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Coordinated MultiPoint transmission in LTE-Advanced femtocell networks

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Resumo

As redes móveis estão a deparar-se com um aumento do número de dispositivos, do tráfego de dados móveis e da densidade de utilizadores, especialmente em áreas urbanas. A densificação espacial que envolve a densa instalação de pequenos nós e os esquemas de coordenação multiponto que envolvem a cooperação entre recetores, são vistos como soluções para lidar com este problema em redes *Long Term Evolution* e *5th Generation* densas.

Tanto os esquemas de diversidade temporal no uplink, como *Hybrid-Automatic Repeat-reQuest*, podem ser usados para resolver colisões e altos niveis de interferência, que resultam em taxas de erro elevadas, especialmente nos utilizadores que se encontram no limite da célula. Em redes densas, estes esquemas podem ser combinados com esquemas de receção multipacote para aumentar o débito da rede. No entanto, estes esquemas não permitem maximizar o débito, pois são necessários slots extra para resolver as colisões. Esquemas de coordenação multiponto foram propostos para redes *Long Term Evolution-Advanced*, para melhorar a sua capacidade. Nesta dissertação, é proposto um esquema de coordenação multiponto onde os pacotes do transmissor são recebidos simultaneamente em diferentes recetores. Estes estão ligados através de ligações de alta velocidade a uma unidade de processamento, que é responsável pela receção da mensagem utilizando as múltiplas cópias recebidas. Em redes densas, estações base de baixa potência, como as femtocélulas, podem ser usadas para fornecer a diversidade espacial necessária para implementar um esquema coordenação multiponto no *uplink*. De forma a receber a transmissão de múltiplos utilizadores, um esquema de transmissão híbrido é proposto, onde o esquema de diversidade espacial é combinado com receção multipacote e diversidade de potência.

O desempenho do esquema proposto é avaliado para um recetor *Iterative Block De-*

cision Feedback Equalization. Os resultados mostram que a inclusão de mais um recetor num esquema de diversidade temporal e de potência, permite a receção da transmissão de mais utilizadores com uma potência de transmissão menor. A capacidade da rede também é melhorada, verificando-se o aumento no número de pacotes recebidos por slot de tempo.

Palavras Chave: 5G, Cooperative MultiPoint, Multi Packet Reception, Redes Heterógeneas, Iterative Block Decision Feedback Equalization.

Abstract

Cellular networks are facing a rise in the number of mobile devices, in the mobile data traffic and an increase in the user density, specially in urban areas. Spatial densification, which involves the dense deployment of small nodes (e.g. femtocells), and Coordinated Multi Point schemes, which involve the coordination between receivers, are seen as a solution to cope with this problem in dense Long Term Evolution and future 5th Generation networks.

Uplink time diversity schemes, such as Hybrid-Automatic Repeat-reQuest, can be used to deal with the collisions and high interference levels which result in high Packet Error Rates, especially for cell edge users. In dense networks, these schemes can be combined with Multiple Packet Reception to increase the throughput of the network. However, they are far from providing the optimal throughput, since extra time slots are needed to solve collisions. Coordinated Multi Point (CoMP) uplink schemes were proposed to be implemented in Long Term Evolution-Advanced networks to enhance their capacity. In this dissertation a CoMP scheme is proposed where the transmitter's packets are received simultaneously at different Evolved Node Bs (eNodeB). The receivers are connected to a processing unit via a high speed link, which processes the signals with the multiple copies of the messages received. In dense networks, low power base stations such as femtocells may be deployed to provide the spatial diversity needed to implement a CoMP uplink scheme. In order to receive the transmission of multiple users, a hybrid transmission scheme is proposed where the spatial diversity scheme is combined with Multiple Packet Reception and a power diversity scheme.

The proposed scheme's performance is evaluated for a Iterative Block Decision Feedback Equalization receiver. Results show that, the inclusion of one more eNodeB in a power and time diversity reception scheme allows the reception of more users' transmissions with a lower reception power. The network's capacity is also improved, since more packets are received per timeslot.

Keywords: 5G, Cooperative MultiPoint, Multi Packet Reception, Heterogeneous Networks, Iterative Block Decision Feedback Equalization.

Acronyms

3G 3rd Generation

3GPP 3rd Generation Partnership Project

4G 4th Generation

5G 5th Generation

ARQ Automatic Repeat-reQuest

BBU BaseBand Unit

BER Bit Error Rate

BS Base Station

CB Coordinated Beamforming

CC Code Combining

CDMA Code Division Multiple Access

CoMP Coordinated Multi Point

CRE Cell Range Expansion

CS Coordinated Scheduling

CSG Closed Subscriber Group

CSI Channel State Information

C-RAN Cloud-Radio Access Network

DAS Distributed Antenna System

DC Diversity Combining

DFE Decision feedback equalization

DFT Discrete Fourier Transform

DFTS Discrete Fourier Transform Spread

DM-RS Demodulation Reference Signal

DPB Dynamic Point Blanking

DPS Dynamic Point Selection

DSL Digital Subscriber Line

eNB Evolved Node B

EPMC Equal Path MultiChannel

FAP Femtocell Access Point

FD Frequency Domain

FDE Frequency Domain Equalization

FDM Frequency Division Multiplexing

FDMA Frequency Division Multiple Access

FEC Forward Error Correction

FFT Fast Fourier Transform

HII High Interference Indicator

HSDPA High-Speed Downlink Packet Access

HSPA High Speed Packet Access

HSUPA High-Speed Uplink Packet Access

H-ARQ Hybrid-Automatic Repeat-reQuest

IA Interference Alignment

IB-DFE Iterative Block Decision Feedback Equalization

IC Interference Cancelation

ICI Inter-Carrier Interference

ICIC Inter-Cell Interference Coordination

IFFT Inverse Fast Fourier Transform

IMT-A International Mobile Telecommunications-Advanced

ISI Inter symbol Interference

ITU International Telecommunication Union

JP Joint Processing

JT Joint Transmission

LTE Long Term Evolution

LTE-A Long Term Evolution-Advanced

MAC Medium Access Control

MAI Multi Access Interference

METIS Mobile and Wireless Communications Enablers for the Twenty-Twenty Information Society

MIMO Multiple Input Multiple Output

MMSE Minimum Mean Square Error

MPD Multi Packet Detection

MPR Multiple Packet Reception

MUD Multi User Detection

MU-MIMO Multiple User-Multiple Input Multiple Output

OFDM Orthogonal Frequency-Division Multiplexing

OFDMA Orthogonal Frequency-Division Multiple Access

OI Overload Indicator

PAPR Peak Average Power Ratio

PDSCH Physical Downlink Shared Channel

PER Packet Error Rate

PIC Parallel Interference Cancelation

PSK Phase-Shift Keying

QAM Quadrature Amplitude Modulation

QoS Quality of Service

QPSK Quadrature Phase Shift Keying

RAN Radio Access Network

RNTP Relative Narrowband Transmit Power

RRH Remote Radio Heads

SC Single Carrier

SC-FDE Single-Carrier Frequency Domain Equalization

SIC Successive Interference Cancelation

SINR Signal-to-Interference-plus-Noise Ratio

SU-MIMO Single User-Multiple Input Multiple Output

TDMA Time Division Multiple Access

TP Transmission Point

TSG-RAN Telecommunication Solutions Group-Radio Access Network

UE User Equipment

UMTS Universal Mobile Telecommunication System

UTRA UMTS Terrestrial Radio Access

UTRAN UMTS Terrestrial Radio Access Network

WCDMA Wide-Band Code-Division Multiple Access

WG1 Work Group 1

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Chapter 1

Introduction

1.1 Current Context

Mobile wireless communication has experienced a sharp growth over the past years, mainly due to the breakthrough of affordable mobile devices (e.g. smart phones and tablets). Wireless operators have accepted the challenge of cost-effectively supporting a great increase in the traffic demand. Network densification, which is a combination of spatial densification (e.g. dense deployment of small cells, increase the number of antennas per node) and spectral aggregation (i.e. utilizing larger portions of electromagnetic spectrum), is seen as a key mechanism for wireless evolution [BLM+14].

The deployment of additional macro Evolved Node B (eNB)s involves significant costs and elaborate site planning. Heterogeneous networks provide spatial densification and involve the deployment of low power nodes inside a macro cell coverage area. The users in the macro cell can also connect to multiple smaller cells (e.g. femtocells), enabling a decrease of the device density per small cell, if an uniform distribution of users among all the eNBs is ensured. These deployments optimize performance in networks where there is unequal user or traffic distribution by improving cell-edge and/or indoor performance [BLM+14]. Femtocell nodes have a low installation cost and are easy to deploy, which make them attractive solutions to provide spatial densification.

The deployment of low power nodes enables a reduction in the distance between the reception points and the transmitters, leading to an increase in the interfering signal levels, therefore the development of interference mitigation techniques is crucial to improve link efficiency. One of Long Term Evolution (LTE)'s latest releases is known as Long Term Evolution-Advanced (LTE-A) and proposes the use of Coordinated Multi Point (CoMP) reception and transmission techniques. CoMP uplink schemes require coordination between reception points in order to reduce inter cell interference and collisions between transmissions. These techniques can be applied in a Distributed Antenna System (DAS) (e.g. Cloud-Radio Access Network (C-RAN)), where multiple reception points are connected to the same processing unit via a high performance fiber-based backhaul, in order to reduce the interfering User Equipment (UE)'s effects. They are also envisioned as part of the technologies that will be applied in the future 5th Generation (5G) cellular networks [ABC$^+$14].

1.2 Objectives and Contributions

This dissertation explores the capacity enhancements with spatial densification in high density heterogeneous networks. In these networks, multiple reception points (e.g. femtocells) with small distances between them are available to receive the device's transmission, to balance the network's load and to provide joint reception. CoMP is employed to reduce the interference and optimize the performance of the receivers. A Single-Carrier Frequency Domain Equalization (SC-FDE) scheme is used by the mobile devices in the uplink transmission, to assure resistance to frequency selective fading and a lower Peak Average Power Ratio (PAPR), compared to Orthogonal Frequency-Division Multiplexing (OFDM). Furthermore, the receiver considered is an Iterative Block Decision Feedback Equalization (IB-DFE) receiver that can employ Multiple Packet Reception (MPR) and Diversity Combining (DC) techniques to improve reception.

Interference mitigation in high density networks with CoMP uplink schemes is also one of the objectives of this dissertation. An interference model is required and is proposed and simulated. The proposed model is based on the relative position of the different interfering devices to the receivers. The IB-DFE receiver model previously presented in [GDBO12] was extended in order to support heterogeneous noise to simulate the different interference effects at the different receivers. Power, time and spatial uplink signal diversity techniques are employed and compared individually, to verify the different improvements that they can bring to the reception scheme. A hybrid reception scheme that combines these diversity techniques, allowing the increase of the number of users handled per receiver, is also proposed, simulated and compared with the time and power diversity uplink scheme.

1.3 Dissertation Structure

The dissertation structure is organized as follows: Chapter 2 contains a literature review about related work. An overview about LTE multiple access schemes is presented, which includes OFDM and SC-FDE, is followed by a description of some interference cancellation and mitigation schemes and by the description of CoMP uplink and downlink. Chapter 2 ends with the explanation of femtocells, heterogeneous networks and interference scenarios in these networks. In Chapter 3, the model of the IB-DFE receiver is explained and its performance is simulated in different scenarios. Uplink signal diversity schemes are explained, simulated individually and compared. Chapter 4 contains the description of the interference model proposed and of the network topology generator. It is concluded with the proposal and simulation of a hybrid CoMP uplink reception scheme, which combines the uplink diversity schemes previously proposed. Finally, Chapter 5 contains the work conclusions and contains possible future work that can be done by taking this dissertation as reference.

Chapter 2

State of the Art

2.1 Long Term Evolution

Nowadays, due to the technological evolution of mobile networks and devices, the world is facing a rise in the amount of users and a diversification of the services provided by mobile devices. For this reason, in order to assure the satisfaction of the user, there was the necessity to provide higher peak and sustained throughputs, larger user capacity and greater spectral efficiency in mobile networks. Universal Mobile Telecommunication System (UMTS) LTE, also known as the 4th Generation (4G) of mobile telecommunications technology, is the wireless broadband technology created by the 3rd Generation Partnership Project (3GPP) destined to cope with this demand and one of its main challenges is to provide support to the internet based services on mobile devices.

The evolution from 3rd Generation (3G) networks to 4G, started with the first release of Wide-Band Code-Division Multiple Access (WCDMA) Radio Access, entitled release 99, which included circuit switched voice and video services, and circuit and packet switched data services. High-Speed Downlink Packet Access (HSDPA) was introduced in release 5 and High-Speed Uplink Packet Access (HSUPA) in release 6 (these two features are often referred together as High Speed Packet Access (HSPA) [DPS13]). These protocols increased the network's peak data rates, capacity and reduced the latency leading to a mobile system that surpassed the definition of 3G mobile networks. 3GPP defined the specifications for UMTS LTE called UMTS Terrestrial Radio Access (UTRA) and UMTS Terrestrial Radio Access Network (UTRAN) in Release 8 [LKL$^+$12]. With a 20 MHz bandwidth it enabled peak data rates that exceeded 300 Mb/s on the downlink and 75 Mb/s on the uplink. It was one of the first releases to be commercialized and it is mainly deployed in a macro/micro cell layout and uses OFDM as the downlink multiple access scheme and Discrete Fourier Transform Spread (DFTS)-OFDM, also known as SC-FDE, as the uplink multiple access scheme [PFD11]. LTE Release 9 includes features that provide minor enhancements to the previous release such as dual layer beam forming and time-difference-of-arrival-based location techniques [GRM+10].

2.1.1 Evolution to LTE Advanced

LTE-A, also known as 3GPP Release 10, is not a new radio access scheme but represents a significant improvement of LTE Release 8, providing a better user experience. It was designed to meet the International Mobile Telecommunications-Advanced (IMT-A) requirements defined by the International Telecommunication Union (ITU) [PFD11] and uses a variety of techniques such as: carrier aggregation, downlink and uplink spatial multiplexing and CoMP transmission and reception. It is also designed to support its implementation in heterogeneous networks, where low-power nodes are introduced in a macro cell network. These nodes lead to enhancements in the network coverage area and capacity [GRM+10]. Carrier aggregation allows achieving wider bandwidths, up to a maximum of 100 MHz [GRM+10]. This technique consists in the usage of multiple frequency blocks known as Component Carriers, which do not need to be contiguous, for the transmission [PFD11]. Carrier aggregation can also be useful to heterogeneous network deployments because different component carriers can be joined together. The peak data rate to be achieved in Release 10 is 1 Gb/s in the downlink and 500 Mb/s in the uplink [GRM+10]. This can be attained by increasing the number of Component Carriers and the number of antennas used by the transmitter and receiver.

To improve the downlink peak throughput it was proposed an increase from the four spatial multiplexing layers provided by Release 9 to eight layers, meaning that up to eight users can be scheduled in the same time-frequency resource. Improvements in the uplink peak rate were also proposed, with the support of a four layer spatial multiplexing for UEs that may have four transmit antennas [GRM+10]. CoMP techniques allow multiple eNBs to cooperate in the transmission or reception, leading to the mitigation of interference in dense networks and to the rise in the data rate of a cell edge user.

LTE-A is a step towards the transition from the 4G to the 5G wireless system. 5G networks will respond to the expected traffic volume explosion and to the new requirements through a combination of evolved existing technologies and new radio concepts [OBB+14]. Extreme network densification and offloading are seen as key technologies to improve spectral efficiency (i.e. more active nodes per unit area) and to achieve the higher data rates required to support the traffic increase [ABC+14]. In this dissertation, the benefits that come from network densification are analysed.

2.2 Multiple Access Schemes

In a cellular network, it is hard to provide coordination amongst users, so there is the necessity to design schemes that enable multiple users to simultaneously use the transmission resource in the most efficient way. The following subsections present the OFDM and SC-FDE schemes.

2.2.1 Orthogonal Frequency Division Multiplexing

OFDM is a method of digital modulation based on Frequency Division Multiplexing (FDM) and has been adopted as the standard multiple access scheme in LTE and LTE-A. FDM uses band pass filters on the receiver to allow channel sharing over the same bandwidth, with each user transmitting on a sub-band. Adjacent frequency bands are used for transmission, therefore a guard band must be added between multiple channels to allow the receiver to filter successfully the desired signal.

OFDM maximizes spectral efficiency since it allows the overlap of adjacent frequency bands without Inter-Carrier Interference (ICI), because the signals overlap orthogonally. As it can be seen in figure 2.1, for the frequency response of each sub carrier at the centre of the frequency band there is no interference from the adjacent bands, so the sub carriers can be sampled at this frequency. In order to do so, a certain sub carrier spacing is also required. However, the overhead is much less than the needed for the FDM frequency guard bands [TW11]. A cyclic prefix (i.e. the repetition of the last data symbols in a block) is also inserted at the beginning of each block. These symbols are discarded at the receiver and their purpose is to increase the reliability by preventing the contamination of a block with Inter symbol Interference (ISI) from the previous block and to make the received block appear to be periodic [FABSE02], allowing an efficient Fast Fourier Transform (FFT) operation.

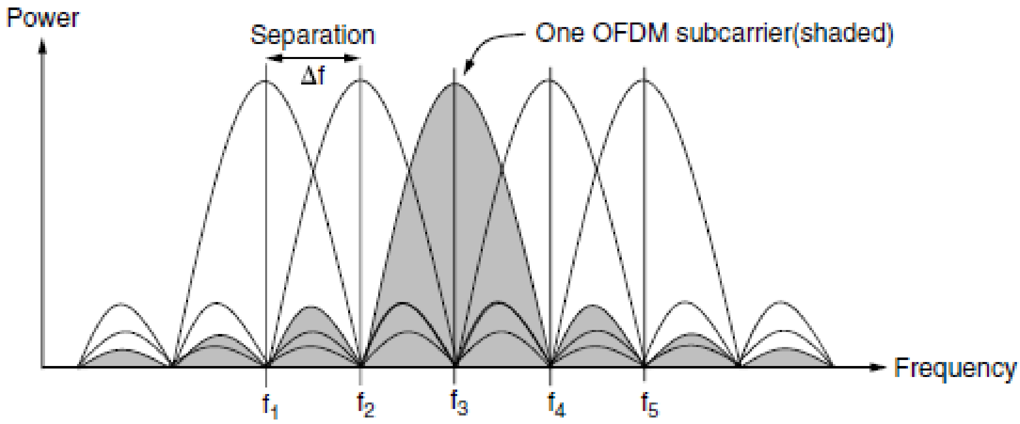

Figure 2.1: OFDM sub-carriers, adapted from [TW11].

This scheme is a Multi-Carrier transmission scheme so the Inverse Fast Fourier Transform (IFFT) is applied to blocks of M data symbols at the transmitter to generate a large number of narrowband sub-carriers that carry different data streams and are transmitted concurrently. Each sub carrier is modulated with a conventional modulation scheme such as Quadrature Amplitude Modulation (QAM) or Phase-Shift Keying (PSK) at a lower data rate than the original data stream, because the data can be spread by multiple carriers. This is an advantage because degradations of the channel are easier to cope at sub carrier level [TW11]. In addition, the use of narrowband sub carriers leads to channels roughly constant over each given sub band, which make equalization simpler at the receiver [BRdTF^{+}08].

OFDM is also resistant to frequency selective fading caused by the use of high transmission rates. The wideband signal channel is divided into multiple narrowband sub carriers that are affected individually by this degradation, so the affected sub carriers can be excluded in favour of the ones that are not affected. ISI is also avoided with the introduction of guard intervals between the symbols.

2.2.2 Single-Carrier with Frequency Domain Equalization

A Single Carrier (SC) system consists in the transmission of a single modulated carrier at a high symbol rate. Equalization is known as the compensation of the linear distortion caused by channel frequency selectivity [BDFT10]. Frequency Domain Equalization (FDE) is more efficient than time domain equalization because operations are carried out in blocks of data at a time [FABSE02]. Frequency domain non-linear equalization consists in using an adaptive equalizer at the receiver to remove ISI, which is one or more linear filters, followed by a cancelling of the remaining interference by using previous detected data [BDFT10]. Decision feedback equalization (DFE) is a non-linear equalization technique that can be used to cancel this interference. In DFE equalizers, symbol-by-symbol decisions are made and the feedback of previous detected symbols is used to remove their interference effect.

OFDM is not the most recommended modulation scheme for the uplink transmission due to the high envelope fluctuations of the waveform [GDBO12] that results of the transmission of data over parallel sub carriers, which can constructively add in phase. This leads to a signal with high PAPR requiring highly linear power amplifiers to avoid intermodulation distortion. High PAPR is critical in the uplink due to power constraints in the UE [BRdTF$^+$08].

SC modulation methods combined with FDE deliver a performance similar to OFDM, guaranteeing immunity to the time-distortion effects introduced by frequency selective fading, with the same overall complexity [FABSE02]. Furthermore the PAPR of the transmitted signal is smaller, since only a single carrier is being used. This enables the use of a cheaper power amplifier than a comparable OFDM system, which is one of the more costly components in a consumer broadband wireless transceiver [FABSE02].

2.3 Wireless Interference Networks

A network where multiple users compete to access the transmission resource is classified as an interference network. These networks can be divided into two types based on the connection between the transmitters and the receivers: wired and wireless networks. Cellular, device to device and WiFi networks are some examples of wireless interference networks.

In interference networks there are two different approaches to handle interfering terminals based on the interference power: if it is weak it should be ignored and treated as noise, as if the interfering terminal is not present in the network; if it is considered to be strong, it should be avoided or cancelled using multiplexing schemes or appropriate pre coding.

These networks deal with the possibility that packets can arrive incorrect or flawed to the receiver due to poor transmission conditions, which can result of high interference level, high noise level or packet collisions. Various techniques that were designed to provide reliability to data transmission over these networks are described in the following subsections.

2.3.1 Hybrid-ARQ with soft combining

The Automatic Repeat-reQuest (ARQ) protocol is used to provide reliability in a data transfer. Basically, once an error is detected in a packet at the receiver, it is discarded and a retransmission is requested to the transmitter. In 1960 a protocol was designed by Wozencraft and Horstein, in which both error correction and error control were provided, known as type-I Hybrid-Automatic Repeat-reQuest (H-ARQ) [CHIW98]. It provided a significant improve in the reliability and throughput provided by pure ARQ protocols, since H-ARQ used the Forward Error Correction (FEC) technique to handle the most common errors, therefore leading to a reduction in the number of retransmissions requested to the transmitter [CHIW98]. However this protocol can be inefficient in good transmission conditions, since the extra parity bits that provide FEC are only increasing the message length and will be wasted, because a strong signal allows the reception of error free messages.

In order to improve this situation, the more sophisticated type-II H-ARQ protocol was designed. This protocol consists in the coding of the message with FEC parity-check bits, only when a retransmission is requested by the receiver. The FEC scheme will only be used if the channel has a bad transmission condition and a packet was received with errors, avoiding the waste of resources that would happen in type-I H-ARQ protocols.

Nowadays these packet combining schemes can be arranged into two categories: Code Combining (CC) and DC schemes. Type II H-ARQ is considered an early version of a code combining scheme. In CC schemes multiple copies of the same packet are concatenated to form noise corrupted codewords with increasingly longer codewords and lower rate codes [CHIW98]. In DC schemes, the individual symbols from identical copies of a packet are combined to create a single packet with more reliable symbols. The DC schemes, such as Sindu's work [CHIW98], usually have a worse performance than CC schemes, however are simpler to implement [GDBO12].

2.3.2 Multiple Packet Reception based on Time Diversity

In networks where multiple users try to access the channel simultaneously, there will be collisions and it is the objective of Medium Access Control (MAC) protocols to avoid them by trying to schedule the multiple transmissions in the most efficient way. H-ARQ techniques are not the best option when multiple users are trying to access the channel because when there is a collision, a user is required to transmit in the next time slot with a given probability [GDBO12]. This does not allow achieving the optimal system throughput, because in a collision between two packets, at least two more time slots will be required, to assure the reception. Furthermore with the usage of this retransmission technique, the flawed packets were still being discarded if the errors were not corrected and no information was exploited from them.

MPR techniques use the resulting signal from a collision between multiple terminals to separate the packets involved [GPB$^+$11]. Time diversity MPR is an approach where the terminals involved in a collision, temporally retransmit the packets under different transmission conditions (e.g. uncorrelated channels, different packet phase rotation, cyclic shifts or frequency-domain scrambling), so the base station can separate successfully all the packets involved in a collision.

Multiple Packet Reception Techniques

MPR allows the receiver to receive two or more signals concurrently [SSCN10]. These schemes require knowledge of the characteristics of the interfering signal. They are more suitable to implement at the eNBs and apply to uplink transmissions [ZANM13]. There are two subdivisions of suboptimal MPR techniques: linear and non-linear.

Linear MPR involves the application of a linear transformation to the soft outputs of the conventional detector to produce a new set of decision variables, decoupling Multi Access Interference (MAI) [LSW12]. The most well-known linear MPR techniques are the decorrelated detectors and the Minimum Mean Square Error (MMSE) detector.

Non-linear MPR can be defined as the reduction of interference at the receiver with the aid of channel estimations provided to the receiver [LSW12]. MultiStage Interference Cancellation is a category of non-linear MPR, where interference cancellation can be carried successively (Successive Interference Cancelation (SIC)) or in parallel (Parallel Interference Cancelation (PIC)). On one hand SIC resolves collisions (i.e. simultaneous arrival of two or more packets to the receiver) by detecting one user per iteration [LSW12]. Considering the collision between the transmissions of two users, the receiver can decode the strongest signal, subtracting it from the combined signal, afterwards the weaker signal can be extracted from the residue. When there is the collision between the transmission of multiple users, firstly the user that delivered the strongest signal is detected and subtracted from the combined signal, afterwards the second strongest and so on [SSCN10], depending on the number of iterations. On the other hand, PIC simultaneously removes from each user the interference produced by the remaining, so it has a higher complexity but a lower latency than SIC [ZANM13]. There is also the Multi User Detection (MUD) technique, that consists in the identification of the signature of each user (e.g. user spreading code used in Code Division Multiple Access (CDMA) transmission) to detect the most probable signal transmitted by a user [ZANM13].

2.3.3 Interference Alignment

In wireless interference networks the frequency spectrum is shared between multiple users, therefore orthogonal access is used to create multiple transmission channels, so the competing information does not get mixed. This can be achieved with multiplexing techniques such as: Time Division Multiple Access (TDMA), where the terminals transmissions are scheduled to different time slots over the same frequency; or Frequency

Division Multiple Access (FDMA), where users transmit at the same time but have their data transmission allocated to different frequency bands.

However multiplexing methods are far from optimal when channel capacity is taken into account [Jaf], since the transmission resource is being cut into multiple smaller pieces. Depending on the amount of users, this leads to the reduction of the data transmission rate of each individual user. The ideal situation would be to have multiple users transmitting simultaneously over the same time and frequency, but this leads to the interference of undesired signals with the transmission of a user.

Interference Alignment (IA) is a pre coding technique that attempts to align multiple interfering signals in space, time or frequency, turning them apparently into one interfering signal not aligned with the intended signals received [Jaf]. Theoretically it allows each transmitter-receiver pair to access half of the spectrum as if there was no interference, since interference can be subtracted. IA is feasible if there is an intelligent design of the signals. It can be done in two ways: by manipulating the transmission channel (using Blind Interference Alignment) or by manipulating the signal input [Jaf].

Although IA can be achieved, shaping the information signal is not a practical application, since it requires that transmitters have full channel knowledge, which is rarely available on wireless networks [Jaf]. If the transmitter has the knowledge of the coefficients that model the channel to the undesired receivers, it just has to invert these coefficients and multiply the signal by them. In this way when all the interfering messages cross the channels they all appear aligned into the same subspace at the receiver and can be treated as a single variable [Jaf].

Blind Interference Alignment

Blind IA [Jaf] is a technique based on the shaping of the transmission channel that provides interference mitigation. It consists in changing the desired transmission channel coefficients and in maintaining the interference carrying channel coefficients over different time transmission slots. This should happen without the transmitters knowing the full channel knowledge or without cooperation between transmitters, not only because it is hard to achieve but because it has been proven that it does not bring any performance improvement to the network capacity [Jaf]. The change in the channel coefficients can be obtained by changing the transmission frequency for a frequency selective fading receiver, by transmitting in a different time slot for a time selective fading receiver or by changing the antenna that receives the transmission at the receiver if it has multiple antennas. Channel shaping allows each receiver to receive the data transmission mixed with the interference. Since, the interfering signal channel may remain constant over simultaneous transmissions, it can be subtracted from the desired signal at the receiver. In a network with M data transmitters and N data receivers a maximum of $M * N$ symbols over $M + N - 1$ channel usages can be send with Blind IA usage [Jaf].

Figure 2.2 depicts a transmission where two transmitters want to send one symbol to each receiver: transmitter 1 wants to send $a1$ to receiver A and $b1$ to receiver B, transmitter 2 wants to send $a2$ to A and $b2$ to B. It can be observed that with Blind IA it is possible to transmit four symbols over 3 channel usages. If the transmission received in the third slot is subtracted to the data received by A in the second slot, the result are two transmissions free of interference (transmission on slot 1 and transmission on slot 2).

2.3.4 Inter-Cell Interference Coordination in Homogeneous Networks

Interference between cells, also known as Inter-cell Interference, is caused by full frequency reuse in 3G and 4G networks, where no frequency partitioning happens between eNBs of the same network [PNS10], so every base station uses full bandwidth for transmission. This leads to performance degradations due to interference, especially at the cell edge where downlink signals from different adjacent transmission cells are received with similar power and uplink signals are transmitted with higher power since they experience high path losses.

In LTE's macro cell deployments, transmission is controlled independently and the scheduling is carried out at the eNB. Inter-Cell Interference Coordination (ICIC) is achieved in a semi-static way through the exchange of coordination messages about the local scheduling plan via the standardized X2 interface [LKL$^+$12], between neighboring eNBs. This information is then used by an eNB to design its own user scheduling. Messages were defined to assist interference coordination in 3GPP's LTE Release 8 specifications

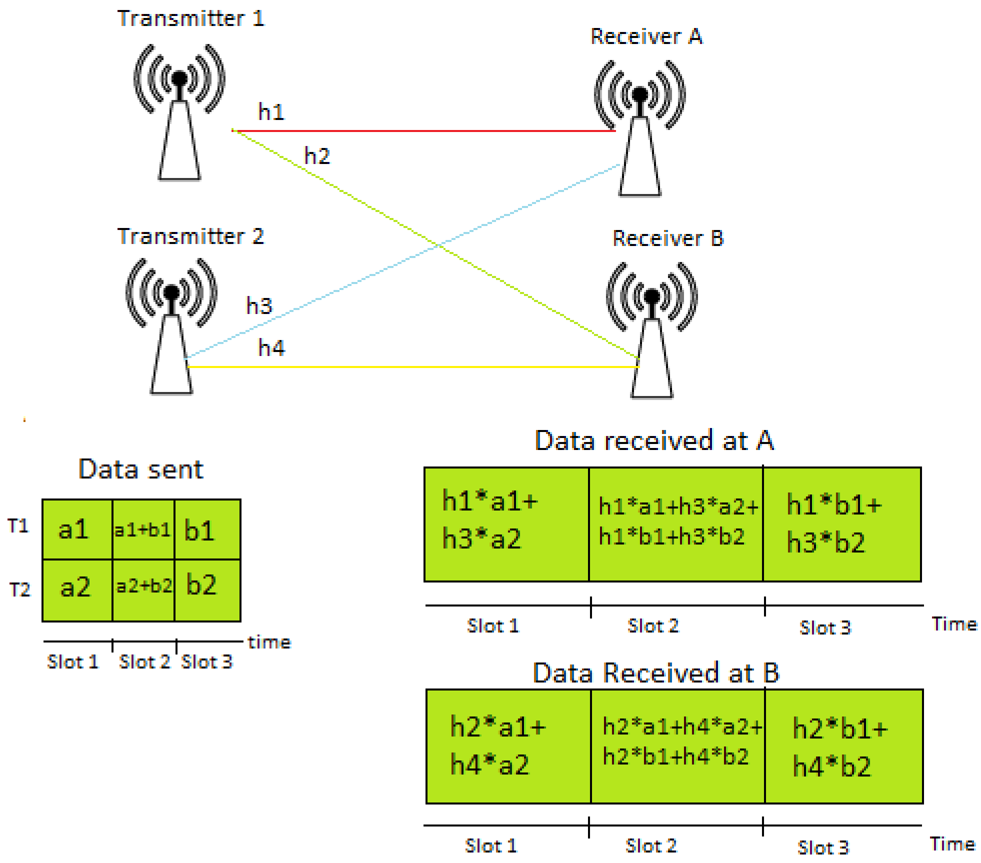

Figure 2.2: Two transmitters simultaneously send 1 message to each receiver over 3 channel usages using Blind Interference Alignment

[PNS10], however the reaction to them was not specified. So it is up to the eNB manufacturer or network manager to define the response to incoming ICIC related messages.

The messages to assist in uplink interference coordination were the: High Interference Indicator (HII) and the Overload Indicator (OI) [DPS13]. The first one provides information about the Resource Blocks that currently have or will have cell edge users scheduled for transmission, which will have high sensitivity for interference. It is classified as a proactive tool for ICIC because it tries to prevent interference before it happens. In order to avoid link degradation for the cell edge users, a viable solution for the eNB that received this message would be to schedule its own cell edge users to a different resource block. The OI is a reactive message that is triggered when high-interference in the uplink is detected by an eNB [PNS10]. It indicates the level of interference experienced in a certain Resource Block, which can have three levels: High, Medium and Low [DPS13].

The neighbouring cell that receives this message should change its scheduling to improve the interference situation for the eNB issuing the OI [DPS13].

The Relative Narrowband Transmit Power (RNTP) message is used to avoid downlink interference. It contains 1 bit per downlink physical resource block, which is set to indicate if the transmission power of the eNB in that specific resource block is going to be greater than a certain threshold [PNS10]. It is a proactive tool since it allows neighbouring cells to use this information to schedule their users' transmissions before the interference happens.

2.4 Coordinated multipoint transmission/reception

Although there were improvements in the peak data rate and network capacity in LTE networks with the upgrade of downlink and uplink techniques such as Single User-Multiple Input Multiple Output (SU-MIMO) and Multiple User-Multiple Input Multiple Output (MU-MIMO), there was still room for improvement with appropriate coordination between points. A point is defined as a set of geographically collocated transmit antennas [LKL+12]. CoMP techniques can be defined as the cooperation between multiple points in order to allow the enhancement of data transmission or reception in cellular networks. They are based on the principle of spatial reuse, where the same time-frequency resource is used for communication at different locations [DPS13]. CoMP was adopted as a key to improve the cell edge user data rate and the spectral efficiency in LTE-A networks at the Telecommunication Solutions Group-Radio Access Network (TSG-RAN) Work Group 1 (WG1) meeting in the 3GPP [SKM+10], allowing higher throughputs. These techniques try to constructively exploit or avoid Inter-Cell interference through coherent base station cooperation [IDM+11]. A study conducted by the 3GPP showed that CoMP can provide not only a higher cell edge user throughput but also an increase in the average system throughput [SKM+10].

These techniques can subdivide themselves in coordination and reception techniques. They are depicted in figure 2.3 and will be explained in the following subsections.

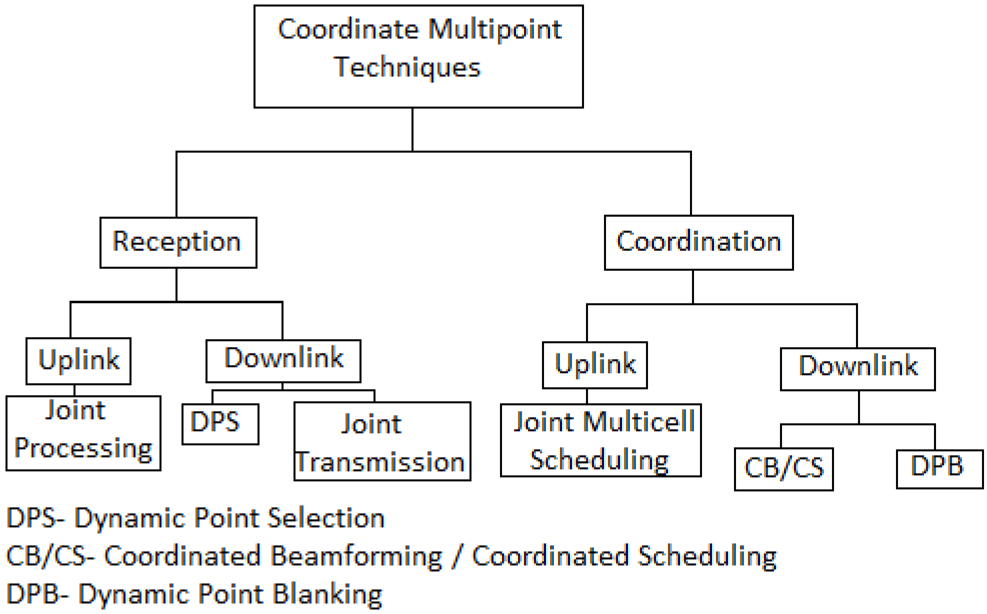

Figure 2.3: Coordinated Multipoint Reception and Transmission techniques

2.4.1 Downlink COMP Schemes

LTE Downlink CoMP schemes can be divided in two different approaches: multipoint coordination, where only one specific point does the transmission but scheduling and link adaptation is done in a cooperative way between transmission points; and multipoint transmission, where the transmission to a single terminal is done simultaneously or dynamically by different transmission points.

Downlink Multipoint Coordination

There were two distinct multipoint coordination schemes presented by 3GPP: Coordinated Beamforming (CB)/Coordinated Scheduling (CS) and Dynamic Point Blanking (DPB). CB is a multipoint coordination scheme where the user beam forming decisions are made in a coordinated manner between the different transmitters. Beam forming weights are generated in a cooperative way for each terminal, by coordinating the pre coder so that the interference to other terminals is reduced [SKM^{+}10] and the power gain in the direction of the receiver is maximized [DPS13], consequently increasing the Signal-to-Interference-plus-Noise Ratio (SINR) of cell edge users.

CS is already deployed in macro cell networks and can be done in a centralized way in distributed networks or by the exchange of scheduling information and ICIC messages between transmitters; this information is used to decide which Transmission Point (TP) should transmit in each slot and to which terminal, in order to prevent the interference experienced by the terminals. The data for the transmission is only available at one base station, called serving cell and the coordination is considered to be semi-static, meaning that it requires previous planning [SKM+10].

LTE-A CoMP admits a more dynamic variation of coordinated scheduling known as DPB. Basically it consists in blanking relevant time/frequency resources in interfering adjacent transmission points on a subframe basis. In order to do that, the network needs to be able to predict dynamically not only the impact on the expected channel quality from neighbouring TPs, but also the improvement of the channel quality if the interfering TPs were not transmitting [DPS13]. This can be done using Channel State Information (CSI) Reports, which reflect different hypotheses regarding the interference of the adjacent TPs.

Downlink Multipoint Transmission

The downlink multipoint transmission schemes can be divided into: Dynamic Point Selection (DPS), where the transmission point can be changed dynamically, and Joint Transmission (JT), where concurrent transmissions are done by multiple points.

The DPS technique only allows the transmission from one point at a single time, however this point can be changed dynamically and this means it can be changed on a sub frame basis. The terminal does not need to be aware of the change in transmission point since it will only see a different Physical Downlink Shared Channel (PDSCH) transmission [DPS13], containing a different Demodulation Reference Signal (DM-RS). The terminal should also provide CSI reports to the different TPs to assist the network in the dynamic selection of the optimal one.

JT is a multipoint transmission technique that takes advantage of the fact that in heterogeneous networks terminals can receive strong signals from multiple TPs simultaneously, and requires the simultaneous transmission of the same data block from multiple coordinated TPs [LKL+12], providing the system with spatial diversity against fading on the radio channel. This technique can be applied if the channels present low mutual correlation [DPS13] and can improve coherently or non-coherently the transmitted signal. Coherent JT exploits the relations in phase and amplitude of downlink signals from different TPs to form precoders that increase the signal quality and throughput, similarly to the coordinated beam forming technique but with the antennas corresponding to different TPs [DPS13]. Non-coherent JT just consists in the delivery of multiple copies of the signal to the receiver by different TPs, representing a power gain in the transmission. Since the extra transmission can produce harmful interference, non-coherent JT is only beneficial in a low load situation where there is no terminal using the extra TP.

2.4.2 Uplink COMP Schemes

Uplink signals can cause interference to nearby receivers which are not the destination of the transmission. Therefore uplink CoMP schemes and better receiver algorithms were designed and standardized, which aim at providing coordination among eNBs of different manufacturers and improving the link quality and cell edge throughput [LKL+12].

The same principles applied in Downlink CoMP schemes can be applied to Uplink CoMP schemes [DPS13]. Therefore, these schemes can be classified as: uplink multipoint coordination schemes, where there is a dynamic coordination of the uplink transmission to reduce interference; and uplink multipoint reception schemes, where the uplink transmission is received at multiple points. Uplink CoMP techniques present less impact on the radio interface specifications for LTE-A than downlink schemes [DPS13] since all the uplink scheduling decisions are made by the network and because a terminal does not need to know where its transmission was received, as long as it receives the corresponding feedback.

Joint multi cell scheduling is a multipoint coordination scheme where the exchange of scheduling and channel information (e.g. SINR) messages between eNBs is required and provided not only to associated terminals but also to neighbouring terminals, in order to allow dynamic link adaptation. This information causes moderate backhaul traffic and requires very low latency [SKM+10], because the channel state indicators lose its purpose if they become outdated.

Since it is hard to provide complete knowledge of the network's different transmission channels at the transmitters, beam-forming is harder to implement on the uplink [DPS13]. However, diversity can be provided with Joint Processing (JP) also known as Cooperative Multiple Input Multiple Output (MIMO), if there is a low mutual correlation between channels. This multipoint transmission technique involves the coordinate transmission of a single traffic flow over multiple points and the exchange of information between cooperating cells, such as the quantized baseband samples of the different receivers, channel state information and resource allocation tables. This causes a high amount of traffic between receivers and increases network complexity, therefore it turns out easier to provide intra-site (i.e. inside the same cell or cluster) JP, since it requires a lower interface throughput and supports a higher latency than intersite JP [IDM+11].

2.5 Femtocells and Heterogeneous Networks

Providing very high system capacity and per-user data rates requires the densification of the network nodes [DPS13], because this leads to the reduction of the distance between the transmitter and the receiver, which diminishes signal fading caused by the path loss attenuation. Low power nodes can coexist in a macro cell network layout forming heterogeneous networks and are seen as a solution to support the increasing demand for network capacity in areas with high clustering of users and high traffic load. Heterogeneous networks are characterized by harsh inter cell interference, due to the different power and types of antennas [LKL+12]. However, these networks will be architected to incorporate an increasingly diverse set of frequency bands [BTAS14].

Femtocells, also called home base stations [CAG08], are short range low-power cheap data access points that can also be deployed in the macro cell coverage and improve the quality of communication by providing good radio coverage to indoor areas where the SINR is low. Heterogeneous networks with Femtocells can reveal themselves really useful since studies on wireless usage show that more than 50 percent of voice traffic and 70 percent of data traffic originate indoors [CAG08] and because indoor attenuation, caused by the penetration losses, is higher than outdoor attenuation. Network's capacity is also increased due to the mitigation of interference of indoor users to outdoor users. The biggest advantage of this network implementation to the telephone companies is the little upfront cost they have [CAG08], since usually these low range cells are bought and installed by the end user.

5G networks require an economically sustainable capacity and performance growth strategy [BTAS14]. Heterogeneous networks are seen as the most promising low-cost approach to meet the industry's capacity growth needs and deliver an uniform connectivity experience [BTAS14], since small cells can be added to increase capacity in high user demand areas and to provide coverage to zones that the macro cell does not cover.

2.5.1 Femtocell Access Modes

Femtocells work as an indoor access point, known as Femtocell Access Point (FAP) [ZANM13], a data connection to multiple devices. Femtocells can be deployed in: an open access, closed access or hybrid access mode. The first consists in the deployment of these low power nodes inside public buildings, improving the coverage of every user in a certain public area, therefore reducing macro cell load and improving their SINR and consequently the network capacity.

The closed access mode is the installation of low power nodes inside closed private buildings, leading to the increase of indoor voice and data coverage and reduction of non-mobile traffic load in the macro cell. It uses a fixed group of subscriber home users, known as Closed Subscriber Group (CSG) [DPS13]. There is also the hybrid access mode, where a limited amount of the femtocell resources are available to all users, while the rest is dedicated solely to the CSG.

Either way the FAP needs be connected to the core operator network via Digital Subscriber Line (DSL), optical fiber cables or cable broadband connection to deliver its data. The connection scheme is depicted below in figure 2.4.

2.5.2 Distributed Antenna System

The DAS is seen as a good solution to implement the deployment of heterogeneous networks, since it provides coordination amongst different base stations. An indoor DAS consists of a set of distributed antennas connected to a home base station (i.e. FAP) [ZANM13], responsible for managing the terminals associated to the antennas. This

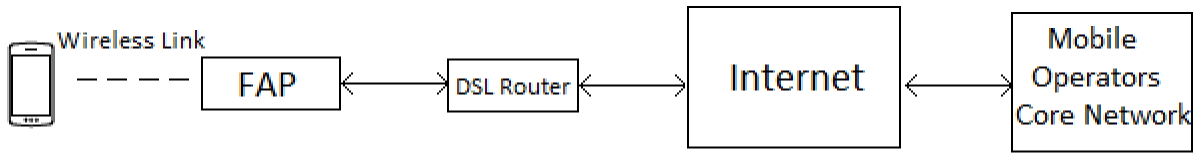

Figure 2.4: Femtocell Access Point Connection to the Operators Core Network using a DSL link

scheme can be generalized into the heterogeneous network layout where home base stations are coordinated together with the high power base stations.

Although the DAS is seen as a good implementation for most heterogeneous networks, some problems can rise in the use of centralized coordination between macro layer networks and femtocell networks. Because of the ad hoc deployment of these low power networks, it becomes hard to provide centralized coordination due to the difficulty in keeping track of neighbouring femtocells [ZANM13].

Cloud-RAN architecture

The Radio Access Network (RAN) of telephone companies consists of base station and base station controllers and provides reliable and available signal coverage over a certain area. Cost savings are only possible if the current RAN architecture is changed, because the biggest capital and operational expenditures of a cell site are the base stations hardware, software and the support of the equipment [HDDM13].

A new RAN architecture based on DAS, uses the IT concept of cloud computing, where software and hardware resources are physically or logically separated from the end user, since these systems have a lot of characteristics in common with mobile systems, like a very large customer base, big geographical service coverage area and high traffic load [HDDM13]. This new architecture is known as C-RAN and consists in the splitting of the classical base station functionalities into a single centralized point (cloud) placed in a technical room, responsible for the BaseBand Unit (BBU) functions such as scheduling and baseband processing, that is connected to multiple Remote Radio Heads (RRH)s placed near the antennas, responsible for the radio frequency operations (e.g. filtering, carrier frequency transposition, power amplification) [LKL+12][HDDM13] in a wide geographical area. The architecture of a C-RAN network is illustrated in figure 2.5.

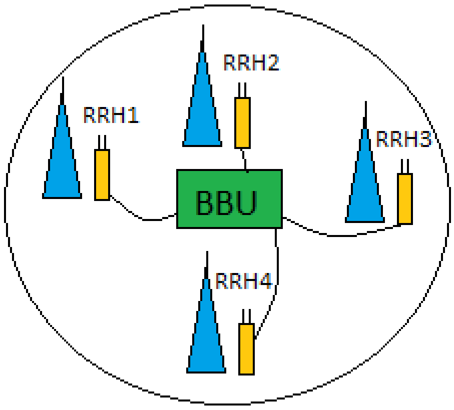

Figure 2.5: C-RAN network Deployment

The decoupling of the BBU functions from the cell site leads to cheaper cell sites due to the lower energy consumption (C-RAN is also known as Green RAN [HDDM13]) and lower complexity of RRH modules, opening up the possibility for an increase of RRHs deployment in areas with high traffic loads, consequently increasing their throughput. This topology allows a BBU to manage several RRHs, leading to unified scheduling of incoming signals and ARQ operations. C-RAN leads to an optimal resource sharing because there is not a fixed dependency between the RRH and the BBU functions, allowing the BBU to allocate dynamically its resource pool according to the network's needs [HDDM13]. The implementation of JP CoMP technique can be easily done in C-RAN networks since all the RRHs in a site are connected to the same BBU and the processing resources inside the BBU are interconnected. There is also a separation between the transmission of terminal control messages and uplink data receivers [LKL+12].

The main obstacle for the implementation of the C-RAN architecture is the transport infrastructure between the centralized BBU unit and the RRH modules. Bandwidth requirements of LTE and LTE-A networks can be very high (for 20 MHz channels and 8x8 MIMO up to 10 Gb/s) and the maximum latency and jitter are very low, allowing a maximum RRH-cloud distance of 20-40 Km considering an optical link connection, due to requirements on the physical layer processing time [HDDM13]. These requirements can only be met with the deployment of high speed optical fiber, that has a high deployment cost. However, the market prices trend for optical links tends to decrease over the next years [HDDM13].

2.5.3 Interference Scenarios in Heterogeneous Networks

Heterogeneous networks present more complex interference scenarios than homogeneous networks, due to the coexistence of high power nodes and low power nodes that use the same frequency spectrum and can be densely deployed in an urban area.

In homogeneous LTE networks a terminal connects itself to a cell based on power measurements of a received downlink signal, more specifically the cell-specific reference signal [DPS13]. No problem arises in these networks since all the nodes have the same transmission power, so the signal received with more strength usually has the lower path loss. However, in heterogeneous networks the TP signal received in the terminal with more strength can have a higher path loss than another low power node signal, since there are TPs with different transmission power. This means that if the node association is done in the same way as in homogeneous LTE networks, terminals will be associated with the highest received power node, even though it has the higher path loss.

To avoid this undesirable effect and increase the efficiency of heterogeneous networks, an offset can be applied to the power measurements done by the terminals in order to compensate the difference in transmission power between different transmission points [DPS13]. This technique is known as Cell Range Expansion (CRE) [BLM+14] and leads to an extension in the coverage area of a low power node. It can be seen as an improvement but as it can be seen in figure 2.6, there will be higher interference levels from the macro TP in the new coverage area since the downlink signal from this TP will be received with a lower path loss fading. Downlink interference to CRE users can be overcome with resource partitioning techniques, where macro cells set aside certain restricted resources for the benefit of CRE users [BLM+14].

In indoor deployments this situation is less critical, since a certain amount of isolation from the macro cell is already provided by the indoor attenuation, so the signal received with more power is usually the one transmitted from the low power node.

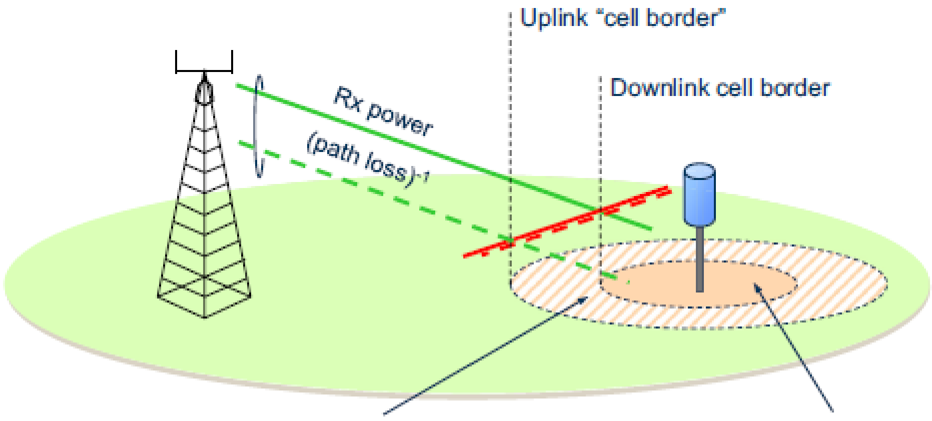

Figure 2.6: High Inter-cell Interference caused by the increase in coverage area of the low power cell. Adapted from [DPS13]

2.5.4 Interference Scenarios in Femtocell Networks

As it was explained in the previous section, if the femtocells are placed specifically in a hot spot (e.g. airports, universities, shopping malls), network gains can be obtained by deploying them without applying a range expansion. Since high capacity is desired in the network, the low power nodes are deployed in a co-channel scheme, meaning that they use the same portion of the frequency spectrum as the macro cells. This leads to inter-cell interference, so some interference management schemes have to be applied in order to mitigate interference. Interference in femtocell networks can be classified as:

Co-Tier Interference - Interference caused between eNBs of the same network that belong to the same tier, i.e. that have the same power and range class. The Quality of Service (QoS) requirement on the femtocell defines the threshold of the SINR needed to create a communication link [ZANM13]. SINR is defined as:

$$SINR = \frac{S}{N + I} \tag{2.1}$$

As it can be seen, interference degrades the SINR and can provoke high link degradation, consequently disabling the communication link between the terminal and the femtocell, creating a dead zone. This probability rises with the quality requirement of the service being provided. Uplink co-tier interference is caused by the UEs when their signal acts as an aggressor to the neighbouring FAPs. On the other hand, downlink co-tier interference is caused by a FAP, since its signal causes interference to the neighbouring UE. In closed access mode it can represent a bigger problem, since the terminals are served by the FAP they subscribed rather than by the strongest FAP.

Cross-Tier Interference - Interference caused between eNBs that belong to different tiers, i.e. have different power and range class. For example, cross tier uplink interference can happen when an UE that uses the services provided by a macro eNB is close to a femtocell operating in closed access mode, to which it does not have access; therefore having its transmission degraded by the strong signals transmitted by the femtocell UE. It can also be concluded that cross tier uplink interference can happen when a macrocell UE does its transmission near the FAP. On the other hand, downlink cross-tier interference happens when the FAP is located near the macro eNB and vice-versa. This kind of interference is more critical when femtocells operate in closed access mode, since in open access mode all the UEs automatically connect to the eNB that provides the strongest signal [ZANM13].

Interference Management in Femtocell Networks

The easiest way to deal with interference is the splitting of the frequency spectrum between adjacent cells. However this leads to the reduction of efficiency in the networks so in order to avoid using this technique, two distinct approaches can be employed to manage interference: avoidance and cancellation.

Interference avoidance schemes involve coordination between the interfering elements to provide a schedule that allows the mitigation of interference. Since it is hard to provide centralized coordination in femtocell networks as it was referred in section 2.4.2, intelligence should be provided to FAP [ZANM13] so they can plan their transmission and their UEs transmission to cope with and avoid interference. Interference Cancelation (IC) schemes use channel estimation and the decoded information, in order to cancel the interference at the receiver. Linear and non-linear MPR can be classified as IC schemes and were described in section 2.3.2.

Interference Avoidance Schemes in Femtocell Networks

The Cooperative schemes presented in section 2.3 (e.g. CS/CB), avoid interference and can be employed on femtocell networks, if the FAP can apply spectrum sensing or if the macro cell eNB can provide the FAP with network information via a backhaul link. Some other interference avoidance schemes that do not involve coordination will be described in this section.

A time hopping scheme can be used on CDMA wireless systems to reduce cross-tier interference [ZANM13]. This scheme suggests that the transmission time period should be divided into multiple smaller portions, being each portion allocated to each user or to a group of users in the same cell, since CDMA systems allow multiple users to transmit at the same time without interfering with each other. No coordination is required between tiers, allowing each tier to divide the transmission time independently [ZANM13].

On Orthogonal Frequency-Division Multiple Access (OFDMA) or CDMA systems, power control schemes can be applied in the low power layer UEs to reduce the interference these can cause to macro cell edge users and eNB. Power control can be performed in Open loop or closed loop [SHLK12]. The open loop setting consists on the adjustment of the transmission power of the UE, based solely on estimations of the cross-tier interference to the macro cell eNB. The performance of this scheme is improved with the usage of the closed loop setting, where the macro cell Base Station (BS) also provides the FAP, via a backhaul link, its noise and interference level [ZANM13].

A particular spectrum splitting scheme can be applied in OFDMA wireless systems without leading to a waste in the network's resources. This scheme consists on the division of the spectrum into two parts, one dedicated to the macro cell and one shared between the macro and the femtocell [SHLK12]. In this way, the macro cell can schedule cell edge users to the dedicated spectrum, avoiding the cross-tier interference they can cause.

There is also a type of Femtocell that is able to perform cognitive functionalities, called cognitive femtocell [ZANM13]. It has the capability of scanning the surrounding frequency spectrum to locate spectrum portions that present low levels of interference and use them for transmission. This intelligent node can be used as an alternative to provide an efficient interference avoidance solution.

Chapter 3

IB-DFE receiver model with uplink signal diversity

CoMP was introduced in LTE advanced to improve the coverage in the border of the cells. In this chapter, it is presented how spatial diversity can improve the performance of the Multi Packet Detection (MPD) receiver presented in [GDBO12]. Power diversity schemes can improve the receiver performance, by determining the optimum offset between the UEs reception's power.

3.1 LTE Femtocell Joint Processing

In order to study the benefits of CoMP transmission techniques, the proposed architecture employs a variation of the uplink MPD scheme used in [GDBO12]. This new scheme uses not only time diversity MPD but also spatial diversity in the reception of the uplink signal. The UEs transmit the packets using time slots, as before, but the signal is received by different eNB (e.g. femtocells) and is combined, providing the uplink signal with spatial diversity.

Even though the reception is done in different eNBs, it works as DAS deployment and allows the uplink signal processing to be done in a centralized way. This allows DC techniques to be used jointly with MPD to deal with packet errors and consequently improve signal reception. This CoMP technique is known as JP and diminishes the transmission degradation caused to cell edge users in dense networks by the harsh interference due to

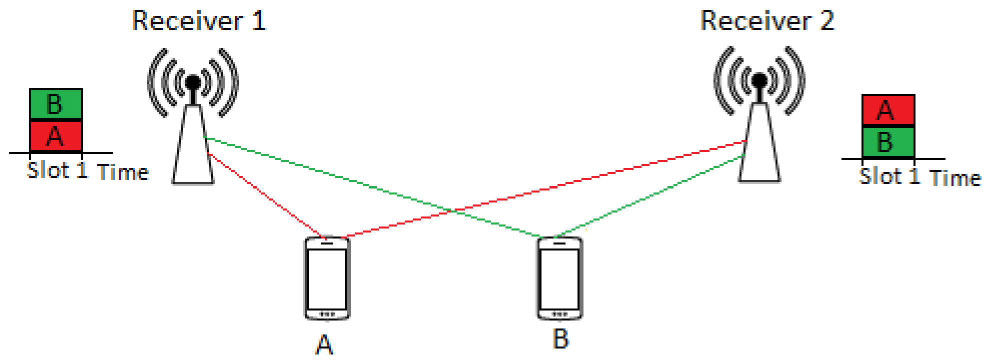

Figure 3.1: Spatial diversity on the uplink

the transmission of nearby terminals.

The benefit that this technique brings to the transmitting devices depends greatly on the distance that the UE has to the multiple eNBs. The path loss attenuation that they have to the eNBs has to be sufficient to allow the reception of the signal with enough power to allow the decoding of the transmission in both eNBs. If this scenario is not achieved, providing the signal with time diversity instead of spatial diversity is more beneficial. Femtocell networks seem a good option to overcome this problem since there is a small distance and consequently a low path loss attenuation between the UE and the multiple reception points. A closed or hybrid access mode deployment is more adequate to implement this system because using femtocell networks can bring coordination problems due to the difficulty in controlling the amount of nodes connected to the network.

JP is also seen as a good scheme to increase system capacity, since the repetition of the uplink packet occurs in the same time slot as the original packet is being sent, so the total bandwidth of the system remains the same. However, when considering one or more extra eNB in the processing of the transmission, the devices associated to that eNB also have to be considered, therefore leading to an increased complexity. A hybrid CoMP solution where time diversity and spatial diversity are combined may be considered to overcome this challenge. In this scenario, the UEs transmit multiple copies of the signal to the different eNBs over the multiple time slots needed to allow a successful separation of all the signals involved in a collision, instead of transmitting only one copy of the signal per eNB.

3.1.1 Network Architecture

The scenario analysed in this dissertation is the uplink communication scheme in a structured wireless system between a set of devices (UEs) and a network of LTE femtocells, using a slotted data channel. UEs are low resource battery operated devices that use SC-FDE with Quadrature Phase Shift Keying (QPSK) modulation in the uplink transmission and femtocells are low power nodes that work as receivers. In every simulation a single small cell layer is considered (of femtocells), which would be part of an heterogeneous layer network using exclusive frequency bands for each layer. These receiver nodes will be deployed in a DAS scheme, so although the reception of the uplink signal can be made in different eNBs, the processing of the received signals is done jointly at the receiver.

In this network, it is considered that all the packets associated to each uplink transmission have the same duration, which corresponds to a FFT block. Perfect channel estimation and synchronization between local oscillators is assumed. A cyclic prefix of different length is added to each FFT block to compensate the different propagation times, so it is assumed that colliding packets arrive simultaneously. In every simulation of this chapter it is admitted that all the UEs transmit with the same power (except when power diversity is introduced) and that every UE present in the network has always a packet to transmit.

Multiple UEs can transmit in the same time slot to the same eNB and more transmissions of the same uplink signal can be used to enhance the reception.

3.1.2 Mobile device association to the eNB

In order to provide spatial diversity to the uplink signal, there can be two or more eNBs deployed in the network. The UEs associate themselves with one of them in order to deliver their uplink transmission. Due to the path loss suffered by the signals transmitted and to the high density of interfering devices in the network, only some of the UEs may have their transmission decoded by the eNBs in the network. In wireless systems, to avoid the waste of battery of the terminal, the uplink transmission usually is done to the eNB that presents the lower path loss. A minimum received power (i.e. a threshold) at the eNB may be defined, so that the power received from the UE is enough to allow the decoding of the transmission in a scenario without interference. The power received at the antenna is obtained using:

$$P_{rx} = P_{tx} + PL \quad (dB). \tag{3.1}$$

The path loss attenuation is a reduction of the power in the transmission caused by the distance to the receiver and by the propagation medium and is modeled using a simplified version of the Friis transmission equation given by:

$$PL = -10nlog_{10}(d) \quad (dB), \tag{3.2}$$

where n is the path loss coefficient and d is the distance between the receiver and the transmitter. In wireless networks, the path loss coefficient value normally ranges from 2 to 4, where 2 is the Free space Path loss coefficient, which is a very optimistic approach. In the simulations in this dissertation it was considered $n = 2.8$ to model the propagation conditions.

The UEs associate themselves with the eNB that receives their uplink transmission with more power, if the power received is higher than a pre-defined threshold. This is considered their primary eNB. Any UE that is not received with enough power at any eNB, cannot be handled unless temporal redundancy is used to enhance the reception. Therefore, for each eNB, there is a maximum range where the UEs can transmit above the power threshold. UEs that are outside of this range are treated as interference. In the CoMP scenario, if an UE is already associated to a primary eNB, it also associates itself to the second nearest eNB, where the original uplink transmission is received, despite the higher path loss their transmission presents to this receiver.

3.2 Receiver Structure

This dissertation considers a MPR scheme based only on the receiver. This means that the receiver is the only responsible for solving possible collisions. Sub optimal MUD techniques are used to separate signals. The signal equalization techniques subdivide themselves in two categories: linear and iterative [LSW12].

3.2.1 Linear Receiver Model

In a Linear MUD, a linear transformation is applied to the soft outputs of the conventional detector in order to produce a new set of decision variables [LSW12]. This allows P concurrent transmissions, for a minimum of $L = P$ individual transmissions, if there is a perfect constant average power control at the reception [GDBO12]. The linear receiver can only solve collisions if the transmission of the colliding UEs is provided with time diversity. This happens when multiple copies of the same packet are transmitted over multiple time slots to the same eNB. A hybrid scheme, where linear MPD is combined with the DC technique, can be used to enhance data reception. In this case, the eNB signals the UEs to transmit their data $L > P$ times when the reception fails with L transmissions. These situations are illustrated in figure 3.2 for the uplink transmission of two devices that are at the same distance from the receiver.

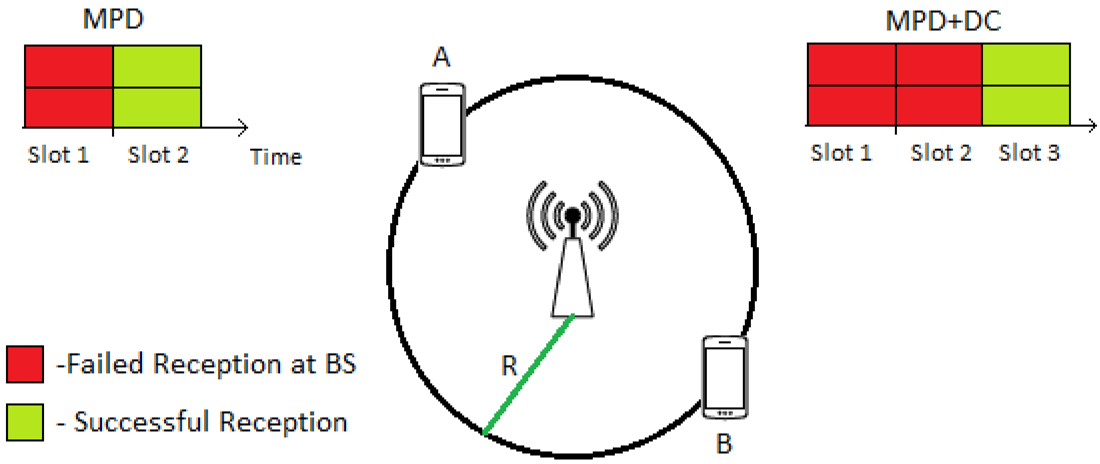

Figure 3.2: MPD and Hybrid MPD+DC technique usage to improve reception at the eNB

The content received at the base station is seen as a linear transformation of the modulated signal transmitted by the UE. Regarding the notation, A is used to denote a matrix, A^T is the matrix transpose of A, A^H is the complex conjugate transpose of A. Considering the frequency domain samples of a data block from a UE p,$\{S_{k,p}; k = 0, \ldots, N-1\}$, assuming we have P UEs transmitting, the transmission is given by $\mathbf{S}_k =$

$[S_{k,1}, \ldots, S_{k,P}]^T$. These P UEs transmit simultaneously during L slots. The received content at the eNB after sampling, removing the cyclic prefix and applying a N-sized Discrete Fourier Transform (DFT) to the received signal is $\{\mathbf{Y}_k; k = 0, \ldots, N-1\}$, where $\mathbf{Y}_k = [Y_k^{(1)}, \ldots, Y_k^{(L)}]$. Every retransmission has a different channel realization due to the physical properties of the propagation medium so $\mathbf{H}_{k,p} = [H_{k,p}^{(1)}, \ldots, H_{k,p}^{(L)}]$. Furthermore the channel noise has to be considered, since wireless networks are being modeled. It is going to be modeled as a Gaussian function and in this work it is considered that noise is heterogeneous (i.e. varies over different transmissions). So $\mathbf{N}_k = [N_k^{(1)}, \ldots, N_k^{(L)}]^T$ represents the channel noise in the frequency domain. The expression of the output in the receiver is given by:

$$\mathbf{Y}_k^T = \mathbf{H}_k^T \mathbf{S}_k + \mathbf{N}_k. \tag{3.3}$$

Equation 3.3 can be expanded:

$$\begin{bmatrix} Y_k^{(1)} \\ \vdots \\ Y_k^{(L)} \end{bmatrix} = \begin{bmatrix} H_{k,1}^{(1)} & \ldots & H_{k,P}^{(1)} \\ \vdots & \ddots & \vdots \\ H_{k,1}^{(L)} & \ldots & H_{k,P}^{(L)} \end{bmatrix} \begin{bmatrix} S_{k,1} \\ \vdots \\ S_{k,P} \end{bmatrix} + \begin{bmatrix} N_k^{(1)} \\ \vdots \\ N_k^{(L)} \end{bmatrix}. \tag{3.4}$$

In section 3.1.2 the path loss fading effect was described and defined as the main criteria to choose which devices are allowed to see its uplink signal treated at the eNB. The attenuation factor for UE p is denoted by $|\xi_{l,p}|$ and the transmission channel $H_{k,p}^{(l)}$ is replaced by $|\xi_{l,p}|\, H_{k,p}^{(l)}$ to account it. Considering that the path loss is constant for all the retransmissions (i.e. its position does not change), equation 3.4 can be changed to:

$$\begin{bmatrix} Y_k^{(1)} \\ \vdots \\ Y_k^{(L)} \end{bmatrix} = \begin{bmatrix} |\xi_1|\, H_{k,1}^{(1)} & \ldots & |\xi_P|\, H_{k,P}^{(1)} \\ \vdots & \ddots & \vdots \\ |\xi_1|\, H_{k,1}^{(L)} & \ldots & |\xi_P|\, H_{k,P}^{(L)} \end{bmatrix} \begin{bmatrix} S_{k,1} \\ \vdots \\ S_{k,P} \end{bmatrix} + \begin{bmatrix} N_k^{(1)} \\ \vdots \\ N_k^{(L)} \end{bmatrix}. \tag{3.5}$$

Since SC modulation is being used, equalization is required to cope with the ISI caused by frequency selective fading. FDE is employed so the estimated data symbol is $\tilde{S}_{k,p} = \mathbf{F}_{k,p}^T \mathbf{Y}_k$. $\mathbf{F}_{k,p}^T = [F_{k,p}^{(1)}, \ldots, F_{k,p}^{(L)}]$ are the feedforward FDE coefficients. A block diagram of the linear receiver with FDE is presented in figure 3.3.

The MUD optimization criterion that is employed in the receiver to minimize ISI

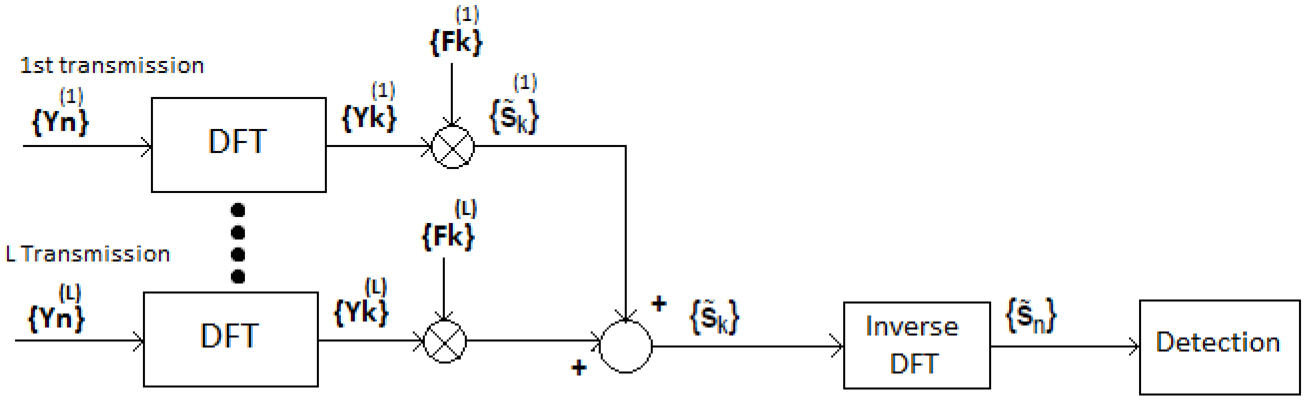

Figure 3.3: Linear Receiver Block Diagram

effects and the channel noise enhancement is the MMSE detection. Knowing that $\mathbf{\Gamma}_p = [\Gamma_{p,1} = 0, \ldots, \Gamma_{p,p} = 1, \ldots, \Gamma_{p,P} = 0]^T$, the mean square error of $S_{k,p}$ for a single UE p is [GDBO12]:

$$\mathbb{E}\left[\left|\tilde{S}_{k,p} - S_{k,p}\right|^2\right] = \mathbb{E}\left[\left|\mathbf{F}_{k,p}^T \mathbf{Y}_k - S_{k,p}\right|^2\right] \tag{3.6}$$

$$= \mathbb{E}\left[\left|\left(\mathbf{F}_{k,p}^T \mathbf{H}_k^T - \mathbf{\Gamma}_p\right) \mathbf{S}_k\right|^2\right] + \mathbb{E}\left[\left|\mathbf{F}_{k,p}^T \mathbf{N}_k\right|^2\right]. \tag{3.7}$$

$\mathbb{E}\left[\mathbf{S}_k \mathbf{S}_k^H\right]$ and $\mathbb{E}\left[\mathbf{N}_k \mathbf{N}_k^H\right]$, represent the variance of the real and imaginary parts of $S_{k,p}$ and $N_{k,p}$, where $\varsigma_N^2 = diag(\sigma_N^{2(1)}, \ldots, \sigma_N^{2(L)})$. In order to obtain the optimal $F_{k,p}$ coefficients under the MMSE criterion, the gradient of the Lagrange function is applied to equation 3.7. resulting [GDBO12]:

$$\nabla J = \nabla \left(\mathbb{E}\left[\left|\tilde{S}_{k,p} - S_{k,p}\right|^2\right] + (\gamma_p - 1)\, \lambda_p \right), \tag{3.8}$$

where λ denotes the Lagrange multiplier and ∇ the gradient of the function. The Lagrange multipliers are constrained to $\gamma_p - 1 = \frac{1}{N} \sum_{k=0}^{N-1} \sum_{l=1}^{L} F_{k,p}^l H_{k,p}^{(l)} - 1$ [GDBO12]. The optimal $F_{k,p}$ coefficients are:

$$\mathbf{F}_{k,p} = \left(\mathbf{H}_k^H \mathbf{H}_k + \frac{\sigma_N^2}{\sigma_S^2} \right)^{-1} \mathbf{H}_k^H \mathbf{\Gamma}_p \left(1 - \frac{1}{2N\sigma_S^2} \right). \tag{3.9}$$

From equations 3.7 and 3.9 results:

$$\sigma_p^2 = \frac{1}{N^2} \sum_{k=0}^{N-1} \mathbb{E}\left[\left|\tilde{S}_{k,p} - S_{k,p}\right|^2\right]. \tag{3.10}$$

For $M^2 - QAM$ constellations with Gray mapping the Bit Error Rate (BER) of a given user p is [GDBO12]:

$$BER_p \simeq \frac{2}{\log_2(M)} \left(1 - \frac{1}{M}\right) Q\left(\frac{1}{\sigma_p}\right), \tag{3.11}$$

being $Q(x)$ the well-known Gaussian Error Function. Considering a QPSK constellation, the BER of a given user p is:

$$BER_p \simeq Q\left(\frac{1}{\sigma_p}\right). \tag{3.12}$$

For an uncoded system with independent and isolated errors, the Packet Error Rate (PER) for a fixed packet size of B bits is given by:

$$PER_p \simeq 1 - (1 - BER_p)^B. \tag{3.13}$$

Linear Receiver Performance

This section presents the PER over $\frac{E_b}{N_0}$ values received at the eNB of the uplink transmission without interference of 3 UEs, for increasing number of copies of the original data packet, obtained using the linear receiver described in section 3.2.1. All packet copies were transmited with the same power and predefined path loss attenuation values were given to the UEs. Although the attenuation was predefined, a normalization of the Path Loss value was admitted to simplify the calculations during the implementation of the algorithm. The attenuation values are all normalized in respect to the UE that has the highest reception power (equivalent to less attenuation when the transmission power is equal), which is set to one. The $\frac{E_b}{N_0}$ values also have to be adjusted because of the normalization. This adjustment is related to the UE that has the lowest path loss attenuation and result in a new set of $\frac{E_b}{N_0}$ values, denoted ω, that is given by:

$$\omega = \frac{E_b}{N_0} + PL_{min} \quad (dB), \tag{3.14}$$

where PL_{min} is the lowest attenuation that an UE has to the eNB. In this example, PL_{min} is not displayed because the path loss values were predefined. UE 1 is the closest to the eNB so does not present attenuation in its uplink transmission, UE 2 has an attenuation of -10 dB and UE 3 has an attenuation of -20 dB. Equal Path MultiChannel (EPMC) channel model is used in the simulations of this dissertation. EPMC models a frequency-selective fading channel, with equal-power multipath components and uncorrelated Rayleigh fading for each path and user. The specifications of the simulation can be observed in table 3.1 and the results are depicted in figure 3.4.

Table 3.1: Specifications for the Linear Receiver performance simulation.

Specifications	
UEs transmitting (P)	3
eNB receivers	1
Transmissions per UE (L)	2 to 4
Iterations of the Receiver	1
Path Loss UE 1	0 dB
Path Loss UE 2	-10 dB
Path Loss UE 3	-20 dB
Channel Type	EPMC

Three different scenarios are depicted in figure 3.4: the first one uses a number of transmissions of the same copy of the packet lower than the number of UEs being treated (i.e. $L < P$), the second uses the same number of transmissions (i.e. $L = P$) and the third one uses a higher number of transmissions (i.e. $L > P$). On the first scenario, only the UE closest to the eNB has a PER lower than 10^{-4}, because its signal was received with more power. This was expected because a linear receiver is being used and as it was referred on section 3.2.1, this type of receivers only allows concurrent transmissions for $L = P$. On the second scenario, MPR was successfully applied and all the 3 packets could be received on the eNB, with PER values below 10^{-4}, although the farther ones required high ω values. The third scenario illustrates the gains in using the hybrid reception scheme with MPR

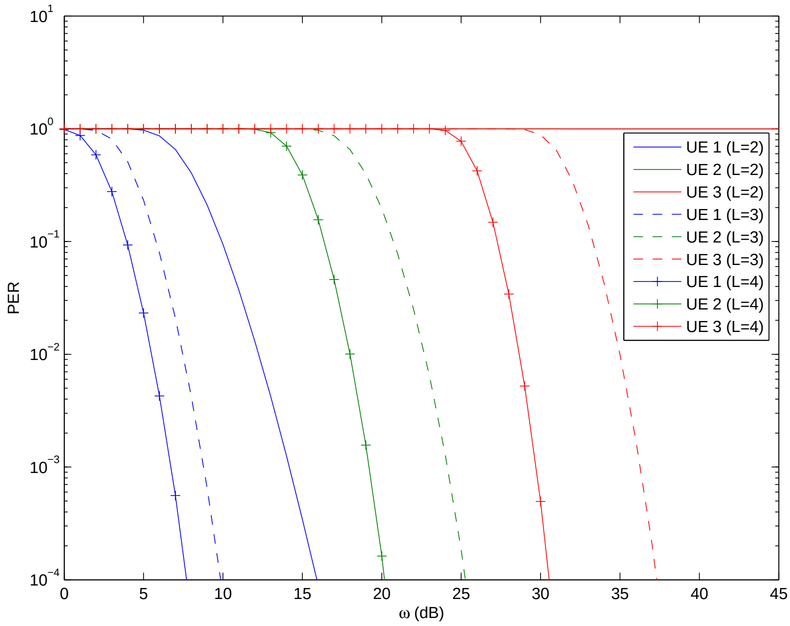

Figure 3.4: PER over ω of 3 UEs in 3 different time diversity scenarios

and DC ($L > P$). The same PERs are achieved with lower values of ω and consequently lower transmission power values. These gains are higher for the devices that are farther away from the eNB. It is also observable that there is a difference in the ω values needed to obtain the same PER values for the three UEs, even though they are using the same number of packet copies, when the three transmissions are successfully decoded. This is due to the path loss attenuation considered in the transmission. UE 3 has the highest distance from the eNB, so it can only get its packet decoded with a higher transmission power and consequently higher ω than the other UE, to compensate the attenuation its signal suffers. On the other hand, since UE 1 has the lowest total attenuation, it is the terminal that can obtain the lowest values of PER with the lowest transmission power values.

3.2.2 Iterative Receiver with soft decisions Model - IB-DFE

The performance of the SC-FDE transmission can be improved if linear FDE equalization is replaced by an iterative equalization technique such as the IB-DFE [GDBO12]. DFE uses the previous decision outputs to estimate the current symbol. The iterative process gradually increases the reliability of the signal estimations, allowing the enhancement of MPR by using SIC. In the first iteration, the receiver behaves like a linear receiver and the feedback coefficients are null.

Using IB-DFE technique, the receiver is capable of successfully receiving more than one packet per time slot. In other words, for a scenario with P colliding UEs they can transmit their data $L < P$ times, and have their transmission successfully decoded. In this scenario each iteration consists of P detection stages. An example of the detection of the collision between two transmissions, where each transmitted simultaneously the same packet twice, is depicted in figure 3.5.

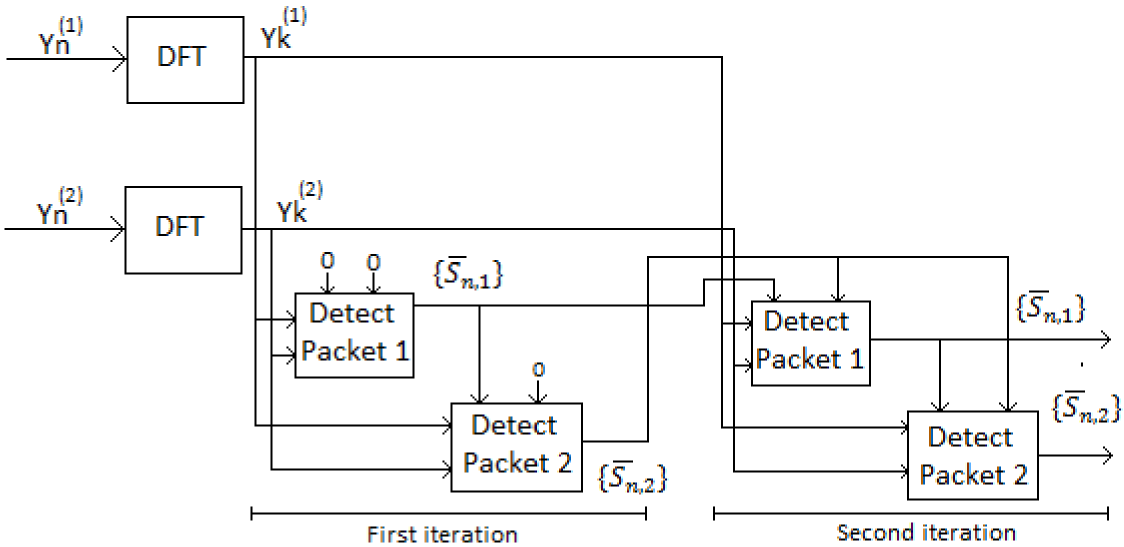

Figure 3.5: Detection diagram of two packets

The IB-DFE equalizer divides itself mainly in two parts: the linear feed forward filter, and the linear, causal, feedback filter. The feedback filter receives the decision from the previous symbol as input and subtracts it to the current estimated symbol to remove ISI and the feedforward filter compensates for channel distortions. The equalization operations are realized in the Frequency Domain (FD), similarly to the linear receiver, where the feed forward equalization was also implemented in the FD. The receiver has as many feedforward filters as the number of copies of the packet transmitted by the UE and as many feedback filters as the number of collisions between packets. The performance of the IB-DFE receiver can be improved using previous symbol averages in the feedback loop instead of blockwise averages (i.e. soft decisions) [DSC07].

Figure 3.6 depicts a block diagram of the detail of the detection of a packet, where there was a collision between N_p different packets and the UEs retransmitted their packet $N_p - 1$ times, using a soft decision IB-DFE receiver.

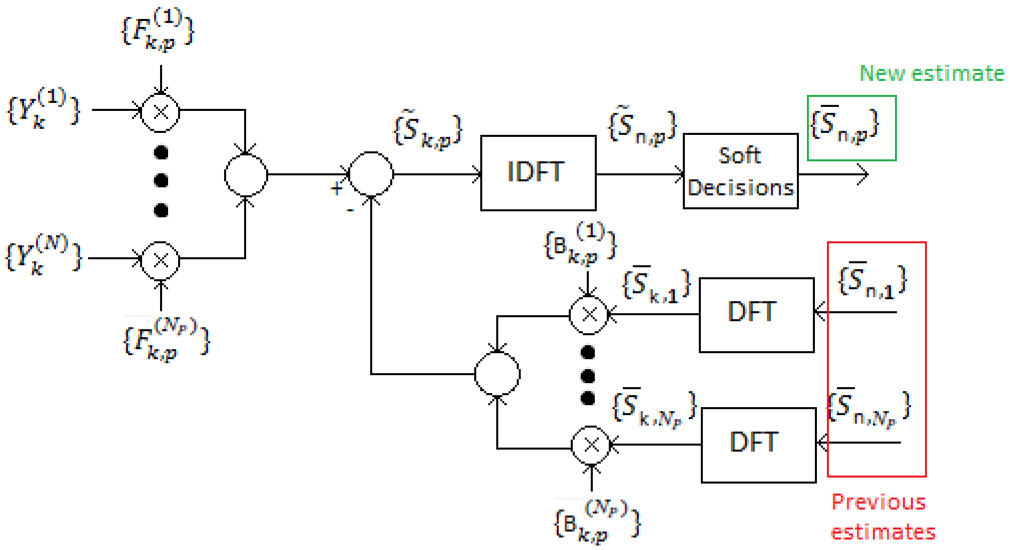

Figure 3.6: Block Diagram of one iteration of the IB-DFE receiver with soft decisions

For a given iteration i and a UE p, the expression of the estimated data symbol is:

$$\tilde{S}_{k,p}^{(i)} = \mathbf{F}_{k,p}^{(i)\,T} \mathbf{Y}_k - \mathbf{B}_{k,p}^{(i)\,T} \bar{\mathbf{S}}_k^{(i-1)}, \tag{3.15}$$

where $\mathbf{F}_{k,p}^{(i)\,T} = [F_{k,p}^{(i,1)}, \ldots, F_{k,p}^{(i,L)}]$ are the feed forward coefficients and $\mathbf{B}_{k,p}^{(i)\,T} = [B_{k,p}^{(i,1)}, \ldots, B_{k,p}^{(i,P)}]$ are the feedback coefficients. $\bar{\mathbf{S}}_k^{(i-1)} = [\bar{S}_{k,1}^{(i-1)}, \ldots, \bar{S}_{k,P}^{(i-1)}]^T$ are the soft decision estimates from the previous iteration for all UEs. $\bar{\mathbf{S}}_k^{(i-1)}$ is related to the symbols' hard decisions, $\hat{\mathbf{S}}_k^{(i-1)}$ and is given by [GDBO12]:

$$\bar{\mathbf{S}}_k^{(i-1)} \simeq \mathbf{P}^{(i-1)} \hat{\mathbf{S}}_k^{(i-1)}, \tag{3.16}$$

where $\mathbf{P}^{(i-1)} = diag(\rho_1^{(i-1)}, \ldots, \rho_P^{(i-1)})$ are the correlation coefficients. For a UE p results:

$$\rho_p^{(i-1)} = \frac{1}{2N} \sum_{n=0}^{N-1} \left| \rho_{n,p}^{I\;(i-1)} \right| + \left| \rho_{n,p}^{Q\;(i-1)} \right|, \tag{3.17}$$

so that:

$$\rho_{n,p}^{I\;(i-1)} = tanh\left(\frac{\left| L_{n,p}^{I\;(i-1)} \right|}{2} \right), \tag{3.18}$$

$$\rho_{n,p}^{Q\ (i-1)} = tanh\left(\frac{\left|L_{n,p}^{Q\ (i-1)}\right|}{2}\right), \tag{3.19}$$

where $L_{n,p}^{I\ (i-1)}$ is the Log likelihood Ratio of the "in phase bit" and $L_{n,p}^{Q\ (i-1)}$ is the LLR of the "quadrature bit" associated to $\tilde{s}_{n,p}^{(i-1)}$:

$$L_{n,p}^{I\ (i-1)} = \frac{2}{\sigma_{n,p}^{2\ (i-1)}} Re\{\tilde{s}_{n,p}^{(i-1)}\}, \tag{3.20}$$

$$L_{n,p}^{Q\ (i-1)} = \frac{2}{\sigma_{n,p}^{2\ (i-1)}} Im\{\tilde{s}_{n,p}^{(i-1)}\}, \tag{3.21}$$

with $\{\tilde{s}_{n,p}^{(i-1)}; n = 0, \ldots, N-1\} = IDFT\{\tilde{S}_{k,p}^{(i-1)}; k = 0, \ldots, N-1\}$. The variance is given by:

$$\sigma_{n,p}^{2\ (i-1)} = \frac{1}{2N} \sum_{n'=0}^{N-1} \left|\hat{s}_{n',p}^{(i-1)} - s_{n',p}\right|^2. \tag{3.22}$$

The Mean Square Error for the estimation of $\tilde{S}_{k,p}^{(i)}$ is given by:

$$\begin{aligned} \mathbb{E}\left[\left|S_{k,p} - \tilde{S}_{k,p}^{(i)}\right|^2\right] &= \\ \mathbb{E}\left[\left|\left(\mathbf{F}_{k,p}^{(i)\ T}\mathbf{H}_k^T - \mathbf{B}_{k,p}^{(i)\ T}\mathbf{P}^{(i-1)^2} - \mathbf{\Gamma}_p\right)\mathbf{S}_k\right|^2\right] & \ldots \\ + \quad \mathbb{E}\left[\left|\mathbf{B}_{k,p}^{(i)\ T}\mathbf{P}^{(i)}\mathbf{\Delta}_k\right|^2\right] + \mathbb{E}\left[\left|\mathbf{F}_{k,p}^{(i)\ T}\mathbf{N}_k\right|^2\right] &= \\ \alpha_{k,p}^{(i)\ *}\mathbf{R}_S\alpha_{k,p}^{(i)\ T} + \mathbf{F}_{k,p}^{(i)\ H}\mathbf{R}_N\mathbf{F}_{k,p}^{(i)} & \ldots \\ + \quad \beta_{k,p}^{(i)\ *}\mathbf{R}_\Delta\beta_{k,p}^{(i)\ T}, \end{aligned} \tag{3.23}$$

where $\mathbf{\Delta}_k$ is a zero mean error vector with correlation $\mathbf{R}_\Delta = \mathbb{E}\left[\mathbf{\Delta}_k\mathbf{\Delta}_k^H\right] \simeq 2\sigma_S^2\left(\mathbf{I}_P - \mathbf{P}^{(i-1)^2}\right)$ and σ_S^2 is the symbol's variance. $\mathbf{R}_S = \mathbb{E}\left[\mathbf{S}_k\mathbf{S}_k^H\right] = 2\sigma_S^2\mathbf{I}_P$ is the correlation of S_k and $\mathbf{R}_N = \mathbb{E}\left[\mathbf{N}_k\mathbf{N}_k^H\right] = 2\sigma_N^2$ with $\sigma_N^2 = diag(\sigma_N^{2^{(1)}}, \ldots, \sigma_N^{2^{(L)}})$ is the noise variance of each transmission. Knowing that $\mathbf{\Gamma}_p = [\Gamma_{p,1} = 0, \ldots, \Gamma_{p,p} = 1, \ldots, \Gamma_{p,P} = 0]^T$, $\alpha_{k,p}^{(i)} = \mathbf{F}_{k,p}^{(i)}\mathbf{H}_k^T - \mathbf{B}_{k,p}^{(i)}\mathbf{P}^{(i-1)^2} - \mathbf{\Gamma}_p$ and $\beta_{k,p}^{(i)} = \mathbf{B}_{k,p}^{(i)\ T}\mathbf{P}^{(i-1)}$. In order to obtain the optimal $\mathbf{F}_{k,p}^{(i)}$ and $\mathbf{B}_{k,p}^{(i)}$ coefficients under the MMSE criterion, the gradient of the Lagrange function is applied to the previous expression, resulting [GDBO12]:

$$\nabla J = \nabla \left(\mathbb{E}\left[\left| S_{k,p} - \tilde{S}_{k,p}^{(i)} \right|^2 \right] + \left(\gamma_p^{(i)} - 1 \right) \lambda_p^{(i)} \right), \tag{3.24}$$

where the Lagrange multipliers are constrained to $\gamma_p^{(i)} - 1 = \frac{1}{N} \sum_{k=0}^{N-1} \sum_{l=1}^{L} F_{k,p}^{(i,l)} H_{k,p}^{(l)} - 1$. So the optimal $\mathbf{F}_{k,p}^{(i)}$ and $\mathbf{B}_{k,p}^{(i)}$ coefficients are:

$$\mathbf{B}_{k,p}^{(i)} = \mathbf{H}_k \mathbf{F}_{k,p}^{(i)} - \mathbf{\Gamma}_p \tag{3.25}$$

$$\mathbf{F}_{k,p}^{(i)} = \mathbf{\Lambda}_{k,p}^{(i)} \mathbf{H}_k^H \mathbf{\Theta}_{k,p}^{(i)} \tag{3.26}$$

$\mathbf{\Lambda}_{k,p}^{(i)} = \left(\mathbf{H}_k^H \left(\mathbf{I}_P - \mathbf{P}^{(i-1)^2} \right) \mathbf{H}_k + \frac{\sigma_N^2}{\sigma_S^2} \right)^{-1}$ and $\mathbf{\Theta}_{k,p}^{(i)} = \left(\mathbf{I}_P - \mathbf{P}^{(i-1)^2} \right) \mathbf{\Gamma}_p - \frac{\lambda_p^{(i)}}{2\sigma_S^2 N} \mathbf{\Gamma}_p$. With equations 3.23, 3.25 and 3.26 the MMSE of the estimated data symbol for iteration i and a UE p is given by:

$$\sigma_p^{2(i)} = \frac{1}{N^2} \sum_{k=0}^{N-1} \mathbb{E}\left[\left| \tilde{S}_{k,p}^{(i)} - S_{k,p} \right|^2 \right]. \tag{3.27}$$

Similarly to the linear receiver, the BER of UE p for the iteration i for a QPSK constellation is:

$$BER_p^{(i)} \simeq Q\left(\frac{1}{\sigma_p{}^{(i)}} \right). \tag{3.28}$$

For an uncoded system with independent and isolated errors the PER for a fixed packet size of B bits is:

$$PER_p^{(i)} \simeq 1 - (1 - BER_p^{(i)})^B. \tag{3.29}$$

IB-DFE receiver performance

Figure 3.7 presents the PER over the ω values of the IB-DFE receiver on the concurrent uplink transmission of 3 UEs, for an increasing number of iterations N_{iter}, up to a maximum of 3. A total of 2 transmissions of the original packet were considered in all scenarios. To compare the gains in performance of employing the SIC technique in the reception, the path loss attenuation values used in the simulations of the linear receiver performance were also used in this section, so the performances can be compared.

Table 3.2: Specifications for the Iterative Receiver performance simulation.

Specifications	
UEs transmitting (P)	3
eNB receivers	1
Transmissions per UE (L)	2
Iterations of the Receiver	1 to 3
Path Loss UE 1	0 dB
Path Loss UE 2	-10 dB
Path Loss UE 3	-20 dB
Channel Type	EPMC

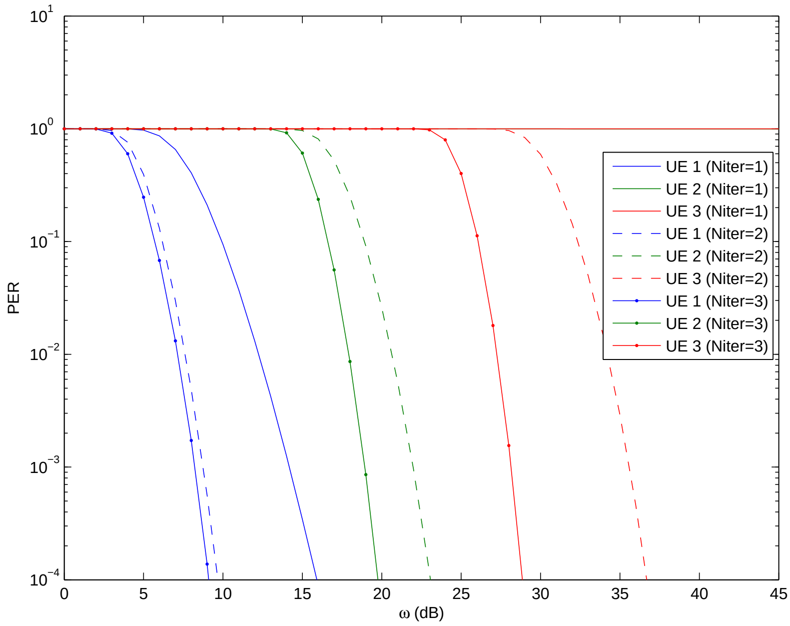

Figure 3.7: PER over ω for 3 UEs with 3 different number of iterations

As expected, for the first iteration the results obtained were the same as the depicted in figure 3.4, which shows the PER obtained in the linear receiver. The IB-DFE receiver behaves as a linear receiver if only one iteration is considered. Only the terminal that is closer to the eNB had its transmission successfully decoded.

When the number of iteration is increased, all the transmissions can be received. Using the IB-DFE receiver with two iterations allows not only the decrease of the PER for the UE that is closer to the eNB but also the decoding of the transmission of the other two UEs. It is observable, as it was referred before, that if a SIC technique is employed, P

collisions can be solved with $L < P$ uplink transmissions.

The increase to three iterations allows the reduction of the PER but this effect is more noticeable for the farther terminals, since the closest device is already close to the optimal PER value (measured in a scenario without interference). The enhancement in the transmission is higher for the UE that is farther away from the eNB.

3.3 Uplink signal Diversity

The IB-DFE receiver can enhance the MPR scheme, increasing the network's capacity. However, this enhancement does not depend solely of the number of iterations used in the receiver scheme. Diversity on the uplink signal is needed to allow the decoding of several UEs on the receiver, thus solving collisions. Uplink signal diversity can be classified into three different categories:

Time Diversity: Provided by the repetition of the signal over the time to the same eNB. Different time slots are used for each retransmission and diversity increases with the number of time slots used to repeat the transmission. The performance of a transmission where time diversity is applied can be observed in section 3.2.1 and in [GDBO12].

Spatial Diversity: The uplink transmission of all UEs involved in a collision is received simultaneously at different nearby eNBs (or using multiple antennas). Only one time slot is used and the processing of the signal has to be done centrally. Diversity increases with the number of eNBs available to receive the transmissions.

Power Diversity: The iterative receiver can separate the packets involved in a collision if they are received with different power levels. The path loss attenuation may be enough to provide the difference between the powers received in the eNB of the different UEs. However, if the different transmissions are received with similar powers, a power control scheme may be needed to introduce the power diversity required.

Although described as individual schemes, the combination of all of the schemes presented above is possible and encouraged since it enhances even more the MPR capacity of the receiver, improving the network's capacity. Power and spatial diversity schemes are explained and exemplified using the IB-DFE receiver in the following sections.

3.3.1 Power Diversity on the IB-DFE receiver

In order to efficiently separate the devices involved in a collision, if time or spatial diversity is not provided by the transmission, a separation is required in the $\frac{E_b}{N_0}$ values received at the eNB. This allows the receiver to extract the packet transmitted with more power in the first iteration, afterwards the second packet transmitted with more power and so on.

There is a minimum power spacing at the receiver $|\xi_{l,p}|$ that is needed to enable the separation of multiple UEs. This spacing can be estimated by simulating a scenario where two UE transmit in the same time slot to the same eNB. It is considered a scenario where two UEs transmit with the same power. One UE keeps its position constant while the other successively increases its distance to the eNB, increasing the path loss attenuation until the aggregate throughput of the eNB is below a predefined threshold. The aggregate throughput represents the number of packets received per time slot and is given by:

$$S^T = \frac{1}{L}(\sum_{p=1}^{P}(1 - PER_p^T)) \quad (packets/timeslot), \tag{3.30}$$

where L represents the number of time slots used per packet and PER_p^T denotes the PER for UE p. The $\frac{E_b}{N_0}$ received at the eNB is directly associated to its transmission power P_t that is obtained using:

$$P_t(d) = \frac{E_b}{N_0} + PL(d) + \sigma_{N_0}^2 + G_0 + 10log_{10}(B) \quad (dB), \tag{3.31}$$

where $PL(d)$ denotes the Path loss for a distance d, B the number of bits in a packet, G_0 denotes the antenna gain and $\sigma_{N_0}^2 = -174 + 10log_{10}(H)$ dB the thermal noise for a bandwidth H. Four iterations were considered in the IB-DFE to assure a good tradeoff between the simulation complexity and the capacity to solve collisions [GDBO12].

In order to guarantee consistent results, the aggregate throughput values in the receiver for each path loss scenario were calculated using PER mean values. This eliminates inconsistencies that can be introduced by the different channel realization coefficients that are generated for each simulation. To do so, each different path loss spacing scenario was simulated 120 times with different channel realizations. Then the arithmetic mean was obtained for the PER results of the group of simulations, excluding the best and worst results, i.e. simulations with the highest and lowest PER. To assure the reliability of the PER estimations, the 95% confidence interval of the aggregate throughput was calculated in the following way:

$$(PER_{mean} - 1.96\frac{\sigma_{PER}}{\sqrt{n}}, PER_{mean} + 1.96\frac{\sigma_{PER}}{\sqrt{n}}), \quad (3.32)$$

where n is the number of simulations, PER_{mean} the PER mean values obtained for each UE and σ_{PER} the standard deviation of the PER values. The remaining specifications of this simulation are presented in table 3.3 and the respective results are depicted in figure 3.8.

Table 3.3: Specifications for the power diversity simulation

Specifications	
UEs transmitting (P)	2
eNB receivers	1
Transmissions per UE (L)	1
Iterations of the Receiver	4
Path Loss UE 1	0 dB
UE 1 $\frac{E_b}{N_0}$ at the receiver	27 dB
Path Loss UE 2	0 to -8 dB
UE 2 $\frac{E_b}{N_0}$ at the receiver	27 to 19 dB
Bandwidth	64 MHz
Bits per packet	256
Repetitions of the simulation	120
Channel Type	EPMC

Figure 3.8 shows that there is a minimum value of power spacing at the receiver required to assure the perfect reception of both packets. When considering the transmission of 2 UEs, the packet reception is successfully completed when there is at least $|\xi_{l,p}| = -6dB$ spacing between the $\frac{E_b}{N_0}$ values in the receiver for each UE. There is a high precision in the throughput values obtained, since they all fall within the 95% confidence interval calculated.

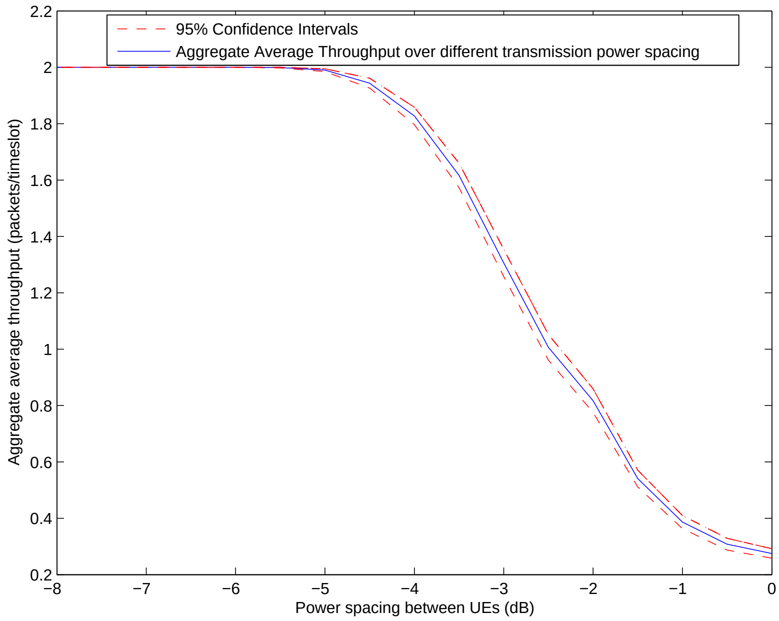

Figure 3.8: Aggregate average throughput for the fourth iteration of the receiver of the transmission of 2 UEs with different power spacing

Power Diversity and Time diversity on the IB-DFE receiver

In order to increase the number of packets received simultaneously by one eNB, it is possible to combine time diversity and power diversity. It is expectable that with the use of time diversity, the number of UEs that are transmitting in the same power level increases proportionally with the number of time slots used to transmit the same packet. This means that if an eNB can receive from two devices with one uplink transmission, as seen in figure 3.8, it can receive four devices transmissions in two slots per UE and P devices using $\lceil \frac{P}{2} \rceil$ slots per UE transmission, where $\lceil \; \rceil$ denotes the ceiling operation, rounding the number to the following integer number. However these terminals need to be separated at least in two different reception power levels: for a scenario where P UEs transmit to the same eNB, $\lceil \frac{P}{2} \rceil$ have to be received with the same power level while the other $\lfloor \frac{P}{2} \rfloor$ should be received with a power that is at least -6 dB lower, where $\lfloor \; \rfloor$ denotes the floor operation, rounding the number to the previous integer number. A group of simulations using up to 8 UEs transmitting to the same eNB is done below to verify the previous assumptions. The specifications used in this simulation are presented in table 3.4.

It can be seen in figure 3.9 that the number of packets being extracted from a collision

Table 3.4: Specifications for the power diversity simulation

Specifications	
UEs transmitting (P)	4 to 8
eNB receivers	1
Transmissions per UE (L)	2 to 4
Iterations of the Receiver	4
Path Loss Group 1	0 dB
Group 1 $\frac{E_b}{N_0}$	27 dB
Path Loss Group 2	0 to -8 dB
Group 2 $\frac{E_b}{N_0}$	27 to 19 dB
Bandwidth	64 MHz
Bits per packet	256
Repetitions of the simulation	120
Channel Type	EPMC

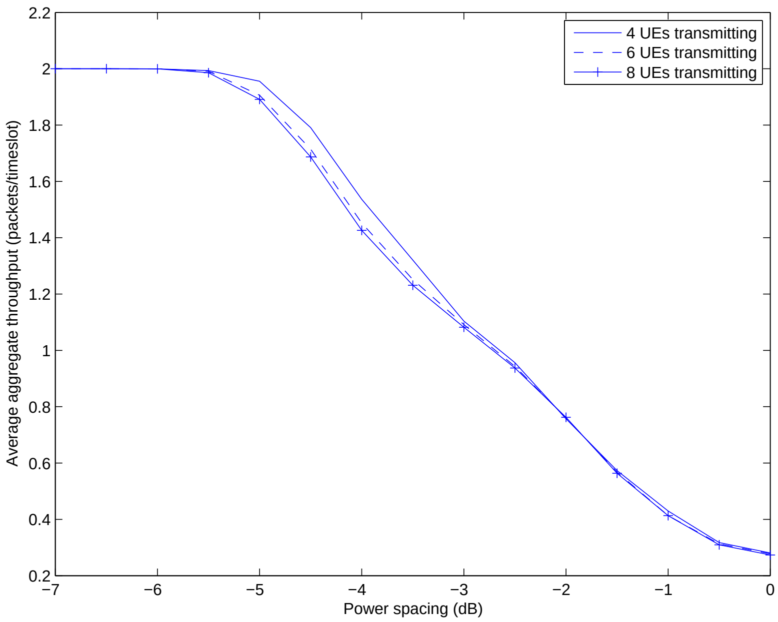

Figure 3.9: Aggregate average throughput for the fourth iteration of the receiver of the transmission of multiple UEs with different power spacing

increases with the number of retransmissions, as long as there are two distinct reception power levels with at least -6 dB spacing. The number of UEs that transmit in each power level is a constraint that can degrade the performance of the receiver. In this simulation it was considered that half of the devices involved in the collision have their transmission received in one power level and the other half in another; this proved to be one possible combination since the maximum throughput was achieved in all scenarios. It is also shown that time diversity can be used to support more UEs but does not increase the network capacity; just divides the existing resources between more UEs. On the other hand, power diversity combined with time diversity, contributes to increase the network capacity because it allows the simultaneous reception of two UE transmission groups.

3.3.2 Spatial Diversity on the IB-DFE receiver

In order to study the benefits of joint processing between eNBs, the uplink transmissions is provided with spatial diversity. This consists in concurrently, receiving the UE's signal at two or more eNBs. Since the processing of the signals is done jointly, the amount of UEs being processed may be large, since it involves the simultaneous processing of devices associated to at least two different eNBs. CoMP may not be enough when the amount of UEs is large, so a hybrid CoMP solution where time diversity is combined with spatial diversity can be employed to solve this problem as it was referred in section 3.1.

When considering only spatial diversity, different receivers are used to receive the copies of the original packet, which have different distances to the UEs. Therefore the transmissions of the multiple copies of the signal are affected by different attenuations. In a network with P UEs transmitting a packet to a total of L different eNBs, the model of the IB-DFE receiver is:

$$\begin{bmatrix} Y_k^{(1)} \\ \vdots \\ Y_k^{(L)} \end{bmatrix} = \begin{bmatrix} |\xi_{1,1}|\, H_{k,1}^{(1)} & \dots & |\xi_{1,P}|\, H_{k,P}^{(1)} \\ \vdots & \ddots & \vdots \\ |\xi_{L,1}|\, H_{k,1}^{(L)} & \dots & |\xi_{L,P}|\, H_{k,P}^{(L)} \end{bmatrix} \begin{bmatrix} S_{k,1} \\ \vdots \\ S_{k,P} \end{bmatrix} + \begin{bmatrix} N_k^{(1)} \\ \vdots \\ N_k^{(L)} \end{bmatrix}, \tag{3.33}$$

where $|\xi_{L,P}|$ denotes the path loss attenuation of UE P to eNB L.

Spatial diversity can be combined with time diversity if the UEs repeat the transmission to the multiple eNBs over different time slots. This technique improves the capacity to decode UE's packets, since it improves the MPR scheme allowing the increase of the number of UEs being treated at each receiver. Therefore, lower PER values are obtained than when using only spatial diversity, for the same attenuation values. When using this technique, in the IB-DFE receiver model the variable L can refer to a transmission with time or spatial diversity. The only difference is that when a time retransmission is considered, the path loss attenuation that the signal suffers is the same as the previous transmission. Figure 3.10 depicts the content received at two different eNBs when the UEs have their signal provided with time and spatial diversity simultaneously.

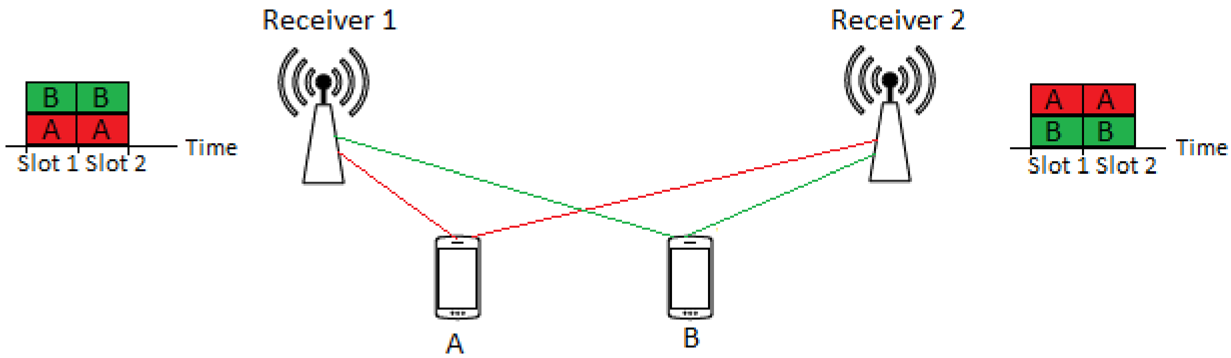

Figure 3.10: Content received at the eNBs when two UEs have their signal provided with spatial and time diversity

3.3.3 IB-DFE receiver performance with spatial diversity

Simulations were done to verify the aggregate throughput improvements that the spatial diversity scheme can bring to the network. Another objective of the simulations was to determine how the throughput drops with the rise of the path loss between the UEs and the two eNBs.

A scenario was defined where two equidistant UEs transmitted once simultaneously to two different eNBs, which are in different positions but placed at the same distance to the two UEs (without any power diversity). The distance between the two eNBs is increased gradually over various simulations, while the position and transmission power of the two transmitting devices remains constant. In this way, the path loss is increased but remains the same for both terminals. The mean aggregate throughput of both receivers was calculated to eliminate inconsistencies that could be introduced by the channel realization coefficients. The simulation specifications considered in this section are presented in table 3.5. The simulated topology is represented in figure 3.11, where it is possible to observe how the eNBs were placed between the first and last simulation. The results for this simulation are depicted in figure 3.12.

Table 3.5: Specifications for the spatial diversity simulation with two UEs

Specifications	
UEs transmitting (P)	2
eNB receivers	2
Transmissions per UE (L)	1
Iterations of the Receiver	4
Initial distance from both UEs to the receivers	2 meters
Initial path loss from both UEs to the receivers	-8.4288 dB
Final distance from both UEs to the receivers	10.19 meters
Final path loss from both UEs to the receivers	-28.2238 dB
Repetitions of the simulation	120
Channel Type	EPMC

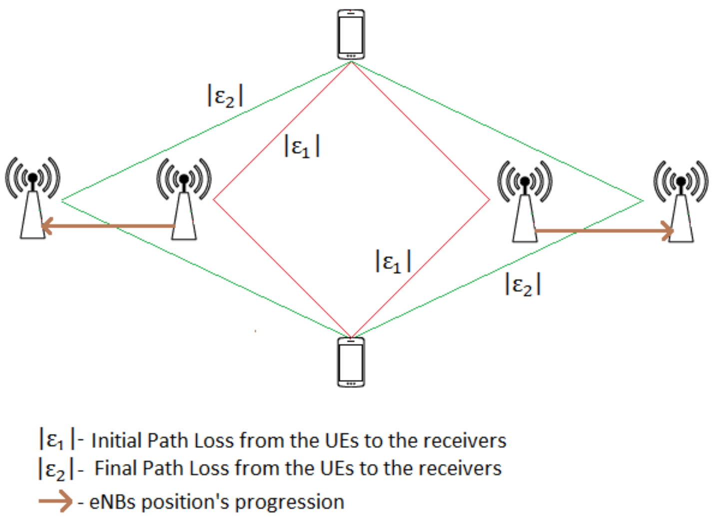

Figure 3.11: Topology used for the simulation of 2 UE's uplink transmissions provided with spatial diversity

It is observable in figure 3.12 that the collision can be solved and that both packets can be decoded up to a certain distance. Afterwards, the mean aggregate throughput drops significantly due to the attenuation that the transmissions suffer. The maximum distance that the UEs can have to the eNBs to allow the perfect reception of their transmission is directly related to their transmission power. This distance can be increased if the

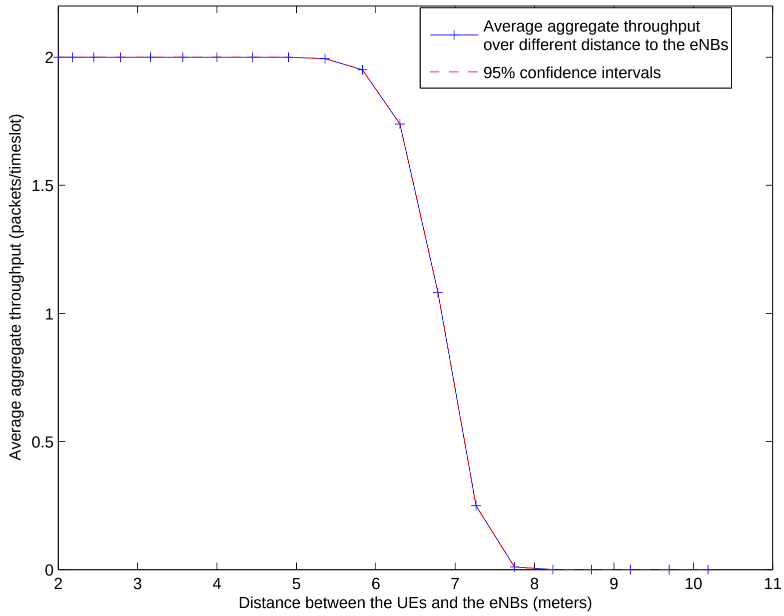

Figure 3.12: Average Aggregate Throughputs for the fourth iteration of the receiver, for increasing distances of 2 MTs when using Spatial Diversity

transmission power is also increased, which also increases the $\frac{E_b}{N_0}$.

Besides proving that providing the uplink transmission with spatial diversity can be beneficial to the network's throughput, it would be interesting to compare the performance of a network that uses power diversity combined with time diversity and another that uses power diversity combined with spatial diversity. In order to do so, a scenario was simulated where two UEs equidistant from one eNB transmit two times, using consecutive time slots. The distance from the two UEs to the eNB will be increased gradually, until the PER is below a predefined threshold. This allows the comparison between the PER of the network and range of the eNBs in the two different scenarios. Since this is a comparison, the mean aggregate throughput does not need to be calculated if the channel realization coefficients are fixed for both transmissions in both simulations. The specifications for the power diversity with time diversity simulation and comparison results are depicted below in table 3.6 and figure 3.13.

From the simulation results in figure 3.13, it can be verified that higher aggregate throughputs are obtained when the UEs transmission is provided with spatial diversity, rather than when the transmission is only provided with time diversity. This enhancement in the network's capacity is due to the simultaneous use of two receivers, which allows the

Table 3.6: Specifications for the time diversity simulation with two UEs

Specifications	
UEs transmitting (P)	2
eNB receivers	1
Transmissions per UE (L)	2
Iterations of the Receiver	4
Initial distance from both UEs to the receivers	2 meters
Initial path loss from both UEs to the receivers	-8.4288 dB
Final distance from both UEs to the receivers	10.19 meters
Final path loss from both UEs to the receivers	-28.2238 dB
Channel Type	EPMC

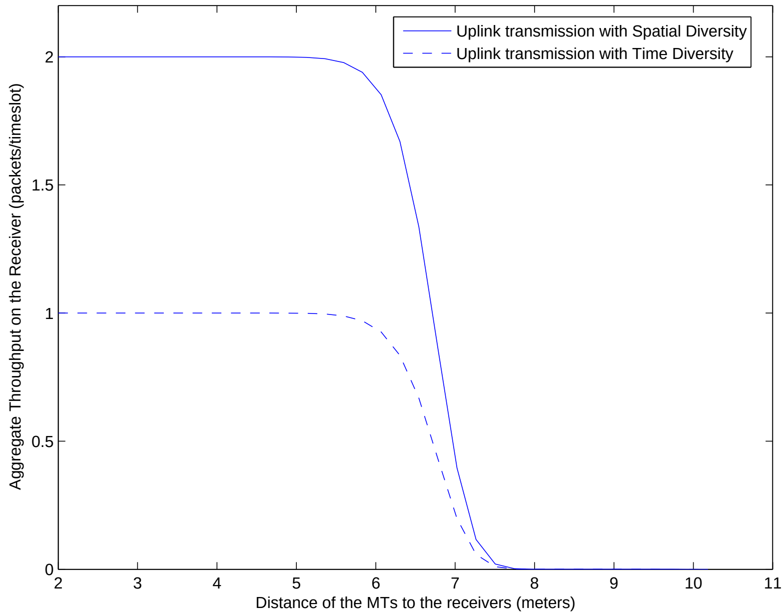

Figure 3.13: Aggregate average throughput for the fourth iteration of the receiver of the transmission the same transmission provided with time diversity and provided with spatial diversity

simultaneous reception of both transmissions and therefore a higher bit rate.

It can be observed that the aggregate throughput sharply drops when the distance of the UEs to the receiver is higher than 5 meters in both scenarios, so there were no significant gains in the range of the receivers when spatial diversity was provided to the transmission. This happens because the UEs have the same path loss to both eNBs. Range gains could be observed if one of the devices had a high attenuation to one of the receivers and another eNB was inserted in the network near this device, providing increased spatial diversity to this UE's uplink transmission.

Even though there were improvements in the aggregate throughput in the spatial diversity scenario, the implementation can be wasteful in some situations, like when the cell density is low (e.g. rural areas). There is a trade-off between the aggregate throughput gains and the complexity of the network. The implementation of a network using a DAS scheme requires the deployment of network infrastructures between the processing unit and the receivers, which may have a high deployment cost. The implementation of this scheme is more justifiable when there is a high probability of collision between UE's transmission, i.e. dense areas, since it allows the reception of more packets per time slot, therefore collisions can be solved with the use of less time slots, leading to an increased network capacity.

Chapter 4

Interference Model and Hybrid CoMP Scheme

The rise in the number of mobile devices is an issue which has to be addressed in order to improve the performance of future 5G networks. Current LTE network deployments fail to provide the capacity and resilience to high interference, needed to assure a quality service. Heterogeneous deployments are seen as a solution to cope with networks that have a high density of devices, which are characterized by high interference levels that may degrade the downlink and uplink transmission.

The objective of this chapter is to evaluate the performance of a spatial, power and time diversity CoMP uplink scheme in dense heterogeneous networks. An interference model was designed to simulate the interference levels that can occur in these networks and will be described in the following subsections. This model depends on the power received at the eNB from the UEs, which depends on their relative position to the eNB. A network topology generator is used to simulate interference scenarios and is also described in this chapter. A hybrid CoMP scheme, which combines the three diversity uplink schemes, was proposed in section 3.3. In this chapter, the scheme is described and simulated in networks with high interference levels, to verify the improvement it can bring to the aggregate throughput of a uplink transmission.

4.1 Interference model with incomplete resolution at the receiver

A UE is interfering when its transmission cannot reach the eNB with enough power to have its transmission decoded (i.e. power below the predefined threshold). From the receiver perspective, the power received by these devices contributes to the channel noise, amplifying its magnitude. So a new parameter representing the interference ϕ_k has to be considered in the expression of the output at the receiver to cope with the interfering UEs

$$\mathbf{Y}_k = \mathbf{H}_k^T \mathbf{S}_k + \mathbf{N}_k + \phi_k. \tag{4.1}$$

Every interfering UE is an independent random variable. Using the central limit theorem, the sum of the interfering UE's power can be approximated by a Gaussian function for a high number of interfering devices. Admitting this approximation, interference can be added to the channel noise, which also is modeled by a Gaussian function. Considering that there is the knowledge at the receiver of all channel realizations of the UEs present in the network (including the received and the interfering ones), ϕ_k is given by:

$$\phi_k = |\xi_p| \, H_k^\dagger S_k^\dagger \tag{4.2}$$

For a topology where P UEs have their uplink transmission received at the eNB and a total of $M - P$ interfering UEs are present in the network, $H_k^\dagger = [H_{k,P+1}^\dagger, \ldots, H_{k,M}^\dagger]^T$ are the channel realizations for each interfering UE, where $H_{k,p}^\dagger = [H_{k,p}^\dagger(1), \ldots, H_{k,p}^\dagger(L)]$ represents the different channel realization for a single interfering UE p for every transmission. The interfering transmission is given by $\mathbf{S}_k^\dagger = [S_{k,P+1}^\dagger, \ldots, S_{k,M}^\dagger]^T$ and for a given m interfering UE $\{S_{k,m}^\dagger; k = 0, \ldots, N-1\}$ are the frequency domain samples of its transmission data. The path loss attenuation of each interfering UE p is represented by $|\xi_p|$.

4.1.1 Interference model with incomplete channel knowledge

The scenario presented above where there is the knowledge of the channel realizations of all the UEs present in the network is unrealistic. Channel prediction of interfering devices is difficult to obtain, especially in highly dense networks. Assuming the approximation that the multipath fading effects can be despised for the interfering UEs, the interference for an UE p is given by $|\xi_p|\, S_{k,p}$. The interference on every transmission is given by:

$$\phi_k \approx \sum_{p=P+1}^{M} |\xi_p|\, S_{k,p}. \tag{4.3}$$

The expanded expression for Y_k is:

$$\begin{bmatrix} Y_k^{(1)} \\ \vdots \\ Y_k^{(L)} \end{bmatrix} = \begin{bmatrix} |\xi_1|\, H_{k,1}^{(1)} & \dots & |\xi_P|\, H_{k,P}^{(1)} \\ \vdots & \ddots & \vdots \\ |\xi_1|\, H_{k,1}^{(L)} & \dots & |\xi_P|\, H_{k,P}^{(L)} \end{bmatrix} \begin{bmatrix} S_{k,1} \\ \vdots \\ S_{k,P} \end{bmatrix} + \begin{bmatrix} N_k^{(1)} + \phi_k^{(1)} \\ \vdots \\ N_k^{(L)} + \phi_k^{(L)} \end{bmatrix}. \tag{4.4}$$

In the presence of spatial diversity, different values of ϕ_k should be considered for each retransmission, because interference is felt differently in each eNB. Both interference and noise are modeled as Normal distribution functions so the sum of these functions is also a Normal distribution given by:

$$\mathbb{E}[N_k] = \mathbb{E}[\phi_k] = 0, \tag{4.5}$$

and

$$\mathbb{E}[N_k^{eq}] = \mathbb{E}[N_k + \phi_k] = 0. \tag{4.6}$$

Interference and noise are two independent Normal distributed random variables. Interference can vary between the different transmissions, so its variance can take different values. For a system where L copies of the signal are received, interference variance is $\varsigma_\phi^2 = diag(\sigma_\phi^{2^{(1)}}, \dots, \sigma_\phi^{2^{(L)}})$. Therefore the variance of N_k^{eq} for a retransmission i:

$$\sigma_{N_k^{eq}}^{2^{(i)}} = \sigma_{N_k}^{2^{(i)}} + \sigma_{\phi_k}^{2^{(i)}}. \tag{4.7}$$

and

$$\varsigma_{N_k^{eq}} = \varsigma_{N_k} + \varsigma_{\phi_k}. \tag{4.8}$$

The noise correlation matrix used in the equation of the MMSE for the estimation of

$\tilde{S}_{k,P}^{(i)}$ is given by:

$$\mathbb{E}\left[\mathbf{N}_k^{eq}\mathbf{N}_k^{eq^H}\right] = \mathbb{E}[(N_k + \phi_k)(N_k + \phi_k)^H] = \mathbb{E}[N_k N_k^H + \phi_k \phi_k^H] = 2\varsigma_{N^{eq}}^2. \tag{4.9}$$

The optimal feed forward coefficients obtained under the MMSE criteria is now given by:

$$\mathbf{F}_{k,p}^{(i)} = \mathbf{\Lambda}_{k,p}^{(i)}\mathbf{H}_k^H\mathbf{\Theta}_{k,p}^{(i)}, \tag{4.10}$$

$$\mathbf{\Lambda}_{k,p}^{(i)} = \left(\mathbf{H}_k^H\left(\mathbf{I}_P - \mathbf{P}^{(i-1)^2}\right)\mathbf{H}_k + \tfrac{1}{\sigma_S^2}\varsigma_{N^{eq}}^2\right)^{-1} \text{ and } \mathbf{\Theta}_{k,p}^{(i)} = \left(\mathbf{I}_P - \mathbf{P}^{(i-1)^2}\right)\mathbf{\Gamma}_p - \tfrac{\lambda_p^{(i)}}{2\sigma_S^2 N}\mathbf{\Gamma}_p.$$

4.1.2 Network elements distribution

The UEs and eNBs' distributions used in the simulations presented in this section are 2D Poisson distributions. These distributions handle the positions of each node as an independent event and are characterized by the average density value λ. According to [FIO+14] the number of users in a area of the network, represented by a random variable X has the following Poisson distribution:

$$P(X = c) = \frac{(\rho_{ON}\beta A_E)^c}{c!}e^{-\rho_{ON}\beta A_E}, c = 0, 1, ..., N, \tag{4.11}$$

where ρ_{ON} represents the probability of finding a device transmitting, β is the UE's spatial density (measured in UEs/m^2), A_E is the area where UEs can be distributed (measured in m^2) and N is the maximum number of UEs. In every simulation, A_E is obtained by calculating the circular area that involves completely a squared area previously considered, so for a square area with side length l meters:

$$A_E = \pi(\frac{\sqrt{2}l}{2})^2 \quad (m^2) \tag{4.12}$$

After obtaining the number of UEs transmitting in the circular area that involves the square area, their coordinates are generated using a uniformly distributed pseudo-random number generator, to assure a random spacing between them. The eNBs coordinates may be generated using the same pseudo-random generator or predefined, depending on the simulation objective.

4.1.3 Interference model performance results

The incomplete resolution approximated model was validated using a set of simulations where two UEs, maintaining a constant position, transmit to the IB-DFE receiver. Different UE density values β were used, ranging from 0.1 to 4.5 UEs/m^2, to understand if the incomplete resolution model performance is comparable to the performance with full channel knowledge. Every setup with a different β value was simulated 400 times with different spatial distributions and the PER average values and the respective 95% confidence intervals were calculated for both models. Even though the incomplete channel knowledge model does not take channel realizations into account, the calculation of average PER value is important to remove the bias in the results introduced by some topologies (e.g. accumulation of interfering UEs in a certain area).

In this simulation, one eNB is considered and deployed in the middle of the square area and the path loss of the UEs that have their transmission received is predefined. UE 1 is the closest and UE 2 transmits with a -6 dB power offset in relation to UE 1, to allow an efficient separation, as described in section 3.3.1. UEs are generated using a 2D Poisson distribution in a ring area centered in the eNB, comprehended between the radius of UE 2 and a predefined maximum radius of 7.5 m.

The other simulation specifications are displayed in table 4.1 and the average aggregated throughput using the fourth iteration of the receiver is depicted in figure 4.1.

In figure 4.1 it is shown that the incomplete channel approximation provides a good approximation to the complete channel realization interference model up to densities of 4.5 UEs/m^2. Both average aggregate throughput have insignificant differences over the different density simulations, so it is shown that the multi path fading effects of the interfering UEs are not significant. Both curves fall inside the respective 95% confidence interval, so the average throughput values can be considered reliable.

It can also be observed from this simulation that uplink power diversity is not enough to overcome interference. Figure 3.8 showed the performance for a similar simulation without considering the interference caused by external UEs. It was observed that both UEs

Table 4.1: Specifications for the interference model performance simulation.

Specifications	
UEs transmitting (P)	2
eNB receivers	1
Transmissions per UE (L)	1
Iterations of the Receiver	4
Path Loss UE 1	0 dB
Path Loss UE 2	-6 dB
ρ_{ON}	1
β	0.1 to 4.5 UEs/m^2
Length of the squared area considered	15 m
Repetitions of the simulation	400
Channel Type	EPMC

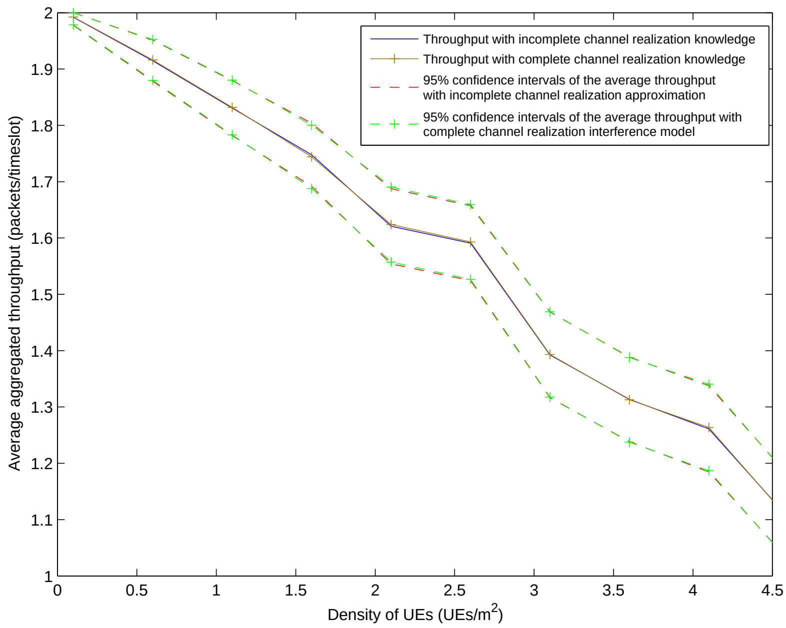

Figure 4.1: Average aggregated Throughput in the IB-DFE receiver over UE density of 2 UEs using a complete channel resolution interference model and an incomplete channel resolution approximation.

could deliver their packet, as long as the minimum power spacing was assured. However, when interference is taken into account, figure 4.1 shows that the aggregated throughput sharply drops over the increase of the UE density, with a 45% decrease when there are 4.5 UEs/m^2. It can be concluded that another diversity scheme needs to be provided to allow the successful reception of all packets in the presence of interference.

In order to observe the negative effects that interference from neighbouring UEs can bring to an UE's transmission, simulations were done where multiple different interference conditions were compared. Firstly, a network topology with one eNB and a certain UE density was generated. In the first simulation scenario, the UEs that could reach the eNB with $\frac{E_b}{N_0}$ above a certain threshold were admitted for reception; the rest of the UEs were considered interference. Then some of the UEs that were being received but had a higher attenuation were added to the interference. In this simulation it is considered that all UEs transmit with the same power. The PER of the transmission of the closest UEs, obtained in three different simulations, is compared. The incomplete channel knowledge interference model was considered, no power diversity scheme was admitted in each simulation and a time diversity scheme where each UE retransmits its packet $P - 1$ times was admitted. The portion of the network which has the UEs available for reception is depicted in figure 4.2.

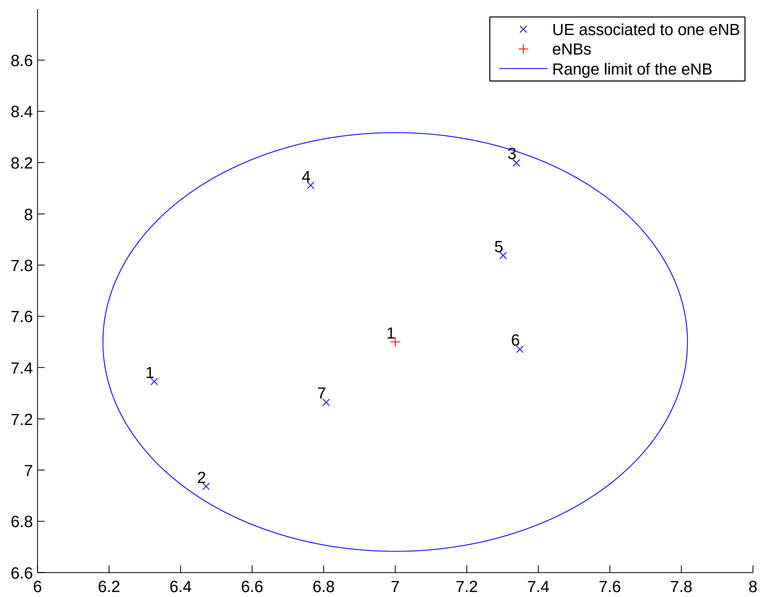

Figure 4.2: Portion of the network with the UEs available for reception at eNB 1.

In the first simulation, the 7 displayed UEs were admitted for reception, since their transmission was received with enough power to be decoded. In the second simulation, UEs 2 and 3 were considered interference because they had the highest attenuation from the UEs being decoded. In the third simulation UEs 1 and 4 were also added to the interference. The PER of UEs 5 and 6 in each simulation is compared. The specifications for each simulation are displayed in table 4.2 and the results are displayed in figure 4.3.

Table 4.2: Specifications for the simulations with two different interference conditions.

Specifications	
UEs transmitting in the first scenario	7
UEs transmitting in the second scenario	5
UEs transmitting in the third scenario	3
eNB receivers	1
ω threshold	-12 dB
Transmissions of each UE in the first scenario	7
Transmissions of each UE in the second scenario	5
Transmissions of each UE in the third scenario	3
Iterations of the Receiver	4
PL_{min}	-14.4578 dB
Interfering UEs in the first scenario	315
Interfering UEs in the second scenario	317
Interfering UEs in the third scenario	319
ρ_{ON}	1
Obtained β	1.43 UEs/m^2
Length of the squared area considered	15 m
Channel Type	EPMC

In figure 4.3, it can be observed that UEs 5 and 6 needed a higher transmission power to achieve similar PERs when the UEs 3 and 2 were added to the interference. The higher transmission power allows the UEs to overcome the higher interference levels and achieve a SINR sufficiently high enough to have their transmission decoded. The transmission power needed to achieve lower PERs becomes even higher when UEs 1 and 4 are added to the previous interference scenario. From these simulations, it can be concluded that the transmission of UEs that are close to the eNB can benefit from the decoding of neighbouring UEs, even in scenarios where their messages are not intended to

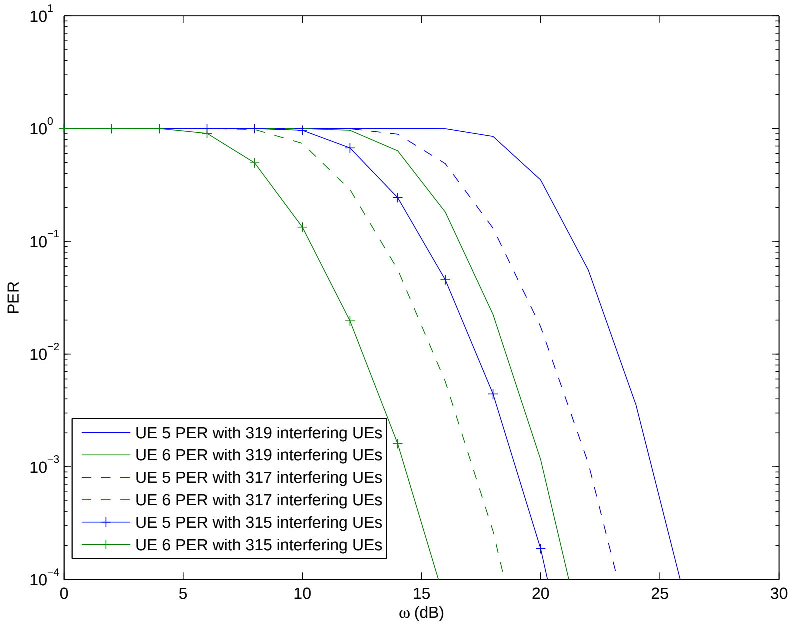

Figure 4.3: PER of UE 5 and 6 for the fourth iteration of the receiver in each different interference scenario.

be received at the same eNB.

4.2 Spatial, Time and Power diversity hybrid scheme

Spatial Diversity is seen as a solution to mitigate interference in heterogeneous networks. CoMP uplink schemes such as JP reduce the probability of collisions and enable the reception of multiple copies of the same transmission without requiring additional packet copies, therefore leading to the enhancement of the maximum throughput in the network.

These schemes can also reduce the effect of interfering UEs in the network. A UE that belongs to a closed access mode femtocell network can interfere with a similar network if it is close enough to the other network's femtocell (e.g. independent femtocell networks deployed inside adjacent houses). One of the ways to deal with this type of interference is to consider the interfering UE in the detection of the UEs at the other eNB. Interfering UEs can have their transmissions received at the eNB, so it can subtract their signals, eliminating their effects.

However problems can rise due to the joint processing of the content received in multiple eNBs. A higher number of UEs are simultaneously processed, which can lead to higher processing times and eventually, the incapacity to process all the received signals. There is also a need to coordinate the multiple receivers and deploy the eNBs required, with increased costs. In areas where the device density is very high, spatial diversity may not be enough to separate collisions between multiple devices if there are not sufficient eNBs deployed, capable of receiving the transmission of the UEs involved in the collision. These extensive deployments are not economically viable, so a solution was designed where there is a combination of several uplink diversity schemes.

The following subsections propose a hybrid CoMP scheme involving the three uplink diversity schemes and performance simulated results. Then, a power correction scheme is explained, which may be applied to allow the efficient separation of devices that are close to each other. Finally, the hybrid scheme's performance is compared with the performance of a time and power diversity scheme.

4.2.1 Hybrid Diversity Scheme implementation

In section 3.3.1 it was shown how time and power diversity can be used to improve the performance of the IB-DFE receiver, allowing it to decode successfully simultaneous uplink transmissions from an increasing number of UEs. In this scheme, the limit in the number of UEs that the receiver can decode depends directly on the number of time retransmissions that they use in the uplink transmission. The reception of up to 8 simultaneous UEs with the transmission of 4 copies of their packets was demonstrated in figure 3.9, with time and power diversity, requiring the minimum power spacing. This result was extrapolated to a collision between P devices, requiring $\lceil \frac{P}{2} \rceil$ packet transmissions and the minimum power spacing.

In order to guarantee the successful reception of all the packets, the devices need to be divided in at least two groups and each group should also have their transmissions received with an $\frac{E_b}{N_0}$ separation. For a system without interference where P devices transmit,the reception of all packets is possible if $\lfloor \frac{P}{2} \rfloor$ devices transmit in a power level that is at least 6 dB inferior to the other $\lceil \frac{P}{2} \rceil$. The minimum power spacing between transmissions may be achieved through the difference of distances and consequently path loss attenuations that the UEs have between them. However, since the topology generation is a pseudo-random event, it can happen that the UEs do not have enough separation in the $\frac{E_b}{N_0}$ at the receiver. Therefore, a power control scheme is applied to some UEs to adjust their transmission power, assuring the reception with the correct power spacing.

The adjustment in the UE's transmission power can be modeled as a path loss adjustment, in the reception model. For an UE transmitting with a path loss attenuation $|\xi_{P,1}|^{PL}$, which adjusts its transmission with a power correction value θ_P, the total equivalent attenuation to the transmission power $|\xi_{P,1}|^{eq}$ is given by:

$$|\xi_{P,1}|^{eq} = |\xi_{P,1}|^{PL} - \theta_P \quad (dB). \tag{4.13}$$

The power adjustment value needs to be applied coherently, assuring that the transmission power of the UE cannot surpass the maximum output power from a LTE/LTE-A Power Class UE [Sei14], which is 33 dBm (3 dB). It can be deducted from equation 3.31, that θ_P must respect the following constraint:

$$\theta_P \geq \frac{E_b}{N_0} + |\xi_{P,1}|^{PL} + \sigma^2_{N_0} + 10log_{10}(B) - 3 \quad (dB). \tag{4.14}$$

A flow chart explaining how UE association is done and how the power control scheme is applied is depicted in 4.4. Initially, each eNB scans its proximity for transmitting UEs that can be received with a power above the predefined power threshold. The UEs that are detected are divided in two different transmission power groups, based on proximity. For a system with a total of P UEs transmitting to one eNB, the $\frac{E_b}{N_0}$ for all the $\lceil \frac{P}{2} \rceil$ UEs of the group that transmits with higher power (group 1) has to be at least 6 dBs higher than the $\frac{E_b}{N_0}$ of the UEs that belong to the group that transmits with lower power (group 2). No power condition was considered in the reception of an UE's transmission in its "secondary" eNB, so the same number of UEs are received at each eNB. Power control is not applied to the devices that belong to the group that has the higher received power. Instead, the devices transmitting in the group with lower received power adjust their power to assure the minimum separation between them and the UE of the group that transmits with higher power that has the lowest received $\frac{E_b}{N_0}$.

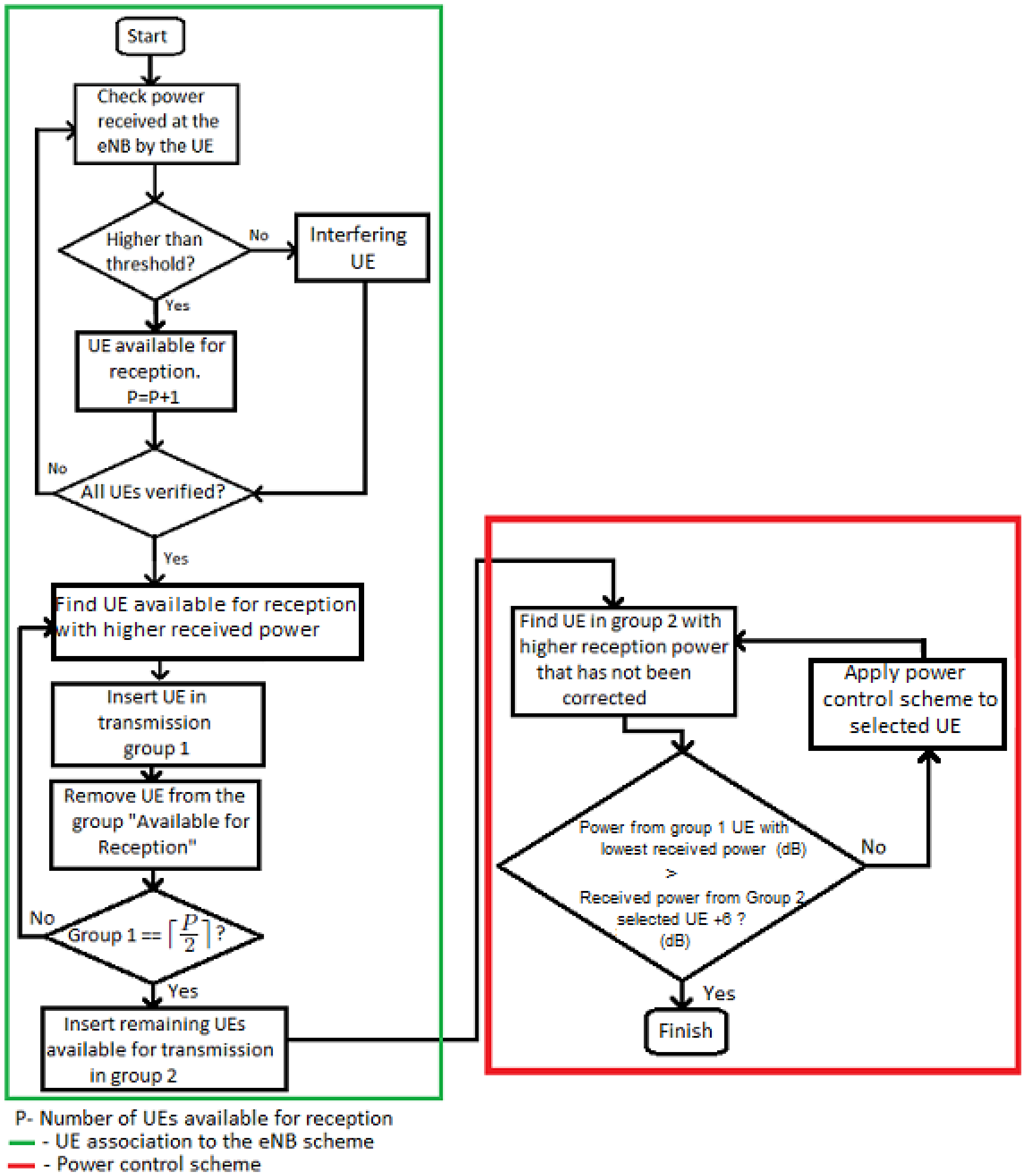

Figure 4.4: Flow Chart explaining UE association to one eNB and the power control scheme.

Spatial diversity can be introduced in the previously proposed scheme to optimize the capacity and increase the aggregate throughput at the receiver. Each time a UE transmits a packet, it is received simultaneously at multiple receivers. Therefore, the number of time slots needed to successfully transmit a packet may be reduced, depending on the number of eNBs available to cooperate in the spatial diversity scenario. In a system with 2 eNBs that employs the hybrid CoMP scheme described, the time resource needed to assure the reception may be cut in half, comparing with the time resources needed when only the time and power diversity schemes are used. The spatial uplink diversity scheme also allows the reduction of interference values in dense networks when two or more eNBs are close, since UEs associated to one eNB will no longer represent an interference threat to the other eNBs, as depicted in figure 4.5. It also provides the network with more resistance to collisions, since multiple copies of the packet involved in the collision are present in different receivers.

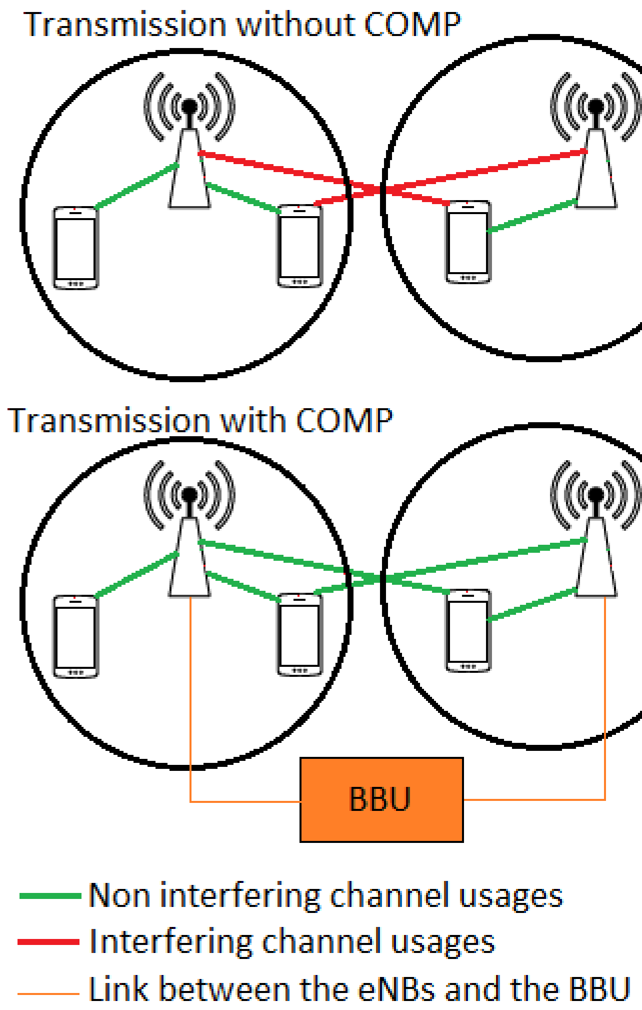

Figure 4.5: Uplink transmission of two UEs with and without using CoMP

Regarding the reception model, spatial diversity introduces an heterogeneous N_k^{eq}. Even though the channel noise may remain constant, every eNB will have a different N_k^{eq} value due to the different UE's neighbourhoods. The incomplete channel knowledge interference model was considered in the simulations presented in the following section about the performance of the hybrid CoMP scheme in high density networks.

Hybrid CoMP Scheme performance

Simulations with different UE density values were performed in order to understand the improvements that the hybrid CoMP scheme described above can bring to the network's capacity. This scheme is useful in networks where there is a high density of transmitters. However a scenario with a low density of transmitters is also analysed to verify the scheme's behaviour in this scenario. The topology generator described in section 4.1.2 was used to recreate the high and low density conditions in a squared area. Two receivers were deployed in the network, one at the centre of a squared area and another with a predefined distance from the centre. A path loss normalization was considered to every UE, with respect to the UE that had the lower path loss attenuation to one of the two eNBs.

A threshold value of the adjusted $\frac{E_b}{N_0}$ (ω) at the receiver was predefined to limit UE association to the eNBs. Firstly, the UEs that have their signal received at one of the eNB with power above this threshold associate themselves with the one that receives the signal with a higher $\frac{E_b}{N_0}$. This is considered their primary eNB. In these simulations, even though the $\frac{E_b}{N_0}$ measured in the other eNB may be below the threshold, if one UE is associated to one eNB, it will also have its signal received at the other eNB. This is possible because the distance between the two receivers is small, therefore the signal attenuation to the "secondary" receiver cannot be large. Afterwards, the number of copies of each packet needed to simultaneously receive all the UEs is defined. In section 3.3.1 it is defined that for a network with P users, at least $\frac{P}{2} - 1$ copies of the original packet are needed to allow the successful reception. In a network with two eNBs, the number of time slots needed to transmit all the packets is equal or higher to $\lceil \frac{P}{4} \rceil$, depending on the node distribution and other existing multi-hop constraint to the power regulation. The simulation compares the performance of a CoMP approach with a non-CoMP approach for the same scenario.

High Density Scenario

In the high density simulation, a total of 10 UEs were considered in the scenario without spatial diversity and 14 UEs where considered in the scenario with spatial diversity. Two eNBs were deployed with 1 meter distance between themselves. For the simulation without spatial diversity, only one of the eNBs and the UEs associated to it will be considered. A total of 1198 interfering users were deployed in a 225 m^2 square area, with a density of approximately 5.4 UEs/m^2. The deployment of the eNBs and UEs that were used is depicted in figure 4.6.

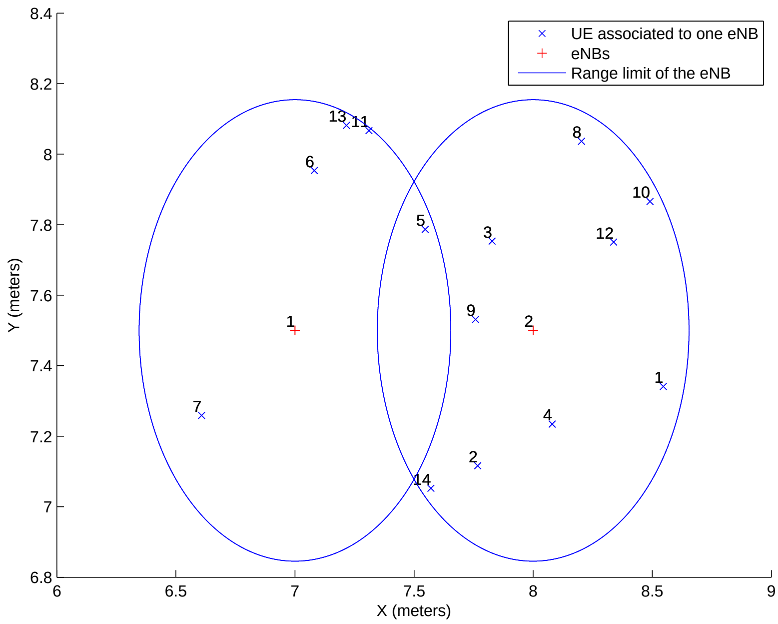

Figure 4.6: Portion of the network considered in the Hybrid Diversity scheme simulation with high device density

Observing the deployment of the UEs, it can be seen that the hybrid CoMP scheme can enhance the reception of UE 5, since it is associated to eNB 2 but it is in the cell edge region of the two eNBs. It is also interesting to analyse if CoMP can enhance the transmission of UE 9, since it has a much higher path loss attenuation to eNB 1 than to eNB 2, however it falls in a region between the two eNBs. UE 1's PER is also going to be represented, even though it has a significant path loss to eNB 1 to depict a scenario where the transmitter does not fall in the optimal CoMP zone. More specifications of the simulation are present in table 4.3, the PER results for the fourth iteration of the receiver for different ω values obtained in the simulations are depicted in figure 4.7 and the average aggregate throughput for the fourth iteration of the receiver for both scenarios for different ω values is shown in figure 4.8.

Table 4.3: Specifications for the interference model performance simulation with high device density.

Specifications	
UEs transmitting in the power and time diversity scheme	10
UEs transmitting in the hybrid CoMP scheme	14
eNB receivers	2
ω threshold	-12 dB
Transmissions of each UE in the power and time diversity scheme	5
Transmissions of each UE to each receiver in the hybrid CoMP scenario	4
Copies of each packet processed in the hybrid CoMP scenario	8
Iterations of the Receiver	4
PL_{min}	-17.1563 dB
Highest Path Loss on UE Group 1 (normalized)	-7.4121 dB
Minimum Path Loss on UE Group 2 (normalized)	-13.4121 dB
ρ_{ON}	1
Obtained β	5.4 UEs/m^2
Length of the squared area considered	15 m
Repetitions of the simulation	200
Channel Type	EPMC

Firstly, it can be observed in table 4.3 that the minimum path loss on the transmission of Group 2 is below the predefined threshold. This happened after the UE was selected to transmit in this group, due to the power correction applied to assure the power separation between all UEs. In figure 4.7, it can be observed that when using the hybrid CoMP scheme, lower PERs are obtained with lower ω values. This enhancement is due to the lower interference values that affect eNB 2 in the hybrid CoMP scheme. UEs such as UE 11 and UE 13 have their transmission received at eNB 1, however they contribute greatly to the interference at eNB 2, due to their proximity. When using spatial diversity, these devices no longer contribute to the interference since they have their transmissions received at eNB 2. The PER enhancement is greater in UE 5 than in UE 1, with an offset in the ω value needed for obtaining the same PER of nearly -10 dB. This is due to the lower path loss attenuation of UE 5 to the secondary eNB, which is accounted in ω. UE 5

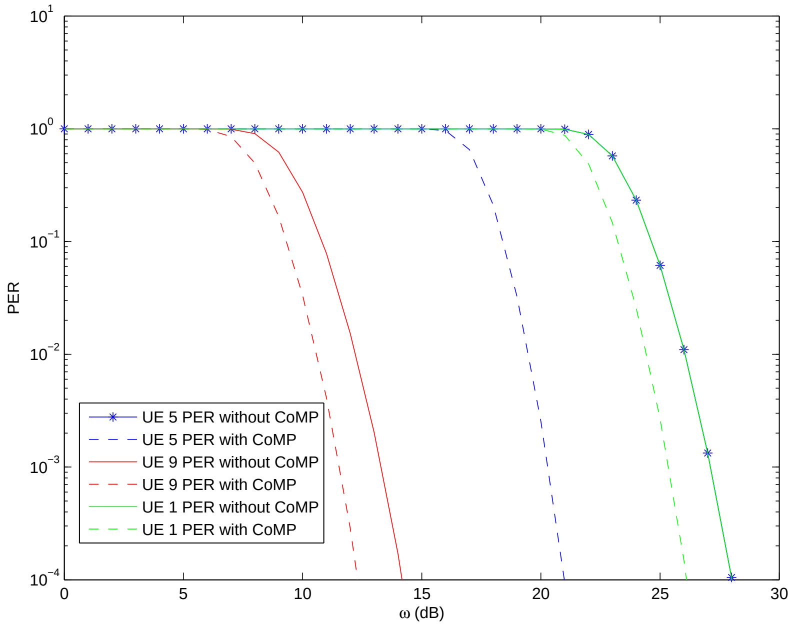

Figure 4.7: PER of UEs obtained in both diversity simulated scenarios with high density

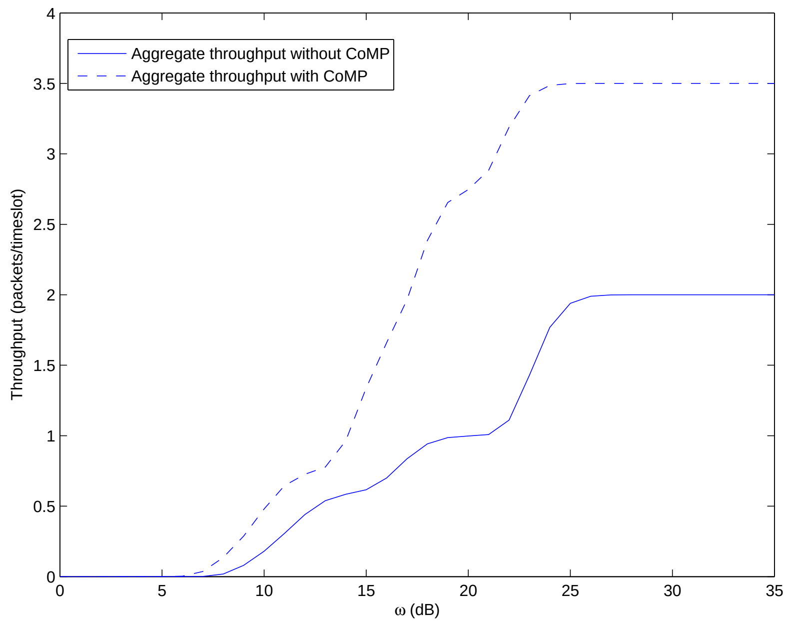

Figure 4.8: Average Aggregate Throughput of both diversity simulated scenarios with high density

is located in an optimal CoMP zone, since it presents almost the same attenuation to both eNBs. UE 9 transmission also has a minor enhancement because the PER is already low, due to the low path loss attenuation this device has compared to the primary receiver. It can be concluded that, depending on the position of the device, it can be better to use only time and power diversity on the uplink transmission than to use the hybrid CoMP scheme proposed, since the power enhancements obtained are not significant.

Observing the aggregate throughput in the receiver depicted in figure 4.8, it can be concluded that all the UEs can be received in both scenarios, for ω values greater than 25 dBs. In the power and time diversity scenario, 5 time slots are used to receive 10 UEs, a throughput of 2 packets/timeslot is obtained, which is the maximum throughput possible to be achieved using this technique for two power levels. In the hybrid CoMP scenario, 4 timeslots are used to simultaneously have packets received at 2 eNBs, in order to receive the transmission of 14 UEs. Therefore a throughput improvement of 3.5 packets/timeslot is achieved, since 4 more UEs are successfully decoded with 1 less timeslot. Concluding, for the simulated topology, CoMP enabled the improvement of the network's capacity, allowing the reception of more UEs with less timeslots. The power enhancement previously described can also be observed in figure 4.8. When using the hybrid CoMP scheme, the same throughputs are achieved with lower ω values than when using the time and power diversity scheme, thus with a lower transmission power.

Low Density scenario

In the low density simulation, a total of 3 UE's transmissions were received in the scenario with power and time uplink diversity and 3 UEs were added in the hybrid CoMP scenario. A total 321 devices were deployed. The density value obtained is approximately 1.43 UEs/m^2. The deployment of the transmitters and the receivers in the network is depicted in figure 4.9.

It can be observed that UEs 6 and 4 are in the optimal zone to have their transmission enhanced by the hybrid CoMP scheme proposed, since they fall in a region between the receivers. The PER of these devices' transmission is depicted. Since UE 1 already is in optimal conditions to have its transmission received without CoMP, it is expected that the improvements are higher for UE 6 when using the hybrid scheme, even though this UE has a higher path loss attenuation to both eNB. More specifications of the simulation are presented in table 4.4. The PER results for the fourth iteration of the receiver over different ω values obtained in the simulations are depicted in figure 4.7 and the average aggregated throughput for the fourth iteration of the receiver over different ω values for

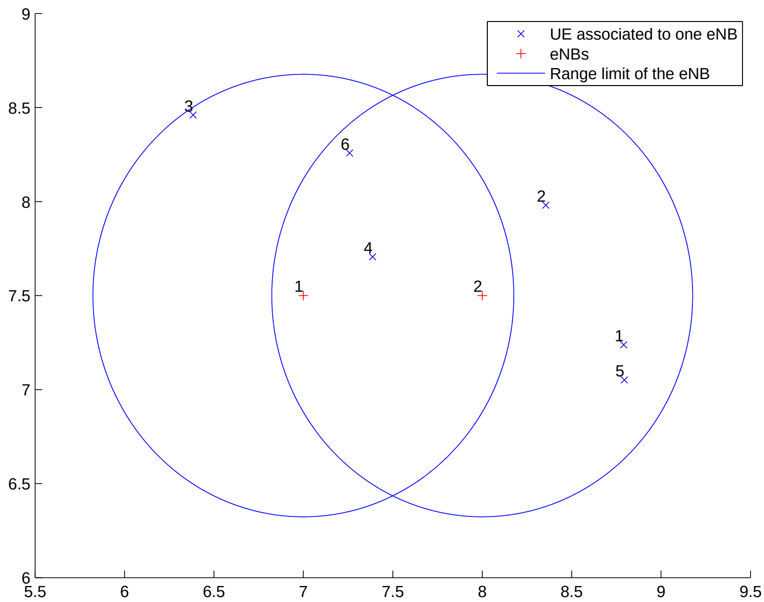

Figure 4.9: Portion of the network considered in the Hybrid Diversity scheme simulation with low device density

both scenarios are observable in figure 4.8

A power enhancement in both transmissions can be observed in figure 4.10, similarly to the high density simulation. There is a bigger offset in the ω values needed to successfully receive UE 6 packet than to receive UE 4 in the two different scenarios. The enhancement in the reception power needed to receive UE 6 transmission is greater than the enhancement in the reception power needed to receive UE 4 transmission, when using the hybrid CoMP scheme. This happens because UE 4 is really close to eNB 1, so the received power is close to optimal. However its transmission can still benefit from the use of the hybrid CoMP scheme, since the eNBs are affected by lower interference levels. From figure 4.11, it can also be observed that, when using the hybrid CoMP scheme, a lower ω at the receiver allows to achieve an equal performance to the uplink power and time diversity scheme. All the devices have their packets received in both schemes, however the successful reception of all packets is achieved with approximately less 5 dBs in the CoMP scenario. In the scenario without CoMP a total of 2 timeslots are used to receive 3 packets and in the scenario with CoMP a total of 2 timeslots are used to receive 6 packets. Therefore, in this simulation an improvement in the network's capacity was registered with the use of the hybrid CoMP scheme, similarly to the high density simulation.

Table 4.4: Specifications for the interference model performance simulation with low device density.

Specifications	
Terminals transmitting in the power and time diversity scheme	3
Terminals transmitting in the hybrid CoMP scheme	6
eNB receivers	2
Maximum path loss attenuation to be considered in the receiver	-12 dB
Transmissions of each UE in the power and time diversity scheme	2
Transmissions of each UE to each receiver in the hybrid CoMP scenario	2
Copies of each packet processed in the hybrid CoMP scenario	4
Iterations of the Receiver	4
PL_{min}	-10.0231 dB
Highest Path Loss on UE Group 1 (normalized)	-11.6305 dB
Minimum Path Loss on UE Group 2 (normalized)	-17.6305 dB
ρ_{ON}	1
Obtained β	1.43 UEs/m^2
Length of the squared area considered	15 m
Repetitions of the simulation	200
Channel Type	EPMC

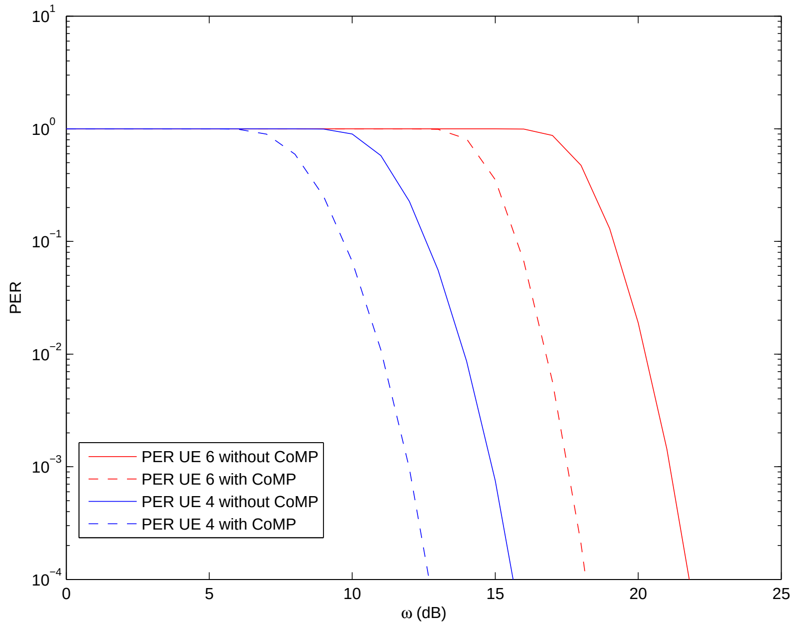

Figure 4.10: PER of UEs obtained in both diversity simulated scenarios with low density

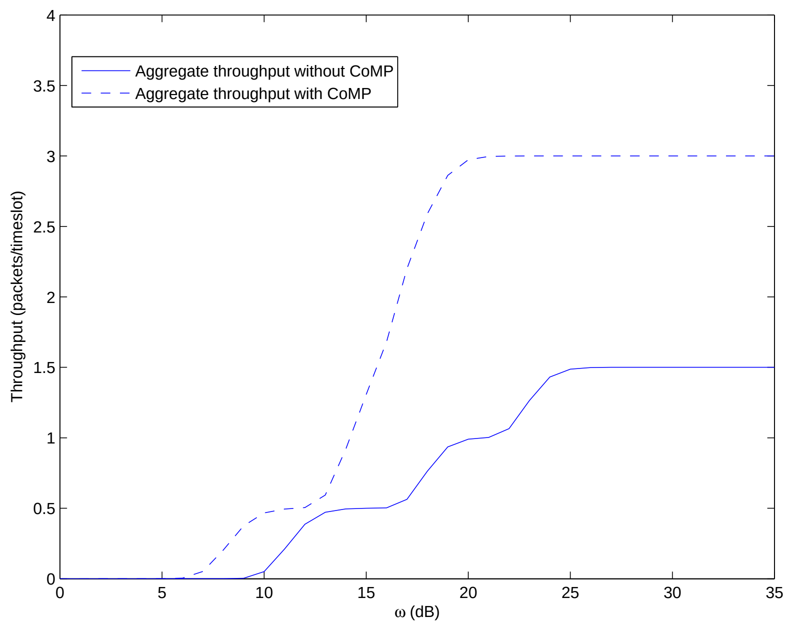

Figure 4.11: Average Aggregate Throughput of both diversity simulated scenarios with low density

Chapter 5

Conclusions

5.1 Final Considerations

This dissertation proposed hybrid CoMP, an uplink scheme designed to enhance the capacity of networks with a high density of users. Hybrid CoMP combines spatial diversity with power and time diversity, in order to reduce the interference levels while optimizing the network's throughput (i.e. the number of packets received per timeslot). The simulations presented in section 4.2.1 showed that the introduction of one more eNB, in a reception scheme that employed power and time diversity of the UE's transmissions, lead to enhancements of the aggregated throughput. Therefore, leading to an increase in the network's capacity, enabling the simultaneous reception of a higher number of users. Furthermore, the higher aggregated throughputs were achieved with the UEs transmitting with lower power. This enhancement is due to the effective lower interference levels achieved with the introduction of the CoMP reception scheme, which allows the decoding of the transmission of highly interfering users.

The improvement of each UE's PER when using the hybrid CoMP scheme is greatly dependant on the position it has to each eNB. Users that had a high PER, but were located in an area between both eNBs, showed a great reduction in the transmission power needed to achieve a low PER. The distance of the UEs to the eNBs also influences the enhancement of the PER achieved by the UEs. The PER improvement is greater when the UE is farther away from its primary eNB.

The proposed technique is designed to be implemented in heterogeneous networks, where the distance between the receivers is small and consequently the attenuation in the transmissions to the different eNBs has similar values. However, there is a trade-off between the throughput gains achieved in these networks and the deployment cost of the infrastructures required. In low density networks, enhancements can also be achieved, however the investment in the deployment of more eNBs may not be justifiable. However in high density networks, hybrid CoMP may be a valid option to provide the increase in the network's capacity to match the expected traffic growth.

5.2 Future Work

This dissertation addressed the enhancements of the uplink reception using a CoMP hybrid scheme, where 2 eNBs were available to provide spatial diversity. Future work may include the use of more than 2 eNBs to verify the capability of further enhancements to the network's capacity. Furthermore, spatial diversity could also be provided by different types of small cells (e.g. picocells, nanocells). This would increase the number of network layers, which would result in more complex interference scenarios.

In the power diversity scheme, in order to simplify the hybrid CoMP scheme, it was admitted the use of only two UE groups with distinct transmission power. A transmission power optimization could be achieved with the IB-DFE receiver, which could reduce the power separation needed to successfully decode the desired transmissions and the number of packet retransmissions.

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