Beam-Forming and Power Control in Flexible Spectrum Usage for LTE Advanced System

Aalborg University

Institute of Electronic Systems

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Project Group 1124, 2008

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TITLE:	Beam-Forming and Power Control in Flexible Spectrum Usage for LTE Advance System
PROJECT PERIOD:	October 2007 to May 2008
PROJECT GROUP:	MOBCOM - 1124
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NUMBER OF PAGES:	98

Abstract

Beamforming and power control algorithms are investigated in intra-system spectrum sharing for LTE Advanced system (named as Flexible Spectrum Usage, FSU) context.

FSU is considered to occupy scarce spectral resources opportunistically in order to increase the average spectral efficiency of the system and to provide less interference to the other system. So, to avoid interference to other systems, beamforming and power control algorithms are investigated and implemented in MATLAB. As a starting point, assuming perfect channel state information at the transmitter, single-user (SU) multiple input multiple output (MIMO) downlink beamforming is implemented to evaluate the link performance of the system. As a case study, a link-level simulator complying UTRAN Long Term Evolution (LTE) standard is considered. Moreover, two multi-user (MU) MIMO downlink with OFDM/SDMA access scheme, beamforming algorithms zero-forcing (ZF) and successive minimum mean square error (SMMSE) are investigated to evaluate performance of the system at link-level by averaging the bit error rates (BERs) and throughputs (THs) of all the candidate users. Dominant eigen transmission (DET) power algorithm is to applied to both to maximize the SNR at the receiver and to minimize the BER. Numerical simulation results show significant gains by 3dB to 5 dB, depending of the modulation using, and 3dB about, for the low SNR, for the considered 2×2 *system in terms of BER and TH, respectively, compared to the same considered system without beamforming. Other results show significant gains by 3 dB and 3 dB, in terms of BER and TH, respectively, comparing SMMSE to ZF beamforming algorithm.*

Dedication

To my parents

Abbreviations

3GPP	Third Generation Partnership Project
ADC	Analog-to-Digital Converter
BER	Bit Error Rate
BF	Beam-Forming
CCI	Co-Channel Interference
CDMA	Code-Division Multiplexing Access
CP	Cyclic Prefix
CR	Cognitive Radio
CSI	Channel State Information
CSIT	Channel State Information at the Transmitter
DAC	Digital-to-Analog Converter
DET	Dominant Eigenmode Transmission
DFT	Discrete Fourier Transform
DOA	Direction Of Arrival
ECR	Effective Coding Rate
FDD	Frequency-Division Duplexed
FDM	Frequency-Division Multiplexing
FDMA	Frequency-Division Multiplexing Access
FFT	Fast Fourier Transform
FSU	Flexible Spectrum Use
HNB	Home Node B
HT	Hilly Terrain
ICI	Inter-Carrier Interference
IDFT	Inverse Discrete Fourier Transform
IFFT	Inverse Fast Fourier Transform
IMT-A	International Mobile Telecommunications-Advanced
ISI	Inter-Symbol Interference
ITU	International Telecommunications Union
LA	Local Area
LOS	Line of Sight
LTE	Long Term Evolution

MA	Metropolitan Area
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
MMSE	Minimum Mean Square Error
MU	Multi User
MUI	Multi User Interference
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiplexing Access
PC	Power Control
PRB	Physical Resource Block
PtoS	Parallel to Serial
QoS	Quality of Service
RA	Rural Area
SDMA	Space-Division Multiplexing Access
SEL	Spectral Efficiency Loss
SISO	Single-Input Single-Output
SM	Spatial Multiplexing
SMMSE	Successive Minimum Mean Square Error
SNR	Signal-to-Noise Ratio
SS	Spectrum Sharing
StoP	Serial to Parallel
SU	Single User
SVD	Singular Value Decomposition
TC	Turbo Coding
TDD	Time-Division Duplexing
TDMA	Time-Division Multiplexing Access
TTI	Transmission Time Interval
TU	Typical Urban
UE	User Equipment
WA	Wide Area
WF	Water Filling
ZF	Zero Forcing

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Chapter 1

1. Introduction

In the recent years, the International Telecommunications Union (ITU) is working on specifying the system requirements towards next generation mobile communication systems, called International Mobile Telecommunications-Advanced (IMT-A), [27]. The deployment of IMT-A systems is believed to take place at mass market level around year 2015 and will realize what has been a buzzword for almost a decade, namely "4G". The 4G radio network concept (Cognitive Radio, CR [1], [2]) covers the full range of operability scenario from Wide Area (WA) over Metropolitan Area (MA) to Local Area (LA). IMT-A systems are expected to provide peak data-rates in the order of $1 \ Gpbs$ in LA. Such data-rates require usage of Multiple-Input Multiple-Output (MIMO) technology [15], [16], to achieve high spectral efficiency and a very wide spectrum allocation in the range of $100 \ MHz$. In MIMO communications systems, multiple antenna are used at both sides of the link.

An important research topic is the study of Multi-User (MU) MIMO systems [17]. With a high number of users it will become even more difficult to identify exclusive spectrum for all user. To solve this problem, together with the MIMO technology, users are needed also to coexist in the same spectrum in an efficient way. This is possible considering a Flexible Spectrum Use (FSU) [28], [29]. The major advantage of FSU is a better spectral scalability of the system compared to classic spectrum management techniques. In this way, in a LA scenario with one cell and one Home Node B (HNB), different users can coexist on the on the same frequency-time domain. This is possible considering as multiple access scheme the Orthogonal Frequency Division Multiplexing (OFDM) with Space Division Multiple Access (SDMA) [6] - [11]. It has been chosen as multiple access for downlink in Long Term Evolution (LTE). Such systems have the potential to combine the high capacity achievable with MIMO processing with the benefits of SDMA. SDMA is an advanced transmission technique, where MU are signalled on the same time and same frequency resource; it is used to enhance the spectral efficiency. So, a large number of User Equipments (UEs) share the whole spectrum. In this scheme HNB prepares a number of directional beams to cover the UEs area. Beamforming (BF) [12], [13] concentrates transmit power to a desired direction and reduces power emissions to undesired directions; this way BF eliminate Multi-User Interference (MUI) caused by all others UEs.

BF and power control (PC) algorithms for MIMO-OFDM/SDMA LTE advanced systems in the FSU context are investigated and implemented in MATLAB. To implement downlink BF algorithm, HNB need the knowledge of the Channel State Information (CSI). CSI are obtained by a Time-Division Duplexing (TDD) systems.

In TDD system, uplink and downlink transmission are time duplexed over the same frequency bandwidth. Using the reciprocity principle it is possible to use the estimated uplink channel for downlink transmission.

We consider two algorithms for downlink BF: ***Successive Minimum Mean Square Error*** (***SMMSE***) [14], [20], [21] and ***Zero Forcing*** (***ZF***) [14], [19], [20]. SMMSE transmits beamforming treats; each receive antenna separately, and it has the advantage that the total number of receiving antennas at the users' terminals may be greater than the number of antennas at the HNB. In ZF, the signal of each user is pre-processed at the transmitter, using a modulation matrix that lies in the null space of all other users' channel matrices; so, the MUI in the system is forced to zero.

PC is also investigated, it's considered a ***Dominant Eigenmode Transmission*** (***DET***) algorithm which transmits just on the dominant eigenmode of each UE. It provides to maximize the Signal Noise Ratio (SNR) at the receivers and to minimize the Bit Error Rate (BER).

As a starting point, assuming perfect channel state information at the transmitter, single-user (SU) multiple input multiple output (MIMO) downlink beamforming is implemented to evaluate the link performance of the system. As a case study, a link-level simulator complying UTRAN Long Term Evolution (LTE) standard is considered. Moreover, two multi-user (MU) MIMO downlink with OFDM/SDMA access scheme, beamforming algorithms zero-forcing (ZF) and successive minimum mean square error (SMMSE) are investigated to evaluate performance of the system at link-level by averaging the bit error rates (BERs) and throughputs (THs) of all the candidate users. Dominant eigen transmission (DET) power algorithm is to applied to both to maximize the SNR at the receiver and to minimize the BER.

BF and PC eliminate the MUI and minimize the total transmitted power and this is exactly the problem that will be considered here, i.e. how to choose the transmit BF vectors so that the total transmitted power is minimized while the system provides an acceptable Quality of Service (QoS) to as many users as possible.

1.1. Organization of this Thesis

This report documents a master thesis in Telecommunication Engineering done in the Mobile Communication Division, Department of Communication Technology, Institute of Electronic System, Aalborg University (AAU), in Denmark; in collaboration with INFOCOM Department, Facoltà di Ingegneria, La Sapienza University Rome, in Italy, which the author is member.

This thesis is organized as follows:

Chapter II gives the background theory about localization techniques and data fusion method. It states the fundamentals of the Cognitive Radio, of the OFDM technology, including the signal generation and reception; of the OFDM multi-user access. In addition, it introduces the BF concept and the MIMO technology.

Chapter III presents the project description: scenario, problem definition, system architecture, scope of the project and the necessary assumptions.

Chapter IV introduces the BF methods (SMMSE and ZF) utilized and the Power Control method (DET).

Chapter V presents the parameter utilized in the simulations and the results obtained for a single-user system and a multi-user system.

Chapter VI summarizes the achievements reached during this thesis. Future work will be also be presented.

Chapter 2

2. Background

This chapter provides technical background that is essential to the thesis. First, it includes an overview on the Cognitive Radio, in particular the function of the Spectrum Sharing, which provides control and access techniques in order to guarantee a free interference communication among several different terminals.

Second, it includes an overview on the OFDM and multi access with OFDM systems; the OFDM symbol (information bits) that are transmitted on a set of orthogonal subcarriers. In particular, it treats various multiple access for the OFDM system: OFDM/FDMA (OFDMA), OFDM/TDMA, OFDM/SDMA.

Third, it includes an overview on the Beamforming, in particular the beamforming-based SDMA that we’ll use to try eliminate the interferences.

2.1 Cognitive Radio

The term ***Cognitive Radio (CR)*** was coined by Joseph Mitola [1] :

*"A **Cognitive Radio** is a radio frequency transmitter/receiver that is designed to intelligently detect whether a particular segment of the radio spectrum is currently in use, and to jump into (and out of, if necessary) the temporarily-unused spectrum very rapidly, without interfering with the transmission of other authorized users."*

*"A **Cognitive Radio** is self-aware, user-aware, RF-aware, and that incorporates elements of language technology and machine vision."*

The concept of a *radio* capable of adapting to the environment and to adjust transmission parameters according to internal and external events is very important in the wireless world.

A radio is cognitive if it is *self-aware*, then if it interacts with the outside world. This is accomplished via the *cognitive cycle*. A cognitive cycle [2] by which a cognitive radio may interact with the environment is illustrated in Figure 1.

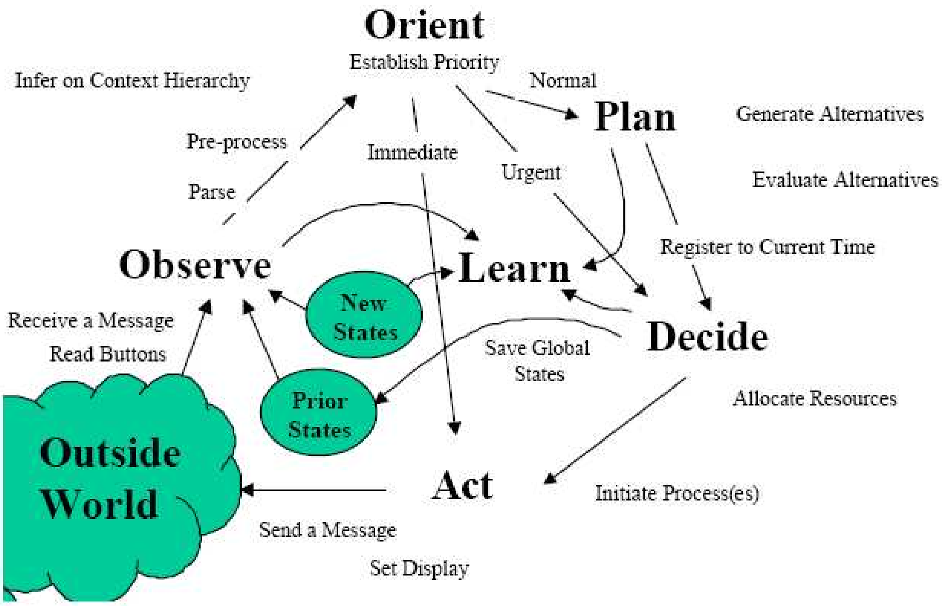

Figure 1. Simplified Cognitive Cycle [1]

A CR executes five main actions:

- **Observe**, cognitive radios are aware of their surrounding environment.
- **Plan**, cognitive radios evaluate among several strategies.
- **Decide**, cognitive radios are always capable to select one strategy of operation.
- **Learn**, cognitive radios can enrich experience by forming new strategies.
- **Act**, cognitive radios perform communication according to the selected strategy.

CR technology is expected to improve spectrum access through:

- **Spectrum Sensing**: monitoring and detecting the spectrum holes to reuse them properly, with two different techniques: *transmitter detection* (the CR terminal decides if the frequency band is free or is not by its own, through two different methods: *Matched Filter* and *Energy detector*); *cooperative detection* (the CR terminal gets sensing information from other users and potentially can reach better results than transmitter detection alone).
- **Spectrum Management**: once the device has monitored the radio environment, according to the results of the monitoring, according to the service requirements (QoS), the cognitive radio terminal must find out the frequency hole which suits better every single particular transmission.
- **Spectrum Mobility**: the transmission frequency can dynamically change if the user signal transmission shows up suddenly.
- **Spectrum Sharing**: it provides control and access techniques in order to guarantee an interference free communication among several different terminals.

So, a Cognitive Radio should be able to determine the spectral characteristics of the radio environment it operates in, and, if necessary, to change some transmission parameters. In particular, CR approach has the potential to alleviate the limitations in the frequency, spatial and temporal domains and provide for real-time spectrum access negotiation and transactions, thus facilitating dynamic spectrum sharing. The problem is that in a spectrum sharing environment, we have a co-channel interference caused by sharing the same radio channel. Power control and array beamforming are two well-known approaches that control co-channel interference and thus improve the system capacity.

2.1.1 Spectrum Sharing

Spectrum Sharing (*SS*) [22] is verified when independent radio system (like military radars, cellular,…) or independent users use the same spectrum in co-operation (time, place, code and/or event,…). The SS process consists of five major step:

- *Spectrum sensing*, an user can just allocate a portion of the spectrum if that portion doesn't used by an unlicensed user.
- *Spectrum allocation*, based on the spectrum availability, the node can then allocate a channel.
- *Spectrum access*, it is possible that more nodes would access to the spectrum, this access must be coordinate.
- *Transmitter-receiver handshake*, once a portion of the spectrum is determined for communication the receiver of this communication should also be indicated about the selected spectrum. So, a transmitter-receiver handshake protocol is needed.
- *Spectrum mobility*, nodes are considered as visitors to the spectrum they allocate.

The classification of the SS is based on architecture, spectrum allocation behavior and spectrum access technique as shown in Figure 2.

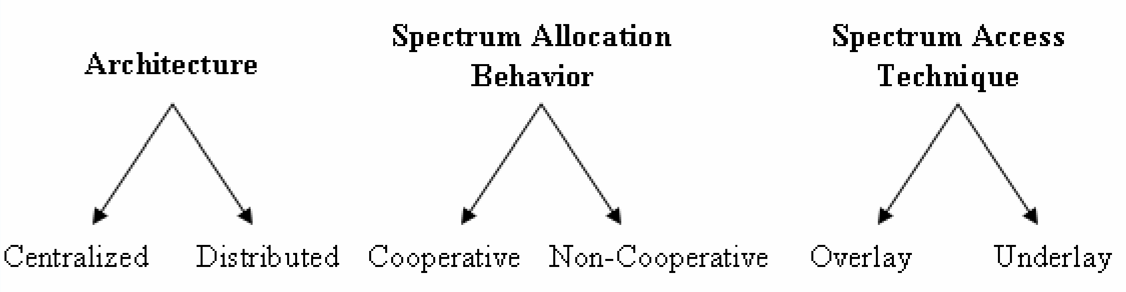

Figure 2. Classification of SS

The first classification for SS technique is based on the architecture:

- *Centralized spectrum sharing*, a centralized entity controls the spectrum allocation and access procedures.
- *Distributed spectrum sharing*, each node is responsible for the spectrum allocation and access is based on local policies.

The second classification for SS techniques is based on the access behaviour:

- *Cooperative spectrum sharing*, it considers the effect of the node's communication on the other nodes, so the interference measurements of each node are shared among other modes.
- *Non-cooperative spectrum sharing*, it considers just the node at hand.

The third classification for SS technique is based on the access technology:

- *Overlay spectrum sharing*, a node accesses the network using a portion of the spectrum that has not been used by licensed users.
- *Underlay spectrum sharing*, a node begins the transmission such that its transmit power at a certain portion of the spectrum is considered as noise by the licensed users.

The networks analyzed to provide opportunistic access to the licensed spectrum using unlicensed users. This causes SS among systems and we can have *Inter-Network Spectrum Sharing* and *Intra-Network Spectrum Sharing* as shows in figure 8.

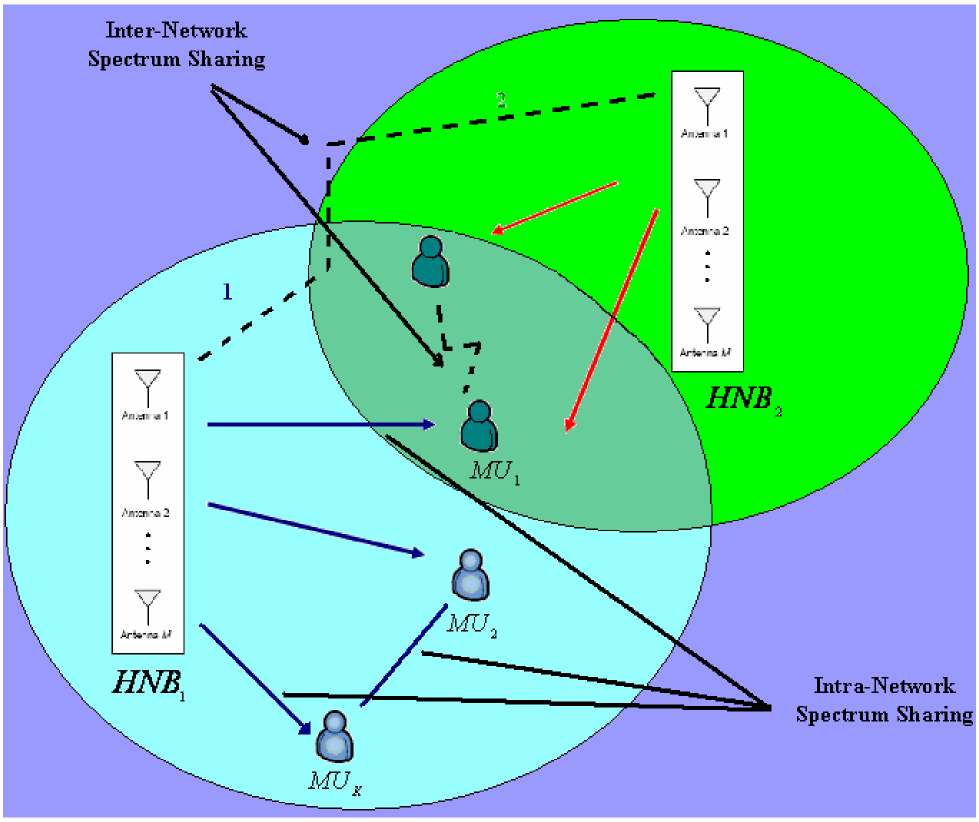

Figure 3. Inter-Network SS and Intra-Network SS

We treat just the Intra-Network SS, where the users try to access the available spectrum without causing interference to others users. In particular, we are in the *Flexible Spectrum Usage* (*FSU*) [28], [29], where the users are able to use spectrum in a flexible way by adapting their operation to the current situation. The major advantage of FSU is a better spectral scalability of the system compared to classic spectrum management techniques.

To facilitate FSU, the system shall dynamically be able to adapt frequency, time and space resource over time in order to maximize the spectral efficiency with the constraint the Quality of Service (QoS) requirements are met.

A multi access with OFDM is suitable candidate for FSU because if its flexible nature to support spectrum sharing.

In this way, a *MUI* (*Multi-User Interference*) is generated by the presence of several users sharing a some resource. To reduce the presence of MUI, we can use an orthogonal multiple access scheme, that then implementing with the Power control and Beamforming technique can eliminate almost totally the MUI.

2.2 OFDM

Orthogonal Frequency Division Multiplexing (*OFDM*) is a digital multi-carrier modulation scheme, which use a large number of closely-spaced orthogonal sub-carriers. It is based on the Frequency Division Multiplexing (*FDM*) technique [3], where different streams of information are mapped into separate parallel frequency channels. The time-frequency representation of the OFDM [4] signal is shown in Figure 4.

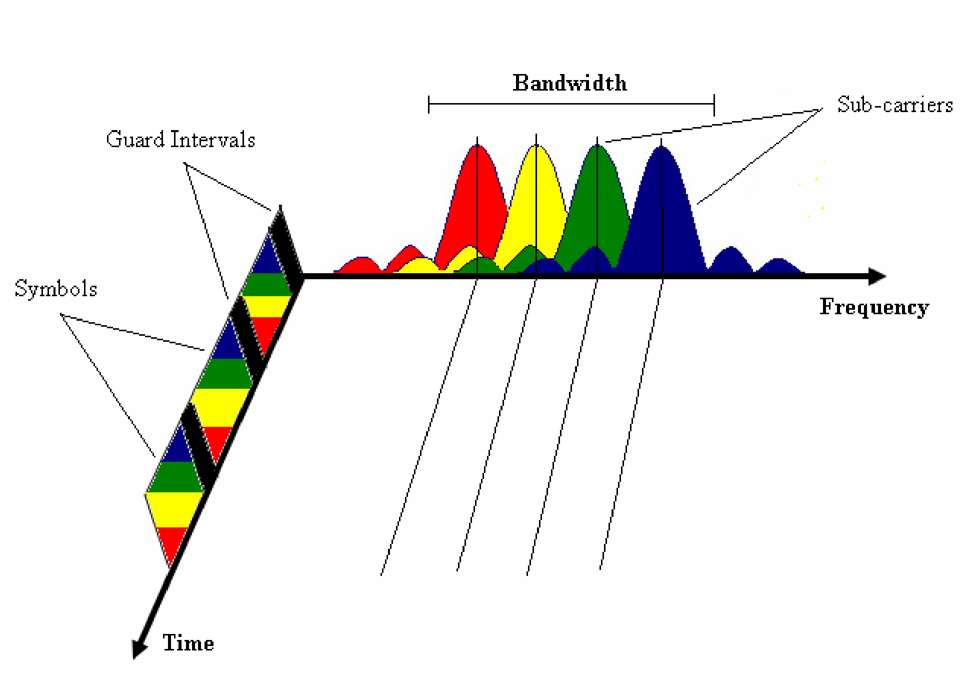

Figure 4. Frequency-Time representation of an OFDM signal

Each sub-carrier is modulated with a conventional modulation scheme (such as QAM/PSK, etc.) at a low symbol rate, maintaining data rates similar to conventional single-carrier modulation schemes in the same bandwidth, as showed in Figure 5.

Figure 5. Modulation of each sub-carrier

The basic principle of OFDM [5] is to split a high-rate data-stream into a number of lower rate streams that are transmitted simultaneously over a certain number of subcarriers. Because the symbol duration increases for the lower rate parallel subcarriers, the relative amount of dispersion in time caused by multipath delay spread is decreased. Intersymbol interference is eliminated almost completely by introducing a guard time in every OFDM symbol. In the guard time, the OFDM symbol is cyclically extended to avoid intercarrier interference. In OFDM system design, a number of parameters are up for consideration, such as the number of subcarriers, guard time, symbol duration, subcarriers spacing, modulation type per subcarriers, and the type of forward error correction coding. The choice of parameters is influenced by system requirements such as available bandwidth, required bit rate, tolerable delay spread, and Doppler values.

After the modulator, the symbol stream enters in the serial-to-parallel converter, that splits the modulated symbol stream into N parallel channels which are modulated onto N different subcarriers $\psi_k(t) = e^{j2\pi f_k t}$ with frequencies $f_0, f_1, \ldots, f_{N-1}$, where k indicates the $k-th$ subcarrier. The spacing between two adjacent subcarriers is Δf, thus the total bandwidth is $N \times \Delta f$, as showed in Figure 6.

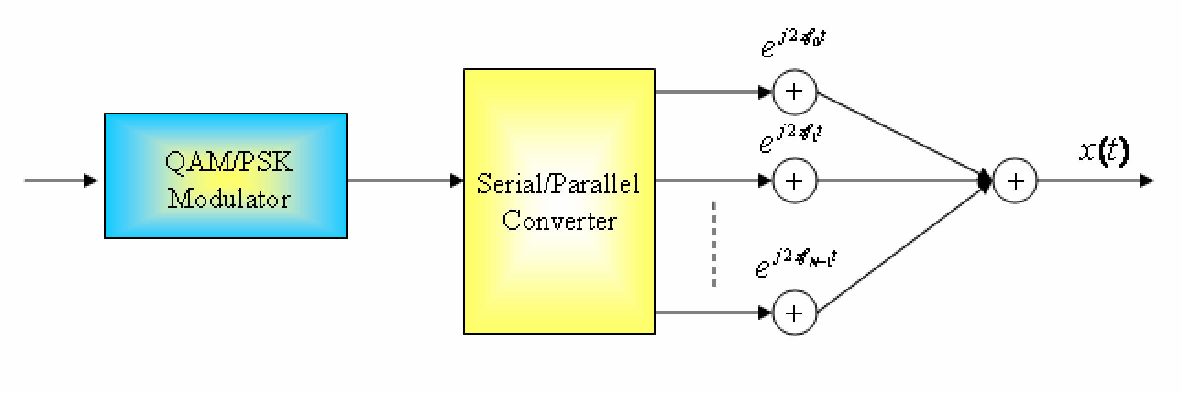

Figure 6. Conceptual OFDM transmitter

The transmitted OFDM signal $x(t)$ is the sum of each symbol $d[k]$ that forms an OFDM symbol $(k \in [0, \ldots, N-1])$ modulated on each subcarrier:

$$x(t) = \sum_{k=0}^{N-1} d[k] \cdot \psi_k(t)$$

So, each modulated data symbol is multiplied by the function $\psi_k(t)$. This kind of functions have got the orthogonality property, which can be expressed both in time and frequency domain:

- ***Time orthogonality:*** if $\psi_k(t)$ has an integer number of cycles during the duration T_S of an OFDM symbol:

$$\int_{t_0}^{t_0+T_S} \psi_k(t) \cdot dt = 0$$

- ***Frequency orthogonality:*** the correlation of two orthogonality functions will be non-zero only if both functions have the same $k-th$ frequency:

$$\int_{t_0}^{t_0+T_S} \psi_k(t) \cdot \psi_l(t) \cdot dt = \begin{cases} 1 & l = k \\ 0 & l \neq k \end{cases}$$

When these properties are satisfied, the subcarriers will be independent to each other and so it is guaranteed the correct separation of each one at the receiver.

The main problem of the transmitter shown in Figure 6 is its complexity. But, we can use an Inverse Discrete Fourier Transform (IDFT) as shown in Figure 7. The OFDM signal can be expressed as:

$$x[n] = \frac{1}{N} \sum_{k=0}^{N-1} d[k] \cdot e^{j2\pi nk/N}$$

that is equivalent to modulating each symbol with a frequency $f_k = \frac{k}{NT_0}$, where T_0 is the sampling period. Furthermore, IDFT is performed with an Inverse Fast Fourier Transform (IFFT) algorithm which is computationally efficient.

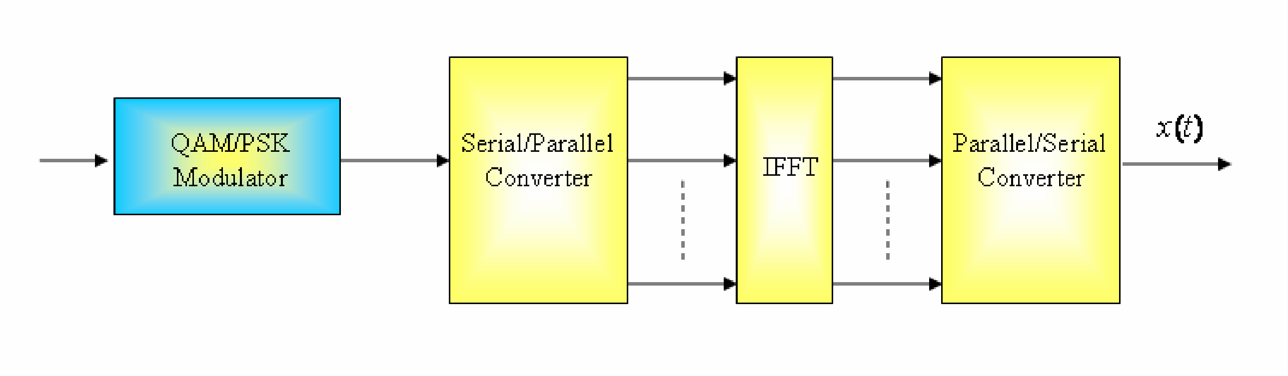

Figura 7. OFDM transmitter with IFFT

The transmission of the signal over a multipath channel may distort this one. So, to mitigate this effect, a guard interval T_G is added at the beginning of each OFDM symbol. The duration of T_G depends on the maximum delay of the channel $\tau_{\max}$, in particular it must be:

$$T_G \geq \tau_{\max}$$

So, all multipath components will arrive in this guard time and in this way the orthogonality between subcarriers will be preserved; in addition, the Inter-Symbol Interference (ISI) and Inter-Carrier Interference (ICI) will be eliminated, as showed in Figure 8.

If the guard interval is generated by copying the last N_G samples of the useful OFDM symbol to the beginning of the same OFDM symbol, it is called Cyclic Prefix (CP).

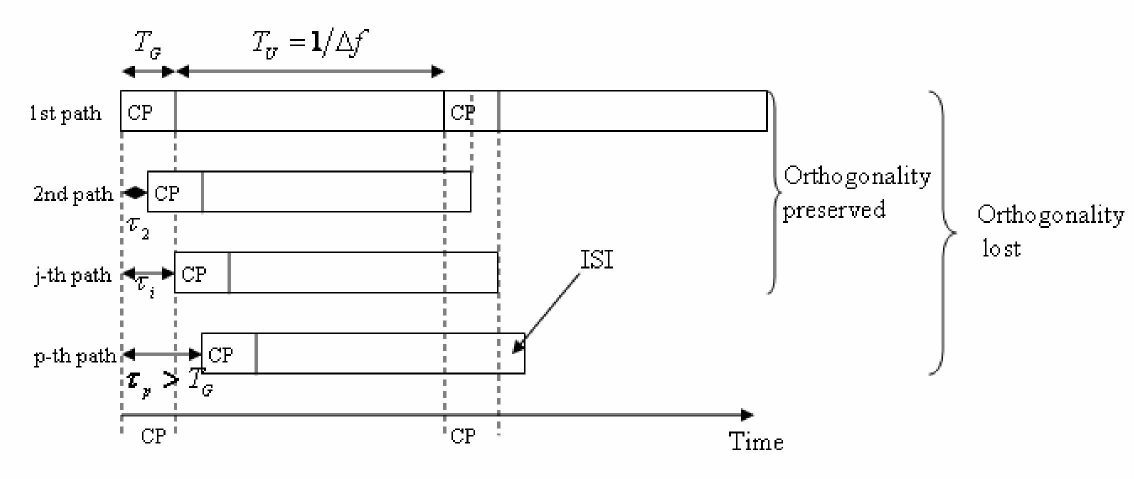

Figure 8. Cyclic Prefix avoiding ISI

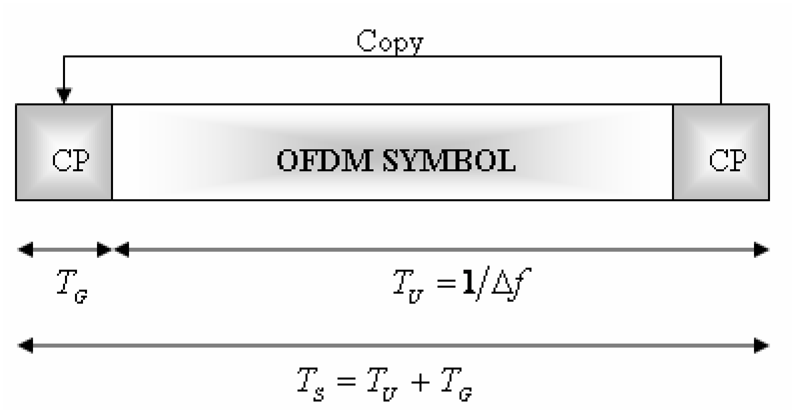

Figure 9. Cyclic prefix as a copy of the last part of an OFDM symbol

Figure 9 shows the cyclic prefix concept where:

- $T_U = N \cdot T_0$, is the useful duration, where the data symbol are transmitted;
- $T_G = N_G \cdot T_0$, is the cyclic prefix duration;
- $T_S = T_U + T_G = (N + N_G) \cdot T_0$, is the total duration of the OFDM symbol.

The cyclic prefix helps to avoid ISI and ICI, in addition it will introduce Spectral Efficiency Loss (SEL). It is directly related to the ratio between T_G and T_S:

$$SEL = \frac{T_G}{T_G + T_U}.$$

When the signal arrives to receiver, the first N_G samples of OFDM symbol is removed. Then, each subcarrier is demodulated multiplying the content of each sub-channel by $e^{-j2\pi f_k}$, where f_k is the frequency of the corresponding subcarrier. If, we use a Discrete Fourier Transform (DFT) over the N useful OFDM symbol samples:

$$z[k] = \sum_{n=0}^{N-1} r[n] \cdot e^{-j2\pi nk/N}$$

where, the subcarrier frequency is $f_k = \frac{k}{NT_0}$ and where T_0 is the sampling period. We can use a Fast Fourier Transform (FFT) algorithm to have a low computational complexity.

Finally, the data symbols are converted to a serial symbol stream and delivered to the next block. Figure 10 shows the block diagram of the OFDM transceiver.

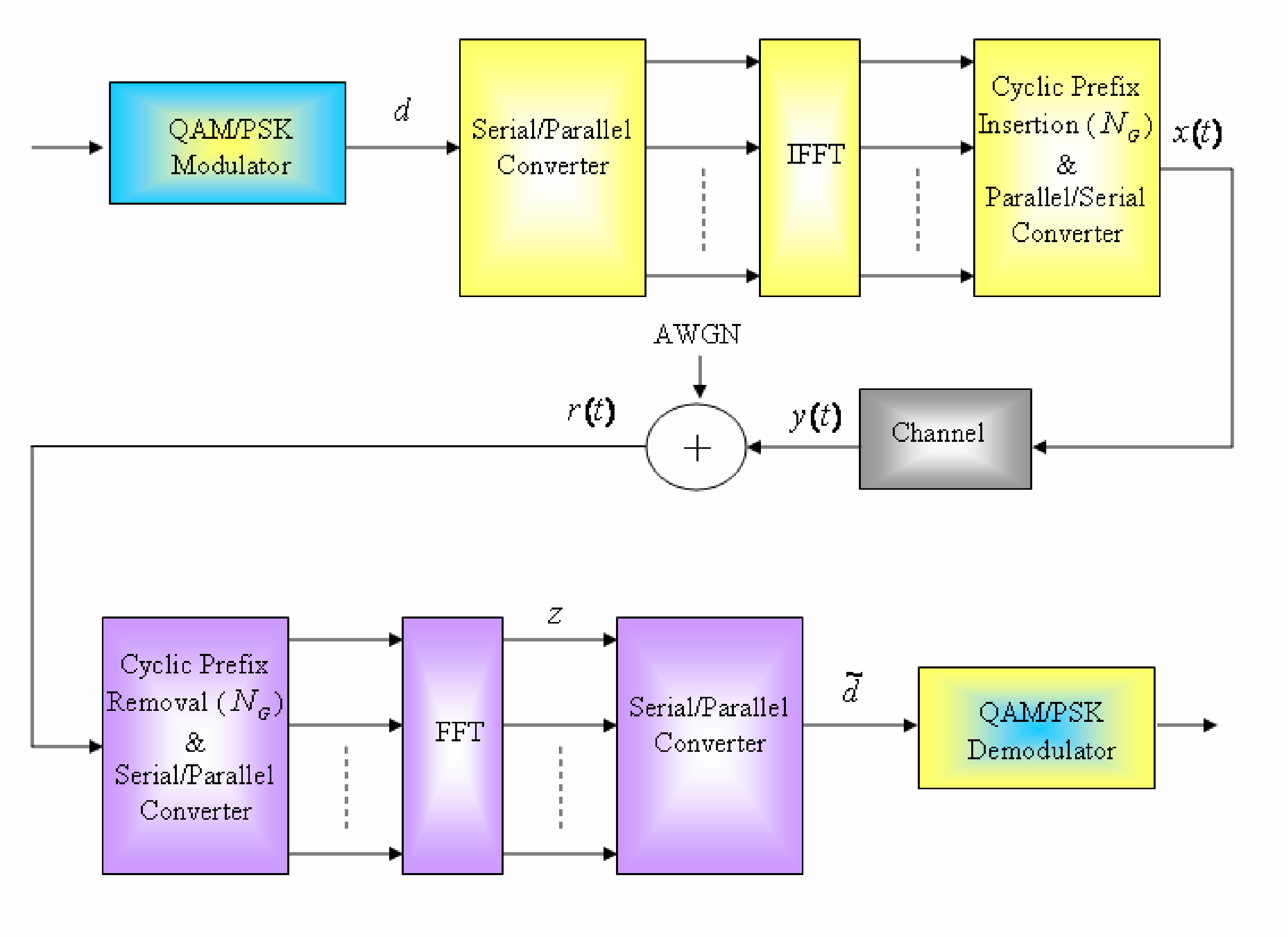

Figure 10. OFDM block diagram

2.3 Multi Access with OFDM

In case of multi-user (numerous users that transmit simultaneously), we have Orthogonal Frequency Division Multiplexing (OFDM) with multiple access [7]. A block diagram of the multi-user OFDM downlink transmission is represented in Figure 11.

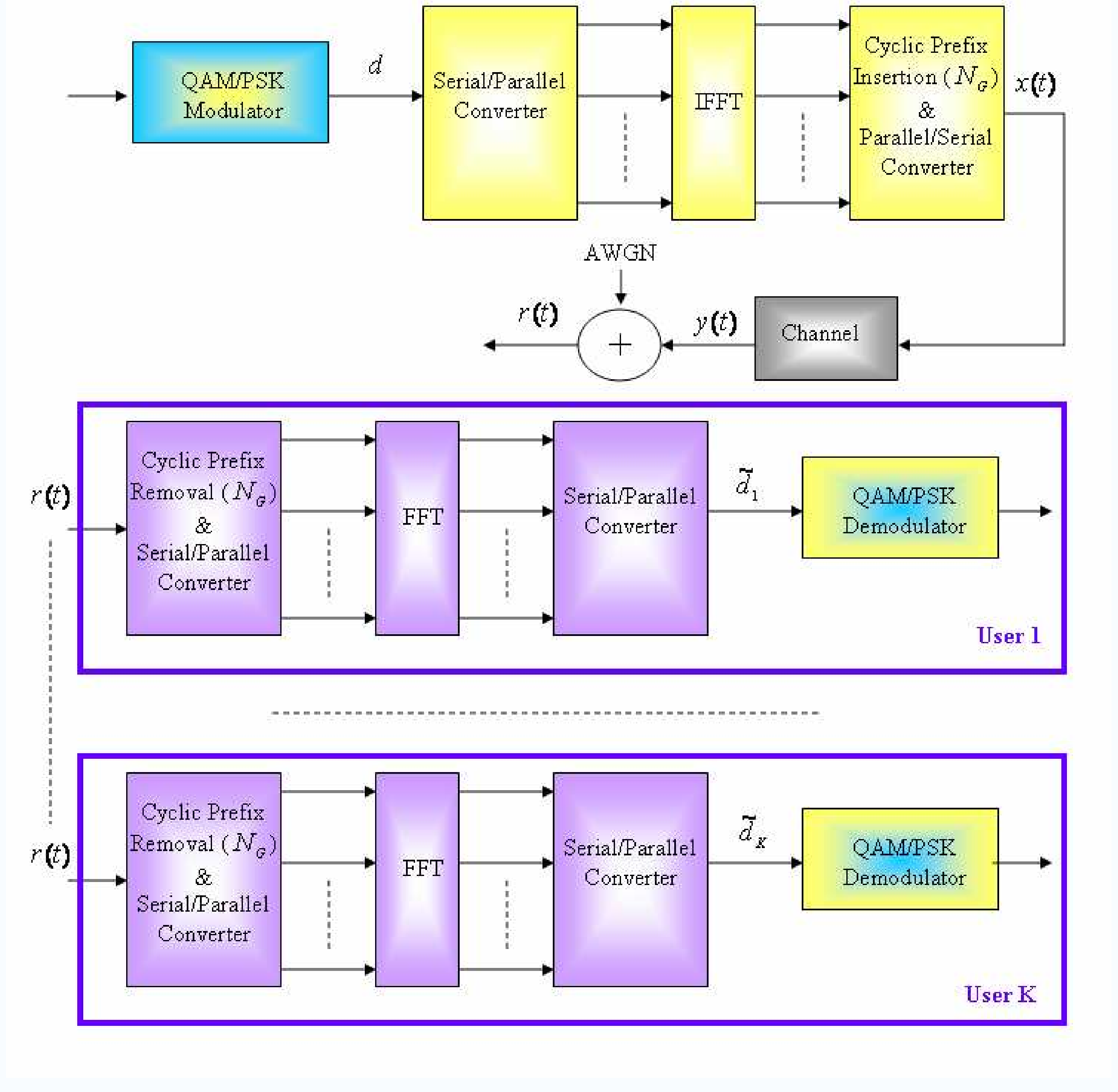

Figure 11. OFDMA downlink block diagram

Multi-User OFDM (MU-OFDM) can be realized using various multiple access techniques: Time-Division Multiple-Access (TDMA), where the users transmit in time slot; Frequency-Division

Multiple-Access (FDMA), where the users transmit on a set of frequency ; Code-Division Multiple-Access (CDMA), where the users transmit using a set of spreading sequences; or Space Division Multiple-Access (SDMA), which reuses bandwidth by multiplexing signals based on their spatial signature. Figure 12 shows an example of OFDM with multi-access. In this case, users are associated with one or more Physical Resource Block (PRB). A PRB is a combination of n sub-carriers and M consecutive OFDM symbols. An overview of these techniques will be done.

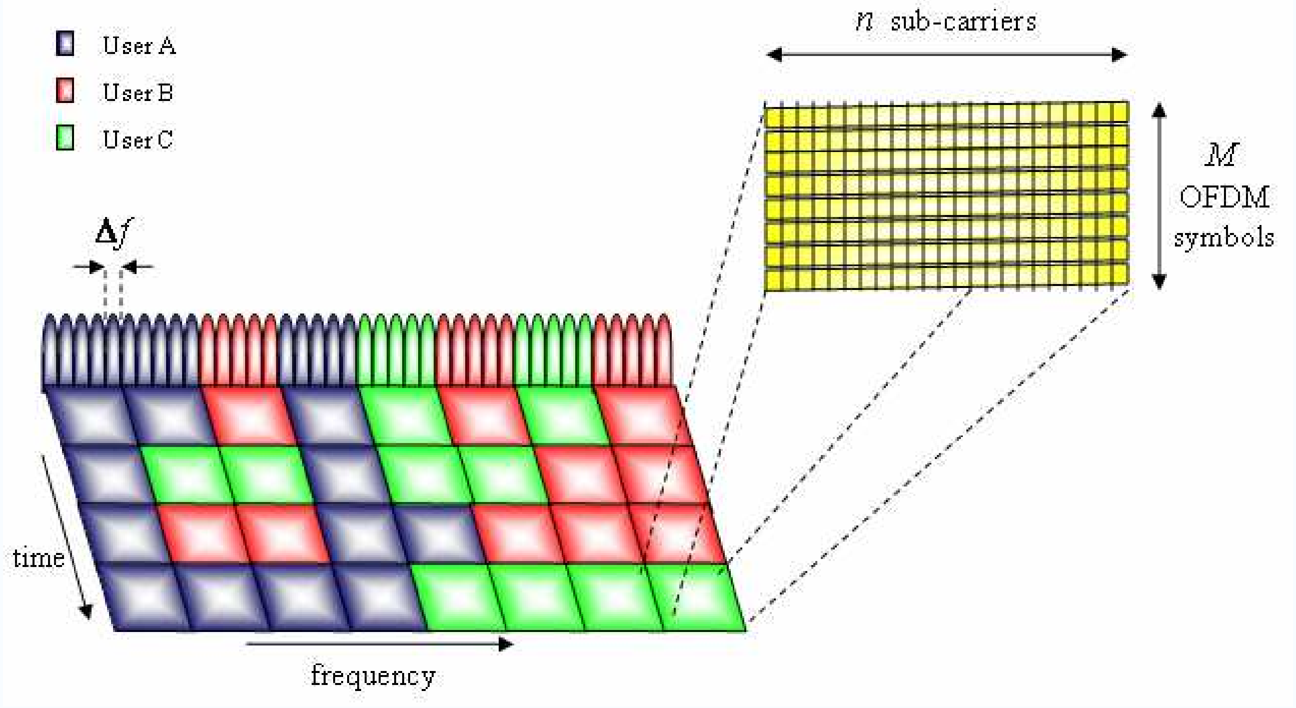

Figure 12. Example of OFDM with multiple access

2.3.1 OFDM/FDMA (OFDMA)

The OFDM technique can be combined with a Frequency Division Multiple Access (FDMA). OFDM/FDMA is achieved assigning subsets of subcarriers for each user, so users are separated across subcarriers [6], as showed in Figure 13. Available subcarriers are distributed among all the users for transmission at any time instant T_S .

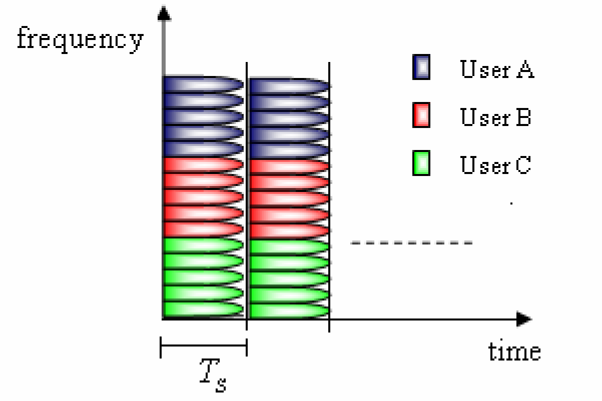

Figure 13. MU-OFDM with FDMA

In OFDM/FDMA [7], the whole spectrum may be divided into multiple adjacent subcarriers. So, a large number of userss share the whole spectrum. In base on the allocation of subcarriers to users, we can have different kind of OFDM/FDMA: *block FDMA* (grouped carriers FDMA), *random allocation* (adaptive frequency hopping) and *interleaved FDMA* (comb spread carriers), as showed in Figure 14.

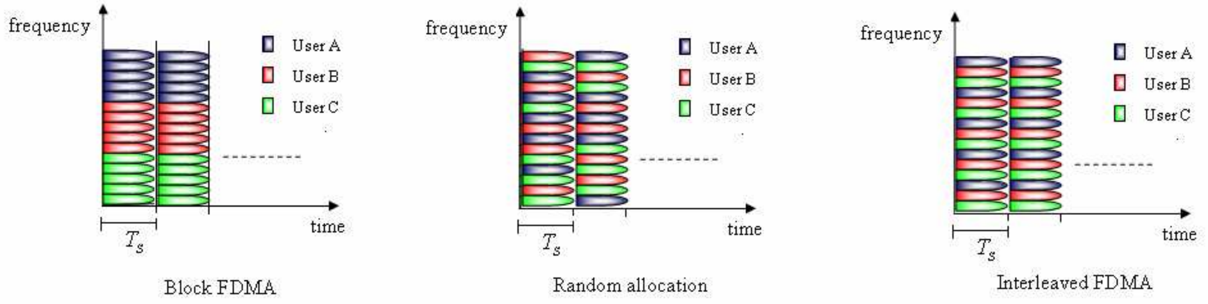

Figure 14. OFDM/FDMA variations

The OFDM/FDMA has significant interest because for its robustness to multipath propagation, appropriateness for coverage extension and high spectral efficiency.

2.3.2 OFDM/TDMA

The OFDM technique can be combined with a Time Division Multiple Access (TDMA) [7], [8]. In OFMD/TDMA, one complete OFDM symbol at a certain time is allocated to an user, as showed in Figure 15. Each user is assigned a time slot T_s during which all the subcarriers can be used for the particular user.

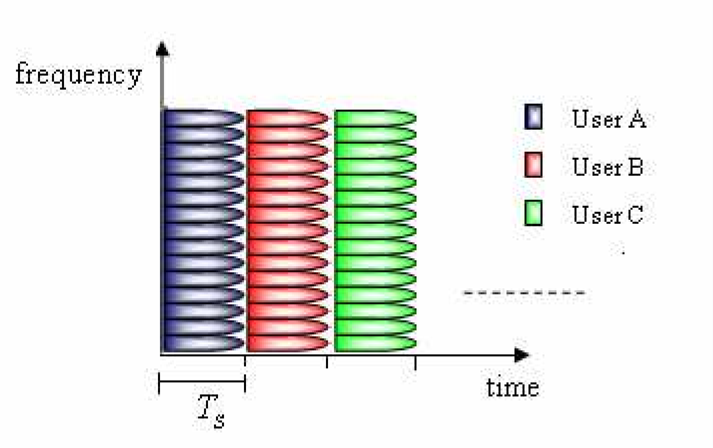

Figure 15. MU-OFDM with TDMA

OFDM symbols in one time slot is the minimum resource unit that can be allocated to a user. Thus, subcarriers of one OFDM symbol cannot be allocate to different users. This limitation reduces the flexibility of resource allocation, especially when the capacity of a time slot is very high.

2.3.3 OFDM/SDMA

The OFDM technique can be combined with a Space Division Multiple Access (SDMA) [9], which reuses bandwidth by multiplexing signals based on their spatial signature, in the same time slot and in the same frequency, obtaining higher spectral efficiency. The transmitter and the receive use array antenna. As a result, Beam-Forming (BF) concentrates transmit power to a desired direction and reduces power emissions to undesired directions.

Figure 16 shows an OFDM/SDMA communication slot. The OFDM/SDMA system model [10], [11] is fully subcarrier-parallel and the SDMA processing can be applied on each subcarrier.

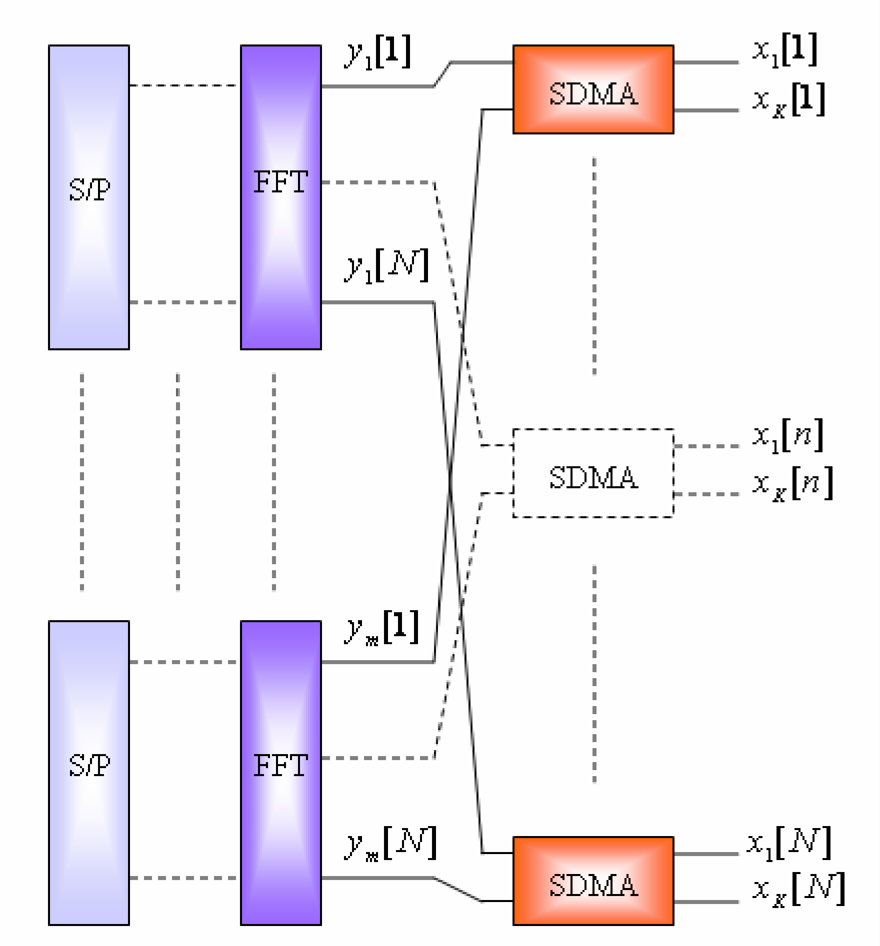

Figure 16. System model in OFDM/SDMA

OFDM/SDMA system with beamforming uses independent beam at the same carrier frequency and at the same time slot to provide service to individual users within a cell, as showed in Figure 17.

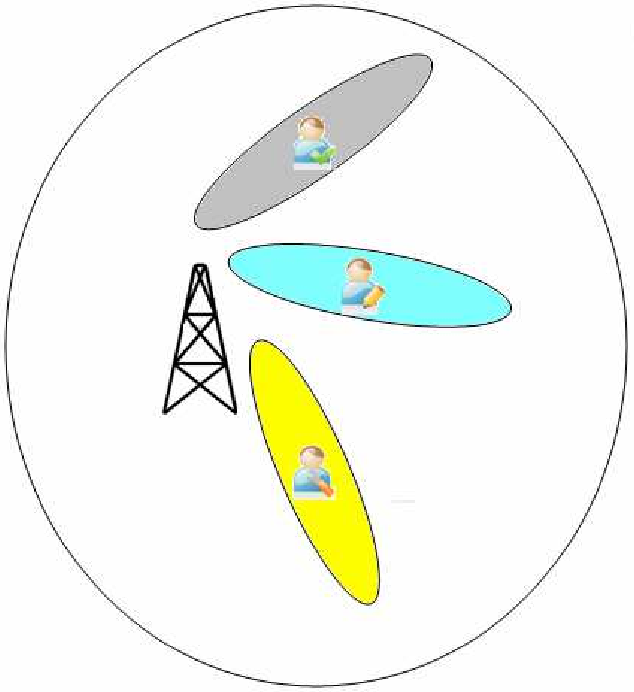

Figure 17. MU-OFDM with SDMA

This allows the same carrier frequency to be reused in different cells, in this way, it exploits diversity and beamforming gain and extracts spatial diversity.

2.4 Beamforming

Beamforming (BF) [12] is a signal processing technique used with arrays of transmitting or receiving transducers that control the directionality of, or sensitivity to, a radiation pattern. When receiving a signal, beamforming can increase the receiver sensitivity in the direction of wanted signals and decrease the sensitivity in the direction of interference and noise. When transmitting a signal, beamforming can increase the power in the direction the signal is to be sent. The change compared with an omnidirectional receiving pattern is known as the receive gain (or loss). The change compared with an omnidirectional transmission is known as the transmission gain. These changes are done by creating beams and nulls in the radiation pattern. Figure 18 illustrates the polar diagram of the antenna array.

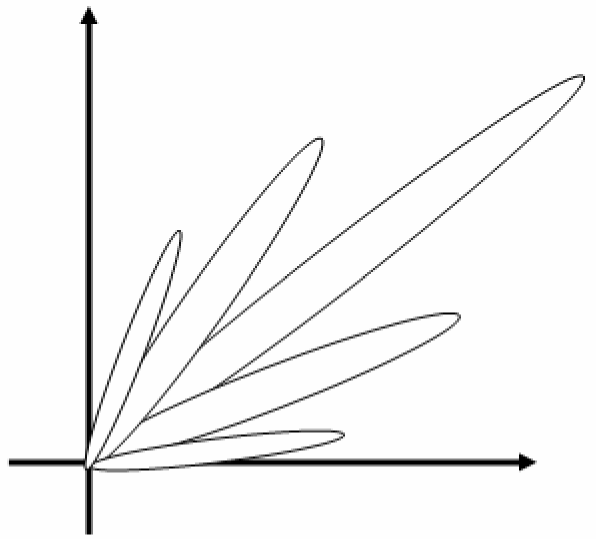

Figure 18. Polar diagram of a typical antenna beampattern.

Beamforming is a mix between antenna technology and digital technology [13]. An antenna can be considered to be a device that converters spatial-temporal signals, thus making them available to a a wide variety of signal processing techniques, in this way, all of the desired information that is being carried by these signals can be extracted. Figure 19 shows a generic BF antenna system.

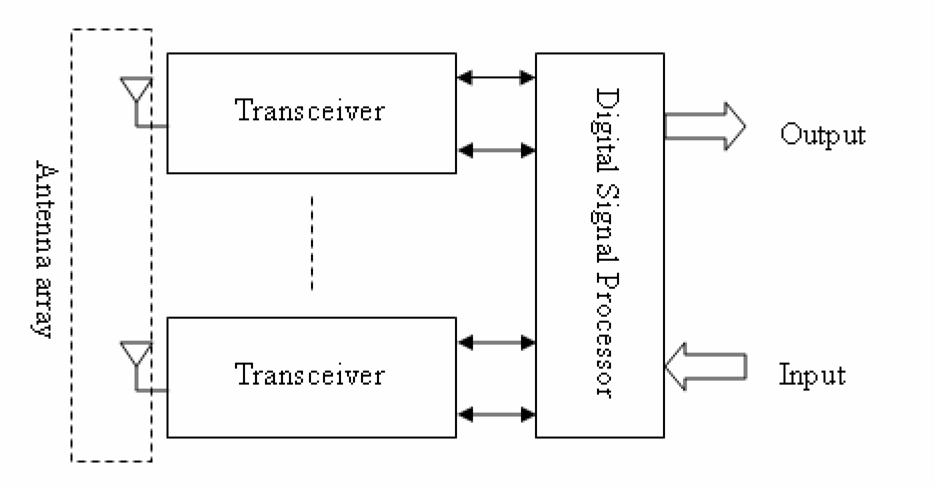

Figure 19. A generic BF antenna system

Antenna arrays using adaptive beamforming techniques can reject interfering signals having a Direction Of Arrival (DOA) different from that of a desired signal [13]. An adaptive BF is a device that is able to separate signals collocated in the frequency band but separated in the spatial domain. This provides a means for separating a desired signal from interfering signals. An adaptive BF is able to automatically optimize the array pattern by adjusting the elemental control weights until a prescribed objective function is satisfied. If a wave (for example a plane wave) arrive perpendicular to the array, it is seen with the same phase from all transducers; so the sum of the array output signals is just wave incident. Instead, if the arrival angle is different from 90°, the array output is attenuated regarding the previous one, and it depends on angle incident, as showed in Figure 20.

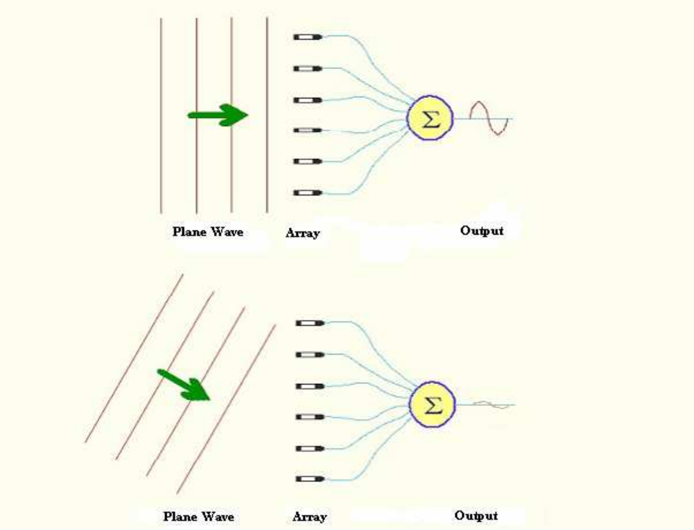

Figure 20. Signal output array [13]

In optimum and adaptive beamforming, the phases (and usually the amplitudes) of the feed network (the interconnection between elements) are adjusted to optimize the received signal. The geometry of an array and the patterns, orientations, and polarizations of the elements influence the performance of the array. Introducing weights (different delays for each transducer), opportunely calculates, is possible to find the just direction of the signal, as showed in Figure 21.

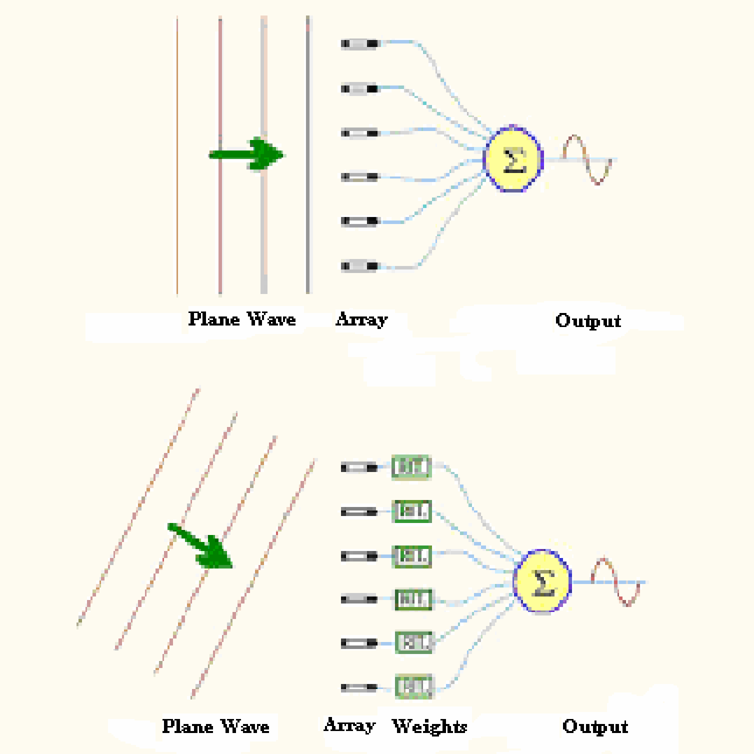

Figure 21. Introduction of the weight to calculate the just direction of the signal [13]

Beamforming takes advantage of interference to change the directionality of the array. When transmitting, a beamformer controls the phase and relative amplitude of the signal at each transmitter, in order to create a pattern of constructive and destructive interference in the wavefront. When receiving, information from different sensors are combined in such a way that the expected pattern of radiation is preferentially observed.

We can consider two types of beamforming. Each of them has its own advantages and disadvantages. The first, which samples the propagating wave field in space, is typically used for processing narrowband signals. The output at time k, $y(k)$, is given by a linear combination of the data at the J sensors at time k:

$$y(k) = \sum_{j=1}^{J} w_j^* x_j(k)$$

where * represents complex conjugate. We assume throughout that the data and weights are complex since in many applications a quadrature receiver is used at each sensor to generate in phase and quadrature (I and Q) data. Each sensor is assumed to have any necessary receiver electronics and an A/D converter if beamforming is performed digitally.

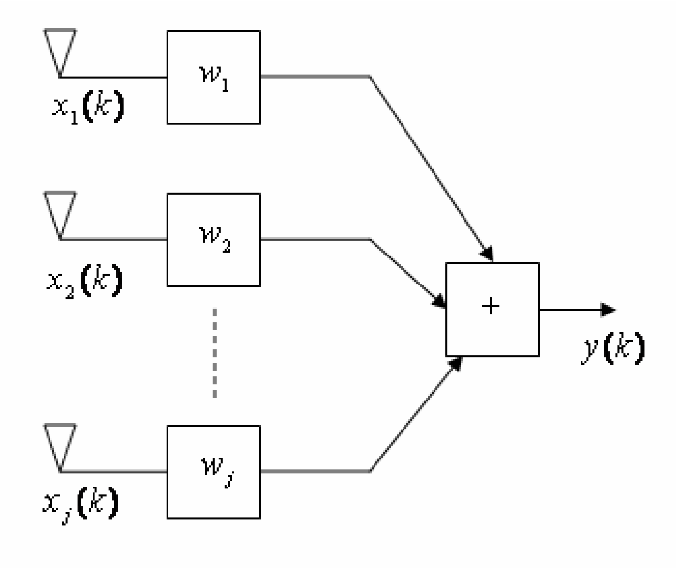

Figure 22. Beamforming for processing narrowband signals.

Instead, the second beamformer, which samples the propagating wave field in both space and time, is often used when signals of significant frequency extent (broadband) are of interest. The output in this case can be expressed as:

$$y(k) = \sum_{j=1}^{J} \sum_{p=0}^{K-1} w_{j,p}^* x_j(k-p)$$

where $K-1$ is the number of delays in each of the J sensor channels. If the signal at each sensor is viewed as an input, then a beamformer represents a multi-input single output system.

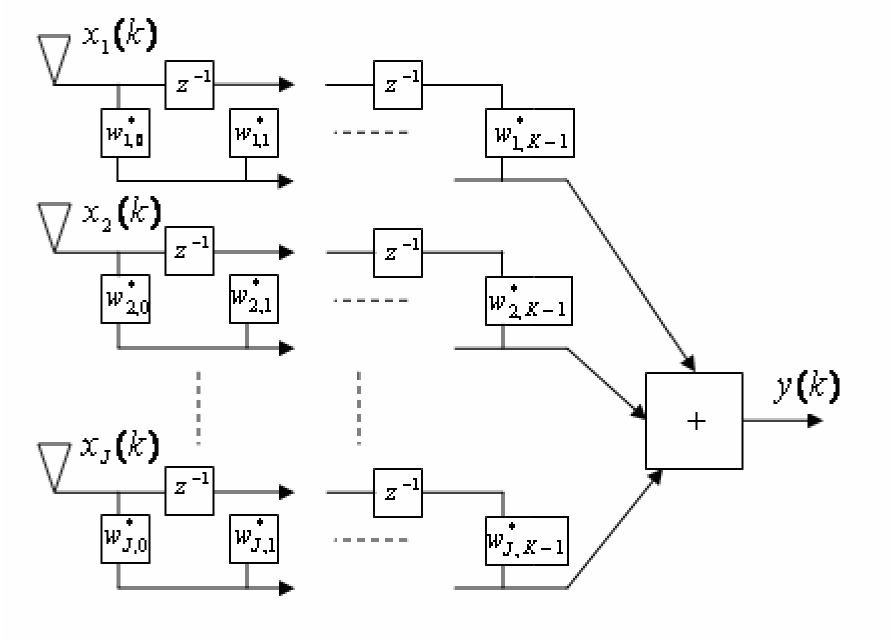

Figure 23. Beamforming for processing broadband signals.

It is convenient to develop notation which permits us to treat both beamformers in Figure 22 and Figure 23 simultaneously, so we can obtain:

$$y(k) = w^H x(k)$$

by appropriately defining a weight vector w and data vector $x(k)$.

Beamforming is sometimes performed in the frequency domain when broadband signals are of interest. Figure 24 illustrates transformation of the data at each sensor into the frequency domain. Weighted combinations of the data at each frequency (bin) are formed. An inverse discrete Fourier transform produces the output time series:

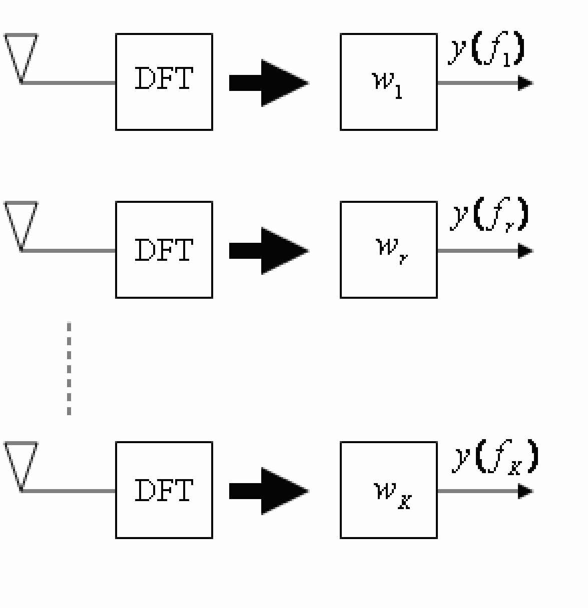

Figure 24. Beamforming performed in the frequency domain for the broadband signals

Beamformer can be classified as either data independent or statistically optimum, depending on how the weights are chosen. The weights in a data independent beamformer do not depend on the array data and are chosen to present a specified response for all signal/interference scenarios. The weights in a statistically optimum beamformer are chosen based on the statistics of the array data to optimize the array response. In the receive BF (uplink case), the main objective is to maximize the Signal Noise Rate (SNR) of the received desired signal. In the transmit BF (downlink case), the objective remains the same, even if the means to obtain it may be different. In fact, is possible to maximize the power in the direction of user, that must receive the signal, and minimize the interference to another users, maximizing the downlink SNR. If the transfer function of the channel is known at the transmitter, the downlink SNR can be maximized by multiplying the desired signal with a set of weights [13]. It can be shown that the weights are a scale version of the uplink weights, that we saw before.

2.4.1 Beamforming-Based SDMA

Without beamforming (BF), the transmitted energy from Home NodeB (HNB) reaches the User Equipment (UE) via just a subsection of the solid angle in space. All energy transmitted in other directions is lost for the UE and also it can create harmful interference to other terminals. Instead, by using BF, we can concentrate the transmitted energy in relevant area or equivalently to receive energy from preferred directions [14]. The associated gain is called beamforming or array gain and results in an increase of the Signal Noise Ratio (SNR) of the corresponding link or equivalently in a shift of the Bit Error Rate on SNR ($BER(E_b/N_0)$) curve. Right from these initial considerations it is evident that BF is a means to efficiently improve the interference that it is created in condition of Flexible Spectrum Usage (FSU) in a multi-user case. BF enables spatial selectivity by allocation different antenna weights to different users, thus allowing for Space Division Multiple Access (SDMA) and achieving interference rejection as well as enhanced by flexibility and adaptivity of the beams, as showed in Figure 25.

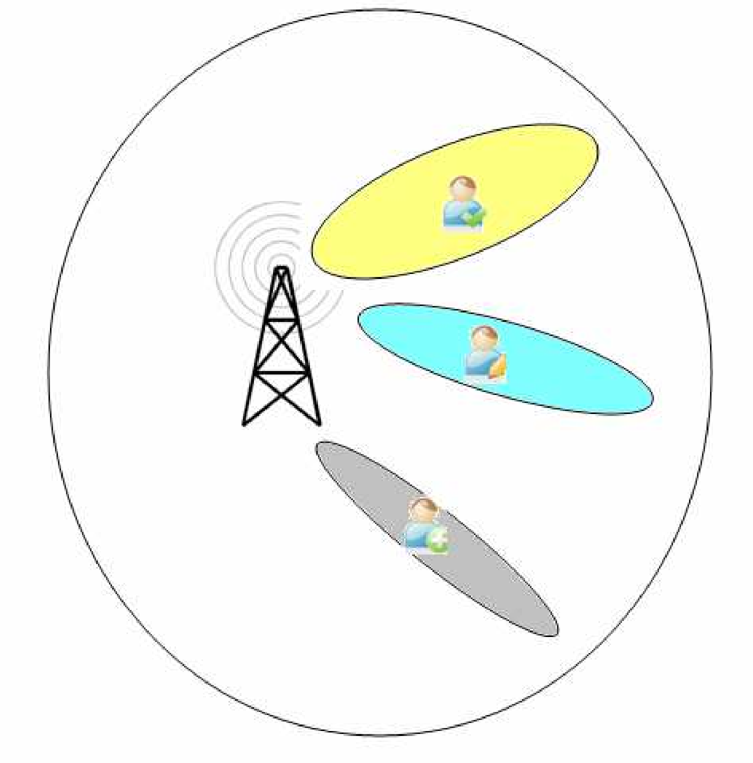

Figure 25. Adaptive beamforming for SDMA

SDMA is an advanced transmission technique, where multi- user (MU) are signalled on the same time and same frequency resource; it is used to enhance the spectral efficiency. So, a large number of User Equipments (UEs) share the whole spectrum. In this scheme HNB prepares a number of directional beams to cover the UEs area. BF concentrates transmit power to a desired direction and reduces power emissions to undesired directions; this way BF eliminate Multi-User Interference (MUI) caused by all others UEs. Another advantages of beamforming techniques are low cost of the UE, high directivity.

2.5 MIMO System

Multiple Input Multiple Output (MIMO) system uses multiple antennas at both the transmitter and receiver to improve communication performance [15], [16]. The research in this field has started approximately 15 years ago about, but it rapidly progressed, attracting attention in wireless communication, because it allows to increase throughput and link range without additional bandwidth or transmit power, in add it is immune to fading, interference and noise.

MIMO to achieve high spectral efficiency and a very wide spectrum allocation in the range of 100 MHz. In MIMO communications systems, multiple antenna are used at both sides of the link. Figure 26 shows the different kinds of MIMO configurations [17]. Where:

- **SISO**: *Single Input Single Output*, one antenna at the transmitter and one at the receiver;
- **SIMO**: *Single Input Multiple Output*, one antenna at the transmitter and many at the receiver;
- **MISO**: *Multiple Input Single Output*, many antenna at the transmitter and one at the receiver;
- **MIMO**: *Multiple Input Multiple Output*, many antenna at the transmitter and many at the receiver.

In a digital communication system, the fundamental performance parameters are the Bit Error Rate (BER) and the number of bits that we are able to send through the channel, per units of time and frequency (Throughput, measured in bit/s/Hz), guaranteeing an arbitrarily low error probability. With SISO, SIMO and MISO to obtain the same advantages, it is necessary to use more power and more bandwidth compared to the MIMO case. MIMO introduces two main gains:

- *Multiplexing gain*: different signals sent through different parallel channels, leading to the information transmission rate increase;
- *Diversity gain*: the same signals sent through different parallel channels, leading to the BER improvement.

MIMO is more complicated than others systems (SISO, SIMO e MISO), in fact it must treat in different manner users with unequal channel conditions. Multiple users cannot cooperate as easily as multiple antennas put on a single device.

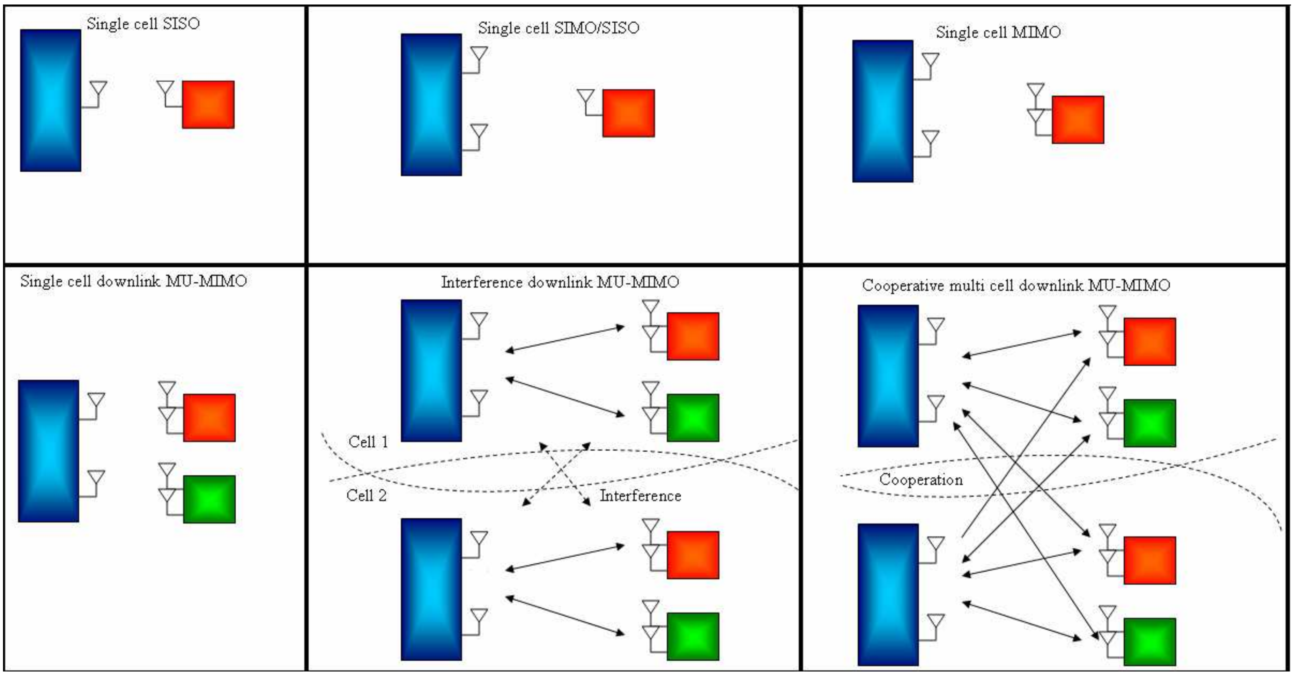

Figure 26. MIMO configuration

The MIMO scheme can be implemented with another scheme to improve the performance. In Long Term Evolution (LTE) is possible to combine the high capacity achievable with MIMO processing with the benefits of the SDMA. SDMA is an advanced transmission technique, where MU are signalled on the same time and same frequency resource; it is used to enhance the spectral efficiency. So, a large number of UEs share the whole spectrum. In this scheme, in the downlink scenario, the transmitter an HNB, equipped with multiple antennas, prepares a number of directional beams to cover the UEs area, each of these UE is also equipped with multiple antenna. BF concentrates transmit power to a desired direction and reduces power emissions to undesired directions; in this way BF eliminate MUI caused by all others UEs. In this context, MIMO downlink system, with MTx transmit antennas and MRx receive antennas, is composed from MIMO channel given by the $MRx \times MTx$ matrix H [26]:

$$H = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,MTx} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,MTx} \\ \vdots & \vdots & \ddots & \vdots \\ h_{MRx,1} & h_{MRx,2} & \cdots & h_{MRx,MTx} \end{bmatrix}$$

where $h_{i,j}$ is the channel impulse response between the $j-th$ ($j = 1,2,...,MTx$) transmit antenna and the $i-th$ ($i = 1,2,...,MRx$) receive antenna.

Chapter 3

3. Project description

This project considers a beamforming and power control algorithm for MU downlink MIMO-OFDM systems, in a LA scenario, with LTE[1] [24], [25]. advanced systems in the FSU context [28], [29].

In this way, considering one cell and one Home Node B (HNB), one or more different users can coexist on the same frequency-time domain. This is possible considering as multiple access scheme the OFDM with SDMA [9] – [11]. In this scheme HNB prepares a number of directional beams to cover the UEs area. Since Beamforming (BF), [13], [14], concentrates transmit power to a desired direction and reduces power emissions to undesired directions; in this way, BF eliminate MUI caused of all others UEs. HNB needs the knowledge of the CSI to implement downlink BF algorithm [19] – [21]. CSI are obtained by a TDD system [18], [26]. Figure 27 shows the representation of the analyzed scenario.

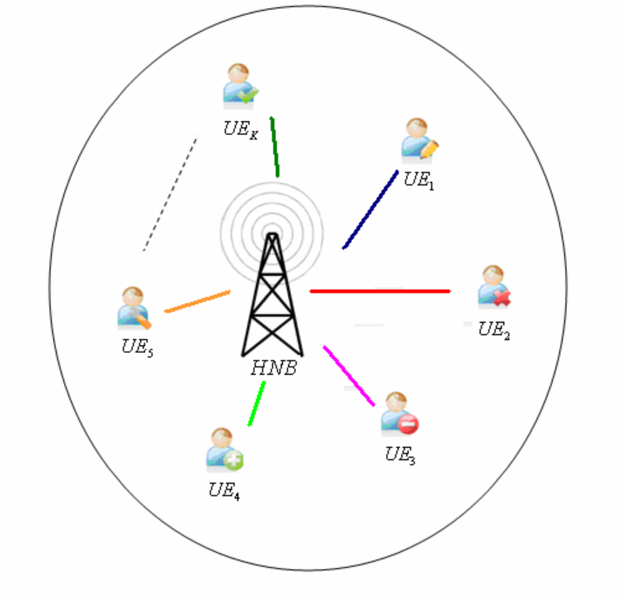

Figure 27. Scenario representation

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[1] LTE context is described in Appendix B

3.1 Scenario

The scenario considers a frequency selective MIMO channel (TU06, Typical Urban [23])[2] where MTx transmit antennas are located at the HNB. K users UE_k, $k=1,...,K$, each equipped with MRx_k receive antennas, are within of the same cell. They request a service from the HNB. So, we have this configuration: $MTx \times MRx$ for the downlink transmission, where $MRx = \sum_{k=1}^{K} MRx_k$.

The MIMO channel for user k is denoted as $H_k \in C^{MRx_k xMTx}$, and the combined channel matrix is given by:

$$H = [H_1^T \quad H_2^T \quad ... \quad H_K^T]^T .$$

The complex baseband received signal by the $k-th$ user is an MRx_k -dimensional vector:

$$y_k = H_k x_k + \sum_{\substack{j=1 \\ j \neq k}}^{K} I_j + n_k, \quad k = 1,...,K$$

where x_k is the signal transmitted, n_k is the complex additive white Gaussian noise (AWGN) at the $k-th$ user and I_j is the interference from all other users.

In FSU context, the users share the same frequency-time resource, generating interference among the users. So, to avoid this interference, BF algorithm is investigated to evaluate performance of the system at link-level by averaging BERs and THs of all candidate UEs. Power control algorithm is applied to maximize the SNR at the UE and to minimize the BER. Figure 28 shows the system model with BF, where d_k, $k=1,...,K$, is the data transmit vector of the $k-th$ user, F is the BF block and G_k, $k=1,...,K$, is the decoding block associated with user k.

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[2] The TU06 channel is described in Appendix A

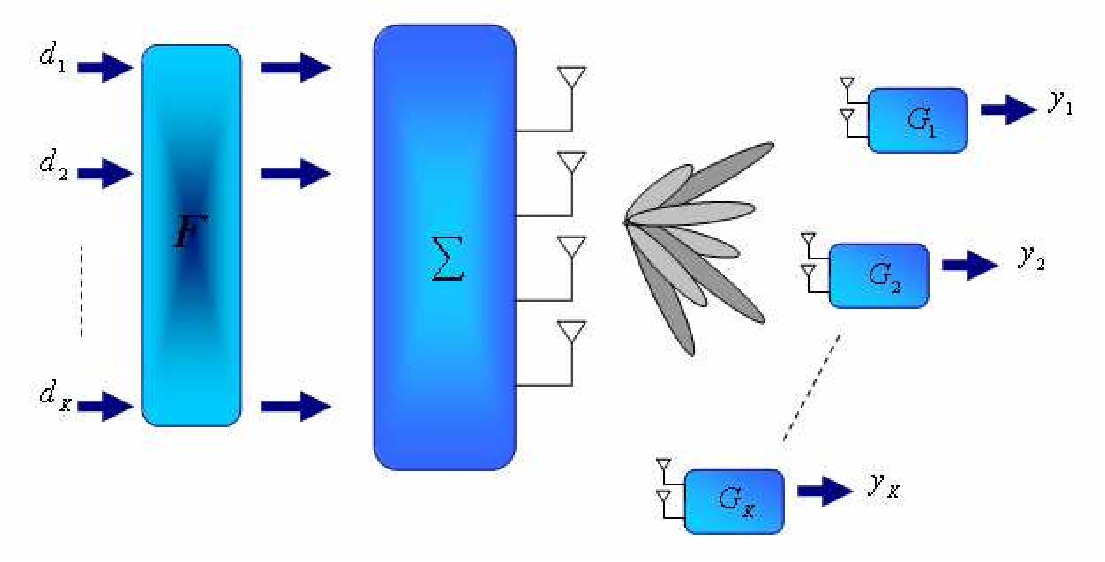


Figure 28. Conceptual diagram of downlink system

3.2 System Architecture for LTE

This section reviews briefly the main physical (PHY) layer and architecture specifications of LTE Release 8 based on the current 3GPP documents [30] - [33]. The overview given below address Time Division Duplexing (TDD) mode and focuses on the PHY layer aspects. Downlink and uplink transmission are organized into frame with $10\ ms$ duration [32]. In the TDD structure, each radio frame consist of $20\ slots$ of length $T_{slot} = 5\ ms$ each, numbered from 0 to 19, as showed in Figure 29.

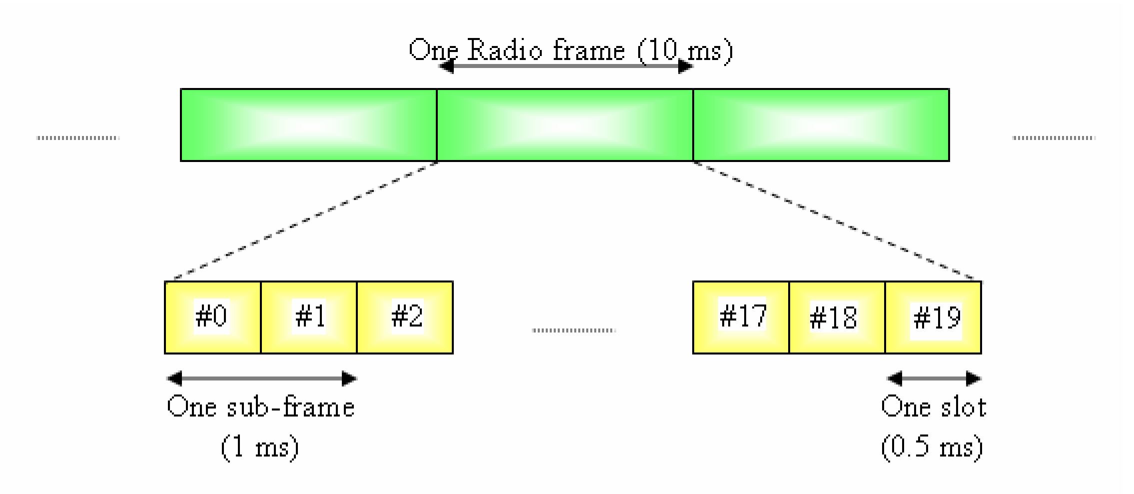
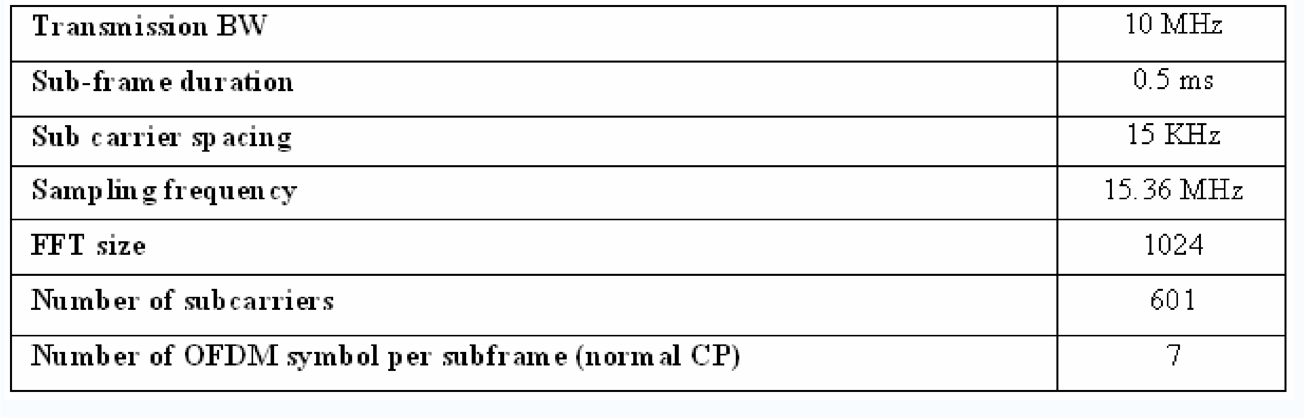


Figure 29. TDD frame structure in LTE for OFDM with 1o ms radio frame duration

The downlink transmission scheme is based on conventional OFDM using a cyclic prefix. The OFDM subcarrier spacing is $\Delta f = 15KHz$ (normal cyclic prefix). The transmitted signal in each slot is described by a resource grid showed in Figure 12 in section 2.3, with $n = 601$ subcarriers and $M = 7$ OFDM symbols.

The basic transmission parameters are specified in Table 1.



Transmission BW	10 MHz
Sub-frame duration	0.5 ms
Sub carrier spacing	15 KHz
Sampling frequency	15.36 MHz
FFT size	1024
Number of subcarriers	601
Number of OFDM symbol per subframe (normal CP)	7

Table 1. Parameters for downlink transmission scheme

3.2.1 Transmitter architecture

In base to the parameters indicted above, the data transmit vector $k-th$ user denoted by:

$$d_k = [d_{k,1}^T, d_{k,2}^T, ..., d_{k,n}^T] \in C^n .$$

where n is the number of the subcarriers indicated above.

Figure 30 shows the transmit block diagram considered in this thesis. Next, d_k is multiplied by a beamforming matrix F and generates the symbols:

$$x_k = F \cdot d_k .$$

It considers as multiple access scheme the Orthogonal Frequency Division Multiplexing (OFDM) with Space Division Multiple Access (SDMA) [6] - [11]. SDMA is an advanced transmission technique, where MU are signalled on the same time and same frequency resource; it is used to enhance the spectral efficiency. So, a large number of users share the whole spectrum, but spatially separated [14]. The use of the SDMA increases the spectral efficiency of a multi-antennas system (antenna array). Specifically, in SDMA the channel is seen as parallel spatial lines through which independent data stream can be transmitted to different users. BF matrix is investigate in section 4.

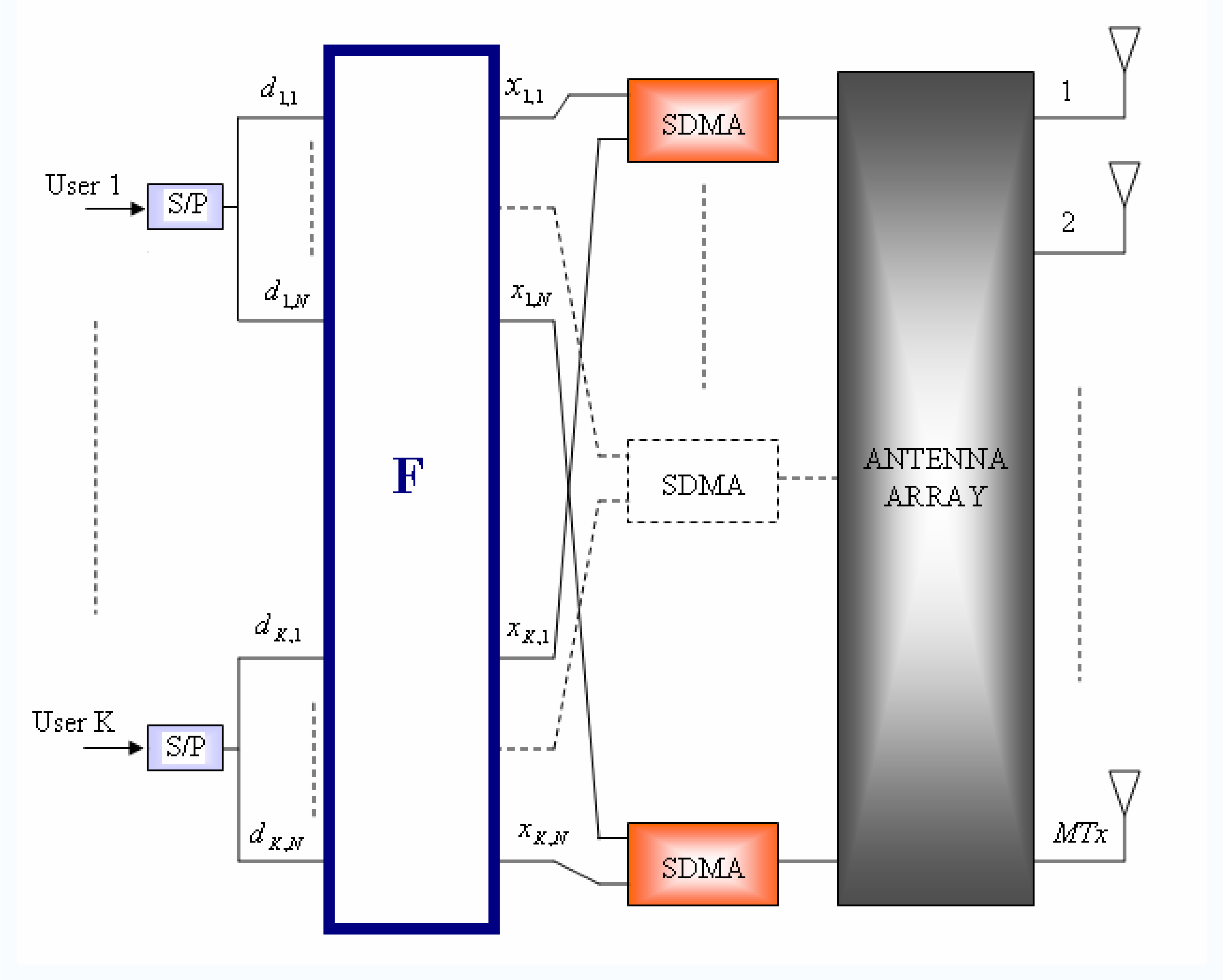


Figure 30. Block diagram of MU case for DL transmission

3.2.2 Channel model

The structure of the MIMO channel $H \in C^{MRx \times MTx}$ [26] depends on the number of transmit and receive antennas and the combined channel matrix is given by:

$$H = [H_1^T \quad H_2^T \quad \ldots \quad H_K^T]^T .$$

where $H_k \in C^{MRx_k \times MTx}$ denoted the matrix channel of the $k-th$ user and is define as:

$$H_k = \begin{bmatrix} h_k^{(1,1)} & \cdots & h_k^{(1,MTx)} \\ \vdots & \ddots & \vdots \\ h_k^{(MRx_k,1)} & \cdots & h_k^{(MRx_k,MTx)} \end{bmatrix}$$

where $h_k^{(i,j)}$ represents the channel coefficient from the $j-th$ transmit antenna at the HNB to the $i-th$ receiver antenna at $k-th$ user.

We assume that the channel transfer matrix H is perfectly know to the HNB, through reverse channel estimation in TDD. In fact, in TDD system, using the reciprocity principle[3] it is possible to use the estimated uplink channel for downlink transmission. In a TDD system, the uplink and downlink transmissions share the same frequency but are using different time slots. If the delay between these two slots is short compared to the coherence time of the channel, the spatial signature of the downlink and uplink will be the same. This means that the instantaneous uplink channel can be used as a good estimate of the downlink channel. But, if the delay between the two slots is longer than the coherence time, this method cannot be used.

So, perfect CSI is assumed at the HNB. It is also assumed that H_k is perfectly known at the $k-th$ user , but other users' channels are not known by $k-th$ user.

---

[3] The reciprocity principle is described in TDD system in Appendix C.

3.2.3 Receive architecture

At the receiver [18], the received signal vector at the $k-th$ user, with $k=1,...,K$ is defined as:

$$y_k = H_k \cdot x_k + n_k = H_k \cdot F \cdot d_k + n_k$$

where H_k is the channel matrix of the $k-th$ user , F is the beamforming matrix, d_k is the transmitted data signal vector at the $k-th$ user and n_k is the AWGN vector at the $k-th$ user. The $k-th$ receiver knows à priori the beamforming matrix F and treats the combination $H_k F$ as an effective channel. It detects and decodes the received signal to obtain an estimate of the transmitted data signal vector d_k. Considering decoding matrix G_k and the received signal at $k-th$ will be:

$$G_k \cdot y_k = G_k \cdot H_k \cdot F \cdot \sum_{k=1}^{K} d_k + n_k$$

Figure 31 represents the block diagram of a linear transmission model for multi-user MIMO beamforming:

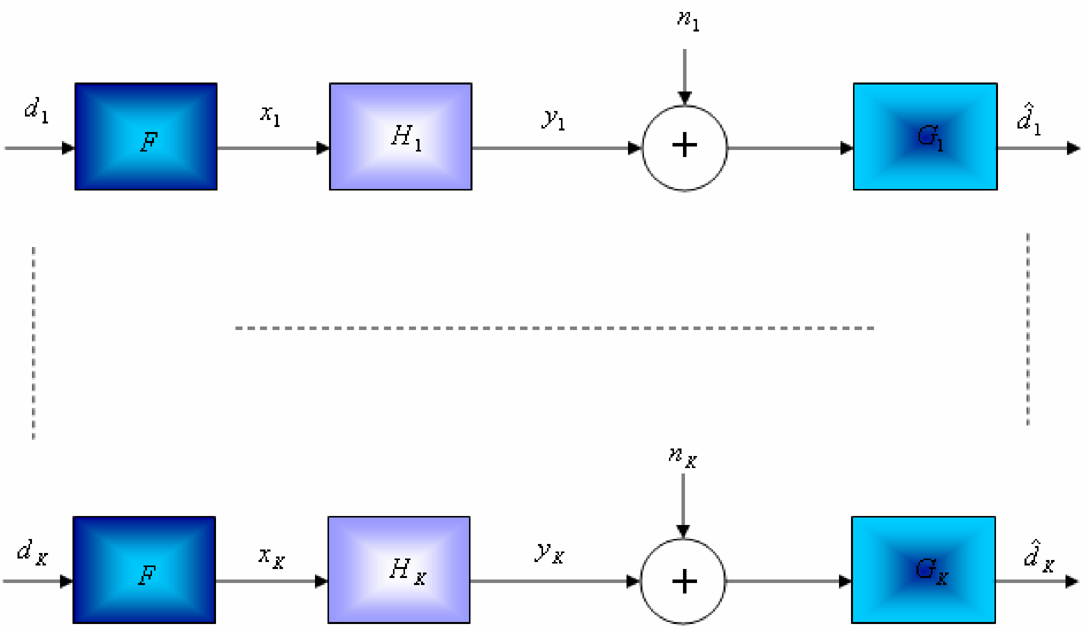


Figure 31. Block diagram for linear transmission model for multi-user MIMO beamforming

The receiver can use one out of several detection methods, depending on the performance and complexity requirements. In this thesis, we use the linear MMSE, where G_k is designed according to [18]:

$$\min_{G_k} E\left\|\hat{d} - d\right\|_F^2 = E\left\|\left(G_k H_k F - I\right)d + G_k n_k\right\|_F^2$$

And the optimum MMSE receiver for the $k-th$ user is given as:

$$G_k = \left(\sigma_{n_k}^2 I + F^H H_k{}^H H_k F\right)^{-1} F^H H_k{}^H$$

where $\sigma_{n_k}^2$ is the noise power of the $k-th$ user.

Chapter 4

4. Beamforming methods

Beamforming techniques can be classified according to the amount of the MUI that is suppressed at the transmitter and according to linearity. The linear beamforming matrix F can be modelled in sub-matrices, each submatricex corresponding to one user:

$$F = \left[F_1 \quad F_2 \quad \dots \quad F_K \right]$$

where $F_k \in C^{MTx \times n}$ is the sub-matrix corresponds to $k-th$ user, MTx is the number of transmitted antenna and n is the number of subcarriers.

The beamforming matrix is a function of the CSIT. When we have perfect CSIT, the MIMO channel can be decomposed into independent and parallel additive white noise channels, so the elements of H_k are complex Gaussian variables with zero-mean and unit-variance. These parallel channels are defined by performing the *Singular Value Decomposition* (*SVD*) of the channel matrix as:

$$H = U_H \Sigma_H V_H{}^H .$$

where the lower H means the matrix is referred to the channel and the upper one indicates the hermitian operator. The channel matrix H is a complex matrix of dimension $MRx \times MTx$, so U_H is an $MRx \times MRx$ square unitary matrix, that is, $U_H{}^H U_H = U_H U_H{}^H = I$; Σ_H is $MRx \times MTx$ matrix with nonnegative real numbers on the diagonal and zeros off the diagonal; and $V_H{}^H$ denotes the hermitian of V_H and it is an $MTx \times MTx$ square unitary square matrix, i.e. $V_H{}^H V_H = V_H V_H{}^H = I$.

The parallel channels can be processed independently, each with independent modulation and coding.

Also the beamforming matrix can be decompose by SVD:

$$F = U_F \Sigma_F V_F{}^H$$

where the left singular vectors U_F represent the orthogonal beam direction; the squared singular matrix Σ_F^2 are associated with the beam power loading; and the right singular vectors V_F form the input shaping matrix.

The optimal beam directions with perfect CSIT for all methods, can be obtained by:

$$U_F = V_H$$

According to the receive model treated above, the optimal beam directions are given by the eigenvectors of $H^H H$.

In this thesis are treated two different methods to calculate the beamforming matrix: ***Zero -Forcing (Z-F) Beamforming*** and ***Successive Minimum Mean Square Error (SMMSE) Beamforming***.

4.1 Zero-Forcing (ZF)

Zero-Forcing (ZF) [14], [19], [20] is a generalization of channel inversion when we have multiple antennas per user. ZF BF algorithm is discussed in details in [19]. The fundamental idea is to select the BF matrix F_j at the $j-th$ receive antenna, with $j=1,...,MRx$.

The signal at $j-th$ receive antenna, $j=1,...,MRx$, can be rewritten as:

$$y_j = \sum_{i=1}^{K} H_j F_i d_i + n_j = H_j F_i d_i + H_j \tilde{F}_j \tilde{d}_j + n_j$$

where, with $k=1,...K$ users:

$$\tilde{F}_j = \begin{bmatrix} F_1 & \ldots & F_{j-1} & F_{j+1} & \ldots & F_K \end{bmatrix}$$
$$\tilde{d}_j^T = \begin{bmatrix} d_1^T & \ldots & d_{j-1}^T & d_{j+1}^T & \ldots & d_K^T \end{bmatrix}$$

The optimal solution under the constraint that all MUI be zero (Zero-Forcing) is that HF is block diagonal. So, to eliminate all MUI, we impose the constraint (Zero-Forcing) that:

$$H_j \tilde{F}_j = 0$$

Defining $\tilde{H}_j$ as:

$$\tilde{H}_j = \begin{bmatrix} H_1^T & \ldots & H_{j-1}^T & H_{j+1}^T & \ldots & H_K^T \end{bmatrix}$$

It cans be decomposed using SVD:

$$\tilde{H}_j = \tilde{U}_j \tilde{\Sigma}_j \tilde{V}_j^H = \tilde{U}_j \tilde{\Sigma}_j \begin{bmatrix} \tilde{V}_j^{(1)} & \tilde{V}_j^{(0)} \end{bmatrix}^H$$

where $\tilde{V}_j^{(1)}$ contains the first $\tilde{L}_j$ right singular vectors, and $\tilde{V}_j^{(0)}$ contains the last $\left(NTx - \tilde{L}_j\right)$ right singular vectors, where $\tilde{L}_j = rank(\tilde{H}_j)$.

Defining the matrix:

$$H' = \begin{bmatrix} H_1\tilde{V}_1^{(0)} & 0 & \dots & 0 \\ 0 & H_2\tilde{V}_2^{(0)} & \dots & 0 \\ \dots & \dots & \ddots & \dots \\ 0 & 0 & \dots & H_K\tilde{V}_K^{(0)} \end{bmatrix}$$

The block structure of H' allow us to apply the SVD for each user:

$$H_j\tilde{V}_j^{(0)} = U_j \begin{bmatrix} \Sigma_j & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_j^{(1)} & V_j^{(0)} \end{bmatrix}^H$$

where Σ_j is $\overline{L}_j \times \overline{L}_j$, and $V_j^{(1)}$ represents the first $\overline{L}_j$ singular vectors, where $\overline{L}_j = rank\left(H_j\tilde{V}_j^{(0)}\right)$.

Finally, the beamforming matrix F is given from:

$$F = \begin{bmatrix} \tilde{V}_1^{(0)}V_1^{(1)} & \tilde{V}_2^{(0)}V_2^{(1)} & \dots & \tilde{V}_K^{(0)}V_K^{(1)} \end{bmatrix} \Lambda^{1/2}$$

where Λ is a diagonal matrix whose elements λ_i scale the power transmitted into each of the columns of the F. The product $\tilde{V}_k^{(0)}V_k^{(1)}$ represents the transmission vectors that maximize the information rate for the $k-th$ user subject to the zero MUI constraint, in way, the system is efficiently set to zero.

4.2 Successive Minimum Mean Square Error (SMMSE)

ZF BF suffers from a performance loss when the space among the antennas is close. To avoid the ZF constraint we can use the Successive Minimum Mean Square Error (SMMSE) [14], [20], [21]. SMMSE BF algorithm is discussed in details in [20]. The fundamental idea is that all users are treated sequentially, and for each user, just one receive antenna is considered at a time. Whereas, the others antennas of this user are ignored. In this way, each user is like one user with a single antenna, and so the MMSE method can be applied. The BF matrix F is generated by successively calculating the columns of the BF matrix F_j for each of the receive antennas separately. In particular, the BF matrix F is planned in two steps. In the first step, we balance the MUI suppression; instead, in the second step, we optimize the system performance. Thus, the BF matrix can be decomposed in the product :

$$F = F_a \cdot F_b$$

where:

$$F_a = \begin{bmatrix} F_{a_1} & F_{a_2} & \dots & F_{a_K} \end{bmatrix}$$

performs joint processing of all $k = 1,\dots,K$ users and:

$$F_b = \begin{bmatrix} F_{b_1} & 0 & \dots & 0 \\ 0 & F_{b_2} & \dots & 0 \\ \dots & \dots & \ddots & \dots \\ 0 & 0 & \dots & F_{b_K} \end{bmatrix}$$

processes each user separately.

The matrix F_a is used to suppress the MUI interference first, and then the matrix F_b is used to optimize the system performance assuming parallel SU MIMO channels.

The SMMSE beamforming F_a is derived from the linear transmit MMSE BF optimization [13]. The interference of other co-channel users to signal arriving at $k-th$ user's $j-th$ antenna is suppressed independently from the other antennas at the same terminal. This is done for each antenna at the same user terminal successively. So, the columns in the precoding matrix F_{a_i}, each corresponding to one receive antenna, are calculated successively. Thus, the $j-th$ column of the $k-th$ user's precoding matrix F_{a_i}, corresponding to the $k-th$ user's $j-th$ receive antenna, is equal to the first column of the matrix $F_{a_{i,j}}$ which is obtained from the following equation:

$$F_{a_{k,j}} = \overline{H}_{k,j}^{H}\left(\overline{H}_{k,j}\overline{H}_{k,j}^{H} + \alpha \cdot I_{MTx \times MTx}\right)^{-1}$$

where $j = 1,\ldots,MRx_k$ is the $j-th$ receive antenna of the $k-th$ user, with $k = 1,\ldots,K$. Instead, $\overline{H}_{k,j}$ is defined as:

$$\overline{H}_{k,j} = \begin{bmatrix} h_{k,j}^{T} \\ H_1 \\ \cdots \\ H_{k-1} \\ H_{k+1} \\ \cdots \\ H_K \end{bmatrix} \in C^{(MRx - MRx_k + 1)\ \times\ MTx}$$

where $h_{k,j}^{T}$ is the $j-th$ row of the $k-th$ user's channel matrix H_k.The first column of $F_{a_{k,j}}$ is then used as $j-th$ column of F_{a_k}. After all columns of F_a have been determined in this way. The parameter α is chosen in accord with the transmit power and it is defined as:

$$\alpha = \frac{tr(\overline{R}_{nn,k,j})}{P_{tr}}$$

where P_{tr} is the average power of the transmit vector $x = F \cdot d$, that is:

$$E\left\{\|x\|^2\right\} = tr(F^H F) = P_{tr}\,.$$

Instead, $\overline{R}_{nn,k,j}$ define the corresponding receive noise covariance matrix. It is a diagonal matrix, having the noise power of the $k-th$ user at $j-th$ receive antenna as element of the diagonal.

After calculating the BF vectors for all receive antennas in this way, the equivalent combined matrix of all users is equal to $HF_a \in C^{MRx\ \times\ MRx}$ after the BF. For high SNR, this matrix is also block diagonal, so we can decompose this matrix by SVD for each user. In fact, $H_k F_{a,k}$ represents the resulting single-user MIMO channel of the $k-th$ user:

$$H_k F_{a,k} = U_k \Sigma_k V_k^H = U_k \Sigma_k [V_k^{(1)} \quad V_k^{(0)}]^H$$

So, we obtain that $F_{b,k}$ is the right column vectors of V_k :

$$F_{b,k} = V_k^{(0)}$$

and then:

$$F_b = \begin{bmatrix} F_{b_1} & 0 & ... & 0 \\ 0 & F_{b_2} & ... & 0 \\ ... & ... & \ddots & ... \\ 0 & 0 & ... & F_{b_K} \end{bmatrix}$$

Finally, the beamforming matrix F is given from:

$$F = F_a \cdot F_b \cdot \Lambda$$

where Λ is a diagonal power loading matrix, analogous to the one for ZF method.

4.3 Dominant Eigenmode Transmission (DET) Power Control

In former two sections, we introduce the methods to calculate the beamforming matrix. Note that both methods need power matrix. The optimal power allocation is a function of the SNR. *Dominant Eigenmode Transmission* (*DET*) power control (PC) algorithm [20], [34], extracts the maximum diversity and array gain, transmitting just on the dominant eigenmode of each user can provide maximum SNR at the receiver and minimum BER performance.

As it is seen above, the channel matrix with the BF matrix can be decomposed by SVD:

$$HF = U\Sigma V^{H}$$

where Σ represents the eigenmodes of all users, with $k = 1,\ldots,K$ ::

$$\Sigma = diag(\Sigma_1,\ldots,\Sigma_K)$$

The power adaptation matrix is calculated and quantized for each diagonal element. So, the power matrix Λ is a diagonal matrix:

$$\Lambda = \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \lambda_K \end{bmatrix}$$

where λ_k is the power allocated to the eigenmode of the $k-th$ user.

A global power constraint is imposed on Λ such that:

$$tr(\Lambda) = P_T$$

where P_T is the total transmit power for the data transmit symbols.

DET algorithm is to applied to both BF algorithm, to maximize the SNR at the receiver and to minimize the BER.

Chapter 5

5. Simulation Results

This chapter will present MATLAB simulation results for the BF algorithms that were treated in the previous chapter. In this section we evaluate the performance of a system employing the BF technique. At the starting point, assuming perfect channel state information at the transmitter (CSIT), SU-MIMO downlink BF is implemented to evaluate the link performance of the system, we quantify the gap between a system with BF and a system without BF, just for one user. Moremore, two MU-MIMO downlink BF algorithm ZF and SMMSE are investigated to evaluate and to compare the performance of the system at the link-level by averaging the BERs and THs of all candidate users. Finally, DET power control algorithm is to applied to both to maximize the SNR at the receiver and to minimize the BER. As a case study, a link-level simulator complying UTRAN-LTE standard is considered.

5.1 Parameters of the Simulation

The parameter of the simulation are shown in Table 1 in section 3.2. Considering one cell and one Home Node B (HNB), equipped by $MTx = 2$ transmit antennas that transmits, through a frequency selective MIMO channel (*TU06*), to one or two different users, UE_1 and UE_2 each equipped with $MRx_k = 2$, $k = 1{,}2$, receive antennas, that coexist on the same frequency-time domain. We analyze the link performance of the system, in particular we will compare *coded BER* performance, *uncoded BER* performance and the *throughput*. The BER curves and the throughput are plotted versus the receive SNR

The receive SNR parameter for the $k-th$ user is define as:

$$SNR_k = 10\log_{10}\left(\frac{|FH_k|P_{T_k}}{\sigma_{n_k}^2 \|G_k\|_F^2}\right) \quad [dB]$$

where F is the BF matrix, H_k is the matrix channel, P_{T_k} is the transmitted power, $\sigma_{n_k}^2$ is the noise power and G_k is the decoding matrix, refer to the $k-th$ user.

Instead, the throughput TH referred to each user, is define as:

$$TH = \frac{Total \quad received \quad bits \quad without \quad error}{T_S \times N_{subframe} \times BW} = TH_{\max}(1 - PER) \quad \left[\frac{b}{s \cdot Hz}\right]$$

where $N_{subframe}$ is the number of transmitted subframe; whereas, the maximum throughput parameter $Th_{\max}$ is defined as the amount of total bits that are successfully received in the unit time (*time slot*):

$$Th_{\max} = \frac{ModOrd \times ECR \times N_{OFDM/subframe} \times N_{Subcarriers}}{BW \times T_S} \quad \left[\frac{b}{s \cdot Hz}\right]$$

where $ModOrd$ is the *Modulation Order*; ECR is the *Effective Coding Rate*; $N_{OFDM/frame}$ is the number of *OFDM symbols* used for data transmission in each *subframe*; $N_{Subcarriers}$ is the number of subcarriers in each OFDM symbol; BW is the *bandwidth* and T_S is the duration of the *time slot*.

5.2 Beamforming for Single User

Here, we analyze the performance obtained with and without the beamforming technique for single user; in particular we compare coded BER performance, uncoded BER performance and the throughput either without BF or with BF. First simulations are conducted using a QPSK modulation and an Effective Code Rates equal to $1/3$ ($ECR = 1/3$). Then, the modulation used is a 16-QAM. Every curve is plotted versus the SNR.

In the figures, we can observe that in presence of BF, the performance are improved.

We can observe from the uncoded BER (Figure 32) in presence of BF, one achieves array gain of about 3 dB, for a value of the BER of 10^{-3}. Changing modulation, with a 16-QAM, we can observe further enhancement in presence of BF (Figure 35). One achieves array gain of about 5 dB of a BER of 10^{-2}.

Instead, from coded BER (Figure 33) in presence of beamforming, one achieves array gain of 4 dB, for a value of the BER of 10^{-3}. Changing modulation, with a 16-QAM, we can observe further enhancement in presence of BF (Figure 36). One achieves array gain of about 5 dB of a BER of 10^{-4}.

The throughput (Figure 34) is better with BF than without BF. We can observe that with BF one goes to maximum throughput faster than without BF. So, when the interference dominates the signal, the beamforming improves the performance and the percentage of erroneous packets is very low and already at $SNR = 5dB$ we have almost the maximum throughput. Changing modulation, with a 16-QAM, we can observe further enhancement in presence of BF (Figure 37) and to value of SNR between $15dB$ and $20dB$ we have almost the maximum throughput.

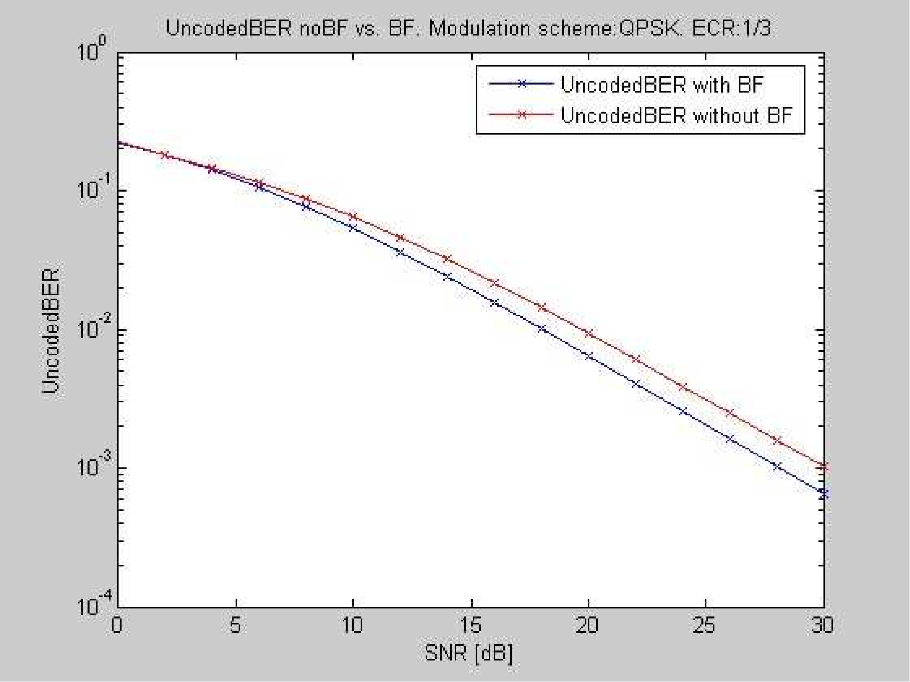


Figure 32. UncodedBER Beamforming vs. no Beamforming with QPSK modulation

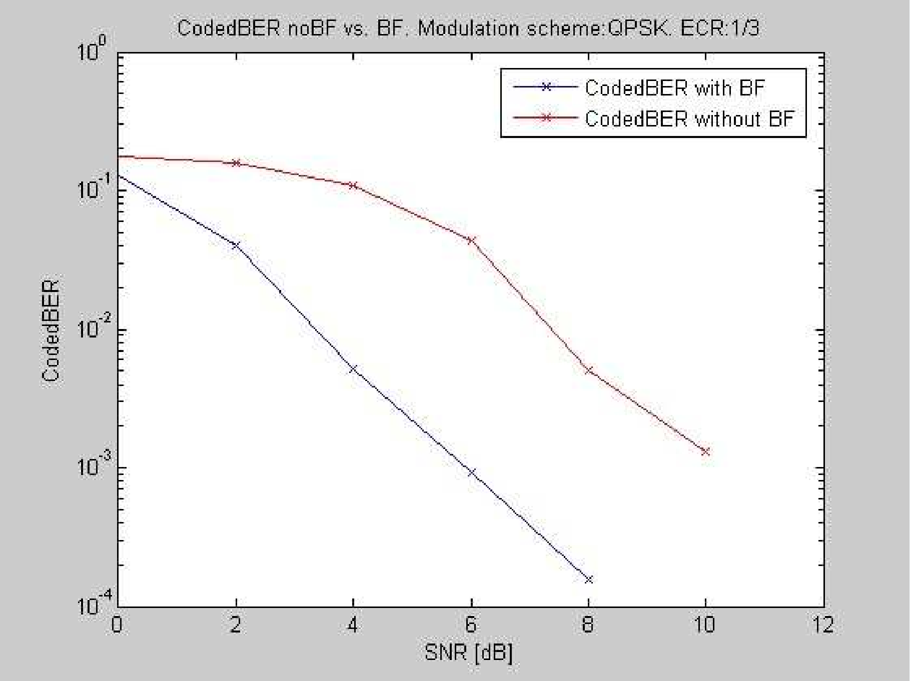


Figure 33. CodedBER Beamforming vs. no Beamforming with QPSK modulation

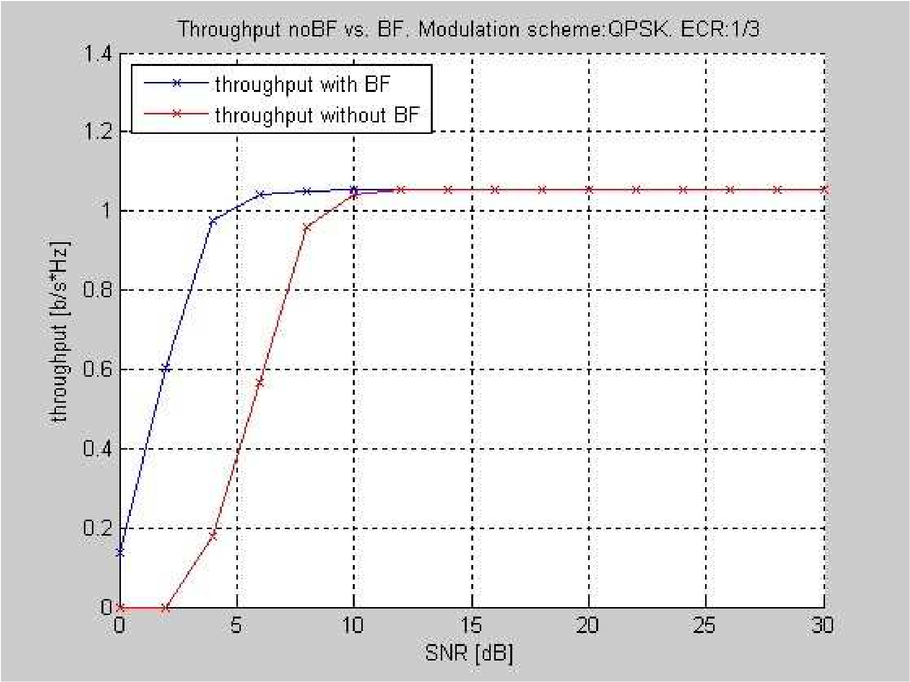


Figure 34. Throughput Beamforming vs. no Beamforming with QPSK modulation

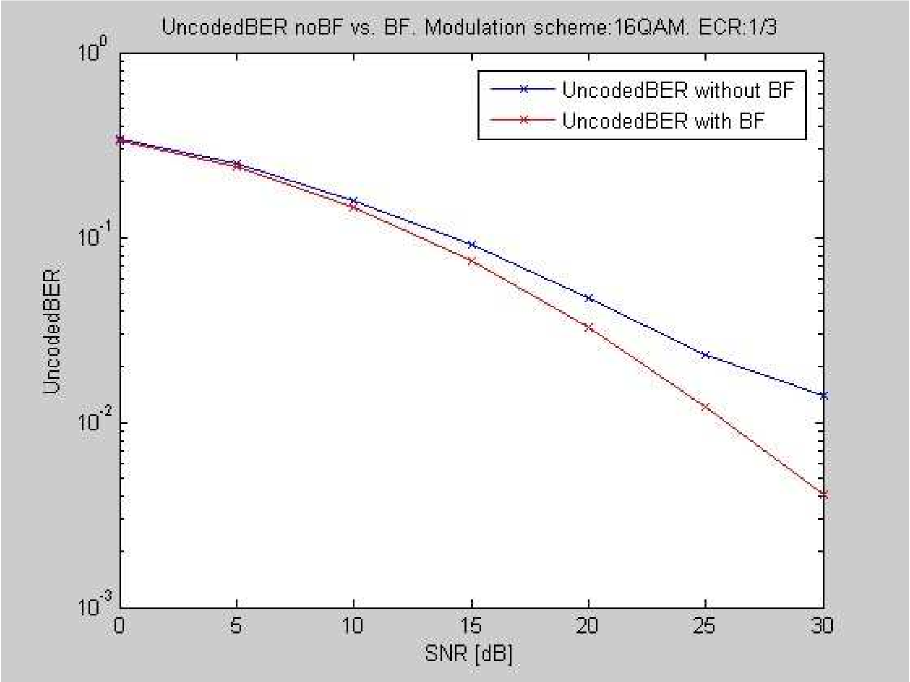


Figure 35. UncodedBER Beamforming vs. no Beamforming with 16-QAM modulation

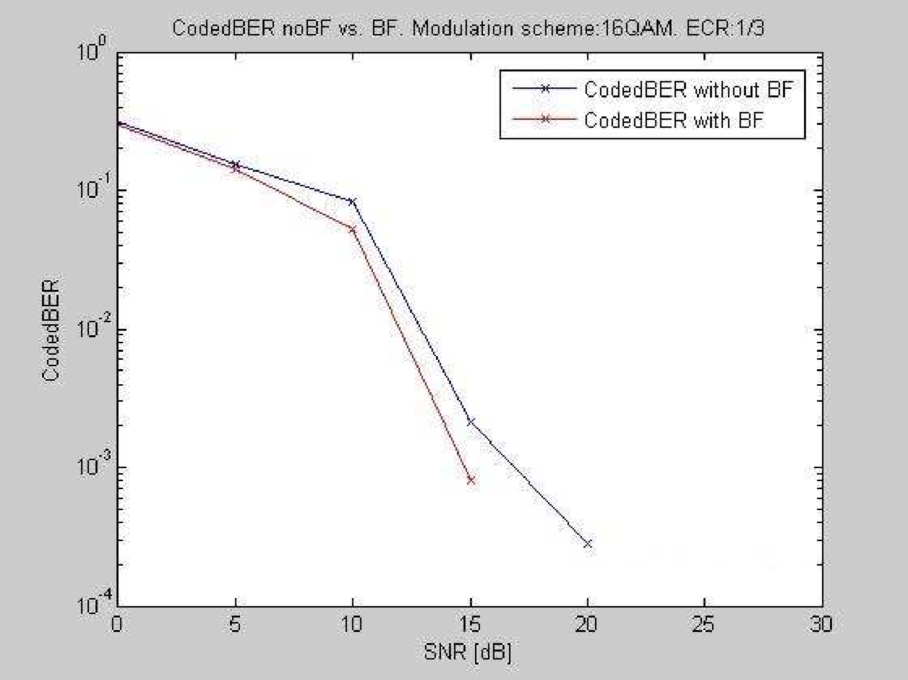


Figure 36. CodedBER Beamforming vs. no Beamforming with 16-QAM modulation

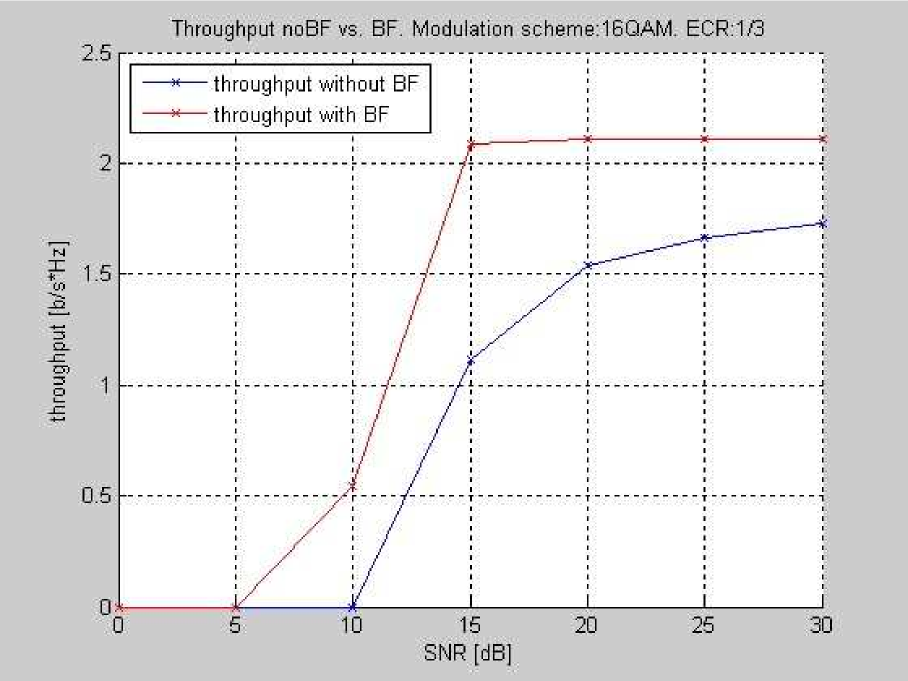


Figura 37.Throughput Beamforming vs. no Beamforming with 16-QAM modulation

5.3 Beamforming for Multi-User

In this section we analyze the performance obtained with the beamforming technique in Multi-User case using the two methods, ***ZF*** and ***SMMSE***, described in the section 4.1 and 4.2. In particular we compare the coded BER performance, uncoded BER performance and the throughput between ZF-BF and SMMSE-BF. The simulations are conducted using a QPSK modulation and an Effective Code Rates equal to $2/3$ ($ECR = 2/3$). Every curve is plotted versus the SNR.

In the figures, we can observe that with SMMSE method, the performance are improved.

We can observe from the uncoded BER (Figure 38) that SMMSE for a value of the BER of 10^{-4} provides a array gain of about 3 dB over ZF.

Instead, from coded BER (Figure 39) we can observe that SMMSE, for a value of the BER of 10^{-2}, provides a array gain of about 3 dB over ZF. We can also observe that SMMSE provides a diversity gain of about 0.5 dB over ZF.

The throughput (Figure 40) is higher with SMMSE than with ZF. We can observe that with SMMSE one goes to maximum throughout faster than ZF. So, when the interference dominates the signal, the SMMSE beamforming improves the performance and the percentage of erroneous packets is very low and already at $SNR = 6dB$ about we have almost the maximum throughput, whereas, in ZF, we have the maximum throughput later, at $SNR = 9dB$.

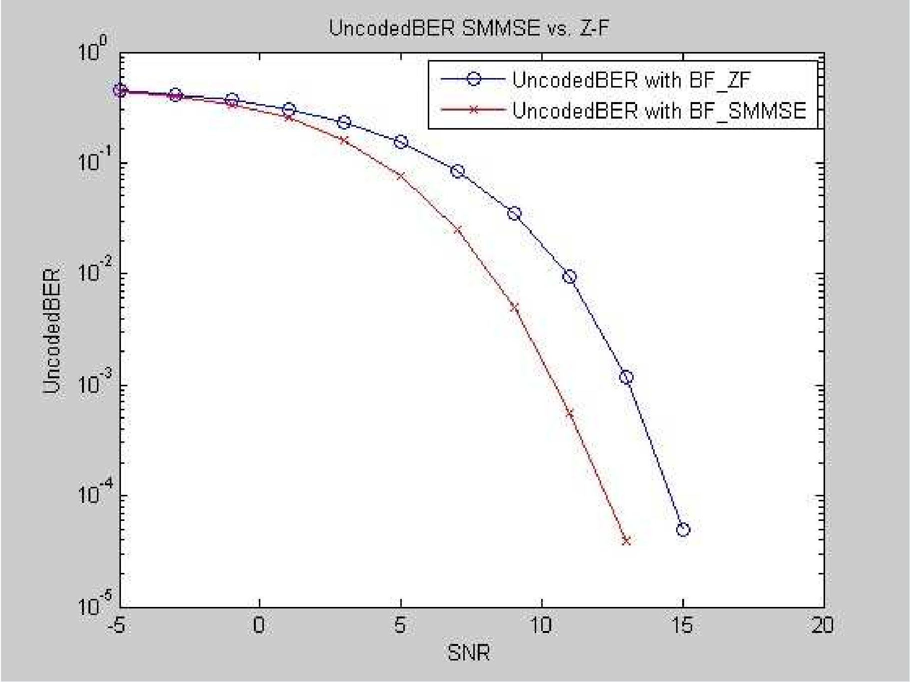


Figure 38. UncodedBER ZF vs SMMSE

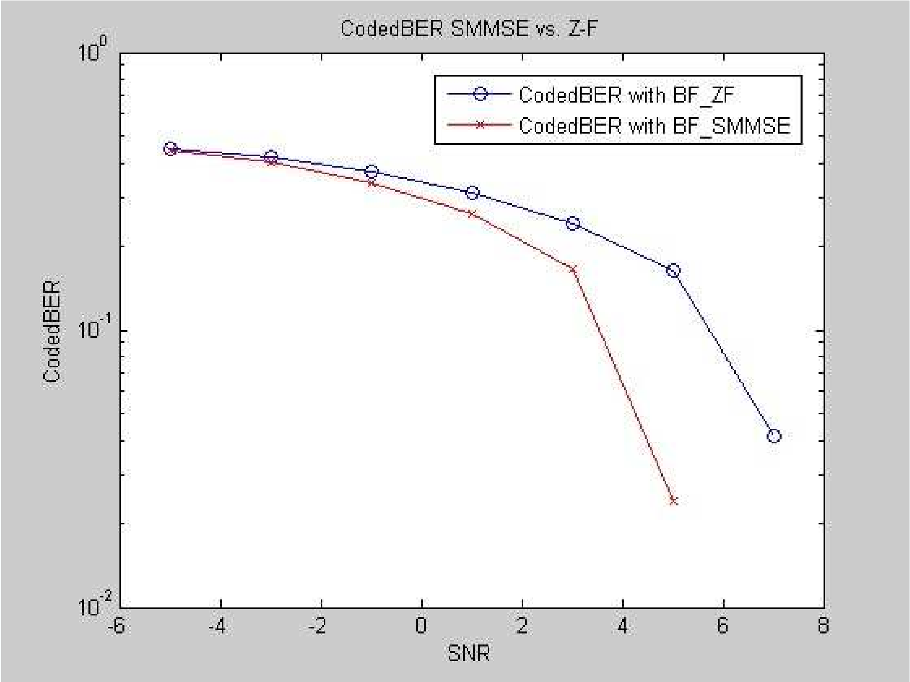


Figure 39. CodedBER ZF vs SMMSE

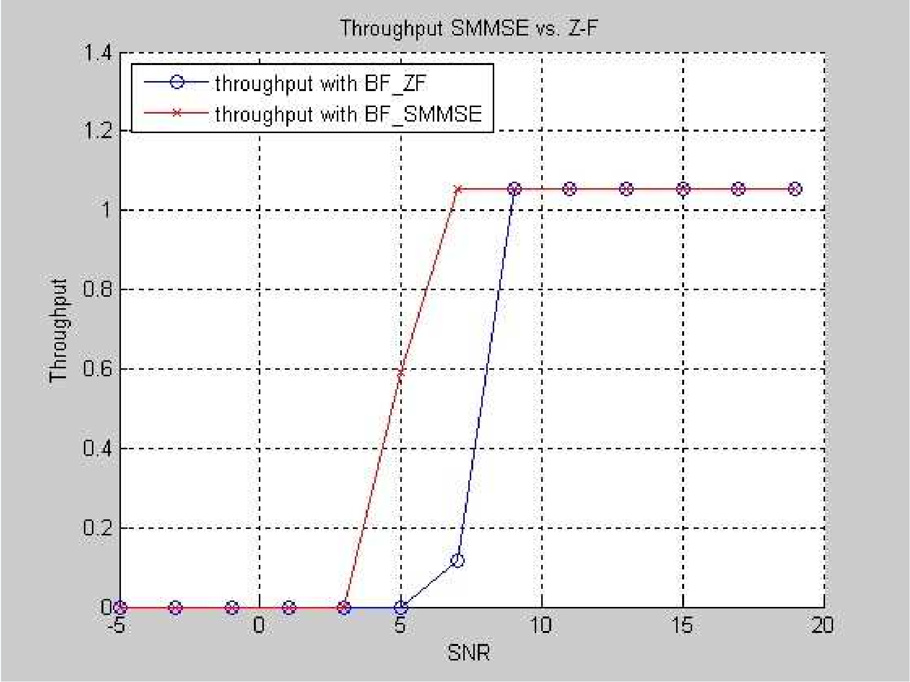


Figure 40. Throughput ZF vs SMMSE

5.4 Beamforming for Multi-User with Power Control

In this section we analyze the performance obtained with the beamforming technique in Multi-User case using the two methods, SMMSE, described in the section 4.1 and 4.2. In addition, we apply Dominant Eigenmode Transmission (DET). In particular we compare the coded BER performance, uncoded BER performance and the throughput between ZF-BF and SMMSE-BF. The simulations are conducted using a QPSK modulation and an Effective Code Rates equal to $1/3$ ($ECR = 1/3$). Every curve is plotted versus the SNR.

We can observe that with the introduction of DET algorithm, the performance are better than without power control, for both users.

Figure 41 shows that the introduction of DET provides enhancement in particular for the second user, where BER of 10^{-3}, provides a array gain of about 2dB over the same user without DET.

Also the throughput (Figure 42) is higher with DET than with without DET, in particular for the second user.

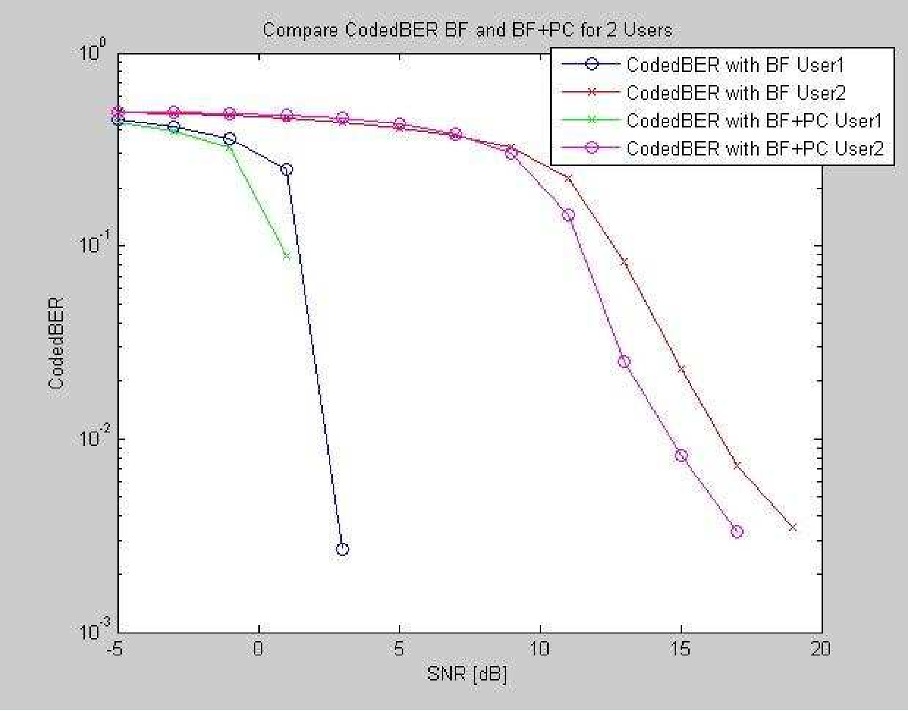


Figure 41. CodedBER SMMMSE+PC vs. SMMSE

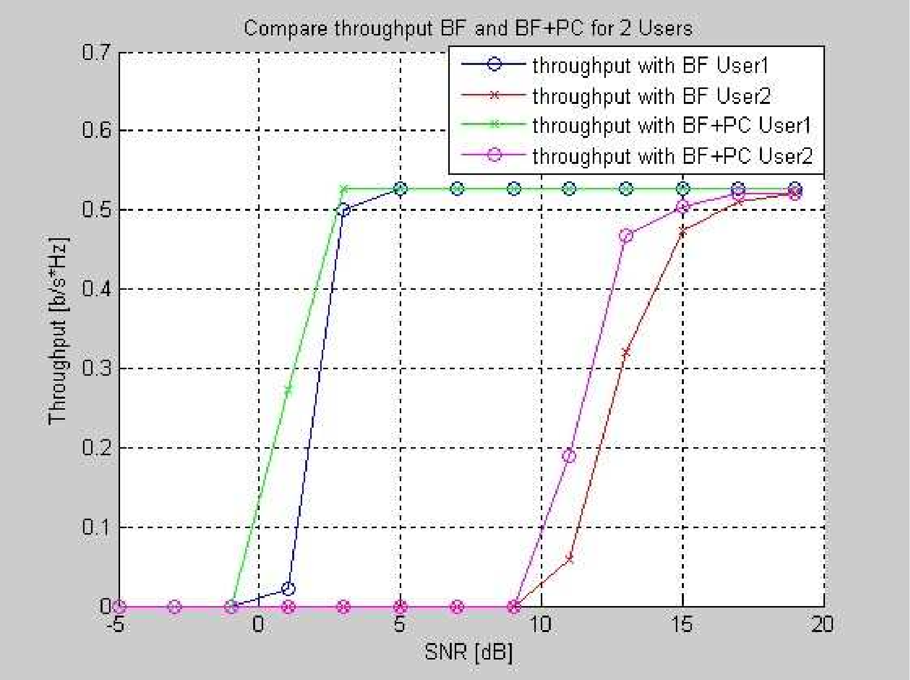


Figure 42. Throughput SMMSE+PC vs. SMMSE

Chapter 6

6. Conclusion and Future work

In this final chapter, the work undertaken in this thesis will be summarised with an emphasis on the overall conclusions. In add, some suggestions for the future work will be also presented.

6.1 Conclusion

This thesis considered a beamforming and power control algorithm for MU downlink MIMO-OFDM systems. Particulary, LTE system with FSU concept.

The major advantage of FSU is a better spectral scalability of the system than another spectrum management. FSU is considered to occupy scarce spectral resources opportunistically in order to increase the average spectral efficiency of the system and provide less interference to the order system. So, to avoid interference to other systems, beamforming and power control algorithms are investigated and implemented in MATLAB. As a starting point, assuming perfect channel state information at the transmitter, single-user (SU) multiple input multiple output (MIMO) downlink beamforming is implemented to evaluate the link performance of the system. As a case study, a link-level simulator complying UTRAN Long Term Evolution (LTE) standard is considered. Moreover, two multi-user (MU) MIMO downlink with OFDM/SDMA access scheme, beamforming algorithms zero-forcing (ZF) and successive minimum mean square error (SMMSE) are investigated to evaluate performance of the system at link-level by averaging the bit error rates (BERs) and throughputs (THs) of all the candidate users. Numerical simulation results show significant gains by 3dB to 5 dB, depending of the modulation using, and 3dB about, for the low SNR, for the considered 2×2 system in terms of BER and TH, respectively, compared to the same considered system without beamforming.

Simulation results showed, also, that SMMSE beamforming reduces the performance loss due to zero MUI constraint and the cancellation of the interference between the antennas located at the same terminal. Through our investigation for the considered system, it can be comprehended that SMMSE outperforms ZF technique. SMMSE has relatively low computational complexity. Another big advantage of SMMSE is that the users can be equipped with more antennas, so the total number of receive antennas in the downlink can be greater than the number of transmit antennas. Furthermore, this technique is especially useful at low SNRs, as the results have showed. Finally, SMMSE provides higher array gain than ZF. Our results show significant gains by 3 dB and 3 dB, in terms of BER and TH, respectively, comparing SMMSE to ZF beamforming algorithm.

The introduction of the DET algorithm improves further the performance of the system. Dominant eigen transmission (DET) power algorithm is to applied to both to maximize the SNR at the receiver and to minimize the BER.

BF and PC avoid co-channel interference and minimize the total transmitted power and this is exactly the problem that is been considered here; i.e., how to choose the transmit BF vectors such that the total transmitted power is minimized while the system provides an acceptable Quality of Service (QoS) serving as many users as possible.

This treats just a single MU-MIMO system. In fact, her we limit our study to the single cell case; i.e. we do not consider the interference from other neighboring cells. An interesting approach would be to use SMMSE with interference inter-cell MU-MIMO system, when the cells are in cooperative mode and/or no. An another interesting approach would be to use a non-linear beamforming techniques and compare it with the SMMSE technique.

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Appendix A

Channel Profiles

Radio wave propagation in the mobile environment can be described by multiple paths which arise due to reflection and scattering in the mobile environment [23]. Approximating these paths as a finite number of N distinct paths, the impulse response for the radio channel may be written as:

$$h(\tau) = \sum_{i=1}^{N} a_i \cdot \delta(\tau_i)$$

which is the well known tapped-delay line model. Due to scattering of each wave in the vicinity of a moving mobile, each path a_i will be the superposition of a large number of scattered waves with approximately the same delay. This superposition gives rise to time-varying fading of the path amplitudes a_i, a fading which is well described by Rayleigh distributed amplitudes varying according to a classical Doppler spectrum:

$$S(f) \propto \frac{1}{\left(1 - \left(\frac{f}{f_D}\right)^2\right)^{0,5}}$$

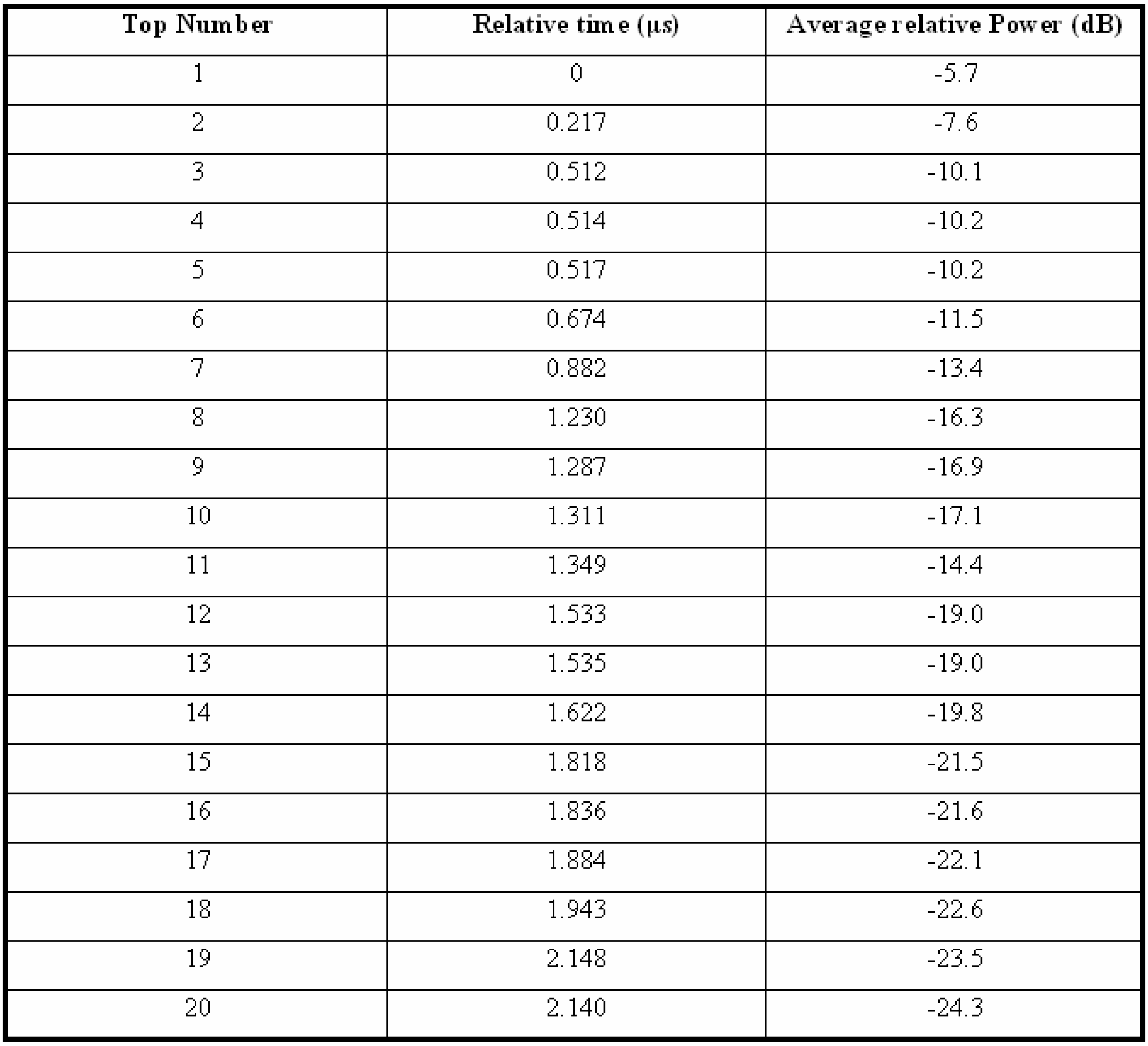
where $f_D = \frac{v}{\lambda}$ is the maximum Doppler shift, a function of the mobile speed v and the wavelength λ. In some cases a strong direct wave or specular reflection exists which gives rise to a non-fading path, then the Doppler spectrum is:

$$S(f) = \delta(f_S)$$

where f_S is the Doppler frequency of the direct path, given by its direction relative to the mobile direction of movement.

The channel models presented here will be described by a number of paths, having average powers $|a_i|^2$ and relative delays τ_i, along with their Doppler spectrum which is either classical or a direct path. The models are named ***TUx (Typical Urban)***, ***RAx (Rural Area)***, ***HTx (Hilly Terrain)***, where

x is the mobile speed in Km/h. Table 2 shows the relative delays and powers of a channel for urban area.



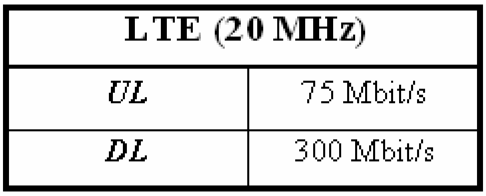
Top Number	Relative time (µs)	Average relative Power (dB)
1	0	-5.7
2	0.217	-7.6
3	0.512	-10.1
4	0.514	-10.2
5	0.517	-10.2
6	0.674	-11.5
7	0.882	-13.4
8	1.230	-16.3
9	1.287	-16.9
10	1.311	-17.1
11	1.349	-14.4
12	1.533	-19.0
13	1.535	-19.0
14	1.622	-19.8
15	1.818	-21.5
16	1.836	-21.6
17	1.884	-22.1
18	1.943	-22.6
19	2.148	-23.5
20	2.140	-24.3

Table 2. Typical Urban relative delays and powers

Appendix B

LTE context

Long Term Evolution (***LTE***) describes standardisation work by the 3GPP to define a new high-speed radio access method for mobile communication systems [24], [25]. Today, specifications for LTE are encapsulated in 3GPP Release 8, the set of standards that defines the technical evolution of 3GPP mobile network system. LTE offers high spectral efficiency, low latency and high peak data rates; it promises rate of *300 Mbit/s* in the downlink and *75 Mbit/s* in the uplink for every *20 MHz* of paired spectrum as shows in table 3.



LTE (20 MHz)	
UL	75 Mbit/s
DL	300 Mbit/s

Table 3. UL and DL data rates in LTE

LTE incorporates the most advanced techniques of OFDMA and antenna techniques such as MIMO, SDMA and Beamforming. LTE's OFDMA technology provides increasingly higher capacity at wider bandwidths. OFDM technology is able to handle the most common radio frequency distortion without the need for complex equalization techniques, and scales easily to fit different bandwidth requirements. MIMO technology increases peak throughput by transmitting and receiving multiple streams of information within the same spectrum. MIMO exploits the multi-path effects typical in wireless environments. MIMO employs multiple transmit and receive antennas to substantially enhance the air interface. It uses space-time coding of the same data stream mapped onto multiple transmit antennas, which is an improvement over traditional reception diversity schemes where only a single transmit antenna is deployed to extend the coverage of the cell. MIMO processing also exploits spatial multiplexing, allowing different data stream to be transmitted simultaneously from the different transmit antennas, to increase the end-user data rate and cell capacity. In add, when knowledge of the channel is available at the transmitter (LTE supports both FDD and TDD modes), MIMO can also implement Beamforming to further increase available data rates and spectrum efficiency.

Appendix C

TDD System

Beamforming is a processing technique that use CSIT by operating on the signal before transmission [18], [26]. In fact, the transmitter can only know CSI indirectly; whereas, the receiver can estimate the channel directly from the channel-modified received signal. Pilots are usually inserted in the transmitted signal to facilitate channel estimation by the receiver. There are two principles for obtained CSIT: *reciprocity* and *feedback*. Reciprocity involves using the reverse channel information (*open-loop*), while feedback requires sending the forward channel information back to the transmitter (*closed loop*). Both reciprocity and feedback methods are used in practical wireless systems, including ***Time-Division-Duplex (TDD)*** and ***Frequency-Division-Duplex (FDD)***. TDD systems may use reciprocity techniques. While the forward and reverse links in a TDD system often have identical frequency bands and antennas, there is time lag is the scheduling delay between the reception of the signal from a user and the next transmission to that user. Such time lags must be negligible compared to the channel coherence time for reciprocity techniques to be applicable. FDD systems, on the other hand, usually have identical temporal and spatial dimensions on the forward and reverse links, but the link frequency offset is often much larger the channel coherence bandwidth, making reciprocity techniques infeasible. FDD systems therefore commonly use feedback techniques.

The reciprocity principle in duplex transmission, the transmitter (HNB) first estimates the reverse link channel, and uses this estimate for the forward link channel. Let us discuss a SISO case. Let $h_f(t_f, f_f, i_f)$ be the forward SISO channel from HNB transmitter antenna to the user and $h_r(t_r, f_r, i_r)$ be the reserve SISO channel, as show in figure 44. where, t_f, f_f and i_f refer to the time, frequency and antenna index used on the forward link; whereas t_r, f_r and i_r are similarly defined for the reverse link. The antenna index specifies the antenna used at the HNB and the user.

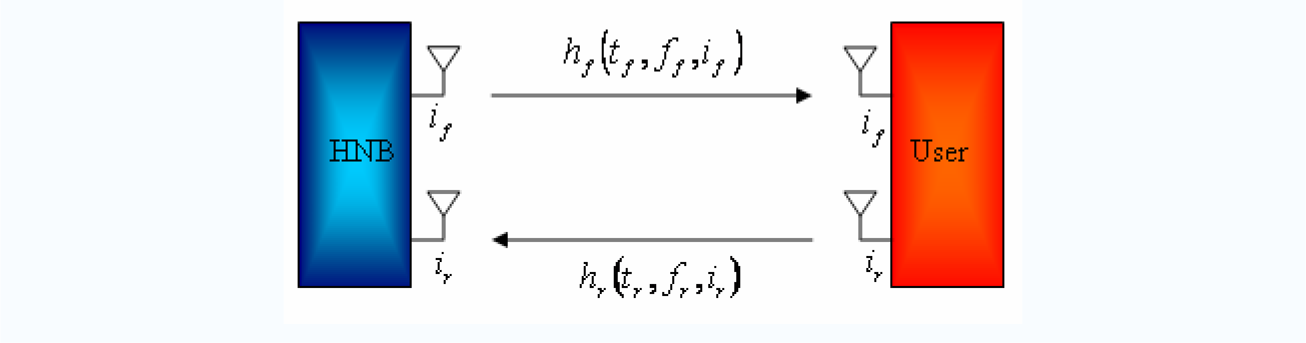


Figure 43. Duplexing in CSI

The reciprocity principle states that if the time, frequency and antennas for channel used are the same ($t_f = t_r, f_f = f_r, i_f = i_r$), then the channels in the forward and reverse link are identical:

$$h_f(t_f, f_f, i_f) = h_r(t_r, f_r, i_r)$$

In TDD, the forward and reverse channels use the same frequency and antennas for the duplex links, but use different time slots (ping-pong) to communicate. Let $\delta_t = t_f - t_r$ be the duplexing time delay. It follows that the forward and reverse channels can be equated only if:

$$\delta_t << T_C$$

where T_C is the coherence time of the channel. Clearly, the more stringent the requirements of accuracy in channel estimates, the smaller $\frac{\delta_t}{T_C}$ will need to be.

Acknowledgement

…So, I'm at the last pages of my thesis….
…I think these are more difficult than another pages, but I will try to write them…
I would like to thank everybody that I have met in these years! I hope to not forget anyone…
This is a logic order not by importance, everybody are very important in my life!
I would like to say thank to…

My supervisors Nicola Marchetti and Shashi Kant for their support and encouragement during the development of this project. Even more important than the wise advice they always gave me, I deeply appreciate the friendly atmosphere in which we worked together. I want to acknowledge the effort and time they spent trying to lead me to a higher level.
Nicola, **grazie**, because, nothing is impossible…
Shashi **शुक्रिया**, because, the great man are also small…

Gila, for the contribution to the work, because you are a genius, because, without you, I was not able to continue the work…

My Prof. Roberto Cusani for the possibility of this fantastic experience! And for all advices given. **Grazie Prof**…

Luna people, Francesco, Jordi, Jop, Pepe, Sergio, Sam, Milos, David, Flora, Berenicè, Richard, Borja, Michal and others, for the beautiful atmosphere in the Luna Kollegium, for the crazy party, for the pussy-man, for the fisherman, for the great moments that we shared together…

All the friends I have met here from all around the world, specially the ones I will most miss and the ones with who I will keep in contact. Thanks for showing me that there is life in Aalborg despite of its wonderful weather. I will always remember the great moments we shared together…

Now I begin to write in Italian…
…oh sorry!!! I don't speak Italian…
…I will continue in Roman languages…
Unlook!!!

Ai miei genitori, le persone senza le quali non sarei mai diventato quello che sono, sempre attenti, affettuosi, disponibili!!Hanno sempre creduto in me, non mi hanno mai fatto mancare niente!!! Mi hanno dato la migliore educazione che si potesse mai avere!!!
Rinco, è sempre bastato un cenno tra di noi, non siamo di tante parole (a parte la Roma..), ma tanto non servono…
Gigliola, bè che dire, oddio rompe le scatole, però nessuno avrebbe mai fatto quello che ha fatto lei per me, anzi per noi. E poi la pizza, gli spaghetti al cartoccio, la pasta al forno, gli gnocchi, mejo smette che me sta a pijà fame…E poi è inutile aggiungere altro se no questa se mette a piagne pe 'na decina d'anni…

Ciccio, mio fratello, anzi FRATELLONE, ogni volta che stai giù, che sei stanco, che ti sei stufato di tutto e di tutti, basta guardarlo, guardi la sua faccia simpatica e tutto passa. Qui in Danimarca me sei mancato da morì!!! Non esiste un fratello migliore!!! Grazie per tutte le volte che abbiamo preso in giro Gil e Rinco insieme. Lo sai benissimo che il prossimo a scrive sti commenti sulla tesi sei tu!! E poi ho bisogno di un dottore in biologia! Daje Ciccio!!!!

Zio Renato, ecco già c'ho le lacrime agli occhi…, quanto me manchi zi…,te dico solo grazie se no non continuo più a scrive…

Zio Enrico, magari non l'ho conosciuto troppo a fondo, però mi ha lasciato il ricordo di una grande persona…

I miei nonni Giovannella e Francesco, Maria e nonno, c'è chi ho conosciuto di più, chi di meno, chi per niente, ma in fondo senza di voi non starei qui…

I miei cugini vicini e lontani perché ci sono sempre quando ne hai bisogno, in particolare un grazie speciale a:
Francesco, che ha trattato con cura i miei capelli e ora si vedono i risultati (non ce l'ho più…), una persona fantastica, schietta e sincera, da lui si può solo apprendere, ovviamente solo per quel che riguarda le scommesse sportive, tutto lo sport in generale, ma in particolare il suo linguaggio…
Alex, cugì, ormai io e te semo come du carabinieri, inseparabili…, anche da lontano, grazie…
Alessandra e Valeria, per le loro lacrime anche quando non c'è ne bisogno e per il loro affetto e per ogni volta che ricordiamo i momenti dell'infanzia passati insieme…
Pamela, Vittorio, Fabrizio, perché credono che sia un genio…

I miei zii Pietro e Anna Maria, Vincenzo e Anna, Peppe e Rita, Domenico e Maria, Teresa, Ernesto e Rita, Dino e Ferrina, Giuseppe Anna Rita, Lucio e Silvia, mi hanno trattato tutti come un loro figlio, è un onore essere vostro nipote…

Roberto e Alessandra, per le serate a mangiare la pizza di mamma, per le risate e perché per me sono semplicemente di famiglia…

Le mie sorelline Marta e Marzia, perché hanno occupato la mia camera per tutto il periodo che sono stato in Danimarca…

Tania, perché è nata il mio stesso giorno, perché in tutte le “foto” più importanti dei miei ultimi 10 anni… te ci sei, perché nessuno mi conosce meglio di te…

Francesca, perché ho semplicemente ritrovato una sorella, che mi consiglia, che mi ascolta, che mi rimprovera e che vuole farmi assolutamente fidanzare, ci riuscirà? Dubito…

I Buddhi, Gaetano, Claudia e Domenico, perché anche se non ci frequentiamo più così tanto spesso, le giornate, le emozioni, le avventure passate insieme, ogni singolo ricordo è indelebile nel mio cuore…

Sabrina, perché in questi anni, per alcuni mesi, studiare è stato più duro, la mente era sempre lontana dai libri; perché anche se non fa più parte della mia vita, rimane una delle persone più importanti…

Bruno, perché è il mio secondo padre e penso che non c’è bisogno di aggiungere altro…

Lisa e Natalia, tutti gli amici di Casali, Emiliano, Armando, Mazza, Russo, Daniela perché le amicizie che durano da quindici anni non si possono dimenticare…

Serena, perché è stata in Danimarca con me, perché mi ha ospitato sul suo pavimento e perché c’ho ragione sempre io e lei mai…

Bestia e Giuglia, perché sono la coppia più divertente del mondo, perché studiare con loro è stato puro divertimento…

Claudia, Jenna, Anna, Palma, Fabbrica e Sità, Fabio e Conte, Claudio e Francesca, Carmine e tutti gli altri amici dell'uni per tutti i pomeriggi passati all'uni a "studiare", al chiostro, allo spaccio,…

Emy, Mary, Viola, Ilaria, per le lingue di gatto, per le lunghe pause di studio, perché sono delle persone eccezionali, perché l'ho conosciute in modo buffo…

Loreto, per le video-chiamate all'una di notte, quando invece di mandarmi a quel paese fermava il suo lavoro e mi ascoltava; per i consigli su matlab, per il grande aiuto su questa tesi, per i fagioli alle 4 del mattino, le salsicce alle 6, per la barba non tagliata, perché io dalla Danimarca guardavo la Roma e lui che stava a Roma no, perché è un grande amico…

Simona, per i messaggi di saluto su msn, perché verrà con me al concerto di Vasco, perché mi ha fatto passare un capodanno "particolare", perché vorrebbe ricambiare il favore, ma io non me ubriaco mai, perché ho scoperto una persona speciale…

Le mie compagne di stanza di capodanno, Silvia, Ary mora, Ary bionda, Sara, perché mi hanno fatto passare un gran capodanno, per le chiacchierate su msn, perché anche se stavo lontano, loro erano vicine…

Tutti gli amici italiani conosciuti qui in Danimarca, Giampaolo (perché è più famoso della Coca Cola), Jo-wow (perché è italiano no portoghese), Francesco cugino (per le simulazioni), Francesco brother (perché è come un fratello), Filippo (perché mi ha insegnato il toscano), Mary (perché è della Roma), Luca & Ane (per la cena danese), Mauro (perché è un pazzo), Valerio e Nicoletta (perché sono unici), Avvocato (per il suo italiano), Chiara (perché non ha condiviso la stanza con noi), Valentina (per la nutella), Stella (per le ricariche telefoniche e perché è troppo simpatica), Francesco Ciccio (perché se no non mi manda alla student house), Anna (per il suo sorriso), Sara (per le foto da ubriacona), Manu (per la sua disponibilità), Antonio (per la sua pizza), Davide (un mito)…

Gli amici del laboratorio di Roma, Mauro, Christian, Nicola, MarioTilli, Massimo, Valeria perché le giornate in laboratorio con loro erano uno spasso.

Valentina e Monica, per le serate passate insieme e perché mi sono sempre vicini…
Simone per la sua straordinaria simpatia…

Tutti gli amici del calcetto, perché fare tutti i tornei che ho fatto insieme a loro è stato un piacere ed un onore!!! Perché hanno contribuito a farmi distrarre ed a tenermi in forma…

Ristorante i Leoni, Carlo, Elenia, Emanuele, Ringo, Franco, perché mi hanno dato la possibilità di mantenermi gli studi e perché mi hanno fatto sentire una famiglia…

Tutti i miei alunni e alunne, perché mi fanno sentire importante, perché per loro sono e sarò per sempre il loro Prof, perché mi hanno fatto vivere una delle più belle esperienze della mia vita, perchè è stato un onore essere il loro insegnante, per tutto quello che mi hanno insegnato, perché vogliono venirmi a vedere alla mia discussione (ma solo per saltare un giorno di scuola), perché non li dimenticherò mai…

Tutte le persone che ho conosciuto nell’ambito scolastico, e che si sono sempre fatti sentire, che non hanno interrotto i contatti, che già “ciao come vanno le cose in Danimarca?”, ti fanno sentire vicino a loro, in particolare un grazie a Fabiola e a tutti quelli a cui ho fatto l’esame di maturità…

Tutti i miei colleghi Prof, perché mi hanno aiutato nella mia prima esperienza, per i consigli, perché mi hanno voluto bene…

…Penso di aver ringraziato tutti, non manca nessuno…
… bè mancano 4 persone…
…per loro una vita intera di ringraziamenti non basta…
…per loro, però, basta una semplice riga …
… sono gli amici che tutti vorrebbero, perché …
…sono semplicemente una parte di me…

Fettina, perché è un FRATELLO…
Miky, perché è un AMICO…
Piastra, perché è un COMPAGNO…
Paolo, perché è un COMPLICE…

Grazie di cuore a tutti quanti, perchè tutti avete contribuito a questo mia tesi e perchè fate parte della mia vita, e perché…
…senza di voi,…io non esisto…