ON THE PERFORMANCE OF GFDM SYSTEMS UNDERGOING NONLINEAR AMPLIFICATION

Lukáš SENDREI, Stanislav MARCHEVSKÝ
* Department of Electronics and Multimedia Communications, Faculty of Informatics and Electrical Engineering, Technical University of Košice, Slovakia (e-mail: {lukas.sendrei, stanislav.marchevsky}@tuke.sk).

ABSTRACT

The demand on high data rate, low latency, high spectral efficiency and low power consumption create an ongoing pressure on the development of communication systems. Although cellular technologies like Long-term evolution and Long-term evolution - Advanced can face many of these demanding challenges the dramatic increase of mobile data transfer in the last years give rise to design even more sophisticated methods. Multi-carrier modulation formats retain great potential to meet the requirements of the next generation 5G systems. Here, Generalized frequency division multiplexing is a promising candidate to deploy. However, as an intrinsic property of multi-carrier modulation, the high signal amplitude fluctuation can cause several degradation effects when the signal is affected by nonlinearities. Therefore, the aim of this paper is to evaluate the performance of Generalized frequency division multiplexing systems undergoing nonlinear amplification. We evaluate the bit error ratio using two model of high power amplifier, namely the Rapp and the Saleh model, respectively. The results show that the fault rate is apparently affected according to the particular high power amplifier model and its transmission parameters.

Keywords: *Generalized frequency division multiplexing, high power amplifier, multi-carrier modulation, non-linearities*

1. INTRODUCTION

Wireless communication has become a key element of modern telecommunication industry. Recently, mobile technologies of the *4-th generation* denoted as Long-Term Evolution - Advanced (LTE-A) are deployed in many countries. These systems allow high data throughput thanks to the application of Orthogonal Frequency Division Multiplexing (OFDM) along with Multiple-Input Multiple-Output (MIMO) techniques. OFDM is widely adopted because of its favorable features like simple implementation based on Fast Fourier Transforms (FFT) and robustness against fading channels [1]. However, the requirements of particular applications scenarios foreseen for 5G might not been coped by OFDM. Along standard *bitpipe* transmission, scenarios like *machine to machine communication* (MTM) [2] and *Wireless Regional Area Network* (WRAN) [3] are in the field of interest for 5G networks. The MTM communication requires extreme low power consumption which can cause serious impact on the synchronization process, thus it is not possible to preserve the orthogonality between individual sub-carriers. Although the cyclic prefix (CP) is a powerful tool to overcome the issues related to multipath fading it is responsible for low spectrum efficiency of OFDM while applying in WRAN. Especially, the high out-of-band (OOB) radiation of OFDM limits the utilization in opportunistic and dynamic spectrum access. Therefore, the focus of recent research efforts is dedicated to alternative physical layer technologies. One of the most discussed is Filter Bank Multi-Carrier (FBMC) [4]. FBMC uses well designed filter banks to shape the individual subcarriers, thus the OOB radiation is kept extremely low. Owing to the suitable filter design in the frequency-time domain, no CP is used, hence extremely high spectral efficiency is achieved. On the other hand, the application of MIMO is not straightforward and the equalization process for rapid time varying channels is more challenging [5, 6]. Generalized Frequency Division Multiplexing (GFDM), proposed in [7], is an another possible approach to meet the requirements on flexible modulation technique. Here, the data symbols are proceeded in frequency-time block manner and pulse shaping is performed per subcarrier. On the one hand, pulse shaping enables to control the OOB and Peak-to-Average Power Ratio (PAPR) [8, 9], on the other hand it causes self-interference, which needs to be compensated, e.g. on the receiver side using interference cancellation technique [10]. Hence, all these properties making GFDM an attractive choice for deployment in 5G communication systems [13].

Since GFDM is a sum of pulse shaped subcarriers it suffers from high signal envelope fluctuations, thus the nonlinear characteristics of the high power amplifier (HPA) causes major performance degradations. Several PAPR reduction techniques, to overcome the issues of nonlinearities, have been introduced in the literature [11]. The evaluation of PAPR reduction techniques for FBMC systems can be found in [12]. In [14], the clipping technique has been investigated as a PAPR reduction scheme in GFDM. The results have shown that GFDM can in special case outperform OFDM. To the authors best knowledge, there is no paper dealing with nonlinear amplification in GFDM systems. Therefore, in this paper, we investigate the impact of nonlinear amplification on GFDM systems and analyze the error probability performance. The *Rapp* and *Saleh* HPA model, respectively, is used throughout this paper. The simulation results show that the particular HPA model and its transmission parameters significantly influences the bit error rate (BER).

The rest of the paper is organized as follows.The system model, where the GFDM transmission chain with the nonlinear HPA model, is described in Section 2. Here, the transmitter and receiver signal processing techniques used in GFDM are discussed in detail. In Section 3, the simulation results are pointed out. Finally, we conclude the paper in the last section.

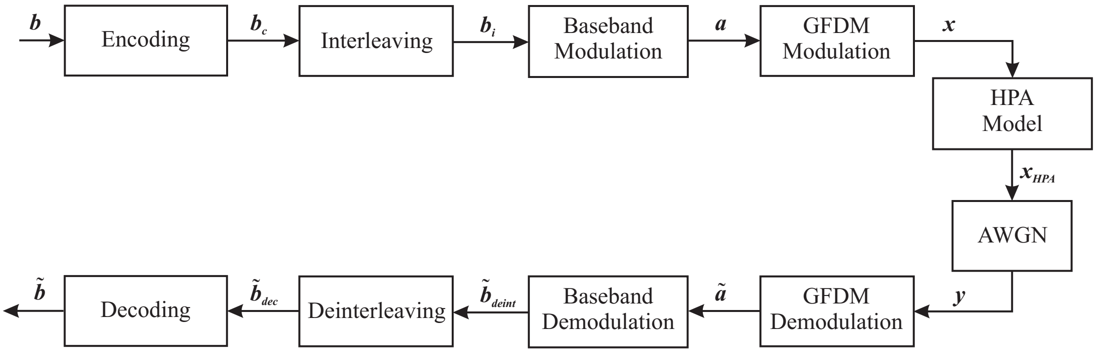

Fig. 1 System model block diagram

2. SYSTEM MODEL

The system model is depicted in Fig. 1. The process of data transmission can described as follows. The binary information to be transmitted is first encoded by an convolutional encoder and then interleaved. The next step is the baseband modulation (e.g. QPSK, 16-QAM, etc.). Subsequently, the complex modulation symbols are partitioned in blocks containing $K \times M$ elements. Where K is the number of subcarriers and M is the number of time slots. Finally, the GFDM modulation is applied, i.e. the individual subcarrier data stream are oversampled, pulse shaped and up-converted. Prior to transmission, the signal is amplified applying the particular HPA model. At the receiver side each operation is provided in inverse manner according to the signal processing steps at the transmitter. The following subsections give detailed information about the GFDM modulation and demodulation techniques and describes the different HPA models.

2.1. Transmitter

GFDM is a flexible block-based muticarrier modulation system, in contrast to FBMC, proposed by Fettweis et al. in [7]. The flexibility stands from the pulse shaping of the individual subcarriers, which is the characteristic property of the GFDM modulation. The generation of the GFDM signal consist of three main steps, i. e. oversampling, pulse shaping and carrier up-conversion. We can describe these operations mathematically as

$$x[n] = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} a_{k,m} g_{k,m}[n], \quad n = 0, \dots, NM-1. \tag{1}$$

where $a_{k,m}$ is the complex data symbol transmitted on the k^{th} subcarrier and m^{th} time slot and $g_{k,m}[n]$ is the circular pulse shaping filter of the length NM defined as

$$g_{k,m}[n] = g[(n - mK) \mod N] w^{k,n} \tag{2}$$

where $w^{k,n} = e^{-j2\pi kn/N}$ and N with $N \geq K$ is the number of samples per time slot.

The pulse shaping filter is the most important part of the system design. It influences the BER performance and also the self-interference, which is the intrinsic property of GFDM [10, 15]. Note that GFDM is not dependent on any specific filter type. It is obvious from (1), that we can describe the modulation process using the matrix form [15], which can be written as

$$x = Ad, \tag{3}$$

where A is the $NM \times KM$ transmission matrix and d is the data vector of order $KM \times 1$.

2.2. Receiver

From the matrix representation in (3), we can derive three standard GFDM receiver types, i.e. zero-forcing (ZF), matched filter (MF) and minimum mean square error (MMSE) receiver [15, 16]. Now, let as assume that the time samples $r[n]$ at the receiver, after the signal is affected by the additive white Gaussian noise (AWGN) channel, are represented by the vector r. Than we can write r as

$$r = x + w, \tag{4}$$

where x is the transmitted vector from (3) and w is the AWGN noise with zero mean and variance σ_n^2.

The ZF receiver is characterized by

$$\tilde{a}_{\mathrm{ZF}} = A^{+} r, \tag{5}$$

where A^{+} can be computed as $A^{+} = (A^H A)^{-1} A^H$.

The second type receiver, i.e. the MF, is described as

$$\tilde{a}_{\mathrm{MF}} = A^H r, \tag{6}$$

Lastly, the linear MMSE receiver is defined as

$$\tilde{a}_{\mathrm{MMSE}} = A^{\dagger} r \quad \text{with} \quad A^{\dagger} = \left(\frac{\sigma_n^2}{\sigma_d^2} I + A^H A \right)^{-1} A^H, \tag{7}$$

where σ_d^2 is the data symbols variance and I is the identity matrix with the corresponding order. From (1), it is clear, that the GFDM system requires higher computation complexity, than traditional OFDM. Therefore, the low complexity GFDM system is introduced in [17].

2.3. HPA models

In order to evaluate the nonlinear effects in the regarded system we use two HPA models. The first is the Rapp model of Solid-State Power Amplifier (SSPA). The Rapp model is defined by following Amplitude-to-Amplitude Modulation (AM/AM) and Amplitude-to-Phase Modulation (AM/PM) characteristics [18]:

$$G_{u_x} = \frac{u_x}{\left(1+\left(\frac{u_x}{O_{sat}}\right)^{2s}\right)^{1/2s}} \tag{8}$$

$$\Phi_{u_x} = 0, \tag{9}$$

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

The second is the Saleh model, used to describe traveling wave tube amplifiers (TWTA), and can be described by the following AM/AM and AM/PM characteristics [19]:

$$G_{u_x} = \frac{\kappa_G \cdot u_x}{1+\chi_G \cdot u_x^2} \tag{10}$$

$$\Phi_{u_x} = \frac{\kappa_\Phi \cdot u_x^2}{1+\chi_\Phi \cdot u_x^2}, \tag{11}$$

where κ_G, χ_G, κ_Φ and χ_Φ are the Saleh model parameters.

The operating point of the nonlinearity is defined by the so called input back-off (IBO) defined as:

$$\mathrm{IBO_{dB}} = 10\log_{10}\frac{P_{sat}}{P_{av}}. \tag{12}$$

which corresponds to the ratio between the saturated power P_{sat} and average input power P_{av}.

3. RESULTS

In this section, the PAPR performance and the the BER performace of GFDM and OFDM signals, respectively, undergoing nonlinear amplification is shown. The effect of the pulse shaping filter parameters on the PAPR and the BER performance will be also investigated. In order to increase the robustness against distortions due to the nonlinear noise the binary source data is encoded using a 4 state convolutional encoder with polynomials $(6,7)_8$ in octal notation and a code rate of $1/2$. After the interleaving operation using a random permutation vector the bits are mapper following QPSK or 16-QAM constellation with Gray mapping. We use 512 subcarriers and 5 subsymbols per block. The pulse shaping filter is the root rise cosine filter with the roll-off factor of 0.2. We us the ZF GFDM receiver model [15]. Because we assume the AWGN channel model, cyclic prefix is not considered in the simulation setup. The the Rapp HPA model parameter s is set to 3 and O_{sat} is set to 1. We set the Saleh model parameters $\kappa_G = 2$, $\chi_G = \pi/3$, $\kappa_\Phi = 1$ and $\chi_\Phi = 1$.

3.1. PAPR

The PAPR is a common metric to describe the envelope fluctuation dynamics of the transmitted signal. The PAPR is calculated as

$$\mathrm{PAPR_{dB}} = 10\log_{10}\frac{\max(|x[n]|^2)}{E(|x[n]|^2)}. \tag{13}$$

The Complementary Cumulative Distribution Function (CCDF) of the PAPR for the OFDM and GFDM system is shown in Fig. 2. It is interesting to note that the PAPR performance is getting worse with higher roll-off factor values. This is the first reason why the GFDM performance is worse in comparison to OFDM, as it will be shown in the next part. The second reason is the self-inflicted intersymbol interference, due to the loss of orthogonality between subcariers, caused by the pulse shaping operation. One can easily observe, depending on the PAPR curves, that that pulse shaping filter significantly influences the signal dynamics and hence the PAPR characteristics.

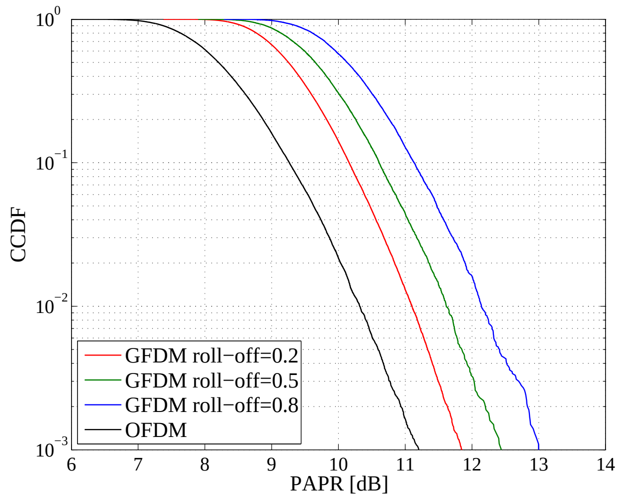

Fig. 2 CCDF of PAPR for OFDM and GFDM with different roll-off factors.

3.2. BER

Note, in each of the following figures the BER performance of GFDM and OFDM when no HPA is applied is shown as a reference. Furthermore, the small performance gap between OFDM and GFDM, is caused by the choice of the pulse shaping filter properties and also because the ZF GFDM receiver. In Fig. 3 the BER performance of GFDM is comparison to OFDM using QPSK as baseband modulation under Rapp model is shown. It can be seen that the error rate is slightly worse when HPA is applied. On the other hand, the BER is highly degraded when the Saleh model is used. Especially for low IBO values the error rate is very high, this can be seen in Fig. 4. Fig. 5 shows the BER performance for 16-QAM. One can observe that the error rate is higher as in the case of QPSK. Again, as it is shown in Fig. 6, the BER is worse when the Saleh model is used. afgaerg waefwe e ewewwe

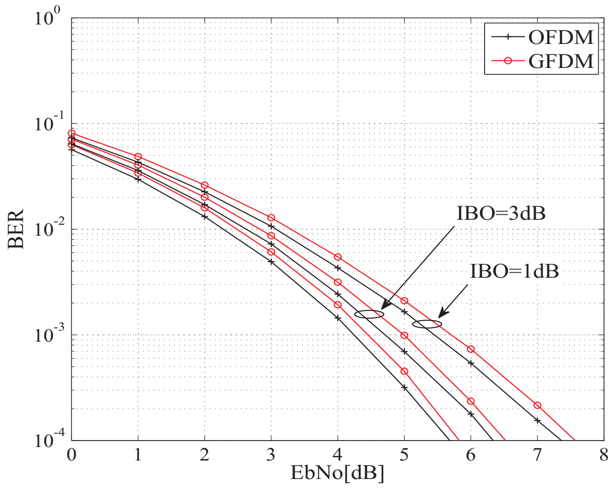

Fig. 3 BER performance of GFDM and OFDM, respectively, using QPSK and Rapp HPA model with different IBO values

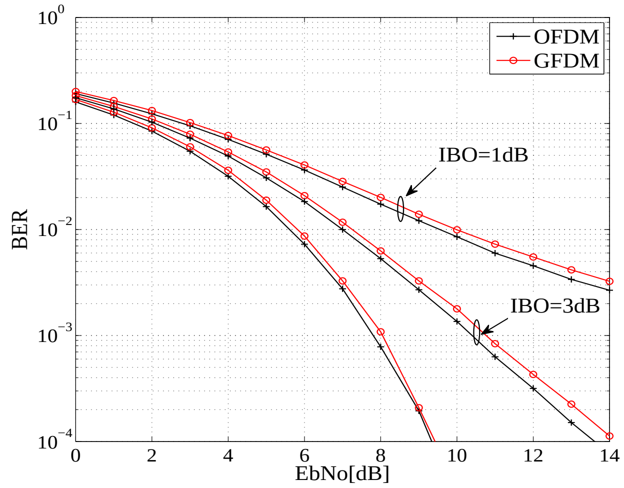

Fig. 5 BER performance of GFDM and OFDM, respectively, using 16-QAM and Rapp HPA model with different IBO values

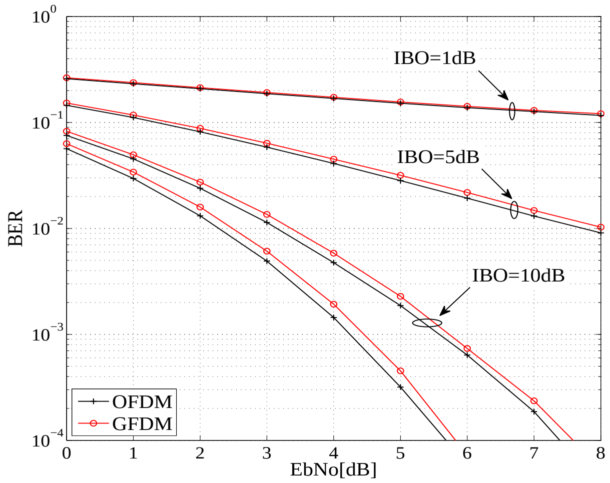

Fig. 4 BER performance of GFDM and OFDM, respectively, using QPSK and Saleh HPA model with different IBO values

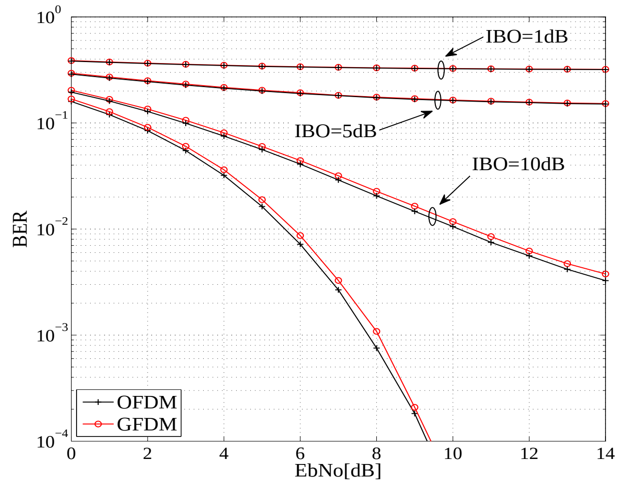

Fig. 6 BER performance of GFDM and OFDM, respectively, using 16-QAM and Saleh HPA model with different IBO values

3.3. The effect of the pulse shaping filter on the BER performance

In this subsection the BER performance of the GFDM system when different IBO values and roll-off factors of the RRC pulse shaping filter, respectively, will be revealed. Here, we set the E_bN_0 values to 4 dB and alternate the IBO and roll-off values. In Fig. 7 the BER performance of GFDM using QPSK as baseband modulation under Rapp model is shown when different IBO values are used and the roll-off factor of the RRC filter is changed. It can be seen that the error rate is strongly dependent on the IBO value as well as the roll-off factor. Especially for low IBO values and and high roll-off factors the error rate is very high. Fig. 8 shows the BER performance for 16-QAM and diffrent IBO and roll-off values. Again, the fault rate is higher for high roll-off and low IBO values.

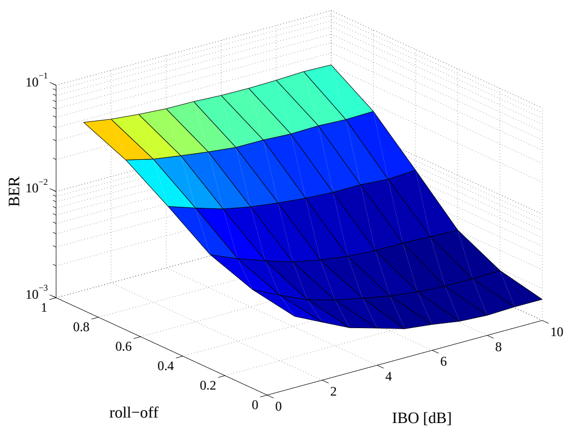

Fig. 7 BER performance of GFDM using QPSK with different filter roll-off factors and IBO values

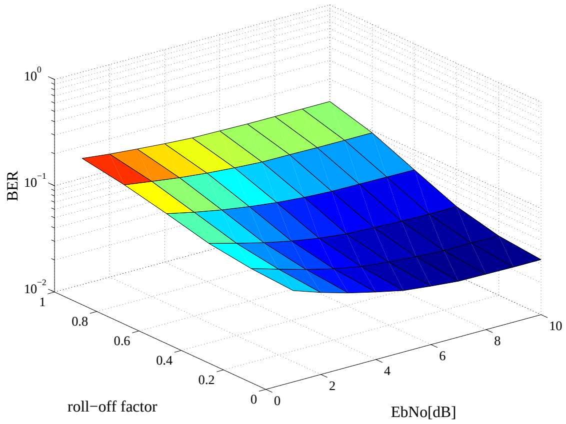

Fig. 8 BER performance of GFDM using 16-QAM with different filter roll-off factors and IBO values

4. CONCLUSIONS

In this paper, we analyzed the impact of nonlinear amplification on the BER performance in GFDM systems. The simulation results showed that the overall BER performance of the GFDM system is highly degraded when nonlinear amplification is performed. It has been also shown that the error rate strongly depends on the HPA model as well as the IBO value. Furthermore, it is obvious that the filter is responsible for the system performance and therefore it is in fact the key element in the GFDM design. Based on this fact, it is crucial to investigate PAPR reduction techniques, e.g. active constellation extension, selective mapping, tone reservation etc., for GFDM in order to face the issues related to nonlinearities. This needs to be appropriately addressed and will be the focus of future research studies in this topic.

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BIOGRAPHY

Lukáš Sendrei was born on 1. 11. 1987. In 2012 he graduated (M.Sc.) with honours at the Department of Electronic and Multimedia Telecommunication of the Faculty of Electrical Engineering and Informatics at Technical University in Košice and currently he is working towards his PhD at the same university. In 2013, he spend two months with the Vodafone Chair Mobile Communications Systems, Technische Universität Dresden, Dresden, Germany as a guest researcher working in the area of nonlinear effects in GFDM. His current research interests include wireless multicarrier communication systems (FBMC, GFDM) for 5G and cognitive radio systems.

Stanislav Marchevský received MSc in electrical engineering at the Faculty of Electrical Engineering, Czech Technical University in Prague, in 1976 and PhD degree in radioelectronics at the Technical University of Košice in 1985. Currently he is a Professor of Electronics and Multimedia Communications Department of Faculty of Electrical Engineering and Informatics of Technical University of Košice. He teaching interests include switching theory, digital television technology, and satellite communications. His research interests include image nonlinear filtering, neural networks, genetic algorithms, and multiuser detection, space-time communication, diversity communication over fading channel, and power and bandwidth efficient multiuser communications.