„POLITEHNICA" UNIVERSITY of BUCHAREST

ETTI-B DOCTORAL SCHOOL

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DOCTORAL THESIS

OPTIMIZING THE PERFORMANCE OF DIGITAL COMMUNICATIONS SYSTEMS

OPTIMIZAREA PERFORMANȚELOR SISTEMELOR DE COMUNICAȚII DIGITALE

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Chapter 1 - Introduction

1.1 Presentation of the field of the doctoral thesis

Wireless communication systems have evolved rapidly in terms of volume and range of services. One of their strengths is the improvement of spectral efficiency to support a very large number of users and very high data rates. A promising approach is the use of multiple antennas for transmission and reception (MIMO). The use of spread spectrum based on code division multiple access (CDMA) is another approach to increase spectral efficiency. This paper also addresses the technique of multi-user shared access (MUSA). An algorithm has been developed to identify a matrix with perfectly orthogonal codes, supplementing it with codes that have a low correlation. A new method of obtaining complex spreading codes has been proposed, starting from real spreading codes. Cooperation is an effective way for a user's communication link to be improved in a sustained manner with the help of relays. To combat the effects of multipath fading that occur on the communication link, orthogonal frequency-division multiplexing (OFDM) is used.

1.2 The purpose of the doctoral thesis

This doctoral thesis aims to analyze the quality of information that reaches the destination after traversing the communication chain when various technologies are introduced, discussed in the development of 5G. It starts from a MIMO system affected by various types of fading and uses CDMA when transmitting random data or images. Matlab is used as the simulation medium, and the performances are analyzed by interpreting graphs in which bit error rates (BER) versus signal-to-noise ratio (SNR) or mean structural similarity index (MSSIM) are represented. In addition to CDMA, OFDM is also introduced into a system where the number of antennas at reception and the number of users vary to see what changes occur and under what conditions. The introduction of channel coding (LDPC) and relays follows. Given the limitations introduced by CDMA, for an even greater improvement of the system developed so far, MUSA multiple access technique has been implemented, whose performance is highlighted by comparison with CDMA and whose development has started from CDMA.

1.3 The content of the doctoral thesis

Chapter 2 and *Chapter 3* make a small theoretical introduction of three modulation techniques also used in the practical part and of OFDM. The elements that affect the signal quality on the communication channel are discussed, and MIMO technology is also presented. The last part of this chapter describes the concept of cooperation. *Chapter 4* begins with a brief introduction of the CDMA technique used in a multi-user system when each user transmits a random bit sequence or a black-and-white image. *Chapter 5* analyzes the performance of LDPC coding taking into account the massive MIMO technique, and at the reception two detectors were considered to estimate the transmitted information: minimmum mean square error (MMSE) and minimmum the mean square error succesive interference cancelation (MMSE-SIC). *Chapter 6* begins with a theoretical presentation of the two protocols used in this doctoral thesis, amplify-and-forward (AF) and decode-and-forward (DF), whose performance will be tested through a number of Matlab simulations. *Chapter 7* begins with a theoretical introduction of MUSA, followed by a performance test by comparison with CDMA. A new method for obtaining complex spreading codes is presented, starting from PN spreading codes. *Chapter 8* summarizes the entire doctoral thesis presenting the conclusions following theoretical and practical descriptions, ideas for further development as well as original contributions and articles by the author, used in writing the thesis.

Chapter 2 – Modulation techniques

2.1 Phase-shift keying modulation

Phase-shift keying is a digital modulation technique where the phase of the analog carrier signal is used to represent binary digital information (binary values of 0 and 1).

2.1.1 Binary Phase-Shift Keying (BPSK)

BPSK is a digital modulation technique in which only one bit per symbol is transmitted, either 0 or 1. Two different phase states are used for this type of modulation.

2.1.2 Quadrature Phase-Shift Keying (QPSK)

QPSK is a digital modulation in which two bits per symbol are transmitted, 00, 01, 10 and 11. For this type of modulation four different phase states are used.

2.1.3 Quadrature Amplitude Modulation (QAM)

A QAM modulated signal is a signal where two carriers displaced in phase with $\frac{\pi}{2}$ radians between them are modulated, and the resulting signal shows a variation in both amplitude and phase.

2.2 Orthogonal Frequency-Division Multiplexing

Multi-carrier modulation is a technique in which data is transmitted across multiple carriers - the data stream with a higher rate to be transmitted is divided into several data streams of lower rates, each being used to modulate an individual subcarrier [1]. There are several forms of multi-carrier modulations, each with its own advantages, moderating the influence of disruptive factors through different approaches, but in the experimental part of this doctoral thesis OFDM was chosen.

2.2.1 Basic principles

OFDM divides the entire channel affected by selective frequency fading into narrowband subchannels affected by flat fading (or subcarrier) in which data is transmitted in parallel and is not affected by inter-symbol interference due to the large symbol period.

2.2.2 Implementation of an OFDM system

A serial binary data signal is applied to the input of such a system which enters a BPSK modulation block, and at its output there will be a signal, in serial form, introduced in a series-parallel converter. Therefore, the OFDM-BPSK signal is

$$s_{OFDM-BPSK}^{bb}(t) = \sum_{l=0}^{L-1} s_l^{bb}(t)\, cos\left(l \frac{2\pi}{T_s} t\right) \quad (2.54)$$

where the notation "bb" refers to a signal in baseband, $s_l^{bb}(t)$ is the signal obtained by multiplying the data with the associated subcarrier.

The OFDM-QAM transmitted signal is

$$s_{OFDM\_QAM}^{bb}(t) = \sum_{l=0}^{L-1} s_l^{bb}(t) = \sum_{l=0}^{L-1} (A_l + jB_l) e^{jl\Omega t}, \quad (2.59)$$

equation valid in $[0, T_s]$ and the QAM symbols QAM, A_l și B_l, constant on $T_{s\_QAM} = 2NT_b$, before the series-parallel conversion.

Chapter 3 – Radio channel modeling

3.1 Elements that lead to deterioration of signal quality

The signal passing through a communication chain can reach the reception modified by the following effects [2][3][4]: pathloss, shadowing, fading. Other phenomena that favor the appearance of fading are the Doppler deviation / effect, reflection, diffraction and scattering.

3.2 Envelope and phase fluctuations of the signal

It is assumed that there are multiple paths to propagate a signal. To each path is associated a propagation delay and attenuation factor. Therefore, the received signal is

$$r(t) = Re\left\{\left[\sum_i \alpha_i(t) e^{-j2\pi f_0 \tau_i(t)} g(t - \tau_i(t))\right] e^{j2\pi f_0 t}\right\}, \quad (3.10)$$

where $g(t)$ is the complex envelope of the transmitted signal, $\alpha_i(t)$ is the attenuation factor for the signal received on ith path, $\tau_i(t)$ is the propagation delay on ith path. From equation (3.10) it can be said that the low frequency equivalent of the received signal (or complex envelope) is

$$g_c(t) = \sum_i \alpha_i(t) e^{-j2\pi f_0 \tau_i(t)} g(t - \tau_i(t)). \quad (3.11)$$

3.3 Channel modeling

The characteristics of a communication channel can be highlighted with the help of the weight function and the transfer function. Therefore, according to relation (3.10), the received signal is obtained as a result of a convolution operation between the signal from the baseband, $s(t)$, and by the low frequency equivalent of the weight function $h(\tau, t)$, defined as [5]

$$h(\tau; t) = \sum_i \alpha_i(t) e^{-j2\pi f_0 \tau_i(t)} \delta(\tau - \tau_i(t)). \quad (3.15)$$

Applying the Fourier transform for $h(\tau; t)$, then the low frequency equivalent is [5]

$$H(f; t) = \int_{-\infty}^{\infty} h(\tau; t)\, e^{-j2\pi f_0 \tau} d\tau. \quad (3.19)$$

3.4 Classification of fading types

The two parameters that are used to classify the channels affected by fading are the coherence band and the coherence time. Then, the following fading classification can be made: *slow fading* ($T_C \gg T_S$ și $B_D \ll B_S$) and *fast fading* ($T_C < T_S$ și $B_D > B_S$); *flat fading* ($B_C \gg B_S$ și $\tau \ll T_S$) and *frequency selective fading* ($B_C < B_S$ și $\tau > T_S$) [6][7][8]. A more general classification of fading can be made as follows: small-scale fading and large-scale fading [6][7][9].

3.4.1 Small-scale fading and large-scale fading

Small-scale fading refers to rapid changes in amplitude and phase over a very short period of time or over a very short distance. Small-scale fading is also called Rayleigh fading because when the number of versions of the transmitted signal reaching reception at slightly different times, the envelope of the received signal is statistically described by the Rayleigh distribution if there is no direct line component. If there is a direct line component, then the received signal envelope is described by a Rice distribution.

3.5 Diversity

In the context of radio communications, diversity techniques [4][8][10] are commonly used to combat fading.

3.5.1 Diversity techniques

Spatial diversity or antenna diversity occurs on the uplink, at the base station receiver. *Temporal diversity*. *Angular diversity*. Since directional beams involve the use of antenna aperture, it is close to spatial diversity [11]. *Frequency diversity*. *Multipath diversity*. *Polarization diversity*.

3.5.2 Techniques for combining diversity

Combining diversity consists in the redundant reception of the message signal on two or more fading channels, then combining these replicas at the receiver to increase the total received SNR.

3.6 Spatial multiplexing

Spatial multiplexing is a transmission technique that is used in wireless systems with multiple antennas, to transmit independently and separately several coded data signals, called streams, from each of the transmission antennas.

3.7 Systems with multiple antennas

Spatial diversity uses multiple antennas at transmission and reception with multiple configurations.

3.7.1 SISO channel

Consider the impulse response of the channel in a time-varying channel $h(\tau, t)$, defined according to (3.15). When a signal $s(t)$ is transmitted, the received signal, $y(t)$, is

$$y(t) = h(\tau, t) * s(t) + n(t), \tag{3.37}$$

where $*$ is the convolution product and $n(t)$ is AWGN.

3.7.2 SIMO channel

A SIMO channel with $N_r$receiving antennas can be decomposed into N_r SISO channels. When a signal s (t) is transmitted, the signal received at the ith receiving antenna

$$y_i(t) = h_i(\tau, t) * s(t) + n_i(t), \qquad i = 1,2,3, \dots, N_r, \tag{3.39}$$

where $n_i(t)$ is the AWGN vector of $(N_r \times 1)$ dimension.

3.7.3 MISO channel

A MISO channel with N_t transmitting antennas and can be decomposed into N_t SISO channels. Assuming $s_j(t)$ the signal transmitted by the jth transmitting antenna, the received signal is

$$\mathrm{y}(t) = \sum_{j=1}^{N_t} h_j(\tau, t) * s_j(t) + n(t). \tag{3.42}$$

3.7.4 MIMO channel

It is considered a MIMO channel with N_t transmitting antennas, N_r receiving antennas. Assuming $s_j(t)$ the signal transmitted by the jth transmitting antenna, the signal received by the ith receiving antenna, is

$$y_j(t) = \sum_{j=1}^{N_t} h_{i,j}(\tau, t) * s_j(t) + n_j(t), \qquad i = 1,2,3, \dots, N_r. \tag{3.45}$$

3.7.5 MIMO channel with multiple users

Multi-User MIMO (MU-MIMO) is a term that defines a system in which a MIMO link is used by multiple users simultaneously and share a single resource in time-frequency to exploit the diversity offered by the existence of multiple users.

1. **The MU-MIMO uplink**

The channel matrix that connects the $u_k, k = 1,2, \dots, K$ user to the base station, is denoted by H_k, of dimension $(N_r \times N_{t_k})$. The signal received at the base station, y, of dimension $(N_r \times 1)$ is

$$y = \sum_{k=1}^{K} H_k s_k + n, \tag{3.47}$$

where n is the AWGN vector, $(N_r \times 1)$ and $s_k(t)$ is the transmitted signal, $(N_{t_k} \times 1)$.

2. **The MU-MIMO downlink**

The channel matrix that connects the $u_k, k = 1,2, \dots, K$ user to the base station, is denoted by H_k, of dimension $(N_{t_k} \times N_r)$. For each user, the vector of the received signal of dimension $(N_{t_k} \times 1)$, $k = 1,2, \dots, K$ is given by the equation

$$y_k = H_k \cdot s + n_k, \qquad k = 1,2, \dots, K, \tag{3.49}$$

where n_k is the AWGN vector, $(N_{t_k} \times 1)$ and s is the transmitted signal vector, $(N_r \times 1)$.

3.7.6 Massive MIMO channel

The massive MIMO technique is the one in which at the base station level are used a few hundred to thousands of antennas, and mobile users use fewer antennas - one or two antennas and has more advantages, presented below. Massive MIMO is a special case of MU-MIMO.

3.8 Cooperative systems

The idea of cooperation was first described in [12], where the foundations of relay channels are laid, important for both wired and wireless networks. In wired networks, several pairs of sources and destinations are connected via relay nodes. In wireless networks, inactive nodes receive the surrounding transmissions, which can repeat the information and contribute to higher transmission rates. The repetition process can be: transparent or regenerative [2].

3.8.1 Advantages and disadvantages of cooperation in wireless communications

The key advantages of using relays: performance gain, balanced quality of services, implementation of systems with low infrastructure, low costs. Disadvantages: complex planning, additional amount of transmitted information, choice of partner, increased interference, additional relay traffic, high latency, strict synchronization, channel estimations.

3.8.2 Compromises for performance

To achieve the best possible performance, a number of trade-offs are needed between various parameters: coverage and capacity, complexity related to processing algorithms and hardware, interference and performance, easy implementation and performance, cost and performance.

3.8.3 Cooperation techniques

There are a variety of methods through which relays can be used in a communication system. They can be classified into about two groups:

1. **Transparent cooperation protocols**

"Amplify-and-Forward" method. Cooperative relays will convert the received analog signal, amplify it and forward it using another frequency band [2]. The "Linear processing-and-forward" method also includes other simple linear operations performed on the analog signal [2]. The *"Non-linear processing-and-forward"* method performs some non-linear operations on the analog signal received before being retransmitted [2].

2. **Regenerative cooperation protocols**

The *"Compress-and-Forward"* method is seen as an extension of AF for which the received analog signal will be sampled, quantized, compressed and resent [2]. *"Decode-and-forward"* method decodes the received signal and recodes with a different code before retransmitted [2].

Chapter 4 – The analysis of the performance of a massive MIMO system in the presence of CDMA

4.1 Introduction

Technological development requires a rapid growth of data transmitted by cellular services which also involves the need for high data rates and low latency. In order to meet the requirements of the users, a series of data processing techniques have been developed, and in this doctoral thesis a massive MIMO and CDMA technique are approached.

4.2 Multiple access

There are many ways to achieve multiple access, but in the following, only Direct Sequence CDMA (DS-CDMA) will be discussed.

4.2.1 Direct Spread Code Division Multiple Access (DS-CDMA)

DS-CDMA makes a spreading of the power spectral density of the signal using a sequence with a high symbol rate that directly multiplies the flow of information symbols. This can be extended to multiple users by providing different $d_k(t)$ spreading codes for each user in the system: Walsh codes can be used for spreading waveforms or pseudo-random sequences (PN). Some PN sequences are: m-sequence [13][14][15], Gold codes [16][17][18] and Kasami sequences [13][17].

4.3 Case study - Performance analysis of a massive MIMO system in the presence of CDMA

This subchapter will analyze the performance of a system whose communication channel is affected by Rayleigh or Rice fading and AWGN. The results were published in [19].

4.3.1 The influence of the number of antennas / MIMO configurations on the performance of a CDMA system that uses Walsh and PN spreading codes in the presence of Rayleigh fading

In Fig. 4.5 four users have the same performance, a perfectly synchronized system was assumed and Walsh codes are perfectly orthogonal. Fig. 4.6 shows the performances obtained by PN codes and are not so good because they are not perfectly orthogonal codes. From Fig. 4.7 it is observed that as the number of receiving antennas increases, the results improve.

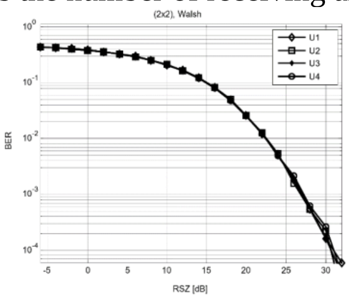


__Fig. 4.5__ BER versus RSZ for BPSK, (2x2) MIMO, Walsh spreading codes

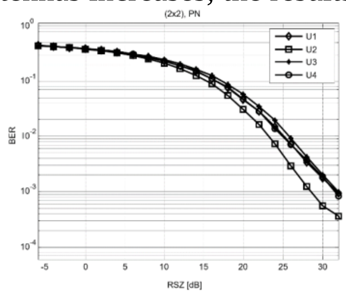


__Fig. 4.6__ BER versus RSZ for BPSK, (2x2) MIMO, PN spreading codes

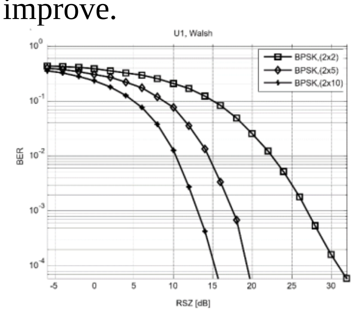


__Fig. 4.7__ BER versus RSZ for BPSK, (2x2), (2x5) and (2x10) MIMO, Walsh spreading codes

4.3.2. The influence of the number of antennas / MIMO configurations on the performance of a CDMA system that uses Walsh and PN spreading codes in the presence of Rayleigh fading when transmitting images

In Table 4.4 and Table 4.5 are the images obtained for Walsh and PN, SNR of 15 dB. The received image was compared with the initial one, through MSSIM. PN codes are not perfectly orthogonal codes, there is information found from other users in the data received by each of the four users due to multiple access interference (MAI).

Table 4.4 *Images transmitted by user 1. Walsh codes.*

(2x2)	**(2x5)**	**(2x10)**
		
MSSIM=0.7555	MSSIM=0.9462	MSSIM=0.9997

Table 4.5 *Images transmitted by user 1. PN codes.*

(2x2)	**(2x5)**	**(2x10)**
		
MSSIM=0.7236	MSSIM=0.9461	MSSIM=0.9974

4.3.3 The influence of the number of antennas / MIMO configurations on the performance of a CDMA system that uses Walsh spreading codes in the presence of Rice fading

Fig. 4.9 and Fig. 4.10 describes the performance obtained by one of the users (randomly chosen) when the channel is affected by Rice fading, (2x2), Walsh codes. The results are presented in [20].

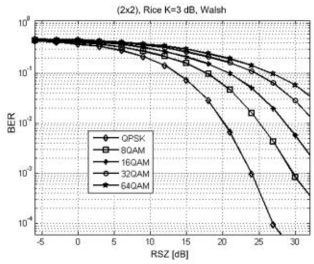


Fig. 4.9 BER versus RSZ for QPSK and M-QAM (M = 8,16,32,64), (2x2) MIMO, fading Rice, K = 3 dB*

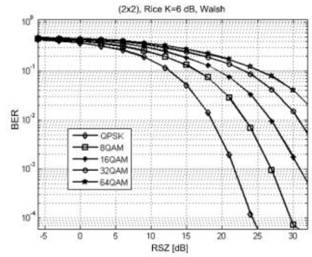


Fig. 4.10 *BER versus RSZ for QPSK and M-QAM (M = 8,16,32,64), (2x2) MIMO, Fading Rice, K = 6 dB*

4.3.4 The influence of the number of antennas / MIMO configurations on the performance of a CDMA system that uses PN spreading codes in the presence of Rice fading

Under the same conditions as above, but using PN, results presented in [20], Fig. 4.15 is obtained, *K* of 3 dB, (2x2). For Walsh codes, *K* of 6 dB brings improvement, but not to PN, Fig. 4.16.

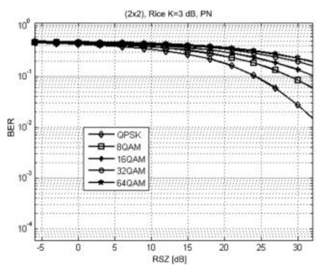


Fig. 4.15 *BER versus RSZ, QPSK and M-QAM (M = 8,16,32,64), (2x2) MIMO, fading Rice, K = 3 dB*

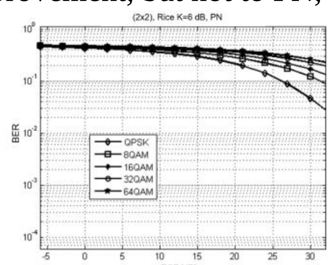


Fig. 4.16 *BER versus RSZ, QPSK and M-QAM (M = 8,16,32,64), (2x2) MIMO, fading Rice, K = 6 dB*

4.3.5 The influence of the number of antennas / MIMO configurations on the performance of a CDMA system that uses Walsh and PN spreading codes in the presence of Rice fading when transmitting images

As in subchapter 4.3.2, random data will be replaced by digitized images that will be transmitted by four users, part of the article [20]. In Table 4.11 and Table 4.12 are the images obtained for the (2x2) MIMO configuration, using Walsh and PN codes, SNR of 20 dB.

Table 4.11 *Recovered images for QPSK, Walsh codes.*

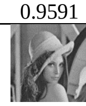
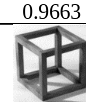
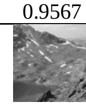
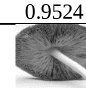
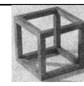
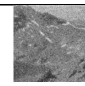
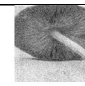
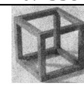
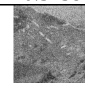
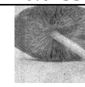
			QPSK			
			Utilizator 1	**Utilizator 2**	**Utilizator 3**	**Utilizator 4**
K = 3 dB	(2x2)	RSZ = 20 dB MSSM	 0.9591	 0.9663	 0.9567	 0.9524
K = 6 dB	(2x2)	RSZ = 20 dB MSSM	 0.9848	 0.9871	 0.9839	 0.9816

__Table 4.12__ Recovered images for QPSK, PN codes.

			QPSK			
			User 1	**User 2**	**User 3**	**Uti 4**
K = 3 dB	(2x2)	RSZ = 20 dB MSSIM	 0.6171	 0.7538	 0.5458	 0.6453
K = 6 dB	(2x2)	RSZ = 20 dB MSSIM	 0.5546	 0.4738	 0.4738	 0.6054

4.4 Conclusions

The purpose of this chapter was to evaluate the performance of a massive CDMA MIMO system. It has been shown that once the number of receiving antennas is increased, BER is improved. Another factor that influences performance is the modulation order. The performances obtained when transmitting images instead of random data were also investigated and the same conclusions can be drawn. Walsh and PN spreading codes are used to separate users, Walsh codes being a better choice than PN.

Chapter 5 - The analysis of the performance of a massive MIMO system in the presence of OFDM and LDPC

5.1 Introduction

Fig. 5.1 describes the model developed for the data transmission, on reception performing these operations in reverse, adding a detector to minimize errors.

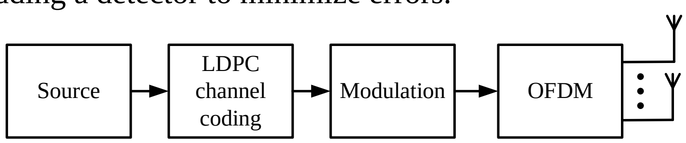


***Fig. 5.1** The data transmission*

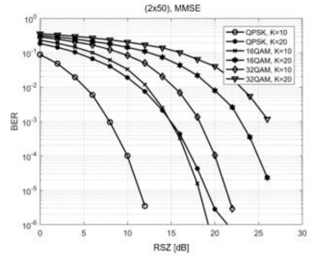
In the following are presented the performances of a massive MIMO system, with LDPC and OFDM.

5.2 The influence of the number of antennas / MIMO configurations on the performance of a system using OFDM modulation and MMSE and MMSE-SIC detectors

This subchapter will analyze the performance of a massive, uplink MIMO system,whose communication channel is affected by fading Rayleigh and AWGN. Results are published in [21].

5.2.1 Performance of a massive MIMO system without OFDM and with MMSE detector

Fig. 5.2 describes the performance for different modulations schemes, fading Rayleigh, (2x50) MIMO. If the modulation order increases, the performance is poorer. By increasing the number of users from 10 to 20, BER is higher. In Fig. 5.3 is represented BER versus the number of users under the same conditions as Fig. 5.2, SNR of 10 dB.



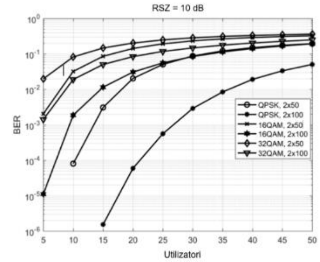
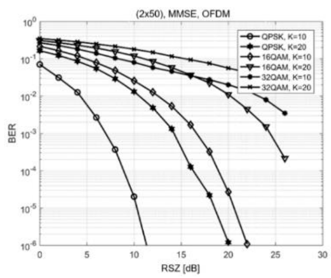


Fig. 5.2 *BER versus RSZ for a MIMO configuration of (2x50)*

Fig. 5.3 *BER versus the number of users for RSZ = 10 dB*

5.2.2 Performance of a massive MIMO system with OFDM and with MMSE detector

Comparing Fig. 5.2 and Fig. 5.4 there may be an increase in performance when OFDM is implemented. Fig. 5.5 highlights this point of view by representing BER versus the number of users, under the same conditions as in Fig. 5.3.



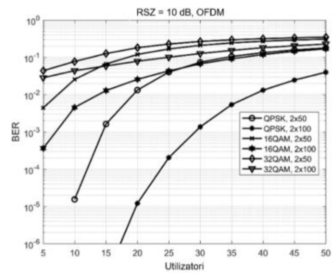
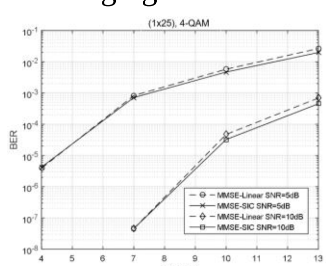


Fig. 5.4 *BER versus RSZ in a MIMO configuration of (2x50), in the presence of OFDM*

Fig. 5.5 *BER versus the number of users for RSZ = 10 dB, in the presence of OFDM*

5.2.3 Performance of a massive MIMO system with OFDM with MMSE-SIC detector

In Fig. 5.6 are the results obtained when the base station has 25 antennas, MMSE and MMSE-SIC detectors. The positive influence of SIC is visible when the number of users increases. The results obtained when changing the modulation, from 4-QAM to 16 and 64-QAM are given in Fig. 5.7.



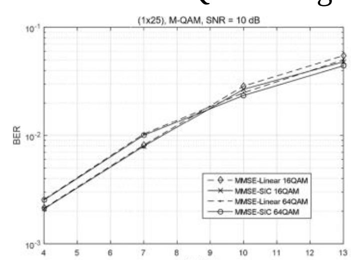


Fig. 5.6 *Linear MMSE and MMSE-SIC, RSZ equal to 5 dB and 10 dB, 4-QAM, base station with 25 antennas depending on the number of users*

Fig. 5.7 *Linear MMSE and MMSE-SIC, RSZ equal to 10 dB, 16-QAM and 64-QAM, base station with 25 antennas depending on the number of users*

5.3 The influence of the number of antennas / massive MIMO configurations on the performance of a system using LDPC channel coding

This subchapter can be seen as a continuation of subchapter 4.3, here is also introduced the LDPC channel coding. The results are published in [22].

5.3.1 Performance of a massive MIMO system, with LDPC, with a small number of users

In Fig. 5.11 a comparison of the performance obtained with and without LDPC is made, when the same simulation conditions are maintained: QPSK and M-QAM modulations (M = 16.32), Rayleigh fading, (2x50), 10 users. If the number of antennas at the base station is increased from 50 to 100, the general remarks made earlier are still valid. This situation is shown in Fig. 5.12.

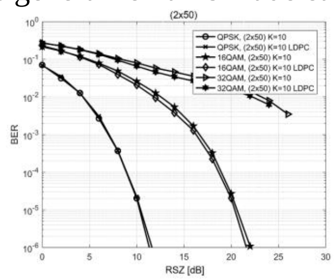


Fig. 5.11 *BER versus RSZ with and without LDPC for 10 active users, in a MIMO configuration of (2x50)*

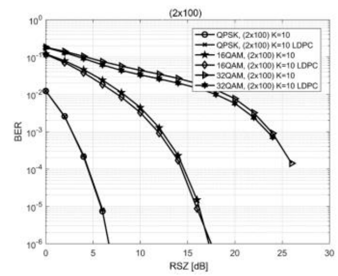


Fig. 5.12 *BER versus RSZ with and without LDPC for 10 active users, in a MIMO configuration of (2x100)*

5.3.2 Performance of a massive MIMO system, with LDPC, with a large number of users

Fig. 5.13 describes the results obtained for (2x50) MIMO and the performance is relatively low because the number of users being increased from 10 to 50, the network must provide the same resources at the same quality to these users. In this case, the benefit of MIMO, namely the gain obtained due to spatial diversity, is no longer enough. The problem is partially solved by increasing the number of antennas from 50 to 100, Fig. 5.14.

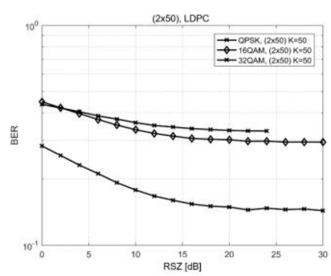


Fig. 5.13 *BER versus RSZ with LDPC for 50 active users, in a MIMO configuration of (2x50)*

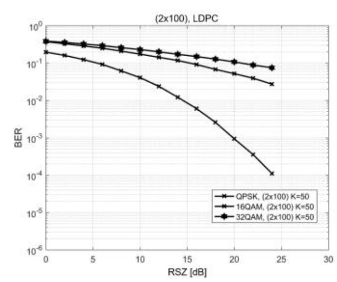


Fig. 5.14 *BER versus RSZ with LDPC for 50 active users, in a MIMO configuration of (2x100)*

5.4 Conclusions

If only the spatial diversity offered by massive MIMO is used, the following are found: with the increase of the modulation order, the system performance deteriorates. The same thing happens when the number of active users at a given time on the channel is increasing. When the number of antennas at the base station is increased, the performance becomes better. Also, with the introduction of OFDM, it was observed that performance continues its upward trend. If until now only the MMSE detector was used, the MMSE-SIC detector was also chosen.

Chapter 6 Analysis of the performance of a massive MIMO system in the presence of LDPC, OFDM and relays

6.1 Introduction

In order to further improve the performance of some communication systems, the idea of cooperative communication has been introduced, discussed in detail in subchapter 3.8. The following simulations address a massive MIMO system and try to explain whether or not the cost of implementing of a much larger number of antennas at the base station is justified.

6.2 Amplify-and-Forward protocol (AF)

The signal received at the relay is scaled and the resulting signal is transmitted to the destination. The scaling operation is made using an amplification factor described as follows

$$A_k = \sqrt{\frac{P_R}{P|\boldsymbol{G}_k|^2 + \sigma_{SR,k}^2}}, k = 1,2,..,K, \qquad (6.3)$$

where $\boldsymbol{G}_k$ is the channel matrix from source to relay for user k, P_R is the relay transmission power. The signal from the relay to the destination can be modelled as follows

$$\boldsymbol{y}_{RD} = \sum_{k=1}^{K} A_k \boldsymbol{F}_k \boldsymbol{y}_{SR,k} + \boldsymbol{n}_{RD,k}, k = 1,2,..,K \qquad (6.4)$$

where $\boldsymbol{F}_k$ is the channel matrix from the relay to the base station, for user k and $\boldsymbol{n}_{RD,k}$ represents the AWGN from the relay to the base station, for user k. Two copies of the same signal will arrive at the base station, one directly from the source and the other from the relay. The two copies are considered synchronous. An MRC detector is used to combine these received signals. Knowing the coefficients of the channel, then

$$\boldsymbol{y} = \alpha_1 \boldsymbol{y}_{SD} + \alpha_2 \boldsymbol{y}_{RD}, \qquad (6.5)$$

where $\alpha_1 = \frac{\sqrt{P}\boldsymbol{H}_k^*}{\sigma_{SD,k}^2}$ and $\alpha_2 = \frac{\sqrt{P_R} A_k \boldsymbol{G}_k^* \boldsymbol{F}_k^*}{A_k|\boldsymbol{F}_k|^2 \sigma_{RD,k}^2 + \sigma_{RD,k}^2}$, for $k=1,2,..,K$.

6.3 Decode-and-Forward (DF)

The approach is similar to the AF protocol, the change occurs for the relay-destination link. Therefore, it will be rewritten as follows

$$\boldsymbol{y}_{RD} = \sum_{k=1}^{K} \sqrt{\widetilde{P_R}} \boldsymbol{F}_k \boldsymbol{x}_k + \boldsymbol{n}_{RD,k}, k=1,2,..,K \qquad (6.9)$$

where $\widetilde{P_R} = P_R$ if the signal is decoded correctly at the relay. Two copies of the same signal will arrive at the base station and an MRC detector is used to combine them. If the channel coefficients are known, the output of the MRC detector follows the previously relationship shown, in the case of AF, but $\alpha_1 = \frac{\sqrt{P}\boldsymbol{H}_k^*}{\sigma_{SD,k}^2}$ and $\alpha_2 = \frac{\sqrt{P_R}\boldsymbol{F}_k^*}{\sigma_{RD,k}^2}$, for k = 1,2, .., K.

6.4 The influence of the number of antennas / massive MIMO configurations on the performance of a system with an AF and DF relay between source and destination

This subchapter will analyze the results obtained by a massive MIMO system when AF or DF relays are introduced. The results are presented in [23]. Fig. 6.2 shows the results obtained with and without AF relay, with 10 to 20 users, the base station has 10 antennas. It is observed that, in both situations, the involvement of the relay brings extra efficiency. Increasing the number of users leads to a deterioration of results. In Fig. 6.3 it can be seen the performance of DF, 20 users, where, as SNR increases, BER decreases faster than when using AF.

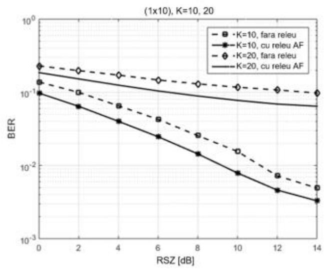


Fig. 6.2 Massive MIMO system with multiple users in configuration (1x10) with and without relay, AF protocol

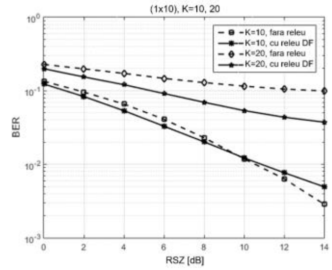


Fig. 6.3 Massive MIMO system with multiple users in configuration (1x10) with and without relay, DF protocol

6.5 The influence of the number of antennas / massive MIMO configurations on the performance of a system with a DF relay between source and destination when the mobile terminal is or is not in the coverage area of the base station

In this subchapter it will be studied the results obtained by a massive MIMO system, on the uplink, when between the source and the destination are introduced relays using DF protocol. Two situations were discussed: one in which the active users are in the coverage area of the base station and the other in which the active users are outside the coverage area of the base station. The results are presented in [24].

6.5.1 The mobile terminals are in the coverage area of the base station

In Fig. 6.6 was taken into account when both the base station and the relay have 10 antennas, with 10 and 20 users, respectively. If the number of users is equal to the number of antennas at the base station and relay, the presence of the relay improves the quality of the data reaching the base station. If the number of users is doubled, the relay does not bring a significant improvement because the interference between users is higher and the MMSE detector installed at the relay cannot reduce it, the data cannot be decoded perfectly and the relay forwards data with errors. If the number of active users is equal to 20 and the number of antennas from the base station is increased to 50, and the number of antennas from the relay varies between 25 and 100, Fig. 6.7 is obtained. When the number of antennas in the relay increases then the performance will be better.

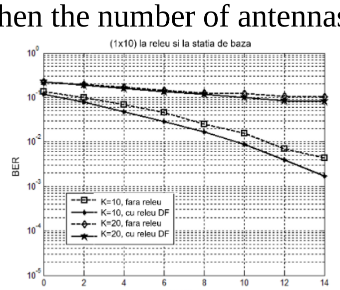


Fig. 6.6 System performance when there are 10 antennas at the base station and 10 antennas at the relay, DF protocol

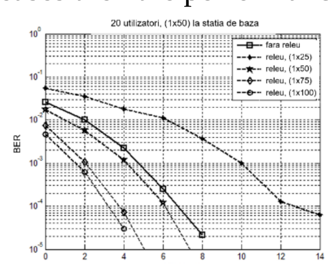


Fig. 6.7 System performance when at the base station are 50 antennas and 20 active users, DF protocol

6.5.2 The mobile terminals are outside the coverage area of the base station

For Fig. 6.9 it should be noted that the number of antennas at the relay varies from 25 to 50. When the number of antennas at the base station is 50 and at the relay there are 25 antennas, the performance is similar to that in which there are 25 antennas at the base station. The quality of the information that reaches the reception is better when the relay is equipped with a larger number of antennas.

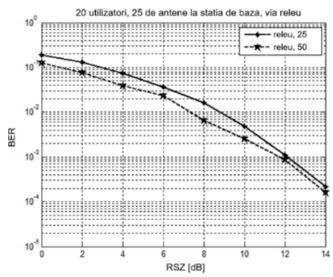


__Fig. 6.9__ System performance when at the base station are 25 antennas and 20 active users, DF protocol

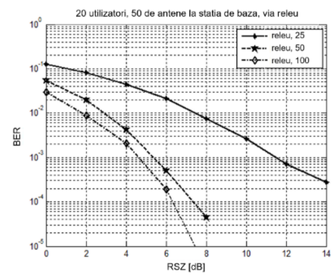


__Fig. 6.10__ System performance when at the base station are 50 antennas and 20 active users, DF protocol

6.6 The influence of the number of antennas / massive MIMO configurations on the performance of a system in the presence of OFDM with an AF relay between source and destination

In order to improve the performance obtained, OFDM modulation has also been introduced and the results can be found in [25]. Fig. 6.11 shows the results obtained by the system when used by 10 and 20 users, respectively (1x10). The increase in the number of active users has a visible effect on the overall performance of the system in both situations, with and without relay. Fig. 6.12 was obtained in conditions similar to the previous one, but the number of antennas at the reception is increased from 10 to 50. The improvement, in this situation, is brought by the spatial diversity offered by the massive MIMO. The advantage of using AF relays is visible when the number of active users increases, especially when SNR has low values.

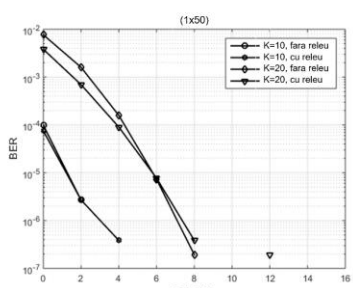


__Fig. 6.11__ BER versus RSZ in configuration (1x10) with and without relay, AF protocol

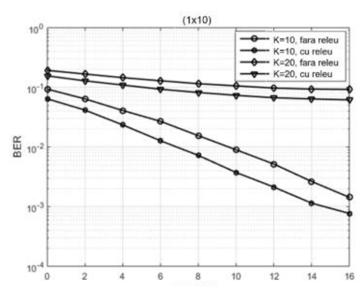


__Fig. 6.12__ BER versus RSZ in configuration (1x50) with and without relay, AF protocol

6.7 The influence of the number of antennas / massive MIMO configurations on the performance of a system in the presence of LDPC, OFDM, with an AF relay between source and destination and MMSE and MMSE-SIC detectors

To complete a digital communications system, coding using LDPC codes has also been added to the previously proposed system. The results are published in [26]. In Fig. 6.14 is evaluated the performance obtained using BPSK, the MMSE-SIC detector, (1x10), 10 users and better results are obtained than when using QPSK. If the number of users increases, then the system resources are divided among them and poorer results are obtained. Fig. 6.17 presents the results obtained by the BPSK modulation and Fig. 6.18 those obtained by QPSK modulation, (1x50). It can be seen that the improvement is greater as the number of users increases.

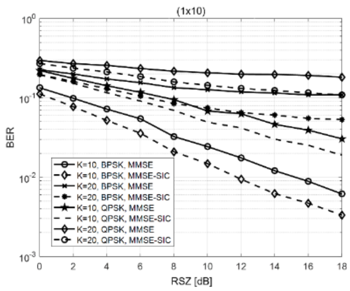


Fig. 6.14 *BER versus RSZ, (1x10) MIMO Massive, with LDPC, when the number of active users is equal to 10 and 20*

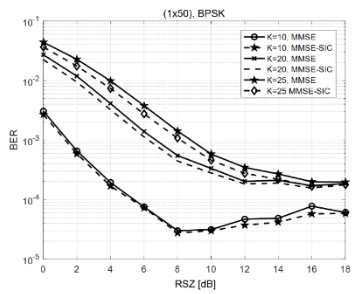


Fig. 6.17 *BER versus RSZ in a Massive MIMO (1x50) configuration, with LDPC and BPSK modulation, when the number of active users is equal to 10, 20, 25*

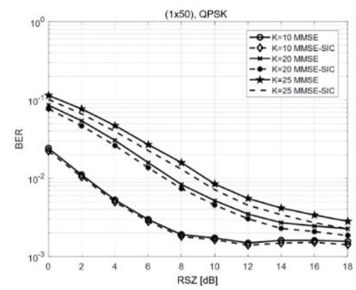


Fig. 6.18 *BER versus RSZ in a Massive (1x50) MIMO configuration, with LDPC and QPSK modulation, when the number of active users is equal to 10, 20, 25*

6.8 Conclusions

The purpose of this chapter was to evaluate the performance of a massive MIMO system with multiple users when a relay is implemented between source and destination. It has been shown that using a relay can improve performance, especially when the number of active users is close to the number of antennas at the base station. When the OFDM modulation was introduced, the results were even better, the cost of their implementation being thus justified. Furthermore, by introducing the LDPC encoding, the MMSE and MMSE-SIC detectors used to estimate the information transmitted by each active user and thus lead to an even more obvious improvement in the quality of the information that reaches the reception.

Capitolul 7 Multi-User Shared Access

Non-Orthogonal Multiple Access (NOMA) in the code domain performs a code multiplexing of users using unique spreading codes for each user with low density and low intercorrelation properties. As long as the orthogonality property is not respected, these schemes can provide grant-free access, but interference between users is present; therefore, at least in the light of these aspects, these schemes can be seen as an involution compared to CDMA [27]. As an example of such a scheme we can give MUSA [28].

7.1 MUSA

In MUSA, short, complex spreading codes are used due to additional grades of freedom offered by the imaginary part, therefore can support a much larger number of users who share the same block of resources, practically performing a superposition process [30]. In this doctoral thesis are used complex spreading codes from the set {-1, -1-i, -1 + i, -i, 0, i, 1, 1-i, 1 + i}. Another idea would be to build complex codes starting from PN or Walsh spreading codes. A code can be obtained by combining the rows of the matrix containing PN or Wlash codes, taking into account that a single row can be used only once.

7.2 The influence of the number of antennas / massive MIMO configurations on the performance of a system in the presence of LDPC, OFDM, with a DF relay between source and destination, using MUSA multiple access and MMSE detector

The performance of the proposed system assessed in this subchapter has been presented in the journal article [31]. Table 7.2 summarizes the results obtained in the simulations using Walsh and PN spreading codes, SNR of 12 dB, 16 users, highlighting that the most favorable combination, to have the best performance, which is the one with 30 antennas at the relay.

Tabelul 7.2 *BER versus SNR for Walsh și PN spreading codes for SNR=12dB*

	(1x26x30)	**(1x30x30)**
Walsh	0.0064606	0.00409
PN	0.01667	0.004346

In Fig. 7.4 and Fig. 7.5 are the results obtained by MUSA and $MUSA_0$, with 12 and 16 active users. Fig. 7.6 presents the results obtained by the complex codes obtained starting from PN.

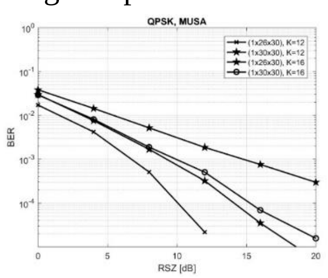


Fig. 7.4 *BER versus RSZ for (1x26x30) and (1x30x30) MIMO Massive configurations, QPSK modulation, MUSA with 12.16 active users*

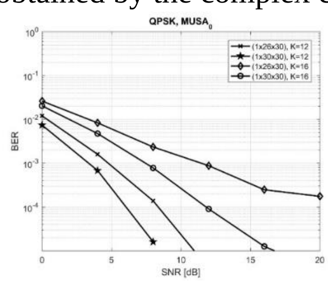


Fig. 7.5 *BER versus RSZ for (1x26x30) and (1x30x30) MIMO Massive configurations, QPSK modulation, $MUSA_0$ with 12.16 active users*

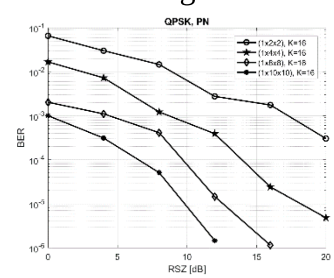


Fig. 7.6 *BER versus RSZ for (1x26x30) and (1x30x30) MIMO Massive configurations, QPSK modulation, MUSA with 12.16 active users*

It is easy to see that the new code combination has significantly reduced the values for BER, the improvement being even more important as SNR increases.

7.3 Conclusions

The purpose of this chapter was to evaluate the performance of a Massive, uplink MIMO system when a DF relay is implemented, using LDPC channel coding and OFDM modulation when users are separated using complex spreading codes from four different sets of MUSA, $MUSA_0$, EMUSA and $EMUSA_0$ codes. The performance of the new code sets is highlighted by comparison with the classic Walsh and PN spreading codes, the latter being outclassed. The situation in which the number of receiving antennas from the relay is different from the number of receiving antennas at the destination was also analyzed and some discussions were made about the compromise to be made between processing complexity, total rate and bandwidth occupied, and the level of performance required. A new approach, described and tested in this doctoral thesis, is that in which complex spreading codes are obtained starting from Walsh and PN. The obtained results are promising and are directly related to the length of the used code.

Chapter 8 Conclusions

The purpose of this doctoral thesis was to analyze the performance of a communication system when implementing a series of technologies to prevent possible factors that may damage the quality of information that reaches the reception.

8.1 The obtained results

In *Chapter 2*, a theoretical presentation of three modulation techniques was made, then of OFDM combined with BPSK and QPSK. In *Chapter 3* were mentioned the elements that influence the quality of the transmitted signal. The MIMO technology and the principle of cooperation were also presented here. In the next chapter, the behavior of the technologies presented in Chapters 2 and 3 was simulated in Matlab, when a randomly modulated bit sequence passes through a channel affected by Rayleigh and Rice fading. In addition, the author replaced this random bit sequence with black-and-white images. *Chapter 5* studies the behavior of LPDC codes in a massive MIMO system, using Matlab. At the reception, the estimation of the transmitted information is done using the MMSE and MMSE-SIC detectors. In *Chapter 6* a theoretical introduction of AF and DF was made, when the system was used by several users simultaneously. *Chapter 7* began with a theoretical presentation of MUSA. Its performance was tested by comparison with CDMA, when the number of receiving antennas for the relay, the number of users and the length of the spreading code used were varied. Moreover, the author also presented a new method to obtain complex spreading codes starting from PN spreading codes.

8.2 Original contributions

The scientific research carried out during the doctoral thesis and presented during this paper brings to the fore the following original contributions:

1. Implementation, in Matlab, of a system with 4 users and multiple access CDMA (Walsh and PN spreading codes) which transmits, in the first phase, random data and then being replaced with images in gray tones. Performance evaluation is made using BER versus SNR and the MSSIM index. The communication channel is affected by Rayleigh fading.
2. The simulations from 3 are repeated, but the communication channel is affected by Rice fading, taking into account various values for the Rice factor.
3. Implementation, in Matlab, of a system with a high number of users and a high number of receiving antennas. Performance evaluation using BER versus SNR, in the absence of OFDM and in the presence of OFDM varying the number of users and the number of antennas at reception. The communication channel is affected by Rayleigh fading.
4. Evaluating the performance of a Massive MIMO system in the absence and presence of OFDM, using MMSE and MMSE-SIC detectors.

5. Evaluating the performance of a Massive MIMO system in the presence of LDPC, using the MMSE detector when there is smaller or smaller number of active users in the network.
6. Evaluation of the performance of a Massive MIMO system when a relay has been inserted between the source and the destination using either the AF or DF protocol. The MMSE detector was used at the destination.
7. Evaluating the performance of Massive MIMO system when a relay has been inserted between source and destination using DF protocol when the user is or is not in the coverage area of the base station. The configuration of base station and relay antennas is different.
8. Evaluating the performance of a Massive MIMO system when a relay using the AF protocol has been introduced between source and destination, in the presence of OFDM.
9. Evaluating the performance of a Massive MIMO system when a relay has been introduced between the source and the destination using the AF protocol in the presence of LDPC, OFDM, MMSE and MMSE-SIC detectors.
10. Theoretical analysis of complex spreading codes and the multiple access technique that uses them, namely MUSA.
11. Propose a new method for obtaining complex spreading codes, starting from PN and Walsh spreading codes.
12. Evaluating the performance of a Massive MIMO system when using complex spreading codes versus Walsh and PN codes.

8.3 List of published papers

The scientific research carried out during the doctoral thesis includes a number of 17 scientific papers published at specialized international conferences or journals. The scientific papers that have been published to support the purpose of the thesis are the following:

1. **M. Berceanu**, C. Voicu și S. Halunga, „Performance analysis of a large MIMO-CDMA system when image transmission is involved," *2016 International Conference on Communications (COMM)*, 9-10 June 2016, DOI: 10.1109/ICComm.2016.7528257 **(ISI, IEEE)**.
2. **M.-G. Berceanu**, C.Voicu și S. Halunga, „The analysis of MAI in large scale MIMO-CDMA system," *Proc. SPIE* 10010, Advanced Topics in Optoelectronics, Microelectronics, and Nanotechnologies VIII (ATOM-N), 1001027, 25-28 August 2016, Constanța, DOI:10.1117/12.2243177 (**ISI**).
3. **M. Berceanu**, C. Voicu și S. Halunga, "Performance Analysis of an Uplink Massive MU-MIMO OFDM-Based System," *2018 International Conference on Communications (COMM)*, București, 2018, pp. 335-9, doi: 10.1109/ICComm.2018.8484273 (**ISI, IEEE**).
4. **M.-G. Berceanu**, C. Voicu, și S. Halunga „Uplink massive MU-MIMO OFDM-based system with LDPC coding-simulation and performances," *Proc. SPIE* 10977, Advanced Topics in Optoelectronics, Microelectronics, and Nanotechnologies IX (ATOM-N), 109770V, Constanța (**ISI**).
5. C. Voicu, **M.-G. Berceanu** și S. Halunga „The use of relays in uplink MU Massive-MIMO system", *Proc. SPIE* 10977, Advanced Topics in Optoelectronics, Microelectronics, and Nanotechnologies IX (ATOM-N), Constanța, 1097722 (**ISI**).
6. **M. Berceanu**, C. Voicu și S. Halunga, „AF Relaying in a Massive Mu-Mimo Ofdm System," *2018 IEEE 24th International Symposium for Design and Technology in*

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8.4 Prospects for further development

The research with massive MIMO and MUSA will be continued, when a sequence of random bits is transmitted in the absence / presence of a relay. In addition, I want to analyze performance when obtaining complex spreading codes from PN and Walsh. Another direction of development is the analysis of the situation when Manchester coding is introduced, for which we started the research in [32] and [33]. I want to further analyze the situation in which the random bit sequence is replaced with black-and-white PNG images, using Walsh and PN codes. Black-and-white PNG images will later be replaced with color images (JPEG) and video (MPEG). Another direction of development is to implement a larger number of relays and to compare the performances obtained with the situation in which only one relay is used. The next step is to implement an optimal relay selection algorithm based on the distance to the destination and power. If so far only the uplink has been analyzed, another development direction is the downlink analysis, for which we started the research in [34].

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