Universidade de Aveiro Departamento de Electrónica, Telecomunicações e Informática
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Vasco Miguel Barroso Da Silveira e Carvalho

TÉCNICAS DE COOPERAÇÃO ENTRE ESTAÇÕES BASE PARA SISTEMAS CELULARES

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Electrónica e de Telecomunicações, realizada sob a orientação científica do Dr. Adão Silva, Professor Auxiliar do Departamento de Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro.

o júri / the jury

presidente /president **Prof. Dr. José Carlos Silva Neves**

Professor Catedrático do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro

vogais / examiners comitee **Prof. Dr. Paulo Jorge Coelho Marques**

Professor Adjunto do Departamento de Engenharia Electrotécnica da Escola Superior de Tecnologia do Instituto Politécnico de Castelo Branco

Prof. Dr. Adão Paulo Soares Silva

Professor Auxiliar do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro (Orientador)

Prof. Dr. Atílio Manuel da Silva Gameiro

Professor Associado do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro (Co-Orientador)

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palavras-chave

MIMO, OFDM, path loss, correlação, alocação de potência, canal de transmissão, agregado de antenas, sistemas de portadora múltipla, propagação multipercurso, sistema cooperativo, sistema multicelular.

resumo

A cooperação entre células é uma das áreas de pesquisa em maior crescimento, sendo uma solução promissora para sistemas celulares sem fio, por forma a amenizar a interferência entre as células, melhorar a equidade do sistema e aumentar a capacidade nos anos vindouros. Esta tecnologia já está em estudo no LTE-Advanced sob o conceito de coordenação multiponto (CoOMP). Esta dissertação insere-se na área de comunicações sem fios e tem como principal objectivo, estudar, implementar e avaliar o desempenho de esquemas de cooperação entre estações base, projectados para os futuros sistemas de comunicações móveis de portadora múltipla (OFDM/A). Especificamente, o sistema cooperativo estudado é constituído por duas estações base equipadas com um agregado de antenas, ligadas a uma unidade de processamento central, e dois terminais móveis equipados cada um com apenas uma antena. O sistema referido foi implementado de acordo com as especificações do LTE e avaliado em diversos cenários de propagação. As técnicas desenvolvidas permitem contornar os problemas relacionados com a má qualidade de canal entre emissor e receptor, melhorando o seu desempenho, especificamente ao nível da taxa de erros de transmissão.

keywords

MIMO, OFDM, path loss, correlation, power allocation, transmission channel, antenna array, multicarrier systems, multipath propagation, cooperative system, multicell system.

abstract

Multicell cooperation is one of the fastest growing areas of research, and it is a promising solution for cellular wireless systems to mitigate intercell interference, improve system fairness and increase capacity in the years to come. This technology is already under study in LTE-Advanced under the coordinated multipoint (CoOMP) concept. This dissertation is inserted in the wireless communications area, with its main objective being the study, implementation and evaluation of the performance of cooperative schemes between base stations designed for the future mobile communication multiple carrier systems (OFDM/A). Specifically, the cooperative system studied consists of two base stations, each with multiple antenna, connected to a central processing unit, and two mobile terminals, each equipped with only one antenna. The system referred to was implemented in accordance with the specifications of LTE and was tested in various different propagation situations. The developed techniques ensure the mitigation of problems related to interference between the portable terminals namely at the cell edges, improving specifically the bit error rate performance.

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List of acronyms

1G - First Generation Mobile Communications Systems
2G - Second Generation Mobile Communications Systems
3G - Third Generation Mobile Communications Systems
4G - Fourth Generation Mobile Communications Systems
3GPP - 3rd Generation Partnership Project
AMPS - Advanced Mobile Phone Service
ARFCN - Absolute Radio-Frequency Channel Number
AWGN - Additive White Gaussian Noise
BER - Bit Error Rate
BS - Base Station
CDD - Code Division Duplex
CDMA - Code Division Multiple Access
CODIV - Enhanced Wireless Communication Systems Employing Cooperative DIVersity
CoMP - Coordinated Multipoint
CP - Cyclic Prefix
CSC - Central System Controller
CSI - Channel State Information
CU - Central Unit
D-AMPS - Digital Advanced Mobile Phone Service
DBWS - Distributed Broadband Wireless System
DL - Downlink
DSL - Digital Subscriber Line
E-GPRS - (Enhanced GPRS)
EDGE - Enhanced Data Rates for Global Evolution
ETSI - European Telecommunications Standards Institute
EV-DO - Evolution Data Optimized
EV-DV - Evolution Data Voice
FER - Frame Error Rate
FDD - Frequency Division Duplex
FDMA - Frequency Division Multiple Access
FFT - Fast Fourier Transform

FH - Frequency Hopping

GPRS - General Packet Radio Services

GSM - Global System for Mobile Communications

HSPA - High-Speed Packet Access

HSDPA - High-Speed Downlink Packet Access

HSUPA - High-Speed Uplink Packet Access

IFFT - Inverse Fast Fourier Transform

IP - Internet Protocol

ISI - Inter Symbol Interference

ITU - International Telecommunications Union

J-TACS - Japanese Total Access Communication System

JPU - Joint Processing Unit

LAN - Local Area Networks

LTE - Long Term Evolution

MIMO - Multiple Input Multiple Output

MISO - Multiple Input Single Output

MRC - Maximum Ratio Combining

NLOS - Non Line of Sight

NMT - Nordic Mobile Telephone

OFDM - Orthogonal Frequency Division Multiplex

OFDMA - Orthogonal Frequency Division Multiple Access

PAR - Peak-Average Ratio

PDA - Personal Digital Assistant

PDC - Personal Digital Cellular

QAM - Quadrature Amplitude Modulation

QoS - Quality of Service

QPSK - Quadrature Phase Shift Keying

RAU - Remote Access Unit

RoF - Radio over Fiber

RTT - Radio Transmission Technology

SIMO - Single Input Multiple Output

SISO - Single Input Single Output

SMS - Short Message Service

SNR - Signal to Noise Ratio

STBC - Space Time Block Coding

STTD - Space–Time Transmit Diversity

TACS - Total Access Communication System

TCP - Transmission Control Protocol

TCP / IP - Internet Protocol Suite

TDD - Time Division Duplex

TDMA - Time Division Multiple Access

UL - Uplink

UMTS - Universal Mobile Telecommunications System

UT - User Terminal

UTRA - Universal Terrestrial Radio Access

VoIP - Voice Over IP

WAP - Wireless Application Protocol

WCDMA - Wideband Code Division Multiple Access

WiFi **-** Wireless Fidelity

WiMAX - Worldwide Interoperability for Microwave Access

CHAPTER I

INTRODUCTION

1.1 History and background of mobile communications

Mobile communication has revolutionized the telecommunications market. The demand for voice services and wireless data with satisfactory coverage has grown too much and with prospects of constant evolution. However, this technological revolution only became possible thanks to the concept of cellular communication.

The history of mobile communication systems begins in 1885 when Thomas Edison developed a wireless communication between trains and stations. Using the theories of Maxwell (1864) and the experiences of Henry (1842), the first system was based on electrostatically coupling signals between the wireless station and metal plates located on the roof of a train [1].

In 1901, using vertical wire antennas with different shapes, Marconi succeeded in establishing a long distance communication through the Pacific Ocean, between Canada and the United Kingdom. The transmission capacity between points beyond the line of sight (NLOS - Non Line of Sight) marks the official beginning of the first generation of mobile communications.

The first international mobile communication system was the analog NMT system (Nordic Mobile Telephony) which was introduced in the Nordic countries in 1981, at the same time as analog AMPS (Advanced Mobile Phone Service) was introduced in North America. Other analog cellular technologies deployed worldwide were TACS (Total Access Communication System) and J-TACS (Japanese Total Access Communication System). They all had in common that equipment was still bulky, mainly car-borne, and voice quality was often inconsistent, with cross-talk between users being a common problem [2].

With an international system such as NMT came the concept of roaming, giving a service also for users traveling outside the area of their 'home' operator. This also gave a larger market for the mobile phones, attracting more companies into the mobile communication business.

The analog cellular systems supported voice with some related supplementary services. With the advent of digital communication during the 1980s, the opportunity to develop a second generation of mobile-communication standards and systems, based on digital technology, surfaced. With digital technology came an opportunity to increase the capacity of the systems, to give a more consistent quality of the service, and to develop much more attractive truly mobile devices.

In Europe, the GSM (Global System for Mobile Communications) project was initiated in order to develop a pan-European mobile-telephony system. The GSM activities were in 1989 continued within the newly formed ETSI (European Telecommunication Standards Institute). After evaluations of TDMA (Time Division Multiple Access), CDMA (Code Division Multiple Access), and FDMA (Frequency Division Multiple Access) based proposals in the mid-1980s, the final GSM standard was built on TDMA.

All these standards were narrowband in the sense that they targeted low bandwidth services such as voice. With the second-generation digital mobile communications came also the opportunity to provide data services over the mobile-communication networks. The primary data services introduced in 2G (Second Generation Mobile Communications Systems) were text messaging (SMS - Short Message Service) and circuit-switched data services enabling e-mail and other data applications. The peak data rates in 2G were initially 9.6 kbps. Higher data rates were introduced later in evolved 2G systems by assigning multiple time slots to a user and by modified coding schemes.

Packet data over cellular systems became a reality during the second half of the 1990s, with GPRS (General Packet Radio Services) introduced in GSM and packet data also added to other cellular technologies such as the Japanese PDC (Personal Digital Cellular) standard. These technologies are often referred to as 2.5G. The success of the wireless data service iMode in Japan gave a very clear indication of the potential for applications over packet data in mobile systems, in spite of the fairly low data rates supported at the time.

With the advent of 3G (Third Generation Mobile Communications Systems) and the higher-bandwidth radio interface of UTRA (Universal Terrestrial Radio Access) came possibilities for a range of new services that were only hinted at with 2G and 2.5G. The 3G radio access development is today handled in 3GPP (3rd Generation Partnership Project). However, the initial steps for 3G were taken in the early 1990s, long before 3GPP was formed.

What also set the stage for 3G was the internationalization of cellular standardization. GSM was a pan-European project, but quickly attracted worldwide interest when the GSM standard was deployed in a number of countries outside Europe. There are today only three countries worldwide where GSM is not deployed. A global standard gains in economy of scale, since the market for products becomes larger. This has driven a much tighter international cooperation around 3G cellular technologies than for the earlier generations. Table 1.1 summarizes the evolution of cellular communications.

Table 1.1: Evolution of cellular communications [3].

Generation	1G	2G	2.5G	3G	3.5G	4G
Applications	Analog voice	Digital voice (and limited data; e.g. sms)	Digital voice and limited data	Digital voice and data	Data and ditigal voice	Wireless internet
Rate		10 Kbps/user		UL: 384 kbps/cell DL: 2Mbps/cell	~20 Mbps/cell	UL: 100Mbps/cell DL: 2Gbps/cell
Bandwidth		1.25 MHz		5 MHz		
Systems	AMPS NTT TACS	IS-95 (CDMA) 1993 GSM (TDMA) early 1990's IS-136 (TDMA) N. American PDC	CDMA one GPRS → EDGE	CDMA2000 (3GPP2) WCDMA (3GPP – UMTS) TD-SCDMA (TDD)	UMB 3G LTE Super 3G (~2012) OFDMA	IMT Adv 2015+ 802.16m 802.11n OFDMA

First generation - 1G

The first generation, or 1G (First Generation Mobile Communications Systems), was characterized by being essentially an analog system. The area coverage was based on dividing cells provided by each of its radio transmitter and low-power receivers. When a mobile call reaches a transmission/reception tower, it is transferred to the regular telephone system. Each cell has multiple channels with the aim of providing services to many users simultaneously. As a user moves within range, the mobile phone signal will automatically switch from one cell to another, without interruption. This technique is called handoff.

The first mobile phone system became known by the acronym AMPS [4].

AMPS

AMPS was a first-generation cellular technology, which went into commercial operation early in 1983, and used separate frequencies, or "channels", for each conversation. It therefore required considerable bandwidth for a large number of users. In this type of network, a voice circuit is permanently allocated for the duration of the call, i.e., it is a connection-oriented service, which only allows voice transmission.

What really separated AMPS from older systems is the "back end" call setup functionality. In AMPS, the cell centers could flexibly assign channels to handsets based on signal strength, allowing the same frequency to be re-used in various locations without interference. This allowed a larger number of phones to be supported over a geographical area. AMPS pioneers fathered the term "cellular" because of its use of small hexagonal "cells" within a system [5].

The growing use of this system quickly saturated the number of available channels per cell, reaching its limit mainly in metropolitan areas.

Second Generation - 2G

After a while, analog systems had reached the limit of their capacity. The need for digital systems with greater, gives rise to second generation technologies, marked by the use of a more robust system, which included digital voice coding, greater spectral efficiency and greater capacity.

This generation was characterized by having much more capacity than the previous one. The signal, which is now digital, is still transported in the same manner as in 1G technology [4].

Once again, several protocols were defined: Digital AMPS (DAMPS), Personal Digital Cellular (PDC), Code Division Multiple Access (CDMA). Out of these, the TDMA-based Global System for Mobile Communications (GSM) stood out.

GSM

Developed in Europe, where it was introduced commercially in 1992, and used almost all around the world, GSM is a standard set developed by the ETSI to describe technologies for second generation digital cellular networks. Developed as a replacement for first generation analog cellular networks, the GSM standard originally described a digital, circuit switched network optimized for full duplex voice telephony. The standard was expanded over time to include first circuit switched data transport, then packet data transport via GPRS. Packet data transmission speeds were later increased via EDGE (Enhanced Data Rates for Global Evolution). The GSM standard is succeeded by the third generation UMTS (Universal Mobile Telecommunications System) standard developed by the 3GPP. GSM networks will evolve further as they begin to incorporate fourth generation LTE Advanced (Long Term Evolution) standards.

It differs from other technologies by the use of SIM Card memory cards in devices, which allows users to take their settings to another device or GSM network. GSM operates in the 850, 900, 1800 and 1900MHz frequency bands, using a combination of FDMA and TDMA access techniques, where GSM a radio frequency carrier (called ARFCN - Absolute Radio-Frequency Channel Number), with a 200kHz bandwidth, through the TDMA technique, is subdivided into eight time intervals [4].

2.5G

The term 2.5G is not recognized by the ITU (International Telecommunications Union), only to be described as a transitional technology between the two generations [6]. The protocols that are included therein may be characterized as an evolution of the previous generation. This distinction arose from a market need to establish a new era in wireless communications that crossed the barriers of transmission rates of 2G [7]. The big difference between this technology and 2G, is that this technology uses an advanced technique of modulation (compared to 2G), capable of switching packets rather than circuits, the same technique adopted by the TCP / IP (Internet Protocol Suite) architecture [4].

GPRS

GPRS is the evolution of GSM technology at 2.5 G. This technology provides a maximum data rate of 115kbps and an average transfer rate of 30 to 40kbps. The data to be sent is divided into packets for later transmission, which benefits the users, since they have a permanent connection data and so they have no need to access the system each time they wish to have access to data services.

GPRS usage charging is based on volume of data, either as part of a bundle or on a pay-as-you-use basis. An example of a bundle is up to 5 GB per month for a fixed fee. Usage above the bundle cap is either charged for per megabyte or disallowed. The pay as you use charging is typically per megabyte of traffic. This contrasts with circuit switching data, which is typically billed per minute of connection time, regardless of whether or not the user transfers data during that period. This is another advantage of GPRS.

GPRS is a best-effort service, implying variable throughput and latency that depend on the number of other users sharing the service concurrently, as opposed to circuit switching, where a certain QoS (Quality of Service) is guaranteed during the connection.

It is the GPRS that allows the connection of most smartphones and mobile phone to the Internet. Currently, GPRS is the standard that offers greater coverage for mobile handsets with Internet access.

EDGE

This technology has caused much controversy, since it can be considered as a 2.5 or 3G technology. EDGE is a technology used to transmit data and access to high-speed Internet, which transmits data up to 384kbps and has an average transmission between 110 and 120kbps. The average rates of transmission are fast enough to allow advanced data services such as streaming audio and video, fast Internet access and downloading relatively large files. EDGE also supports "push to talk" services.

This technology is also called E-GPRS (Enhanced GPRS), since it increases the capacity and data throughput of GPRS technology in three or four times. EDGE is also a packet-based service that offers customers a permanent connection for data transmission.

Third generation - 3G

Third generation mobile systems arose from the need to develop a system communication standard that allows communication anywhere, anytime [8].

Systems with 3G services provide telephone and data communications at higher speeds than previous technologies. The 3G standard specifies 144kbps in mobile environments, 384kbps in pedestrian environments and 2Mbps in fixed environments [4]. Some of these assumptions were met and a few independent and incompatible systems were established.

UMTS

This system evolved from the second generation (GSM) and was developed by 3GPP. Compatibilities with the GSM system were kept, in order to take advantage of its big investment structure.

UMTS is an IP-based technology that supports voice and data packages, offering maximum rates of data transmission up to 2 Mbps and average speeds of 220 to 320kbps when the user is moving. UMTS is designed to provide services with high levels of bandwidth consumption, such as streaming, large file transfers and video conferencing for a variety of devices such as mobile phones, PDAs (Personal Digital Assistant) and laptops. It is compatible with EDGE and GPRS allowing the user to leave an area of UMTS coverage and be automatically transferred to an EDGE or GPRS, depending on factors such as network availability and bandwidth consumption of the application.

CDMA 1xEV-DO (Evolution Data Optimized)

CDMA 1xEV-DO is the 3G CDMA technology, which has high performance for data transmission with peaks of up to 2.4 Mbps. Different carriers are needed for data and voice in this type of system.

CDMA 1xEV-DV (Evolution Data and Voice)

The evolution of CDMA 1xEV where a single carrier can now be used to transmit voice and data. The 1xEV-DO, has a 1.25 MHz carrier that is dedicated for data only, while in 1xEV-DV has a single dedicated carrier for data and voice.

WiFi (Wireless Fidelity)

This standard has become the most widely used and widespread form of wireless access in recent years. It was initially developed for access to personal networks, such as laptops and PDAs, but access techniques to networks with greater reach such as Internet and VoIP (Voice Over IP) were quickly implemented. It reaches a rate of transmission of about 54 Mbps and utilizes OFDM (Orthogonal Frequency Division Multiplexing) technology for transmission rates above 20Mbps.

3G+

The UMTS system proposed to achieve higher ends, with transmission rates up to 2Mbps in indoor cells. Faced with the failure of this goal, the 3GPP decided on improving the UMTS system, improving the WCDMA (Wideband Code Division Multiple Access) interface to values beyond those proposed for third generation systems [9]. The HSPA (High-Speed Packet Access) system was thus adopted, particularly on DL (Downlink) schemes (HSDPA - High-Speed Downlink Packet Access) where it introduced adaptive modulation and coding, retransmission mechanisms and, at a later stage, multiple antennas for transmission and reception. These exploit the decorrelation between different channels, using properties of diversity and achieving better spectral efficiency.

Analyzing the history of mobile communications, we can conclude that its evolution follows cycles of about ten years. In the 80s the advent of the first generation, ten years after the second generation, with 3G becoming a reality around 2001. It is expected that a new decade brings a new certification by the ITU [10]. The major change that will characterize this new generation (4G - Fourth Generation Mobile Communications Systems) will be characterized by the unification of the various existing wireless communication systems, all based on the TCP / IP layer, the basic protocol of the Internet. It is estimated that the next generation of wireless networks will provide transmission rates of between 50Mbps and 150Mbps. New coding and modulation techniques have been studied and developments related to power consumption and a better use of the spectrum are also expected. Currently the systems that best characterize this generation, despite its name 4G not being entirely correct, are LTE and WiMAX (Worldwide Interoperability for Microwave Access).

LTE

The Long Term Evolution was established by 3GPP as the next IP technology based on OFDMA modulation (Orthogonal Frequency Division Multiple Access). It emerges as a successor of the GSM and UMTS network technologies, using their interface, but differs from them in a better downlink spectral utilization, using a multiple antenna system.

Its main goals are to maintain the ability to transmit real-time voice and data for speeds of up to 500Km/h and to reach up to 100Mbps on downlink and 50Mbps on uplink.

WiMAX

WiMAX is a telecommunications protocol that provides fixed and mobile Internet access. The current WiMAX revision provides up to 40 Mbit/s with the IEEE 802.16m update expected to offer up to 1 Gbit/s fixed speeds. The name "WiMAX" was created by the WiMAX forum, which was formed in June 2001 to promote conformity and interoperability of the standard. The forum describes WiMAX as "a standards-based technology enabling the delivery of last mile wireless broadband access as an alternative to cable and DSL (Digital Subscriber Line) ".

1.2 Objectives and motivation

The wireless communications field is experiencing a rapid and steady growth. It is expected that the demand for wireless services will continue to increase in the near and medium term, asking for more capacity and putting more pressure on the usage of radio resources. The conventional cellular architecture considers co-located MIMO (Multiple Input Multiple Output) technology, which is a very promising technique to mitigate the channel fading and to increase the cellular system capacity [11]. On the other hand, OFDM is a simple technique to mitigate the effects of inter-symbol interference in frequency selective channels [12][13]. However, the problems inherent to these systems such as shadowing, significant correlation between channels in some environments and intercell interference significantly degrade the capacity gains promised by MIMO techniques [14]. Although theoretically attractive, the deployment of MIMO in commercial cellular systems is limited by interference between neighboring cells, and the entire network is essentially interference-limited. As such, the practical system capacity gains achieved by MIMO are below the theoretical promises, especially in dense urban environments and hotspots [15]-[17].

UFR (Universal Frequency Reuse), meaning that all cells/sectors operate on the same frequency channel, is mandatory if we would like to achieve spectrally-efficient communications. However, as it is pointed out in [15][17], this requires joint optimization of resources in all cells simultaneously to boost system performance and to reduce the radiated power. Such systems have the advantage of macro-diversity that is inherent to the widely spaced antennas and more flexibility to deal with intercell interference, which fundamentally limits the performance of UTs (User Terminals) at cell edges [14].

Different transmit strategies can be considered, depending on the capacity of the backhaul that connects the coordinated base stations. Recently, an enhanced cellular architecture with an high-speed backhaul channel has been proposed and implemented, under the European FUTON project [18]. This project aims at the design of a DBWS (Distributed Broadband Wireless System) by carrying out the development of a RoF (Radio over Fiber) infrastructure transparently connecting the BSs (Base Station) to a CU (Central Unit) where centralized joint processing can be performed. Also, multicell cooperation is already under study in LTE under the CoMP (Coordinated Multipoint) concept that although not included in the current releases, will probably be specified for the future ones.

This thesis aims at the implementation and assessment of cooperative precoding techniques, considering enhanced cellular systems where several base stations are linked to a central unit, therefore allowing for joint processing. Specifically, some precoding techniques proposed in [19] were implemented in a SIMULINK simulation chain based on LTE specifications. The objective is to evaluate these precoding algorithms in realistic cellular scenarios.

1.3 Structure of the dissertation

The remaining dissertation is divided in five more chapters.

In chapter 2 a more detailed overview of OFDM will be given. OFDM has been adopted as the downlink transmission scheme for the 3GPP LTE and is also used for several other radio technologies.

Chapter 3 will provide a general overview of different multi-antenna techniques, which can be used to achieve improved system performance, including improved system capacity (more users per cell) and improved coverage (possibility for larger cells), as well as improved service provisioning, for example, higher per-user data rates.

Chapter 4 presents an overview of the theory and currently known techniques for multi-cell MIMO cooperation in wireless networks. In dense networks where interference emerges as the key capacity limiting factor, multi-cell cooperation can dramatically improve the system performance. Remarkably, such techniques literally exploit inter-cell interference by allowing the user data to be jointly processed by several interfering base stations, thus mimicking the benefits of a large virtual MIMO array.

In Chapter 5, the cooperative diversity scheme implemented in this dissertation is presented in detail. This scheme is designed for a system based on LTE and its performance is evaluated in various scenarios.

The last chapter presents the final conclusions of this work and some possible future applications of the work developed in this dissertation are referred.

CHAPTER II

OFDM BASED SYSTEMS

2.1 Multi-carrier transmission

The wireless technology developments in the past years transformed the simple, narrow banded, circuit switching systems, in broadband systems mainly based on IP technology [20]. Since the electromagnetic spectrum is limited and with plenty of restrictions with respect to certain frequency bands, it becomes crucial to use it efficiently.

The most promising way to obtain more reliable systems and to make better use of the electromagnetic spectrum is to use modulation techniques based on multiple carriers. A multi-carrier system is characterized by dividing a sequence of information to be transmitted over sub-sequences of smaller size, which will be sent through the same number of sub-channels. The information to be sent by each of these sub-channels has a transmission rate lower than the original, as well as bandwidth used by that channel.

OFDM modulation is the basis of virtually all of the techniques based on multiple carriers. Its main advantage is that it is not as susceptible to multipath interference, as well as its ease of implementation and spectrum efficiency. It was precisely these advantages that justified this choice for current and future mobile communication systems, WiFi, WiMAX and LTE. It is the one that has gained more acceptance as the modulation technique for high-speed wireless networks and 4G mobile broadband standards.

The OFDM modulation can also be used as multiple access technique, called Orthogonal Frequency Division Multiple Access.

2.2 Basic OFDM principles

The basic principle of OFDM systems is the division of the available spectrum into small frequency bands. In order to prevent interference between signals from adjacent carriers it must be ensured that these are mutually orthogonal. This orthogonality means that each carrier has an integer number of cycles per symbol period [20]. Thus it is guaranteed that the spectrum of each carrier has a null in the center frequency of another carrier in the system, as can be seen on figure 2.1.

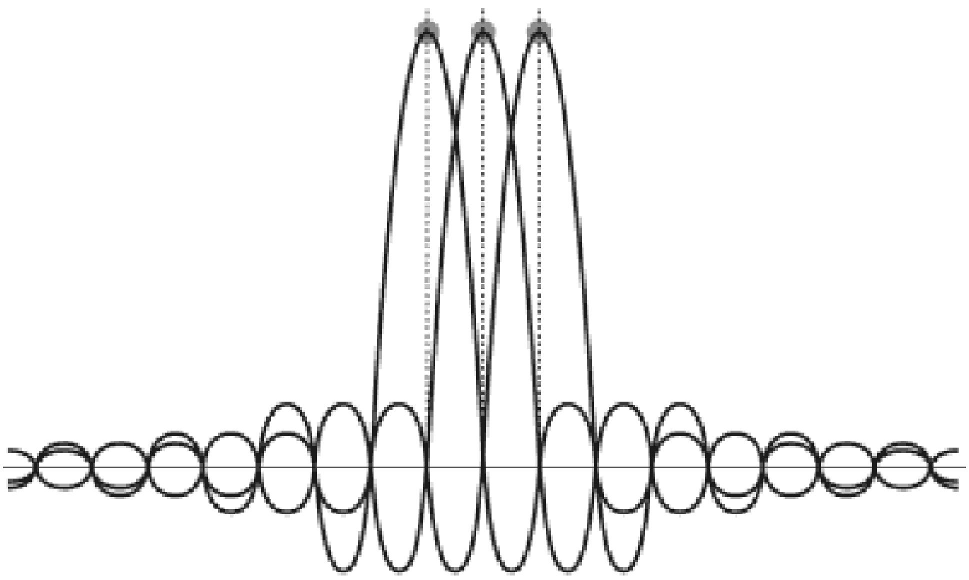

Figure 2.1: Orthogonality in the frequency domain [38].

Another distinguishable feature of OFDM is its simple rectangular pulse shaping, which corresponds to a sinc-square-shaped per-subcarrier spectrum, as we can see on Figure 2.2.

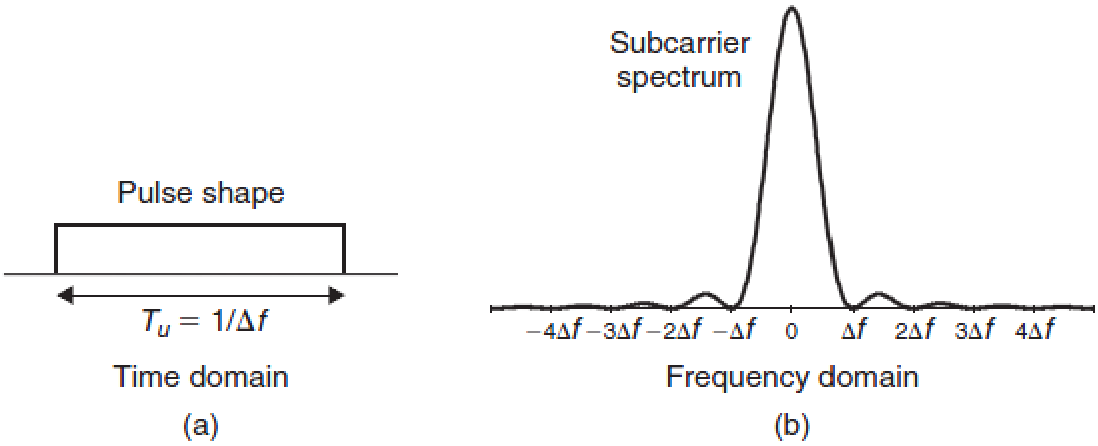

Figure 2.2: a) Per-subcarrier pulse shape b) spectrum for basic OFDM transmission [2].

OFDM transmission uses of a relatively large number of narrowband subcarriers, in contrast with a straightforward multi-carrier extension which would typically consist of only a few subcarriers, each with a relatively wide bandwidth.

The number of OFDM subcarriers can range from less than one hundred to several thousand, with the subcarrier spacing ranging from several hundred kHz down to a few kHz. What subcarrier spacing to use depends on what types of environments the system is to operate in, including such aspects as the maximum expected radio-channel frequency selectivity (maximum expected time dispersion) and the maximum expected rate of channel variations (maximum expected Doppler spread).

Once the subcarrier spacing has been selected, the number of subcarriers can be decided based on the assumed overall transmission bandwidth, taking into account acceptable out-of-band emission, etc. [2].

Figure 2.3 shows the tight frequency-domain packing of the subcarriers with a subcarrier spacing of $\Delta f=1/Tu$, where Tu is the per-subcarrier modulation-symbol time.

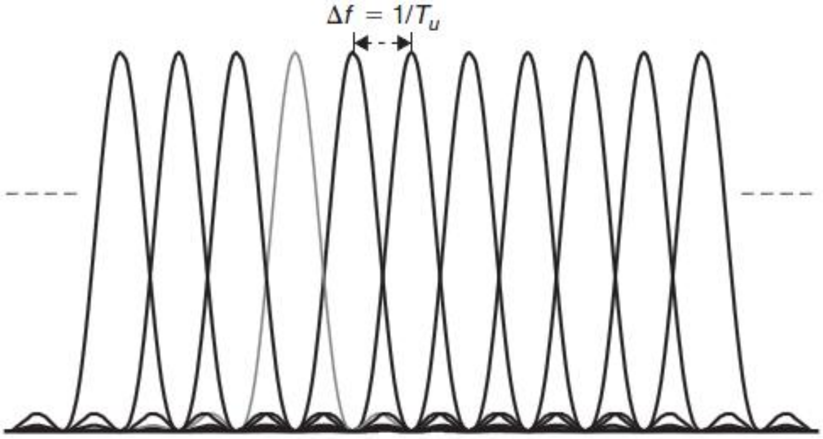

Figure 2.3: OFDM subcarrier spacing [2].

As an example, for 3GPP LTE the basic subcarrier spacing equals 15 kHz. On the other hand, the number of subcarriers depends on the transmission bandwidth, with in the order of 600 subcarriers in case of operation in a 10 MHz spectrum allocation and correspondingly fewer/more subcarriers in case of smaller/larger overall transmission bandwidths.

The OFDM signal to be transmitted can then be represented as a sum of sub-carriers, as shown in the equation below, for a baseband signal. T_{OFDM} is the duration of a sub-symbol.

$$x(t) = \frac{1}{N}\sum_{k=0}^{N-1} c_k e^{j\frac{2\pi k}{T_{OFDM}}t} \quad ,where \qquad t < T_{OFDM} \qquad (2.1)$$

The total time of transmission of OFDM symbols is given by $T_{OFDM} = N_c.Ts$, where N_c is the number of sub-carriers, and Ts is the length of the data symbols.

The term Orthogonal Frequency Division Multiplex is due to the fact that two modulated OFDM subcarriers x_{k_1} and x_{k_2} are mutually *orthogonal* over the time interval $mT_u \leq t < (m+1)T_u$

$$\int_{mT_u}^{(m+1)T_u} x_{k_1}(t)x_{k_2}^*(t)dt = \int_{mT_u}^{(m+1)T_u} a_{k_1}a_{k_2}^* e^{j2\pi k_1\Delta f t} e^{-j2\pi k_2 \Delta f t} dt = 0 \quad , for \quad k_1 \neq k_2 \tag{2.2}$$

Thus basic OFDM transmission can be seen as the modulation of a set of orthogonal functions ϕk (t), where

$$\varphi_k(t) = \begin{cases} e^{j2\pi k\Delta f t} & 0 \leq t < T_u \\ 0 & otherwise \end{cases} \tag{2.3}$$

2.3 OFDM implementation

Figure 2.4 shows a general block diagram of an OFDM system.

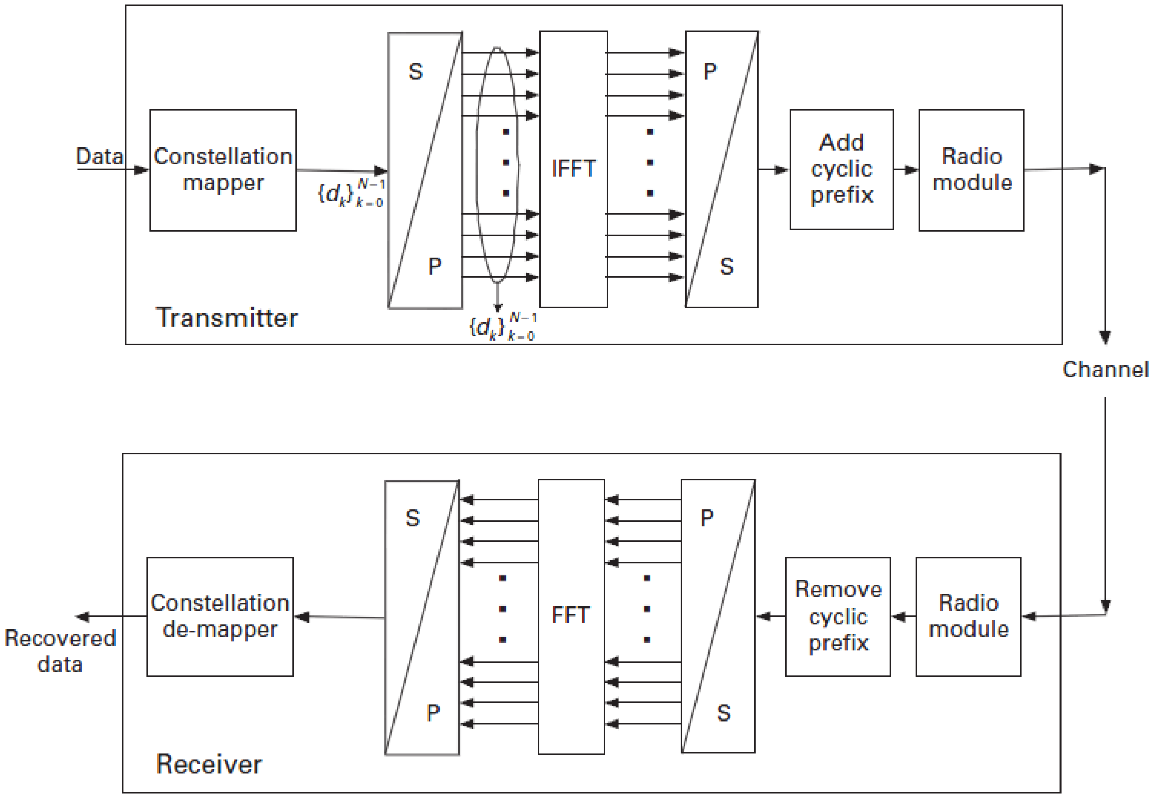

Figure 2.4: Block diagram of an OFDM transmitter and a receiver [2].

Through application of the FFT (Fast Fourier Transformation) and IFFT (Inverse Fast Fourier Transformation), the signal is converted between frequency and time domains.

Each carrier has its own value of amplitude and phase, and it is ensured that the signal does not change when switching between the domains and that orthogonality is maintained.

However, in case of a time-dispersive channel the orthogonality between the subcarriers will, at least partly, be lost. The reason for this loss of subcarrier orthogonality in case of a time dispersive channel is that, in this case, the demodulator correlation interval for one path will overlap with the symbol boundary of a different path, as illustrated in Figure 2.5.

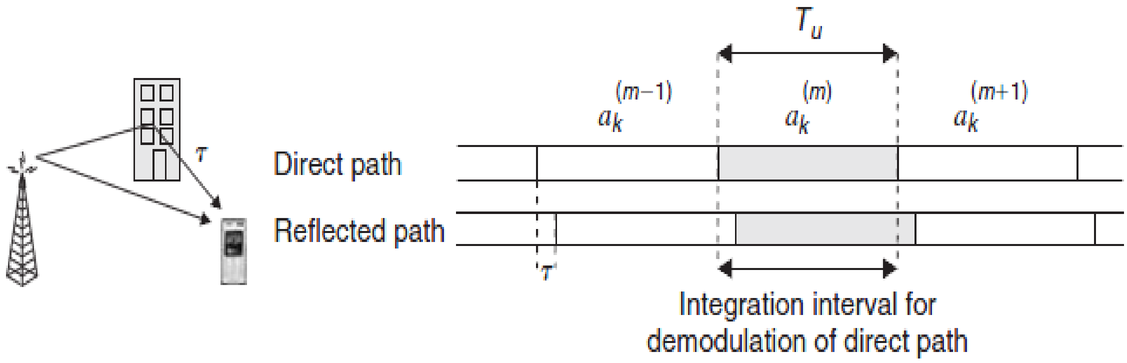

Figure 2.5: Time dispersion and corresponding received-signal timing [2].

To deal with this problem and to make an OFDM signal truly insensitive to time dispersion on the radio channel, cyclic-prefix insertion is typically used in case of OFDM transmission.

The blocks add CP (Cyclic Prefix) and CP removal describe this technique. This aims to reduce interference between symbols caused by multipath propagation and involves inserting a cyclic prefix. This prefix, with a period greater than the maximum delay of the channel, is introduced with the purpose of completely eliminating the ISI (Inter-Symbol Interference), maintaining the orthogonality between the signals in different sub-carriers. It is no more than a cyclic extension of each OFDM symbol.

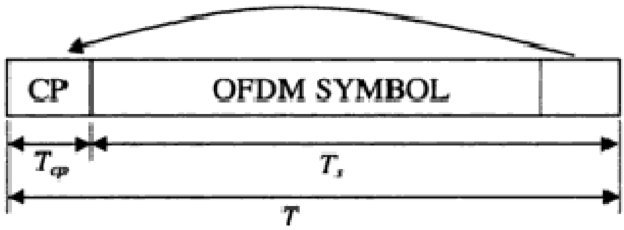

Figure 2.6: Cyclic prefix in OFDM [21].

The duration of this new OFDM symbol will be changed from T_u to $T_u + T_{CP}$ where T_{CP} is the length of the cyclic prefix, with a corresponding reduction in the OFDM symbol rate as a consequence.

In practice, cyclic-prefix insertion is carried out on the time-discrete output of the transmitter IFFT. Cyclic-prefix insertion then implies that the last N_{CP} samples of the IFFT output block of length *N* is copied and inserted at the beginning of the block, increasing the block length from *N* to $N + N_{CP}$. At the receiver side, the corresponding samples are discarded before OFDM demodulation by means of FFT processing.

The degradation of signal to noise ratio due to the introduction of this time is given by [21]:

$$SNR = -10\log_{10}\left(1 - \frac{T_{CP}}{T}\right) \tag{2.4}$$

With these considerations, the choice of cyclic prefix time to add the symbol will have to be well thought, so as to not compromise the quality of the system by either high inter-symbol interference or by a low signal to noise ratio.

OFDM signal demodulation requires two operations by the receiver. The first is the time synchronization, which is to determine the optimum time at which reading of the symbols must be made. The structure used by OFDM allows a reasonable degree of temporal synchronization error without incurring this error at the reception. The second operation, the frequency synchronization, consists in aligning the maximum carrier frequency of the receiver and of the transmitted signal. This should be done very accurately, since the correct receipt of the signal depends on the orthogonality of sub-carriers, which can be severely affected if this synchronization is not accurate.

Another problem related to OFDM implementation is the PAR (*Peak-Average Ratio*). Since, in the time domain, the transmitted signal is equal to the sum of several signals in narrow band, it has a high change in value. This implies lower efficiency and a need for an improved power amplifier, one of the most expensive components of a radio system. Some techniques for reducing the PAR are peak cancellation and signal mapping.

2.4 Orthogonal frequency division multiple access

In a system with multiple users, they share the channel resources to broadcast. The basic principle of this multiple access technique is to share the channel by the multiple users, each having access to a subdivision of the carriers. Holders of these subchannels will be spread over the entire spectrum of the channel in order to achieve high multiuser diversity.

OFDMA is a multi-user version of the OFDM digital modulation scheme. Multiple access is achieved in OFDMA by assigning subsets of subcarriers to individual users as shown in Figure 2.7. This allows simultaneous low data rate transmission from several users.

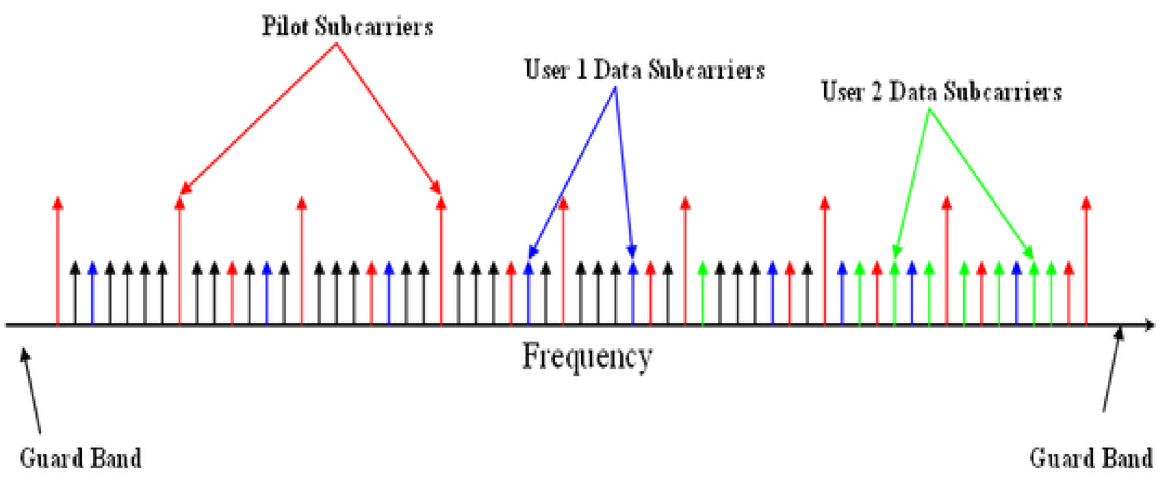

Figure 2.7: Subcarrier allocation in OFDMA.

The division in OFDMA resembles the FDMA technique, adding to it the relation of orthogonality between the carriers. It has an easier subcarrier filtering, with no need for long guard bands and complex filters as in FDMA. The introduction of the randomness of frequencies allocated to each user can be viewed as a technique of frequency hops usually used in GSM [23].

The main advantages of multiplexing OFDMA are:

Granularity: Being a technique that allows the allocation of bandwidth depending on the needs of its users, this feature allows multiple users to use the channel resources simultaneously.

Spectral gain: The accommodation of users with lower data rates in of bandwidths corresponding to their needs can reduce the total bandwidth used in the channel.

Simplicity in the receiver: Being more robust against channel imperfections by mitigating the effects of multiuser detection, the receiver of these systems do not have to be as complex as systems that use user encryption.

CHAPTER III

MULTIPLE ANTENNA SYSTEMS

3.1 Basic concepts

The use of multiple antennas in communication systems gained popularity in the last decade due to the high transmission capacity that can be achieved by these systems, in comparison with SISO (Single-Input-Single-Output) systems.

One of the most important contributions to the progress of wireless communications in recent years has been the MIMO technology, which has been recently adopted in LTE. In this case, both terminals are equipped with multiple antennas. This technique allows a wide range of benefits, which are crucial in systems that require high performances in adverse situations. It significantly improves the signal quality and increases the rate of data transmission without compromising the bandwidth of the system. This performance is achieved using the techniques of digital signal processing to format and combine the signals received from the different channels established between the antennas of receivers and transmitters. Besides the use of time and frequency dimensions, these systems make use of the space dimension to further increase overall system performance.

A MIMO system consists of *m* transmit antennas and *n* receive antennas. Since the same channel is used, each antenna receives the direct component intended for it as well as the indirect components for the other antennas, as we can see on figure 3.1.

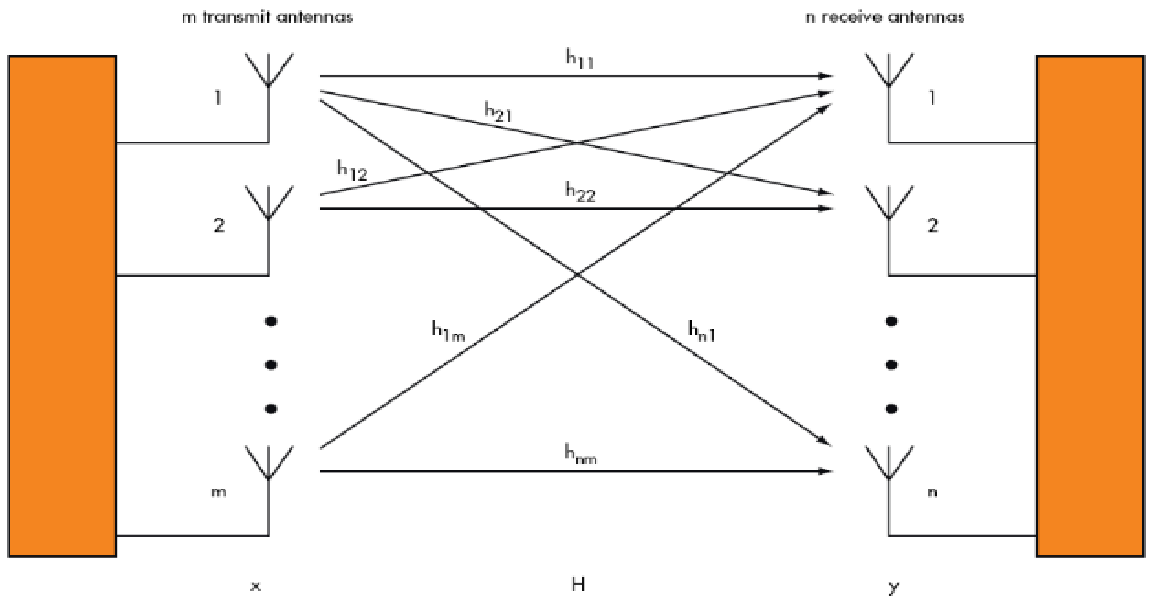

Figure 3.1: Block diagram for a MIMO system.

An important characteristic of any multi-antenna configuration is the distance between the different antenna elements, to a large extent due to the relation between the antenna distance and the mutual correlation between the radiochannel fading experienced by the signals at the different antennas.

The antennas in a multi-antenna configuration can be located relatively far from each other, typically implying a relatively low mutual correlation. Alternatively, the antennas can be located relatively close to each other, typically implying a high mutual fading correlation, that is in essence that the different antennas experience the same, or at least very similar, instantaneous fading. Whether high or low correlation is desirable depends on what is to be achieved with the multi-antenna configuration (diversity, beamforming, or spatial multiplexing) [2].

In beamforming, the same signal is emitted from each of the transmit antennas with appropriate phase (and sometimes gain) weighting such that the signal power is maximized at the receiver input. The benefits of beamforming are to increase the received signal gain, by making signals emitted from different antennas add up constructively, and to reduce the multipath fading effect. In the absence of scattering, beamforming results in a well defined directional pattern, but in typical cellular conventional beams are not a good analogy. When the receiver has multiple antennas, the transmit beamforming cannot simultaneously maximize the signal level at all of the receive antennas, and precoding with multiple streams is used. Note that precoding requires knowledge of CSI (Channel State Information) at the transmitter.

Spatial multiplexing requires MIMO antenna configuration. In spatial multiplexing, a high rate signal is split into multiple lower rate streams and each stream is transmitted from a different transmit antenna in the same frequency channel. If these signals arrive at the receiver antenna array with sufficiently different spatial signatures, the receiver can separate these streams into (almost) parallel channels. Spatial multiplexing is a very powerful technique for increasing channel capacity at higher SNRs (Signal-to-Noise Ratio). The maximum number of spatial streams is limited by the lesser in the number of antennas at the transmitter or receiver. Spatial multiplexing can be used with or without transmit channel knowledge. Spatial multiplexing can also be used for simultaneous transmission to multiple receivers, known as space-division multiple access. By scheduling receivers with different spatial signatures, good separability can be assured.

Diversity coding techniques are used when there is no channel knowledge at the transmitter. In diversity methods, a single stream (unlike multiple streams in spatial multiplexing) is transmitted, but the signal is coded using techniques called space-time.

The signal is emitted from each of the transmit antennas with full or near orthogonal coding. Diversity coding exploits the independent fading in the multiple antenna links to enhance signal diversity. Because there is no channel knowledge, there is no beamforming or array gain from diversity coding.

In case of base-station antennas in typical macro-cell environments (relatively large cells, relatively high base-station antenna positions, etc.), an antenna distance in the order of ten wavelengths is typically needed to ensure a low mutual fading correlation. At the same time, for a mobile terminal in the same kind of environment, an antenna distance in the order of only half a wavelength (0.5λ) is often sufficient to achieve relatively low mutual correlation [24]. The reason for the difference between the base station and the mobile terminal in this respect is that, in the macro-cell scenario, the multi-path reflections that cause the fading mainly occur in the near-zone around the mobile terminal. Thus, as seen from the mobile terminal, the different paths will typically arrive from a wide angle, implying a low fading correlation already with a relatively small antenna distance. At the same time, as seen from the (macro-cell) base station the different paths will typically arrive within a much smaller angle, implying the need for significantly larger antenna distance to achieve low fading correlation.

On the other hand, in other deployment scenarios, such as micro-cell deployments with base-station antennas below roof-top level and indoor deployments, the environment as seen from the base station is more similar to the environment as seen from the mobile terminal. In such scenarios, a smaller base-station antenna distance is typically sufficient to ensure relatively low mutual correlation between the fading experienced by the different antennas [1].

Another means to achieve low mutual fading correlation is to apply different polarization directions for the different antennas [24]. The antennas can then be located relatively close to each other, implying a compact antenna arrangement, while still experiencing low mutual fading correlation.

3.2 Benefits of multi-antenna techniques

The availability of multiple antennas at the transmitter and/or the receiver can be utilized in different ways to achieve different aims:

Multiple antennas at the transmitter and/or the receiver can be used to provide additional diversity against fading on the radio channel. In this case, the channels experienced by the different antennas should have low mutual correlation, implying the need for a sufficiently large inter-antenna distance (spatial diversity), alternatively the use of different antenna polarization directions (polarization diversity).

Multiple antennas at the transmitter and/or the receiver can be used to shape the overall antenna beam (transmit beam and receive beam, respectively) in a certain way, for example, to maximize the overall antenna gain in the direction of the target receiver/transmitter or to suppress specific dominant interfering signals. Such beam-forming can be based either on high or low fading correlation between the antennas.

The simultaneous availability of multiple antennas at the transmitter and the receiver can be used to create what can be seen as multiple parallel communication channels over the radio interface. This provides the possibility for very high bandwidth utilization without a corresponding reduction in power efficiency or, in other words, the possibility for very high data rates within a limited bandwidth without an un-proportionally large degradation in terms of coverage.

3.3 Diversity

A diversity scheme refers to a method for improving the reliability of a signal by using two or more communication channels with different characteristics. Diversity plays an important role in combatting fading and channel interference and avoiding error bursts. It is based on the fact that individual channels experience different levels of fading and interference. Multiple versions of the same signal may be transmitted and/or received and combined in the receiver.

Various diversity techniques are used in wireless communication systems, which are given different designations depending on how they are applied. The concepts of time diversity, frequency diversity and space diversity will be discussed below.

Time diversity

In this technique, multiple versions of the same signal are transmitted at different time instants. These time slots are uncorrelated and should have a temporal separation between them greater than the coherence time of the channel [25].

Alternatively, a redundant forwards error correction code is added and the message is spread in time by means of bit-interleaving before it is transmitted. Thus, error bursts are avoided, which simplifies the error correction.

The drawback of implementing this technique is related to the loss of spectral efficiency of the system.

Frequency diversity

The signal is transmitted using several frequency channels or spread over a wide spectrum that is affected by frequency-selective fading. Similarly to time diversity, the separation between transmitting carriers must be greater than the coherence bandwidth of the channel. This repeated transmission of the signal also causes spectral inefficiency, due to the introduction of signal redundancy and the introduction of guard bands between carriers [25]. However, the application of multiplexing techniques such as FDM and OFDM in particular allow the system to have a larger spectral efficiency.

Space diversity

The spatial diversity, also referred to as antenna diversity, is used in MIMO systems with its basic concept being the use of multiple antennas for transmitting and receiving signals. The signal is transmitted over several different propagation paths. In the case of reception diversity, a diversity combining technique is applied before further signal processing takes place.

A separation between antennas greater than ten wavelengths allows the signals to be considered uncorrelated, thus achieving the maximum order of diversity [26]. Unlike other diversity techniques, this does not cause the decrease in spectral efficiency of the system, however, sending signals through multiple antennas will require other resource, besides the cost of the physical implementation of multiple antennas.

3.4 Different multiple antenna systems

Depending on the number of antennas used at both the transmitter and the receiver, four types of setups can be defined:

- SISO, a radio system where neither the transmitter nor receiver have multiple antenna.
- MIMO, the most general case, which uses a set of antennas at both terminals.
- SIMO, a degenerate case of MIMO, when the transmitter has a single antenna.
- MISO, a degenerate case of MIMO, when the receiver has a single antenna.

The three multi-antenna setups will be discussed in the next sub-sections.

3.4.1 MIMO

In a MIMO system, as briefly described in Section 3.1, we have *m* transmitting antennas and *n* receiving antennas. The connections that will form between them will be N_T x N_R and each one will be designated $h_{N_T N_R}$.

A MIMO channel can be represented by a matrix [27]:

$$\boldsymbol{H} = \begin{bmatrix} h_{11} & \dots & h_{N_T 1} \\ \vdots & \ddots & \vdots \\ h_{1 N_R} & \dots & h_{N_T N_R} \end{bmatrix} \tag{3.1}$$

The transmitted and received signal formulas are the following:

Transmitted signal $\boldsymbol{x} = \left[x_1, x_2, \dots, x_{N_T}\right]^T$ (3.2)

Received signal $\boldsymbol{y} = \boldsymbol{H}_{N_T N_R}\boldsymbol{x} + \boldsymbol{\eta}$ (3.3)

where η is the noise vector consisting of Gaussian complex values with zero mean and variance σ_n^2.

The use of multiple antennas at both the transmitter and the receiver can simply be seen as a tool to further improve the signal-to-noise/interference ratio and/or achieve additional diversity against fading, compared to the use of only multiple receive antennas or multiple transmit antennas. However, in case of multiple antennas at both the transmitter and the receiver there is also the possibility for so-called spatial multiplexing , allowing for more efficient utilization of high signal-to-noise/ interference ratios and significantly higher data rates over the radio interface.

Multiple antennas at the receiver and the transmitter can be used to improve the receiver signal-to-noise ratio in proportion to the number of antennas by applying beam-forming at the receiver and the transmitter. In the general case of N_T transmit antennas and N_R receive antennas, the receiver signal-to noise ratio can be made to increase in proportion to the product N_T x N_R [2].

Such an increase in the receiver signal-to-noise ratio allows for a corresponding increase in the achievable data rates, assuming that the data rates are power limited rather than bandwidth limited. However, once the bandwidth-limited range-of-operation is reached, the achievable data rates start to saturate unless the bandwidth is also allowed to increase.

One way to understand this saturation in achievable data rates is to consider the basic expression for the normalized channel capacity

$$\frac{C}{BW} = \log_2\left(1 + \frac{S}{N}\right) \tag{3.4}$$

where, by means of beam-forming, the signal-to-noise ratio *S*/*N* can be made to grow proportionally to N_T x N_R. In general $\log_2(1+x)$ is proportional to *x* for small *x*, implying that, for low signal-to-noise ratios, the capacity grows approximately proportionally to the signal-to-noise ratio. However, for larger *x*, $\log_2(1+x) \approx \log_2(x)$, implying that, for larger signal-to-noise ratios, capacity grows only logarithmically with the signal-to-noise ratio.

However, in the case of multiple antennas at the transmitter *and* the receiver it is, under certain conditions, possible to create up to $N_L = \min\{N_T, N_R\}$ parallel channels each with N_L times lower signal-to-noise ratio (the signal power is split between the channels), i.e. with a channel capacity given by

$$\frac{C}{BW} = log_2\left(1 + \frac{N_R}{N_L}.\frac{S}{N}\right) \tag{3.5}$$

As there are now N_L parallel channels, each with a channel capacity given by (3.5), the overall channel capacity for such a multi-antenna configuration is thus given by

$$\begin{aligned} \frac{C}{BW} &= N_L log_2\left(1 + \frac{N_R}{N_L}.\frac{S}{N}\right) \\ &= \min\{N_T, N_R\}.log_2\left(1 + \frac{N_R}{\min\{N_T, N_R\}}.\frac{S}{N}\right) \end{aligned} \tag{3.6}$$

Thus, under certain conditions, the channel capacity can be made to grow essentially linearly with the number of antennas, avoiding the saturation in the data rates. This is referred to as Spatial Multiplexing .

To understand the basic principles how multiple parallel channels can be created in case of multiple antennas at the transmitter and the receiver, consider a 2x2 antenna configuration, that is two transmit antennas and two receive antennas, as outlined in Figure 3.2. Furthermore, assume that the transmitted signals are only subject to non-frequency-selective fading and white noise, i.e. there is no radio-channel time dispersion.

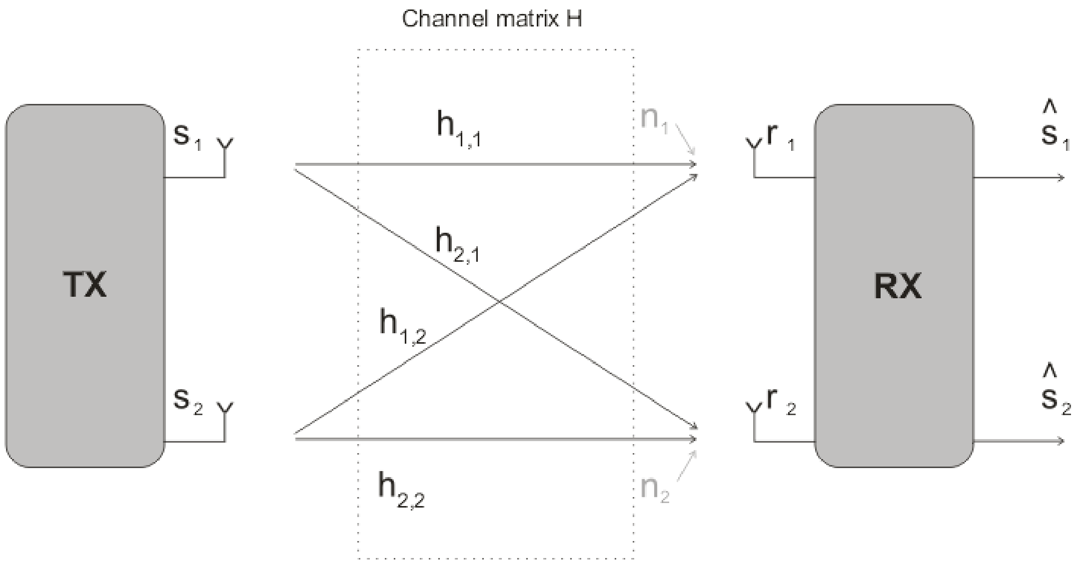

Figure 3.2: 2x2 antenna configuration.

Based on Figure 3.2, the received signals can be expressed as

$$\bar{r} = \begin{pmatrix} r_1 \\ r_2 \end{pmatrix} = \begin{pmatrix} h_{1,1} & h_{1,2} \\ h_{2,1} & h_{2,2} \end{pmatrix} . \begin{pmatrix} s_1 \\ s_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix} = H.\bar{s} + \bar{n} \tag{3.7}$$

where H is the 2x2 channel matrix .

<u>3.4.2 SIMO</u>

Perhaps the most straightforward and historically the most commonly used multi-antenna configuration is the use of multiple antennas at the receiver side. This is often referred to as receive diversity, even if the aim of the multiple receive antennas is not always to achieve additional diversity against radio-channel fading.

Figure 3.3 illustrates the basic principle of linear combining of signals $r_1,...,r_{NR}$ received at N_R different antennas, with the received signals being multiplied by complex weight factors $W^*_{1,...,}W^*_{NR}$ before being added together. In vector notation this *linear receive-antenna combining* can be expressed as

$$\hat{\boldsymbol{s}} = [W_1^* \ldots W_{N_R}^*][r_1 \ldots r_{N_R}] = \overline{\boldsymbol{W}}^{\boldsymbol{H}}.\bar{\boldsymbol{r}} \quad (3.8)$$

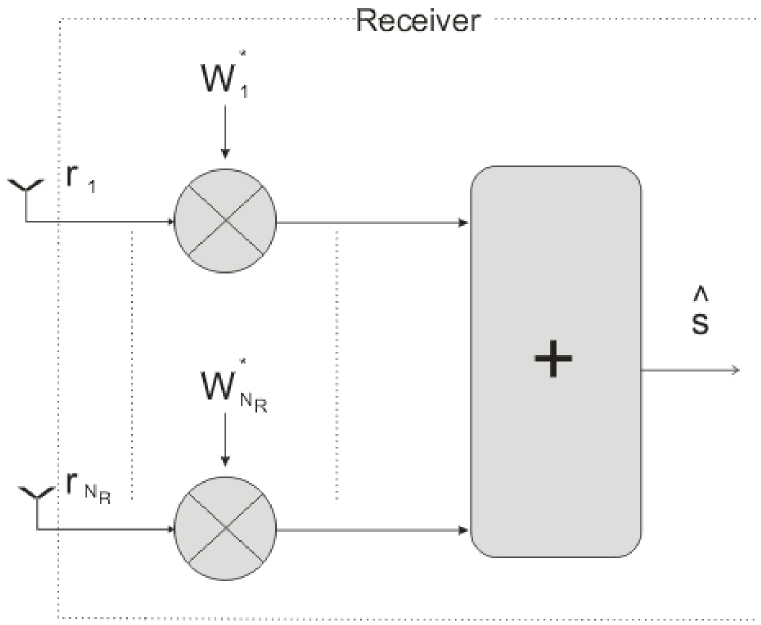

Figure 3.3: Linear receive-antenna combining.

Assuming that the transmitted signal is only subject to non-frequency-selective fading and (white) noise, meaning there is no radio-channel time dispersion, the signals received at the different antennas in figure 3.3 can be expressed as

$$\bar{r} = \begin{bmatrix} r_1 \\ \vdots \\ r_{N_R} \end{bmatrix} = \begin{bmatrix} h_1 \\ \vdots \\ h_{N_R} \end{bmatrix}.s + \begin{bmatrix} n_1 \\ \vdots \\ n_{N_R} \end{bmatrix} = \bar{h}.s + \bar{n} \quad (3.9)$$

where s is the transmitted signal, the vector h consists of the N_R complex channel gains, and the vector n consists of the noise impairing the signals received at the different antennas.

To maximize the signal-to-noise ratio after linear combining, the weight vector w should be selected as [28]:

$$\overline{w_{MRC}} = \bar{h} \tag{3.10}$$

This is also known as MRC (Maximum-Ratio Combining). The MRC weights fulfill two purposes [2]:

- Phase rotate the signals received at the different antennas to compensate for the corresponding channel phases and ensure that the signals are phase aligned when added together (coherent combining).

- Weight the signals in proportion to their corresponding channel gains, that is apply higher weights for stronger received signals.

In case of mutually uncorrelated antennas, that is sufficiently large antenna distances or different polarization directions, the channel gains $h_1,...,h_{NR}$ are uncorrelated and the linear antenna combining provides diversity of order N_R . In terms of receiver-side beamforming, selecting the antenna weights according to (3.10) corresponds to a receiver beam with maximum gain N_R in the direction of the target signal. Thus, the use of multiple receive antennas may increase the postcombiner signal-to-noise ratio in proportion to the number of receive antennas.

3.4.3 MISO

As an alternative or complement to multiple receive antennas, diversity and beam-forming can also be achieved by applying multiple antennas at the transmitter side. The use of multiple transmit antennas is primarily of interest for the downlink, at the base station. In this case, the use of multiple transmit antennas provides an opportunity for diversity and beam-forming without the need for additional receive antennas and corresponding additional receiver chains at the mobile terminal. On the other hand, due to complexity reasons, the use of multiple transmit antennas for the UL (Uplink), at the mobile terminal, is less attractive.

Figure 3.4: Multiple antenna transmission.

Space-time coding is a general term used to indicate multi-antenna transmission schemes where modulation symbols are mapped in the time and spatial (transmit-antenna) domain to capture the diversity offered by the multiple transmit antennas. Two-antenna STBC (Space–Time Block Coding), more specifically a scheme referred to as STTD (Space–Time Transmit Diversity), has been part of the 3G WCDMA standard already from its first release.

As shown in Figure 3.5, STTD operates on pairs of modulation symbols. The modulation symbols are directly transmitted on the first antenna. However, on the second antenna the order of the modulation symbols within a pair is reversed. Furthermore, the modulation symbols are sign-reversed and complex conjugated as illustrated in Figure 3.5.

In vector notation STTD transmission can be expressed as

$$\bar{r} = \begin{pmatrix} r_{2n} \\ r^{*}_{2n+1} \end{pmatrix} = \begin{pmatrix} h_1 & -h_2 \\ h^{*}_2 & h^{*}_1 \end{pmatrix} . \begin{pmatrix} s_{2n} \\ s^{*}_{2n+1} \end{pmatrix} = H.\bar{s} \qquad (3.11)$$

where r_{2n} and r_{2n+1} are the received symbols during the symbol intervals 2*n* and 2*n*+1, respectively.

It should be noted that this expression assumes that the channel coefficients h_1 and h_2 are constant over the time corresponding to two consecutive symbol intervals, an assumption that is typically valid. As the matrix *H* is a scaled unitary matrix, the sent symbols s_{2n} and s_{2n+1} can be recovered from the received symbols r_{2n} and r_{2n+1}, without any interference between the symbols, by applying the matrix $W = H^{-1}$ to the vector $\bar{r}$.

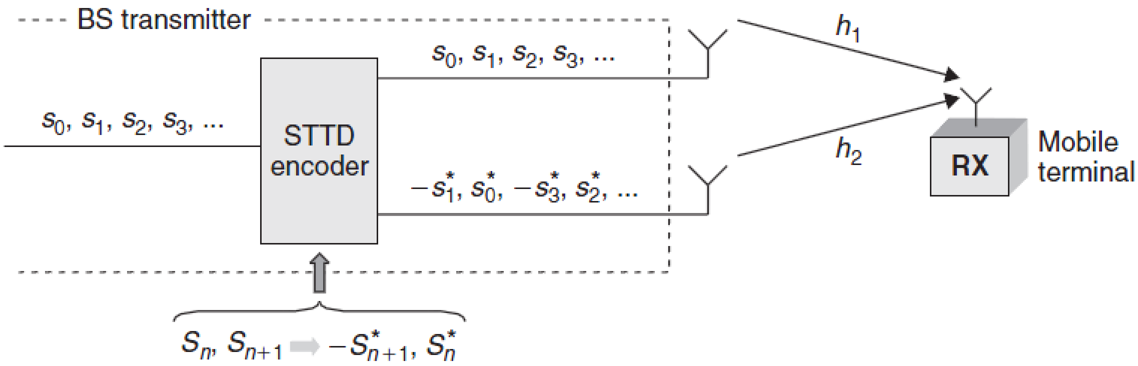

Figure 3.5: WCDMA Space–Time Transmit Diversity [2].

The two-antenna space–time coding of Figure 3.5 can be said to be of rate one, implying that the input symbol rate is the same as the symbol rate at each antenna, corresponding to a bandwidth utilization of one. Space–time coding can also be extended to more than two antennas. However, in case of complex-valued modulation, such as QPSK (Quadrature Phase Shift Keying) or 16/64 QAM (Quadrature Amplitude Modulation), space–time codes of rate one without any inter-symbol interference (orthogonal space–time codes) only exist for two antennas [29]. If inter-symbol interference is to be avoided in case of more than two antennas, space–time codes with rate less than one must be used, corresponding to reduced bandwidth utilization.

Alamouti coding

Alamouti invented the simplest of all STBCs in 1998 [30]. This STBC was designed for a two-transmit antenna system and has the following coding matrix:

$$C_1^2 = \begin{bmatrix} C_1 & C_2 \\ -C_2^* & C_1^* \end{bmatrix} \quad (3.12)$$

where * denotes complex conjugate and c_1 and c_2 are the data symbols to be transmitted. The superscript of C represents the number of transmission antennas, and the lower index denotes the encoding rate of this code.

It takes two time-slots to transmit two symbols. The lines of this matrix represent the two transmission instants, while the columns represent the data symbols coded in each antenna. On the first time-slot the signals c_1 and c_2 are transmitted from antenna 1 and antenna 2, respectively. On the second time-slot, antenna 1 transmits the signal $-c_2^*$ while antenna 2 transmits the signal c_1^*.

An important aspect of this STBC is that the sequences of coded data symbols transmitted by each antenna are orthogonal.

This is a very special STBC. It is the only orthogonal STBC that achieves rate 1 [31]. That is to say that it is the only STBC that can achieve its full diversity gain without needing to sacrifice its data rate. Strictly, this is only true for complex modulation symbols. Since almost all constellation diagrams rely on complex numbers however, this property usually gives Alamouti's code a significant advantage over the higher-order STBCs even though they achieve a better error-rate performance.

The significance of Alamouti's proposal in 1998 is that it was the first demonstration of a method of encoding which enables full diversity with linear processing at the receiver. Earlier proposals for transmit diversity required processing schemes which scaled exponentially with the number of transmit antennas. Furthermore, it was the first open-loop transmit diversity technique which had this capability. Subsequent generalizations of Alamouti's concept have led to a tremendous impact on the wireless communications industry.

CHAPTER IV

MULTICELL SYSTEMS

4.1 Global concepts

Fading and interference are the two key challenges faced by designers of mobile communication systems. While fading puts limits on the coverage and reliability of any point-to-point wireless connection, e.g., between a base station and a mobile terminal, interference restricts the reusability of the spectral resource (time, frequency slots, codes, etc.) in space, thus limiting the overall spectral efficiency expressed in bits/sec/Hz/base station. At least, so has been the conventional view until recent findings in the area of cooperative transmission.

Multicell systems are enhanced cellular systems where several base stations are linked to a central unit, therefore allowing for joint processing and creating possibilities for novel designs and efficient intercell interference cancellation algorithms.

Figure 4.1 illustrates the main elements in the cellular structure of a multicell based system, including neighbouring base stations, user terminals and a central processing unit, which coordinates the system operation.

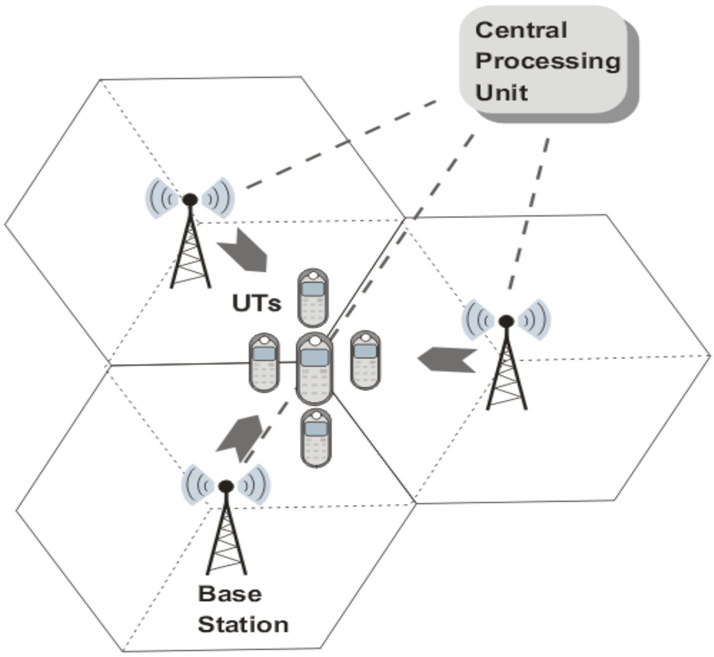

Figure 4.1: Multicell system.

As discussed above, in a multicell based system the BSs are linked to a central unit. This allows for joint processing and creates possibilities for novel designs and efficient intercell interference cancellation algorithms. The performance improvement of the multicell processing based systems strongly depends on the capacity of the backhaul network [32].

In a hierarchical telecommunications network, the backhaul portion of the network comprises the intermediate links between the core network and the small subnetworks at the edge of the entire hierarchical network.

Two types of backhaul networks can be considered: high speed (e.g. fiber optical based as proposed under European FUTON project [18]) and low speed (radio based). In the former, the CSI and the data of all UTs of the different cells can be known at the CU and an optimal joint processing can be done. In the latter, there are limitations in the amount on information that can be shared by the BSs typically the data and some CSI information.

Some interference mitigation is offered by limited inter-cell coordination, which is conventionally restricted to scheduling or user assignment mechanisms (e.g. cell breathing) or soft handover techniques. Inter-cell interference is treated as noise at the receiver side and is handled by resorting to improved point-to-point communications between the BS and the MS (Mobile Station), using efficient coding and/or single-link multiple-antenna techniques [33]. This approach to dealing with interference may be characterized as passive.

In contrast, the emerging view on network design advocates a more *proactive* treatment of interference, which can be accomplished through some form of interference-aware multi-cell coordination, at the base station side. Although the complexity associated with the coordination protocols can vary greatly, the underlying principle is the same: Base stations no longer tune separately their physical and link/MAC layer parameters (power level, time slot, subcarrier usage, beamforming coefficients etc.) or decode independently of one another, but instead coordinate their coding or decoding operations on the basis of global channel state and user data information exchanged over backhaul links among several cells.

4.2 Challenges of multi-cell MIMO

Despite their promise, multi-cell MIMO systems still pose a number of challenges, both theoretical and practical, with some of them being mentioned below.

First, a thorough understanding of the information-theoretic capacity of multi-cell MIMO system accounting for fading and path loss effects, even with an ideal backhaul, is yet to be obtained. Even though capacity results exist for simplified interference models, such results provide intuition for the general performance behavior but are difficult to extend to general channel models.

Also, as multi-cell channels may involve a large number of antennas and users, algorithm development work is required to reduce the complexity of currently proposed precoding and decoding schemes. Optimal precoding over the broadcast (downlink) MIMO channel as well as optimal joint decoding over the uplink involve non-linear computationally intensive operations [34][35] which scale poorly with the size of the network.

Finally, the equivalence between multi-cell systems and MIMO systems only holds in the case of ideal backhaul conditions. Practical cooperation schemes must operate within the constraints of finite capacity, finite latency communications links between base stations. Deriving good theoretic performance bounds for MIMO cooperation over a channel with limited information exchange capability between the cooperating transceivers is a difficult task.

From a practical point of-view, a major research goal is to find good signal processing and coding techniques that approach ideal cooperative gains while relying on mostly local channel state information and local user data. This problem, referred to as distributed cooperation, is as challenging as it is important. Efficient partial feedback representation methods building on classical MIMO research [34] are also desirable. From a system level perspective, simulations indicate that substantial gains in capacity and increased fairness across cell locations will be accrued from the adoption of multi-cell MIMO techniques. Yet, a number of important practical issues must be addressed before a very realistic assessment of system gains can be made, such as the impact of imperfect synchronization between base stations, imperfect channel estimation at the receiver side, and network latency.

4.3 Multi-cell levels of cooperation

Depending on the backhaul capacity, different levels of cooperation can be distinguished. Communication strategies vary in complexity and information sharing requirements. We shall classify them in four levels; the simplest one is interference coordination, where the main idea is to program the BSs to share their CSI and minimize the interference between users. In contrast to interference coordination, MIMO cooperation considers that channel state information and data are both fed back to the central processing unit of the network. More data available for processing leads to more processing possibilities, and ultimately system gains. Rate limited MIMO cooperation in an intermediate case between the two aforementioned strategies, and tries a tradeoff between the relative ease of implementation of the first one and the performance gains of MIMO cooperation. Finally, in relay assisted schemes, the relay assisted cooperation represent an alternative of cooperation, by the deployment of relays inside the network to aid in the communication.

<u>Interference coordination</u>

The performance of current cellular networks can already be improved if the BSs share the channel state information of both the direct and interfering links, obtained from the users via feedback channels. Such concept is depicted in Figure 4.2. The BSs acquire and exchange channel state information (but not the data symbols) pertaining to all relevant direct and interfering links, so as to accomplish joint optimization of their transmission parameters. The availability of CSI allows BSs to coordinate in their signaling strategies, such as power allocation and beamforming directions, in addition to user scheduling in time and frequency. This basic level of coordination requires a relatively modest amount of backhaul communication and can be quite powerful if enough users co-exist in the system (multi-user diversity). No sharing of transmission data or signal-level synchronization between the base stations is necessary. We refer to such schemes as *interference-coordination*. In this case, the downlink signal at the *bth* base station is a combination of symbols intended for its *K* users alone.

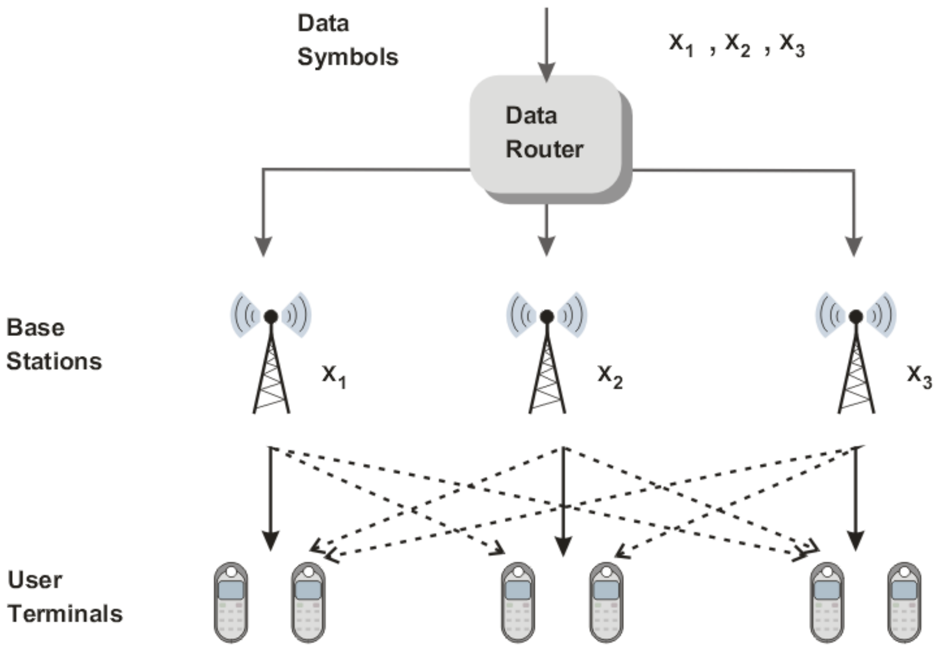

Figure 4.2: Interference coordination for the downlink.

<u>MIMO cooperation:</u>

When base stations are linked by high-capacity delay-free links, they can share not only channel state information, but also the full data signals of their respective users. In this way, a more powerful form of cooperation can be achieved. As depicted in Figure 4.3, in this scenario, the concept of an individual serving base for one terminal disappears since the network as a whole, or at least a group of cells, is serving the user. The combined use of several BS antennas belonging to different cells to send or receive multiple user data streams mimics transmission over a MIMO channel and is referred to here as MIMO cooperation. In principle, MIMO cooperation transforms the multi-cell network into a multiuser MIMO (MU-MIMO) channel for which all propagation links (including interfering ones) are exploited to carry useful data, upon appropriate precoding/decoding.

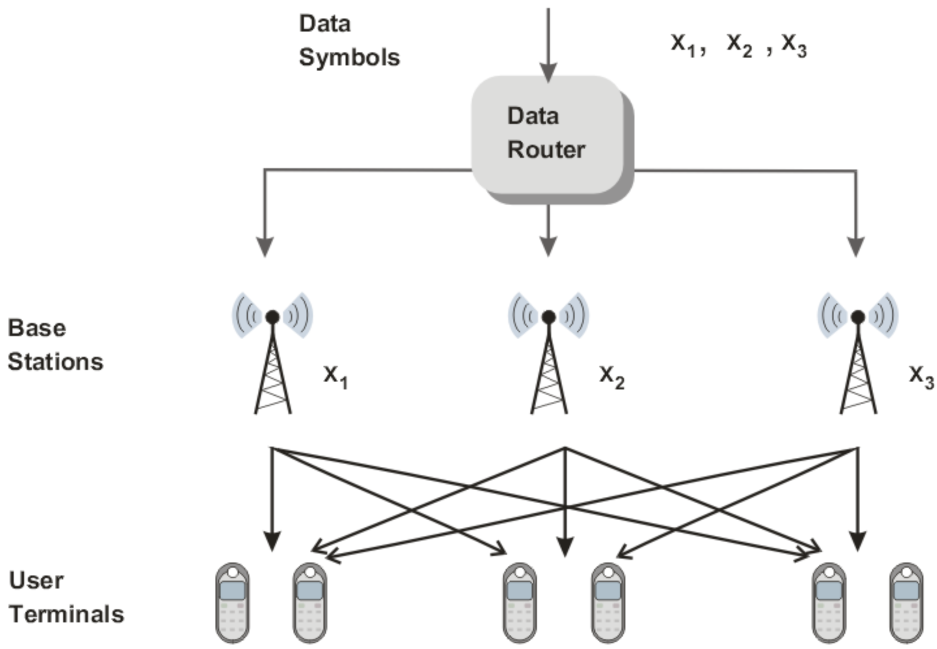

Figure 4.3: Multi-cell MIMO for the downlink.

Each BS is equipped with J antennas. It acquires and shares CSI and user data, so as to mimic the behaviour of a large MIMO array with M.J antennas.

In this case, the downlink signal, xl, is a combination of symbols intended for all M.K users. For instance, beamforming may be used in each cell if the base stations are equipped with multiple antennas. In this case, the beams typically try to strike the best compromise between elimination of the inter-cell interference and maximization of the received energy to/from the user within the cell of interest. Ideally, the choice of such beams across multiple cells is coordinated.

Rate-limited MIMO cooperation:

It is possible to consider an intermediate case, at with the base stations are linked by limited-capacity backhaul links. Typically, channel state information is shared first, then only a substream of user data or a quantized version of the antenna signals are shared among the base stations, which allows partial interference cancellation. These categories of scenarios offer the possibility of tradeoff between reduced complexity and benefits of cooperation.

Relay-assisted cooperation:

It is also possible to consider channel models in which a separate relay node is available to assist the direct communication within each cell. Relay communication is relevant to the multi-cell MIMO network because it can be beneficial not only in strengthening the effective direct channel gain between the BS and the remote users, but also in helping with intercell interference mitigation. The concept of cooperation and relay deployment can be extended for allowing cooperation through backhaul links, within each cell.

Figure 4.4 depicts the basics of this technique, with one Relay (R) assisting the communication between the BS and the UT.

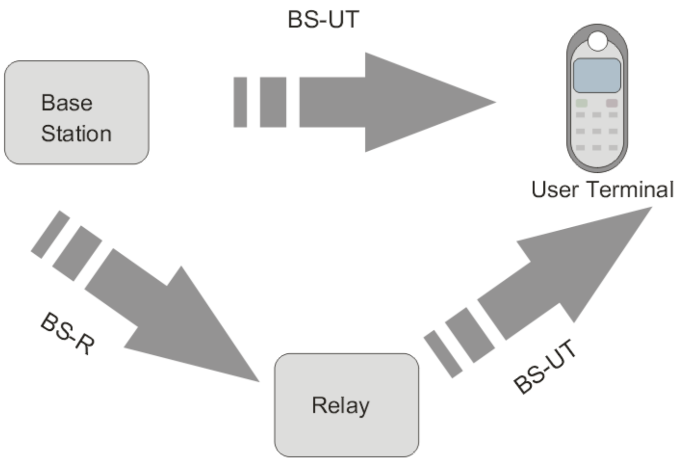

Figure 4.4: System model of a relay scheme.

4.4 Multicell Architectures

Within this section two multicell architectures shall be presented: Enhanced Cellular Scenario and Advanced Cellular Scenario. Both were first proposed and described in the project FUTON [18]. A brief description of the 4G LTE Coordinated Multipoint will also be provided, as it is an important future application of cooperation between systems base stations.

Enhanced Cellular Scenario

Figure 4.5 depicts the overall infrastructure the enhanced cellular scenario. It assumes a multicell system where the base stations are transparently linked by optical fiber to a central unit. It resembles a conventional cellular planning, but goes a step beyond by assuming cooperation between the RAUs (Remote Access Unit) associated with each cell. The region covered by the set of cooperating BSs (also referred to as RAUs in the scope of FUTON project) will be referred to a supercell. The serving area denotes to the area that is defined by all the supercells that are linked to the same CSC (Central System Controller).

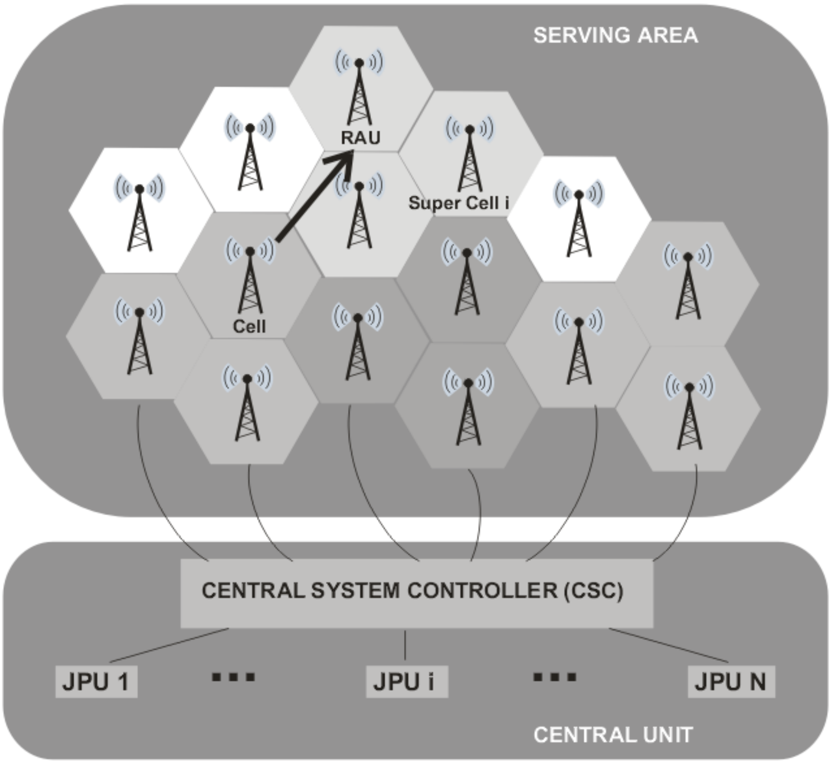

Figure 4.5: Enhanced Cellular Scenario, which is a fixed architecture where each supercell is controlled by a joint processing unit.

The BSs corresponding to a supercell are processed jointly by a JPU (Joint Processing Unit), to which the signals are conveyed using the radio over fiber infrastructure. The number of cooperating BSs depends on the cell size, the environment, etc. Irrespective of the specific transmission technique, the bandwidth of the fiber is high enough so that the radio signals can be available at the CSC. This fact implies that all the information of all BSs is available at the CSC.

Advanced Cellular Scenario

It is expected that there will be a need for flexible RAU deployment in public facilities without the need to acquire sites and install large towers so as for upgradeable and reconfigurable networks (support for random and dynamic planning). Plus, it should be possible to add RAUs to accommodate additional traffic demand without the need for a complete re-planning of the network. The configuration of the network would be handled dynamically at the CU.

The architecture for a scenario that meets the aforementioned requirements is shown in Figure 4.6.

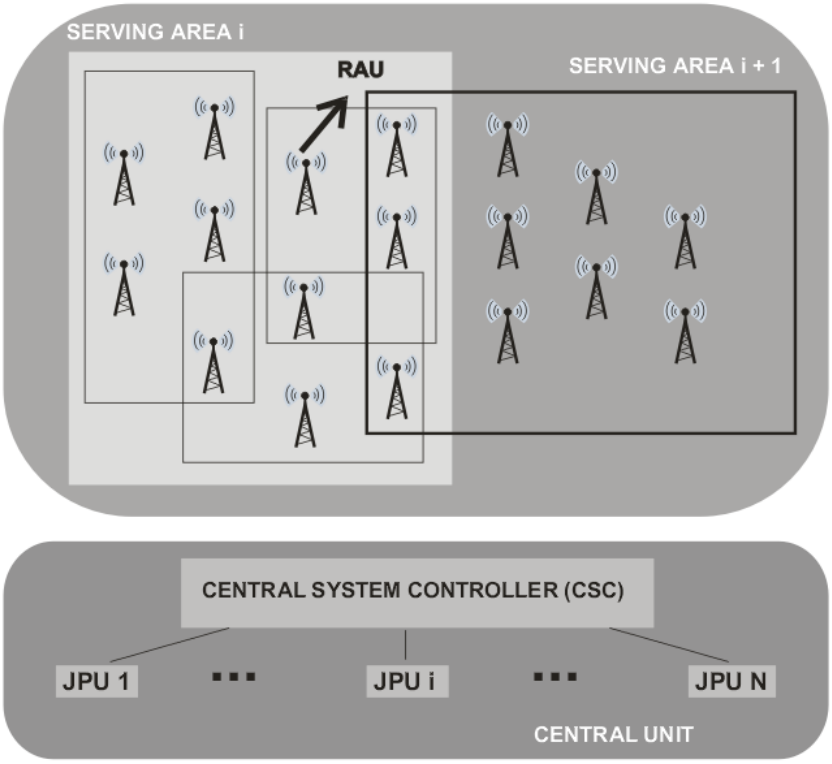

Figure 4.6: Advanced Cellular Scenario, which accommodates situations where dynamic configurability of the network is mandatory, as in public facilities.

The terminology is identical to the one used in the enhanced cellular scenario. However, since there is no precise static *a priori* planning, the concepts of cell and supercell are no longer precise, and, therefore, we use the concept of *joint processing area*, which is the area covered by the set of RAUs that are processed by the same JPU.

Similarly to the enhanced cellular scenario, Figure 4.6 also illustrates the possibility of overlapping between the RAUs processed by different JPUs, which can facilitate handover. The cooperative algorithms for this scenario should be able to handle dynamic patterns. RAUs are expected to be accommodated in public facilities and to provide easy upgrades. The advanced scenario requires dynamic allocation of resources to be performed in real time at the CU. These requirements will increase the complexity of the cooperative algorithms.

4G LTE Coordinated Multipoint basics

One of the key parameters for LTE as a whole, and in particular 4G LTE Advanced is the high data rates that are achievable. These data rates are relatively easy to maintain close to the base station, but as distances increase they become more difficult to maintain. Obviously, the cell edges are the most challenging. Not only is the signal lower in strength because of the distance from the base station (eNB), but also interference levels from neighboring eNBs are likely to be higher as the UE will be closer to them. LTE CoMP or Coordinated Multipoint is a technology that is being developed for LTE Advanced. It is a method of transmitting to or receiving from a UT using several base stations. This has a number of advantages in terms of data throughput; essentially, LTE CoMP turns the inter-cell interference into useful signal, especially at the cell borders where performance may be degraded.

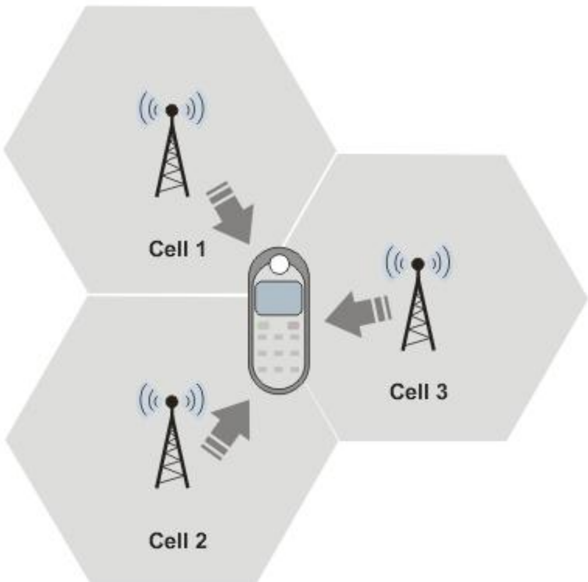

Figure 4.7: Concept of LTE Advanced CoMP - Coordinated Multipoint. Multiples BSs cooperate to provide joint processing to the UTs.

4G LTE CoMP, Coordinated Multipoint requires close coordination between several geographically separated eNBs. They dynamically coordinate to provide joint scheduling and transmissions, as well as proving joint processing of the received signals. In this way, a UT at the edge of a cell is able to be served by two or more eNBs to improve signals reception / transmission and increase throughput particularly under cell edge conditions.

In essence, 4G LTE CoMP, Coordinated Multipoint allows different modes of operation, but to achieve either of them, highly detailed feedback is required on the channel properties in a fast manner. For downlink and uplink in LTE CoMP, a number of scenarios may arise, with variable network configuration and channel estimation requirements.

CHAPTER V

IMPLEMENTED SYSTEM

5.1 System description

In this chapter, multiuser linear precoding techniques for the downlink of multicell OFDM based systems proposed in [19], are implemented and evaluated in a MatLab SIMULINK simulation chain based on LTE specifications.. The precoder is designed in two phases: first the intercell interference is removed by applying a set of precoding vectors based on zero-forcing criterion and computed in a distributed manner at each BS; then the system is further optimized through power allocation. Three centralized power allocation algorithms with per-BS power constraint and different complexity tradeoffs are implemented: one optimal to minimize the average BER and two suboptimal [19].

Since the precoder vectors are computed in a distributed fashion on each BS, the proposed scheme allows to reduce the feedback load over the backhaul network when compared with the full centralized precoding approaches.

The considered multicell system comprises B distributed BSs, with each BS being equipped with N_{t_b} antennas, transmitting to K UTs, the total number of transmitting antennas will be $N_t = \sum_{b=1}^{B} N_{t_b}$. Having the user terminals equipped with single antenna and assuming that $N_{t_b} \geq K$, an OFDM based system with N_c available subcarriers and linear precoding, the signal transmitted by the BS *b* on sub-carrier l is given by,

$$\boldsymbol{x}_{b,l} = \sum_{k=1}^{K} \sqrt{p_{b,k,l}} \boldsymbol{w}_{b,k,l} s_{k,l} \tag{5.1}$$

where $p_{b,k,l}$ represents the power allocated to UT k on sub-carrier l and BS b, $\boldsymbol{w}_{b,k,l} \in \mathbb{C}^{N_{t_b} x1}$ is the precoder of user k at BS b on sub-carrier l with unit norms, i.e., $\left\|\boldsymbol{w}_{b,k,l}\right\| = 1,\ b = 1,...,B,\ k = 1,...,K, l = 1,...,N_c$. The data symbol $s_{k,l}$, with $\mathrm{E}\left\{\left|s_{k,l}\right|^2\right\} = 1$, is intended for UT k and is assumed to be available at all BSs.

The average power transmitted by the BS b is then given by,

$$E\{\|\boldsymbol{x}_b\|^2\} = \sum_{l=1}^{N_C} \sum_{k=1}^{K} p_{b,k,l} \tag{5.2}$$

where $\boldsymbol{x}_b$ is the signal transmitted over the N_c subcarriers. The received signal at the UT k on sub-carrier l , $y_{k,l} \in \mathbb{C}^{1x1}$, can be expressed by,

$$y_{k,l} = \sum_{b=1}^{B} \boldsymbol{h}_{b,k,l}^{H} \boldsymbol{x}_{b,l} + \boldsymbol{\eta}_{k,l} \tag{5.3}$$

where $\boldsymbol{h}_{b,k,l} \in \mathbb{C}^{N_{t_b} x1}$ represents the frequency flat fading channel between BS b and UT k on sub-carrier l and $n_{k,l} \sim \mathcal{CN}\left(0,\sigma^2\right)$ is the noise.

The channel $\boldsymbol{h}_{b,k,l}$ can be decomposed as the product of the fast fading $\boldsymbol{h}^{c}_{b,k,l}$ and slow fading $\sqrt{\rho_{b,k}}$ components, i.e., $\boldsymbol{h}_{b,k,l}=\boldsymbol{h}^{c}_{b,k,l}\sqrt{\rho_{b,k}}$, where $\rho_{b,k}$ represents the long-term power gain between BS b and user k and $\boldsymbol{h}^{c}_{b,k,l}$ contains the fast fading coefficients.

Figure 5.1 shows the scheme implemented and evaluated in this dissertation, which comprises two base stations, here referred to as BS1 and BS2, each equipped with two antennas linked to the central unit (CU), and two single antenna user terminals referred as UT1 and UT2.

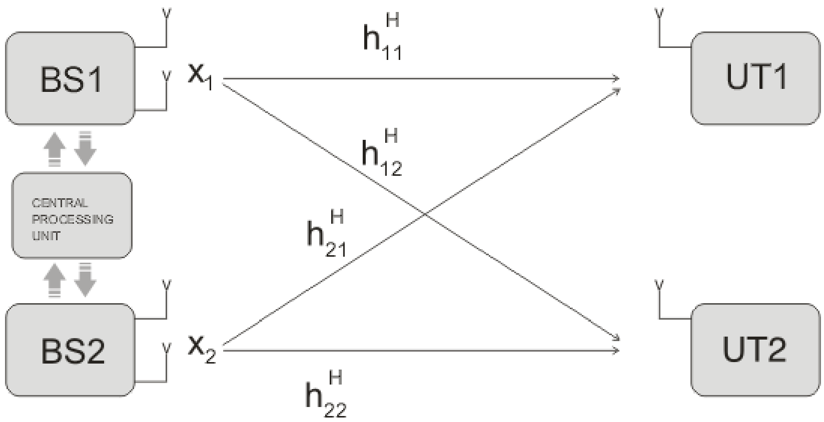

Figure 5.1: Diagram of the implemented system.

Thus, in the previous figure we can be identify the following channels: $\mathbf{h}_{11}$, between BS1 and UT1, $\mathbf{h}_{12}$, between BS1 and UT2, $\mathbf{h}_{21}$, between BS2 and UT1 and $\mathbf{h}_{22}$, between BS2 and UT2.

Both BSs use their respective channels to perform the cancellation of interference between each UT so that each receives only their own data. As it is assumed that the BSs transmit in the same frequency band, the filters applied to the data are calculated to eliminate the ISI. The signals transmitted by each BS are be given by

$$\boldsymbol{x}_1 = \boldsymbol{w}_{11}s_1 + \boldsymbol{w}_{12}s_2$$
$$\boldsymbol{x}_2 = \boldsymbol{w}_{21}s_1 + \boldsymbol{w}_{22}s_2 \quad (5.4)$$

with $\mathbf{w}_{bk}$ being the pre-coding vectors, where b represents the BS and k represents the destination UT.

The signals received at each UT are given by,

$$\boldsymbol{y}_1 = (\boldsymbol{w}_{11}.\boldsymbol{h}_{11}^H + \boldsymbol{w}_{21}.\boldsymbol{h}_{21}^H)s_1 + (\boldsymbol{w}_{12}.\boldsymbol{h}_{11}^H + \boldsymbol{w}_{22}.\boldsymbol{h}_{21}^H)s_2 + \boldsymbol{\eta}_1$$

$$\boldsymbol{y}_2 = (\boldsymbol{w}_{11}.\boldsymbol{h}_{12}^H + \boldsymbol{w}_{21}.\boldsymbol{h}_{22}^H)s_1 + (\boldsymbol{w}_{12}.\boldsymbol{h}_{12}^H + \boldsymbol{w}_{22}.\boldsymbol{h}_{22}^H)s_2 + \boldsymbol{\eta}_2 \tag{5.5}$$

where n_1 and n_2 represent the Gaussian noise present at UT1 and UT2, respectively.
It follows from the above equations that to completely eliminate the interference one has to impose the following conditions:

$$\boldsymbol{w}_{12}.\boldsymbol{h}_{11}^H = 0$$

$$\boldsymbol{w}_{22}.\boldsymbol{h}_{21}^H = 0$$

$$\boldsymbol{w}_{11}.\boldsymbol{h}_{12}^H = 0 \tag{5.6}$$

$$\boldsymbol{w}_{21}.\boldsymbol{h}_{22}^H = 0$$

which leads to a new expression for the signal received at each UT,

$$\boldsymbol{y}_1 = (\boldsymbol{w}_{11}.\boldsymbol{h}_{11}^H + \boldsymbol{w}_{21}.\boldsymbol{h}_{21}^H)s_1 + \boldsymbol{\eta}_1$$

$$\boldsymbol{y}_2 = (\boldsymbol{w}_{12}.\boldsymbol{h}_{12}^H + \boldsymbol{w}_{22}.\boldsymbol{h}_{22}^H)s_2 + \boldsymbol{\eta}_2 \tag{5.7}$$

A block diagram illustrating the implemented transmitter can be seen on Figure 5.2.

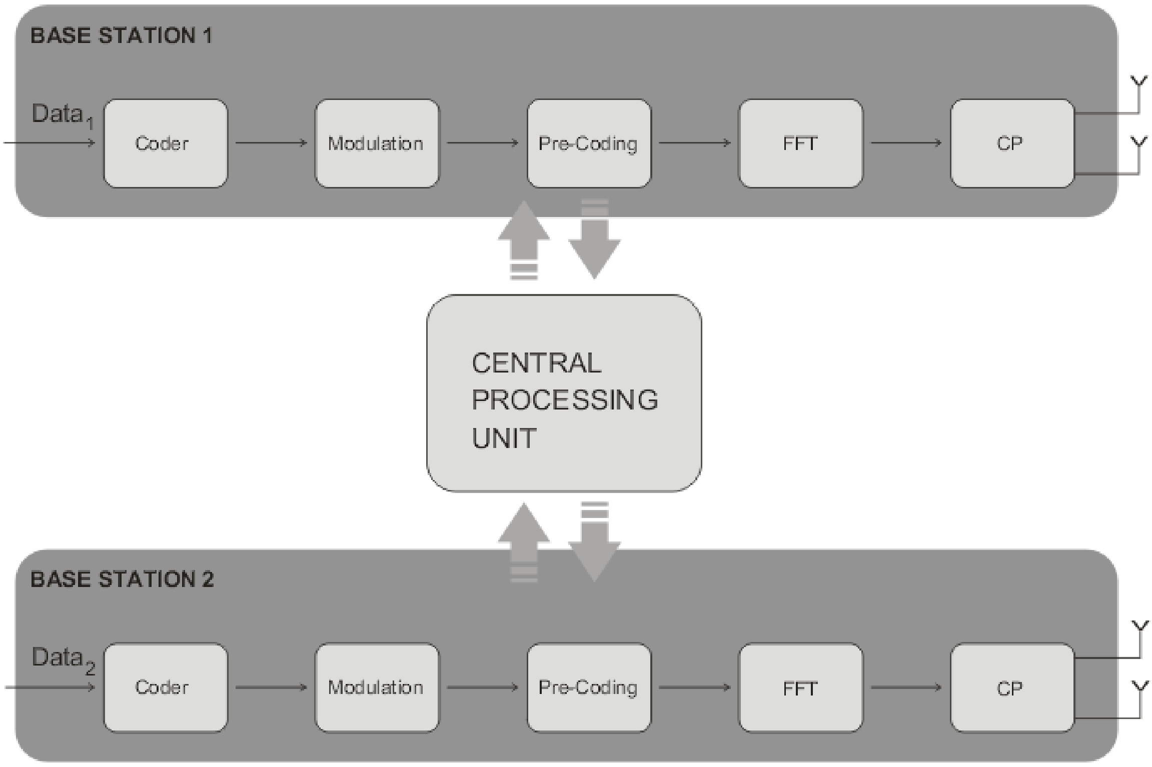

Figure 5.2: Block diagram of the implemented transmitter.

5.2. Distributed Precoder Vectors

To design the distributed precoder vector at each BS we assume that the BSs have only knowledge of local CSI, i.e., BS b knows the instantaneous channel vectors $\boldsymbol{h}_{b,k,l}, \forall k,l$, reducing the feedback load over the backhaul network as compared with the full centralized precoding approach. We consider a zero forcing transmission scheme with the phase of the received signal at each UT aligned. From (5.1) and (5.3) the received signal at UT k on sub-carrier l can be decomposed in [19],

$$y_{k,l} = \underbrace{\sum_{b=1}^{B} \sqrt{p_{b,k,l}}\boldsymbol{h}_{b,k,l}^{H}\boldsymbol{w}_{b,k,l}s_{k,l}}_{Desired\ Signal} \underbrace{+\sum_{b=1}^{B} \boldsymbol{h}_{b,k,l}^{H} \sum_{j=1,j\neq k}^{K} \sqrt{p_{b,j,l}}\,\boldsymbol{w}_{b,j,l}s_{j,l}}_{Multiuser\ Multicell\ Interference} + \underbrace{\boldsymbol{\eta}_{k,l}}_{Noise} \tag{5.8}$$

where $\boldsymbol{w}_{b,k,l}$ is a unit-norm zero forcing vector orthogonal to $K-1$ channel vectors, $\left\{\boldsymbol{h}_{b,j,l}^{H}\right\}_{j\neq k}$. Such precoding vectors always exist because we assume that the number of antennas at each BS is higher or equal to the number of single antenna UTs, i.e. $N_{t_b} \geq K$. By using such precoding vectors, the multicell interference is canceled and each data symbol on each subcarrier is only transmitted to its intended UT. These precoding vectors can be easily computed, so if $\bar{\boldsymbol{W}}_{b,k,l}$ is found to lie in the null space of $\left\{\boldsymbol{h}_{b,j,l}^{H}\right\}_{j\neq k}$, the final precoding vector $\boldsymbol{w}_{b,k,l}$, $b=1,...,B, k=1,...,K, l=1,...,N_c$, with the phase of the received signal at each UT aligned, is given by [19],

$$\boldsymbol{w}_{b,k,l} = \overline{\boldsymbol{W}}_{b,k,l}\frac{\left(\boldsymbol{h}_{b,k,l}^{H}\overline{\boldsymbol{W}}_{b,k,l}\right)^{H}}{\left\|\boldsymbol{h}_{b,k,l}^{H}\overline{\boldsymbol{W}}_{b,k,l}\right\|} \tag{5.9}$$

where $\bar{\boldsymbol{W}}_{b,k,l} \in \mathbb{C}^{N_{t_b} x\left(N_{t_b}-K+1\right)}$ holds the $\left(N_{t_b}-K+1\right)$ singular vectors in the null space of $\left\{\boldsymbol{h}_{b,j,l}^{H}\right\}_{j\neq k}$. The equivalent channel between BS b and UT k, on sub-carrier l can be expressed as,

$$\boldsymbol{h}_{b,k,l}^{H}\boldsymbol{w}_{b,k,l} = \boldsymbol{h}_{b,k,l}^{H}\overline{\boldsymbol{W}}_{b,k,l}\frac{\left(\boldsymbol{h}_{b,k,l}^{H}\overline{\boldsymbol{W}}_{b,k,l}\right)^{H}}{\left\|\boldsymbol{h}_{b,k,l}^{H}\overline{\boldsymbol{W}}_{b,k,l}\right\|} = \left\|\boldsymbol{h}_{b,k,l}^{H}\overline{\boldsymbol{W}}_{b,k,l}\right\| = h_{b,k,l}^{eq} \tag{5.10}$$

from (5.10) we can observe that the equivalent channel, $h_{b,k,l}^{eq}$, is a positive real number.

5.3 Power Allocation Strategies

In this dissertation, the criteria used to design power allocation are minimization of the average BER and sum of inverse of SNRs proposed in [19], which essentially lead to a redistribution of powers among users and therefore provide users fairness.

The optimal power allocation problem with per-BS power constraint can be formulated as [19],

$$\min_{\{p_{b,k,l}\}} \left(\frac{1}{KN_c} \sum_{l=1}^{N_c} \sum_{k=1}^{K} Q\left(\frac{\sum_{b=1}^{B} \sqrt{p_{b,k,l}} h_{b,k,l}^{eq}}{\sigma} \right) \right) s.t. \begin{cases} \sum_{l=1}^{N_C} \sum_{K=1}^{K} p_{b,k,l} \leq P_{t_b}, \forall\, b \\ p_{b,k,l} \geq 0, \forall\, (b,k,l) \end{cases} \tag{5.11}$$

Since the objective function is convex in $p_{b,k,l}$, and the constraint functions are linear this is a convex optimization problem. Therefore, it may be solved numerically by using for example the interior-point method [36]. This scheme is referred as per-BS optimal power allocation (per-BS OPA). However, its complexity is too high, and thus it is not of interest for real wireless systems and thus a less complex suboptimal solution is also studied.

This alternative power allocation method is based on minimizing the sum of inverse of SNRs, for which a closed-form expression can be obtained. Note that minimizing the sum of inverse of SNRs is similar to the maximization of the harmonic mean of the SINRs discussed in [37].

This suboptimal scheme, referred to as per-BS closed-form power allocation (per-BS CPA) as the closed form solution given below. The deduction of this formula can also be found in [19].

$$p_{b,k,l} = \frac{P_{t_b}\left(h_{b,k,l}^{eq}\right)^2}{\sqrt{\left(\sum_{i=1}^{B}\left(h_{i,k,l}^{eq}\right)^2\right)^3} \sum_{p=1}^{N_c} \sum_{j=1}^{K} \frac{\left(h_{b,j,p}^{eq}\right)^2}{\sqrt{\left(\sum_{i=1}^{B}\left(h_{i,j,p}^{eq}\right)^2\right)^3}}} \tag{5.12}$$

5.4 Simulation of the system

The proposed system is evaluated in four different scenarios.

- Scenario I, In the first scenario the antenna channels are uncorrelated, i.e. it is assumed that the distance between antennas is large enough to consider that the channels between antennas of the same BS are independent. Also, in the first case the path loss is set to one.

- Scenario II, The second scenario assumes correlated antenna channels and the existence of path-loss is now considered as well, as shown in Table 5.2.

- Scenario III, In the third scenario, the channels between each antenna of each BS are correlated, path-loss is considered, but now the concept of interleaving is introduced. i.e., the data symbols of each user are mapped on distance position on the OFDM symbol.

- Scenario IV, In the fourth scenario the channels between each antenna of each BS are correlated, with the existence of path-loss in consideration, with interleaving but this time using channel coding.

The following tables present the main simulation parameters used in the simulations, which are based on LTE standard.

Table 5.1: General data for the system simulation.

Sampling interval	**65.1ns**
Carrier frequency	**2GHz**
Number of sub-carriers	**1024**
Number of available sub-carriers	**128**
Modulation	**QPSK**
Channel coding	**No channel coding (Scenarios I, II, III)**
	Convolutional Turbo-Code (CTC) with half code rate (Scenario IV)
Frame length	**12 OFDM symbols**
Number of samples of CP	**80**
Mobile speed	**10Km/h**
Number of users	**2**
Number of antennas per user	**1**
Number of antennas per base station	**2**

Table 5.2: Data related to the system considering path loss.

Path loss between BS1 and U1	**1**
Path loss between BS1 and U2	**uniformly distributed on interval [0.2, 0.6]**
Path loss between BS2 and U1	**uniformly distributed on interval [0.2, 0.6]**
Path loss between BS2 and U1	**1**

5.5 Results

In this following section, the obtained results will be presented and discussed.

For each scenario, simulations were made for the following three different cases:

- Per-BS power constraint with equal power allocation (per-BS EPA), in this case no power allocation is performed.
- Per-BS power constraint with closed power allocation (per-BS CPA), with power given by (5.12)
- Per-BS power constraint with optimum power allocation (per-BS OPA), with the power given by (5.11).

The results are presented for the bit error rate (BER) averaged over the two users, according to the Eb/No, where Eb is the bit energy transmitted and No is the noise spectral density.

5.5.1 Numerical results for Scenario I

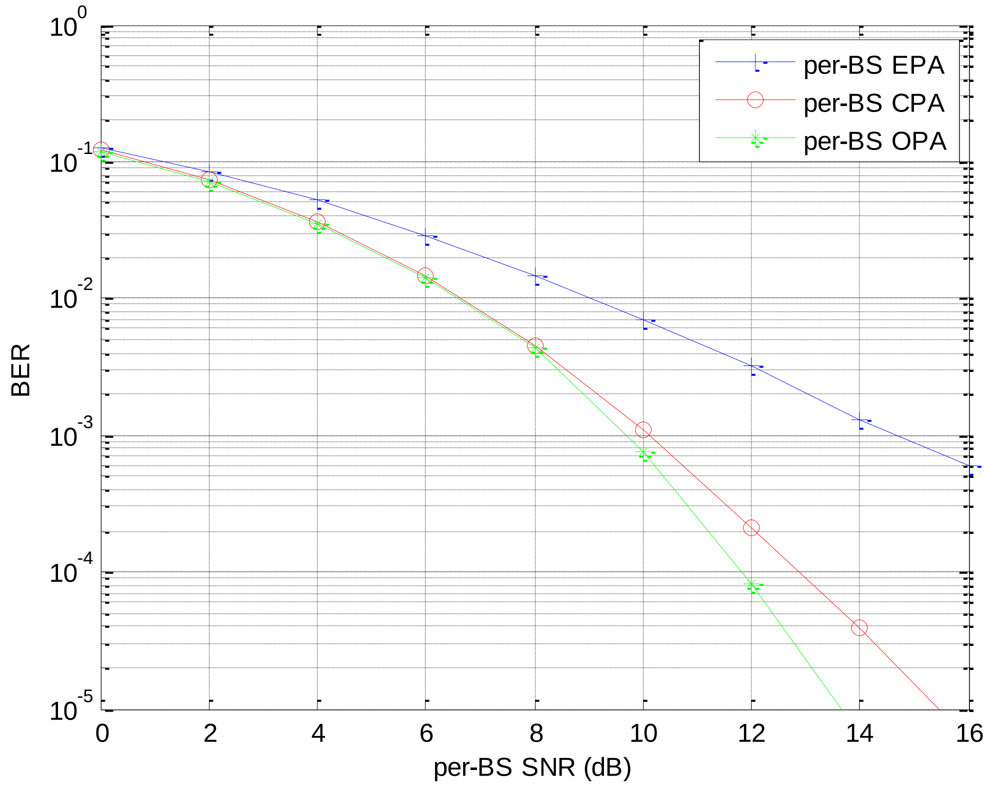

Figure 5.3: Results obtained for scenario I.

From this figure, we conclude that the systems with closed power allocation and optimum power allocation (per-BS CPA and per-BS OPA) have better performance than their equal power counterpart. This is due to the fact that, on the first two cases, the power available is distributed between the UT's in a more efficient manner.

Comparing these two techniques, it is clear that per-BS OPA shows better results, as expected. As we can see, the system with closed power allocation has a SNR of 15,2dB for a BER of 10^{-5} while the optimum power allocation system achieves a SNR of 13,7dB for the same BER.

5.5.2 Numerical results for Scenario II

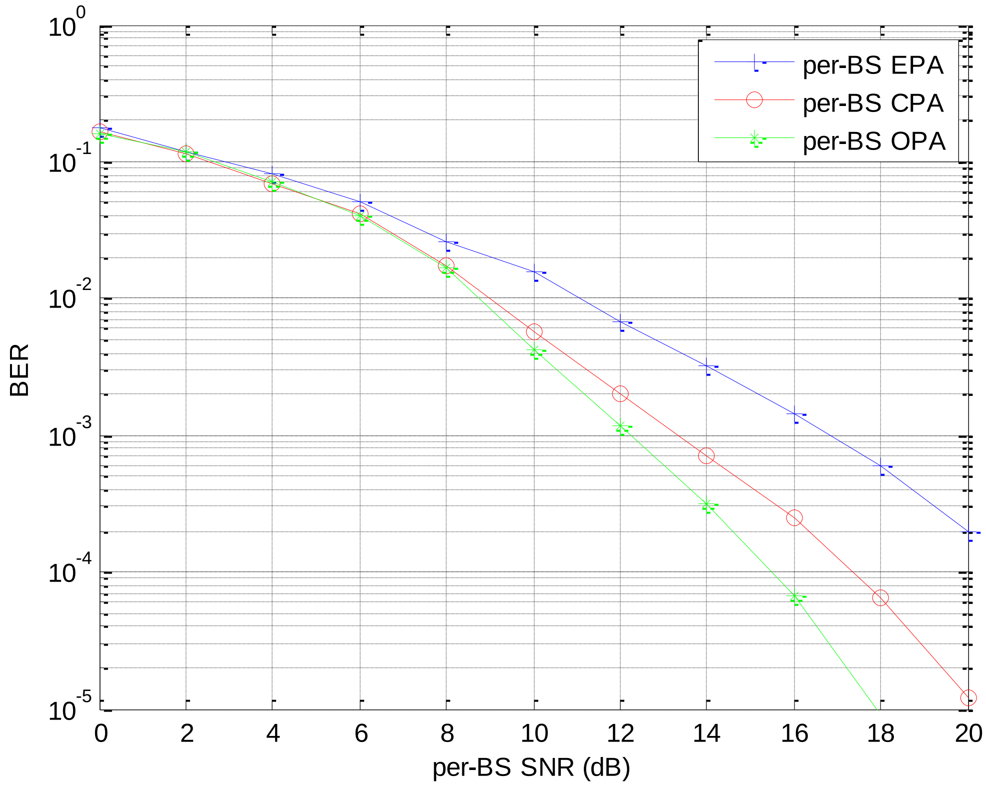

Figure 5.4: Results obtained for scenario II.

The values from both table 5.1 and table 5.2 were considered to obtain the results for this simulation.

It follows from the graph that, just like in the previous case, the systems with per-BS CPA and per-BS OPA show better results. This was explained in section 5.5.1.

If we compare this scenario with the previous one, we can see that the performance of the systems, for any power allocation scheme, was damaged by the action of the path-loss that was introduced. The fact that the channels are no longer independent must also be take into account as a reason why the global performance of the system was affected. The 20dB SNR obtained with closed power allocation this time is clearly a worse result than the 15,2dB obtained with independent channels and without path-loss.

5.5.3 Numerical results for Scenario III

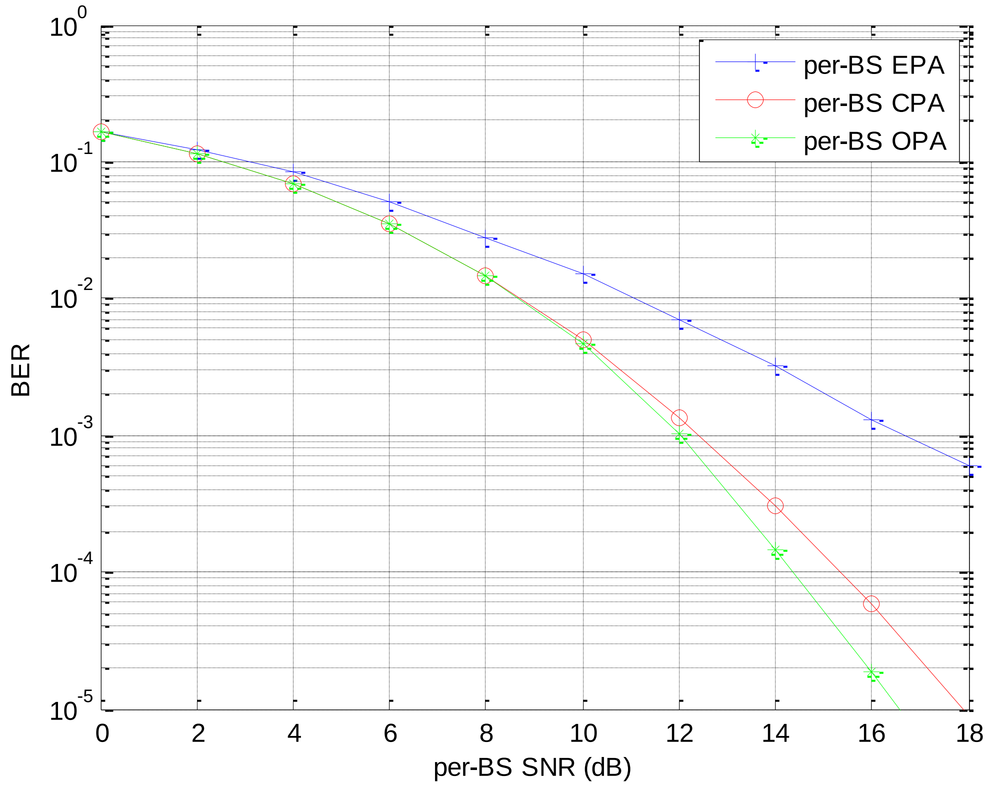

Figure 5.5: Results obtained for scenario III.

The values from both table 5.1 and table 5.2 were considered to obtain the results for this simulation.

Once again, per-BS CPA and per-BS OPA show much better results than per-BS EPA. Also, just like before, per-BS OPA is once again, and without surprise, the one with better results.

Even though this system, like the previous one, has correlated channels and considers path-loss, it achieves a better performance than the one in section 5.5.2. This is due to the implementation of interleaving, a way to arrange data in a non-contiguous way, which helps achieving a better performance.

5.5.4 Numerical results for Scenario IV

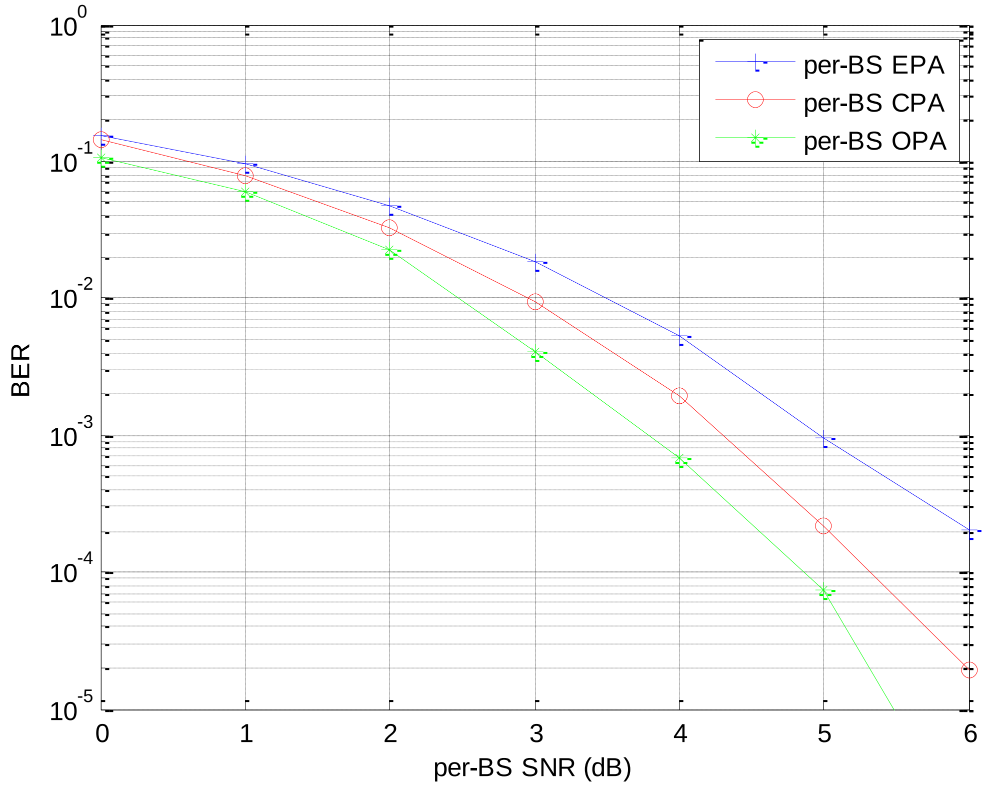

Figure 5.6: Results obtained for scenario IV - Bit Error Rate.

The values from both table 5.1 and table 5.2 were considered to obtain the results for this simulation.

The channel coding is an essential part of any practical system of communications. Its function is to introduce redundancy in the bit stream of data transmitted in order to correct any errors.

As can be seen, using channel coding, we obtained even better results when compared to the previously simulated scenarios. Once again, per-BS OPA obtains the better results, followed by per-BS CPA, with per-BS EPA being far behind.

Figure 5.7 shows the FER (Frame Error Rate) obtained for this scenario.

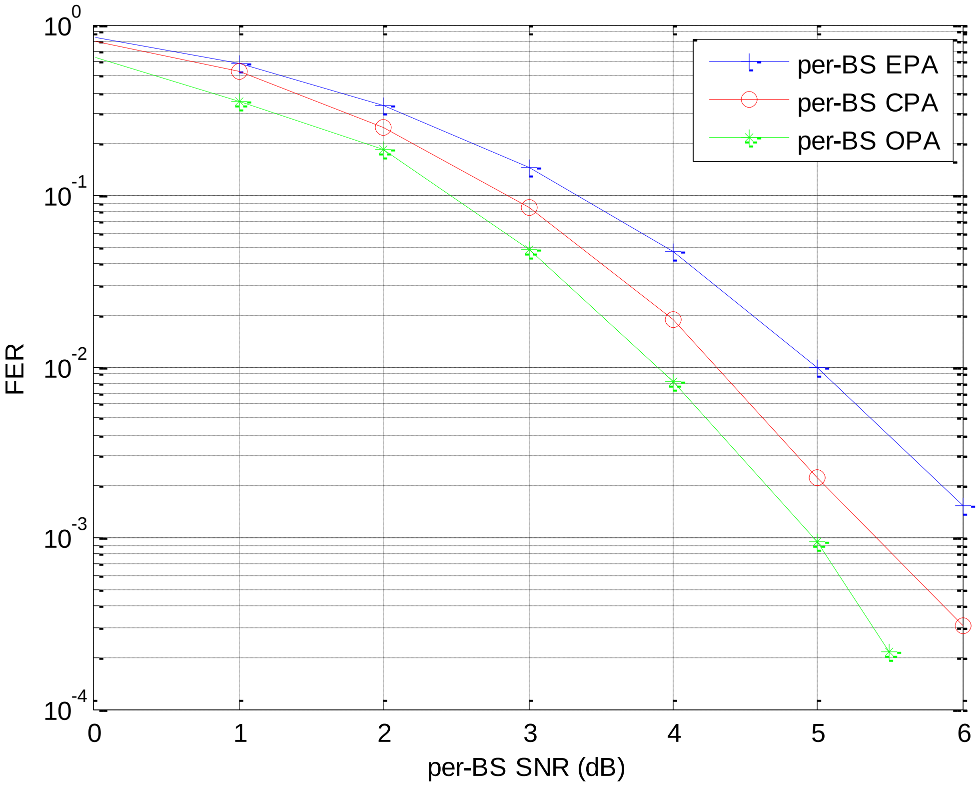

Figure 5.7: Results obtained for scenario IV - Frame Error Rate.

CHAPTER VI

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

The wireless communication systems experienced major developments in the last three decades, with each one marking a different generation. From a simple analog communication to the transmission with high transmission rates, long distance and fidelity, several new techniques and technologies have been implemented. This evolution was described in Chapter I of this dissertation, and some concepts on the mobile communication systems were presented.

In the second chapter, signal processing techniques were studied. These techniques help to achieve better results in terms of spectral efficiency of the system. The multiple carrier techniques, such as OFDM, allow us to achieve high spectral gains. Other techniques such as OFDMA, which as also been described, are key strategies in improving system performance.

Then, in Chapter III, the concept of multiple antennas in the two elements of the transmission (transmitter and receiver) is introduced. The importance of different settings to achieve high or low mutual correlation values between signals (depending on the distance between the antennas), as well as its benefits. It was shown that the use of systems that include multiple antennas, will help achieve crucial gains in said systems, including the introduction of techniques for encoding the signals and the concept of diversity. The three types of multiple antenna systems, MIMO, MISO and SIMO, were briefly studied.

Chapter IV was devoted to the study of multicell systems. Its emphasis lays in the development and assessment of cooperative precoding techniques, considering modified cellular systems where several base stations are transparently linked to a central unit, therefore allowing for joint processing and creating possibilities for novel designs and efficient intercell interference cancellation algorithms. Relevant architectures for multicell systems, such as the enhanced and the advanced cellular scenarios have been identified.

In the fifth chapter the proposed system was described, the deductions of the essential formulas to perform the desired simulations were presented as well. Finally, the results of the simulations are shown and explained.

This thesis was based on the simulation of wireless communication systems, through the tool Matlab ™, on which we implemented and tested in several scenarios the scheme discussed in Chapter 5.

We implemented and evaluated multiuser precoding schemes for multicell OFDM based systems. The considered precoder vectors are computed at each BS in a distributed manner, allowing a low complexity UT. The power allocation is computed at the central unit.

By analyzing the results obtained in the graphs presented in Chapter V, it can be concluded that the systems with a power allocation scheme have better performance compared to systems where there is no such scheme, in any of the scenarios simulated. This is due to the fact that when this allocation of power exists, we can supply more power to the channels with lower quality, i.e., the channels whose signals suffer greater wear due to the effects of fading, reflections, refractions, among other phenomena.

As for the path-loss effect, it was also observed that this factor affects system performance, since this phenomenon leads to a decrease in the power received in the UTs.

Also, it appears that when the transmission channels are uncorrelated, the system performs better. As it is known, when channels are correlated, if we have an error present in one of the channels, the same error will also be present in other channels correlated, and consequently, system performance decreases. In the event that the channels of the system are not correlated, if there is an error in the channels, the other channels are independent and will not be affected by this error.

Significantly better results were achieved by using the system with channel coding, and once again the system with power allocation performs far better.

In conclusion, we have observed that the use of power allocation becomes quite useful when connections between the transmitter-receiver are of poor quality. This is justified since this optimization greatly improves system performance in this scenario, since it helps combat the adversities that the signal encounters on its path, providing the system with more power to more channels affected by these adversities.

6.2 Future work

Some points can be identified for future work:

It was estimated that the channels were perfect, i.e., estimated without errors, which in practical system is will hardly occur. It would be interesting to study the impact of imperfect channel estimation on system performance.

This study did not consider the situation of correlation between the antennas of each base station. In a real system, that will be a problem which will have to be dealt with.

It would also be interesting to evaluate the system with more user terminals and base stations.

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