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Considerations on CDMA–OFDM System Performances in Different Channel Environments for Different Modulation and Coding Scenarios

Razvan Craciunescu · Oana Manea · Simona Halunga · Octavian Fratu · Dragos Nicolae Vizireanu

Abstract This paper presents a number of results obtained based on a CDMA–OFDM simulator developed in Matlab. The simulator has been extended to accommodate in a flexible manner to different modulation schemes, multiple access techniques, spreading codes types and lengths, convolutional codes rates, number of users and types of channels. The performances are evaluated and compared based on the Bit Error Rate (BER) as a function of the Signal to Noise Ratio (SNR) results achieved in different scenarios. In this paper are presented the results obtained by the developed simulator for two types of spreading codes—perfectly orthogonal Walsh type codes versus pseudo-orthogonal Gold type codes. The performances are evaluated in different channel environments the classical AWGN, pedestrian, vehicular and indoor ITU-R M.1225 models, for BPSK and QPSK modulations and 1/2 respectively 3/4 rate channel coding. Furthermore, since the results shown that the Gold spreading codes, QPSK modulation and 1/2 rate coding achieves the best performances in all type of channels analyzed, the authors investigate the effect of the code length and of the number of users on these results.

Keywords OFDM · CDMA · Spreading codes · Performances · BER

1 Introduction

During the last decades several modulation and multiple access schemes have been developed, each of them having their specific advantages and disadvantages. The classical Orthogonal Frequency-Division Multiplexing (OFDM) system has numerous advantages, among which we can mention that it can face severe fading channel conditions without the need of complex equalization algorithms, the Inter Symbol Interference (ISI) is reduced due to longer bit or symbol period and by the proper choose of the cyclic prefix. However it proves to be sensitive

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R. Craciunescu · S. Halunga (✉) · O. Manea · O. Fratu · D. N. Vizireanu
Faculty of Electronics, Telecommunications and Information Technology, Politehnica University of Bucharest, Splaiul Independentei, nr. 313, Sector 6, 060042 Bucharest, Romania
e-mail: shalunga@elcom.pub.ro

to frequency offset errors or timing issues and may lead to relatively high Peak-to Average Power Ratios (PAPR).

The Orthogonal Frequency-Division Multiple Access (OFDMA) multiple access schemes are efficient if the subcarrier frequency allocation is properly developed, providing flexibility of deployment into fragmented spectrum environment but, on the other hand, requires complex software/hardware equipment to be implemented, it proves to be sensitive to frequency selective channels when only a small number of carriers are used and requires a coordination of the carrier allocation in neighboring cells to ensure a reduced level of co-channel interference. Code Division Multiple Access (CDMA) is significantly simpler to implement then OFDMA and is significantly affected by frequency selective channels due to its large bandwidths, but it does not offer spectrum aggregation options, the capacity is limited by multiuser interference and, may achieves lower spectral efficiency then OFDMA with Multiple-Input and Multiple-Output (MIMO) [1].

In order to exploit all the advantages of these systems, one can find a method to combine them in order to take benefit of all their advantages. Such a combination may be made between the OFDM technique and the CDMA systems, such that each spread symbol is mapped on an OFDM subcarrier. In such a way, the system will take benefit of both OFDM advantages, such as adjacent channel interference avoidance, the ability of reducing the inter-symbol interference by choosing appropriately the cyclic prefix and the facility to implement low complexity channel equalizers as well as on the Multi-Carrier CDMA (MC-CDMA) benefits, like a low complexity implementation and a more straight-forward channel allocation technique. Such an OFDM–MC-CDMA system has numerous advantages, such as the ability operate in worse channel conditions, determined by selective fading or multipath phenomena with low cost implementation techniques, as well as good anti-jamming properties and low probability of intercept.

A second advantage stands from the fact that the CDMA-type systems has a soft limit of the capacity, since the number of codes in CDMA system is relatively high, the limitation appearing from the self-interference of the codes if they are pseudo-orthogonal. Moreover, the CDMA–OFDM combination allows optimal detection at the receiver, offers the possibility to use the available spectrum in an efficient way, it allows simple cell-separation by using frequency hopping, and a simple hardware realization then OFDMA [2].

Several papers published lately address the issue of performances in an MC-CDMA system under different circumstances. In [3] the authors investigate the resource allocation issues multiuser wireless transmissions based on OFDM technique based on convex and stochastic optimization tools. In [4] are investigated some aspects regarding subcarrier and power allocation issues for an OFDM-based multiuser cognitive radio (CR) system.

In [5] a based blind channel estimation scheme is proposed for downlink wideband Wideband-CDMA (W-CDMA) systems using chaotic codes under Weibull and Lognormal fading channel conditions, results showing that the multiuser-OFDM system achieves better performance than the W-CDMA one. In [6] the authors investigate the near far effects in Minimum Mean Square Error (MMSE) linear multiuser detection, proposing a method to reduce the transmit-power dependent user-specific bit error rates by introducing an additional post-processing by a combination of nonlinear parallel and successive interference cancellation.

In [7] a low bit error rate/low complexity MIMO multiuser detector for OFDM systems is proposed, and performances are analyzed under different channel environments. In [8] the authors derive the error probability expression for an MC-CDMA system with maximal ratio combining in correlated Nakagami channels, and evaluate the error probability bounds for spatially multiplexed MC-CDMA systems with zero forcing unified successive interference cancellation technique, while in [9,10] the authors analyze the effect of blind residual carrier frequency offset and timing offset on minimum output variance criterion using uplink MC-CDMA systems in AWGN and multipath channel environment.

In [11] the authors evaluates the performances of efficient image transmission over MC-CDMA systems using chaotic interleaving while in [12] are presented the results obtained by several multiuser detectors when image transmission is involved. In [13] the performances of multiuser CDMA systems with different space time code schemes are analyzed when the channel is affected by Nakagami fading and in [14] the authors presents the performances of different modulation schemes in a multi-user OFDM system for different lengths of the cyclic prefix, while in [15] the performances of three subcarrier allocation methods used by OFDMA for different modulation schemes and under different channel conditions are analyzed.

The main scope of the present work is to evaluate the performances of a CDMA–OFDM system depending on the type of the spreading codes used—perfectly orthogonal Walsh type codes versus pseudo-orthogonal Gold type codes. The performances are evaluated in different channel environments the classical AWGN, pedestrian, vehicular and indoor ITU-R M.1225 models [16], for BPSK and QPSK modulations and 1/2 respectively 3/4 rate channel coding. The performances are evaluated and compared based on the BER as a function of the SNR results obtained based on extensive simulation performed in Matlab. Furthermore, since the Gold spreading codes, QPSK modulation and 1/2 rate coding show the best performances, the authors investigate the effect of the code length and of the number of users on these results.

The paper is organized as follows: Sect. 2 describes the OFDMA and CDMA main characteristics and the MC-CDMA system used to evaluate the performances, Sect. 3 presents the numerical results based on BER performances as a function of SNR and these performances are compared in different environments. In the final section, Sect. 4, a number of interesting conclusions are highlighted.

2 The OFDM–MC-CDMA System Model

In the OFDM systems, the frequency range is divided into a high number of orthogonal subcarriers, transmission being performed in parallel on all subcarriers, at a lower symbol rate, increasing thus the spectral efficiency. The data rate transmitted on each sub-carrier becomes lower as the number of subcarrier increase, therefore the symbol duration increases and the ISI caused by the multipath phenomenon or other channel imperfections is also reduced. The cyclic prefix (CP), added at the beginning of each symbol, help us in controlling the ISI, depending on the channel characteristics. Moreover, since the data transmitted on each sub-band has of narrow bandwidth, the transfer equivalent characteristic of the channel may be considered as being flat on each sub-band, so the estimation and compensation of the channel effects should be easier than in the case of wideband systems. The complex OFDM signal, during the $[mT_u, ; (m+1)T_u]$ time interval, can be written as

$$s_{OFDM}(t) = \sum_{k=1}^{N_c} x_k(t) = \sum_{k=1}^{N_c} a_k^{(m)} \mathrm{e}^{\jmath 2\pi k \Delta f t} \tag{1}$$

where N_c is the number of subcarriers used, $x_k(t)$ is the sub-stream modulated on the k-th subcarrier with the frequency of $f_k = k\Delta f$, $k = 1 \ldots N_c$ and is the m-th symbol transmitted on k-th subcarrier in each useful symbol duration T_u of the OFDM signal.

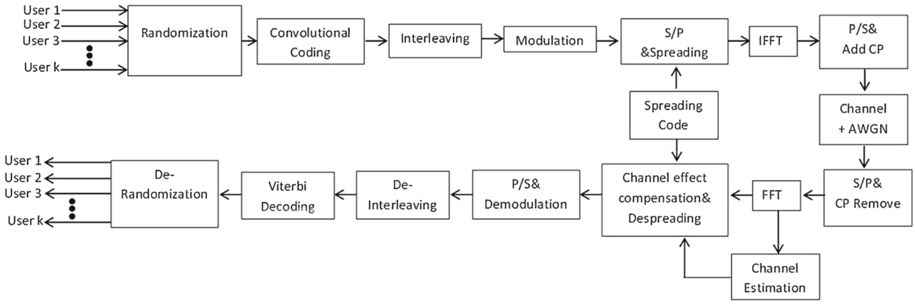

Fig. 1 The proposed MC-CDMA system

In order ensure the multiple access, we choose to use the CDMA principle, in which the users are identified based on their specific codes, with the chip rate larger than the data rate. Data receiving has to be performed based on the correlation between the received signal and each user's code, considered as being known at the receiver. In this paper we considered, for spreading purposes, two families of codes, namely the Walsh–Hadamard family and the pseudo-noise (PN) family, that includes the M-sequences, Gold codes and Kasamy codes. For a N users system, if $\sum_{j=1}^{N} c_{j,i}^{(m)}$ is the spreading code sequence used by user i, the OFDM–CDMA signal is

$$s_{OFDM-CDMA}(t) = \sum_{i=1}^{M} \sum_{k=1}^{N_c} a_{k,i}^{(m)} \sum_{j=1}^{N} c_{k,i}^{(m)} e^{J2\pi k\Delta f t} \tag{2}$$

The MC-CDMA system model used in our simulation is presented in Fig. 1. For simplicity purposes a two user system is implemented, even though the system can be extended to a larger number of users. One can see that the data from each user is first randomized, in order to avoid long data blocks of successive '0's or '1's, ensuring a better synchronization at the receiver. Next, the data is convolutionally encoded with a 1/2 or 1/3 rate code, in order to be able to detect and correct part of the errors at the receiver. The data stream is data is then interleaved in order to map the data on non-adjacent subcarriers but also to map the data bits, in the signal constellation, on relevant and irrelevant symbols. In the modulation block the data is modulated in accordance with one of the basic modulation schemes BPSK, QPSK, 16QAM, 32QAM, depending on the quality of the channel. Next the data is serial to parallel converted and spread with the user specific codes. In this paper the results obtained with 32 Walsh-Hadamard codes and 31 Gold codes respectively are presented. After that the Inverse FFT (IFFT) algorithm is applied, to convert the data form frequency domain to time domain. Finally the CP is added and the data is converted parallel to serial in order to be transmitted over the radio channel.

The radio channel is modelled using the ITU-R M.1225 recommendations, which empirically specify three types of environments that can be used for testing purposes: indoor office—inside a building, outdoor to indoor pedestrian for low speed users and vehicular-high antenna for high speed users. The channel parameters are given in Tables 1, 2 and 3 [16].

The indoor and pedestrian channels are characterized by low transmit powers and small cells. In the indoor case, the path loss varies due to scatter and attenuation by walls, floors, partitions and other cabinets. A log-normal shadow fading standard deviation of 12 dB can be expected. Fading ranges from Rician to Rayleigh, with Doppler frequency offsets set by

Table 1 Channel models for indoor office [16]

Path	Channel A		Channel B		Doppler spectrum
	Relative delay (ns)	Mean power (dB)	Relative delay (ns)	Mean power (dB)	
1	0	0	0	0	Flat
2	50	−3	100	−3.6	Flat
3	110	−10	200	−7.2	Flat
4	170	−18	300	−10.8	Flat
5	290	−26	500	−18	Flat
6	310	−32	700	−25.2	Flat
Doppler shift	1 Hz		1 Hz		

Table 2 Channel models for indoor office [16]

Path	Channel A		Channel B		Doppler spectrum
	Relative delay (ns)	Mean power (dB)	Relative delay (ns)	Mean power (dB)	
1	0	0	0	0	Classical
2	110	−9.7	200	−0.9	Classical
3	190	−19.2	800	−4.9	Classical
4	410	−22.8	1,200	−8	Classical
5			2,300	−7.8	Flat
6			3,700	−23.9	Classical
Doppler shift	70 Hz		70 Hz		

Table 3 Channel models for indoor office [16]

Path	Channel A		Channel B		Doppler spectrum
	Relative delay (ns)	Mean power (dB)	Relative delay (ns)	Mean power (dB)	
1	0	0	0	−2.5	Classical
2	310	−1	300	0	Classical
3	710	−9	8,900	−12.8	Classical
4	1,090	−10	12,900	−10	Classical
5	1,730	−15	17,100	−25.2	Flat
6	2,510	−20	20,000	−16	Classical
Doppler shift	100 Hz		100 Hz		

walking speeds. In the pedestrian case, the antennas are placed in higher locations then in the indoor case. A path loss rule of R^{-2} can be used in the areas with Fresnel clearance, while a loss proportional to R^{-4} is valid for the areas with no direct visibility, and even R^{-6} for shadowed areas. Log-normal shadow fading with a standard deviation of 10 dB can be used in the pedestrian case, as well as Rayleigh and/or Rician fading, with the rates set by

Table 4 Main parameters of the simulator

Bandwidth	10 MHz
FFT length	1,024
OFDM symbol duration	102.86 µs
Cyclic Prefix	11.429 µs
Total number of subcarriers	1,024
Number of useful/pilot/guard/DC subcarriers	720/120/183/1
Multiple access scheme	CDMA–OFDM/OFDMA
Modulation scheme	BPSK; QPSK; 16QAM; 64QAM
Coding rate	1/2; 2/3; 3/4
Number of users	2· · · 30
Spreading codes used for CDMA	Walsh; PN Gold; Kasami

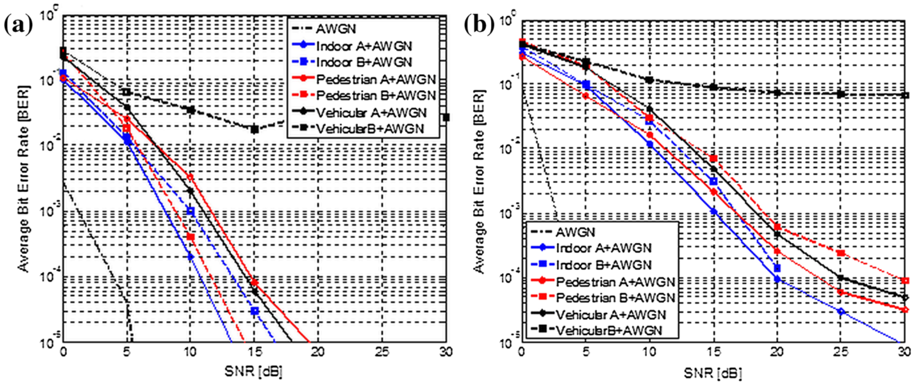

Fig. 2 Average BER versus SNR for 32 bits Walsh code spreading, BPSK modulation and convolutional coding. **a** Coding rate 1/2, **b** Coding with the rate 3/4

walking speeds. The vehicular channel model is characterized by higher transmit power and larger cells. A path loss proportional to R^{-4} fits the best for suburban or rural areas, while in mountain areas R^{-2} may be appropriate [16]. For each of the three environments are defined 2 types of testing parameters A and B, which show the time spread of the path delays as shown in Tables 1, 2 and 3 [16,17].

At the receiver the reverse operations has to be performed in order to recover the data: FFT, Derandomization, Despreading, DeInterleaving, Demodulation. Additionally, the receiver has to estimate the communication channel based on the symbols transmitted on the pilot sub-carriers, which have a fix position in the OFDM symbol. For this paper we used the Least Square (LS) method [18]. Finally, the decoding part is performed based on Viterbi decoding algorithm. The main parameters of the simulator are summarized in Table 4.

3 Simulation Results

Based on the Matlab Implementation of the system model described in Sect. 2, a large number of simulations have been performed to evaluate the performances of the proposed

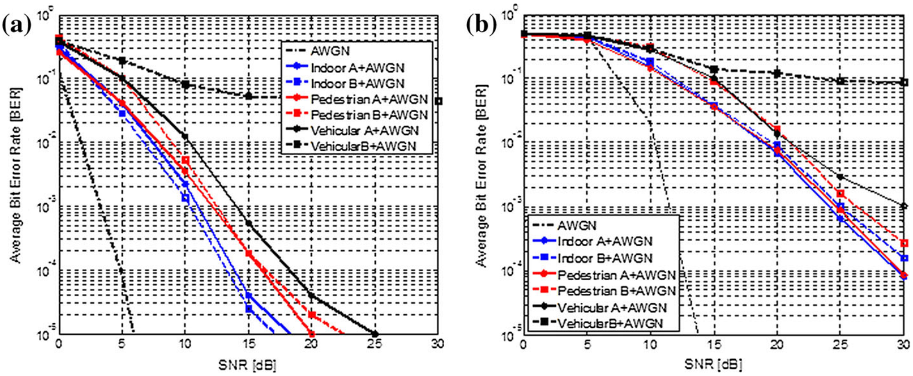

Fig. 3 Average BER versus SNR for 33 bits Walsh code spreading, QPSK modulation and convolutional coding. **a** Coding rate 1/2, **b** Coding rate 3/4

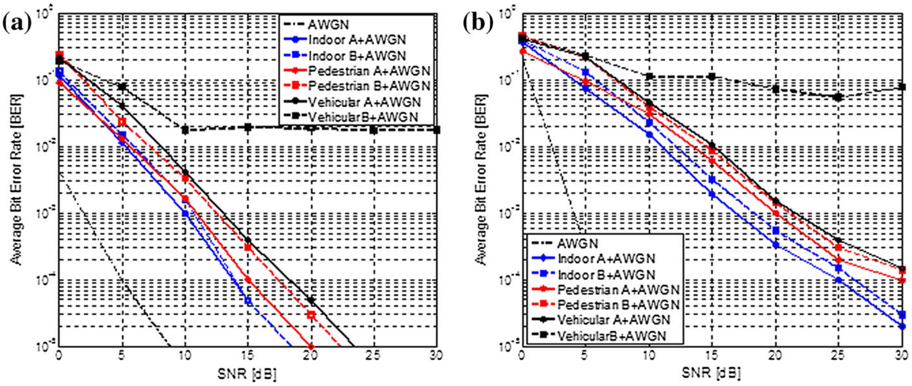

Fig. 4 Average BER versus SNR for 31 bits Gold code spreading, BPSK modulation and convolutional coding. **a** Coding rate 1/2, **b** Coding rate 3/4

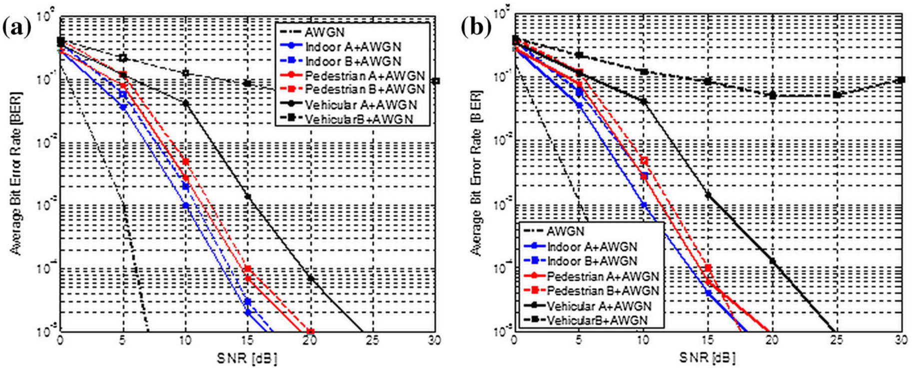

Fig. 5 Average BER versus SNR for 31 bits Gold code spreading, QPSK modulation and convolutional coding. **a** Coding rate 1/2, **b** Coding rate 3/4

Table 5 The average values for BER for the CDMA–OFDM strategies presented above at SNR = 15 dB

	AWGN	Ind. A	Ind. B	Ped. A	Ped. B	Veh. A	Veh. B
Walsh 32, BPSK, rate 1/2	0	14.63×10^{-5}	7.5×10^{-4}	2.65×10^{-3}	5.75×10^{-4}	2.25×10^{-3}	6.125×10^{-2}
Walsh 32, BPSK, rate 3/4	0	1.45×10^{-2}	2.2×10^{-2}	2.05×10^{-2}	3.5×10^{-2}	4.05×10^{-2}	0.155
Walsh 32, QPSK, rate 1/2	0	6.75×10^{-5}	13.5×10^{-5}	20.95×10^{-4}	2.4×10^{-4}	5.5×10^{-4}	0.1
Walsh 32, QPSK, rate 3/4	0	21.45×10^{-2}	1.05×10^{-2}	23.25×10^{-2}	4.5×10^{-2}	5.75×10^{-2}	0.225
Gold 31, BPSK, rate 1/2	0	4.02×10^{-5}	1.1×10^{-4}	5.175×10^{-4}	4.5×10^{-4}	4.75×10^{-4}	2.7×10^{-2}
Gold 31, BPSK, rate 3/4	0	2.15×10^{-3}	4.05×10^{-3}	6.02×10^{-3}	8.25×10^{-3}	1.3×10^{-2}	0.11
Gold 31, QPSK, rate 1/2	0	0.75×10^{-4}	15.75×10^{-4}	15.95×10^{-4}	1.45×10^{-4}	20.75×10^{-3}	9×10^{-2}
Gold 31, QPSK, rate 3/4	0	5.5×10^{-5}	5.5×10^{-5}	1.05×10^{-5}	9.75×10^{-5}	9.5×10^{-4}	8.25×10^{-2}

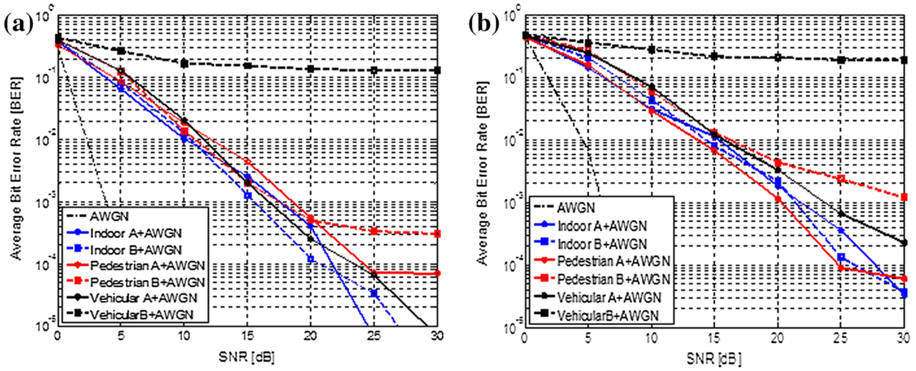

Fig. 6 Average BER versus SNR basic PUSC, QPSK modulation and convolutional coding. **a** Coding rate 1/2, **b** Coding rate 3/4

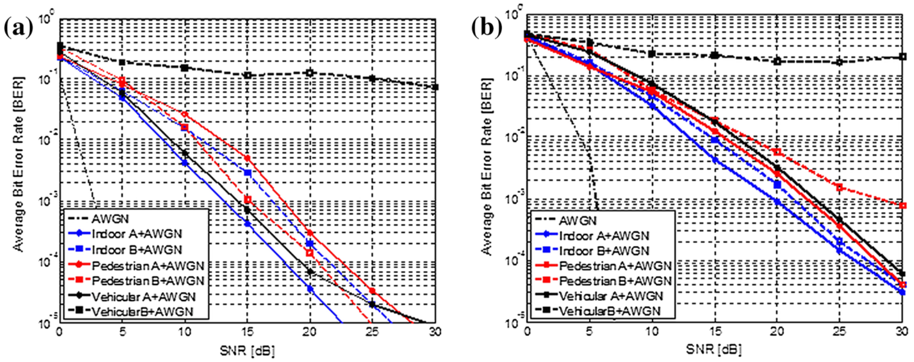

Fig. 7 Average BER versus SNR optional PUSC, QPSK modulation and convolutional coding. **a** Coding rate 1/2, **b** Coding rate 3/4

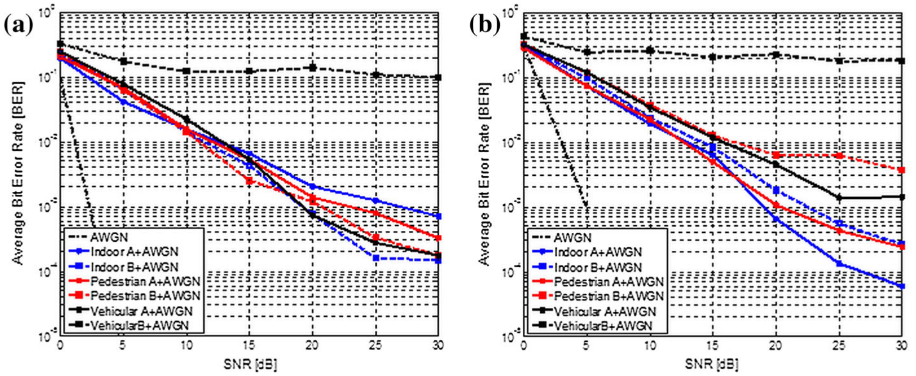

Fig. 8 Average BER versus SNR, AMC, QPSK modulation and convolutional coding. **a** Coding rate 1/2, **b** Coding rate 3/4

Table 6 The average values for BER for the CDMA–OFDM strategies presented above at $\mathrm{SNR} = 15\,\mathrm{dB}$

	AWGN	Ind. A	Ind. B	Ped. A	Ped. B	Veh. A	Veh. B
Basic PUSC, rate 1/2	0	1.3×10^{-3}	2.8×10^{-3}	3.5×10^{-3}	1.1×10^{-3}	1.2×10^{-3}	1.8×10^{-1}
Basic PUSC, rate 2/3	0	1.2×10^{-3}	8.5×10^{-3}	7.2×10^{-3}	1.2×10^{-3}	1.1×10^{-3}	0.19
Optional PUSC, rate 1/2	0	5.1×10^{-4}	2.3×10^{-3}	4.8×10^{-3}	1.2×10^{-3}	7.9×10^{-4}	0.12
Optional PUSC, rate 2/3	0	4.1×10^{-3}	8.6×10^{-3}	1.2×10^{-2}	2.1×10^{-2}	2.9×10^{-2}	0.13
AMC, rate 1/2	0	5.3×10^{-3}	2.5×10^{-3}	3.5×10^{-3}	5.2×10^{-3}	6.3×10^{-3}	0.12
AMC, rate 2/3	0	3.1×10^{-2}	2.8×10^{-2}	2.3×10^{-3}	5.8×10^{-3}	7.1×10^{-3}	1.9×10^{-3}

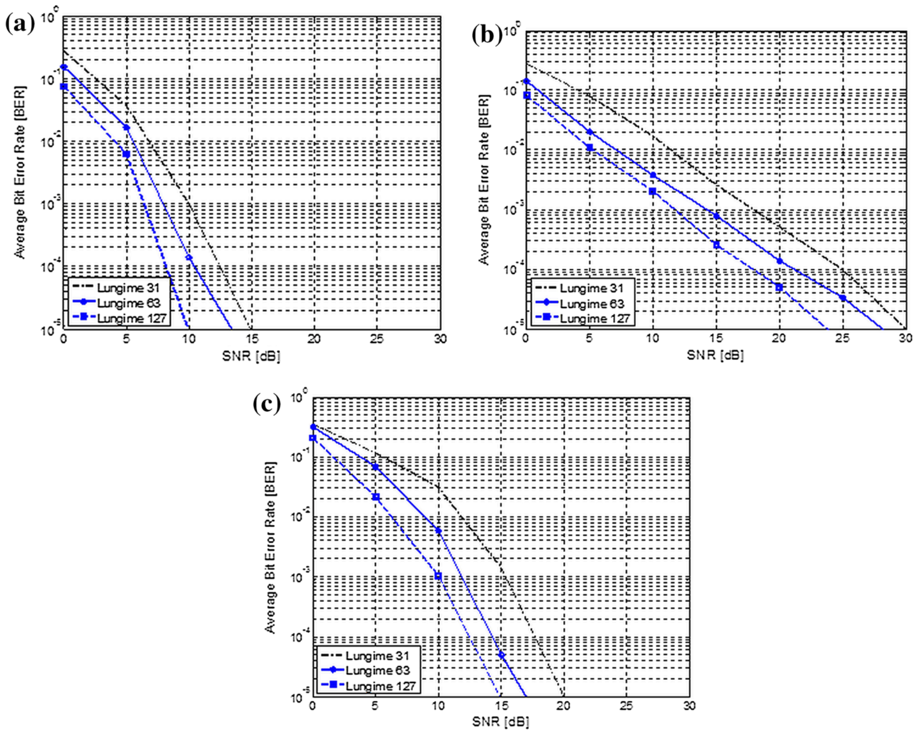

Fig. 9 Average BER versus SNR for 31/63/127 bits Gold code spreading, QPSK modulation and convolutional coding with the rate 1/2 for different channels. **a** Indoor A channel, **b** Pedestrian B channel, **c** vehicular A channel

system in terms of Bit Error Rate (BER) as a function of Signal to Noise Ratio (SNR). First we will present the performances of a two user CDMA–OFDM system for a Walsh–Hadamard spreading codes of length 32 (the code bit rate being thus 202.4 kbps) and for Gold spreading codes of length 31 (with the code bit rate of 211.6 kbps), for AWGN only channel and the six channel models presented above.

The results are presented for one of the two users in different circumstances regarding the modulation scheme used, namely BPSK and QPSK, with 1/2 and 1/3 convolutional coding rates, as follows. In Fig. 2 are presented the results obtained by using a 32 bits Walsh spreading code, BPSK modulation and convolutional coding with the rate 1/2 (Fig. 2a) and respectively 3/4 (Fig. 2b). In Fig. 3 the same results but for QPSK modulation are presented, in Fig. 4 the results obtained for 31 bits Gold spreading code and BPSK modulation will be presented. In Fig. 5 the results under the same conditions with QPSK modulation. The average BER obtained for each configuration at SNR = 15 dB are given in Table 5.

From those results we can highlight the following conclusions:

- the use of rate 1/2 code is significantly more efficient with respect to the performances achieved then the 3/4 rate code, the values of BER achieved with the first ones being 10^{-2}, 10^{-3} times lower then with the former ones;
- as expected, the use of BPSK modulation leads to lower BER values then the QPSK modulation, in a ratio of $10 : 10^{-2}$;

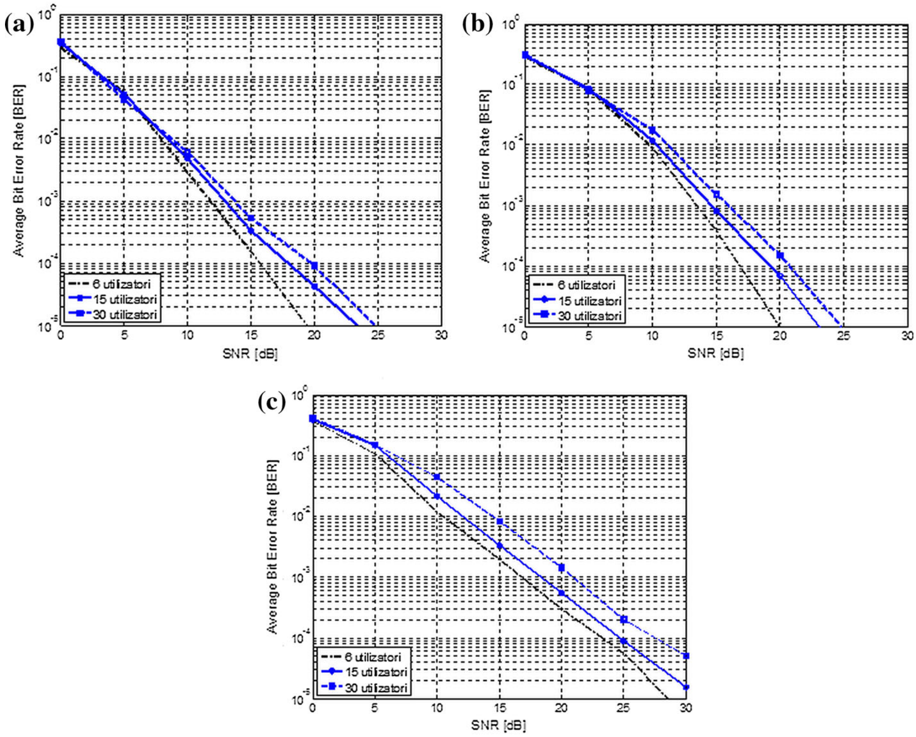

Fig. 10 Average BER versus SNR for 31/63/127 bits Gold code spreading, QPSK modulation and convolutional coding with the rate 1/2 for different channels. **a** Indoor A channel, **b** Pedestrian B channel, **c** vehicular A channel

- the best results are achieved with the AWGN only channel, which obtains values of BER less than 10^{-5} for SNR values less than 14 dB for all scenarios studied;
- in most cases the Indoor channels leads to smaller BER results then the Pedestrian ones, even though the difference is not very large;
- the use of Gold codes for spreading leads to better performances then the use OVSF ones, in the latter situation the results being dependent on the particular choice of code;
- the Vehicular A channel achieves higher BER results then the Indoor or Pedestrian ones, the highest difference being observed for Gold code spreading and QPSK modulation; the Vehicular B achieves the worse results in all environments, the values of BER decreasing very slowly as the power increase at about 10^{-1} at SNR = 30 dB.

As a comparison, in Figs. 6, 7 and 8, the results obtained under the same simulation scenarios by the classical OFDMA technique are presented. For the OFDMA simulations the basic Partially Usage of Sub-Channels (PUSC) subcarrier permutation algorithm, Optional PUSC algorithm, and Adaptive Modulation and Coding (AMC) algorithm, used in IEEE Std 802.16 [16] are implemented. The average BER obtained for each configuration at SNR = 15 dB summarized in Table 6. It can be easily observed that, for all algorithms, the BER values are significantly higher than the ones obtained by the OFDM–CDMA system.

To study the effect of the spreading code length on the system performances, in Fig. 9 are shown the results obtained for three different type of channels using 31, 63 and 127 bits Gold spreading codes, QPSK modulation and 1/2 rate coding. It can be easily observed that the

BER results are lower as the length of the code increases. On the other hand, as the spreading code is longer the rate of the spreaded data is higher, therefore we have to extend to overall bandwidth of the system has to increase, either by increasing the number of subcarriers, by increasing the frequency spacing between subcarriers allowing the increase of the bandwidth around each subcarrier or by increasing the order of the modulation (M-QAM with M = 32, 64 etc).

Finally, to study the effect of the number of users increase in the system performances, in Fig. 10 we represented the results obtained for the same type of channels using 31 bits Gold spreading codes, QPSK modulation and 1/2 rate coding, the system being use, in each case, by 6, 15 and 30 users. It can be observed that, as the number of users increase, the BER results increase slowly, this increase becoming more important when the SNR is high. For example, for 6 users we have a value of BER around 10^{-5} at a SNR = 20 dB for Indoor A and Pedestrian A channels and at SNR = 26 dB for Vehicular A channel, while for 30 users we need a SNR = 25 dB to reach a BER of 10^{-5} Indoor A and Pedestrian A channels and of 42 dB for Vehicular A. If the number of users will further increase is to be expected that the performance will degrade.

4 Conclusions

This paper studied the results obtained by an OFDM–CDMA system in different channel environments, based on the channel models recommended by ITU-R M.1225 for BPSK and QPSK modulation schemes, 1/2 and 3/4 convolutional encoding, 32 bits Walsh–Hadamard and 31 bits Gold codes for data spreading. We observed that the best performances are achieved by the AWGN only channel in all cases, followed by the Indoor type channels and the Pedestrian type ones. The worst results are obtained in all cases by the Vehicular B channel model, for which the BER values does not go under $2 \cdot 10^{-2}$ in any scenario. Since the QPSK modulation, rate 1/2 encoding and Gold codes spreading seemed to achieve better results than the other combinations, we further studied the effect of the code length increase on the BER performances based on this combination.

Simulations have shown the fact that the performances increase as the code length increases, but, on the other hand, since the data rate increase we have also to increase the system bandwidth. Finally, for the same scenario, we studied the effect of number of users increase on the system performances. Simulation results have shown that the BER increase as the number of users is higher, this effect being more pronounced at high SNR values.

The simulator is still under development to include multiuser techniques at the base station receiver, to introduce other type of codes, to study other channel models or to search optimization techniques for resource allocation in cognitive systems.

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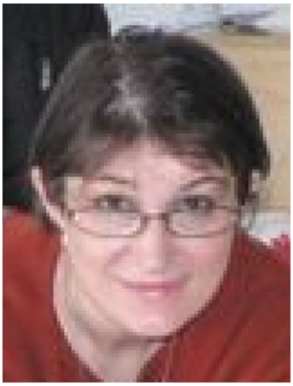
Razvan Craciunescu received the Engineer's degree and the Master's degree in electronic engineering and telecommunications from the University POLITEHNICA of Bucharest, Bucharest, Romania, in 2010 and 2012, respectively. He is currently a Ph.D. student, in the field of communication systems and optimization, at University POLITEHNICA of Bucharest, Romania. Since 2012 he is Teaching Assistant at the Faculty of Electronics, Telecommunications and Information Technology within the University POLITEHNICA of Bucharest. His research interests include Mobile Communications, Wireless Sensor Networks and System Optimization. His publications include more than 10 papers published in nationally and abroad or presented at international conferences. He participated as researcher in national and international projects such as "Optimization and Rational use of wireless Communication bAnds (ORCA)", NATO Science for Peace Research project (2013–2016), "eWALL—eWall for Active Long Living" (FP7 project, 2013–2016).

Oana Manea received the Engineer's degree in electronic engineering and telecommunications from the University POLITEHNICA of Bucharest, Bucharest, Romania, in 2013. Currently studying for the Master's degree in mobile communications at University POLITEHNICA of Bucharest, Romania. Current interests include broadband and mobile communication networks and systems. She is currently working as Radio Access Network (RAN) support engineer at ERICSSON Romania.



Simona Halunga received the M.S. degree in electronics and telecommunications in 1988 and the Ph.D. degree in communications from the University POLITEHNICA of Bucharest, Bucharest, Romania, in 1996. Between 1996–1997 she followed post-graduate courses in Management and Marketing, organized by the Romanian Trade and Industry Chamber and Politehnica University of Bucharest, in collaboration with Technical Hochschule Darmstadt, Germany, and in 2008- post-graduate courses in Project Management — Regional Centre for Continuous Education for Public Local Administration, Bucharest She has been Assistant Professor (1991–1996), Lecturer (1997–2001), Associate Professor (2001–2005) and from 2006 she is a full professor at in Politehnica University of Bucharest, Electronics, Telecommunications and Information Theory Faculty, Telecommunications Department. Between 1997–1999 she has been a Visiting Assistant Professor at Electrical and Computer Engineering Department, University of Colorado at Colorado Springs, USA. Her domain of interest are Multiple Access Systems & Techniques, Satellite Communications, Digital Signal Processing for Telecommunication, Digital Communications -Radio Data Transmissions, Analog and Digital Transmission Systems and Digital Signal Processing for Telecommunications.

Octavian Fratu received the PhD degree in Electronics and Telecommunications from the University POLITEHNICA of Bucharest, Romania in 1997. He achieved postdoctoral stage as senior researcher in 3rd generation mobile communication systems, based on a research contract between CNET—France, ENS de Cachan—France and Universite Marne la Vallee—France. He is currently an associated professor in Electronics, Telecommunications and Information Theory Faculty. His research interests include Digital Mobile Communications, Radio Data Transmissions, Mobile Communications and Wireless Sensor Networks, Radio communication networks. His publications include more than 100 papers published in national or international scientific journals or presented at international conferences. He participated as director or collaborator in many international research projects such as "Optimization and rational use of Wireless Communication Bands (ORCA)", NATO Science for Peace Research project (2013–2016), "Reconfigurable Interoperability of Wireless Communications Systems (RIWCoS)", NATO Science for Peace Research project (2007–2010), "REDICT—Regional Economic Development by ICT/New media clusters" (FP7 CSA project, 2008–2009), "ATHENA—Digital Switchover: Developing Infrastructures for Broadband Access", (FP6 STREP project, 2004–2006) and other.

Dragos Nicolae Vizireanu received the B.S. degree in electronics and telecommunications in 1992 and the Ph.D. degree in radiocommunications from the University Politehnica of Bucharest, Bucharest, Romania, in 1998. He has been Assistant Professor (1994–1999), Lecturer (1999–2002), Associate Professor (2002–2007) and from 2007 he is a full professor at University POLITEHNICA of Bucharest, Electronics, Telecommunications and Information Theory Faculty, Telecommunications Department. His domains of interest are Digital Signal Processing for Telecommunications, Image Processing and Electronic Measurements. He is author of 9 books and more than 100 papers published in journals or presented in international conferences.