Performance improvement of MC-CDMA microstatistic multi-user detection in nonlinear fading channels using spreading code selection

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In this paper, we present a novel method for joint suppression of multiple-access interference (MAI) and nonlinear distortion introduced by high power amplifiers (HPA) in multicarrier code division multiple access (MC-CDMA) transmission system performing over frequency selective channel. The proposed method combines a proper selection of the spreading code at the transmitter side and application of the advanced microstatistic multi-user detector (MSF-MUD) at the receiver side. This scheme exploits relatively low peak-to-average power ratio (PAPR) and orthogonality of Golay codes in conjunction with MSF-MUD ability of effective suppression of MAI and nonlinear distortion. In order to have a good reference for the performance results of the proposed scheme, conventional minimum mean square error multi-user detector (MMSE-MUD) is introduced as well. As it will be shown by means of computer simulations, MSF-MUD with Golay codes employed for spreading can clearly outperform the other tested spreading codes and MMSE-MUD. The performance improvement is more remarkable, if Saleh model of HPA is employed.

1. Introduction

Future wireless communication systems must be able to accommodate a large number of users and simultaneously to provide the high data rates at the required quality of service. MC-CDMA is taking the advantage of two advanced technological concepts of wireless communications such as orthogonal frequency division multiplex (OFDM) and the code division multiple access (CDMA), what results especially in high spectral efficiency, the multiple access capability, robustness in the case of frequency selective channels, simple one-tap equalization, narrow-band interference rejection and high flexibility of the MC-CDMA. The outlined potential properties of the MC-CDMA represent the fundamental reasons, why MC-CDMA has been receiving a great attention over the last decade (e.g. [1,2]) and has been considering to be a promising candidate for the future advanced wireless communication systems.

One of the major requirements posed to the MC-CDMA is to reach the required date rate at the acceptable bit error rate (BER) and acceptable complexity for the defined number of the active users. It has been shown e.g. in [3-5], that in the case of MC-CDMA systems, the BER at the constant number of the active users is affected especially by nonlinear effects due to the HPA of the MC-CDMA transmitter, MAI resulting from cross-correlation properties of the spreading codes assigned to the particular users and by transmission channel complexity.

The analyses of the MC-CDMA signals have shown that due to their multi-carrier nature, the transmitted MC-CDMA signal is characterized by large envelope fluctuation [6]. This property of MC-CDMA signals forces the MC-CDMA transmitter HPA to operate with large input back-off (IBO) in order to keep the required BER and the out-of-band radiation below imposed limits. However, the large IBO will result in inefficient exploiting of HPA and consequently decreasing the coverage of the area of interest by acceptable MC-CDMA signals. As a consequence of this fact, it is crucial to minimize the impact of the nonlinear amplification on the transmission system performance at low IBO.

There are several metrics applied for signal envelope fluctuation quantifying [7]. Here, PAPR has been widely accepted for that purpose. The analyses of the PAPR of the transmitted MC-CDMA signals presented in [3,4] have shown that PAPR can be reduced by proper selection of the spreading codes. The alternative solutions of MC-CDMA performance improvement can be achieved by the application of additional methods of PAPR reduction (e.g. [8,9]) and by the compensation methods of the nonlinear distortion due to the nonlinear HPA. The nonlinear distortion compensation methods can be implemented at the transmitter or receiver side of MC-CDMA transmission system. Frequently used solutions at the transmitter side include pre-distortion [10], tone reservation [11], active constellation extension, selected mapping [9], different code allocation strategies [12], etc. The strategies applied at the receiver side usually combine iterative decoding [13] and nonlinear multi-user detection [14,15].

Because of the CDMA exploited in the MC-CDMA structure, the BER reached by the particular users is strongly dependent on MAI. The level of MAI is primarily determined by the spreading codes assigned to the particular users and the transmission channel properties [6]. As the spreading codes for MC-CDMA, Walsh codes, Gold and orthogonal Gold codes, polyphase Zadoff-Chu codes as well as complementary Golay codes are mostly employed (e.g. [3-5]). In the case of wireless MC-CDMA systems, the transmitted signals are firstly nonlinearly distorted and subsequently they are affected by a fading channel. This effects can result in spreading code orthogonality loss and consequently, MAI increasing. Then, the level of the MAI can be reduced by the application of multi-user receivers [14,16].

As it follows from this short overview of the MC-CDMA performance degradation sources (PAPR, MAI, nonlinear distortion due to HPA), there are a number of approaches how to improve MC-CDMA performance (spreading code selection, PAPR reduction methods, multi-user receiver and nonlinear distortion compensation methods). Here, the application of the nonlinear multi-user receiver and simultaneously the properly selected set of spreading code application are considered as the very perspective solution.

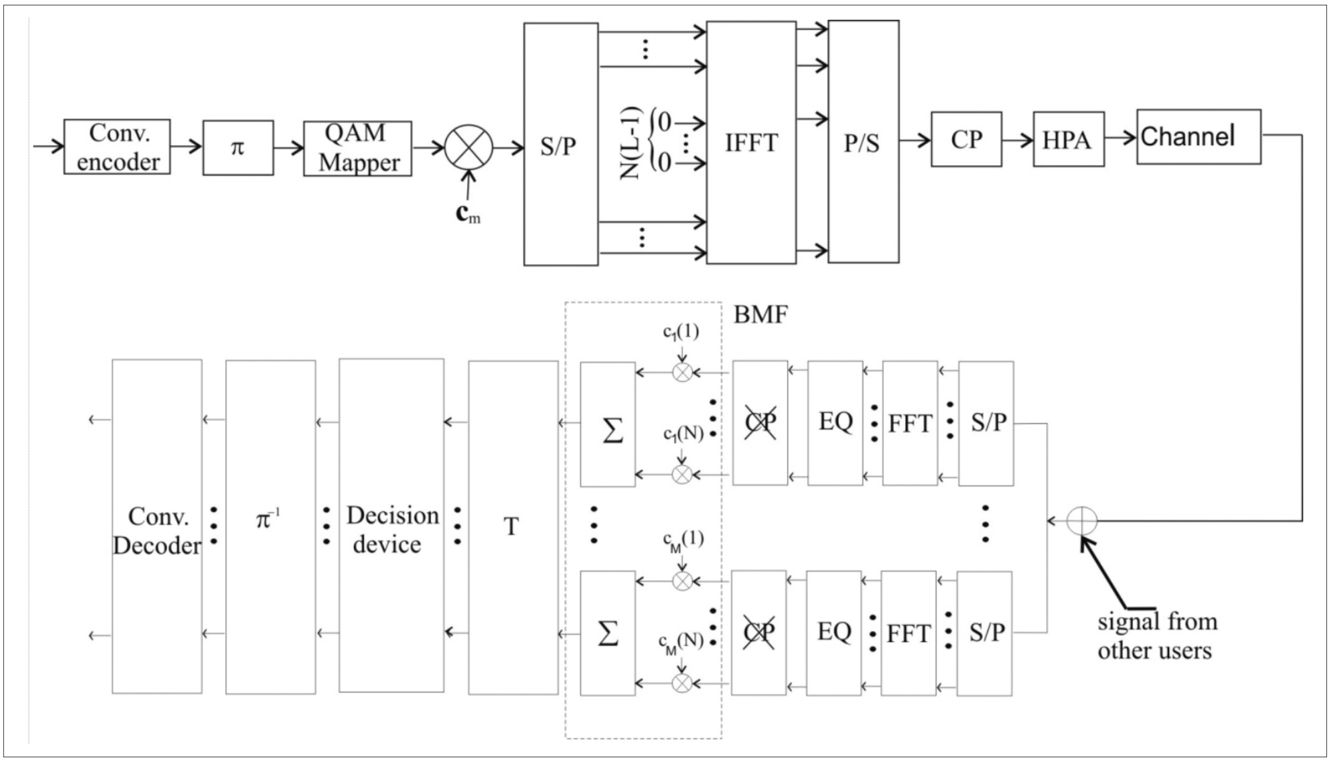
In this paper, we will deal with the performance analyses of MC-CDMA transmission system employing the nonlinear MSF-MUD and the different spreading codes. Originally, the MSF-MUD has been proposed in [14] as the multi-user receiver able to compensate the nonlinear distortion due to the HPA of transmitter. The performance properties of the MSF-MUD with regard to the different spreading codes for AWGN channel scenario have been discussed in [17]. This contribution is the extension of our previous study introduced in [17] to the analysis of MSF-MUD performance properties for the frequency-selective fading channel if Walsh codes, Gold and orthogonal Gold codes, polyphase Zadoff-Chu codes and complementary Golay codes are used as spreading sequences. As the nonlinear HPA model, Saleh and Rapp models have been taken into account. In order to illustrate the MSF-MUD performance, MMSE-MUD will be also applied as the MC-CDMA receivers. Because in [14,17], the design procedure of the MSF-MUD has been outlined only, the deeper description of the design procedure of the optimum MSF-MUD is included in this paper. The aim of our study is to find by means of computer simulations the pair of a receiver and a set of the spreading codes able to provide the best BER performance under the mentioned conditions. The simulation results show that the maximum improvement of the MC-CDMA performance compared to other system configurations (i.e. to all combination of MMSE-MUD with the different spreading codes) is achieved by MSF-MUD if the Golay codes are used as the spreading sequence. It will be also shown that this result is true especially for the scenario with strongly nonlinearly distorted MC-CDMA signals (i.e. for low values of IBO parameter).

The structure of our contribution is as follows. In the next section, the transmitter and channel model are briefly discussed. The MSF-MUD description and its design procedure are given in Section 3. The core of the paper is Section 4, where the computer simulations and obtained results are presented. Finally, some conclusions from the presented work are drawn in Section 5.

2. Transmitter and channel model

The block diagram of the simplified baseband model of MC-CDMA transmitter is depicted in *Fig. 1.* It can be seen from this figure that the information bits to be transmitted by a particular user are firstly fed to the block of non-

Figure 1. Block diagram of MC-CDMA communication system



recursive, non-systematic convolution encoder followed by the block of interleaving labeled by π in the presented scheme. Then, a baseband modulator transforms the encoded binary input to a multilevel sequence of complex numbers in M-QAM modulation formats.

The data obtained in such a way are spread by using a specific spreading sequence c_m, where c_m denotes the spreading sequence of the m-th user. As the spreading sequences, Walsh codes, Gold codes, orthogonal Gold codes, complementary Golay codes and polyphase Zadoff-Chu codes are considered [3]. The PAPR upper bound of the mentioned spreading codes is summarized in *Table 1* [3]. As it can be observed from this table, the PAPR bound of Golay codes and Zadoff-Chu codes is independent of the spreading code length L. If we assume that the subcarrier number N_c is a multiple of L, then PAPR of the Walsh codes is upper-bounded by $2N_c$ [3].

Spreading Codes	PAPR (upper bound)
Walsh codes	$\leq 2N_C$
Gold codes, orthogonal Gold codes	$\leq 2\left[t(m)-1-\frac{t(m)}{L}+\frac{2}{L}\right]$
Golay codes	≤ 4
Zadoff-Chu codes	2

Table 1.
PAPR bounds for MC-CDMA uplink signal

The spread symbols are modulated by the multi-carrier modulation implemented by the inverse fast Fourier transformation operation (IFFT). After parallel-to-serial (P/S) conversion, the cyclic prefix (CP) is inserted in order to mitigate the inter-symbol interference (ISI) caused by the frequency-selective fading channel. Finally, this resulting signal represents the HPA input signal.

Because of the high fluctuations of the envelope of the HPA input signal, the real HPA have to be modeled as nonlinear amplifiers. Following this idea and taking into account the recommendations concerning HPA modeling for OFDM communication systems presented in [18], Saleh and Rapp model of the HPA are assumed in our contribution [19,20]. It is well-known (e.g. [18]), that HPA for OFDM and MC-CDMA transmission systems can be modeled with advantage by the amplitude-to-amplitude *(AM/AM)* and the amplitude-to-phase *(AM/PM)* characteristics denoted as G_{u_x} and Φ_{u_x}, respectively.

Now, let us assume that the HPA input signal is given by

$$x(t) = u_x(t)e^{-j\phi(t)} \tag{1}$$

Then, the HPA output can be expressed by using and as

$$y(t) = G_{u_x}\left[u_x(t)\right]e^{-j\Phi_{u_x}\left[\phi(t)\right]} \tag{2}$$

In the case of Saleh model, AM/AM and AM/PM characteristics are given by [18,19]

$$G_{u_x} = \frac{\kappa_G u_x}{1+\chi_G u_x^2} \qquad \Phi_{u_x} = \frac{\kappa_\Phi u_x^2}{1+\chi_\Phi u_x^2} \tag{3}$$

In our considerations, the values of the Saleh model parameters of HPA have been set as follows: $\kappa_G = 2$, $\chi_G = \chi_\Phi = 1$ and $\kappa_\Phi = \pi/3$ what corresponds to the so-called Saleh model with simplified parameters [18]. On the other hand, Rapp model of HPA is described by the characteristics [20]

$$G_{u_x} = \frac{\kappa_G u_x}{\left[1+\left(u_x/O_{sat}\right)^{2s}\right]^{\frac{1}{2s}}} \qquad \Phi_{u_x} = 0 \tag{4}$$

Based on the recommendations of [18], the values of the Rapp model parameters such as $\kappa_G = 2$, $s = 3$ and $O_{sat} = 1$ are employed in our contribution.

The channel model considered in this paper is commonly uses the finite-length tapped delay line model of a frequency-selective multipath channel. In our simulations, we will consider the 6-tap multipath channel model where each tap is Rayleigh distributed. The cascade combination of the nonlinear HPA and the frequency-selective multipath channel can be considered to be the nonlinear fading channel.

3. Receiver structure

In this section, the receiver part of the MC-CDMA transmission system with multiuser detection is discussed. The block diagram of the baseband model of MC-CDMA receiver is given in Fig. 1. The receiver consists of the serial-to-parallel converter (S/P), blocks of the fast Fourier transformation (FFT), channel equalization (EQ) using zero forcing method, CP removal, bank of matched filters (BMF), block of linear or non-linear transformation (labeled as T), M-QAM demapper block and finally blocks of de-interleaving and convolution decoding. A more detailed description of the basic blocks of MC-CDMA receiver (FFT, EQ, CP removal and M-QAM demapper) can be found e.g. in [6].

The simplest receiver of MC-CDMA transmission system referred to as the single-user receiver can be obtained if the T-transformation block is represented by multiplication by a unit matrix. This kind of the receiver can provide acceptable BER if orthogonal spreading codes are used under the condition of linear HPA application and for AWGN channel scenario. If the transmission channel has to be modeled as a nonlinear fading channel, the single-user receiver cannot provide good performance. Because of the aforementioned properties of the transmission channel, the spreading code orthogonality is destroyed and consequently, MAI is increased. In order to avoid this performance degradation without requiring large back-offs in the transmitter amplifier, it becomes necessary to use multi-user detection techniques at the receiver side [6].

Conventional multi-user detectors such as MMSE-MUD e.g. are designed for linear environments and, as a result, might not exhibit enough performance improvement if the nonlinear models of HPA have to be taken into account.

It follows from the aforementioned facts that the MC-CDMA performance expressed by BER strongly depends on the spreading sequences, HPA model and the applied receiver. The spreading sequences selection depends on the PAPR of MC-CDMA signals as well as on the level of MAI due to cross-correlation properties of the particular spreading sequences. Because of the nonlinear distortion due to HPA and MAI inherency, it is expected that the application of nonlinear and multi-user receiver will overcome the linear receiver. Following this idea, a new nonlinear multi-user detector based on microstatistic filtering referred to as MSF-MUD has been introduced in [14]. The MSF-MUD uses piecewise linear filtering in conjunction with the threshold decomposition of the input signal, which introduces a nonlinear effect, to improve performance when a nonlinearity at the transmitter is present.

MMSE-MUD and MSF-MUD can be described by the same block scheme given in Fig.1. In the case of MMSE-MUD, the T-transformation block is represented by the multi-channel linear Wiener filter. The details concerning optimum MMSE-MUD design can be found e.g. in [6, 16]. On the other hand, in the case of MSF-MUD, the complex-valued multi-channel conventional microstatistic filter (C-M-CMF) is used as the T-transformation block. A simple outline of the optimum C-M-CMF design can be found e.g. in [14,17]. In the next section, we will present the design procedure of the optimum C-M-CMF for MSF-MUD in detail, originally presented in [21].

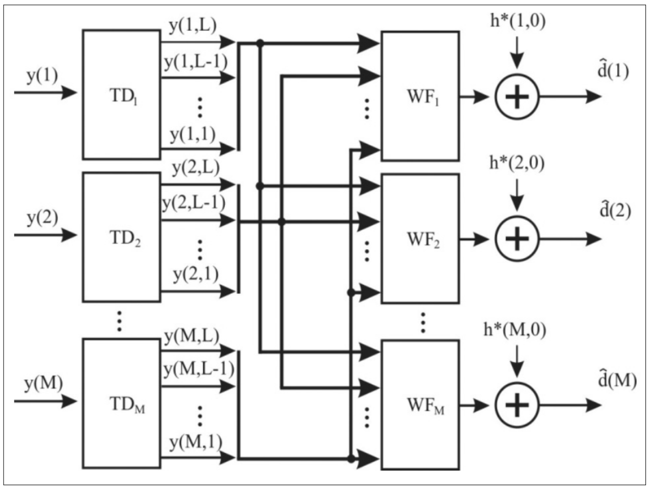


Figure 2.
Complex-valued multi-channel conventional microstatistic filter

3.1 Optimum C-M-CMF design procedure

A block scheme of the C-M-CMF is given in *Fig. 2.* Here, M, $y^{(i)}(n)$ and $\hat{d}^{(k)}(n)$ are the number of the input and output channels, the i-th input complex signal and the k-th output complex signal of the C-M-CMF, respectively. It can be seen from this figure that the C-M-CMF consists of M complex decomposers (TD) and the set of M complex multi-channel Wiener filter (C-M-WF).

Because the input signals to the TD are complex, a simple real-valued threshold decomposer (R-TD) applied in the M-CMF [22] cannot be used for their decomposition directly. In order to develop a suitable TD let us assume, that the complex signal $y^{(i)}(n)$ is expressed in the form

$$y^{(i)}(n) = Y^{(i)}(n)e^{j\phi(i,n)} \tag{5}$$

where

$$Y^{(i)}(n) = \left| y^{(i)}(n) \right| \tag{6}$$

and

$$\phi(i,n) = \arg\left[y^{(i)}(n) \right] \tag{7}$$

Generally, the performance of the i-th TD (TD_i) of C-M-CMF can be described as

$$D_C^{(i)}[y^{(i)}(n)] = \left[y^{(i,1)}(n) \ \dots \ y^{(i,L)}(n) \right]^T \tag{8}$$

In this expression, $D_C^{(i)}[.]$ represents the complex threshold decomposition of the signal $y^{(i)}(n)$ due to TDi into a set of the L signals $y^{(i,j)}(n)$ and the superscript T signifies transposition.

The intention of the piecewise linear filter applications is e. g. to model a nonlinear system, where the nonlinearity is related especially to the magnitude of signals to be processed (e. g. AM/AM characteristic for the Saleh and Rapp models). On the other hand, the signal arguments $\phi(i,n)$ are usually uniformly distributed (e. g. in the case of the Rayleigh fading channel). Therefore, a decomposition of the argument of $y^{(i)}(n)$ does not result in any clear benefit. With regard to these considerations, the following decomposition of the complex signals can be used:

$$\begin{aligned} y^{(i,j)}(n) &= D_C^{(i)}[y^{(i)}(n)] = D_R^{(i)}[Y^{(i)}(n)]e^{j\phi(i,n)} = \\ &= \left[Y^{(i,1)}(n) \ \dots \ Y^{(i,L)}(n) \right]^T e^{j\phi(i,n)} = \\ &= \left[y^{(i,1)}(n) \ \dots \ y^{(i,L)}(n) \right]^T \end{aligned} \tag{9}$$

where

$$y^{(i,j)}(n) = Y^{(i,j)}(n)e^{j\phi(i,n)} \tag{10}$$

In (9), $D_R^{(i)}[.]$ represents the real-valued threshold decomposition of the positive real-valued signal $Y^{(i)}(n)$ due to R- TD_i into a set of the L signals given by

$$Y^{(i,j)}(n) = D_R^{(i,j)}[Y^{(i)}(n)] = \begin{cases} 0 & for \quad Y^{(i)}(n) < l_{j-1}^{(i)} \\ Y^{(i)}(n) - l_{j-1}^{(i)} & for \quad l_{j-1}^{(i)} < Y^{(i)}(n) \le l_j^{(i)} \\ l_j^{(i)} - l_{j-1}^{(i)} & for \quad l_j^{(i)} < Y^{(i)}(n) \end{cases} \tag{11}$$

for $1 \le j \le L$. The parameters $l_j^{(i)}$ constituting the vector $\mathbf{L}^{(i)} = \left[l_1^{(i)} \ l_2^{(i)} \ \dots \ l_L^{(i)} \right]^T$ are the positive real-valued constants known as threshold levels of TD_i. The threshold levels are confined as $0 < l_1^{(i)} < \dots < l_L^{(i)} = \infty$. The output signals of all TD are fed into the k-th M-WF (M-WF_k). Then, the k-th output of the C-M-CMF $\left(\hat{d}^{(k)}(n)\right)$ is given by the following expressions:

$$\hat{d}^{(k)}(n) = h_{(k,0)}^{*}(n) + \sum_{i=1}^{M} \hat{d}_k^{(i)}(n) \tag{12}$$

$$\hat{d}_k^{(i)}(n) = \sum_{j=1}^{L} d_k^{(i,j)}(n) \tag{13}$$

$$\hat{d}_k^{(i,j)}(n) = \mathbf{H}_k^{(i,j)H}\mathbf{Y}^{(i,j)}(n) \tag{14}$$

$$\mathbf{H}_k^{(i,j)} = \left[h_{(k,0)}^{(i,j)} \quad h_{(k,1)}^{(i,j)} \quad \dots \quad h_{(k,N)}^{(i,j)} \right]^T \tag{15}$$

$$\mathbf{Y}^{(i,j)}(n) = \left[y^{(i,j)}(n) \quad \dots \quad y^{(i,j)}(n-N) \right]^T \tag{16}$$

where the asterisk denotes complex conjugation, the superscript H denotes Hermitian transposition, the sequence $h_{(k,l)}^{(i,j)*}$ represents the part of impulse response of the M-WF$_k$ fed by signal $y^{(i,j)}(n)$. The constant term $h_{(k,0)}^{*}$ is applied in the C-M-CMF structure in order to obtain an unbiased C-M-CMF output. Now, let us define the block vector $\mathbf{H}_k^{(i)}$ containing the vectors $\mathbf{H}_k^{(i,j)}$ and the block vector $\mathbf{Y}^{(i)}(n)$ containing the vectors $\mathbf{Y}^{(i,j)}(n)$ as follows

$$\mathbf{H}_k^{(i)} = \left[\mathbf{H}_k^{(i,1)T} \quad \dots \quad \mathbf{H}_k^{(i,L)T} \right]^T \tag{17}$$

$$\mathbf{Y}^{(i)}(n) = \left[\mathbf{Y}^{(i,1)T}(n) \quad \dots \quad \mathbf{Y}^{(i,L)T}(n) \right]^T \tag{18}$$

Then, by using (17) and (18), the expression (13) can be obtained in this form

$$\hat{d}_k^{(i)}(n) = \mathbf{H}_k^{(i)H}\mathbf{Y}^{(i)}(n) \tag{19}$$

Finally, let us define the vector $\mathbf{H}_k$ and the vector $\mathbf{Y}(n)$ as follows

$$\mathbf{H}_k = \left[h_{(k,0)} \quad \mathbf{H}_k^{(1)T} \quad \dots \quad \mathbf{H}_k^{(M)T} \right]^T \tag{20}$$

$$\mathbf{Y}(n) = \left[1 \quad \mathbf{Y}^{(1)T}(n) \quad \dots \quad \mathbf{Y}^{(M)T}(n) \right]^T \tag{21}$$

Then, by using (20), (21) and (12), the k-th output of the M-CMF $\hat{d}_k(n)$ is given by

$$\hat{d}^{(k)}(n) = \mathbf{H}_k^H\mathbf{Y}(n) \tag{22}$$

In this expression, $\mathbf{H}_k^H$ represents the impulse response of M-WF$_k$. It can be seen from (22) that the C-M-CMF responses are given by a linear combination of vector elements obtained by the decomposition of the input signals of the filter. With regard to that fact, the C-M-CMF responses are still linear functions with respect to the C-M-CMF coefficients.

Let us assume that $y^{(i)}(n)$ (the input signals of C-M-CMF) and $d^{(k)}(n)$ (the desired signals) are stationary random processes. Because the C-M-CMF is a minimum mean square estimator, the set of parameters of the optimum time-invariant M-CMF given by

$$\mathbf{L} = \left[\mathbf{L}^{(1)T} \quad \dots \quad \mathbf{L}^{(M)T} \right]^T$$

and $\mathbf{H}_k$ is obtained as the solution that minimizes the cost functions

$$MSE(\mathbf{H}_k, \mathbf{L}) = E\left[e^{(k)}(n)e^{(k)*}(n) \right] = E\left[\left| e^{(k)}(n) \right|^2 \right] \tag{23}$$

where

$$e^{(k)}(n) = d^{(k)}(n) - \hat{d}^{(k)}(n) = d^{(k)}(n) - \mathbf{H}_k^H\mathbf{Y}(n) \tag{24}$$

In these expressions, E[.] denotes the expectation operator and (23) is the cost function referred to as the mean-square error of $d^{(k)}(n)$ estimation.

In order to minimize $MSE(\mathbf{H}_k,\mathbf{L})$, it is necessary to first estimate of the TD$_i$ parameters (**L** vector). Generally, for the L vector estimation, the scanning method, the genetic algorithm based method and the method of the cumulative distribution function can be applied [21]. The application of these method will lead onwards to an iterative procedure of the optimum C-M-CMF design [21]. On the other hand, it has been shown in [23] that if the C-M-CMF is used as the part of MSF-MUD applied for the M-QAM symbol detection, suboptimum parameters of C-M-CMF can be determined by a very efficient non-iterative method based on an analysis of the M-QAM symbol constellation diagram. It is well-known that the M-QAM symbols in the signal constellation are localized on a set of the circles with the center in the origin of the coordinate system. Then, the **L** vector can be estimated based on the estimation of the radiuses of the circles where the M-QAM symbols obtained at the output of BMF receiver are located. Because the mentioned radiuses can be estimated efficiently by using of the histogram of the modules of the complex M-QAM symbols detected by the BMF, the method under consideration is referred to as the histogram method. It has been shown in [23], that the histogram method can provide a robust estimation of the suboptimum parameters of the TDi providing very good performance of MSF-MUD.

If a suitable estimation of **L** is available, the optimum coefficients of the M-WFs can be computed as follows

$$\mathbf{H}_k^{opt} = \mathbf{R}^{-1}\mathbf{P}_k \tag{25}$$

where

$$\mathbf{R} = E\left[\mathbf{Y}(n)\mathbf{Y}^H(n) \right] \tag{26}$$

$$\mathbf{P}_k = E\left[d^{(k)}(n)\mathbf{Y}(n) \right] \tag{27}$$

In these expressions, **R** and $\mathbf{P}_k$ are the correlation matrix of vector sequence $\mathbf{Y}(n)$ and the cross-correlation vector of the desired signal $d^{(k)}(n)$ and vector sequence $\mathbf{Y}(n)$, respectively. **R** and $\mathbf{P}_k$ can be estimated by using a training sequence. Under the condition that $\mathbf{H}_k^{opt}$, **R** and $\mathbf{P}_k$ are computed according to (26) and (27), the mean-square error corresponding to optimum C-M-CMF is given by

$$\begin{aligned} &MSE(\mathbf{H}_k^{opt}, \mathbf{L}) = \\ &= \sigma_d^2 - \mathbf{P}^H\mathbf{H}_k^{opt} - \mathbf{H}_k^{optH}\mathbf{P} + \mathbf{H}_k^{optH}\mathbf{R}\mathbf{H}_k^{opt} = \\ &= \sigma_d^2 - \mathbf{P}^H\mathbf{H}_k^{opt} = \sigma_d^2 - \mathbf{P}^H\mathbf{R}^{-1}\mathbf{P}_k \end{aligned} \tag{28}$$

where

$$\sigma_d^2 = E\left[d^{(k)}(n)d^{(k)*}(n) \right] \tag{29}$$

By the evaluation of the vectors **L** and $\mathbf{H}_k^{opt}$, the design procedure of the optimum or suboptimum C-M-CMF and coincidentally MSF-MUD is got done.

4. Simulation results

In this section, we report on the simulation experiments that were carried out to study the effectiveness of the several variations of the described MC-CDMA transmission system performing through nonlinear fading channel. In our simulations, we consider the synchronous uplink transmission (i.e. the transmission from the mobile terminal to the base station) for MC-CDMA systems employing N_c=128 subcarriers at the oversampling rate of 4, 16-QAM base-band modulation and 25% user load. For the sake of brevity, the perfect channel state information has been assumed at the receiver. For the channel equalization, zero forcing method has been applied. The convolution encoder with the coding rate $R=1/3$ followed by the interleaver with the block size of 32 has been used in order to improve the system performance.

The summary of the simulation parameters is listed in *Table 2*.

Parameter	Description
Modulation type	16-QAM
Cyclic prefix length	32 samples
Total number of sub-carriers	128
Oversampling rate	4
User load	25%
Interleaver block size	256
Channel model	6-tap multipath model, each tap Rayleigh distributed
Channel estimation	Perfect
Channel estimation	Perfect
Equalization	Zero forcing
Channel coding	Convolutional code with rate 1/3
Spreading codes	Walsh codes, Gold codes, orthogonal Gold codes with the period of L = 32 chips; Complementary Golay codes, polyphase Zadoff-Chu codes with the period of L = 31 chips
HPA	Saleh model, Rapp model
Receivers	MMSE-MUD, MSF-MUD
Simulation software	MATLAB

Table 2. Simulation parameters

In order to model the nonlinear HPA, Saleh and Rapp model of the HPA have been assumed. The particular parameters of the models have been listed in Section 2. The operating point of HPA has been given by the IBO parameter defined as $IBO_{dB}=10\log_{10}(P_{\max}/\bar{P}_x)$, where $P_{\max}$ and $\bar{P}_x$ are the saturated power $P_{\max}$ and average input power $\bar{P}_x$ [14]. It is well known that the lower IBO is set, the higher nonlinear distortion due to HPA nonlinearity reveals. In our simulations, IBO has been set to 3 dB and 0 dB for Saleh model and 0 dB for Rapp model.

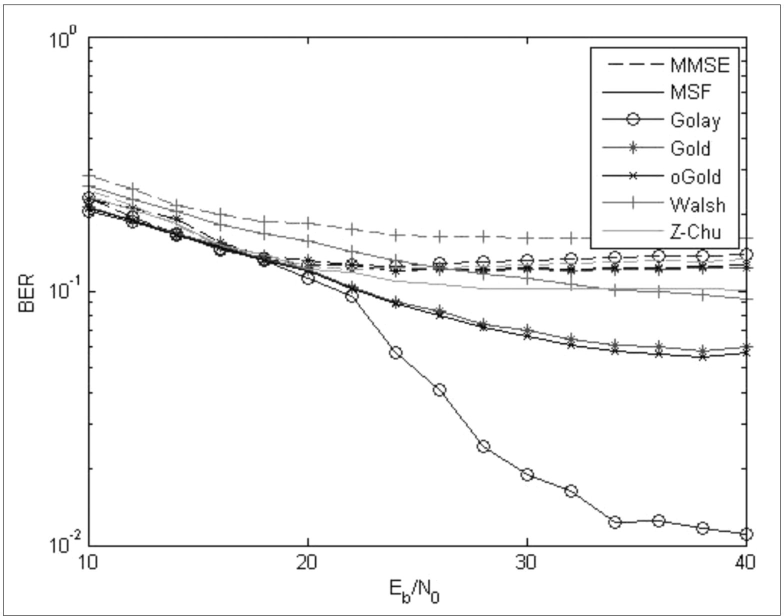
The channel model considered in our simulation has been represented by finite-length tapped delay line model of a frequency-selective multipath channel. Here, we used 6-tap multipath model where each tap is Rayleigh distributed. The intention of contribution is to study MSF-MUD performance properties if it is applied to a MC-CDMA system performing through frequency-selective fading channel and simultaneously, if Walsh codes, Gold and orthogonal Gold codes, polyphase Zadoff-Chu codes and complementary Golay codes are used as the spreading sequences.

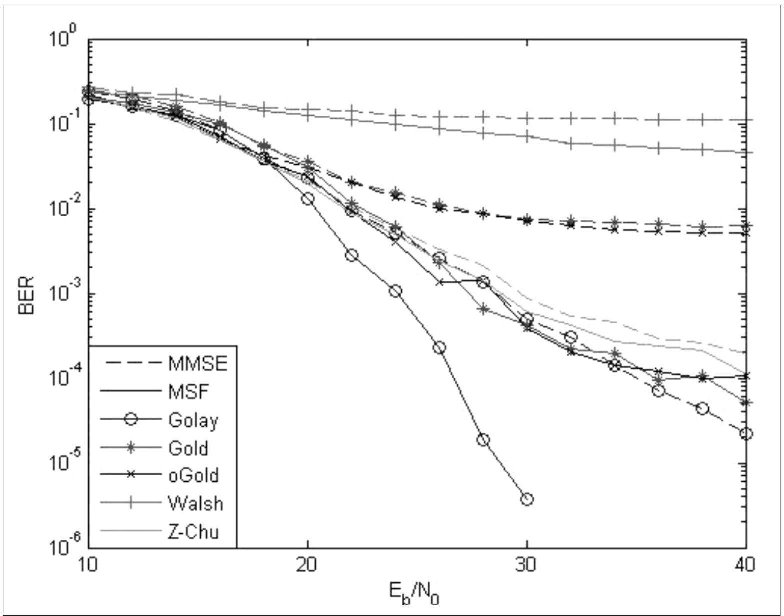
In order to decrease the receiver complexity, very simple C-M-CMF with two-level TDi (L=2) has been exploited in the MSF-MUD structure. For the C-M-CMF design, the procedure described in the Section 3 has been applied. The matrix $\mathbf{R}$ and $\mathbf{P}_k$ have been estimated by using the training sequence consisting of 500 uniformly distributed of 16-QAM symbols. The training sequence has been transmitted before the information data transmission. For all TD of C-M-CMF, the same value of the threshold level $l_1^{(i)}$ has been applied. By using the histogram method mentioned in the Section 3, $l_1^{(i)}$ has been set to 0,6 for $i=1,2,\ldots,M$. In order to illustrate the MSF-MUD performance, MMSE-MUD has been employed as the MC-CDMA receiver, as well. For the MMSE-MUD design, the procedure described in [6], exploiting the above mentioned training sequence has been applied.

The performance of the above described variations of the MC-CDMA systems (different HPA models, different receivers and different spreading codes) has been evaluated by *BER vs.* E_b/N_0 for the different values of IBO setting. The obtained results are given in *Figs. 3-5*.

Let us assume firstly that HPA is modeled according to Saleh model. Here, *BER vs.* E_b/N_0 for $IBO=0dB$ is given in *Fig. 3*. It can be seen from this figure that the minimum *BER* equal to 10^{-2} is reached at $E_b/N_0=40dB$. It indicates very clearly, that both receivers and all codes provide insufficient results for the analyzed scenario with strongly nonlinearly distorted MC-CDMA signals ($IBO=0dB$). In spite of that fact, it can be observed that the application of MSF-MUD in conjunction with Golay codes provides the evident improvement of the MC-CDMA performance in comparison with the application of the other codes in this scenario. On the other hand, it can be seen from the Fig. 3, that data receiving fails completely if MMSE-MUD is employed.

The simulation results for the Saleh model of HPA and for $IBO=3dB$ are presented in *Fig. 4*. It can be seen from this figure that the worst performance of MC-CDMA is provided if Walsh codes are employed, independently on the applied receiver. Here, this effect can be explained by the high PAPR of MC-CDMA signal (Table 1) in combining with the severe nonlinear distortion resulting in the loss of Walsh code orthogonality. On the other hand, the best performance is provided by joint application of MSF-MUD and Golay codes. This performance follows from relatively low PAPR of MC-CDMA signal (Table 1), when Golay codes are used and simultaneously, by MSF-MUD ability to compensate nonlinear distortion due to HPA. Fig. 4 indicates also that MMSE-MUD can provide the best results if the Golay codes are exploited. However, the results provided by the MMSE-MUD and the Golay codes are still worse than that provided by MFS-MUD what is due to by the nonlinear structure of the MSF-MUD. The joint application of the other codes (Gold codes, orthogonal codes and Zadoff-Chu codes) and both receivers provides the greater *BER* than that of Golay codes application but still better than that of the Walsh codes exploiting. The presented results confirm clearly that MSF-MUD overcomes still MMSE-MUD.





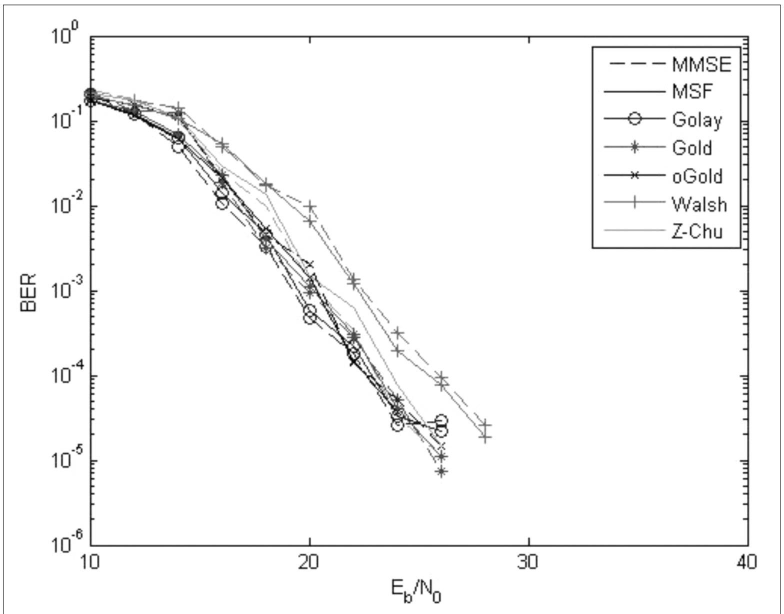


Figure 3.
Performance of the system for different spreading sequences, Saleh model of the HPA and IBO=0dB

Figure 4.
Performance of the system for different spreading sequences, Saleh model of the HPA and IBO=3dB

Figure 5.
Performance of the system for different spreading sequences, Rapp model of the HPA and IBO=0dB

Finally, we can describe the MC-CDMA performance for the scenario where Rapp model of HPA and $IBO = 0dB$ are set. Here, the obtained results given in *Fig. 5* show that except Walsh codes applications, the receivers and the other codes in view provide almost the same curves of *BER*. This behaviour of the Walsh code application can be explained by the same manner as in the case of the scenario analysed in the previous passage. The comparable performance of MSF-MUD and MMSE-MUD follows from the fact that the nonlinear distortion due to Rapp model of HPA at $IBO = 0dB$ is not so strong and therefore MSF-MUD cannot offer significant performance improvement over MMSE-MUD.

5. Conclusion

In this contribution, we have studied MC-CDMA transmission system properties performing through the frequency-selective fading channel for the uplink scenario. Within this study, we are focused on the analyses of the MC-CDMA performance if the different models of nonlinear HPA (Saleh and Rapp model), different spreading sequences (Walsh codes, Gold and orthogonal Gold codes, polyphase Zadoff-Chu codes and complementary Golay codes) and different multiuser receivers (MSF-MUD and MMSE-MUD) are considered.

The results of the computer simulations for a number of variations of the outlined scenario have shown that the best performance expressed by *BER vs.* E_b / N_0 is always provided if MSF-MUD in combination with Golay codes is employed. These results have confirmed fully the results obtained for the same MC-CDMA system configuration performed through AWGN channel [17]. This performance can be explained by the low level of the Golay code PAPR and by the ability of the MSF-MUD to compensate of the nonlinear distortion due to its nonlinear piecewise structure. The performance improvement is more remarkable, if Saleh model of HPA is employed. If the Rapp model of the HPA has to be considered, the performance of the MSF-MUD and MMSE-MUD are almost the same. Following [24], this effect could be explained by the migration style of M-QAM symbols of signal constellation detected at the output of the receiver BMF.

If we sum up the results of the MC-CDMA performance analyses presented in this contribution and the outputs of [17] and [24], it can be recommended to apply MSF-MUD and Golay codes in the structure of MC-CDMA transmission systems. A possible improvement of MC-CDMA performance for small IBO values (e.g. $IBO = 0dB$) if Saleh model of HPA is used is an open question. It could be expected, that the solution of that problem could be provided by MSF-MUD exploiting a bit more complex TD, i.e. TD with more threshold level than one. The solution of the problem will be the topic of our follow-up research.

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