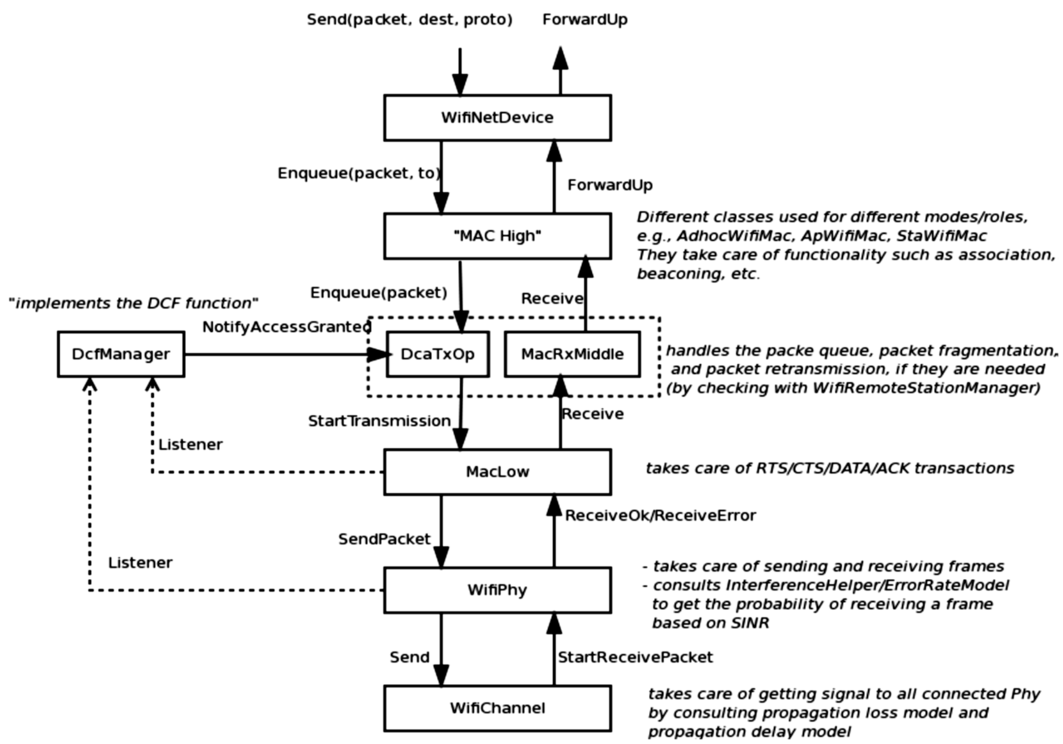



Figure 5.4 Wi-Fi module

However, it does not allow any co-channel interference. For this reason, the ns-3 community has proposed the integration of a specific module (*laa-wifi-coexistence*) for the coexistence issue, even if this change it is not applied in the last stable version yet. An explanation of this propose will be address later in this chapter.

### 5.3.2 LTE Module

The development of the LTE module is more recent than the one of Wi-Fi module. It is one of the most complex module in the simulator and it allows the analysis of small cells / macro cells interaction in both outdoor and indoor scenarios. This module offers the evaluation of the following aspects of LTE systems:

- Radio Resource Management
- QoS-aware Packet Scheduling
- Inter-cell Interference Coordination
- Dynamic Spectrum Access

LTE model at the radio level has a granularity up to the Resource Block (level). This granularity is finer than the one of the Wi-Fi error model that is based on a BER then extended to a whole packet under the assuming it constant over a whole packet.

It must be stressed that the LAA concepts, such as duty cycle and LBT approaches, were not available in the past and they are not included in the LTE module but integrated thanks to the addition of the *Laa-Wifi-Coexistence* module.

### 5.3.3 Internet Module

This module contains the features of the TCP/IP stack and offers the following available models:

- IP (v4 and v6)
- ICMP (v4 and v6)
- UDP
- TCP (NewReno, Westwood, Westwood+, with more being developed)

This module works in coordination with the *Application* one and it is used in the simulation for assigning IP address to the core network and to the devices.

### 5.3.4 Flow Monitor Module

The Flow Monitor module makes it possible to flexibly measure the performance of network protocols. It utilizes probes for tracking the exchange of packets between nodes and gives to screen a set of parameters. The module currenty works only at IP level and gives as output the transmitted and received packets and bytes, the duration of the transmission and the value of throughput per flow; all these statistics on monitor can be also exported in XML format. In particular for the task of this performance evaluation study, the IP-based Flow Monitor tool provides user perceived throughput.

An example of the output given by the flow monitor is:

```
Flow 1 (1.0.0.2:49153 -> 7.0.0.2:50000) proto UDP
Tx Packets: 354
Tx Bytes:   521912
TxOffered:  0.405369 Mbps
Rx Bytes:   521912
```

```
First Received Packet: 2.97842s
Last Received Packet: 3.044s
RxDuration: 0.06558s
Throughput: 63.6672 Mbps
Mean delay:  34.3173 ms
Mean jitter:  0.175141 ms
Rx Packets: 354
```

The throughput value achieved in this excerpt of the simulations carried out is calculated as the throughput from the receiver side, i.e. it is obtained as the ratio between the size of the packet sent and the time spent for its reception.

### 5.3.4 Laa-Wifi-Coexistence Module

At the time of writing, the last stable release (ns-3.26) of the simulator does not allow to perform a coexistence analysis of LTE-LAA with Wi-Fi. The following points must be addressed to achieve a useful tool for such a study:

- A change of Wi-Fi module in its MAC and PHY models to allow the use of Spectrum-based channels (utilized in LTE module).
- LTE should enable discontinuous transmissions, based on both duty-cycle and energy detection (LBT).
- Update of LTE module for the use of 5GHz channels.
- Update of both LTE and Wi-Fi to sense the other technology signals as interference.

All these changes have been integrated and implemented in the recent *LAA Wi-Fi Coexistence* module [23]. This module is part of a project sponsored by Wi-Fi Alliance with the aim of facilitating analysis of coexistence of Wi-Fi and unlicensed LTE, on the same channel, with the intent to align to the procedures defined by 3GPP RAN1 and IEEE 802.11ax. Such a project has been mainly conducted by CTTC - Centre Tecnològic de Telecomunicacions de Catalunya and by Tom Henderson, professor of University of Washington. In three different phases, several enhancements have been added to the previous ns-3 models:

- Improvements of Wi-Fi Clear-Channel Access (CCA) model;

- Introduction of new indoor and outdoor propagation models, e.g. ITU InH channel model;
- Development of Duty-cycle and Listen-Before-Talk (LBT) modes for LTE;
- Addition of indoor and outdoor scenarios defined in [12];

The results obtained in these phases resulted in a Wi-Fi Alliance contribution to 3GPP RAN1 in November 2015 and in August 2016.

Thereby, in simulations this coexistence module provides the addition features to complete and enhance the LTE and Wi-Fi modules. It has to be clarified that the module is finalized for LAA technology proposed by 3GPP, while other unlicensed technologies as LTE-U, not working with Duty-Cycle or LBT model, do not have a proper ns-3 mode.

In the following figure, it is shown the LBT design as implemented in the simulator. The LBT Access Manager allows to modify parameters such as Energy Detection (ED) using several thresholds above which the LTE senses the channel as occupied.

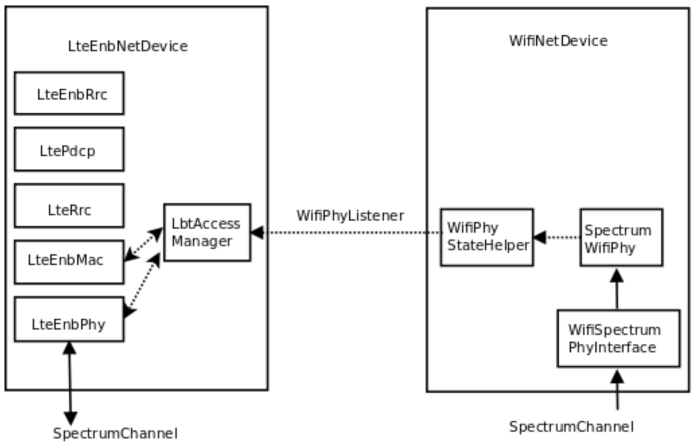



Figure 5.5 LBT design implementation in ns-3

The class called *LbtAccessManager* is the implementation of listen-before-talk and exponential back-off according to 3GPP RAN 1 design [24].

For the simulation of a coexistence scenario, in addressing the problem of interference it has been demonstrated by a study of Università di Firenze that the IEEE 802.11 signal can be modelled as additive Gaussian noise [25].

Following the guidelines in [12] there are different available classes of traffic for the coexistence scenarios: small file transfers, voice flows, constant bit rate streams. It is possible to choose among three types of application: varying the argument –

transport=<mode> it can be select either FTP over UDP (*Ftp*), FTP over TCP (*Tcp*) or constant bit rate UDP (*Udp*).

```
./waf --run "laa-wifi-indoor --transport=Ftp ..."
./waf --run "laa-wifi-indoor --transport=Tcp ..."
./waf --run "laa-wifi-indoor --transport=Udp ..."
```

The *Ftp* traffic model is the implementation of FTP Model 1 suggested in Annex A of TR36.889 and presented in TR36.814. The files arrive, in the network, for transfer according to a Poisson process characterized by a certain $\lambda$ value that determines the intensity of the traffic with its increase. In fact, a new file arrival takes places every $1/\lambda$ second on average.

This traffic model will be the one used in the following simulation session, because of its performance and possibility it offers to correctly evaluate a coexistence indoor scenario. The *Tcp* option instead gives the support to substitute the UDP transport protocol with TCP.

The Udp transport mode provides a full buffer traffic model, using constant bit rate streams. Its configuration in the simulator is:

```
--transport=[Udp]
    whether to use 3GPP Ftp, Udp, or Tcp
--udpPacketSize=[1000]
    Packet size of UDP application
--udpRate=[75000000bps]
    Data rate of UDP application
```

In simulation, the use of Udp traffic can cause the full occupation of the channel and its saturation with consequences of denied service for some UEs.

## 5.4 Simulations

The aim of the simulation phase of this thesis is to provide helpful results to better understand the features of LTE Licensed Assisted Access and the enhancement offered by such technology.

First of all, it will be addressed the coexistence issue, conducting simulations in a scenario with the compresence of Wi-Fi and LTE sharing the same channel at 5 GHz band. The behaviour of LAA will be studied through charts of Cumulative Density Function, comparing the effects on throughput and latency of two cases: on the one hand two different operators (LAA and Wi-Fi), on the other hand two operators both Wi-Fi.

Once the coexistence is analysed, then the attention will be given to the performances that can be achieved using a bandwidth of 20 MHz in the unlicensed spectrum as a supplemental downlink for an anchor on the licensed band. This means that the simulated configuration will be a two carrier-aggregation (2 CA) with a PCell in licensed spectrum (2100 MHz or 2600 MHz) and a SCell in unlicensed spectrum (5180 MHz).

Due to a current limitation of the software used for the simulations, all the configuration implemented (SISO, MIMO 2x2, MIMO 4x4) will use a 64QAM modulation scheme, because there is no possibility to implement 256QAM yet.

For the same reasons of limited implementation, it is not possible to overcome the number of 2 carriers in CA so that it is not possible to simulate the same conditions seen in the trials performed by Qualcomm with 40 MHz bandwidth in unlicensed.

Really interesting for this work is to compare the performances offered by the unlicensed spectrum with the ones offered by the standard LTE in licensed spectrum; performances that will be studied above all in terms of average user perceived throughput. For the licensed spectrum, the choice of using the band 1 (2100 MHz) instead of the more common band 3 (1800MHz) it is due to the non-feasibility of the second within the channel model ITU InH that can be applied in the range 2-6 GHz.

### 5.4.1 Wi-Fi Coexistence

First simulations that have been carried out illustrate the behaviour of LBT mechanism for a fair coexistence of LTE with Wi-Fi system. They share the same channel – number 36 for Wi-Fi – at frequency 5180 MHz with a bandwidth of 20 MHz. The following results correspond to the reference deployment scenario with 3 eNBs and 20 LAA UEs, 2 Wi-Fi APs and 16 STAs. The position of APs and eNBs is fixed at a height of 25m, middle of the shorter wall, and there is a shift between the different operators of 5m.

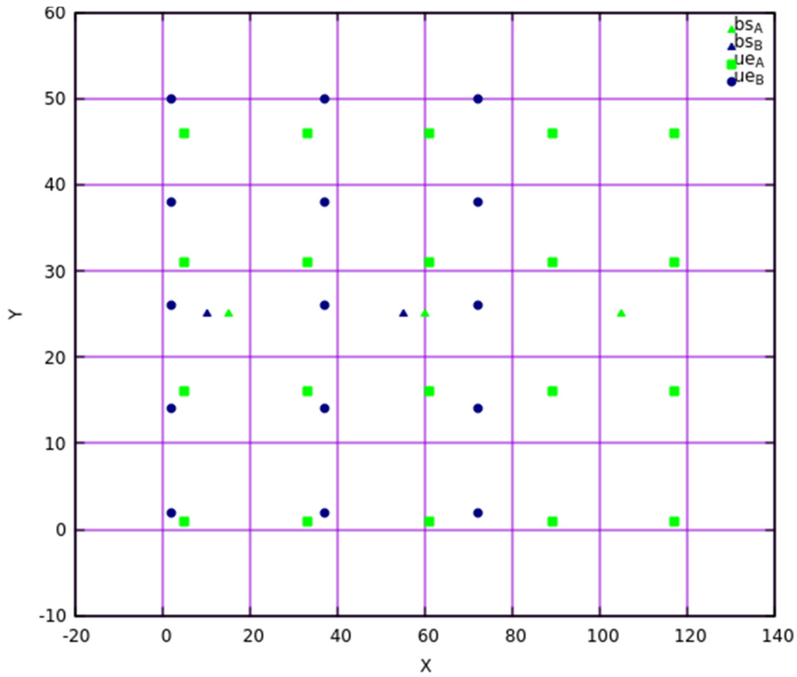



Figure 5.6 Reference scenario

This choice of deployment with 3 eNBs and 2 APs is due to the trial of studying a case with an eNodeB with minor interference due to the proximity of other operators.

The position of the users is static: the absence of mobility makes it possibile to reuse the same scenario for licensed spectrum, with no diversity in channel model and path-loss values of UEs. In such a way, it is possible to consider the same scenario with eNBs that work in licensed (2100 MHz and 2600 MHz) and unlicensed bands (20 MHz at 5 GHz band) in separated simulations, so that the performance results obtained in unlicensed simulations can be added to the licensed ones as a supplemental downlink to achieve higher throughput. In order to do that, it is fundamental to prove the fairness of the coexistence mechanism adopted by LTE Licensed Assisted Access.

Hence, the simulations produce as output the Cumulative Density Function (CDF) of the throughput in an interesting comparison between the situation of two different operator: on the one hand LAA and Wi-Fi operators as presented in the reference scenario, on the other hand two Wi-Fi operators.

In this way, it is possible to observe the impact that LTE LAA has on Wi-Fi.

Therefore, for *Energy Detection Threshold* = -62 dBm the charts describe these two deployments in three different cases of lambda value.

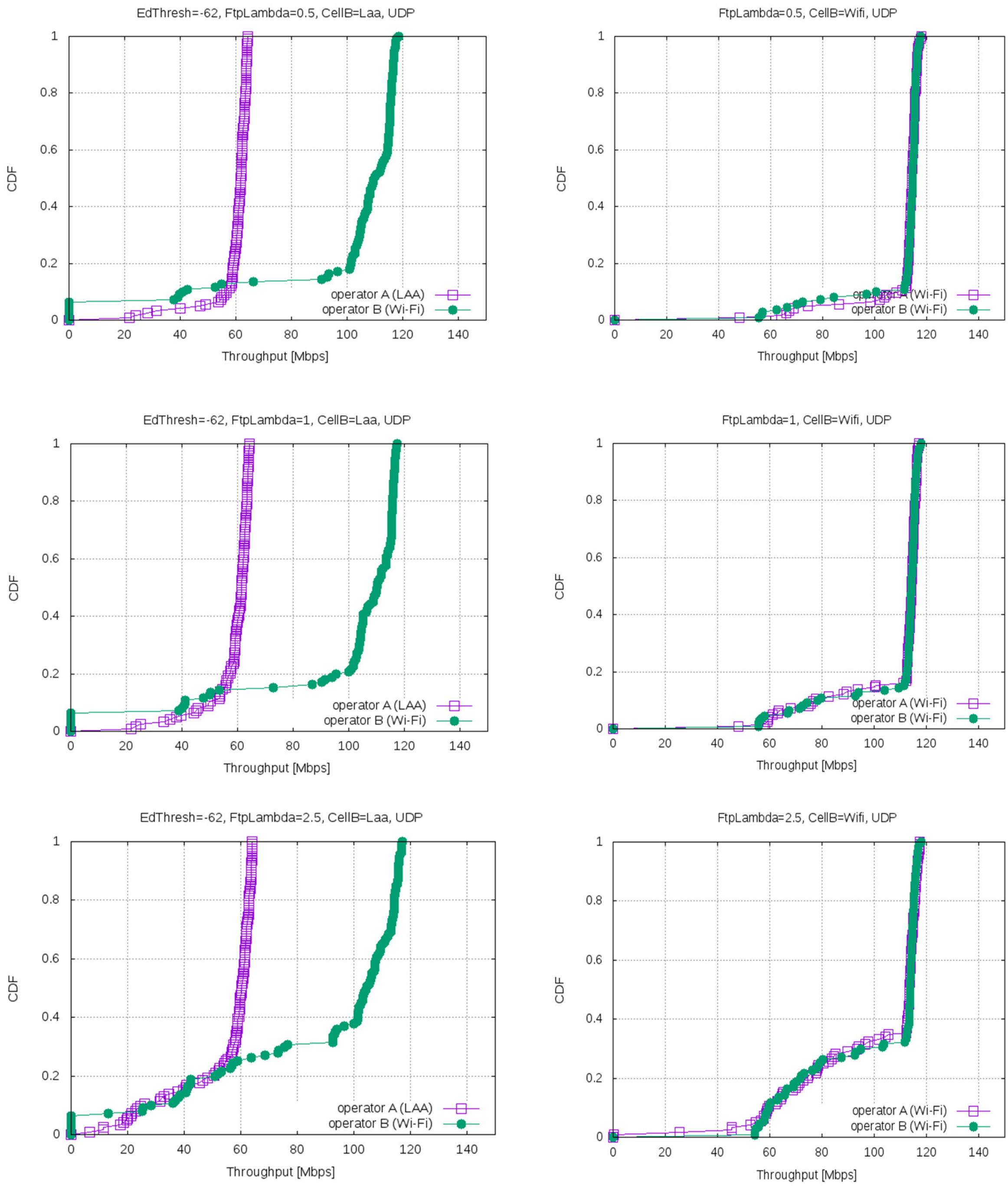



Figure 5.7 CDF of throughput for Energy Threshold -62dBm, at λ 0.5, 1, 2.5

It can be observed in general that the LBT mechanism implemented in the ns-3 simulator provide LTE users with a fair coexistence tool. In fact, Wi-Fi performances are mainly respected also with the introduction of an operator LAA instead of a Wi-Fi operator. It appears from the figures that the performances of both Wi-Fi and LTE LAA are worse corresponding to higher values of $\lambda$, i.e. to higher traffic intensity.

For this first case of energy threshold, it is presented also a comparison of another performance indicator such as the latency.

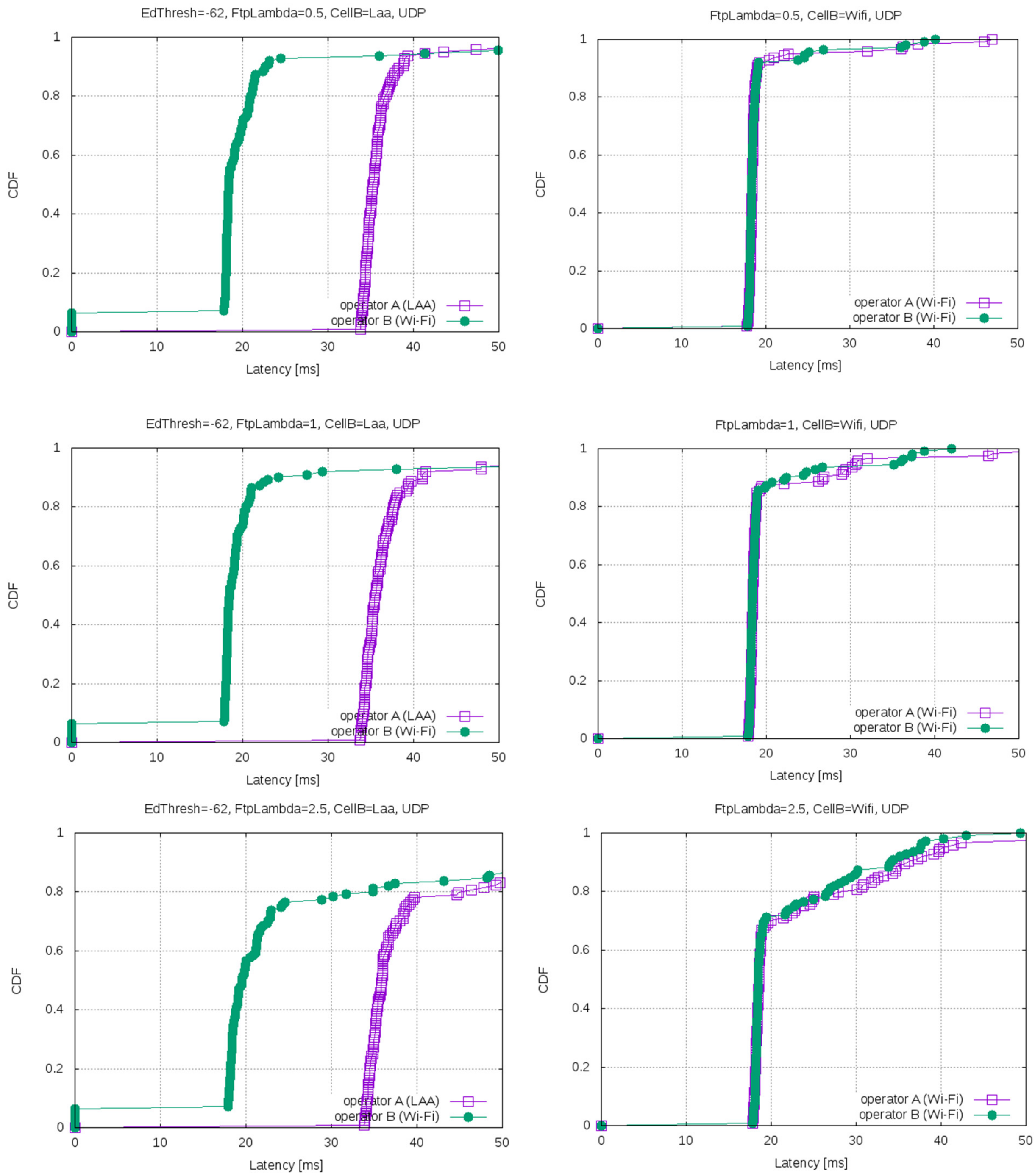



Figure 5.8 CDF of latency for Energy Threshold -62dBm, at $\lambda$ 0.5, 1, 2.5

It can be noted that LAA has a high latency in comparison with Wi-Fi's one, but it is still under the limits required for a phone call. It is interesting to compare LAA using LBT with LTE using DutyCycle as *ChannelAccessManager*.

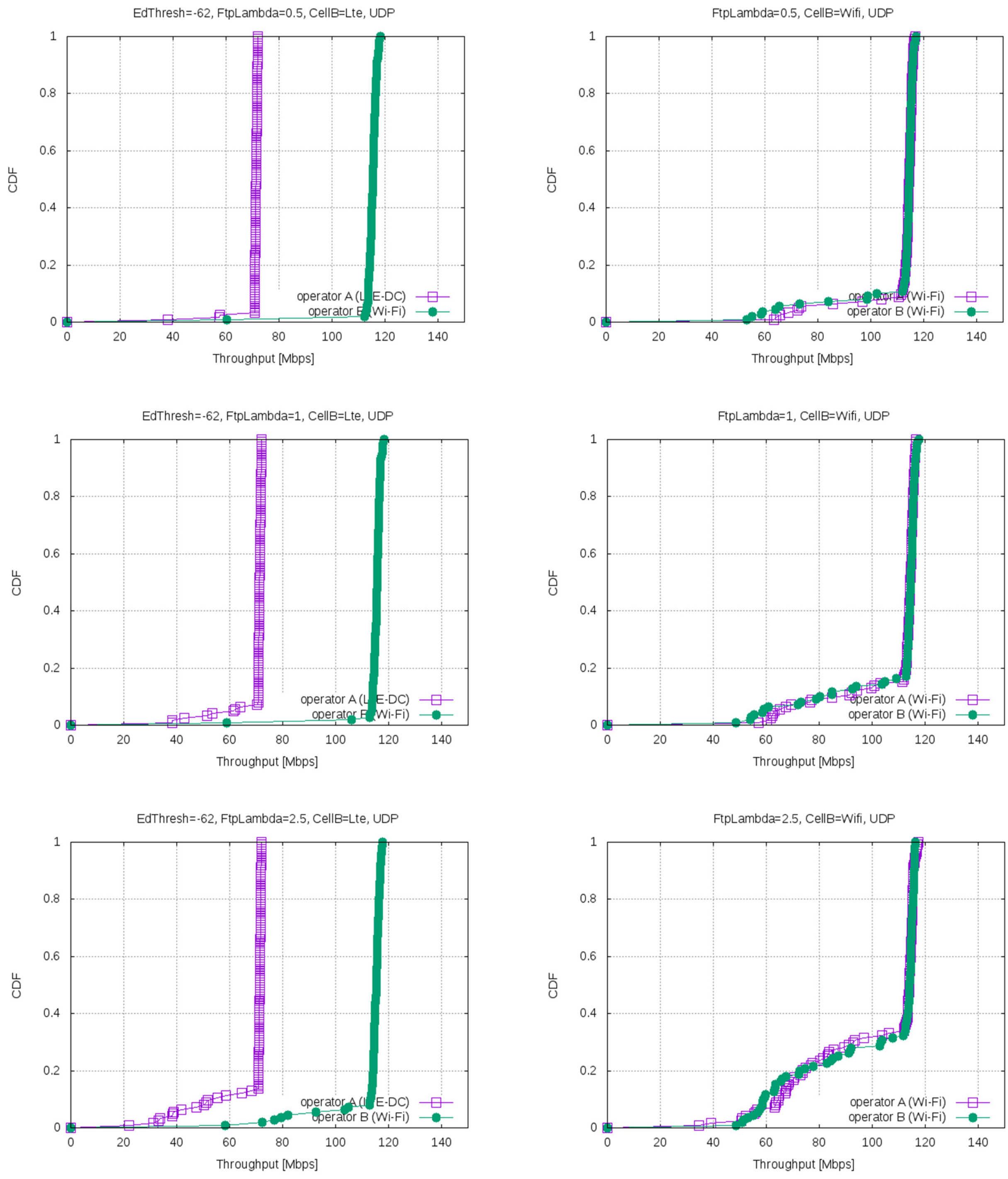



Figure 5.9 CDF of throughput in LTE at $\lambda$ 0.5, 1, 2.5

Clearly LTE in licensed band (2100 MHz) using a duty-cycle value equal to 1, Wi-Fi performances are respected even more than the case with another Wi-Fi neighbour. LTE offers higher throughput than LAA.

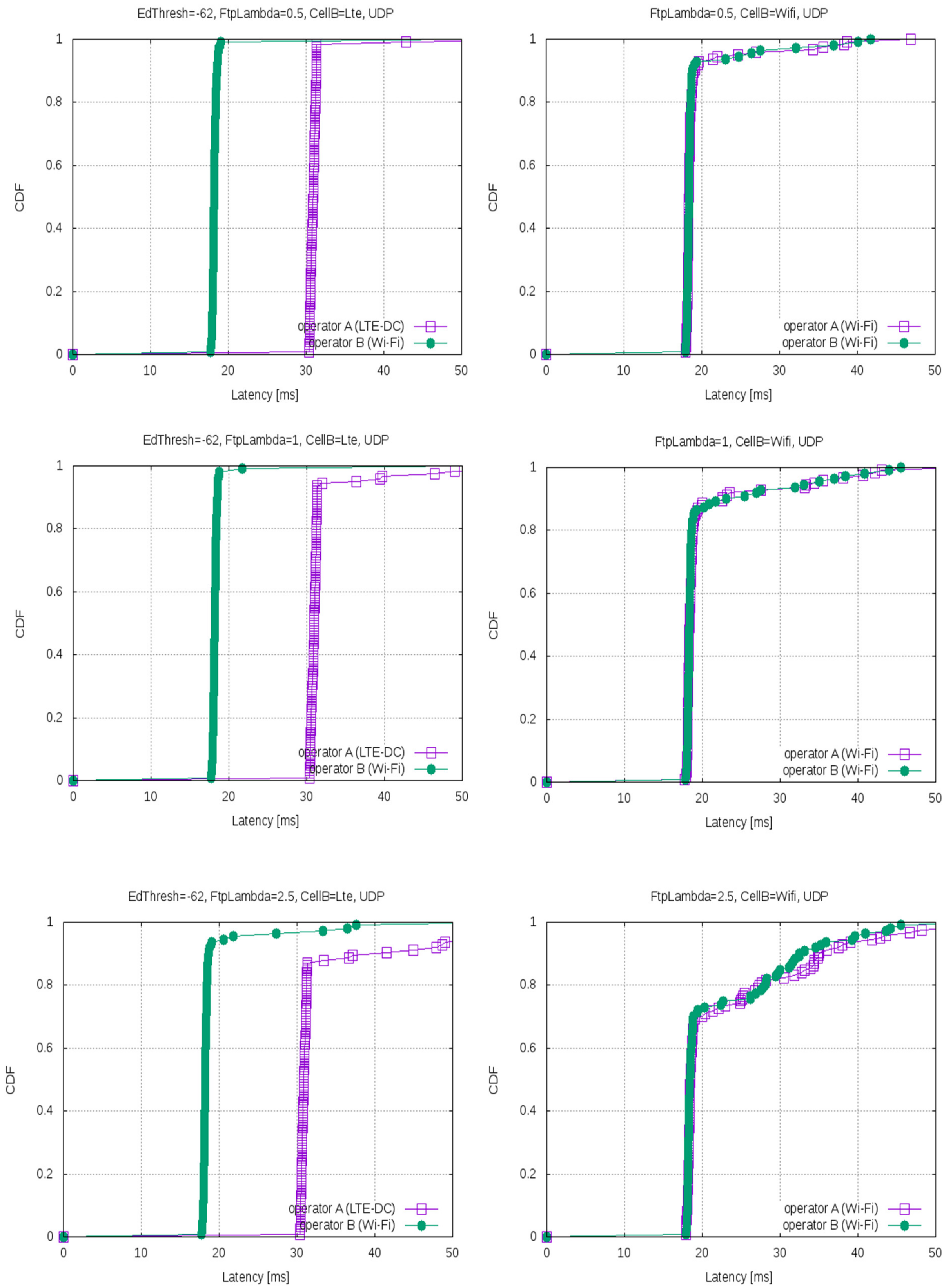



Figure 5.10 CDF of Latemcy in LTE at λ 0.5, 1, 2.5

The latency of LTE is a little lower than the one observed in LAA and the latency of Wi-Fi is respected more.

The following figures show the throughput trend of LBT mechanism in LAA changing the Energy Detection Threshold to -72 dBm.

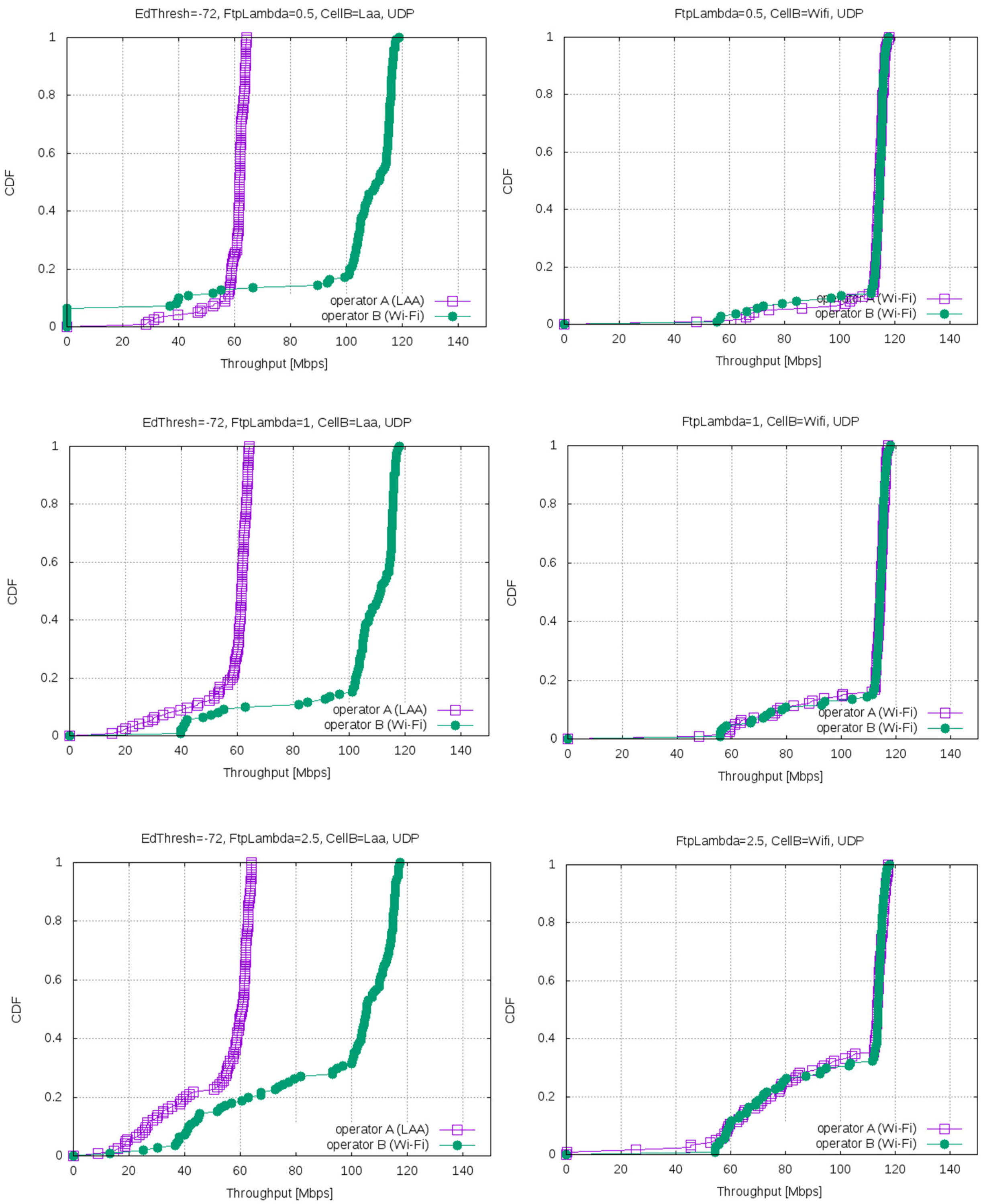



Figure 5.11 CDF of throughput for Energy Threshold -72dBm, at $\lambda$ 0.5, 1, 2.5

It represents an intermediate case, if compared with the other two energy detection thresholds cases: however the differences among these situations are really slight.

Then, the results for lowering the energy level up to -82 dBm.

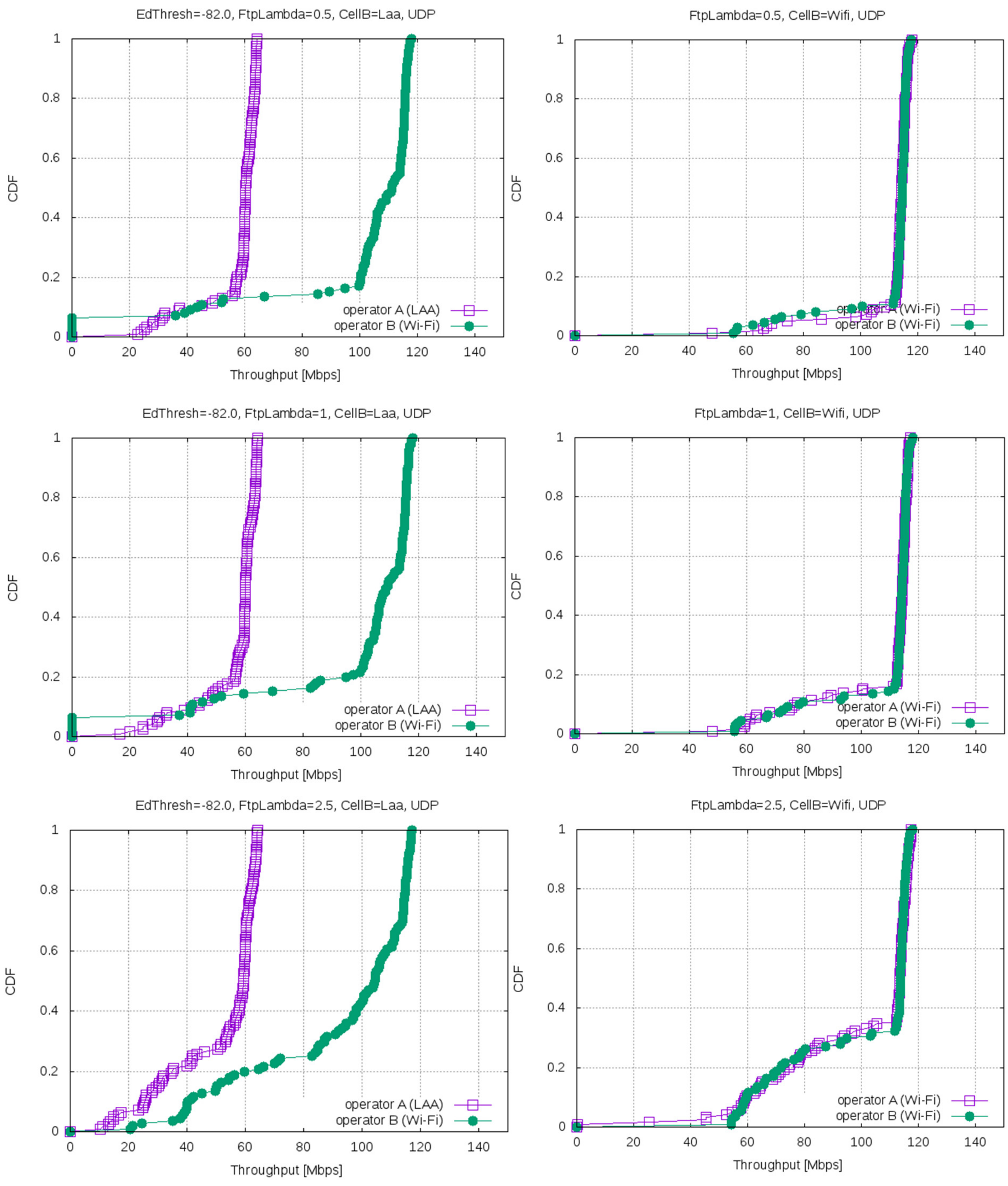



Figure 5.12 CDF of throughput for Energy Threshold -82dBm, at λ 0.5, 1, 2.5

Thereby, the CDFs of these three cases reveal that the use of a different threshold in the LBT mechanism can affect the throughput performances of both LAA and Wi-Fi systems. In particular, it can be observed that a level of -82 dBm makes the LAA trend worse, not going to increase considerably Wi-Fi system. Hence, it appears that a threshold of -62 dBm it is sufficient for respecting Wi-Fi transmissions; the simulations with energy threshold of -72 dBm offer performances in the middle between the two other cases.

These results confirm the fairness provided by LBT mechanism for the coexistence of LAA and Wi-Fi: the introduction of LAA introduces a bit of degradation of the performances but the throughput level of Wi-Fi remains acceptable.

It is worth analysing also the effects of different traffic loads determined by the $\lambda$ values used. For all the cases of energy thresholds, it is clear that with a higher traffic load – due to high $\lambda$ (2.5) – the performances deteriorate. So, the best case occurs when $\lambda$ is equal to 0,5.

Therefore, in the next simulations - that will be focused on LTE Licensed Assisted Access downlink average user perceived throughput - since the results obtained above, the choices of energy threshold and traffic load will consider values of -72 dBm and $\lambda$ equal to 1. In such a way, simulations will analyse a situation in the middle between the best and the worst case.

### 5.4.2 LAA Simulations

In this section, the results of simulations on LTE Licensed Assisted Access performances are presented and analysed. It is worth remembering that four different deployment scenarios are evaluated for the primary purpose of comparing the data-rate achieved using the unlicensed spectrum for supplemental downlink with the data-rate offered using entirely licensed spectrum. The results of this study can help to understand the LAA potential for future commercial deployment in the path toward 5G and ever better user experience.

The presentation of the results obtained is mainly divided in two parts: one for the reference scenario and the other for a similar scenario in stress conditions of interference. Each part is composed of the four test cases - presented at the beginning of this chapter - where the changing aspects are: spectrum bandwidths, working frequencies and MIMO configurations.

As already written, all the simulations carried out are based on the following settings.

| Parameter | Wi-Fi | LAA | LTE |
|---|---|---|---|
| Transport | FTP Model 1 | | |
| $\lambda$ | 1 | | |
| File Size | 0.5 MB | | |
| Energy Detection Threshold | | -72 dBm | |
| Dutycycle | | | 1 |

Table. 5.3 Simulation settings

### 5.4.2.1 Reference Scenario

The reference scenario of the simulation consists of

- *LAA*: 3 eNBs, 20 UEs;

  *Wi-Fi*: 2 base stations (BS) and 16 clients (STAs).

In the following figure, it is shown a representation of that scenario, already observed in the previous coexistence section, with a focus on the distribution of the SINR values.

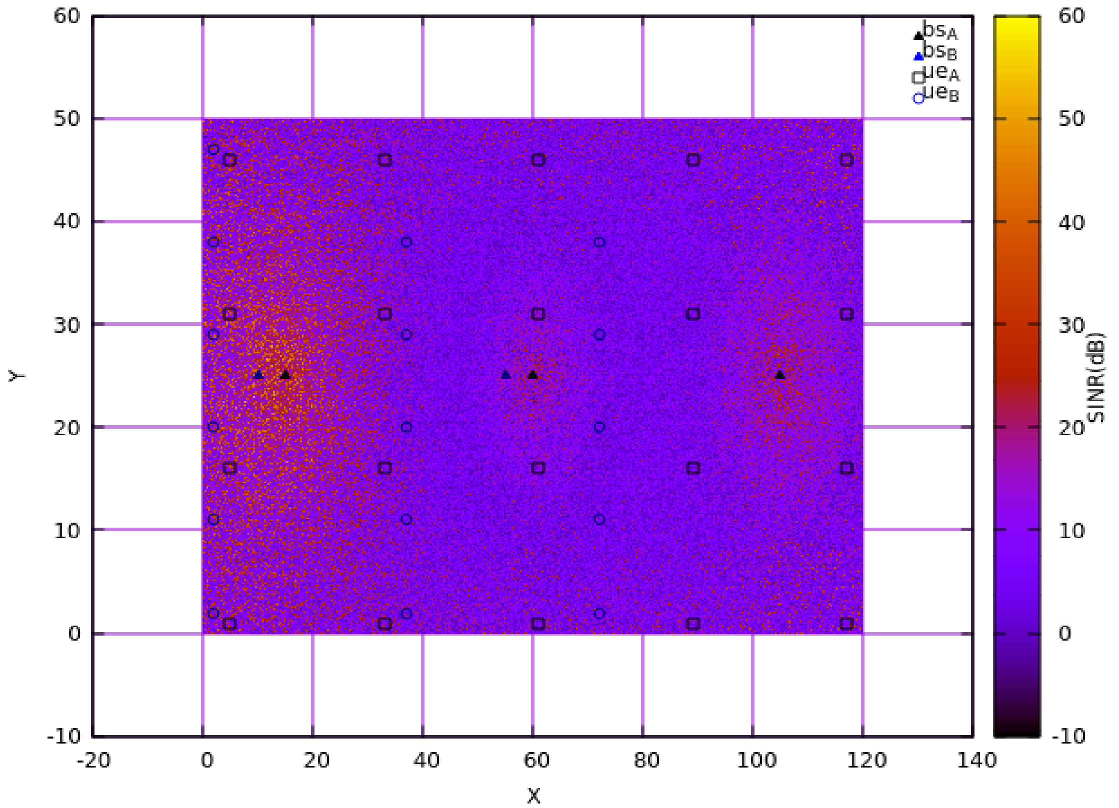



Figure 5.13 SINR distribution in the reference scenario

It can be seen that level perceived by the users inside the floor building is sufficiently high to get good values of *MCS*. For all the test-cases addressed, the settings for the transmission power, noise, gains are the following:

```
phyParams.m_bsTxGain = 5; // dB antenna gain
phyParams.m_bsRxGain = 5; // dB antenna gain
phyParams.m_bsTxPower = 18; // dBm
phyParams.m_bsNoiseFigure = 5; // dB
phyParams.m_ueTxGain = 0; // dB antenna gain
phyParams.m_ueRxGain = 0; // dB antenna gain
phyParams.m_ueTxPower = 18; // dBm
phyParams.m_ueNoiseFigure = 9; // dB
```

In such a scenario, the first configuration to be analysed is:

1) Indoor small cells, 35 MHz of aggregated spectrum bandwidth: 20 MHz in unlicensed band at 5180 MHz and 15 MHz in licensed spectrum at 2600 MHz.

The results obtained in the ns-3 simulation are exposed in the following graph, relative to the SISO configuration.

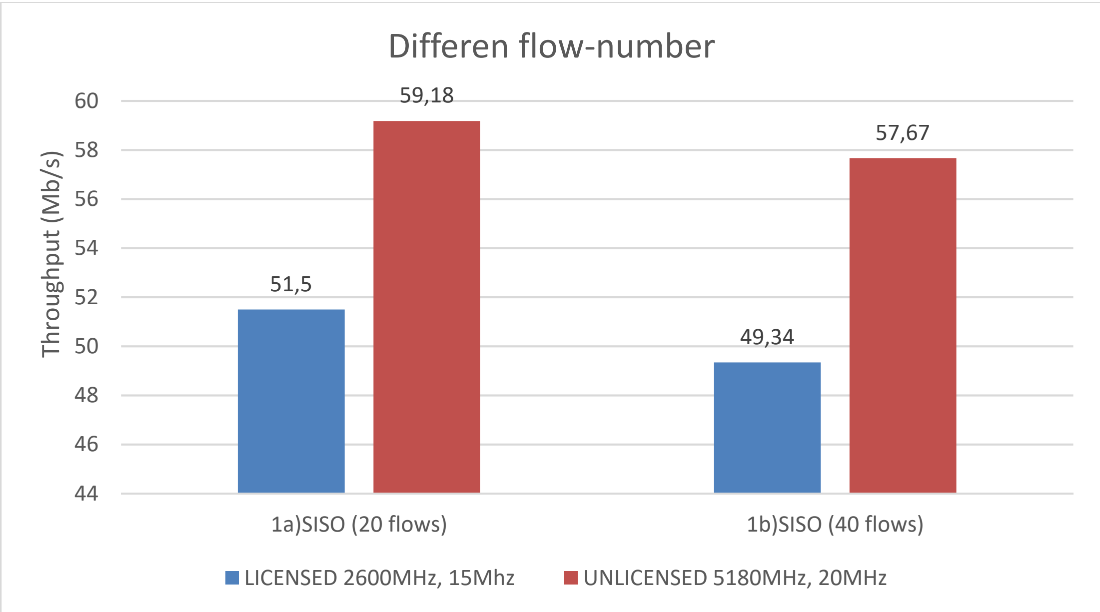



Figure 5.14 Average UPT computation for different flow number, SISO, test-case 1

In this first graph, two different comparison are shown according to the number of flows – from the flow monitor information – analysed to get the average user perceived throughput. For the simulation of the other cases it will be chosen the average on the higher number of flows to work in a worst-case hypothesis. Hence, the presentation of the data obtained by ns-3 simulator for the different configuration of antenna techniques: SISO, MIMO 2x2 and MIMO 4x4.


Figure 5.15 Aggregated throughput in LTE-LAA, SISO, test-case 1

The values obtained show that LTE Licensed Assisted Access, working in a configuration of 2 CA, in SISO, provides a LTE user with a downlink throughput equal to 107,01 Mbps.

It is difficult to directly compare, in this configuration, the data-rate offered by licensed band with unlicensed band because of the difference of bandwidth used in this case (15 MHz vs. 20 MHz).

The results obtained instead using *MIMO 2x2* on both licensed and unlicensed carriers are:

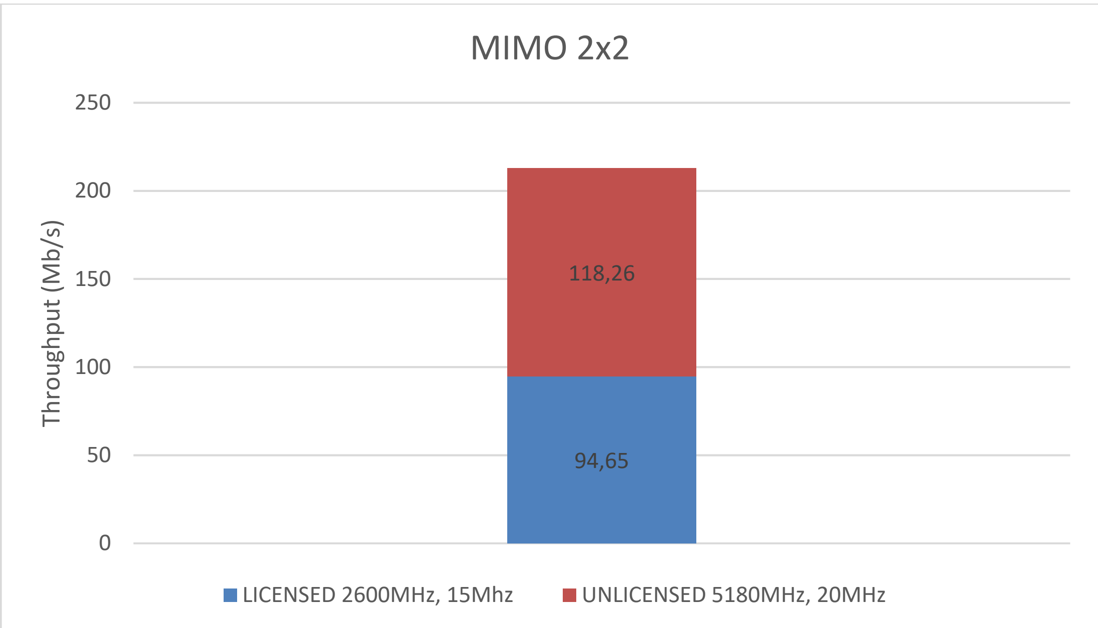



Figure 5.16 Aggregated throughput in LTE-LAA, MIMO 2x2, test-case 1

In MIMO 2x2, the throughput offered by LTE-LAA is equal to 212,91 Mbps, showing more or less a doubling respect to the SISO performance (107 Mbps).

Adopting MIMO 4x4 exclusively on the licensed band, the total throughput is:

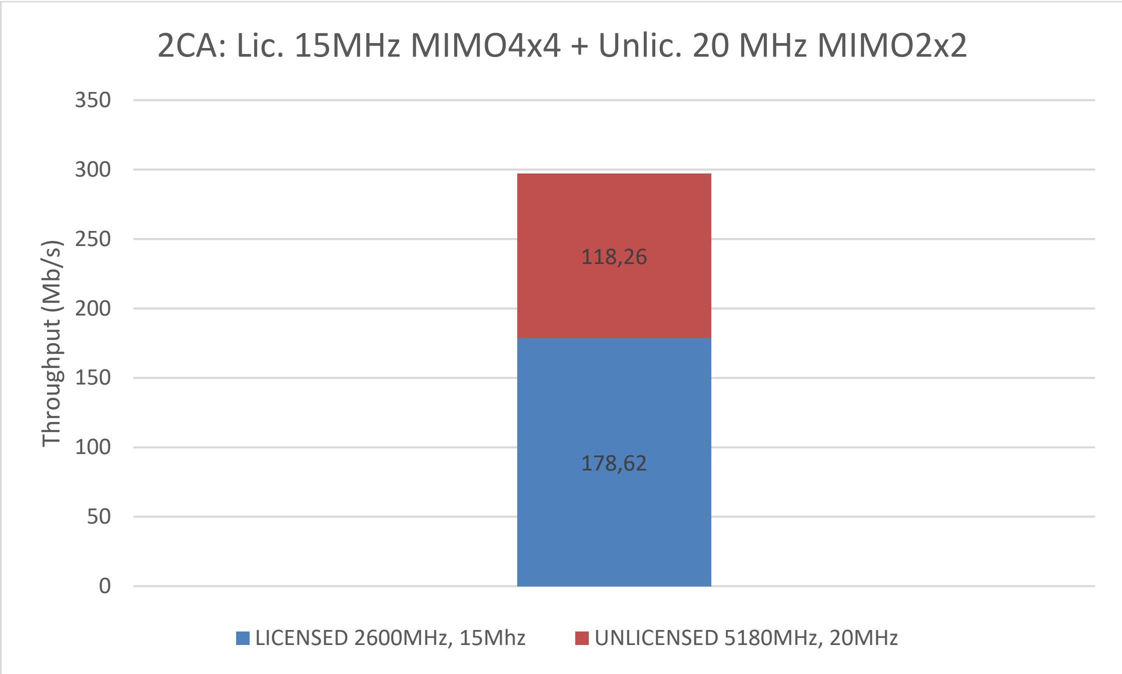



Figure 5.17 Aggregated throughput in LTE-LAA, MIMO 4x4 + MIMO 2x2, test-case 1

It offers an average user perceived throughput (UPT) equal to 296,88.

This choice of simulating different multi-antenna techniques on licensed and unlicensed spectrum is due to the current and future deployment of LAA that are not be expected to have MIMO 4x4 in unlicensed spectrum – at least in first commercialization.

A further configuration - even if not immediately foreseen in commercial deployment but interesting for futures development - it is represented by the implementation of MIMO 4x4 on both licensed and unlicensed spectrum.

In this way, there is the possibility to compare such a case with the configuration MIMO 4x4 commercially available for the licensed LTE, that will be presented further in test-case 2.

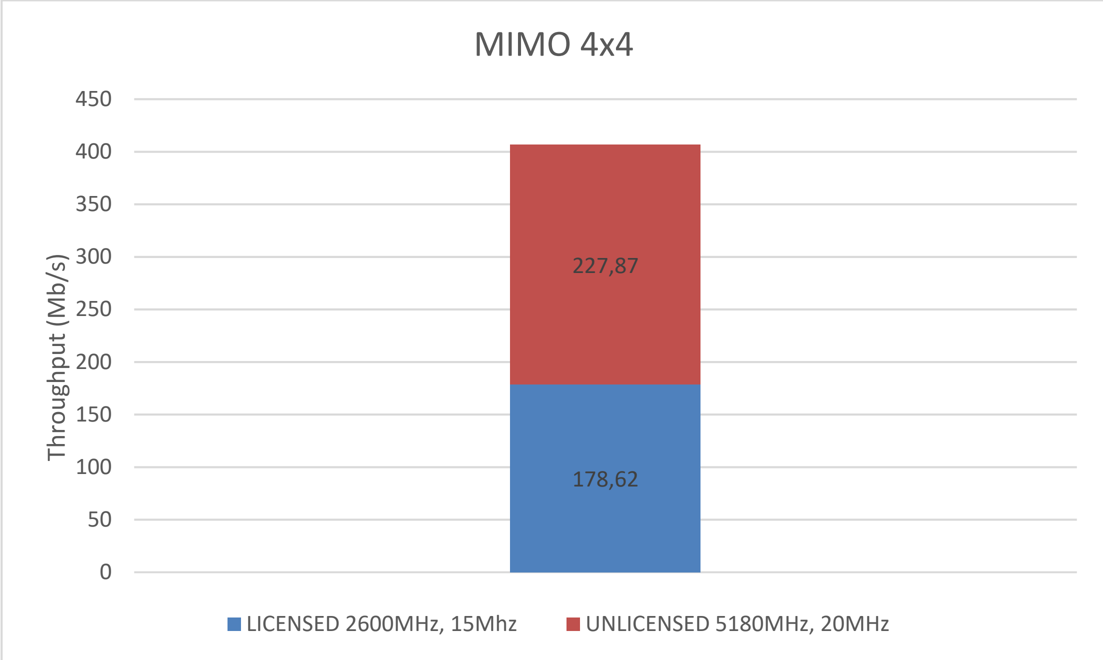



Figure 5.18 Aggregated throughput in LTE-LAA, MIMO 4x4, test-case 1

This figure shows the potential of LAA in 64QAM, with an overall UPT of 406,49 Mbps.

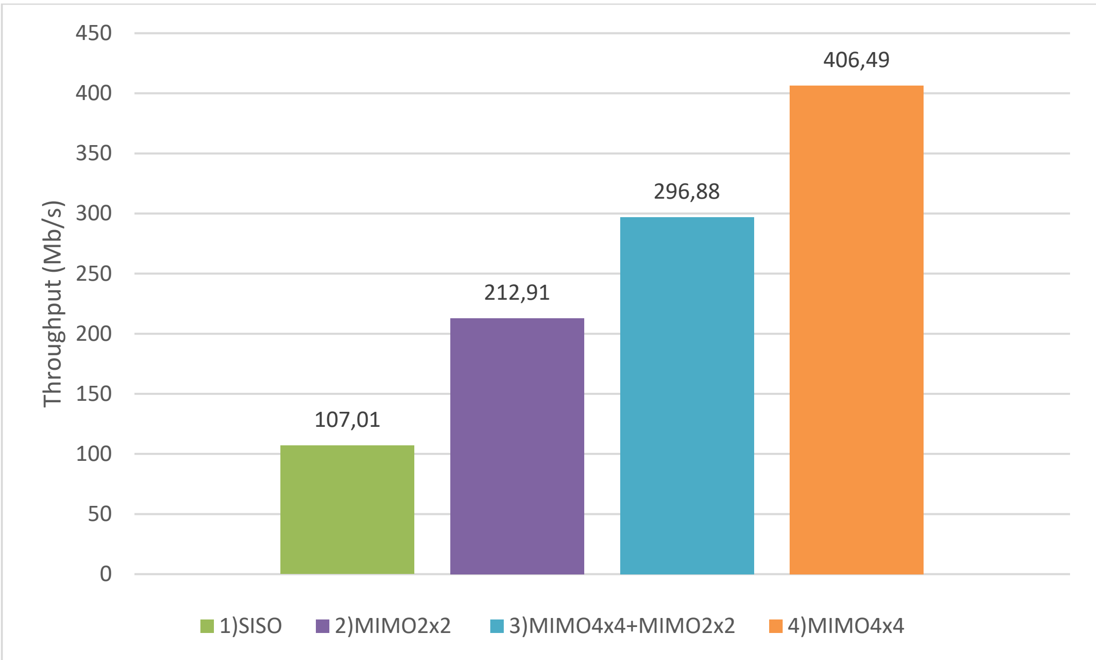



Figure 5.19 Overview, test-case 1

The second test-case, instead, is structured as it follows:

2) Indoor environment with small cells, 35 MHz bandwidth entirely in licensed bands: 20 MHz at 2100 MHz and 15 MHz at 2600 MHz;

Therefore, it offers a possibility to compare the performances of an entirely licensed deployment with the ones obtained using the unlicensed spectrum described above.

As with the first test-case, there will be presented the average UPT values in SISO, MIMO 2x2 and MIMO 4x4.

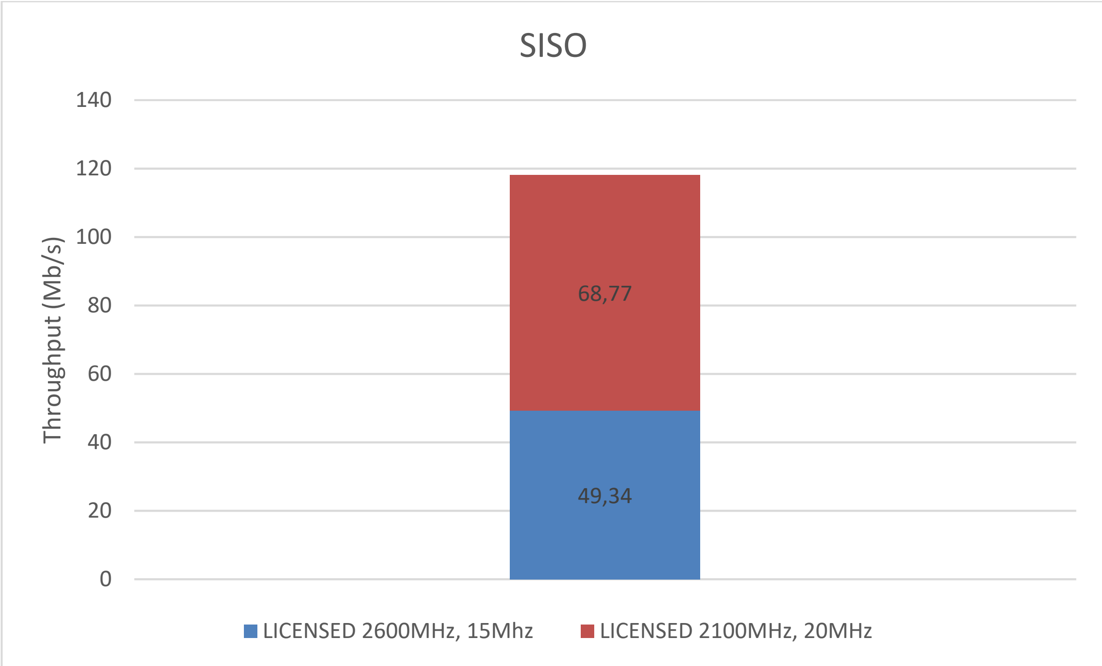



Figure 5.20 Aggregated throughput in LTE, SISO, test-case 2

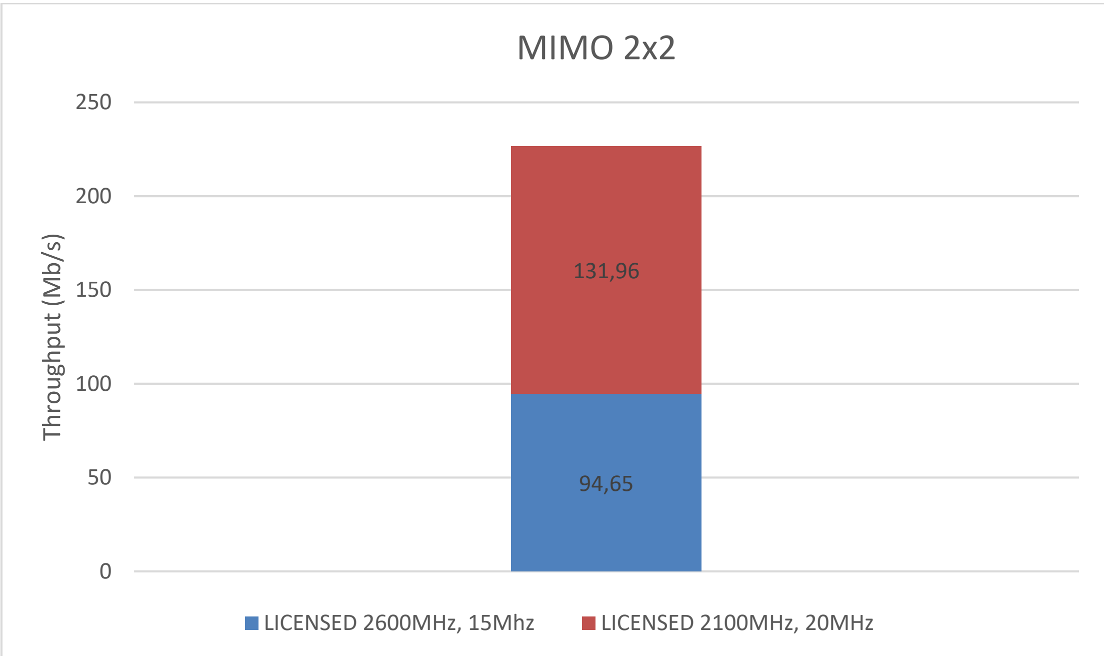



Figure 5.21 Aggregated throughput in LTE, MIMO 2x2, test-case 2

In MIMO 2x2, 35 MHz of bandwidth, LTE offers a throughput of 226,61 Mbps.

In test-case 2 with classical LTE in licensed spectrum, it is possible to consider directly the case of MIMO 4x4 on both the two carriers.

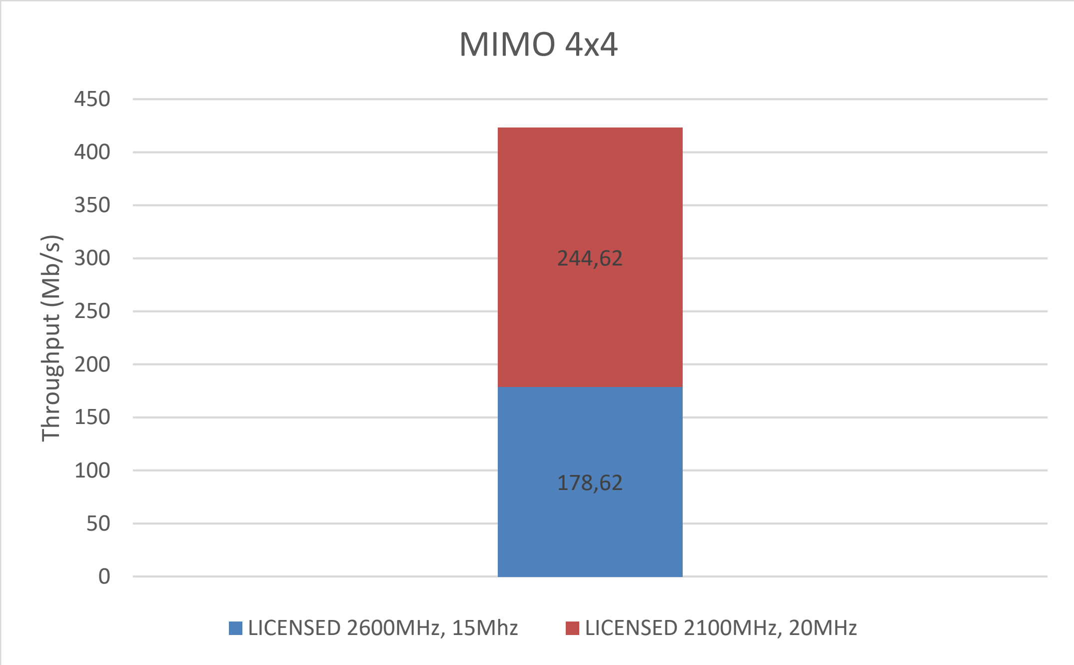



Figure 5.22 Aggregated throughput in LTE, MIMO 2x2, test-case 2

And the average UPT resulted is 423,24 Mbps.

For an overview of the results of this test-case:

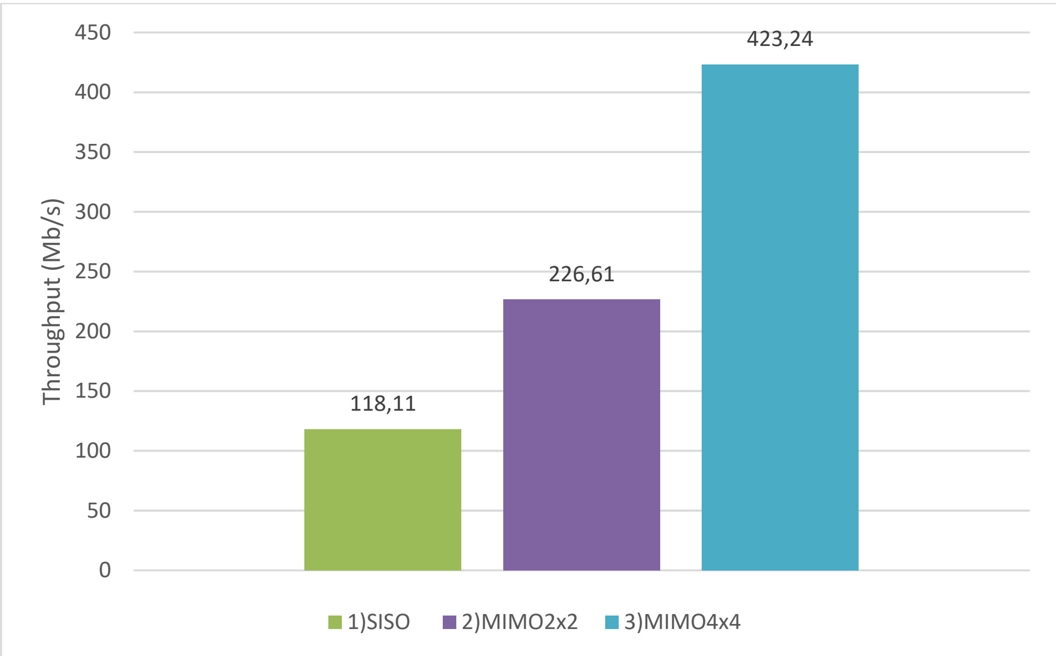



Figure 5.23 Overview of test-case 2

The results of this test-case are useful to understand the possibilities of a scenario deployment that is currently adopted by several mobile operators: in fact, in many cases there are only 15 MHz available on the band 2600MHz.

At the end of these two first cases, characterized by a spectrum bandwidth of 35 MHz, it is worth highlighting the differences of such configurations in terms of UPT.

| | LICENSED 2600MHz, 15MHz | LICENSED 2100MHz, 20MHz | UNLICENSED 5180MHz, 20MHz | LAA (L+U) 35MHz | LICENSED LTE (2CA) 35MHz |
|---|---|---|---|---|---|
| 1)SISO | 49,34 Mb/s | 68,77 Mb/s | 57,67 Mb/s | 107,01 Mb/s | 118,11 Mb/s |
| 2)MIMO2x2 | 94,65 Mb/s | 131,96 Mb/s | 118,26 Mb/s | 212,91 Mb/s | 226,61 Mb/s |
| 3)MIMO4x4 | 178,62 Mb/s | 244,62 Mb/s | 227,87 Mb/s | 406,49 Mb/s | 423,24 Mb/s |

Table. 5.4 Performance comparison between test-case 1 and test-case 2

The table above reveals that the completely licensed case offers higher data-rate, with a difference of about 9 Mbps in SISO and up to 17 Mb/s in MIMO 4x4. This represents an interesting result because it shows that the addition of unlicensed spectrum for a supplemental downlink offers data-rate that are one hand lower than the licensed ones, on the other hand they are sufficiently high to represent a valid alternative. Such an alternative could provide mobile operators with the possibility to offload data in unlicensed band; besides LAA solution could avoid interference between macro and small cells.

The second pair of test-cases is characterized by a spectrum bandwidth of 40 MHz.
The third test-case has the following configuration:

3) Indoor environment with small cells, 40 MHz of spectrum bandwidth: 20 MHz in unlicensed at 5180 MHz and 20 MHz in licensed spectrum at 2100 MHz.

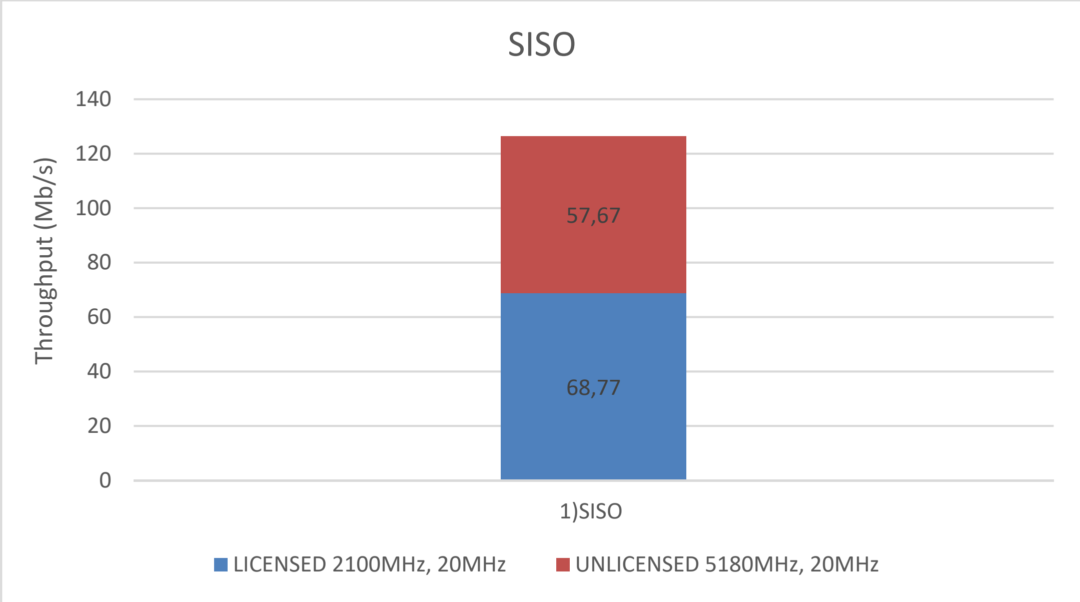



Figure 5.24 Throughput in licensed and unlicensed spectrum, SISO, test-case 3

Then, MIMO results:

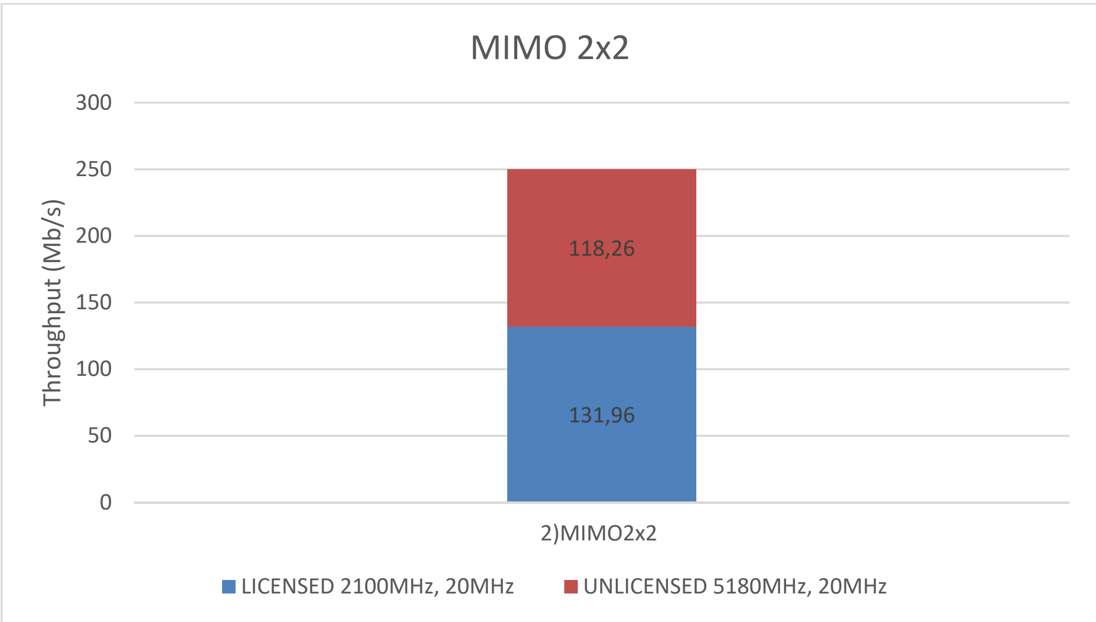



Figure 5.25 Aggregated throughput in LTE-LAA, MIMO 2x2, test-case 3

It is immediately possible to observe a difference between licensed and unlicensed spectrum in terms of throughput: the licensed band offers a data-rate higher than the one achieved in the unlicensed ban. This difference increases going to use a higher number of antennas.

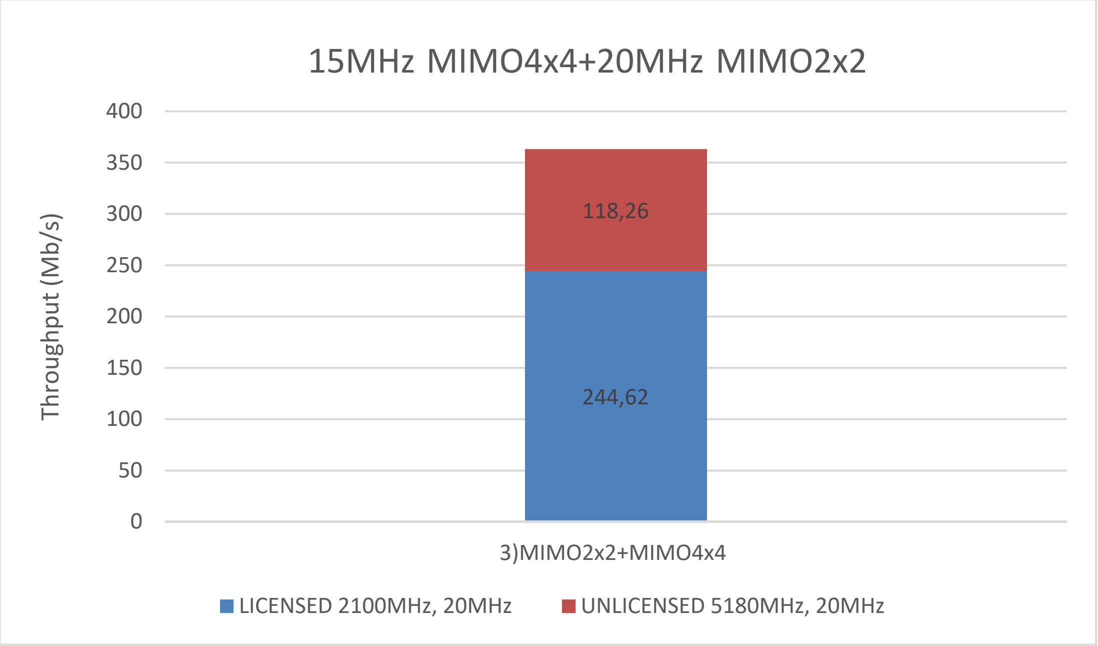



Figure 5.26 Aggregated throughput in LTE-LAA, MIMO 4x4 + MIMO 2x2, test-case 3

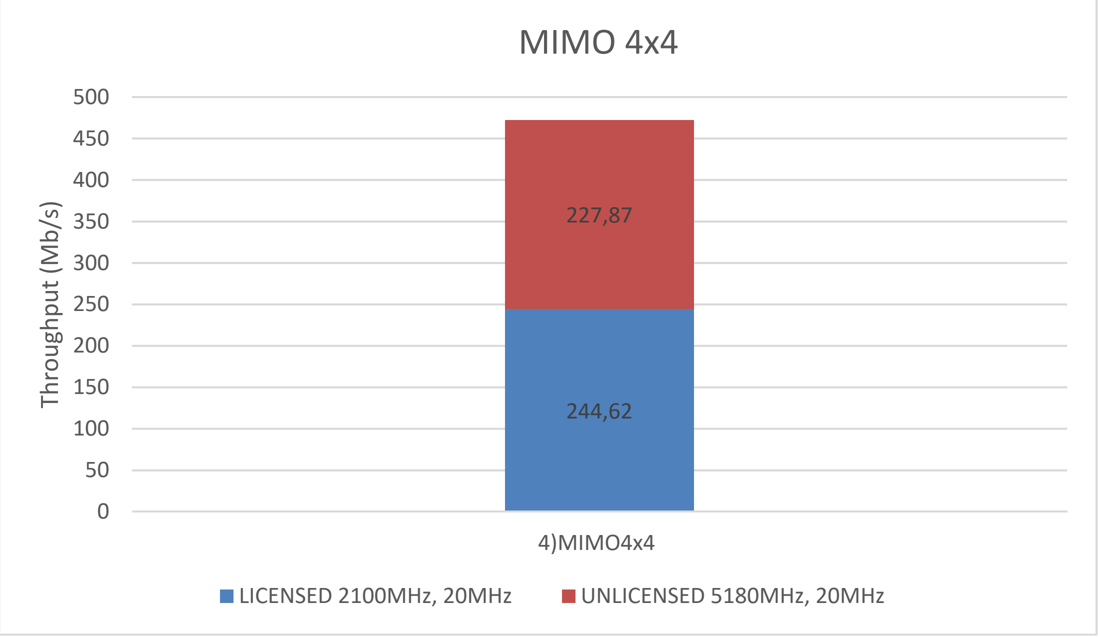



Figure 5.27 Aggregated throughput in LTE-LAA, MIMO 4x4, test-case 3

This test-case gives an indication of the throughput achievable with LAA technology fully exploiting the two carrier-aggregation.

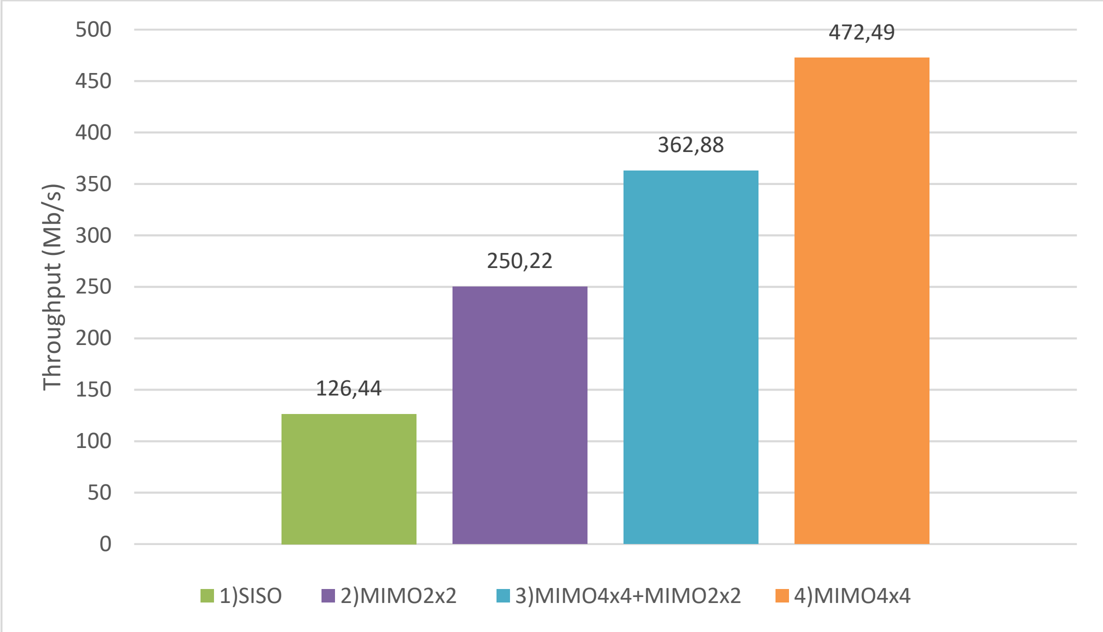



Figure 5.28 Overview, test-case 3

Finally, the last test-case in the two licensed bands B1 and B3, each one with 20 MHz of bandwidth.

4) Indoor environment with small cells, 40 MHz of spectrum bandwidth entirely in licensed bands: 20 MHz at 2100 MHz and 20 MHz at 2600 MHz.

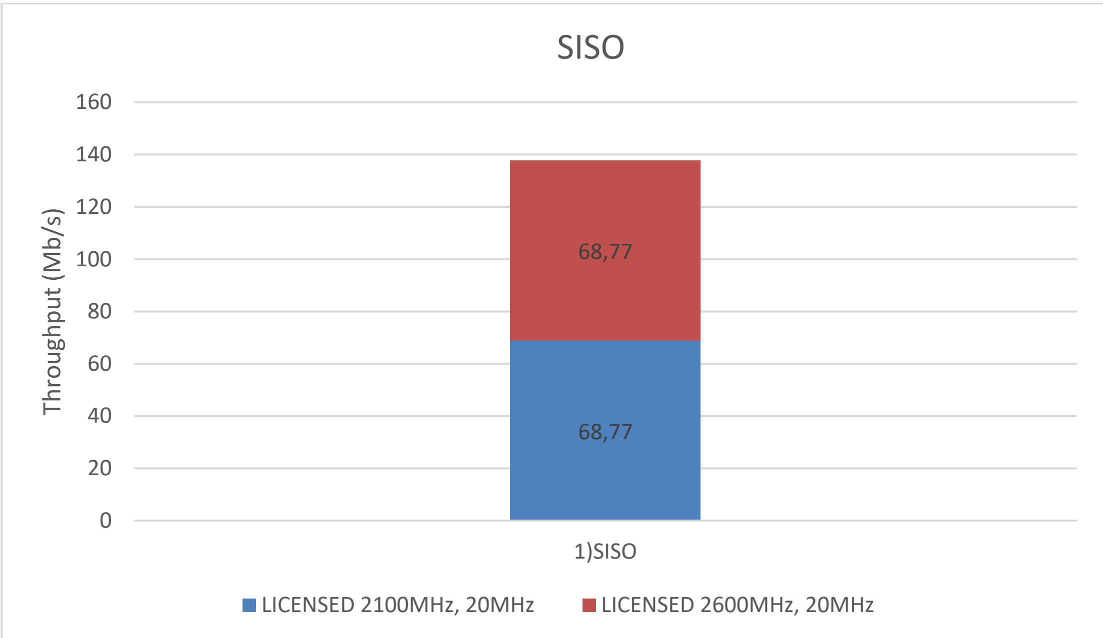



Figure 5.29 Aggregated throughput in LTE, SISO, test-case 4

It can be observed that the values of UPT obtained in the two licensed bands are the same and this is due to the same path-loss value for the two frequencies. In fact, the composition of total throughput in SISO is composed of two equal halves of 68,77 Mbps.

Thereby, for this test-case it is presented directly the final comparison of the four-possible configuration of antenna techniques. So, an overall evaluation of the performance of this test-case it is shown in the following chart.

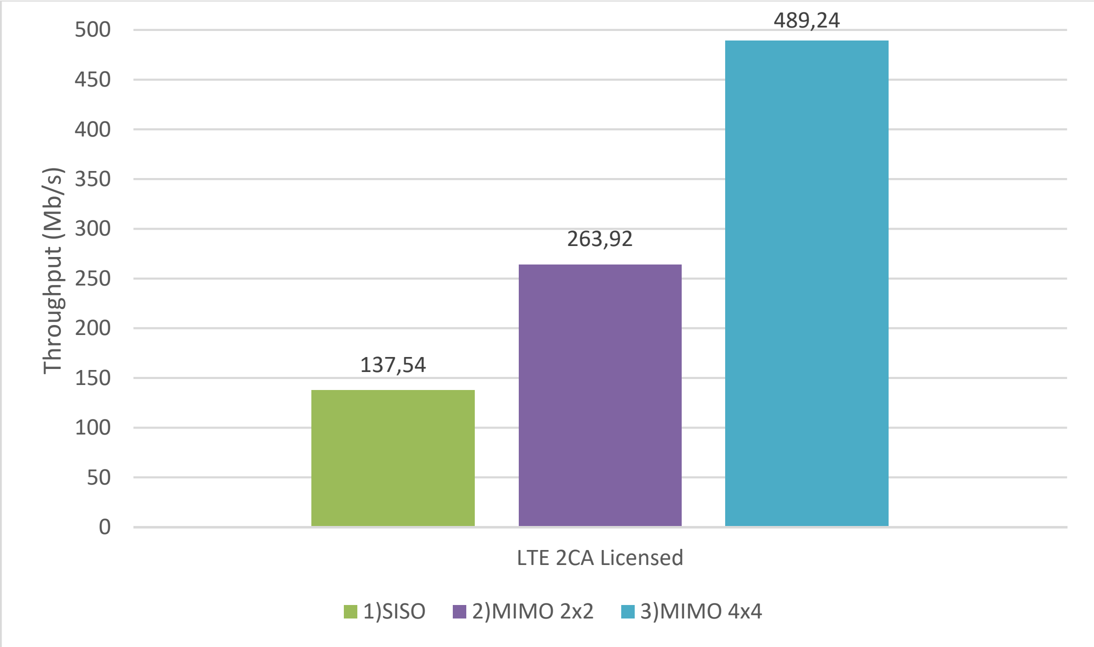



Figure 5.30 LTE overview, test-case 4

It is worth comparing the data-rates obtained by simulation of the two test-cases, as already done for the previous pair.

| | LICENSED 2100MHz, 20MHz | LICENSED 2600MHz, 20MHz | UNLICENSED 5180MHz, 20MHz | LAA (L+U) 40MHz | LICENSED (2CA) 40MHz |
|---|---|---|---|---|---|
| 1)SISO | 68,77 | 68,77 | 57,67 | 126,44 | 137,54 |
| 2)MIMO2x2 | 131,96 | 131,96 | 118,26 | 250,22 | 263,92 |
| 3)MIMO4x4 | 244,62 | 244,62 | 227,87 | 472,49 | 489,24 |

Table. 5.5 Performance comparison between test-case 3 and test-case 4

Licensed solution, again, offers the highest performance as expected; but observing the two last columns, LAA achieves interesting values that are lower of 17 Mbps at most.

#### 5.4.2.2 Adverse Scenario

All these results analysed so far are relative to the reference scenario. A further step of the simulation process carried out in this thesis consists of the study of a similar scenario with a higher presence of the Wi-Fi system.

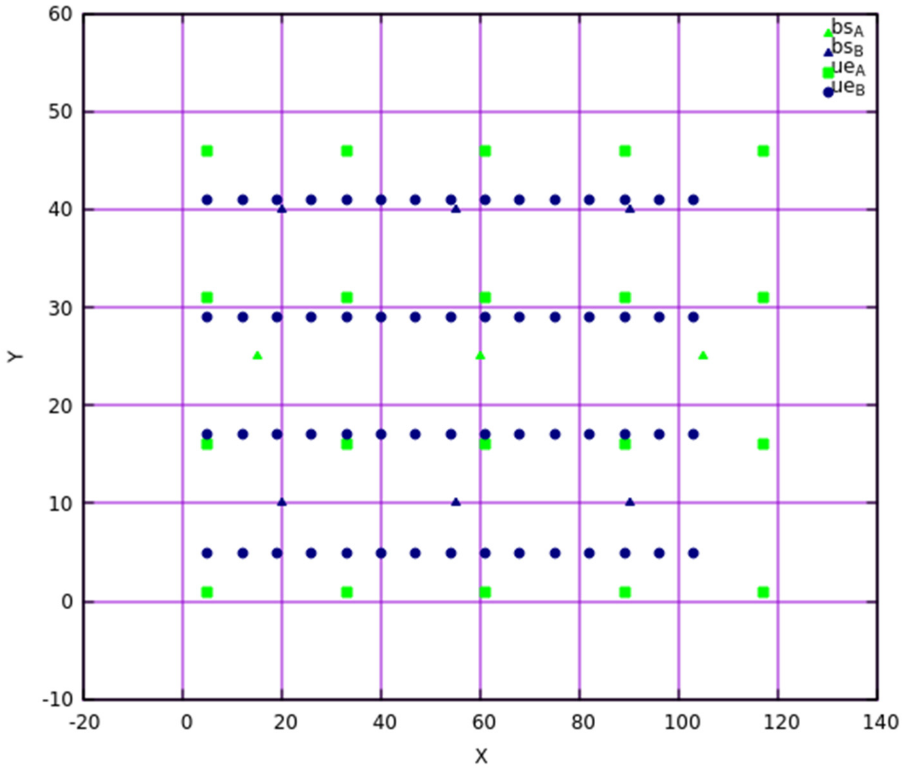



Figure 5.31 Deployment of the scenario with Wi-Fi densification

The purpose of is to observe the behaviour of LAA performance when the level of Wi-Fi interference is increased.

The scenario evaluated for a stress testing is described below:

- *LAA*: 3 eNBs, 20 UEs;

  *Wi-Fi*: 6 base stations (BS) and 60 clients (STAs)

For this scenario, the results reported by the simulations are those concerning the three different utilized bands – B1, B3 and 5GHz band – that can be useful for a comparison with the results obtained in the simulations of reference scenario.

Hence, two tables are shown containing the throughput values registered.

| | Wi-Fi Dense Scenario | | |
|---|---|---|---|
| | LICENSED 2600MHz 15MHz | LICENSED 2100MHz 20MHz | UNLICENSED 5180MHz 20MHz |
| 1)SISO | 49,34 Mb/s | 69,5 Mb/s | 56,16 Mb/s |
| 2)MIMO 2x2 | 94,65 Mb/s | 133,61 Mb/s | 114,21 Mb/s |
| 3)MIMO 4x4 | 178,62 Mb/s | 247,67 Mb/s | 226,53 Mb/s |

Table. 5.6 Performances obtained in an adverse scenario

| | Reference Scenario | | |
|---|---|---|---|
| | LICENSED 2600MHz 15MHz | LICENSED 2100MHz 20MHz | UNLICENSED 5180MHz 20MHz |
| 1)SISO | 49,34 Mb/s | 68,77 Mb/s | 57,67 Mb/s |
| 2)MIMO 2x2 | 94,65 Mb/s | 131,96 Mb/s | 118,26 Mb/s |
| 3)MIMO 4x4 | 178,62 Mb/s | 244,62 Mb/s | 227,87 Mb/s |

Table. 5.7 Performances obtained in the reference scenario

It emerges that the increased presence of the Wi-Fi has above all effects on the unlicensed bands: in MIMO 2x2 there is a difference of 4 Mbps in the throughput from the 20 MHz of bandwidth in unlicensed spectrum, while in the other two configuration there is a lower difference.

This behaviour can be observed in a better way from the graph below.

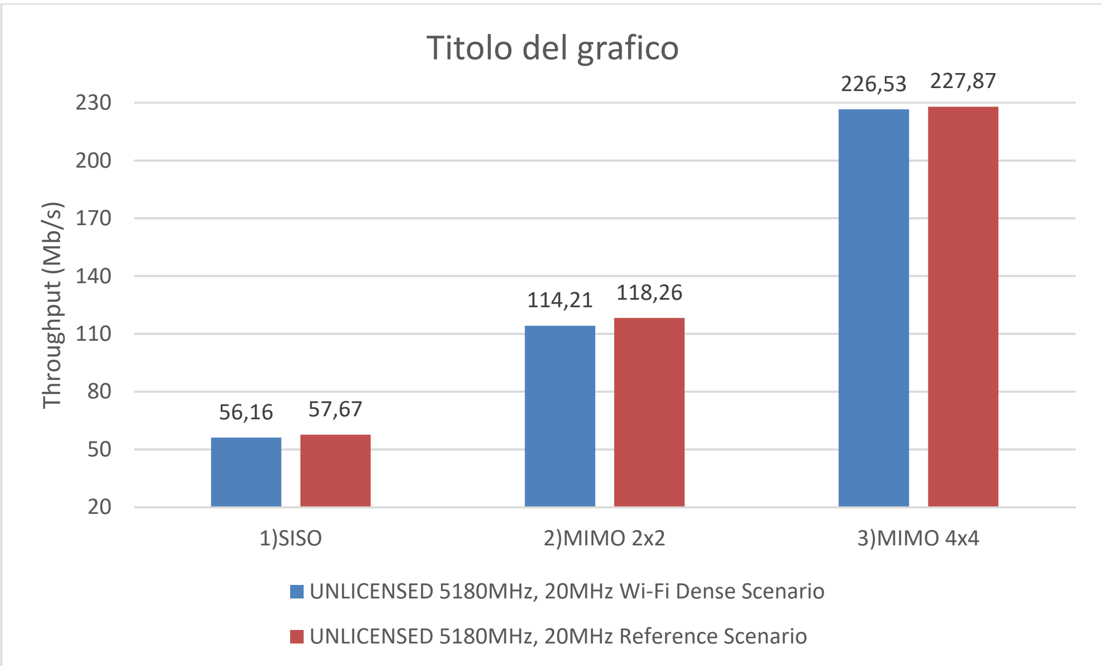



Figure 5.32 Effects of Wi-Fi densification on throughput of the unlicensed band

# 6 Conclusions

The features of LTE Licensed-Assisted Access and its potential to overcome the data rate issue - coexisting fairly with pre-existing technologies - have been discussed in this thesis. It has been described the key LBT mechanism that allows LAA to fully respect a Wi-Fi system when using the same shared channel.

Demonstrations of the effectiveness of LBT has been proved thanks to both OTA trials and ns-3 simulation results for indoor environment, where it is foreseen the majority of the service demand. Such a confirmation represents the starting point for the deployment of LAA and the possibility to globally exploit this technology for achieving higher capacity and offering better user experience.

In the simulation section, it has been conducted an extensive evaluation of the downlink performance of LAA showing that use of the unlicensed spectrum provides mobile operators with the fundamental opportunity to reach high level of throughput with low impacts on the pre-existing Wi-Fi technology. Comparing the LAA results with those offered by LTE in licensed bands, using in both situations two carriers, it has been noted that the throughput values are not so different; such a difference can be explained by the presence of LBT mechanism.

This fact promotes and encourages the use of LAA, especially considering that in the upcoming commercial deployment LAA will allow to use up to 60 MHz contiguous in the unlicensed spectrum as supplemental downlink. It means that on the one hand the use of continuous unlicensed spectrum offers higher data rate, on the other hand it gives a chance to reduce the number of antenna ports, so opening for optimization of MIMO deployment on several carriers.

Besides LAA represents an opportunity for mobile operators to offload data from licensed bands to unlicensed bands. Thereby, it implies an optimization of the scarce licensed resources. Avoiding the exploitation of licensed bands in indoor environment makes it possible to reduce the interference between the macro cell outside and small cells inside the buildings.

These multiple implications and the possibilities to reach the Gigabit LTE offered by LAA are such that its commercial deployment is expected to be by the end of 2017. Being on the path of hyper-dense networks and providing end-users with excellent reliability and enhanced experience, LAA is at this moment crucial and strategical towards 5G.

The focus of this research has been the downlink (DL) aspects of LAA already defined in LTE Release 13. Experimental results of this study are restricted to the cases of one or two secondary component carriers in unlicensed spectrum studies because of current limitation of ns-3 software and capabilities of first commercial compatible with LAA.

Future works will explore the performance of LAA technology using more carriers, higher modulation order and number of antennas through testbeds and improved simulation tools. Also the evaluation of uplink (UL) LAA - currently investigated in Release 14 that has not been frozen yet - is left to future researches.

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