Effects of Spreading Sequences on the Performance of MC-CDMA System with Nonlinear Models of HPA

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Abstract. *Performance evaluation and comparison of multi-carrier code division multiple access (MC-CDMA) system model for different spreading sequences at the presence of Saleh and Rapp model of high power amplifier (HPA) is investigated. Nonlinear amplification introduces degradation of bit error performance and destroys the orthogonality among subcarriers. In order to avoid performance degradation without requiring extremely large back-offs in the transmitter amplifier, it becomes convenient to use nonlinear multi-user detection techniques at the receiver side. In order to illustrate this fact, microstatistic multi-user receiver (MSF-MUD) and conventional minimum mean square error receiver (MMSE-MUD) are considered and mutually compared. The results of our analyses based on computer simulations will show very clearly, that the application of nonlinear MSF-MUD in combination with Golay codes can provide significantly better results than the other tested spreading codes and receivers. Besides this fact, a failure of Walsh codes especially at the Saleh model of HPA will be outlined by using constellation diagram.*

Keywords

MC-CDMA, HPA, Saleh model, Rapp model, PAPR, multi-user receivers.

1. Introduction

In recent years, MC-CDMA has been receiving widespread interests for future wireless communications. Combining orthogonal frequency division multiplex (OFDM) modulation and CDMA, this scheme benefits from the main advantages of both techniques [1], [2]: high spectral efficiency, multiple access capability, robustness in case of frequency selective channels, high flexibility, narrow-band interference rejection, simple one-tap equalization, etc. However, OFDM signal has the large peak to average power ratio (*PAPR*), which severely limits its applications, and as long as the basic operation of MC-CDMA is identical to OFDM system, this undesirable property remains. The high *PAPR* is a major drawback of MC-CDMA especially when nonlinear elements such as HPA are used in the transmitter. Large peaks in the transmitted signal will occasionally reach the amplifier saturation region and cause nonlinear distortion of multi-carrier signal, which results in a large degradation of performance, i.e. increase of both the bit error rate (*BER*) and the out-of-band radiation (spectral spreading) [1].

It has been shown in [2], [3], that the *PAPR* of MC-CDMA signals is given by spreading codes assigned to particular active users. On the other hand, the *BER* of MC-CDMA transmission system depends strongly on multiple access interference (MAI) due to cross-correlation properties of applied spreading codes. 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. [2], [3], [4]). Then, in order to minimize the *BER*, the spreading codes jointly reducing *PAPR* and MAI have to be used.

In spite of a suitable selection of spreading codes minimizing *PAPR*, the MC-CDMA symbols will be usually nonlinearly distorted by HPA working in nonlinear area of their characteristics. The conventional solution to this problem is to back-off the operating point of nonlinear amplifier; this approach results in significant power efficiency penalty. Alternative solutions of MC-CDMA performance improvement are given by the application of additional methods of *PAPR* reduction [5], [6] as well as methods of compensation of nonlinear distortion due to nonlinear HPA. Nonlinear distortion compensation methods can be implemented at the transmitter or receiver side of MC-CDMA. Frequently used solutions at the transmitter side include predistortion [7], active constellation extension, tone reservation, selected mapping [6], different code allocation strategies [8], etc. Strategies at the receiver side usually combine iterative decoding [9] and multi-user detection [10] in such a way that both HPA nonlinearity compensation and MAI suppression are taken into account.

As it follows from the above given short overview of 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). In this paper, we will propose a new method of performance improvement for uplink MC-CDMA transmission systems based on joint selection of spreading codes, nonlinear distortion compensation at the receiver side and MAI suppression. The proposed approach includes the Golay codes application as spreading codes in combination with MSF-MUD.

The paper is organized as follows. Section 2 describes the MC-CDMA system mode1, which is considered consistently throughout the paper. A short review of nonlinear effects due to HPA is outlined in Section 3. In Section 4 (the core part of the paper) the performance properties of uplink MC-CDMA transmission system at AWGN channel will be studied and analyzed by using a set of computer simulations. Within these simulations, Walsh codes, Gold codes, orthogonal Gold codes, Zadoff-Chu codes and Golay codes will be used as the spreading codes and Saleh and Rapp model of HPA will be applied for the purpose of nonlinear behavior description of a terminal amplifier of transmitter. Finally, the MSF-MUD and MMSE-MUD will be employed as receivers. In this section, it will be shown, that the Golay codes and MSF-MUD application are able with regard to *BER* to overcome very clearly the other combinations of discussed spreading codes and receivers. In order to explain some properties of selected *BER* curves obtained at the simulations, a new method of M-QAM symbol constellation migration will be introduced and used with advantage. Finally, conclusions and final remarks to this contribution are drawn in Section 5.

2. MC-CDMA System Model

The basic scenario of our study of nonlinear effects in MC-CDMA systems is represented by uplink of MC-CDMA transmission system performing through AWGN transmission channel, at K active users.

A block diagram of the simplified baseband model of MC-CDMA transmitter is given in Fig. 1. It can be seen from this figure, that the information bits to be transmitted from a particular user are firstly baseband modulated into M-QAM modulation symbols and then they are spread by using a specific spreading sequence c_m. In the case of MC-CDMA, as the spreading codes Walsh codes, Gold codes, orthogonal Gold codes, polyphase Zadoff-Chu codes and complementary Golay codes are used mostly [2]. The spread symbols are modulated by multi-carrier modulation implemented by inverse fast Fourier transformation operation (IFFT). The IFFT block outputs after parallel-to-serial conversion represent the input signal of HPA. In the transmitter model according to Fig. 1, the traditional block of cyclic prefix insertion is not included due to AWGN channel assumption.

The basic structure of receivers considered in this paper is sketched in Fig. 2. It can be seen from this figure, that the receiver consists of a serial-to-parallel converter (S/P), blocks of fast Fourier transformation (FFT), a bank of matched filters (BMF), a block of linear or nonlinear transformation (labelled as T) and a decision device. Here, the operation of a single-user receiver known as BMF consists of a set of simple matched filters (correlators). A deeper description of MC-CDMA transmission systems can be found e.g. in [1] or [11].

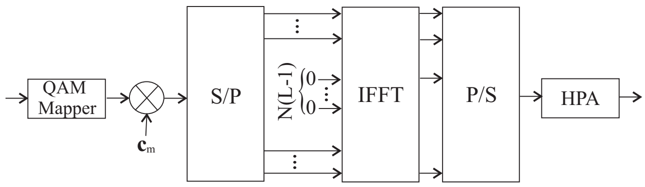

Fig. 1. MC-CDMA transmitter.

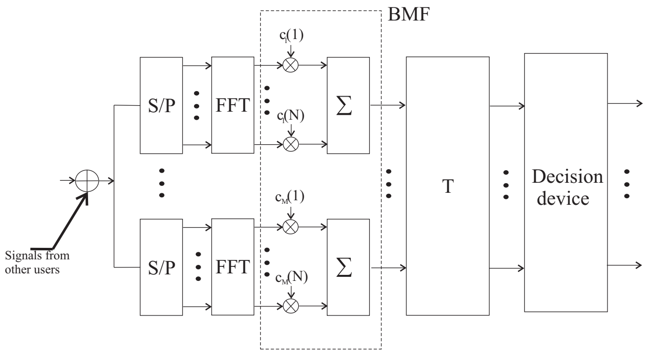

Fig. 2. MC-CDMA receiver.

In order to extend BMF into a multi-user receiver, the T-transformation block is included in the receiver structure [12]. In this paper, the linear MMSE-MUD [11] as well as nonlinear MSF-MUD for MC-CDMA [10], [13] are considered. The T-transformation block in MMSE-MUD is represented by multi-channel linear Wiener filter. In the case of MSF-MUD, the T-transformation block is represented by a complex valued-multichannel nonlinear microstatistic filter (C-M-CMF). C-M-CMF is the minimum mean-square error estimator based on the estimation of desired signals by using a linear combination of vector elements obtained by threshold decomposition of filter input signals [10]. The detailed description of MMSE-MUD and MFS-MUD structure, design and performance is beyond the scope of this paper and can be found e.g. in [10], [11], [12].

3. Nonlinear Effects in MC-CDMA

Multi-carrier schemes such as MC-CDMA are known to suffer from large envelope fluctuation of the transmitted signal, caused by the addition of a large number of independently modulated subcarriers. The output of multi-carrier modulation based on IFFT operation is usually characterized by high *PAPR*, which can be defined as [6]:

$$PAPR = \frac{max|s(t)|^2}{E[|s(t)|^2]} \quad (1)$$

where $E[\,.]$ is the expectation operator. It can be shown (e.g. [2]), that in the case of MC-CDMA systems, *PAPR* parameter strongly depends on the applied spreading sequence.

Because of the large envelope fluctuations of the input signal of HPA, the real HPAs have to be modeled as nonlinear amplifiers. The nonlinear HPA can be modeled as a memoryless device. Let $x(t) = u_x e^{-j\phi(t)}$ be the HPA complex input signal with amplitude u_x and phase $\phi(t)$. The corresponding output signal of HPA can be expressed as:

$$y(t) = G_{u_x} e^{-j\Phi(t)} \quad (2)$$

where $G_{u_x} = f(u_x)$ and $\Phi(t) = g(u_x)$ describes the amplitude-to-amplitude (AM/AM) and amplitude-to-phase (AM/PM) conversion, respectively [14].

In this paper, nonlinear effects of Saleh and Rapp models of HPA have been compared. In the case of Saleh model of HPA, AM/AM and AM/PM characteristics are given by [14]:

$$AM/AM : G_{u_x} = \frac{\kappa_G u_x}{1+\chi_G u_x^2} \quad (3)$$

$$AM/PM : \Phi_{u_x} = \frac{\kappa_\Phi u_x^2}{1+\chi_\Phi u_x^2}. \quad (4)$$

On the other hand, Rapp model of HPA is described by the following AM/AM and AM/PM characteristics [15]:

$$AM/AM : G_{u_x} = \frac{\kappa_G u_x}{(1+(\frac{u_x}{O_{sat}})^{2s})^{\frac{1}{2s}}} \quad (5)$$

$$AM/PM : \Phi_{u_x} = 0 \quad (6)$$

where s is the smoothness factor and O_{sat} is the output saturation level.

The HPA operation in the region of its nonlinear characteristic causes a nonlinear distortion of a transmitted signal, that subsequently results in increasing *BER* and out-of-band energy radiation. The operating point of HPA is defined by input back-off (*IBO*) parameter which corresponds to the ratio of saturated input power (P_{max}) and average input power ($\overline{P_x}$) [10]:

$$IBO_{\text{dB}} = 10\log_{10}(\frac{P_{max}}{\overline{P_x}}). \quad (7)$$

The measure of effects due to nonlinear HPA could be decreased by the selection of relatively high value of *IBO*. However, this approach will result in inefficient use of HPA performance resulting in decreasing radius of the area covered by the effective MC-CDMA signals. Another solutions include compensation of nonlinear distortion due to HPA implemented in the transmitter or/and receiver side of MC-CDMA transmission system [5], [6]. It has been proposed in [10], [13] that MC-CDMA performance improvement under the nonlinear HPA application could be reached also by the application of nonlinear receivers.

It follows from the above mentioned facts that the MC-CDMA performance expressed by *BER* depends strongly on spreading sequences, HPA model and the applied receiver. The spreading sequence selection depends on the *PAPR* of MC-CDMA signal (the lower *PAPR* the better performance is expected) as well as on the level of MAI due to cross-correlation properties of the particular spreading sequences. It will be shown in the next section, that in the case of the spreading sequence selection, the HPA model including *IBO* parameter should be taken into account. Because of nonlinear distortion due to HPA and MAI inherency, it is expected that the application of nonlinear and multi-user receiver will provide better performance than that of linear receiver.

The performance analysis of MC-CDMA for the different spreading sequences, *IBO* parameters, models of HPA and receiver types is presented in the next section.

4. MC-CDMA Performance Analysis

MC-CDMA performance analysis presented in this section is based on computer simulations. The basic scenario of our simulations is represented by the uplink MC-CDMA transmission system performing through AWGN transmission channel, at 16-QAM baseband modulation, for K active users ($K = 16$).

As the spreading sequences, Walsh codes, Gold codes and orthogonal Gold codes with period of 32 chips as well as complementary Golay codes and polyphase Zadoff-Chu codes with period of 31 chips have been applied. The total number of sub-carriers has been set to $N = 128$. In order to avoid aliasing and the out-of-band radiation into the data bearing tones, the oversampling rate of 4 has been applied [7]. Then, $N_u = 32$ (Walsh codes, Gold codes and orthogonal Gold) and $N_u = 31$ (complementary Golay codes and Zadoff-Chu codes) carriers per transmitted block have been used for the spread 16-QAM symbol transmission. For the precise specification of the Saleh model of HPA, the parameters $\kappa_G = 2$, $\chi_G = \chi_\Phi = 1$ and $\kappa_\Phi = \pi/3$ have been chosen. In case of Rapp model of HPA, its parameters have been set to $\kappa_G = O_{sat} = 1$ and $s = 3$.

It follows from M-ary QAM theory that symbols generated by M-ary QAM modulator are located on finite number of circles of signal constellation. For example, in the case of 16-QAM, there are 3 circles where the particular symbols are located. The signal symbols located on the same circle have the same magnitude. Let us assume nonlinear HPA modeled by Saleh model at single user scenario under noiseless condition. In this case, all M-ary QAM symbols located on the same circle will be mapped by nonlinear HPA following (3) from the original circle into another circle called an image circle. Because the nonlinear HPA will cause also a phase distortion, the particular symbols at the receiver side will be rotated along the image circle in an angle given by (4). It follows from (3), that the image circle radius (i.e. the magnitudes of the symbols located on the image circles) depends on the particular symbols and *IBO* parameter expressing of HPA operating point. Particular behavior of signal constellations for different spreading sequences is studied in the next part of the paper.

4.1 Saleh Model

Firstly, let us assume the Saleh model of HPA for different spreading codes and different receivers.

In the Fig. 3 - 7, the signal constellations at the outputs of 16-QAM mapper and BMF for $E_b/N_0 = 40$ dB are given. In these figures, small empty circles represent signal constellation of the symbols at the output of 16-QAM mapper and other small filling blue circles determine signal constellation of 16-QAM symbols at BMF output at $IBO = 0$ dB. The black solid curves illustrate the symbol constellation migration due to changing *IBO* from 0 dB to 20 dB. The direction of the symbol migration is outlined by the arrow. It can be seen from these figures, that if $IBO = 20$ dB then the signal constellation at the outputs of 16-QAM mapper and BMF are the same. It means, that for $IBO = 20$ dB HPA modeled by Saleh model operates in linear region of its characteristic.

If we observe Fig. 3 devoted to Walsh codes in detail, very interesting phenomenon can be found. All symbols of symbol constellation of the signal at BMF output (red asterisk) are located on the same image circle for $IBO = 5$ dB. It means, that the trajectories of all migrated symbols intersect the same red-dash image circle, if $IBO = 5$ dB. This special phenomenon can be explained as the result of relatively high fluctuation of the envelope of the MC-CDMA signal at the input of HPA for Walsh codes (i.e. relatively high *PAPR*) and characteristic nonlinear shape of Saleh model of HPA [7]. This critical *IBO* is varied in dependence on particular Walsh codes considered for transmission. Following [11], this feature of Walsh codes is critical for all conventional receivers and as we can see in Fig. 8, even for MSF-MUD.

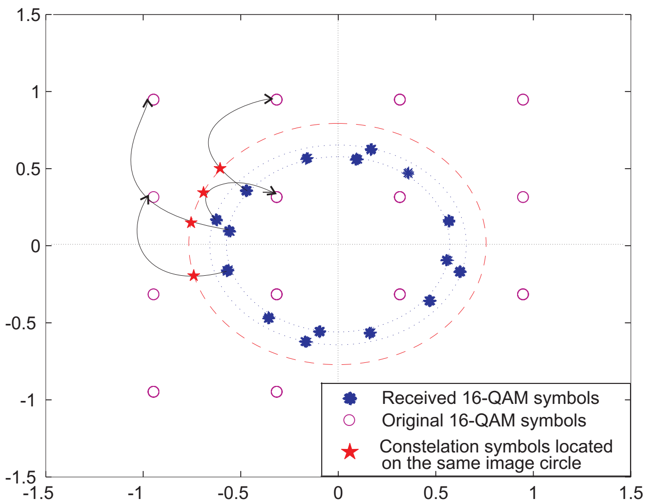

Fig. 3. Original symbol constellation at the output of the 16-QAM mapper and the symbol constellation at BMF output. Spreading sequences: Walsh codes. HPA model: Saleh model.

It can be observed from Fig. 4 - 7, that the other tested codes (Golay, Gold, orthogonal Gold, Zadoff-Chu) do not generate the effect similar to that of Walsh codes behavior. Fig. 4 - 7 indicate that the application of Golay

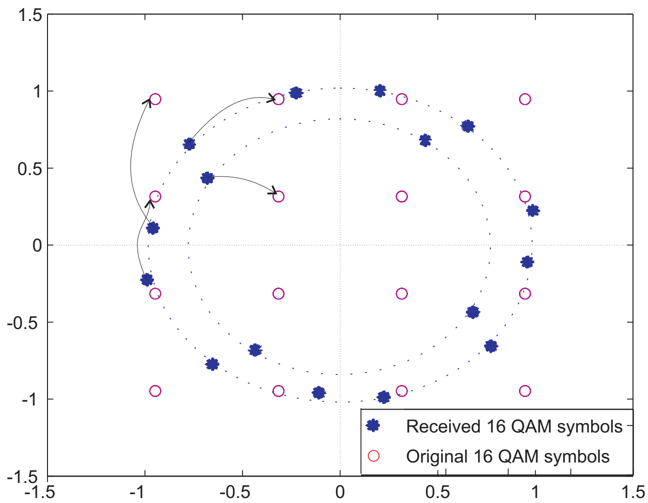

Fig. 4. Original symbol constellation at the output of the 16-QAM mapper and the symbol constellation at BMF output. Spreading sequences: Golay codes. HPA model: Saleh model.

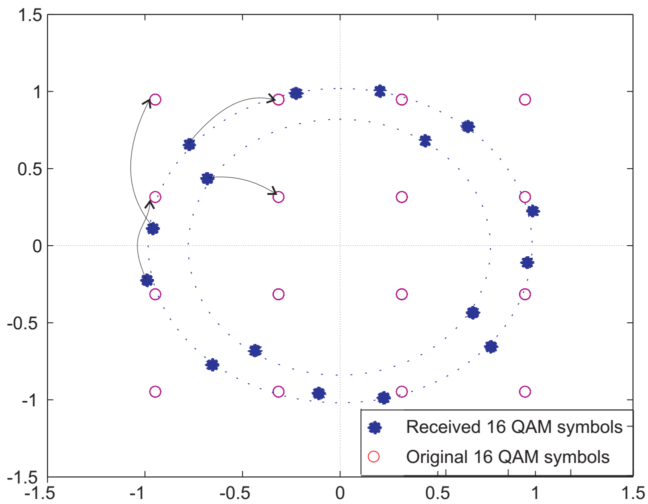

Fig. 5. Original symbol constellation at the output of the 16-QAM mapper and the symbol constellation at BMF output. Spreading sequences: Gold codes. HPA model: Saleh model.

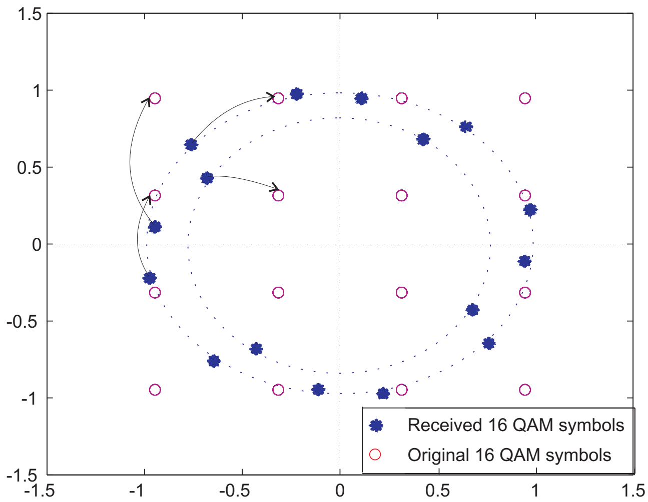

Fig. 6. Original symbol constellation at the output of the 16-QAM mapper and the symbol constellation at BMF output. Spreading sequences: orthogonal Gold codes. HPA model: Saleh model.

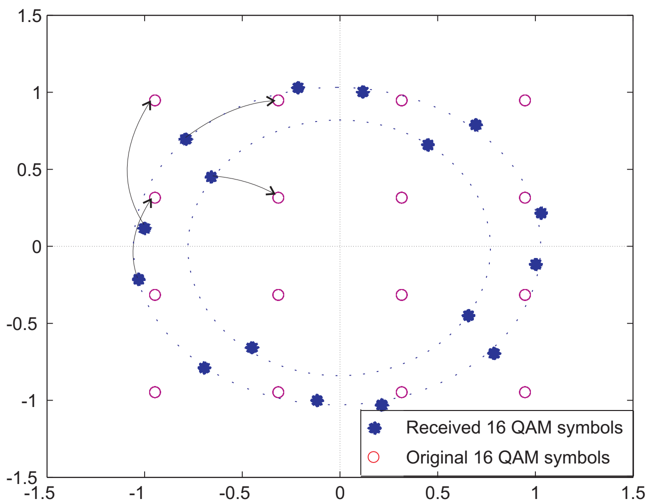

Fig. 7. Original symbol constellation at the output of the 16-QAM mapper and the symbol constellation at BMF output. Spreading sequences: Zadoff-Chu codes. HPA model: Saleh model.

codes, Gold codes, orthogonal Gold codes and Zadoff-Chu codes should provide better performance of MC-CDMA transmission systems than using Walsh codes. This conclusion is confirmed by the simulation results given in Fig. 8 - 11. In Fig. 8, *BER* vs. *IBO* for $E_b/N_0 = 17$ dB is illustra-ted. It can be seen from this figure, that the worst performance of MC-CDMA is provided by the Walsh code application due to the effect outlined in Fig. 3. On the other hand, the best performance can be provided by the application of Golay codes in combination with MSF-MUD. This performance can be explained by relatively low *PAPR* of MC-CDMA signal, when Golay codes are employed, and the MSF-MUD ability to compensate nonlinear distortion due to HPA. It follows from this figure, that there is the interval of *IBO* values for which the application of MSF-MUD can provide meaningful improvement of the MC-

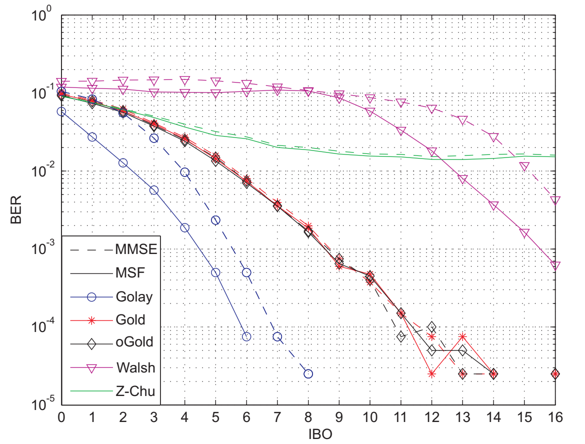

Fig. 8. *BER* vs. *IBO* for MC-CDMA transmission system for different spreading sequences. HPA model: Saleh model. $E_b/N_0 = 17$dB.

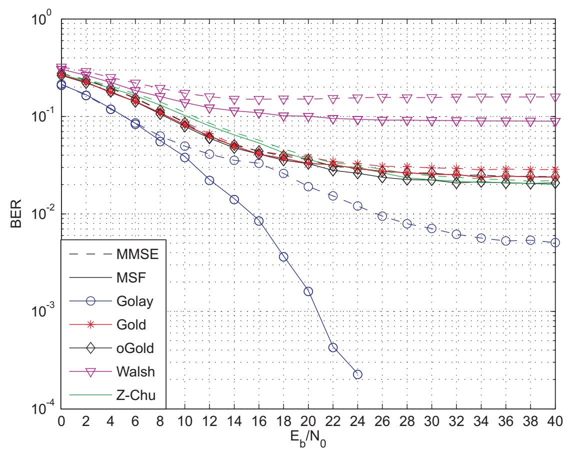

Fig. 9. *BER* vs. E_b/N_0 for MC-CDMA transmission system for different spreading sequences. HPA model: Saleh model. $IBO = 3$dB.

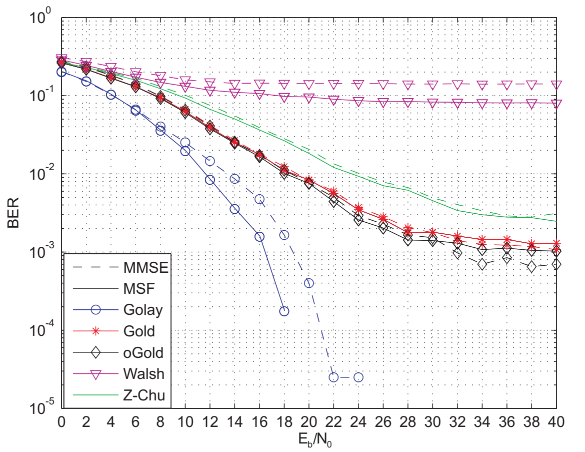

Fig. 10. *BER* vs. E_b/N_0 for MC-CDMA transmission system for different spreading sequences. HPA model: Saleh model. $IBO = 5$dB.

CDMA performance in comparison with that of MMSE-MUD application.

The performance of the MC-CDMA transmission system expressed by *BER* vs. E_b/N_0 for different values of *IBO* (*IBO* = 3 dB, *IBO* = 5 dB, *IBO* = 7 dB) is illustrated by Fig. 9 - 11. These simulation results confirm the previous conclusions i.e. good bit error performance can be obtained by using Golay codes in combination with MSF-MUD. On the contrary, the other investigated codes show extremely poor results, that can be explained by high *PAPR* of MC-CDMA signal when these codes are adopted for spreading. Note, that in these cases it is highly recommended to use an additional method for *PAPR* reduction at the transmitter side in order to suppress this undesirable effect and to get improved bit error performance.

4.2 Rapp Model

In this section Rapp model of HPA for different spreading sequences has been assumed.

Fig. 12 shows constellation diagram corresponding to Golay codes. Constellation diagrams corresponding to other codes (Gold, orthogonal Gold, Zadoff-Chu and Walsh) generate similar figures like that of Golay codes do and therefore are not depicted here. It can be seen from this figure that in the case of Rapp model, spreading codes do not generate effect similar to that of Walsh codes behavior for Saleh model. We can observe from Fig. 12 that for Rapp model of HPA all points of symbol constellation are located close to their original position. It can be concluded that distortion caused by Rapp model of HPA is smaller than that of Saleh model.

Fig. 13 demonstrates *BER* vs. E_b/N_0 for MC-CDMA transmission system for *IBO* = 0 dB. From this figure it can be observed that in the case of Rapp model of HPA the best results are obtained by using Golay codes in combination with MSF-MUD.

5. Conclusions

In this paper, we have investigated performance of MC-CDMA transmission system for two different models of HPA (Saleh and Rapp model), the different spreading sequences (Walsh, Golay, Gold, orthogonal Gold and Zadoff-Chu), *IBO* parameter values and receiver types (MMSE-MUD, MSF-MUD). It has been found that Saleh model of HPA introduces much higher nonlinear distortion and causes more significant degradation of MC-CDMA transmission system performance than that of Rapp model. Application of Golay codes as the spreading sequences in combination with MSF-MUD can overcome clearly the other investigated spreading sequences and receivers for both assumed HPA models, especially for a certain interval of the *IBO* values. On the other hand, the application of Walsh codes provides the worst performance of MC-CDMA

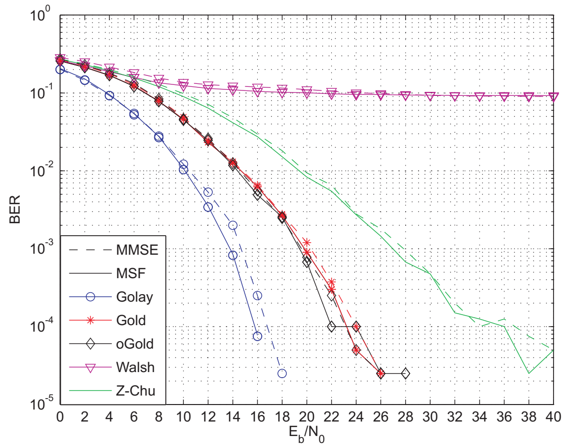

Fig. 11. *BER* vs. E_b/N_0 for MC-CDMA transmission system for different spreading sequences. HPA model: Saleh model. *IBO* = 7dB.

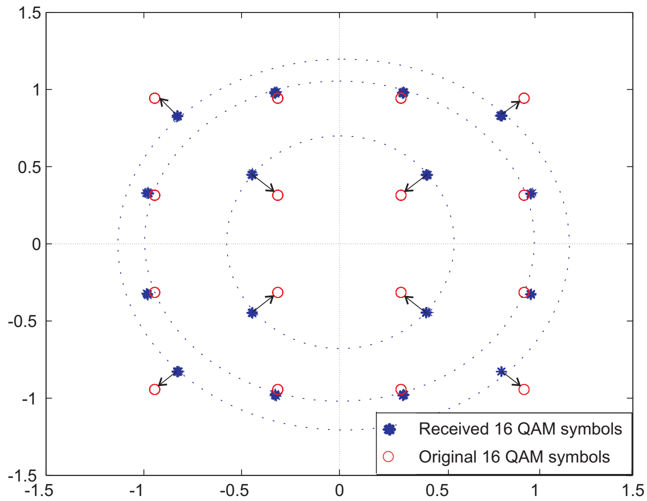

Fig. 12. Original symbol constellation at the output of the 16-QAM mapper and the symbol constellation at BMF output. Spreading sequences: Golay codes. HPA model: Rapp model.

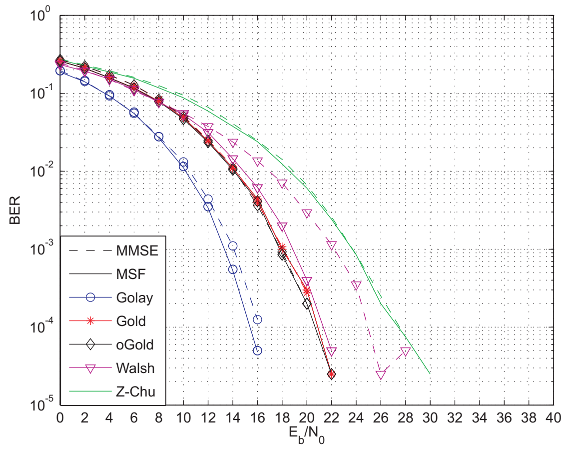

Fig. 13. *BER* vs. E_b/N_0 for MC-CDMA transmission system for different spreading sequences. HPA model: Rapp model. *IBO* = 0dB.

transmission system due to high *PAPR* of MC-CDMA signal and HPA model according to Saleh resulting in the described phenomenon. Presented results indicate that Walsh codes are unsuitable for the scenario where HPA is described by Saleh model.

Authors' further analysis will lead up to investigation of discussed topic in more complex channels (e.g. frequency selective fading channels). It is expected, that the joint application of MSF-MUD and Golay codes will provide better results than that of other spreading codes and receivers even for this scenario.

Acknowledgements

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