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Pico Cell Range Expansion toward LTE-Advanced Wireless Heterogeneous Networks

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Abstract

The Long Term Evolution (LTE) of the Third Generation Partnership project (3GPP) has recently been investigating new deployment options to deal with sudden increase in demand for mobile broadband services. These strategies are being included in the already frozen Release 10 and in the almost finished Release 11. The final aim is to provide a significant network performance leap especially in densely populated areas and cell-edges, where other advanced technologies, including LTE Release 8 and 9 are unable to achieve the performance required by the International Telecommunications Union (ITU) to be considered 4th Generation standards (4G) of mobile networks.

Deploying low power nodes within a macro cell layout, also known as heterogeneous networks (HetNets), is a promising solution to enhance system performance overall, cell-edges and indoor coverage. Indeed this type of deployment leads to an improvement of spatial efficiency understood as bps/Hz/km^2 and achieves kind of load balance by offloading macro cell traffic to low power nodes. Nevertheless, HetNets deployment includes new technical challenges related to interference issues and throughput degradation. To handle with them, advanced interference coordination techniques are introduced. In this sense, Range expansion allows attracting more users and thus achieving performance improvement, but causes extra downlink interference which becomes severe for higher bias values and so the benefits translate into important degradation. For that, range expansion should be jointly designed with inter-cell interference coordination/enhanced inter-cell interference coordination (ICIC/eICIC) schemes to overcome these issues.

In this project, it is discussed LTE-Advance as evolution of LTE release 8, and describe the concept of HetNets, range expansion, the major technical challenges and interference coordination schemes. Finally, results are presented related to HetNets (Macro-Pico scenario) and range expansion with/without interference coordination techniques using system level simulation to evaluate their impact on system performance for different configurations.

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Chapter 1. Introduction and Problem Statement

1.1. Mobile Broadband Technologies Evolution

With around six billion mobile subscribers today [1], new services and improved device capabilities, the mobile broadband traffic and consumer data rate demands are growing at an unprecedented rate. In particular, mobile broadband traffic has seen almost exponential increases, and in late 2009 overtook voice as the dominant traffic in mobile networks [2].

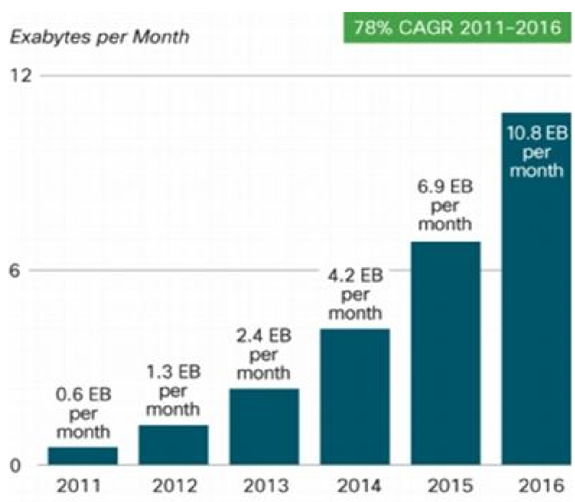


Figure 1.1: Forecast yearly data traffic.

As illustrated in figure 1.1 [3], overall mobile data traffic will almost double every year through 2014, increasing 18 times between 2011 and 2016. Mobile data traffic will grow at a compounded annual growth rate (CAGR) of 78 percent between 2011 and 2016, reaching over 10 EB (10^{15} kB) per month by 2016.

Handling with these huge volumes of mobile data traffic needs an effective response of mobile broadband networks to meet ever increasing consumer data rate demands. An efficient radio access technology is essential to achieve this, and several technologies are currently available, figure 1.2 [4] shows the evolution of mobile broadband technologies.

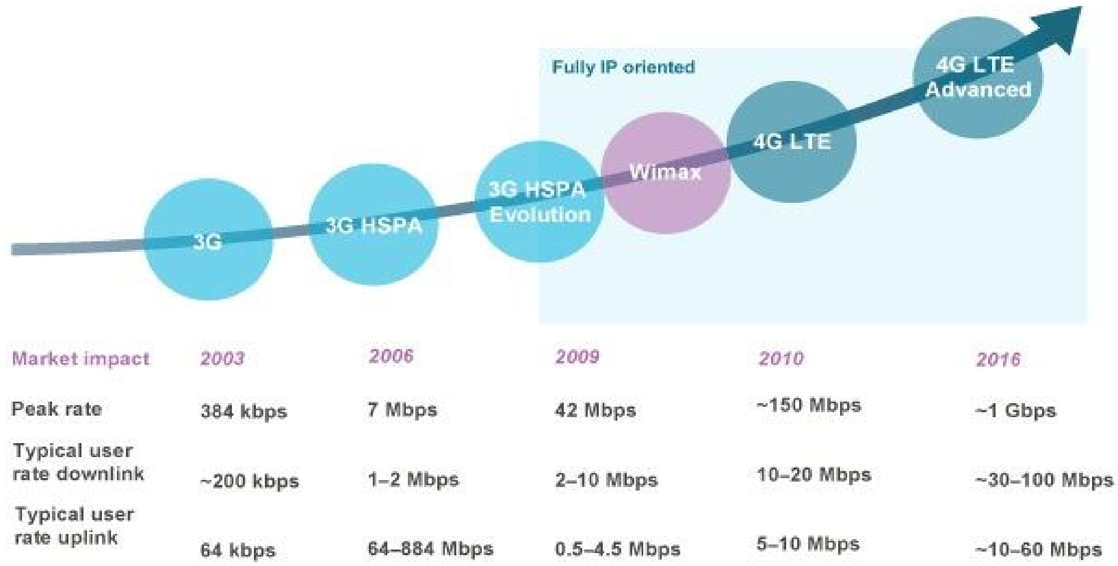


Figure 1.2: Evolution of mobile broadband technologies.

These technologies are:

1.1.1. HSPA / HSPA+

One mostly wide approach to achieve that is the third generation (3G) evolution based on HSPA (high speed packet access). HSPA / HSPA+ is a technology developed from the 3GPP UMTS (3rd Generation Partnership Project, Universal mobile telecommunications system) in 2003 to support broadband data communications with 7.2 Mbps peak data rate, also known as 3.5G. The 3GPP continued the standardization process of this system through its releases 7 (up to 28 Mbps), 8 (<48.2 Mbps), 9 (<84 Mbps) and more recently Release 10 (<168 Mbps) in what has been called HSPA+ [5]. Today, there are more than 330 HSPA-capable mobile broadband networks serving more than 375 million users worldwide [6]. HSPA continues to evolve, and it will remain a highly capable and competitive radio access solution during the next decade.

1.1.2. WiMAX

A new wireless technology has been developed by the Institute of Electrical and Electronics Engineers (IEEE) for wireless data communications. WiMAX (Worldwide interoperability for microwave access) is an internet protocol (IP) based wireless broadband access technology, also known as IEEE 802.16, which provides performance similar to 802.11/WiFi (Wireless Fidelity) networks with the coverage and Quality of service (QoS) of cellular networks, including handover in its last versions. With WiMAX, WiFi-like data rates are easily supported, but the issue of interference is lessened. However, WiMAX is popular in limited areas and a development path forward is not clear [7].

1.1.3. Long Term Evolution (LTE)

In parallel with the above mentioned technologies, LTE radio access technology has been developed by 3GPP to offer a fully fourth generation (4G)-capable mobile broadband platform, with its long development path. In 2004, a workshop was held to work on the 3GPP LTE radio interface. Requirements and design targets comprised high data rate at the cell edge, low latency in addition to the normal capacity, peak data rates of 100 Mbps and spectrum flexibility. LTE design targets were approved in 2005 [8]. By the end of 2005, 3GPP decided that LTE radio access should be based on orthogonal frequency-division multiplexing (OFDM) in downlink (DL) and discrete Fourier transform spread OFDM (DFTS-OFDM) in uplink (UL) [9], and by the end of 2007, the LTE specifications were approved [10]. Later, the work has continued on, with the addition of new features in each release of the specification. By the end of 2008 the first release of LTE specifications - LTE Release 8 - was ready. Release 9 was introduced by the end of 2009 with more features. In March 2010, LTE Release 10 [11] was introduced as a major step in the evolution of LTE. The most important features included in this release were support for carrier aggregation (CA), advanced MIMO (multiple-input multiple-output) techniques, coordinated multipoint transmission / Reception (CoMP), heterogeneous networks (HetNets), and relaying, this release has been denoted as LTE-Advanced (LTE-A) and it is recognized as a 4G system by the International Telecommunications Union (ITU). Work is ongoing now for Release 11.

Due to the high data rate which is provided by LTE releases comparing with the previous technologies, in addition to being a technology continuously evolving to meet future requirements and user expectations, it promises to be the basic future technology in the mobile broadband networks field and will occupy the first place in terms of the number of subscribers around the world in the next few years. The figure 1.3 shows the forecast subscriptions in mobile broadband networks [12].

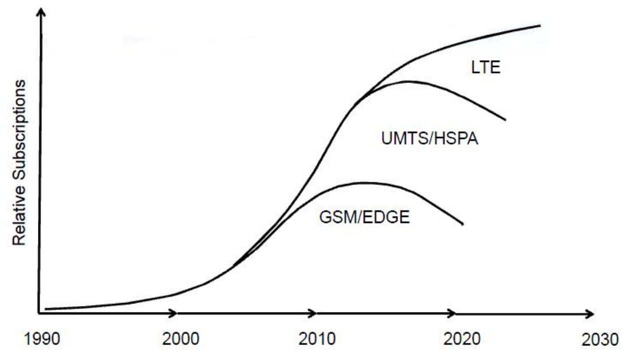


Figure 1.3: Forecast subscriptions in mobile broadband networks.

1.2. Problem Statement

The sudden increase in demand for mobile broadband services all around the world (videos, audio, online TV and other streaming services, real time multimedia services, etc.) that takes place nowadays, puts mobile network operators and researchers in a continued case of working, researching and developing to meet users requirements, improve services quality and coverage, increase data rates and capacity, increase overall cell-site performance and cell-edge data. Moreover, The International Telecommunication Union Radiocommunication Sector (ITU-R) issued in 2008 strong requirements for a mobile network to be considered as 4G, which have been named International Mobile Telecommunications-Advanced (IMT-Advanced) requirements [13].

Fulfilling 4G requirements led researchers and mobile network operators to enhance the current infrastructure by adding new technologies and improving other ones. The new modulation schemes and coding techniques allow to reach theoretical bounds, and in order to achieve that high required data rate more bandwidth is needed, the desired bandwidth in IMT-Advanced is 40 MHz and 100 MHz is included in LTE Release 10 specifications [11], these bands are unlikely to be contiguous for each single operator. Therefore, carrier aggregation (CA) techniques are needed to do so. Moreover, a higher order MIMO is also considered in order to improve spectral efficiency in terms of bps/Hz. However, since MIMO only works properly under high signal to interference noise ratio (SINR) conditions, cell edge UEs cannot take profit of it and they can only take the benefits of classic multi-antenna diversity. To deal with this issue, denser topologies (HetNets), which was included in 3GPP LTE Release 10 as one of the new features to meet IMT-Advanced requirements [14], are being investigated in conjunction of cooperative strategies and inter-cell interference coordination (ICIC), so that the cell edge spectral efficiency and the individual bps/Hz/cell/user metric are maximized.

Heterogeneous networks imply deploying new base stations with different types of transmission power, antenna patterns, backhaul connectivity, etc. According to 3GPP 36.814 [15], the local macro cell layer will embed LPNs (Low Power Nodes) placed to offload some traffic from the macro cell, overcome the problem of coverage holes and enhance the spectral efficiency at the cell edge and eventually per unit area. However, the interference is still a predominant phenomenon in such configurations. If LPNs are not installed in a hotspot, very few UEs are likely to connect to them, this would limit the gain from traffic offloading, besides since cell selection criteria are typically downlink based, macro users would generate high interference in the LPN. For that, a technique of range expansion with interference mitigation schemes is a candidate option that operators might use to extend the LPNs coverage, to further increase the number of users being offloaded from the macro cell.

This master thesis investigates the LTE Release 10 specifications, and how its new features fulfill IMT-Advanced requirements, focusing on heterogeneous networks and comprising the study of new deployment scenarios, challenges to be solved, coordination interference, and above all the technique of range expansion (RE). In particular, it has been studied and analyzed some key performance indicators of pico cell range expansion scenario with different configurations. Figure 1.4 summarizes all these objectives.

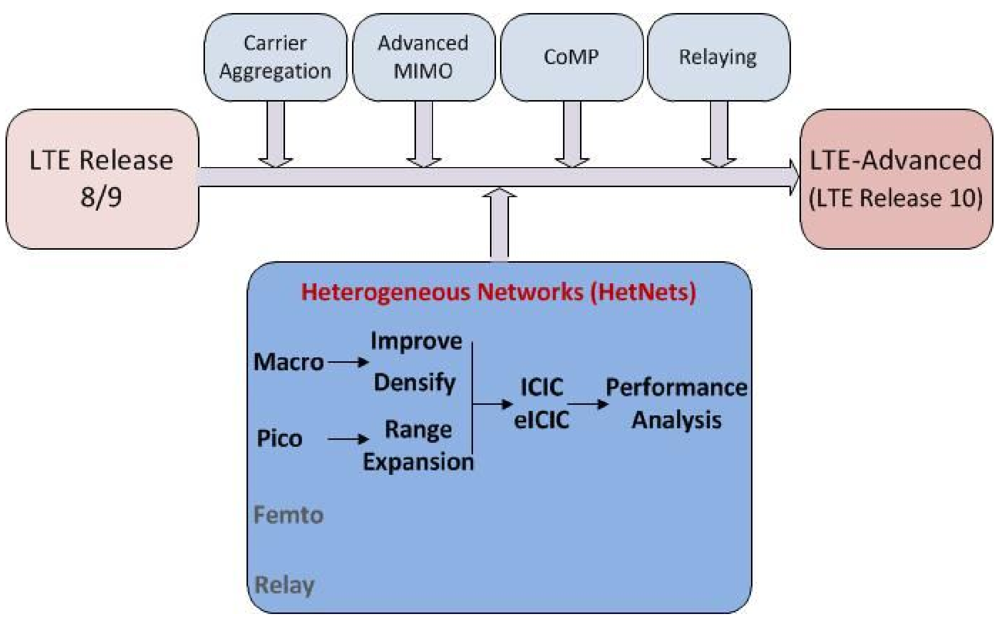


Figure 1.4: The thesis objectives.

1.3. Thesis Outline

This master thesis is divided into 6 chapters:

- The current one, Chapter 1, corresponds to the introduction describing the mobile broadband technologies evolution, general LTE background and the motivation of this master thesis.

- Chapter 2 presents an overview of 3GPP LTE evolution, including LTE Release 8, LTE Release 9 and LTE Release 10, and describes the new features of Release 10 to fulfill IMT-Advanced.

- Chapter 3 discusses HetNets comprising concepts, challenges, interference, range expansion, interference coordination, as well as HetNets deployment scenarios.

- Chapter 4 describes the LTE system level simulation (SLS) framework, its assumptions to study HetNets and macro-pico scenario configurations. In addition to present some results to validate SLS.

- Chapter 5 analyses macro-pico scenario performance with/without RE for all proposed configurations, evaluates the performance results, and reports a study of the impact of cell range expansion on HetNets.

- Chapter 6 summarizes the concluding remarks and the results of macro-pico with RE scenarios. It also proposes the future work to be done in order to continue the investigation performed in this master thesis.

Chapter 2. Overview of the 3GPP LTE Evolution

2.1. LTE Evolution

LTE has been standardized by 3GPP international standardization organization and it has gone through a number of evolutionary stages since its first proposal in 2004. After five years of continued work and research, the first specification version of its first release - LTE Release 8 - completed in March 2009.

In LTE Release 9, the research has been continued to improve system performance through developing some components such as improved functions for Home enhanced nodes B (eNodeB) such as the management of closed subscriber group (CSG, a closed Subscriber Group identifies subscribers of an operator who are permitted to access a particular Home eNodeB) and self-organizing networks (SONs), and improving features and services such as improved location services (LCS) and multimedia broadcast multicast services (MBMS). Since that, the LTE standard has been developed toward commercialization in various countries in the world [16, 17].

To further extend the performance and capabilities of the LTE radio-access technology, 3GPP initiated work on LTE Release 10 in April 2008. One target was to ensure that LTE fully complies with the IMT-Advanced requirements for 4G technologies, defined by ITU. LTE Release 10 is also referred to as LTE-Advanced, and it is important to emphasize that LTE-Advanced is not a new radio access technology, but simply the name given to LTE Release 10 and beyond [18, 19]. The following sections describe characteristics and features of LTE Release 8 and LTE-Advanced contributing to improve performance and meet the requirements, indicated in subsequent sections.

2.2. Overview of LTE Release 8

3GPP Long Term Evolution is the name given to the 3GPP standard required to deal with the increasing data throughput requirements of the market. Working groups from 3GPP RAN started to work on standardization for LTE in late 2004. By 2007, all LTE features related to its functionality were finished and by 2008 [10], most protocol and performance specifications were finished and included in Release 8. All these features, protocols, performance specifications are explained in Appendix 1.

2.3. LTE Release 10 (LTE-Advanced)

LTE Release 10, also known as LTE-Advanced, is an evolution of LTE Release 8 to further improve performance. As illustrated in figure 2.1, It includes all the features of Release 8/9 and adds several new features [11], the most important - which are discussed in the following sections – are:

- Carrier Aggregation (CA).

- Advanced MIMO Techniques.

- Coordinated Multipoint Transmission/ Reception (COMP).

- Relaying.

- Support of Heterogeneous Networks (HetNets).

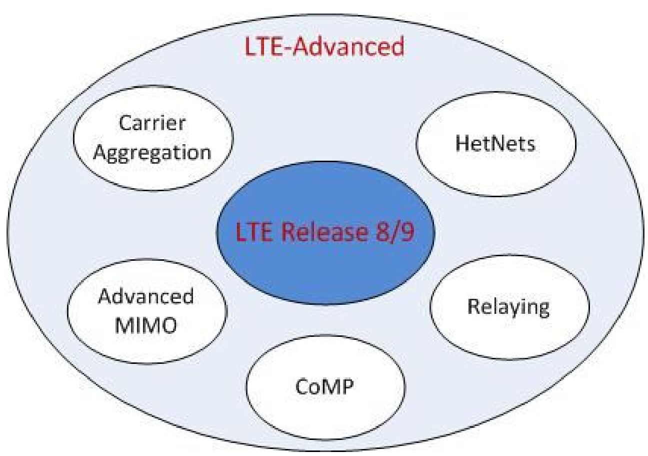


Figure 2.1: LTE-Advanced Technology.

These new features are used to fulfill all IMT-Advanced requirements in order to approve LTE Release 10 as an IMT-Advanced technology. This includes the possibility of peak data rates of 1 Gbit/s in the DL and 500 Mbit/s in the UL, which will be achieved by enhanced MIMO and a transmission bandwidth of up to 100 MHz [13]. Moreover, it is possible to provide high data rates over a larger portion of the cell. The peak spectral efficiency of LTE Release 10 is 30 /15 bps/Hz in the DL/UL, respectively, while the capacity and cell-edge user throughput targets for LTE-Advanced were set considering 1.4 to 1.6 times gain increase from LTE Release 8 performance [19]. The following table shows key IMT-Advanced requirements and current LTE Release 8 and LTE Release 10 capabilities.

	IMT-Advanced requirement	**LTE Release 8**	**LTE Release 10**
Transmission bandwidth	At least 40 MHz	Up to 20 MHz	Up to 100 MHz
Peak spectral efficiency			
– Downlink	15 b/s/Hz	16 b/s/Hz	16.0 [30.0]* b/s/Hz
– Uplink	6.75 b/s/Hz	4 b/s/Hz	8.1 [16.1]** b/s/Hz
Latency			
– Control plane	Less than 100 ms	50 ms	50 ms
– User plane	Less than 10 ms	4.9 ms	4.9 ms

*Value is for a 4 × 4 antenna configuration. Value in brackets for 8 × 8.

** Value is for a 2 × 2 antenna configuration. Value in brackets for 4 × 4.

Table 2.1: key IMT-Advanced Requirements.

In 2010 3GPP submitted LTE Release 10 to ITU and, based on this submission, ITU approved LTE Release 10 as one of two IMT-Advanced technologies (in addition to WiMAX). The self-evaluations were conducted and confirmed that LTE Release 10 meets all the requirements of IMT-Advanced in terms of capacity, data rates and low-cost deployment. Being an evolution of LTE, LTE Release 10 should be backwards compatible in the sense that it should be possible to deploy LTE Release 10 in spectrum already used by LTE Release 8 with no impact on existing LTE terminals. The compatibility is of a great importance for a smooth, low cost transition to LTE Release 10 capabilities within the network [13].

2.3.1. Carrier Aggregation

Already the first release of LTE, Release 8, provides extensive support for deployment in spectrum allocations of various characteristics, with bandwidths ranging from around 1.4 up to 20 MHz in both paired and unpaired bands. In Release 10 the transmission bandwidth can be further extended by means of so-called CA where multiple component carriers are aggregated and jointly used for transmission to/from a single mobile terminal [11], as shown in figure 2.2. Each component carrier can be configured in a backwards compatible way with LTE Release 8, hence, each component carrier will appear as an LTE Release 8 carrier, while a carrier aggregation-capable terminal can utilize the total aggregated bandwidth enabling higher data rates. In the general case, up to 5 different component carriers can be aggregated for the DL/ UL and allowing for transmission bandwidth up to 100 MHz [20].

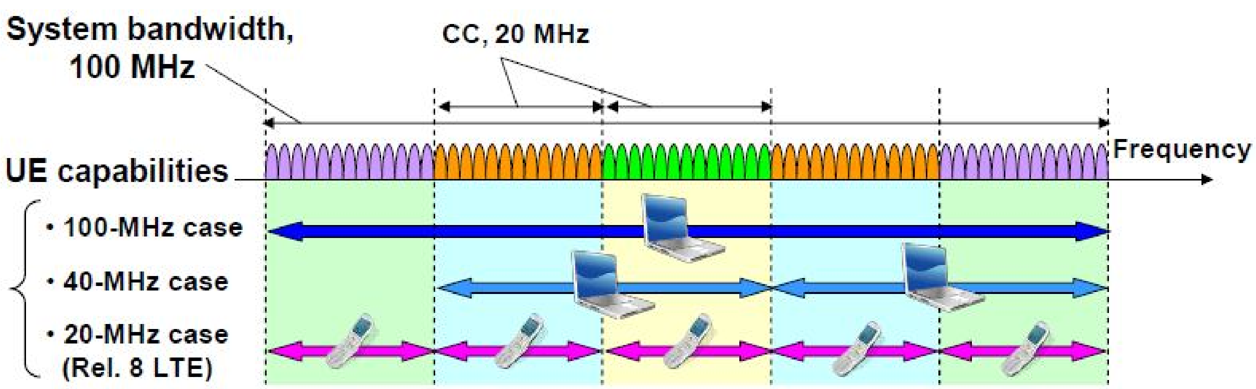


Figure 2.2: Carrier Aggregation.

CA supports both contiguous and non-contiguous spectrum and asymmetric bandwidth for FDD. Depending on component carrier's frequency locations, there are three types of Carrier Aggregation:

- Intra-band aggregation with contiguous carriers.

- Inter-band aggregation.

- Intra-band aggregation with non-contiguous carriers.

The possibility to aggregate non-adjacent component carriers enables exploitation of fragmented spectrum, operators with a fragmented spectrum can provide high-data-rate services based on the availability of wide overall bandwidth even though they do not possess a single wideband spectrum allocation.

CA is terminal dependent, it is beneficial to balance the load across the component carriers from the network perspective as well as it will include more capabilities between terminals in a way that some terminals may transmit and receive via different component carriers while the other terminals may use only one carrier [13]. This feature will obviously make it possible to serve terminals from Release 8, 9 and 10, simultaneously.

The control signaling is being sent through the same component carrier with the possibility to use the technique of cross carrier scheduling. This will be used when sending the scheduling decisions via a different component carrier than the one that was used for the concerned data. CA in LTE Release 10 is shown in the following figure.

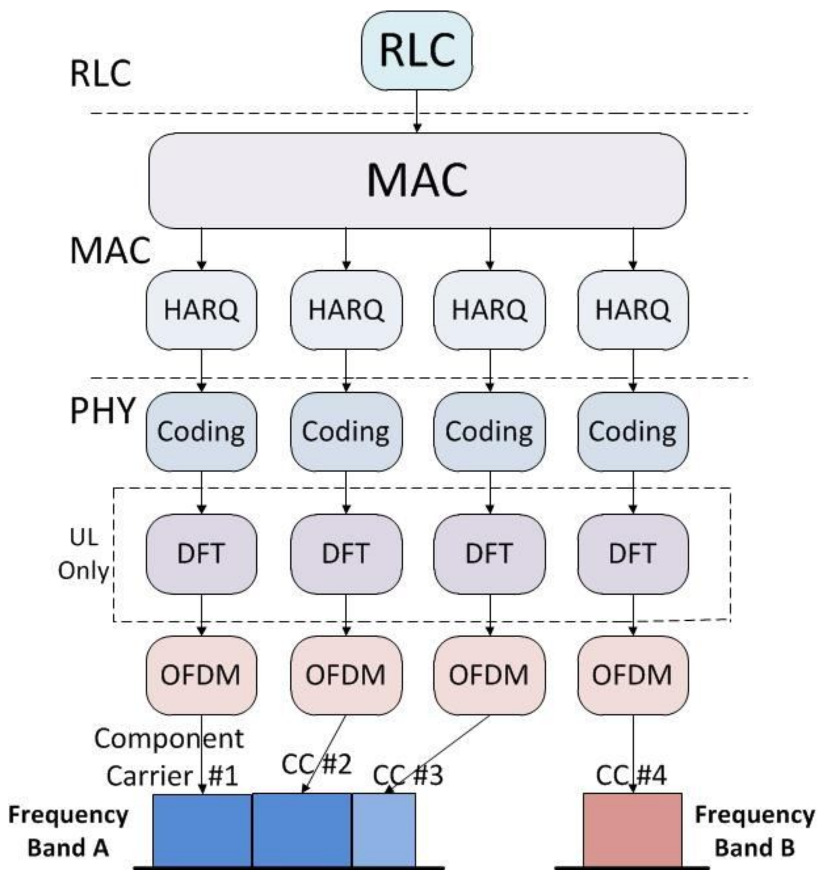


Figure 2.3: Carrier aggregation in LTE Release 10.

2.3.2. Advanced MIMO Techniques

LTE Release 8 supported up to four layers of MIMO multiplexing for DL and no MIMO for UL. Whereas LTE Release 10 extends the LTE multi-antenna transmission capabilities to support single-user MIMO (SU-MIMO) scheme up to eight layers (8x8 MIMO) for DL and up to four layers (4x4 MIMO) for UL. Together with the bandwidth up to 100 MHz enabled by carrier aggregation, this allows for peak spectral efficiency of 30 bit/s/Hz for DL and 15 bit/s/Hz for UL. The following figure shows advanced MIMO techniques in LTE-Advanced (LTE Release 10) [20].

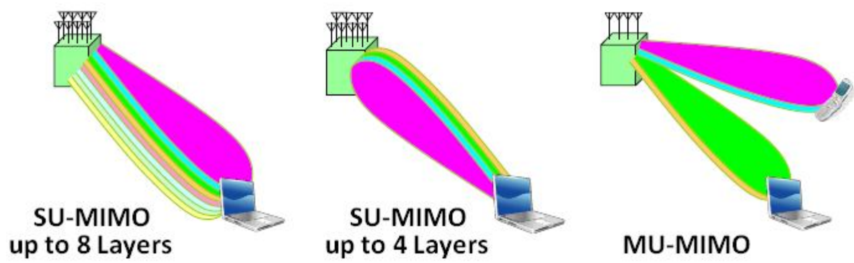


Figure 2.4: Advanced MIMO Techniques.

LTE Release 10 also supports Multi-user MIMO (MU-MIMO) that enables communication with multiple terminals, and CoMP - will be described later-, which are important technologies to increase peak data rate as well as the system capacity and cell edge user throughput, and applying various advanced signal processing techniques, e.g. dedicated DL beamforming, adaptive transmission power control, and multi cell simultaneous transmission [21].

2.4.3. Coordinated Multipoint Transmission/Reception (CoMP)

As previously mentioned, CoMP is a DL/UL technique of transmission/reception where transmitters/receivers do not have to be geographically co-located and are linked by some type of high speed data connection and can share payload data, to increase peak data rate as well as the system capacity and cell edge user throughput [22]. There are two different approaches for CoMP techniques given its control approach [21], the first option is a decentralized autonomous control based on independent eNodeBs and the second is a centralized control. With independent eNodeB architecture, CoMP is performed by means of signaling interchange between eNodeB. This technique can utilize legacy cells, but the disadvantage is signaling delay and other overheads. In the second approach, the eNodeB can centralize and control all radio resources by transmitting baseband data directly between eNodeBs on optical fiber connections. There is little signaling delay or other overheads in this technique, and Intra-cell radio resource control is relatively easy.

DL CoMP also has two approaches, as seen in figure 2.5, under consideration for LTE-Advanced which are [21]:

- Joint transmission (JT) with the corresponding Joint Processing (JP) at the receiver.

- Coordinated Scheduling/Beamforming (CS/CB).

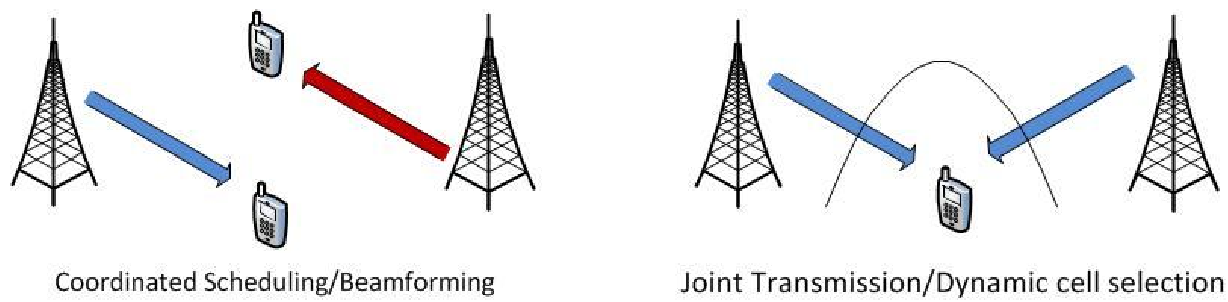


Figure 2.5: DL CoMP Approaches.

In CS/CB, the transmission to a single UE is performed from the serving cell, exactly as in the case of non-CoMP transmission. However, the scheduling is dynamically coordinated between the cells, including any beamforming functionality. In that way, the interference between different transmissions can be controlled and reduced. In principle, schedule optimization will be performed based on the serving set of users, so that the transmitter beams are constructed to reduce interference to other neighboring user, while increasing the served user's signal strength.

In JP, the transmission to a single UE is simultaneously performed from multiple transmission points. The multipoint transmissions will be coordinated as a single transmitter with multiple antennas that are geographically separated. This scheme has the potential for higher performance, compared to CS/CB, but comes at the expense of more stringent requirement on backhaul communication.

UL CoMP utilizes geographically separated antennas for signal reception from UE, and scheduling decisions are coordinated by multiple cells to control interference from each other. UE is not aware of multi-cell reception of its signal, so that impact on radio interface specification is at minimal. Implementation of UL CoMP largely depends on scheduler and receiver in the cells. UL CoMP is illustrated in the following figure.

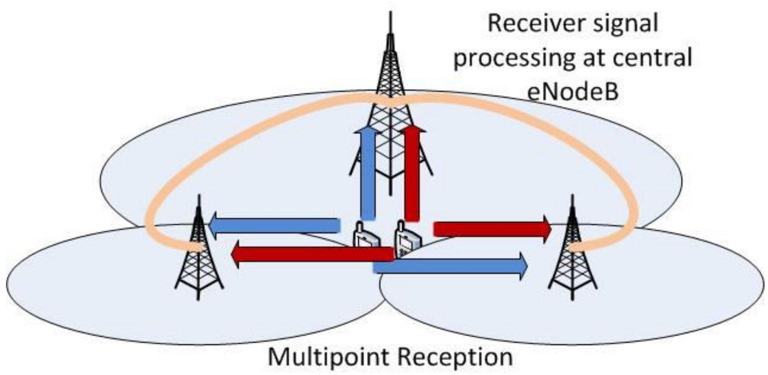


Figure 2.6: UL CoMP.

2.3.4. Relaying

Relaying functionality allows UE to communicate with the network via a relay node wirelessly connected to a donor eNodeB using the LTE radio access technology and LTE spectrum. Relay nodes may provide a fast and lower cost way to extend the coverage area (so-called Type 1 Relay Node), and increase data rate (so-called Type 2 Relay Node) [13], as shown in figure 2.7. From a UE point of view, the relay node will appear as a normal eNodeB, meaning that earlier release UEs can also access the network via the relay node.

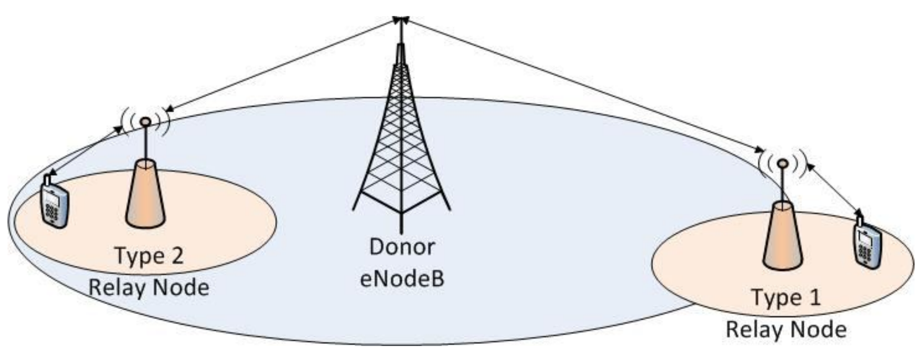


Figure 2.7: Relaying functionality.

Type 1 relay nodes control their cells with their own cell identity, including transmission of synchronization channels and reference symbols. Type 1 relays appear as a Release 8 eNodeB to Release 8 UEs, which ensures backward-compatible operation. Type 2 relay nodes will not have their own cell identity. Therefore, the UE will not be able to distinguish between signal transmission from the donor eNodeB and the relay. Control information can be transmitted from the eNodeB and user data from the relay.

2.3.5. Support of Heterogeneous Networks (HetNets)

Deployment of new low power eNodeBs within existing macro layer would enhance the SINR levels for users off-loaded to new eNodeBs and also for users that remain connected to the macro cells, and extend traffic and data rate capabilities when needed. These new eNodeBs are LPNs, including pico cells and femto cells (HeNBs), some authors also include in this type of heterogeneous deployment relays and remote radio units (RRUs). The combination of all these eNodeBs form the so-called HetNet [13, 23], which will be discussed in detail in the following sections. An example of HetNets is shown in Figure 2.8.

HetNets deployments are already possible in currently implemented mobile communication networks, including LTE Release 8. But, LTE Release 10 includes features that can be used to further mitigate interference between the different cell layers, thereby extending the potential scope of HetNets deployments.

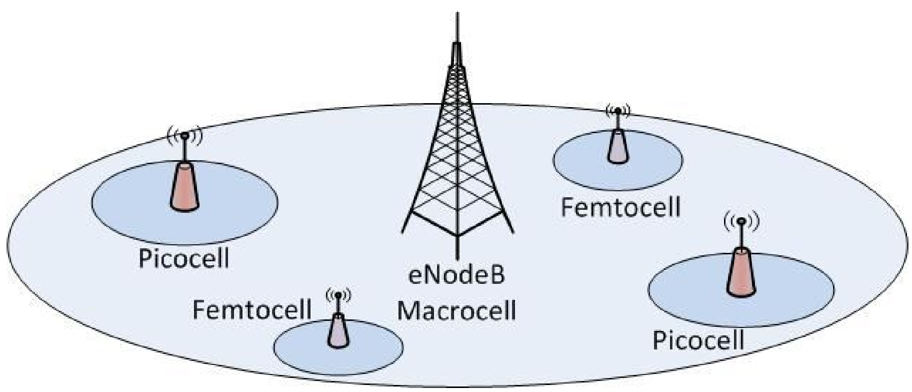


Figure 2.8: Heterogeneous Networks.

Chapter 3. Heterogeneous Networks (HetNets)

3.1. Heterogeneous Networks Concepts

HetNets, as mentioned formerly, have been introduced in the LTE-Advanced standardization in order to provide a significant network performance leap when other advanced technologies (CA, MIMO, and CoMP) are unable to achieve that, as they are reaching theoretical limits. Such techniques may not always work well either, especially under low SINR conditions, where received powers are low due to attenuation and/or interference might be high, whereas HetNets can do.

Complementing macro cells with LPNs and dedicated indoor solutions based on the 3GPP standard is a good approach to meet the predicted requirements for higher data rates and additional capacity. This approach can include the use of pico cells, femto cells, relays and remote radio units (RRUs), which delivers high per-user capacity and rate coverage in areas covered by LPNs, with the potential to improve performance in the macro network by offloading traffic generated in hotspots. By adding LPNs to the existing macro layer, the operator creates a two-layer cell structure with eNodeBs of different types, that is why it is called HetNet [13, 23], *heterogeneous* in the deployment sense. The degree of integration that can be achieved throughout the HetNet will determine the overall network performance.

HetNets improve the overall capacity as well as provide a cost-effective coverage extension and higher data rates to hot spots such as airports and shopping malls by deploying additional network nodes within the local-area range. In addition, they also increase overall cell-site performance and cell-edge data rates by bringing the network closer to end users. In that way, radio link quality can be enhanced due to the reduced distance between transmitter and receiver, and the larger number of eNodeBs allows for more efficient spectrum reuse and therefore larger data rates [24].

These LPNs can be either operator deployed or user deployed, share the same spectrum, and may coexist in the same geographical area. The following table shows specification of different elements in HetNets according to typical transmit power, coverage area, typical backhaul features and access [25].

Type of node	Typical transmit power	Coverage	Typical backhaul features	Access
Macro cell	46 dBm	Few Km	S1 Interface	Open to all UEs
Pico cell	23 – 30 dBm	< 100 m	X2 Interface with macro	Open to all UEs
Femto cell	< 23 dBm	< 50 m	User local loop	CSG
Relay	30 dBm	300 m	Wireless link with donor node	Open to all UEs
RRU	46 dBm	Few Km	Fiber link with parent site	Open to all UEs

Table 3.1: Specification of different elements in HetNets.

To obtain maximum value from the radio spectrum, operators will need flexible eNodeB site solutions that allow for ideal placement of the radio site. Operators may need to consider alternatives for site location by connecting with new partners such as municipalities, retailers and external agencies rather than traditional deals made with landlords and tower-approval committees. For outdoor HetNets deployments, reusing existing site infrastructure and maximizing the value of acquisition contracts should be the first priority for operators, together with technological and automatic solutions that reduce cell-site maintenance costs. When deploying LPNs as a complement to macro cells, careful network planning is needed to minimize the total number of cells-reducing the overall cost of ownership, and ensuring robust and seamless service [26].

In metropolitan areas, additional LPNs at street level need to be implemented using small antennae in such a way that the equipment is almost invisible. The deployment of these nodes as indoor sites makes infrastructure and interference issues easier to manage. HetNets can also be integrated smoothly with Wi-Fi, which is a more cost-effective solution for indoor mobile broadband coverage for enterprise and residential users than femto cells [24]. Figure 3.1 shows

HetNets, where LPNs are deployed in different scenarios (indoor, outdoor, at cell-edge, in hotspot).

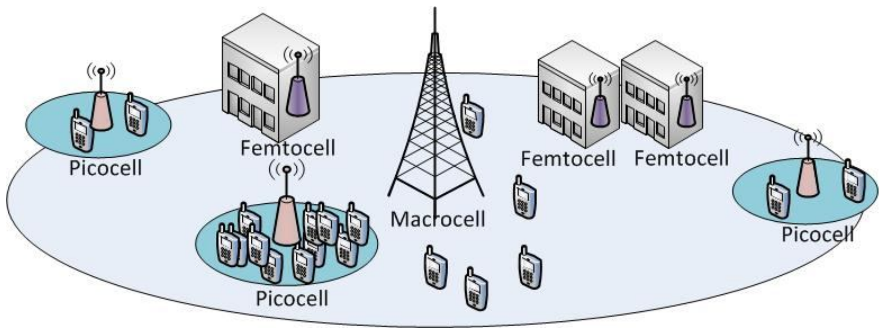


Figure 3.1: HetNets deployments scenarios.

In HetNets, the coordination between macro cells and small cells has a positive impact on the performance of the radio network and consequently on the overall user experience. Coordinated embedded LPNs improve performance, increasing both network data capacity and throughput without the need to split the available spectrum. Coordinating features like joint transmission and reception, provides the user with significantly higher speeds than would be possible with separate, uncoordinated, macro and LPNs layers [27].

3.2. Heterogeneous Networks Deployment Challenges

Frequency allocation, backhauling, handover, self-organization and interference reduction are considered the key deployment challenges of HetNets, which are discussed in this section.

3.2.1. Frequency Allocation

Frequency allocation is an essential issue in the HetNets deployment and it should be carefully considered. As the radio spectrum is a scarce resource, it is desirable that macro cells and LPNs will entirely share the same frequency band.

Given that different capacities might be required in the different coverage areas, it is possible to use just a partial spectrum between macro cells and LPNs that are assigned to a part of the whole frequency resource, as seen in figure 3.3 [28].

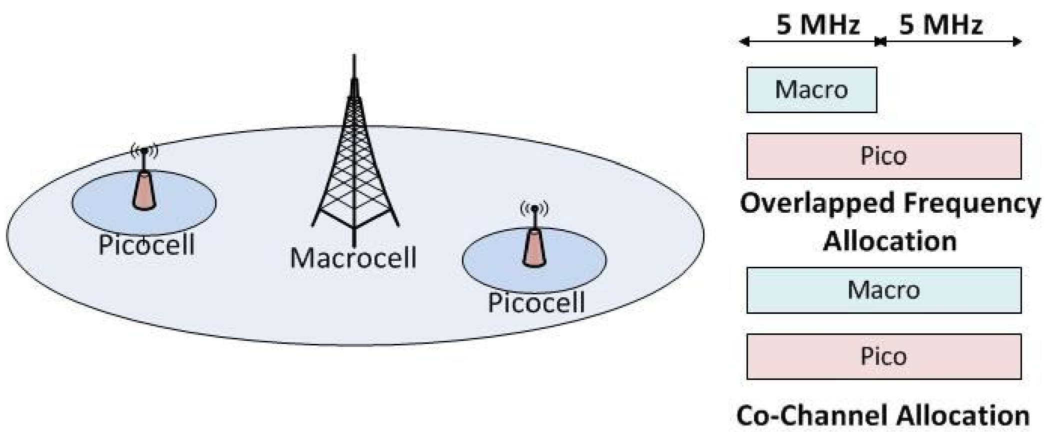


Figure 3.2: HetNets frequency allocation challenge.

3.2.2. Backhauling

Backhauling will be a tricky part in the HetNets deployment because of the complex topology of the various types of LPNs deployed along with the macro cells. For instance, the availability of power and network backhauling of pico cells might be difficult and expensive. Conversely, femto cells have lower backhauling costs compared to pico cells, but difficulties in maintaining QoS appear because they are unplanned and so interferences might be more difficult to control. Some LPNs may have their own connections to the core network, whereas some other nodes may construct a cluster to concatenate and route the traffic to the core network, and other nodes may rely on relays as an alternative route option [25].

3.2.3. Handover

Handovers are necessary in order to provide a non-intermittent uniform service when users are moving around different cell coverage. Furthermore, handovers are a means to offload the traffic from highly congested cells by shifting users at the border to the less congested neighbor nodes. However, the situation is different in HetNets due to the large number of small cells and the different types of backhaul links for each type of cell [29, 30]. In addition, the probability of handover failure increases the probability of user outage. For that, the handover parameter configuration for LPNs needs to be carefully planned and probably different from that of the macro cells.

3.2.4. Self-organizing

Self-Organizing Networks (SONs) are a step forward towards automated operation in mobile networks, which reduce the Operation and Maintenance (O&M) cost of mobile networks by using automated and intelligent procedures to replace human intervention without compromising network performance. Some LPNs such as femto cells are user deployable and no cellular operator intervention is needed, this approach is conceptualized by SONs features [25, 30]. SONs features of HetNets can be categorized in to three processes:

- **Self-configuration**, newly deployed cells download required software and self-configure automatically before entering them into the operational mode.

- **Self-healing,** where cells are auto-recovered whenever failures occur.

- **Self-optimization**, where cells monitor the network status and adapt their settings to improve performance and reduce interference.

3.2.5. Interference

The simultaneous use of the same spectrum between different cell layers that run on different values of transmit power creates interference that will become more severe compared to homogeneous networks. For pico cells the interference does not create coverage hole due to open access to all UEs, but that is not true when it is expanded (that will be discussed later in the range expansion and interference coordination sections).

The situation is different for femto cell due to being equipped with the CSG feature that results into new and severe interference conditions. Figure 3.3 illustrates interference scenarios in relation to femto cell deployments. There are two scenarios that create severe interference when macro UE (MUE) does not belong to femto cell CSG and being close to it [31]. In DL, MUE is being jammed by femto cell, frequency of the occurrence of this issue can be reduced by femto cell power control, with or without macro UE assistance, but it cannot completely solve the problem [32]. In UL, femto cell is being jammed by MUE Since MUE is power controlled by the macro cell, MUE will cause likely strong bursty interference to femto cell. Noise padding technique which is a method of wireless communication includes detecting UL interference in a received uplink transmission of a UE, where the received UL transmission is padded with noise based on the detected interference and also based on a frequency domain partition [33]. This technique can smooth out interference in this case, but it also decreases capacity at serving femto cell and increases interference to the neighboring cells. In case the MUE is closer to femto cell that the UE that is served by femto cell, noise padding cannot solve the problem and the UE served by femto cell would experience outage [34].

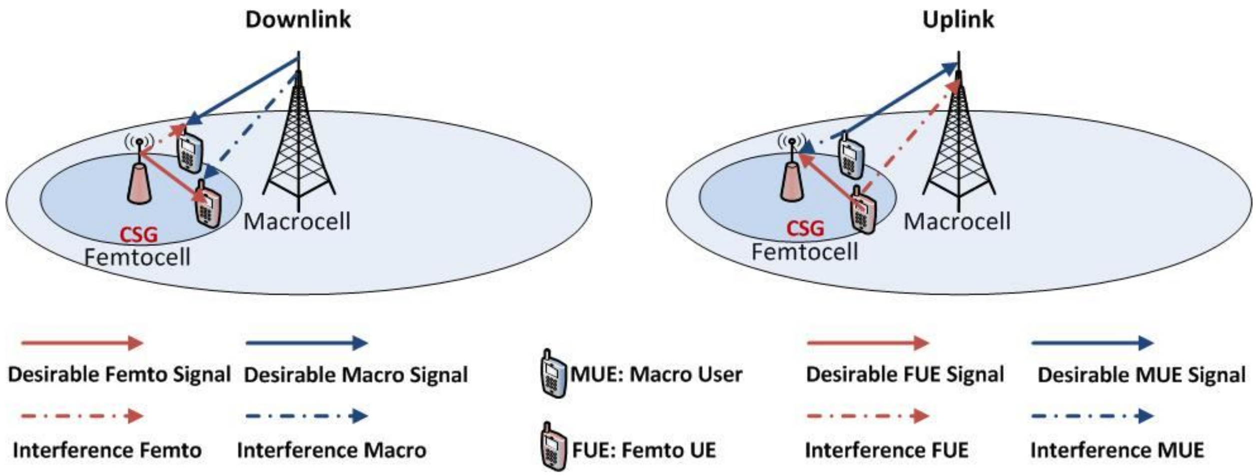


Figure 3.3: Macro-Femto Interference Scenarios.

3.3. Range Expansion

LPNs coverage is quite limited by its transmission power and the strong interference from macro cells, which means that only a small percentage of users can benefit from LPN deployment, especially in cell edges where there is no many UEs as in hotspots case. This leads to a state of coverage unbalance and for that, a new technique was required to increase HetNets efficiency, offload the more macro cell traffic, i.e. attract more UEs to LPNs and solve the UL and DL coverage unbalance. Moreover, the performance of LPNs is significantly improved if UEs are allowed to connect to a weaker SINR LPNs, which refers to extend LPNs boundaries for load balancing purposes. This improves LPNs performance, since more UEs can connect to LPNs and take advantage of the spectrum offered by them, and multiple LPNs can reuse the disused resources on the macro side, allowing for cell-splitting gains.

For these purposes, RE is introduced for LPNs, pico cells and relays particularly, with a positive bias to them in the cell selection. RE is considered a key design feature to enhance HetNets efficiency, which adds an offset to the pico cell received signal strength (RSS) in order to increase its DL coverage footprint [13].

Figure 3.4 illustrates the RE concept as follows [35]. The natural LPN boundaries in DL and UL are different in HetNets, as opposed to a homogeneous and correctly planned network. In the DL, the DL SINRs observed from the macro cell and the pico cell are equivalent at a location that is closer to the pico cell, which forms the equal-SINR cell boundary. In the UL, on the other hand, the location of the natural cell boundary is where the pathloss to the macro cell and the pico cell are equivalent. This is due to the fact that macro and LPN can reach different maximum power levels, however the UE has the same maximum power for bot h cases.

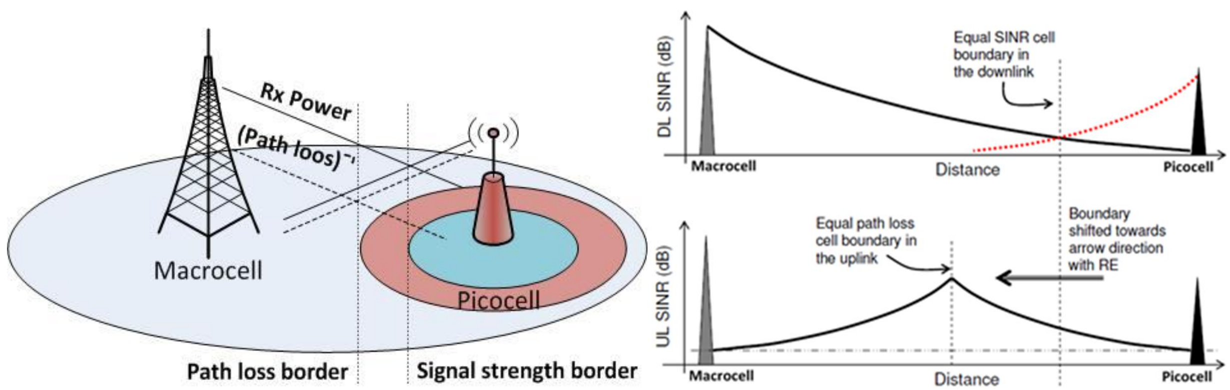


Figure 3.4: Range Expansion Concept.

In the normal case without RE, the serving cell choice is determined by the highest DL received power, this technique is referred as maximum reference signal received power (Max RSRP) [36]. With RE the serving cell of a UE is selected from the set of neighbor cells Λ according to the rule given as:

$$\textit{Serving Cell} = \underset{i \in \Lambda}{argmax}(\, RSRP_{\mathrm{i}} + Bias_{\mathrm{i}}\,) \qquad (3 - 1)$$

Where *RSRP* and *Bias* are expressed in dB, this rule implies that a UE does not necessarily connect to the eNodeB that has the strongest DL received power.

As mentioned, the LPN boundaries in DL and UL are different in HetNets. For that, the best UL cell does not necessarily correspond to the best DL cell. With RE technique, the DL serving cell is determined based on the formula (3 - 1), whereas the UL serving cell is defined according to the minimum path loss. The following figure shows handover in HetNets with RE [26].

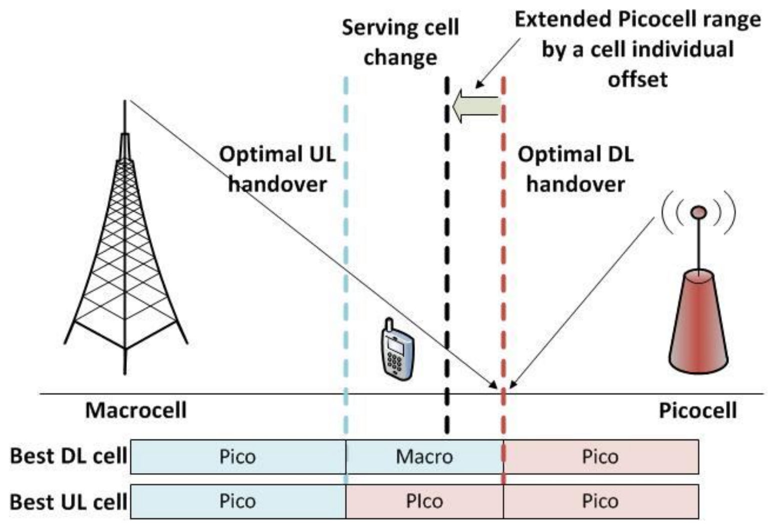


Figure 3.5: Handover in HetNets with RE.

Even though RE significantly mitigates cross-tier interference in the UL, this comes at the expense of reducing the DL signal quality of those users in the expanded region. Such users may suffer from DL SINRs below 0 dB since they are connected to cells that do not provide the best DL RSS [25], for this reason interference coordination strategies may well help to solve this tradeoff and reduce DL degradation in the cell border. Thus, it is usual to find that RE is jointly designed with ICIC/eICIC schemes, which will be discussed in the next section

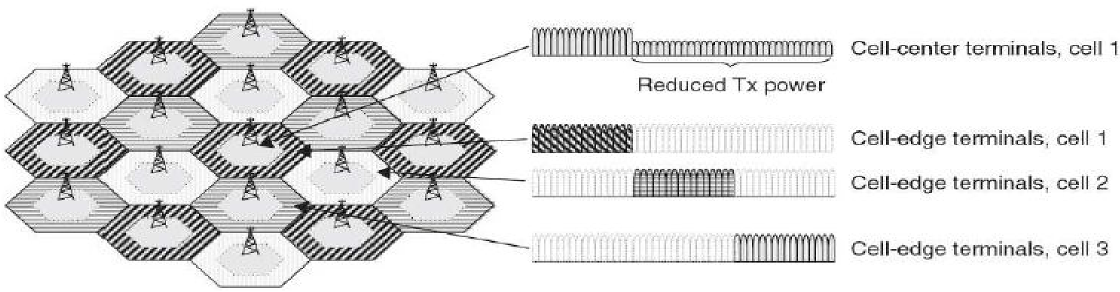
3.4. Interference Coordination

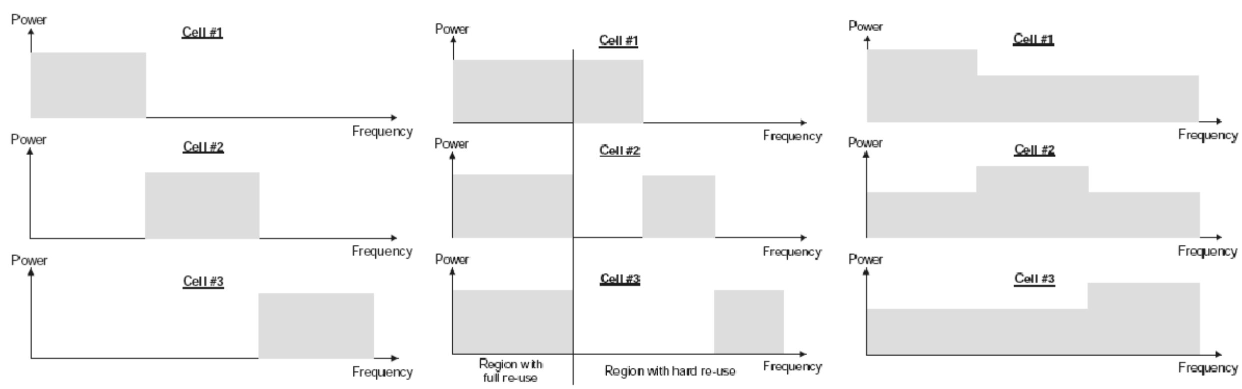
The interference issues may significantly degrade the overall system performance, which requires the adoption of coordination techniques to mitigate the interference and optimize its operation.

3.4.1. Inter-cell Interference Coordination

In order to maximize spectrum efficiency, it is desired that LTE uses a frequency reuse 1, which means that all the cells are using the same frequency channels. However, this also means that QoS will largely depend on the geographical position of the user equipment with a particular degradation on the cell edge. ICIC is introduced in 3GPP LTE Release 8 to deal with interference issues especially at cell-edge.

There are three schemes of ICIC par excellence, which use power and frequency domain to mitigate cell-edge interference from neighbor cells on traffic channels only [25]. One scheme of ICIC is where neighbor eNodeBs use different sets of resource blocks throughout the cell at given time (Hard Frequency Reuse), whereas in the second all eNodeBs utilize complete range of resource blocks for centrally located users but for cell-edge users neighbor eNodeBs do not use the same set of resource blocks at given time (Fractional Frequency Reuse), and in the third all the neighbor eNodeBs use different power schemes across the spectrum so that high power is used in the frequency blocks devoted to the edge and low power levels are allocated to the inner ones (Soft Frequency Reuse) [31]. All three options are graphically illustrated for three adjacent cells in figure 3.6.





a) Hard Frequency Reuse *b) Fractional Frequency Reuse* *c) Soft Frequency Reuse*

Figure 3.6: ICIC Schemes.

Using such schemes for HetNets, where macro cells and many LPNs are overlapping in many scenarios may lead to radio link failure (RLF) under severe interference, and experience service outage due to the unreliable DL control channels.

Another important aspect in ICIC, is collaboration with the potential interferers so that resource allocation can be coordinated in terms of power, frequency, and time to enhance network capacity and mitigate user outages. This might be particularly interesting for HetNets based on pico cells. As with other neighbor cells, macro cells are connected to pico cells through an X2 interface. In this sense, the ICIC messages defined in Release 8 that can be exchanged via the X2 interface can be listed as follows [25]:

- Relative Narrowband Transmit Power (RNTP) Indicator: An indicator sent by a specific cell used to coordinate with the adjacent cells about transmission power threshold in specific resource blocks (RBs) in the DL transmissions. An adjacent cell can utilize the RNTP information in the scheduling of it is own cell-edge terminals subjected to the interference from the adjacent cells who are willing to transmit with high power at certain RBs.

- Overload Indicator (OI): The OI is an indicator to exchange the average interference plus thermal noise power measurements for each RB between different cells for UL transmissions. It would be possible for an adjacent eNodeB that received the OI to change its scheduling to reduce the interference for the eNodeB that issued the OI.

- High Interference Indicator (HII): An indicator used by a certain cell to notify the adjacent cells that one of its cell-edge users will be scheduled for UL transmission in the near future. The HII indicator is a way to prevent the low SINR scenarios by avoiding scheduling of the cell-edge terminals on the same RB and hence reducing the UL interference for cell-edge transmissions to the receiving eNodeB.

Applying of the aforementioned techniques of ICIC may not efficiently cover all the HetNets interference scenarios discussed previously, as the control signaling in each sub-frame is more problematic as it spans the full cell bandwidth and therefore not subject to ICIC.

3.4.2 Enhanced Inter-cell Interference Coordination

The enhanced inter-cell interference coordination (eICIC) is introduced in 3GPP LTE Release 10 to deal with interference issues in HetNets, and mitigate interference on traffic and control channels using power, frequency and also the time domain. eICIC in the time domain introduces a resource-specific cell-selection (RS-CS) method based on subframe blanking, known as Almost Blank Subframe (ABS), that does not send any traffic channels and are mostly control channel frames with very low power. When macro cell configures ABS subframes the UEs connected to the LPN can send their data during such ABS frames and avoid interference from macro cell, and the configuration of ABS is shared via O&M for femto cells or X2 interface for pico cells [35]. However, for backward compatibility, the reference signals RS-CSs still need to be transmitted from the aggressor node (macro cell), resulting in some interference to the users in the victim node, that turn to be severe in high RE biases scenarios. For that, another time domain solution is introduced to deal with RS-CSs interference that mutes RS-CSs in the data channel filled of RBs such as MBSFN (Multicast/Broadcast over Single frequency network) subframes scheme, also known as MB scheme [17, 35]. The both techniques, ABS and MBSFN-subframes, are shown in figures 3.7 and 3.8.

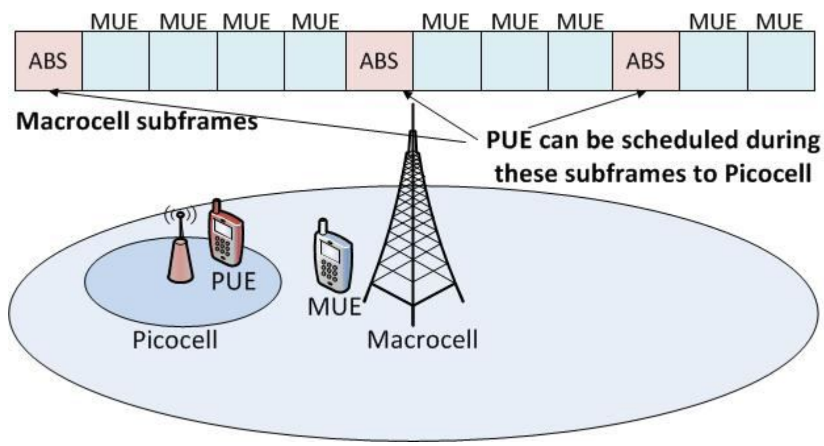


Figure 3.7: Almost Blank Subframes (ABS) technique.

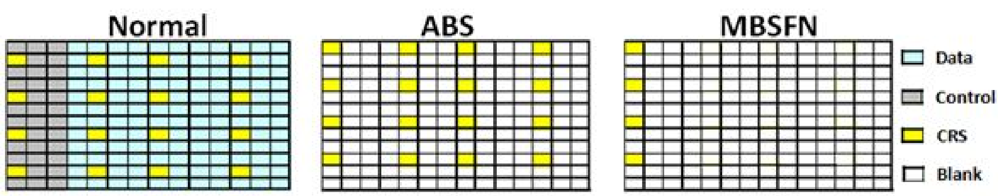


Figure 3.8: ABS and MBSFN-subframes.

There is another interference issue when deploying HetNets with CRE, since RE may cause low SINR from the pico cell users in the extended regions. This low SINR make decoding the Layer1/Layer2 control channels more complicated. To deal with L1/L2 control signaling, interference specific methods of frequency domain schemes are adopted. The interference cancellation of signaling channels is performed by separating control signaling in different component carriers (recall that carrier aggregation is supported by LTE Release 10) for the different cell layers where at least one component carrier in each cell layer is protected from interference from other cell layers by not sending control signaling (PDCCH, PCFICH, PHICH) on the component carrier in the other cell layers, as seen in figure 3.9 [20].

The macro cell sends control signaling on component carrier f1 but not on component carrier f2, while the situation is the reverted in the LPN (pico cell with RE) deployed within the macro cell [13]. Since Release10 introduces cross-carrier scheduling, resources on f2 can be utilized for data transmission, scheduled by control signaling received on f1. This approach will create frequency reuse for the control signaling while still permitting terminals to utilize the full bandwidth and accordingly enabling the highest data rates.

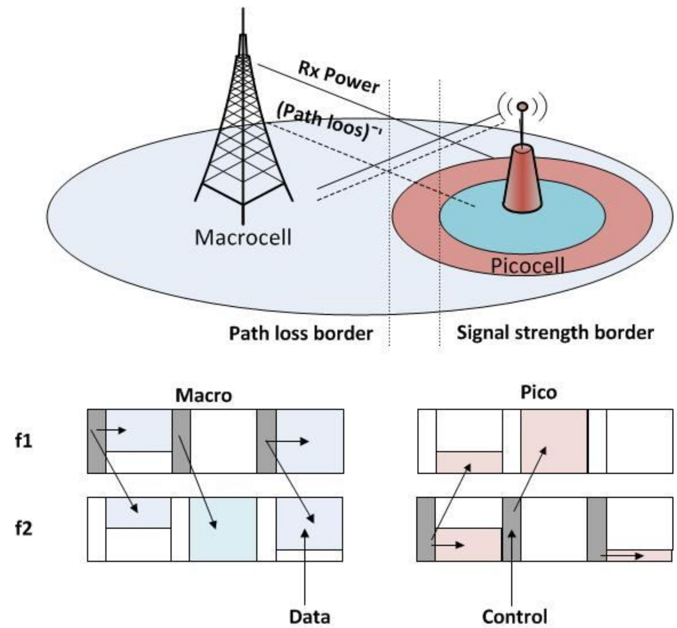


Figure 3.9: Interference Cancellation in HetNets.

3.5. Heterogeneous Networks Scenarios

According to the type of LPN (pico cell, femto cell) and deployment mode (indoor, outdoor), we can get a lot of HetNets scenarios to study and analyse. In this project, the assumed scenario is macro-pico with outdoor deployment of pico cells, in addition to apply RE technique to pico cells. In order to achieve the main objects of this thesis.

Chapter 4. System Level Simulation (SLS)

4.1. System Level Simulation (SLS)

System level simulation (SLS) is essential to evaluate the performance of new mobile networks technologies, which aim at determining the impact of link level gains on the network performance overall. It also reflects the effects of issues that are unavailable to study in link level simulation, such as cell planning, scheduling and interference. Simulating the totality of the radio links between the UEs and eNodeBs is an impractical way of performing SLS due to the vast amount of computational power that would be required. Thus, in SLS the physical layer is abstracted by simplified models that capture its essential characteristics with high accuracy and simultaneously low complexity.

SLS allows large scale network representation, a lot of macro cells and users, up to a hundred UEs attached per base stations, radio resource management algorithms, interference mitigation techniques, coverage estimation and more. This way it aims at evaluating the system performance in this large scale configuration through gathering various statistics for this purpose like throughput, interference, cell activity, outage probability, quality fairness among UEs and other traffic statistics (frame/packet error rate, frame/packet acknowledgment time delay, etc.).

In this thesis, SLS is needed to evaluate the impact of HetNets deployment in macro layer on the network performance overall, in case of macro-pico scenario, using some key performance indicators of those mentioned above. In addition, to study and analyze effects of applying RE techniques to pico cell on the system performance for different bias values, which is considered the main object of the thesis. The LTE SLS that has been used in this research is based on C++ and Matlab, it was split in two parts, the first part being developed based on C++, the second part making use of a developed edition of the Matlab Vienna LTE system level simulator [37].

The following section describes the LTE system level simulator framework and gives the guidelines for this kind of simulators, its entities and how to build it, In addition to present some results to validate SLS based on macro cell simulation assumptions that mentioned in table A3.1, which will appear later in this chapter.

4.2. System Level Simulation Description

The approach that is typically used in the development of SLS is the so-called Monte-Carlo approach [45]. This means that several independent snapshots or *photos of the system* are evaluated in order to obtain statistics about the global system behavior. Whenever one snapshot is evaluated, several modules are executed. These modules are illustrated in figure 4.1. Where the components are classified into two groups, static and dynamic [31].

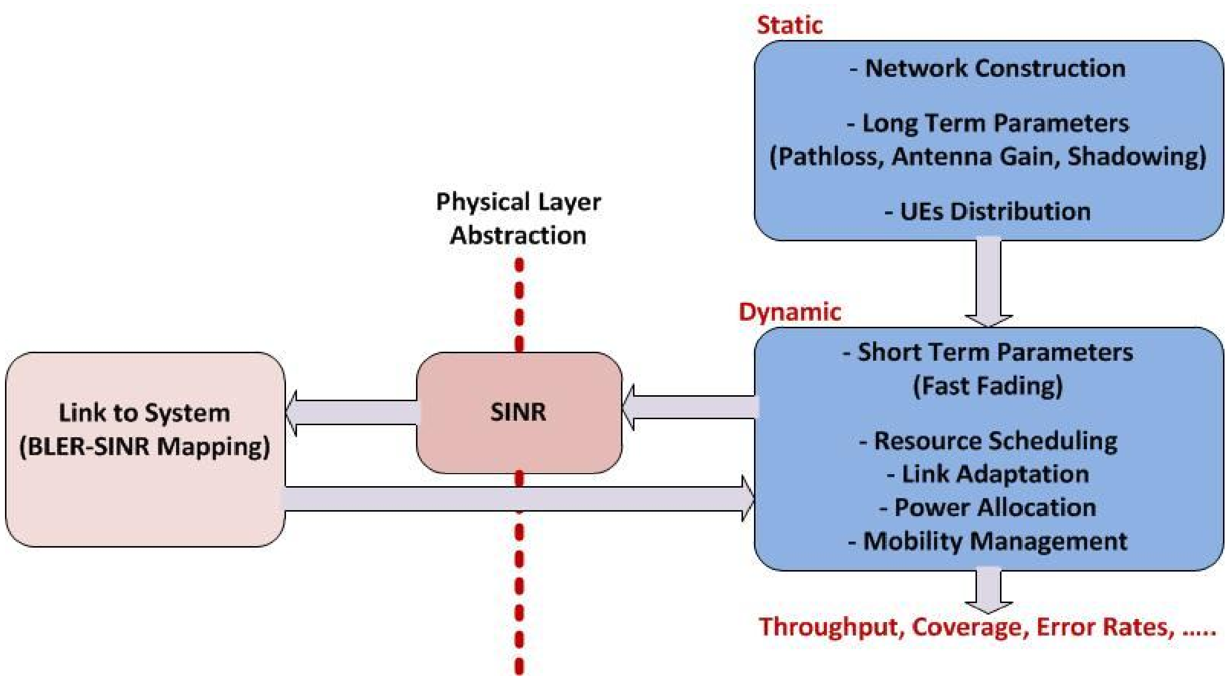


Figure 4.1: LTE system level simulation block diagram.

The static component includes the network construction (network layout, base stations deployment) and long term parameters (antenna gain pattern, pathloss and shadowing), which are used to calculate the interference *structure* (SINR Map). UEs deployment according to an assumed configuration is the next step. On the other hand, the dynamic components are required to run SLS and get more realistic outputs, which include short term parameters (fast fading), resource scheduling, power allocation strategy, link adaptation techniques (HARQ) and traffic model. In addition to physical layer abstraction as mentioned above and link layer input (BLER Curves) that is used for SINR-to-BLER mapping. The basic components of SLS will be subsequently discussed in more detail.

4.2.1. Network Layout (Macro Layer)

It is 2D hexagonal layout, each site, has 3 sectors (cells). A group of sites consist of one central site, first tire of 6 sites and second tire of 12 sites, forms a cluster. Copying this cluster allows wrapping the scenario around to combat the border effect (lack of interference in the border cells imply that they are unrealistically characterized). Network layout for macro layer is illustrated in figure 4.2.

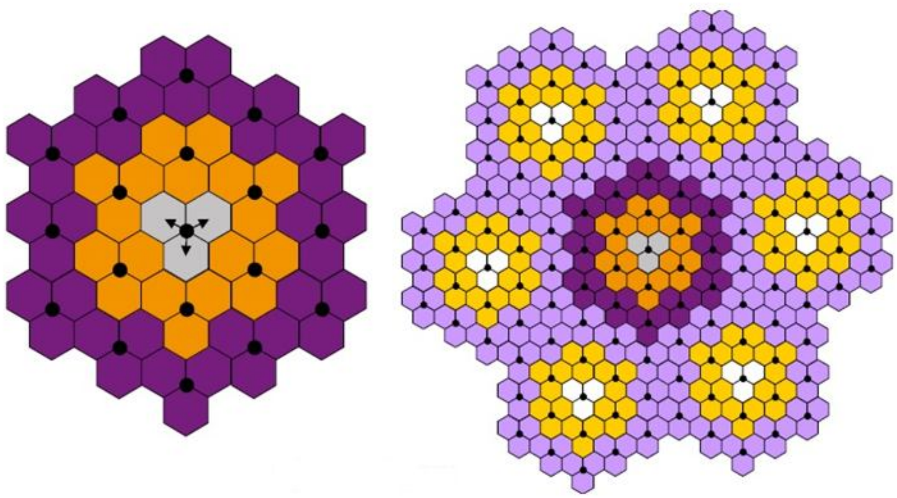


Figure 4.2: SLS, Network layout for macro layer.

4.2.2. Antenna Gain Pattern

The macro cell antenna radiation pattern to be used for each sector in 3-sector cell is modeled through its horizontal and vertical radiation patterns. This has been done using a file of antenna radiation pattern as SLS input which is provided by antennas manufacturers [38]. That gives more effective and credible to SLS results than just using the horizontal pattern (typically defined by $A(\Theta)= -min[12(\Theta/\Theta 3dB)^2, Am]$ [39]). Figure 4.3 shows the horizontal and vertical antenna radiation patterns that are used in SLS.

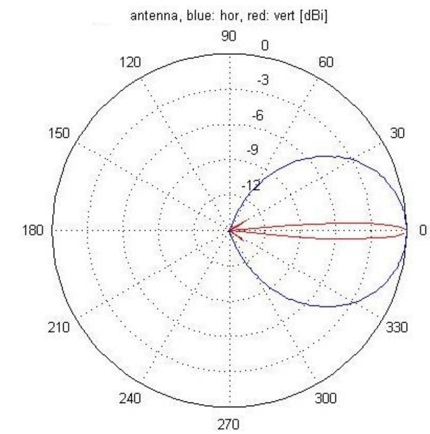


Figure 4.3: SLS, macro cell antenna radiation pattern.

The antenna radiation pattern for UEs is assumed to be omnidirectional with constant gain equal to zero.

4.2.3. Propagation Pathloss

The propagation pathloss between a macro eNodeB and outdoor UE located in a point P in the 2D plan at distance *R* in km, is modeled as [39]:

$$PL(R) = 128.1+37.6 \log10 R \qquad (4 - 1)$$

Where *PL(R)* is expressed in dB. Outdoor PL is computed once for attached eNodeB (desired signal) and interfering eNodeBs for all the points in the network layout, and saved as a pathloss map. This map can be reused during SLS, as long as the network layout is kept. The following figure shows PL model that is used in SLS for outdoor UEs deployments.

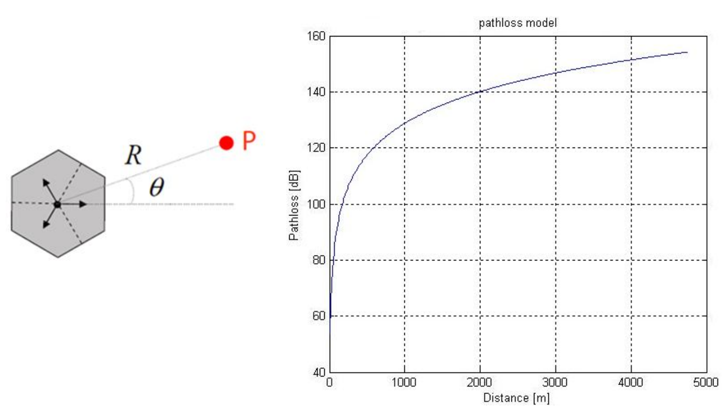


Figure 4.4: SLS, Pathloss model for macro layer.

4.2.4. Shadowing (Large-scale Fading)

Shadowing is caused by obstacles in the propagation path between the UE and the eNodeB and can be interpreted as the pathloss variations induced by irregularities of the geographical characteristics of the terrain with respect to the average pathloss obtained from the pathloss model.

Shadowing is modeled as a random variable that is added to the propagation path loss. Shadowing value changes as UE changes its position where shadowing is not distance-dependent it is position-dependent. This fact means that, shadowing should not be modeled independently for each UE in the simulation since it is common to have several UEs operating within limited area, which implies proximity between UEs. It is typically approximated by a log-normal distribution of zero mean and standard deviation equal to σ dB, as shadowing effects occur over a large area, in order to be able to capture the dynamics affecting macro-cell diversity in a realistic way a two-dimensional Gaussian process with appropriate spatial correlation is desirable [40].

In this SLS, log-normal shadowing, correlated shadowing between eNodeBs, shadowing auto-correlation and spatial correlation are implemented and modeled using two dimensional shadowing model [41]. The procedure that is used to generate *n* 2D shadowing maps corresponding to *n* eNodeBs (sites) could be summarized as follows:

- Generate *n+1* matrices {*g0 ,g1 ,g2, g3 …. gn*}, every elements of these matrices is a Gaussian random variable with zero mean and standard deviation equal to σ dB (8 dB for macro cell), considering spatial correlation of shadowing as:

$$R(\Delta r) = 2^{-\Delta r/d} \qquad (4 - 2)$$

Where Δr is the space shift (change in position), d is auto-correlation distance of shadowing which is equal to 50 m for macro cell.

- Given a correlation coefficient of shadowing from different eNodeBs equal to *p* (1 between intra-site cells, 0.5 between inter-site cells), produce n shadowing maps, according to next equation:

$$G_i = p^{1/2}\, g_0 + (1-p)^{1/2}\, g_i \quad ;\ i = 1, 2, 3 \ldots n \qquad (4 - 3)$$

- Use a numerical algorithm to compute tow-dimensional Fourier and inverse Fourier transforms in order to obtain *h(x,y)* [40].

- Utilize tow-dimensional convolution to filter each shadowing map G_i, hence obtaining filtered maps $\breve{G}_i$.

Figure 4.5 depicts the result of applying the previous procedure to get the shadowing for a given eNodeBs (site 1), where shadowing value grades through the 2D map within range approximately equal to [-25, 25] dB which looks logical for the proposed values in table A3.1:

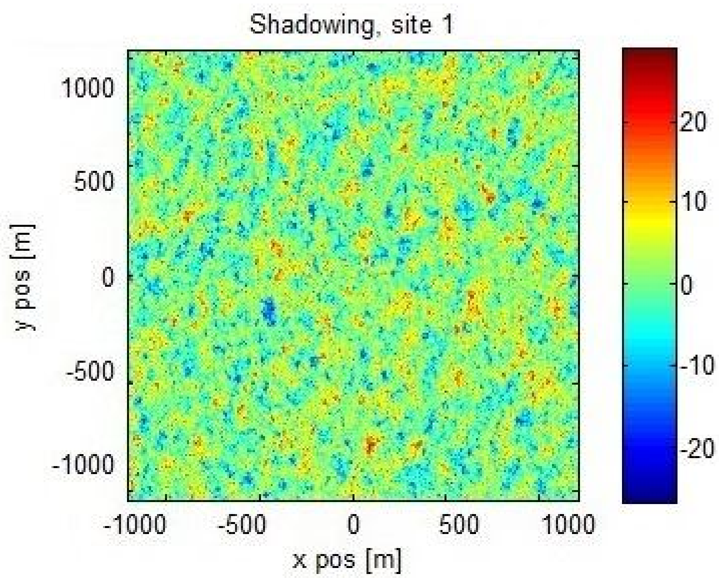


Figure 4.5: SLS, 2D shadowing map for site 1.

4.2.5. Signal to Interference plus Noise Ratio (SINR)

Based on long term parameters, the power received by a point P on 2D network layout from a given eNodeB in dB is:

$$P_{Rx}(eNodeB) = P_{tx}(eNodeB) + G_{eNodeB}(\Theta) + G_{UE} - PL(R) - Shadowing \qquad (4 - 4)$$

Where $P_{tx}(eNodeB)$ denotes the eNodeB transmit power in dB, $G_{eNodeB}(\Theta)$ denotes the eNodeB antenna gain in dBi, G_{UE} denotes UE antenna gain in dB which is equal to zero.

Now, SINR can be computed for the whole points in the network layout, as follows:

$$SINR = P_{Rx}(eNodeB) / (\sum_{interferers} P_{Rx}(eNodeB) + P_{therm}) \qquad (4 - 5)$$

Where P_{therm} is the thermal noise in dB. SINR values are saved as a SINR 2D map, like pathloss map, and can be reused during SLS, as long as the network layout is kept. Figure 4.6 illustrates the 2D SINR map that is produced after using previous equation, based on table A3.1 assumptions. The figure on the left shows 2D SINR map without shadowing not wrap-around, as we can see the highest SINR values are located close to macro cells in their antennas directions and reach 20 dB, these values decrease gradually away from eNodeBs and reach the lowest value which is -5 dB at sector's borders. The figure on the right shows 2D SINR map after applying warp-around and adding shadowing which has been generated in the previous step.

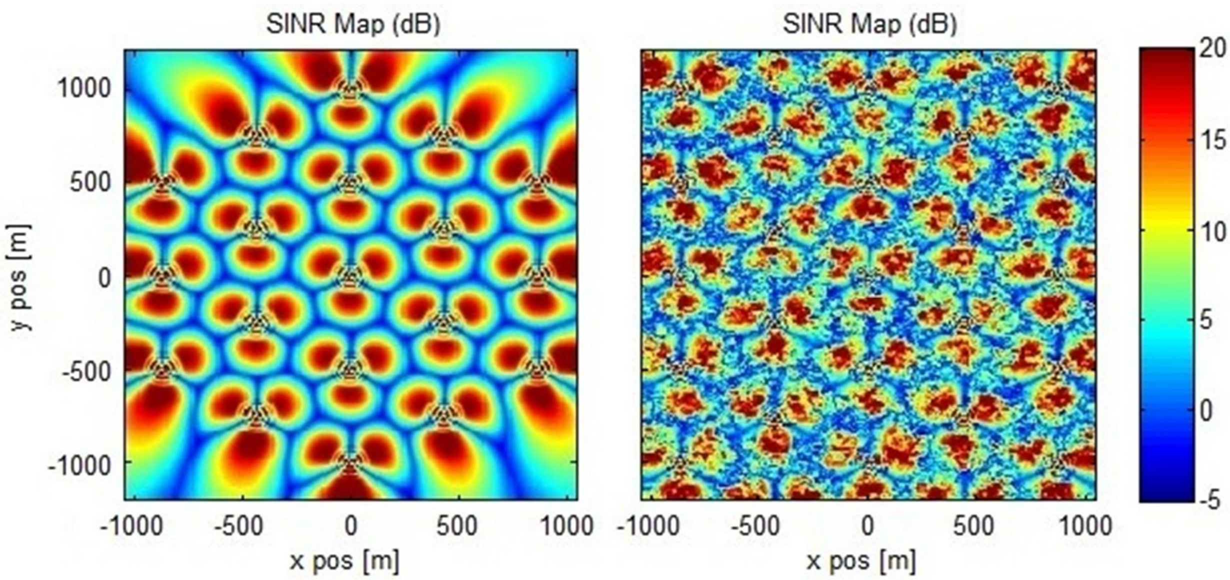


Figure 4.6: SLS, 2D SINR map without shadowing nor warp-around, with shadowing and warp-around.

4.2.6. UEs Deployments

UEs are dropped in what has been called region of interest (ROI), which could be the whole network layout or a part of it. ROI is the area where UEs movement and transmission of DL channel are simulated. In ROI the UEs and eNodeBs are positioned within a certain simulation length and UEs are moved in each transmission time intervals (TTIs), where TTI is equal to 1 ms. This movement will be determined by a random direction for each user and a position displacement equivalent to the UE's speed introduced when the channel was generated. As long as a UE is still in ROI, this UE does not change its direction with each time step. If a UE leaved the specified ROI, it would be reallocated randomly in it with assigning a new movement direction to this UE, which begins moving using it till exit the network layout once more. Figure 4.7 shows macro eNodeBs and UEs positions within SLS network layout, where the number of UEs that are deployed per macro cell (site's sector) is 25 UEs.

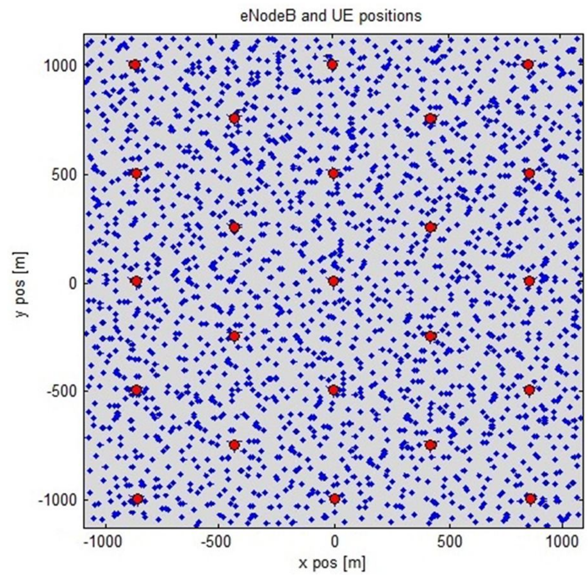


Figure 4.7: SLS, eNodeBs and UEs positions within ROI for macro layer.

4.2.7. Small-scale Fading (Fast Fading)

Small-scale Fading refers to the dramatic changes in signal amplitude and phase that can be experienced as a result of small changes (as small as half a wavelength) in the spatial separation between a receiver and transmitter. It is caused by two main factors [42]. First, the motion between the transmitter and receiver which results in the appearance of Doppler effect and so a parasitic frequency modulation, which is known to be a time-variant mechanism due to motion. Frequency spread due to Doppler translates into time selective fading, which can be categorized as fast fading or slow fading. Second, the multiple paths in the radio signal, which is known to be a time-spreading mechanism, its fading can be categorized to frequency-selective fading and flat fading.

Depending on the interference analysis methodology, small-scale fading may or may not be modeled for HetNets purposes [39]. Nevertheless, small-scale fading has been modeled in this project as a time-dependent process, whilst the losses caused by propagation pathloss and shadowing are position-dependent and time-invariant. Adding Fast fading to SLS means that, SINR should be computed on each subcarrier. However, both time and angular dispersion properties can be modeled for the fast fading.

The approach that has been used to model small-scale fading is a pre-computed matrix, based on [43]. This approach allows generating this matrix prior to SLS itself using a channel simulator for supposed UEs velocities [44], save this matrix in binary files and loading it to SLS when needed, which reduces the run-time computational complexity significantly. After that, matrix's values are quantified to reduce the large dimension of the associated file. At this point, the matrix or binary file could be used as input to SLS. Thus, a trace of fading parameters modeling the time-and-frequency variant behavior of the channel has been generated.

The final step is, loading the matrix to SLS and assignation of UEs to its rows through a pointer to a position in the obtained matrix. As the simulation time increases, the pointers will move along the matrix according to the user‘s mean speed. When a user gets to the end of the matrix, in the following time step it will start in the first position. So, in order to reduce the abrupt channel change, a smooth effect is needed and done by adding positions to the matrix which will progressively weight the average between the values of the last row and the first one.

Thus, the final channel response is a combination of several contributions, propagation pathloss, shadowing (large-scale fading) and fast fading (small-scale fading).

4.2.8. MIMO Transmission Modes

During SLS (dynamic module) more parameters should be considered to get more realistic SINR values, such as the receiver noise, enhancement receiver noise in case of using MIMO and channel estimation errors. MIMO transmission modes (Transmission Diversity (TxD), Open Loop Spatial Multiplexing (OLSM), Closed Loop Spatial Multiplexing (CLSM) are integrated in the SLS [45, 46], since they should be considered and modeled for HetNets purposes [39].

The channel modeling aims at computing a per-layer SINR, a spatial layer is the term used for the different streams generated by spatial multiplexing. A layer thus can be described as a mapping of symbols onto the transmit antenna ports. Each layer is then identified by a (precoding) vector of size equal to the number of transmit antenna ports [47].

4.2.9. Reference Signals

The LTE standard defines three different types of Reference Signals (RSs), also known as pilot signals which are constantly transmitted in the DL. The reference signals are used for cell search and initial acquisition, DL channel estimation for coherent demodulation/detection at the UE, and DL channel quality measurements [43]. These three types of RSs are, cell-specific RSs (RS-CS) that often referred to as common RSs as they are available to all UEs in a cell, UE-specific RSs that may be embedded in the data for specific UEs and MBSFN-specific, i.e. RSs that are only used for Multimedia Broadcast Single Frequency Network (MBSFN) operation. The most important RSs are the cell-specific, the others are additional RSs. For that, the RS-CS interference which is considered essential especially for range expansion scenarios, is modeled and implemented for this project.

In the SLS, the RS-CS interference is modeled through interference averaging over one resource block (RB), since RS-CS are not sent in all subcarriers. As the power of the reference signal is not defined in the standard, with considering equally power distribution through RBs during simulation time (TTIs) and each RB has 12 RS-CS, so that the average interference factor that is used to define RS-SC is equal to 0.1. That means, the interference of RS-CS belongs a given RB is around 10% of the average interference from that RB. When using ABS, RS-CS are still present so those frames are considered to generate just 10% of interference of a normal frame, as opposed to MBSFN-frames, in which no RS-CS are transmitted and so interference is zero.

4.2.10. BLER-SINR Mapping

BLER curves are a set of adaptive white Gaussian noise (AWGN) link-level performance curves, as seen in figure 4.8 [48], which are essential to assess block error rate (BLER) at the receiver for received transport blocks (TBs), since BLER at the receiver defines whether TB was received correctly or not and HARQ ACK/NAK reporting is subsequently generated, and also gives a certain resource allocation and modulation and coding schemes (MCS). In the LTE SLS, and for sake of simplicity only a subset of MCSs is simulated, this subset includes 15 different MCSs driven by 15 channel quality indicator (CQI). This subset of MCSs has been chosen so that there is a univocal relationship with CQIs. The defined CQIs use coding rates between 1/13 and 1 combined with 4-QAM, 16-QAM, and 64-QAM modulations [49].

Assessing BLER is achieved by SINR-to-BLER mapping, which requires an effective SNR value that is obtained from mapping the set of subcarriers-SINRs assigned to UE TB to an AWGN equivalent SNR. The technique that achieves that is MIESM (Mutual Information Effective Signal to Interference and Noise Mapping) [50], which is a mutual-information-based method used to obtain a TB effective SNR (SNReff) that can be used to map to the BLER obtained from AWGN link-level simulation. In the SLS, the MIESM mapping is given by the following equation [51]:

$$SNR_{eff} = \beta\, f^{\,-1}\left(R^{-1}\sum_{r=1}^{R} f\left(\frac{SINRr}{\beta}\right)\right) \qquad (4 - 6)$$

where R corresponds to the number of subcarriers to be averaged, β is calibrated by means of link-level simulation to obtain a close match between the BLER of the equivalent AWGN channel and the BLER of the real fading channel and the function f is given by the Bit Interleaved Coded Modulation (BICM) capacity [52].

The mapping from SNReff to a corresponding CQI value is carried out such that a BLER lower than 0.1 is achieved. For this purpose SISO AWGN simulations have been carried out for each CQI value that delivered this mapping, which turned out to be a linear function. The obtained CQIs are afterwards floored to obtain the CQI values that are reported back to the eNodeB, which provides the eNodeB with a figure of merit of the state of the channel of the UE.

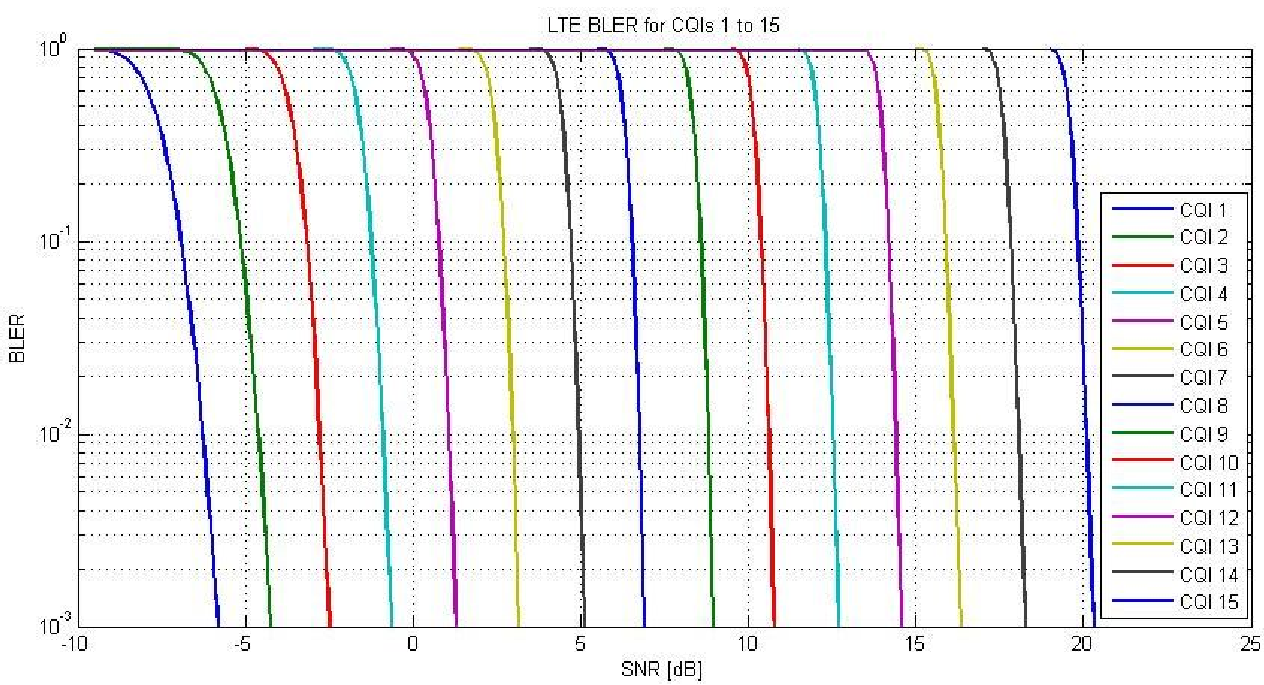


Figure 4.8: LTE DL Reference (AWGN) BLER vs. SNR for SISO configuration and RB size = 1.

4.2.11. Pico Layer

LPNs deployment (pico cells) requires a new layer to embed them into the macro layer. The approach that has been used to deploy outdoor pico cells is illustrated in figure 4.9, where one pico cell is modeled as a 2-dimensional rectangular block (100 x 100 meters) and placed randomly in each site sector with a minimum distance between macro cell and pico cell equal to 40 m. Using this approach may allow to place two pico cells that belong to adjacent macro cells very close, to avoid that a minimum separation between pico cells which is equal to 40 m is applied. To reduce the complexity and running time of SLS, pico cells are deployed only in the central macro cell and its surrounding (Tire-1). The complete guide to model LPNs (pico cell, femto cell) whether indoor or outdoor has been included in appendix 2.

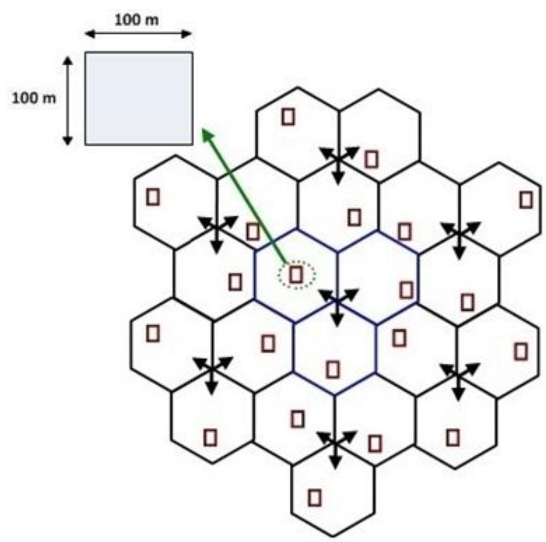


Figure 4.9: SLS, Outdoor Pico cells deployment within macro layout.

The antenna radiation pattern for LPNs is assumed to be omnidirectional with constant gain. The other remaining assumptions for pico layer are located in the table A3.2.

The same technique that is used to keep macro cell UEs within the assumed network layout (ROI) is applied for each pico cell, in order to avoid passing pico cell UEs pico's region to macro's region.

- The remaining assumptions and dynamic components that have been modeled in the SLS for this project are mentioned in the table A3.1.

- Finally, the following figure shows a chart that summarizes how SLS runs.

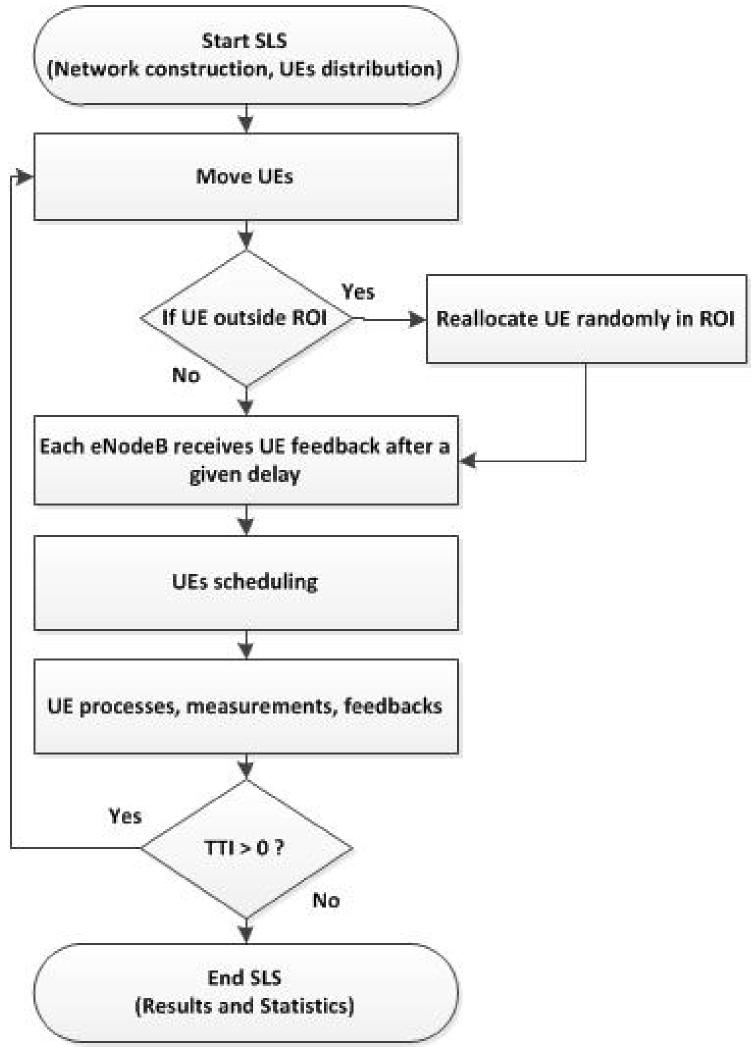


Figure 4.10: SLS flow chart.

4.3. System Level Simulation Metrics

In In this research, several performance metrics have been identified to be used as a means to evaluate and compare all the studies similarly.

- SINR

SINR refers to the amount of useful signal in any transmission divided by the interference combined with noise, averaged over the simulation time t, is measured in dB.

- Throughput

Throughput refers to the number of received bits during SLS for time t seconds, whether by a UE (UE throughput) or by a cell (cell throughput), is measured in Mbps.

- Cell Connection Ratio

Cell connection ratio refers to the number of UEs from a set of them that are connected to a specific cell, it is expressed as a percentage.

- Spectral Efficiency

Spectral Efficiency refers to the information rate that can be transmitted over a given bandwidth, is measured in bps/Hz.

4.4. System Level Simulation Parameters

The assumptions and parameters that are being used in SLS for macro layer and pico layer are summarized in the tables A3.1 and A3.2 in the appendix 3.

Chapter 5. Simulations and Results

5.1. Simulation Stages

Once the theoretical concepts of LTE, LTE-Advanced, HetNets, range expansion have been explained, and part of the system level simulator has been created and validated, the next step is to obtain results in order to compare and evaluate the system performance in the different supposed scenarios.

In this project, there are two main stages of simulation that are used to investigate how could HetNets and range expansion help to meet IMT-Advanced requirements. The first one is to evaluate the impact of HetNets deployment within a macro layer on the system performance overall. The second stage is to evaluate applying range expansion strategy on pico cells for different bias values on the pico cell and overall system performance and so find the maximum possible extension, which is considered the main object of this project.

All assumptions and parameters that were mentioned in the previous chapter, which were summarized in tables A3.1 and A3.2, are implemented during the both simulation stages, unless otherwise stated.

5.2. HetNets Performance Evaluation

As previously mentioned in chapter 3, HetNets are considered an important solution that has been introduced in order to meet and exceed IMT-advanced requirements, as they can improve the system performance overall. Especially in densely populated areas and cell-edges, where other advanced technologies that included in LTE release 8 are unable. The main object of this stage is to investigate the impact of HetNets deployment (pico cell based in this project) using

SLS that has been run twice (macro scenario and macro+pico scenario), the simulation results are discussed with regard to SINR and throughput.

- SINR

The SINR values decrease gradually away from eNodeBs and become less than zero at cell-edges. These less than zero values of SINR cause a severe interference issue for UEs that located at cell-edge. As a result of that, a UE got poor services with lower data rates, since the radio channels and especially the control channels cannot work properly under these bad interference conditions. This situation becomes worse whenever these values go less than zero more.

Deploying pico cells at cell-edges represents an efficient solution to deal with this issue. Figure 5.1 shows 2D SINR maps of the 7 centralized sites where pico cells are drooped for the two assumed scenarios, and the right part shows pico cell positions within macro layer based on table 4.2 assumptions. As it is clear, embedding pico cells improves SINR at macro cell-edges, whereas it is increased if pico cells are placed closer to macro eNodeBs. Deploying pico cells at cell-edges has a positive impact on the entire system, since UEs deal with better interference conditions.

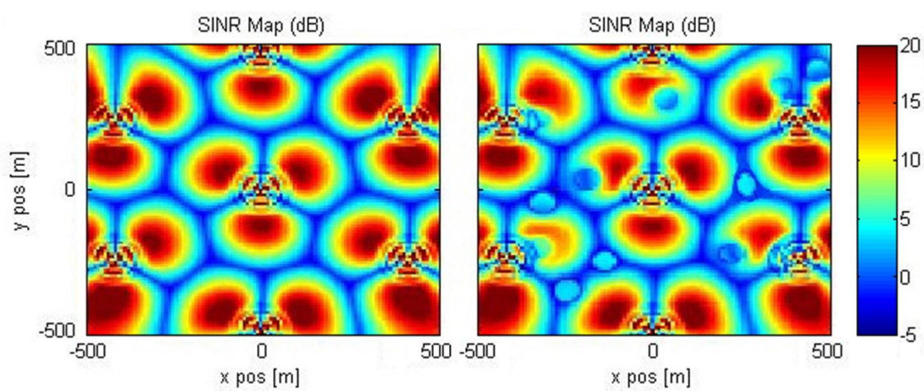


Figure 5.1: HetNets, SINR 2D map with/without pico cell placing.

Shadowing was not included to generate 2D SINR maps in the previous figure only, in order to distinguish pico cells positions and their effects on SINR values easily and clearly.

The following figure illustrates CDFs curves of average UEs SINR for the both scenarios considering all interference factors. The effects of adding pico cells are obvious by comparing the both curves, where the blue curve that represents the macro+pico scenario reflects better interference conditions than macro scenario's curve.

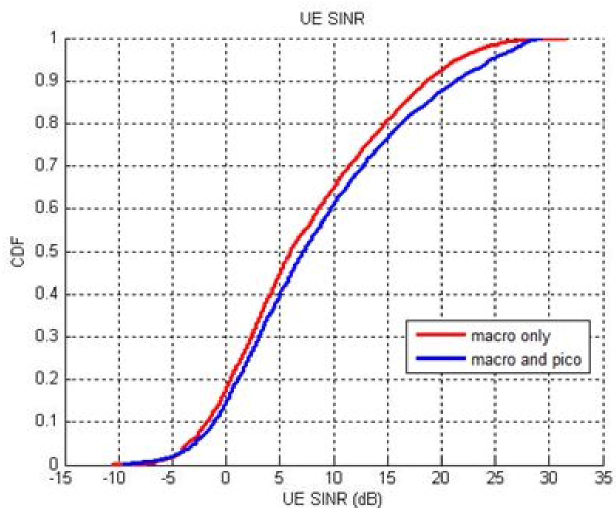


Figure 5.2: HetNets, CDF curves of Average UEs SINR.

- Average UE Throughput

As a result of the offloading of the macro cells traffic to pico cells, the better SINR conditions, the larger number of eNodeBs that allows for more efficient spectrum and bringing the network closer to end UE. The UEs throughput is improved significantly and UEs reach higher peak throughput after pico cells (HetNets) deployment, as is cleared in figure 5.3 that shows CDF curves of Average UE throughput for the both scenarios.

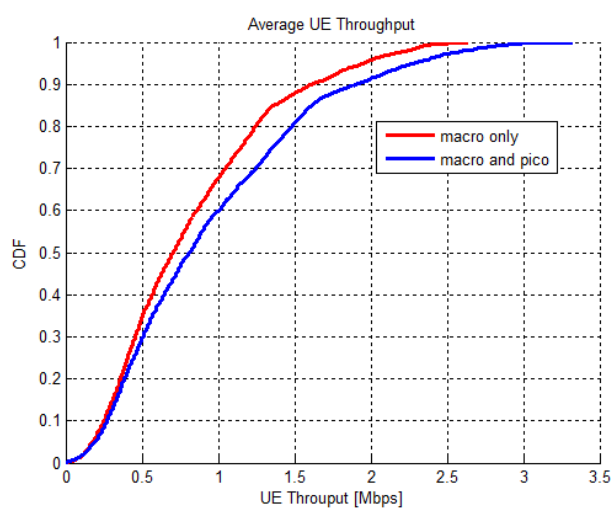


Figure 5.3: HetNets, CDF curves Average UE throughput.

5.3. Pico Cell Range Expansion Performance Evaluation

As pico cells (LPNs) are quite limited by their transmission power and the strong interference from macro cells, which means that only a small percentage of users can benefit from HetNets deployment, especially in cell edges where there is not as many UEs as in hotspots case, which leads to a state of coverage unbalance in terms of UL versus DL. For that, range expansion technique has been proposed to increase HetNets efficiency, offload the macro cell traffic more, attract more UEs to LPNs and solve the UL and DL coverage unbalance.

The considered scenario in this stage is the macro-pico scenario with applying RE technique to pico cells for different bias values. In order to evaluate the RE technique impact on the system performance overall, and investigate of its benefits, the issues that could appear and cause the system performance degradation and the techniques that can be introduced to deal with them. To Achieve that, the study has been divided into two parts considering whether eICIC techniques are implemented in the simulation or not.

In both parts the range expansion technique is applied for different bias values, in order to define the serving cell of a UE from the set ***ʌ.*** The following rule is used:

$$\textit{Serving Cell} = \underset{i\in\Lambda}{argmax}(\ RSRP_{\mathrm{i}} + Bias_{\mathrm{i}}\ ) \qquad (5\text{ - }1)$$

Where *RSRP* and *Bias* are expressed in dB. Bias values that are assumed in this project are {0, 6, 12, 16} dB. In the normal case without RE (bias = 0 dB), the serving cell choice is determined by the highest DL received power (Max RSRP). With RE a UE does not connect to the eNodeB that has the strongest DL received power, for UL the serving cell is determined by the lowest path loss.

5.3.1. Range Expansion Evaluation Without eICIC

The resource partitioning scheme reuse1 is still implemented in this section, since there is no need to mute resource at pico cell side as eICIC technique are not used. The SLS has been run 4 times corresponding to RE bias values. The results are presented and discussed with regard to SINR, average DL/ UL UE throughput and pico cell connections. For SINR, the statistics have been collected for the 7 centralized sites, where pico cells are dropped. Whereas for average DL/UL UE throughput and pico connection ratio, the statistics have been collected for the canalized site (3 macro cells, 3 pico cells).

- SINR

The following figure depicts the CDF curves of UE SINR in the case of pico cell with RE for the assumed RE bias values:

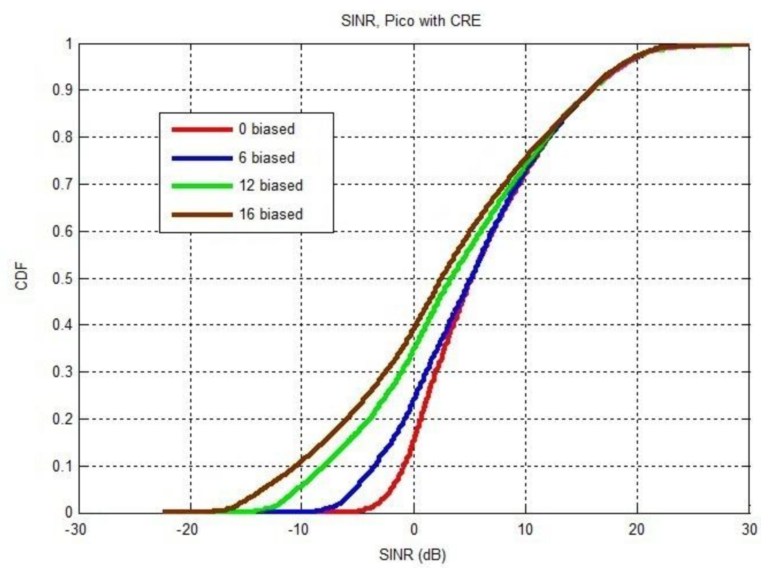
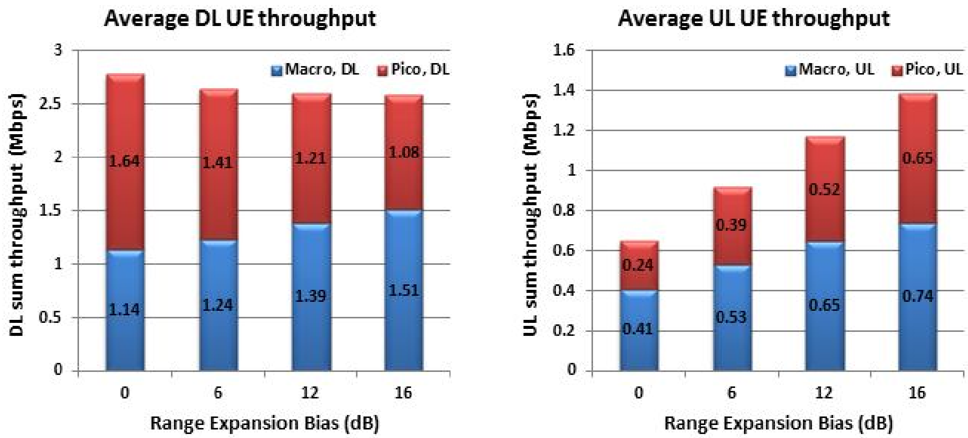


Figure 5.4: RE, CDF curves of UE SINR for assumed RE bias values.

These curves demonstrate that, RE causes obvious interference problem especially when the bias is large and UEs deal with SINR values less than zero too much. This occurs due to UEs being connected to cells that do not provide the strongest DL power at UEs positions. Therefore, RE has a negative impact on the DL, as will be explained more in the next figure.

- Average DL/UL UEs Throughput

Results in Figure 5.5 show the DL sum throughput (figure a) and the UL sum throughput (figure b) of one sector (1 macro cell, 1 pico cell) for the assumed RE bias values. It is clear from left figure that, the downlink sum throughputs decrease with increasing RE bias. While the range expansion is beneficial for MUEs as well in the downlink due to offloading of low-SINR MUEs to pico cells, degradation in the aggregate PUEs throughput is observed for large bias values. This is because the PUEs in the RE region observe poor interference conditions, where the SINRs of these users are always lower than zero. For that, the eICIC techniques should be required.



a) Average DL UE throughput. *b) Average UL UE throughput.*

Figure 5.5: RE, Average DL/ULUE throughput for assumed RE bias values.

On the contrary of DL, that uplink sum throughputs of both the macro cell and the pico cell are improved with increasing bias values. The reason for the improvement is that, with increasing bias, pico cell coverage region is shifted closer to its optimum location, which was limited by the macro cell effect. Since the UEs get connected to closer nodes, they decrease their transmit powers, and cause lower interference to the other nodes. Also low-SINR MUEs are offloaded to the cell-edge pico cells, which further improves the aggregate macro cell throughput. For that, the eICIC techniques should be required.

- Pico Connection Ratio

The following figure illustrates the results of pico cells connection ratio of the centralized site (3 macro cells, 3 pico cells) for the assumed RE bias values:

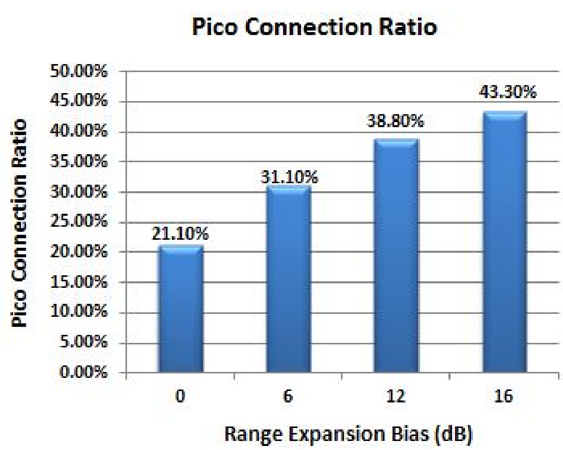


Figure 5.6: RE, pico connection ratio for assumed RE bias values.

Attraction of more UEs to pico cells is considered as an important benefit of RE. As From figure 5.6, it is obvious that pico connection ration increases with RE bias values. The RE technique can adjust the UEs connection ratio to Pico and macro eNodeBs through adjusting bias value, resulting in a positive effect of load and coverage balance between pico cells and macro cells and it is expected that this effect can be more remarkable in actual traffic cases, such as non-full buffer traffic

5.3.4. Range Expansion Evaluation With eICIC

The previous analysis of RE without eICIC demonstrated that, RE technique has important benefits since increases the uplink UEs throughput for both macro cell and pico cell. The attraction of more UEs to pico cells leads to a kind of load and coverage balance between pico cells and macro cells. Nonetheless, RE causes an apparent interference problem which results downlink throughput degradation.

In this section, it is implemented eICIC techniques that can handle with DL interference and so throughput degradation. These are ABS and MBSFN-subframe, which have been explained in chapter 3. For that, the overlap resource partitioning is used to mute corresponding resources of macro cells at pico cells side. The muting ratio of macro cell resource is fixed and equal to 0.5, which implies that half of macro resources, subframes, are muted. In this case the muted subframes could be even subframes or odd subframes. In this project we considered that, even subframes of macro cell are muted and MUEs are always scheduled in the odd subframes, whereas PUEs can be scheduled in all subframes. This implies that PUEs are protected from macro cell interference, and the range extended PUEs may be scheduled in the macro cell even subframes to improve their SINR, which results in DL throughput increasing.

The reference signals (RS-CS) have been implemented as explained in chapter 4, which is modeled through interference averaged over one RB with the average interference factor is equal to 0.1. That is for ABS, where RS-CS are still transmitted in muting resources. Whereas they are put equal to zero for MBSFN-subframes, since the entire resource are muted.

To evaluate RE with eICIC, the SLS has been run first with the basic assumptions (reuse1 and without eICIC) for the assumed RE bias values including zero (without RE). Then the SLS has been run for each eICIC technique (ABS, MBSFN-subframes) 3 times for the RE bias values except 0 dB, which was decided to left as a reference to make the comparison more clear, moreover, ABS and MBSFN-subframes are considered here as solution for RE issues. Although, they could be applied even RE is not implemented. The results have been collected for the centralized site in terms of spectral efficiency of the 5% worst cell-edges UE and cell area (macro+pico), as illustrated in figures 5.7 and 5.8.

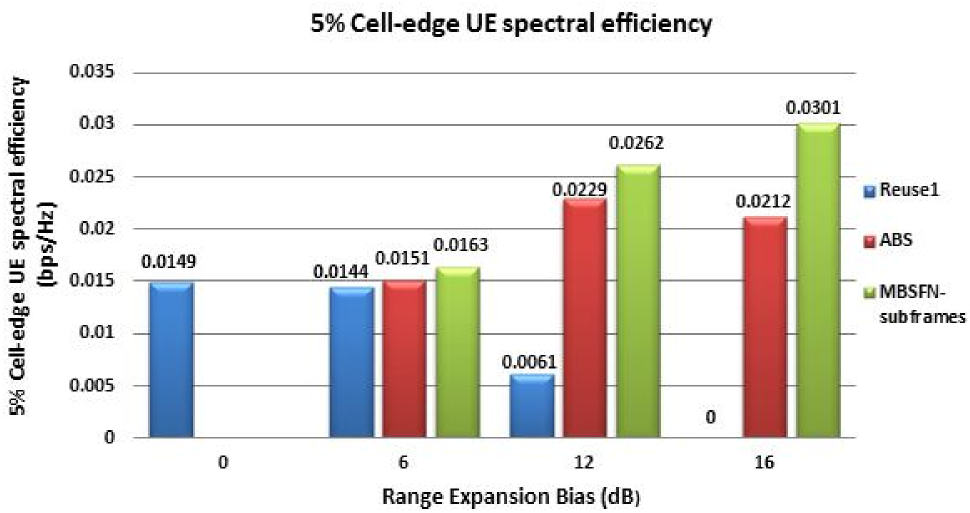


Figure 5.7: RE, 5% Cell-edges UE spectral efficiency.

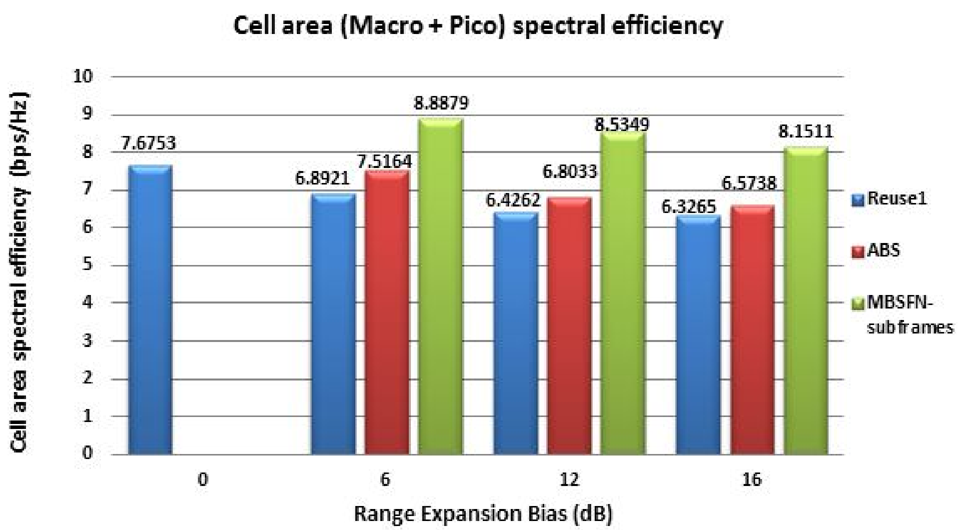


Figure 5.8: RE, Cell area (macro+pico) spectral efficiency.

These results show that, in the reuse1 case there is an apparent degradation problem of the DL throughout whether at cell-edge or cell overall. This results in significant system performance degradation.

ABS can provide a significant benefits to throughput both for edge performance and average performance, and the performance in case of RE with ABS is better than the reference case (reuse1, without RE). In any case, there is a slight degradation especially when a large bias is adopted, since RS-CS are still transmitted and their interference has an impact.

MBSFN-subframes can provide additional benefits than ABS both for cell average performance and edge performance, since RS-CS are not transmitted and muted. That implies more resources are reserved for PUEs. Even when RS-CS are muted, there is a slight degradation with increasing RE bias values, in this sense the resource allocation method could be optimized further, such as by means of advanced resource partitioning schemes and resource muting ratio. Moreover, the increasing of RE bias values is up to a certain value, that can achieve good traffic load balance between macro cells and pico cells and the better system performance, and hence it is not advisable to increase the bias unlimitedly.

Chapter 6. Conclusions and Future Work

6.1. Conclusions

In this report, heterogeneous networks have been evaluated as a part of LTE-Advanced features to meet IMT-Advanced requirements, range expansion has been introduced as an advanced technique to get more benefits from HetNets, and enhanced ICIC techniques (ABS and MBSFN) have been implemented to deal with RE disadvantages. All these steps have been simulated using system level simulator, the first part being developed based on C++, the second part making use of a developed edition of the Matlab Vienna LTE SLS [37]. The results that have been obtained using the simulator in each step have been used to evaluate these technologies, their benefits, their disadvantages and the assumed solution to handle them.

The conclusions from this project are summarizing as follows:

- HetNets deployment improves the system performance overall when compared to the reference case. It improves coverage, capacity, system throughput as well as SINR values, and allows for more efficient spectrum reuse. This results in allowing higher data rates.

- Range expansion technique enhances the UL throughput, coverage and achieves kind of load and traffic balance between macro cell and pico cell by attracting more UEs to pico cell, which is considered as a significant improvement of HetNets deployments. However, with higher RE bias, interference issues become severe and that leads to a DL performance degradation problem of cell-edges UEs. For that, eICIC should be required.

- Enhanced ICIC techniques, such as ABS and the use of MBSFN-subframes, provide an efficient solution to deal with RE disadvantages. Using ABS technique enhances both edge performance and average performance, which increases RE benefits. However, when a large bias is adopted a slight degradation appears due to reference signals (RS-CS) interference, which needs more efficient technique to mitigate such as the use of MBSFN-subframes. MBSFN-subframes can provide additional benefits than ABS both for cell average performance and edge performance, since RS-CS are not transmitted, they are muted. That implies resources for cell-edges UEs perceive less interference in pico cells.

- In any case, the increasing of RE bias values is up to a certain value, that can achieve good traffic load balance between macro cells and pico cells and the better system performance, and hence it is not advisable to increase the bias unlimitedly.

6.2. Future Work

This project opens several lines for further long-term investigation as for example, evaluating the current scenarios for special types of data like, voice and video. Improving the scenarios performance using different assumptions. Developing the system level simulator by adding more components such as, different schedulers, more ICIC and eICIC techniques in order to make fairer the distribution of RBs among users and also to reduce the interference impact. Deploying more pico cells with different configurations and evaluating the effects on the system performance (Hyberdense Networks). Also, adding femto cells within the same macro cell would be interesting in order to investigate the deployment of open access and closed access eNodeBs and see how this mix will effect on the performance of each cell and system performance overall. Introducing an adaptive strategy to set range expansion bias values dynamically according to the changing environment would be important to achieve a better performance of the whole system.

Glossary of Acronyms

3G	Third Generation.
3GPP	3rd Generation Partnership Project
4G	Fourth Generation
ABS	Almost Blank Subframes
ACK/NAK	Acknowledgement/Negative Acknowledgement
ARQ	Automatic Repeat Request
BICM	Bit Interleaved Coded Modulation
BLER	Block Error Rate
CA	Carrier Aggregation
CAGR	Compounded Annual Growth Rate
CDF	Cumulative Density Function
CLSM	Closed Loop Spatial Multiplexing
CoMP	Coordinated Multipoint Transmission/Reception
CQI	Channel Quality Indicator
CP	Cyclic Prefix
CS/CB	Coordinated Scheduling / Beamforming
CSG	Closed Subscriber Group
DFT	Discrete Fourier Transform
DL	Downlink
DSCP	Differentiated Services Code Point
DwPTS	Downlink Pilot Time Slot
EESM	Exponential Effective Signal to Noise Ratio Mapping
eICIC	Enhanced ICIC
eNodeB	Enhanced Node B
EPC	Evolved Packet Core
E-UTRAN	Evolved-UMTS Terrestrial Radio Access Network
FDD	Frequency-Division Duplex

FFT	Fast Fourier Transform
GP	Guard Period
GPRS	General Packet Radio Services
GSM	Global System for Mobile Communications
GTP	GPRS Tunneling Protocol
GW	Gateway
HARQ	Hybrid Automatic Repeat Request
HeNB	Home eNodeB
HetNets	Heterogeneous Networks
HII	High Interference Indicator
HSPA	High-Speed Packet Access
HSPA+	High-Speed Packet Access Plus
HSS	Home Subscriber Server
ICI	Inter Carrier Interference
ICIC	Inter-Cell Interference Coordination
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
IMT	International Mobile Telecommunication
IP	Internet Protocol
IRAT	Inter Radio Access Technology
ISI	Inter Symbol Interference
ITU	International Telecommunication Union
ITU-R	ITU-Radiotelecommunication Sector
JP	Joint Processing
JT	Joint Transmission
L1	Layer 1
L2	Layer 2
LPN	Low Power Node
LTE	Long Term Evolution

MAC	Medium Access Control
MBMS	Multimedia Broadcast/Multicast Service
MBSFN	Multicast/Broadcast Over Single Frequency Network (MB)
MCS	Modulation and Coding Schemes
MIESM	Mutual Information Effective Signal to Interference and Noise Mapping
MIMO	Multiple-Input Multiple-Output
MME	Mobile Management Entity
MUE	Macro User Equipment
MU-MIMO	Multi-User MIMO
NAS	Non-Access Stratum
O&M	Operations and Maintenance
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
OI	Overload Indicator
OLSM	Open Loop Spatial Multiplexing
PCFICH	Physical Control Format Indicator Channel
PCRF	Policy and Charging Rules Function
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
P-GW	Packet Data Network Gateway
PHICH	Physical Hybrid ARQ Indicator Channel
PHY	Physical Layer
PMIP	Proxy Mobile IPv6
PMI	Precoding Matrix Indicator
PRB	Physical Radio Block
PS	Packet Switched
PUE	Pico User Equipment
QAM	Quadrature Amplitude Modulation
QCI	QoS Class Index

QoS	Quality-of Service
QPSK	Quadrature Phase-Shift Keying
RAN	Radio Access Network
RB	Resource Block
RE	Range Expansion
RI	Rank Indication
RLC	Radio Link Control
RLF	Radio Link Failure
RNTP	Relative Narrowband Transmit Power Indicator
ROHC	Robust Header Compression
ROI	Region of Interest
RRC	Radio Resource Control
RRU	Remote Radio Unit
RS-CS	Resource-Specific Cell-Selection
RSRP	Reference Signal Received Power
RSS	Received Signal Strength
SC-OFDM	Single Carrier OFDM
S-GW	Serving-Gateway
SINR	Signal-to-Interference plus Noise Ratio
SLS	System Level Simulator
SONs	Self-Organizing Networks
SU-MIMO	Single-User MIMO
TB	Transport Block
TDD	Time-Division Duplex
TTI	Transmission Time Interval
TxD	Transmission Diversity
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunication System

UpPTS	Uplink Pilot Time Slot
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access

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Appendixes

Appendix 1. Overview of LTE Release 8

A1.1. LTE Release 8 Radio Access

LTE is an OFDM-based radio-access technology, with conventional OFDM on the DL and DFTS-OFDM on the UL [53]. As it has been specified by 3GPP [5], it is characterized by high bandwidth flexibility and simple receiver design, which makes it suitable for receiving high bit rates using large bandwidth, up to 20 MHz. The peak data rate in LTE is 100 Mbps in the DL and 50 Mbps in the UL with 20 MHz spectrum. LTE supports by both time division duplex (TDD) and frequency division duplex (FDD) [54]. LTE spectrum and duplexing schemes are illustrated in figure A1.1.

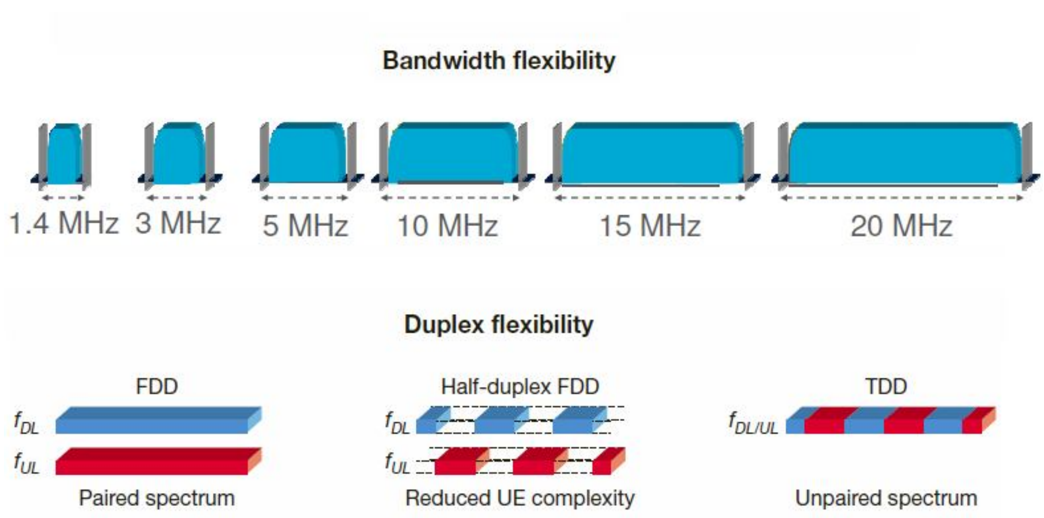

Figure A1.1: LTE spectrum (bandwidth and duplex) flexibility.

In TD-LTE (also known as TDD-LTE) the UL coverage with respect to a specific data rate in is generally worse than FDD-LTE due to the fact that the UL transmission is not continuous. However, the percentage of coverage for control and data channels is very similar in the both cases. Moreover, in FDD-LTE every DL subframe can be associated with an UL subframe, whilst in TD-LTE the number of DL and UL subframes is different and such association is not possible. In terms of spectrum efficiency, the performances of TD-LTE and FDD-LTE are similar for non-delay sensitive traffic, and the lower performance of TD-LTE is due to the guard periods that are essential in TDD [54].

An important requirement in the LTE design has been to avoid unnecessary fragmentation and strive for commonality between the FDD and TDD modes of operation while still maintaining the possibility to fully exploit duplex-specific properties, such as channel reciprocity in TDD. Aligning the two duplex schemes to the extent possible does not only increase the momentum in the definition and standardization of the technology but also further improves the economy of scale of the LTE radio access technology.

A1.2. LTE Release 8 Transmission Schemes

The LTE E-UTRAN (evolved-UMTS terrestrial radio access network) transmission schemes, according to 3GPP specification, are defined as orthogonal frequency-division multiple access (OFDMA) for DL and single carrier frequency division multiple access (SC-FDMA) for UL. OFDMA is parallel transmission of large number of narrowband sub-carriers. SC-FDMA is DFT-precoded OFDM, which will allow for more efficient power amplifier operation, thus providing the opportunity for reduced terminal power consumption. The use of OFDMA on the DL combined with DFTS-OFDM on the UL thus, minimizes terminal complexity on the receiver side (DL) as well as on the transmitter side (UL), leading to an overall reduction in terminal complexity and power consumption [55].

Data symbols are independently modulated and transmitted over a high number of closely spaced orthogonal sub-carriers. The OFDM signals can be generated using inverse fast Fourier transform (IFFT) and demodulated fast Fourier transform (FFT) digital signal processing techniques. Firstly, the OFDM sub-carriers are assigned to some data symbols to transmit and the amplitude and phase of the sub-carriers are determined with the modulation scheme used.

This type of orthogonal spacing removes the inter-carrier interference (ICI). On the other hand, typical multipath phenomena gives rise to the delay spread in the transmission and consequently delayed versions of the signals lead to inter-symbol interference (ISI). This can be easily compensated for by adding the copy of the last samples of the symbol to the beginning part of the symbol [56]. This part is called the cyclic prefix (CP), which comes at the cost of additional power and increased bandwidth requirements to achieve a given target data rate.

The available modulation and coding schemes both in the DL and UL are QPSK (Quadrature phase-shift keying), 16QAM (Quadrature amplitude modulation) and 64QAM for LTE. Then, the frequency domain modulated inputs are transformed into the time domain signal after the IFFT operation. As the last step, the CP is added and digital to analog conversion is performed and the signal is given to the transmission channel. The same stages are executed at the receiver part in reverse order [28], as shown in figure A1.2.

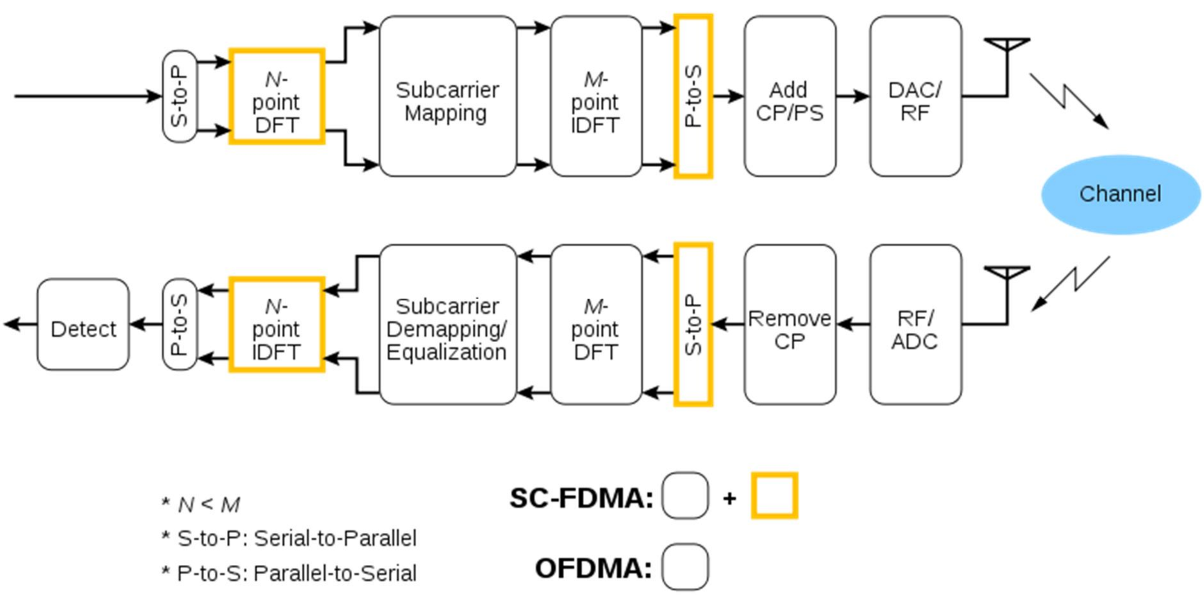

Figure A10.2: OFDMA and SC-FDMA Transmitter and Receiver.

The radio frame structure used for both uplink and DL transmissions is the same. Two frame structure types are defined in E-UTRAN, one for FDD mode and the other is for TDD mode [29], as seen in figure A1.3.

The first type is applicable to both full duplex and half duplex FDD. Each radio frame consists of 10 subframes of 1 ms duration, and twenty 0.5 ms equal length slots, numbered from 0 to 19. Each subframe consists of 2 slots. For FDD, 10 subframes are available for DL transmission and 10 subframes are available for UL transmission in each 10 ms interval. The UL and DL transmissions are separated in the frequency domain.

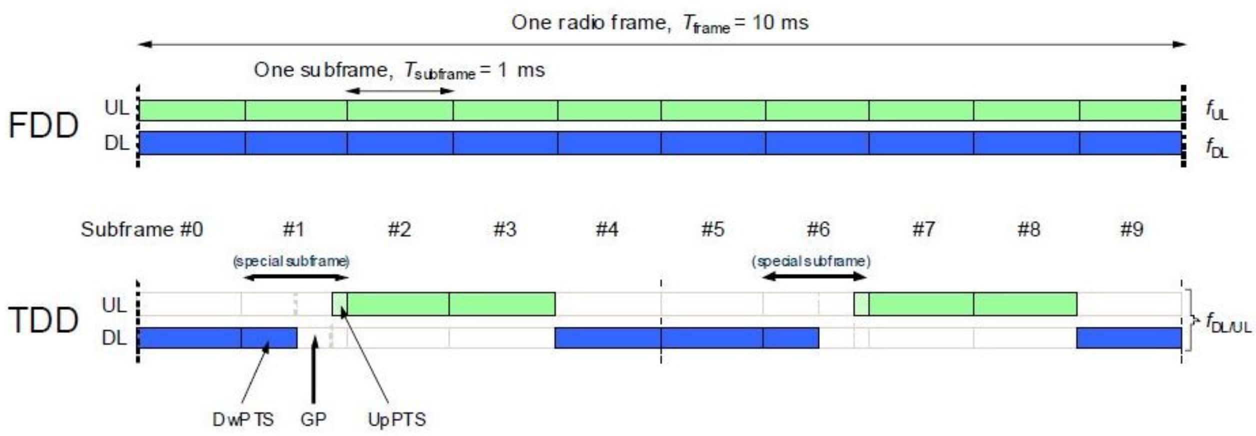

Figure A1.3: LTE Frame Structure.

The second type of frame structure is applicable only in TDD and is provided for compatibility with legacy universal terrestrial radio access (UTRA) TDD systems. Each radio frame consists of two equally sized half-frames. Both half-frames consist of eight 0.5 ms slots and in addition there are special fields called downlink pilot time slot (DwPTS), guard period (GP) and uplink pilot time slot (UpPTS). The DwPTS is used for DL synchronization and initial cell search. The GP determines the maximum cell size and it ensures that a UE transmitting the UpPTS does not disturb the reception of the DwPTS for other close-by UE. The UpPTS is used by the eNodeBs to determine the received power level and received timing from the UE. Subframes 0 and 5 and DwPTS are always reserved for DL transmission. The first switching point between UL and DL is allowed at GP [57, 58].

In the time domain, each subframe consists of 14 OFDM symbols (also called resource elements) which represent a one sub-carrier (sub-frequency). A collection of 12x14 resource elements form one physical radio block (PRB) of 180 kHz and 1 slot. As shown in figure A1.4, each subframe consists of control region of one to three OFDM symbols, used for control signaling, and a data region comprising the remaining part and used for data transmission. The data transmissions in each subframe are dynamically scheduled by the base station using specific reference signals, also called cell reference signals (CRS), are also transmitted in each subframe. These reference signals are used for data demodulation at the terminal, and for measurement purposes [59].

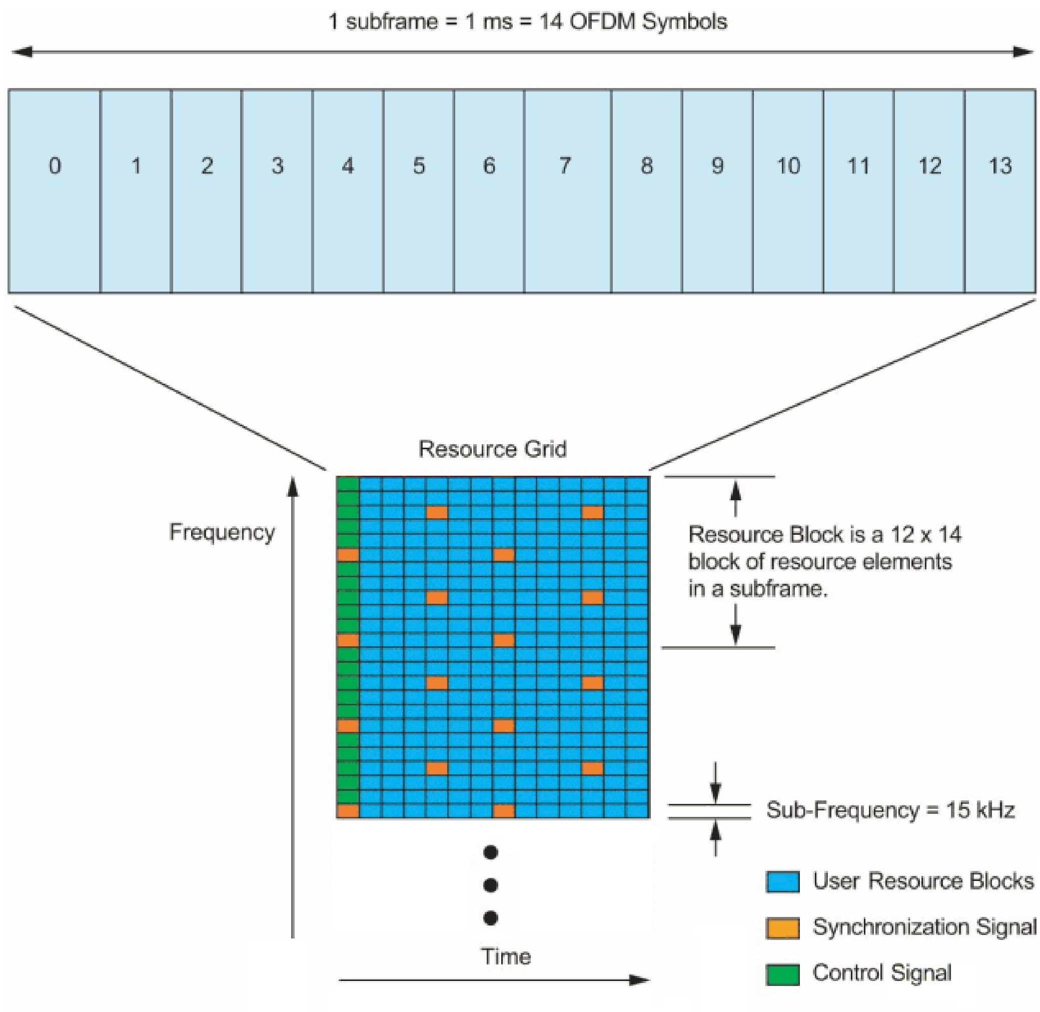

Figure A1.4: LTE Subframe and Resource Grid.

Support for multi-antenna transmission (MIMO) is an integral part of LTE from the first release. DL multi-antenna schemes supported by LTE include transmit diversity, spatial multiplexing, and beamforming [60].

A1.3. LTE Release 8 Network Architecture

LTE is based on a flat network architecture with base stations (eNodeBs in LTE terminology) which provide the user plane functions (PDCP (Packet Data Convergence Protocol), RLC (Radio Link Control), MAC (Medium Access Control) and PHY (Physical Layer)), and control plane terminations towards UEs, including radio resource control (RRC). Against previous 3GPP systems, the eNodeBs are now connected with each other via the X2 interface, connection to the core network (EPC, Evolved Packet Core in LTE) is done via S1 [16], as illustrated in figure

A1.5. The EPC is an evolution from the GSM/GPRS (Global System for Mobile Communications / General Packet Radio Services) core network and supports access to the packet switched (PS) domain only. The EPC consists of the mobile management entity (MME), serving-gateway (S-GW), home subscriber server (HSS), packet data network-gateway P-GW, and policy and charging rules function (PCRF) [60].

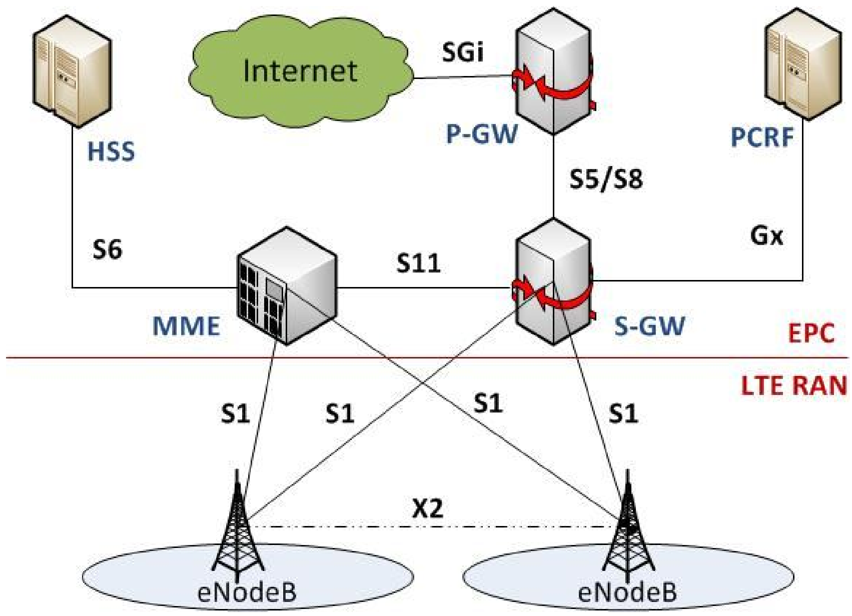

Figure A1.5: LTE network architecture.

The eNodeB is responsible for cell resource management, broadcast information, MME selection, transfer of transparent NAS (non-access stratum) signaling (NAS is highest stratum of the control plane between UE and MME at the radio interface. It supports the mobility of UEs and session management procedures to establish and maintain IP connectivity between the UE and P-GW), routing of user data to S-GW, intra-LTE handover, inter-MME handover, QoS realization and security as well as IP header compression.

The MME is the control plane node of EPC, responsible for connection/release of bearers to terminals, NAS signaling, GW selection, roaming, idle to active mode tracking, paging, inter MME and IRAT (inter radio access technology) mobility, NAS protocols ciphering and integrity protect.

Regarding, user data gateways, the S-GW is a user-plane node connecting EPC to the LTE RAN. It is responsible for the local Mobility Anchor point for inter-eNodeB handover, mobility anchoring for other 3GPP technologies (GSM/GPRS and HSPA) handover (inter-RAT), packet routing and forwarding to PDN (packet data network) via P-GW, lawful intercept, LTE idle mode DL buffering, charging per UE, transporting level packet marking in UL and DL to set DSCP (Differentiated Services Code Point) based on the QCI (QoS class index) of the associated bearer, bearer bindings for both traditional 3GPP networks and non-3GPP networks using GPRS tunneling protocol (GTP) and proxy mobile IPv6 (PMIP) via S5/S8. On the other hand, the P-GW is responsible for working as external IP point, IP address allocation, packet routing and forwarding, lawful intercept, as well as policy enforcement.

The HSS is responsible for subscription data management, user identification handling, access authorization, keys for authentication and encryption, user registration management, as well as maintaining used P-GW. The PCRF is responsible for service data flow gating, setting of QoS for each data flow, defining charging for each data flow, enabling bearer QoS control, correlating application and bearer charging, notifying bearer events to application function, as well as bearer bindings towards S-GW.

A1.4. LTE Release 8 Protocol Stack

The LTE RAN discussed above provides one or more radio bearers to which IP packets are mapped according to their QoS requirements. Figure A1.6 [59] shows different protocol entities of LTE RAN, which are:

- **PDCP,** performs IP header compression (based on robust header compression (ROHC) [61]) to reduce the number of bits to transmit over the radio interface, is also responsible for ciphering and for the control plane, integrity protection of the transmitted data, as well as in sequence delivery and duplicate removal of data during handover.

- **RLC,** is responsible for segmentation, concatenation, retransmission (handling duplicate detection) and in sequence delivery to higher layers. RLC provides services to the PDCP in the form of radio bearers. There is one RLC entity per radio bearer configured for the terminal.

- **MAC,** handles multiplexing of the logical channels, HARQ (hybrid automatic repeat request) transmissions as well as UL/DL scheduling.

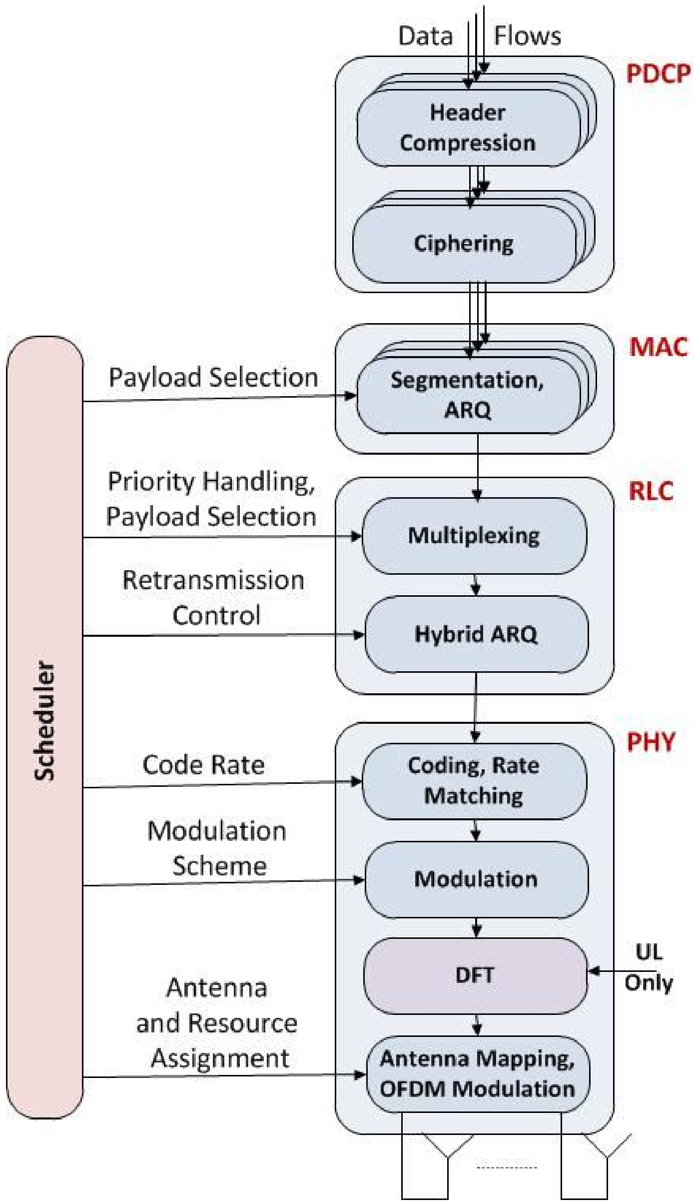

Figure A1.6: LTE Release 8 protocol stack.

The scheduler is a part of the MAC layer, and controls the assignment of UL/DL resources in terms of PRB pairs. The scheduling decision will be taken by eNodeB and the information will be sent to the selected UE for each TTI. The X2 interface will manage the coordination of scheduling decisions between different cells in different eNodeBs.

The HARQ protocol part is present in both the transmitting and receiving ends of the MAC protocol. MAC provides services to the RLC in the form of logical channels.

- **PHY,** handles coding / decoding, modulation / demodulation, multi antenna mapping, and other typical physical layer functions. The physical layer offers services to the MAC layer in the form of transport channels.

Appendix 2. Low Power Nodes Modeling Guide

A2.1. Pico Deployment

A2.1.1. Pico Outdoor Model

- Pico cell is modeled as a 2-dimensional rectangular block (100 x 100 meters) as seen in figure A2.1, which has been used in this project.

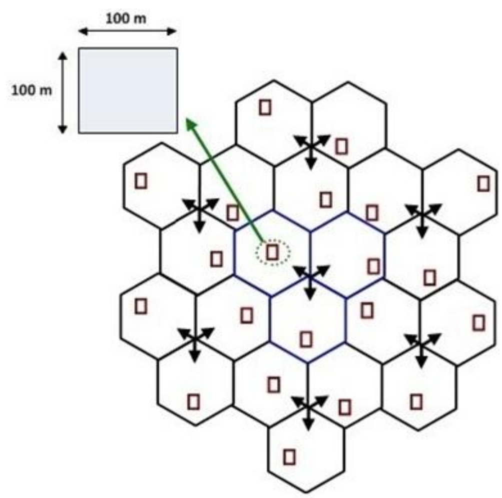

Figure A2.1: Outdoor Pico cells deployment within macro layout.

- Propagation pathloss model:

$$PL\ (dB) = 140.7 + 37.6\log10\ R,\quad R \text{ in km} \qquad (A2-1)$$

A2.1.2. Pico Indoor Model

- The model is a large office building with an open floor plan layout [62]. Figure A2.2 shows a diagram of the environment. The parameters of the Pico environment are the following:

- Building size = 100 x 100 meters
- Room size = 23 x 20 meters
- Corridor width = 4 meters

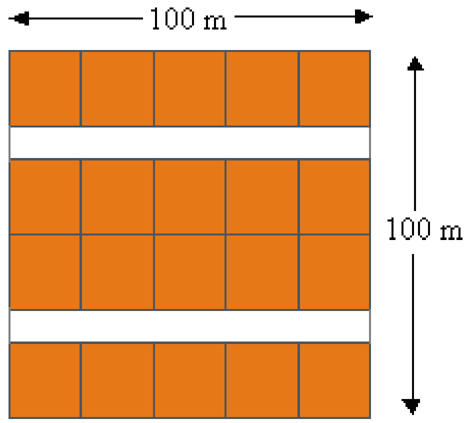

Figure A2.2: Pico indoor model.

- Propagation pathloss model:

$$PL\ (dB) = 38 + 30 \log10 R,\ \ R \text{ in meters} \qquad (A2 - 2)$$

- Outdoor wall penetration loss = 10 dB.

A2.2. Femto Deployment

A2.2.1. Femto Suburban Model

- the model is a 2-dimensional rectangular house (12 x 12 meters), or as a 2-dimensional rectangular house with lot (12f x 12f meters) with f chosen to give desired probability of Femto UE being outdoors in the lot [39].

- Propagation pathloss model:

  - UE is inside the same house:

$$PL\ (dB) = 38.46 + 20 \log_{10}R + 0.7d_{2D,indoor} + 18.3\ n^{((n+2)/(n+1)-0.46)} \qquad (A2 - 3)$$

Where n is the number of penetrated floors, in case of a single-floor house, the last term is not needed.

  - UE is outside:

$$PL\ (dB) = max(15.3 + 37.6log_{10}R,\ 38.46 + 20log_{10}R) + 0.7d_{2D,indoor} + 18.3\ n^{((n+2)/(n+1)-0.46)} + L_{ow} \quad (A2 - 4)$$

- UE is inside a different house:

$$PL(dB) = max(15.3 + 37.6log_{10}R,\ 38.46 + 20log_{10}R) + 0.7d_{2D,indoor} + 18.3\ n^{((n+2)/(n+1)-0.46)} + L_{ow,1} + L_{ow,2} \quad (A2 - 5)$$

Where n is the number of penetrated floors, R is the Tx-Rx separation in m, $d_{2D,indoor}$ is the distance inside the house in m, L_{ow} is the penetration loss of an outdoor wall which is 10dB or 20dB, $L_{ow,1}$ and $L_{ow,2}$ are the penetration losses of outdoor walls for the two houses.

A2.2.2. Femto Urban Model (Dual Stripe Model)

- The model is a 2-dimensional rectangular block that consists of two stripes of apartments, each stripe has 2 by N apartments (N is 10 in the example illustrated in figure A2.3). Each apartment is of size 10m x 10m. There is a street between the two stripes of apartments, with width of 10m. Each femto cell block is of size 10(N+2)m x 70m to make sure that the femto cells from different femto cell blocks are not too close to each other. Each femto cell block has L floors, L is chosen randomly (L could be a number between 1 and 10) [31, 39].

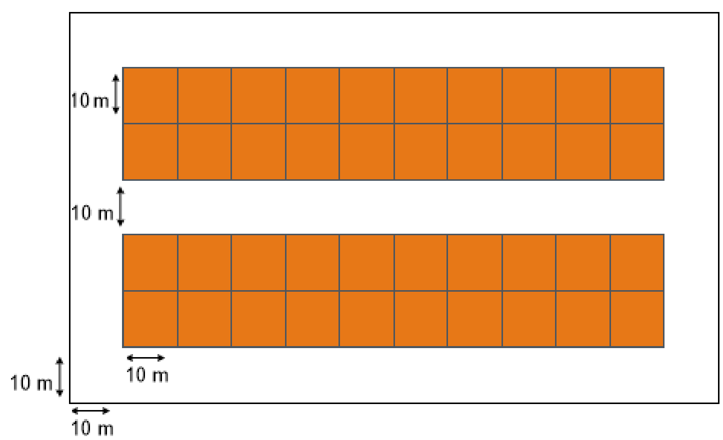

Figure A2.3: Femto urban model (dual stripe model).

- Propagation pathloss model:

- UE is inside the same apartment stripe:

$$PL\ (dB) = 38.46 + 20\ log_{10}R + 0.7d_{2D,indoor} + 18.3\ n^{((n+2)/(n+1)-0.46)} + q*L_{iw} \quad (A2 - 6)$$

In case of a single-floor apt, the last term is not needed.

- UE is outside the apartment stripe:

$$PL\ (dB) = \max(15.3 + 37.6\log_{10}R,\ 38.46 + 20\log_{10}R) + 0.7d_{2D,indoor} + 18.3\ n^{((n+2)/(n+1)-0.46)} + q*L_{iw} + L_{ow} \quad (A2 - 7)$$

- UE is inside a different apartment stripe:

$$PL(dB) = \max(15.3 + 37.6\log_{10}R,\ 38.46 + 20\log_{10}R) + 0.7d_{2D,indoor} + 18.3\ n^{((n+2)/(n+1)-0.46)} + q*L_{iw} + L_{ow,1} + L_{ow,2} \quad (A2 - 8)$$

Where R and d2D, indoor are in m, n is the number of penetrated floors, q is the number of walls separating apartments between UE and femto cell, L_{iw} is the penetration loss of the wall separating apartments, which is 5dB.

A2.2.3. Femto Urban Model (5x5 Grid)

- The model is a single floor building with 25 apartments. The apartments are 10mx10m and are placed next to each other on a 5x5 grid on each floor [31, 39], as seen in figure A2.4.

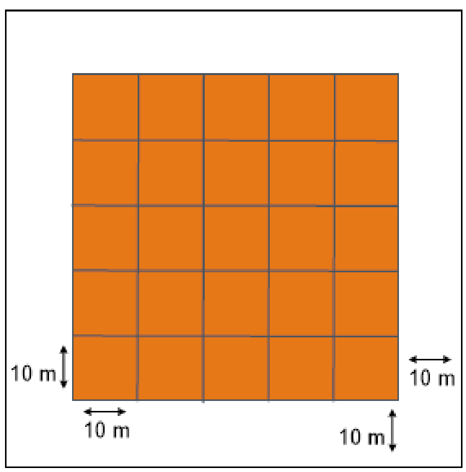

Figure A2.4: Femto urban model (5x5 grid model).

- Propagation pathloss model (No wall modeling):

$$PL(dB) = 127+30\log10\ R,\ \ R\ in\ Km \qquad (A2 - 9)$$

Appendix 3. System Level Simulation Parameters

The assumptions and parameters that are being used in SLS for macro layer and pico layer based on [39, 62] and TR 36.814 [15], are summarized in the following tables.

Parameter	Assumption
Cellular Layout	Hexagonal grid, 3 sectors per site.
Inter-site distance	500 m
Number sites	19 sites (=57 cells) with wrap-around.
Resource Partitioning Scheme	reuse1 (conventional co-channel deployment), where all eNodeBs whether macro cells or pico cells can transmit on all subframes.
Carrier Frequency	2.0 GHz
System bandwidth	10 MHz
RB width	180 KHz, total 50 RBs
eNodeB antenna gain after cable loss	15 dBi
eNodeB noise figure	5 dB
Number of eNodeB antennas	2 Rx, 2 Tx
Antenna Bore-sight points toward flat side of cell (for 3-sector sites with fixed antenna patterns)	
BS TX power	46 dBm
UE Antenna gain	0 dBi
Number of UE antennas	2 Rx, 1 Tx
UE power	23 dBm
UE Noise Figure	9 dB
Thermal noise density	-174 dBm/Hz
Inter-cell Interference Modelling	Explicit modelling (all cells occupied by UEs)
Transmission scheme	CLSM (Closed Loop Spatial Multiplexing)
UEs distribution	UEs dropped with uniform density within the macro coverage area, constant number of users per cell equal to 25 (=75 UEs per site).
Minimum distance between UE and cell	>= 30 m
UE speeds	5 km/h
Pathloss model	PL (dB) =128.1+ 37.6log10R, R in Km
Minimum coupling loss (MCL)	70 dB

Shadowing standard deviation		8 dB
Auto-correlation distance of Shadowing		50 m
Shadowing correlation	Between cells	0.5
	Between sectors	1.0
Fast Fading Model		Pre-Computed Matrix Model
Scheduling algorithm		Round Robin, equally assigns physical resources (RB) to all UEs.
Link to system mapping		MIESM
Link adaptation		CQI/PMI/RI reports with 3ms delay.
HARQ scheme		HARQ-IR, up to 5 retransmission

Table A3.1: SLS, macro cell assumptions.

Parameter	**Assumption**
Cellular Layout	Non uniform distribution, correlated to hotspots
Number of Pico cells	1 Pico cell per Macro cell/site sector
Min. distance between Pico and Macro	50 m
Min. distance between Pico cells	40 m
Carrier Frequency	2.0 GHz
System bandwidth	10 MHz
Pico BS antenna gain after cable loss	2 dBi
Antenna pattern	Omnidirectional
Total Pico BS TX power	24 dBm
Antenna pattern	Omnidirectional
UE distribution	UEs dropped with uniform density within the Pico coverage area, constant number of users per cell equal to 5.
Min. distance between UE and Pico cell	>= 10 m
UE speeds of interest	3 km/h
Pathloss model	PL (dB) =140.7+ 37.6log10R, R in km
Shadowing standard deviation	6 dB
Auto-correlation distance of Shadowing	3 m
Shadowing correlation	0.0

Table A3.2: SLS, pico cell assumptions.