Adaptive Predistortion techniques for non-linearly amplified FBMC-OQAM signals

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***Abstract*—The Filter Bank Multicarrier with Offset Quadrature Amplitude Modulation (FBMC-OQAM) is emerging as one of the alternatives to Orthogonal Frequency Division Multiplexing (OFDM) for next generation broadband wireless access systems. In this paper, we focus on the nonlinear distortion effects in a FBMC-OQAM system when the signal is passed through a nonlinear High Power Amplifier (HPA) which is modeled as Saleh's one exhibiting amplitude and phase distortions. First, we develop an analysis showing that the FBMC-OQAM signals are more sensitive to the phase distortion than OFDM signals. Then, we address the problem of the compensation of these distortions in FBMC-OQAM systems using digital predistortion (DPD) at the transmitter. Therefore, two DPD schemes are considered in this investigation and their performance are compared in OFDM and FBMC-OQAM systems.**

***Index Terms*—FBMC-OQAM, OFDM, High Power Amplifier (HPA), Digital Predistortion (DPD), phase error sensitivity.** [1]

I. Introduction

Multi-Carrier (MC) communications are widely being deployed in broadband wireless communication systems due to their robustness to multi-path effects and efficient implementation using an Inverse Fast Fourier Transform (IFFT). Since many years, the Orthogonal Frequency Division Multiplexing (OFDM) modulation is the leading MC transmission scheme for many wireless standards.

However, if OFDM is now adopted in many wireless broadband systems, it cannot be considered as the ultimate MC technique. Indeed, it sacrifices data transmission rate because of the insertion of Cyclic Prefix (CP) in order to reduce the inter-symbol interference. In addition, OFDM systems suffer from fast time variations of the radio channel and timing offset due to imperfect synchronization [1]. OFDM is then not well suited to Cognitive Radio (CR) networks in which there is no strict synchronization between users [3]. In order to overcome the previously mentioned problem, Filter Bank based Multi-Carrier with Offset Quadrature Amplitude Modulation (FBMC-OQAM) has emerged as a definitely attractive solution [4], [5]. With this technique the modulated signals are shaped with very efficient time/spectral waveforms [4].

Nevertheless, similar to OFDM, a fundamental drawback of FBMC-OQAM systems is the high Peak-to-Average Power Ratio (PAPR) of the modulated signals, which are very sensitive to nonlinear distortions caused by the High Power Amplifier (HPA).

To reduce distortions and improve power efficiency, both linearization techniques and PAPR reduction are applied in transmission systems. In this paper, we will deal only with linearization techniques and the reader interested to PAPR reduction is referred to [15].

In the literature, various linearization techniques for OFDM have been proposed, among which digital predistortion attracted much attention. Recently, many predistortion methods for OFDM have been proposed such as: inverse Volterra series [8], the rational function [18], Wiener-Hammerstein systems [16], [17], memory polynomials [19], look-up table (LUT) [21], [20], and neural networks [7]. The review of the different methods for predistortion is not the main object of this paper and the interested reader is referred to [7], [21], [20].

However, it is worth noting and to the best of authors knowledge that no previous investigation on the HPA nonlinearity effects on FBMC-OQAM performances has been published in the open literature.

Due to the similarity between OFDM and FBMC-OQAM systems, it is natural to consider employing DPD to compensate amplitude and phase nonlinear distortions of FBMC-OQAM signals. However, FBMC-OQAM systems have a different signal structure compared with OFDM. Therefore, directly applying the DPD schemes of OFDM systems to FBMC-OQAM systems may be not very effective.

Novelty of this paper consists on the investigation of the HPA nonlinearities effects on FBMC-OQAM systems. First, we develop an analysis showing that the FBMC-OQAM signals are more sensitive to the phase distortion than OFDM signals. Then, we address the problem of the compensation of these distortions in FBMC-OQAM systems using Digital Predistortion (DPD) at the transmitter. Therefore, two DPD schemes were considered in this investigation and their performance are compared in OFDM and FBMC-OQAM systems.

The organization of our paper is as follows. Section II presents the considered FBMC-OQAM system with HPA nonlinearity. In section III, the phase error sensitivity of FBMC-OQAM/OFDM signals is analyzed and two different DPD schemes are introduced. Simulation results are presented in section IV, followed by the conclusion in section V.

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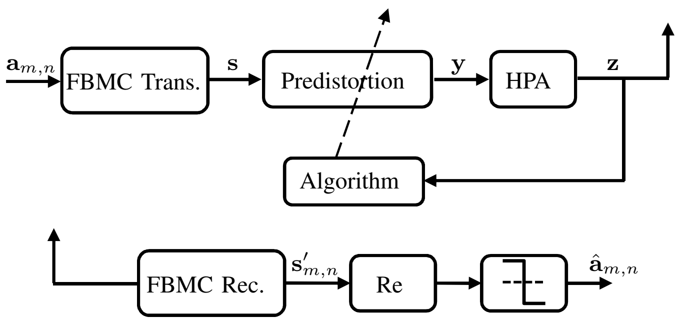

Fig. 1. The communication transceiver model OFDM/FBMC-OQAM.

II. System Model

A. FBMC/OQAM signal model

The main idea of FBMC/OQAM is to transmit OQAM data symbols instead of conventional QAM ones [4], [11], where the in-phase and the quadrature components are time staggered by half a symbol period, $T/2$.

Accordingly, the baseband continuous-time model of the FBMC transmitted signal can be defined as follows [4]:

$$s(t) = \sum_{m=0}^{N-1} \sum_{n=-\infty}^{+\infty} a_{m,n} h(t - nT/2) e^{j\frac{2\pi}{T}mt} e^{j\varphi_{m,n}} \quad (1)$$

where, N is the number of subcarriers, $h(t)$ is the prototype filter and $a_{m,n}$ are real-valued symbols. The phase term $\varphi_{m,n}$ is given:

$$\varphi_{m,n} = \frac{\pi}{2}(m+n) - \pi mn$$

Considering the shifted versions of $h(t)$ in time and frequency:

$$\gamma_{m,n}(t) = h(t - nT/2) e^{j\frac{2\pi}{T}mt} e^{j\varphi_{m,n}} \quad (2)$$

We can rewrite equation (1) as follows,

$$s(t) = \sum_{m=0}^{N-1} \sum_{n=-\infty}^{+\infty} a_{m,n} \gamma_{m,n}(t) \quad (3)$$

In a distortion-free noiseless channel, the demodulated signal s'_{m_0,n_0} at time instant n_0 and subcarrier m_0 is given by:

$$\begin{aligned} s'_{m_0,n_0} &= \langle s(t), \gamma_{m_0,n_0}(t) \rangle = \int_{-\infty}^{+\infty} s(t) \gamma^*_{m_0,n_0}(t) dt \\ &= \sum_{m=0}^{N-1} \sum_{n=-\infty}^{+\infty} a_{m,n} \int_{-\infty}^{+\infty} \gamma_{m,n}(t) \gamma^*_{m_0,n_0}(t) dt \\ &= a_{m_0,n_0} + \sum_{m\neq m_0} \sum_{n\neq n_0} a_{m,n} \int_{-\infty}^{+\infty} \gamma_{m,n}(t) \gamma^*_{m_0,n_0}(t) dt \end{aligned} \quad (4)$$

where $\gamma^*_{m_0,n_0}(t)$ is the complex conjugate of $\gamma_{m_0,n_0}(t)$ and $\langle .,. \rangle$ stands for the inner product.

According to [4], the prototype filter is designed such that the intrinsic interference term is orthogonal to the useful symbol i.e.

$$ju_{m_0,n_0} = \sum_{m\neq m_0} \sum_{n\neq n_0} a_{m,n} \underbrace{\int_{-\infty}^{+\infty} \gamma_{m,n}(t) \gamma^*_{m_0,n_0}(t) dt}_{\Psi_{\Delta m, \Delta n}} \quad (5)$$

is pure imaginary.
Considering the PHYDYAS prototype filter proposed in [13], the coefficients $\Psi_{\Delta m, \Delta n}$ are given in Table I.
Consequently, a perfect reconstruction of transmitted real symbols a_{m_0,n_0} is obtained by taking the real part (OQAM decision) of the demodulated signal s'_{m_0,n_0}.

TABLE I
Transmultiplexer impulse response (main part)

	n_0-3	n_0-2	n_0-1	n_0	n_0+1	n_0+2	n_0+3
m_0-1	$0.043j$	$0.125j$	$0.206j$	$0.239j$	$0.206j$	$0.125j$	$0.043j$
m_0	$-0.067j$	0	$-0.564j$	1	$0.564j$	0	$0.067j$
m_0+1	$0.043j$	$-0.125j$	$0.206j$	$-0.239j$	$-0.206j$	$-0.125j$	$0.043j$

B. HPA nonlinearities

Traditional works [1], [2], [3], [10] on FBMC-OQAM systems have assumed that the HPAs is linear introducing no distortion to the signal. This is true for large backoff but, in that case, the efficiency is considerably low. When the backoff is reduced and HPAs are operating in the vicinity of their saturation level, the resulting FBMC-OQAM channel is nonlinear meanwhile the performance is significantly degraded due to the amplitude and phase distortions on the input data.

The signal at the output of the nonlinear HPA can be expressed as follows:

$$z(t) = f(y(t)) = F_A(r) e^{j(\varphi(t) + F_P(r))} \quad (6)$$

where r is the input modulus, $\varphi(t)$ is the input phase. $F_A(.)$ and $F_P(.)$ denote the AM/AM and AM/PM conversions, respectively.

For nonlinear HPA model, we considered Saleh's model [9]. The AM/AM and AM/PM conversions of the HPA can be represented as follows:

$$F_A(r) = \frac{\alpha_a r}{1 + \beta_a r^2} \quad \text{and} \quad F_P(r) = \frac{\alpha_p r^2}{1 + \beta_p r^2} \quad (7)$$

where α_a and β_a are the parameters to decide the non-linear level, and α_p and β_p are phase displacements. The values for these parameters are assumed to be: $\alpha_a = 2, \beta_a = 1, \alpha_p = 4$ and $\beta_p = 9$. We define the input back-off (IBO) as the difference in decibels between the saturation input power (A_{sat}) and the average input power.

III. Phase error sensitivity of OFDM and FBMC and Predistortion

A. Phase error sensitivity of OFDM and FBMC

In AWGN channel, the QPSK-BER is defined by [14]:

$$\text{BER} = \frac{1}{2}\text{erfc}\left(\frac{d}{2\sqrt{N_0}}\right) \tag{8}$$

where $N_0/2$ is the power spectral density of the additive white Gaussian noise (AWGN). The distance d in this case is equal to $2\sqrt{E_b}$ (E_b is the energy per bit).
However, in the case of a phase shift $\delta\varphi$ between the transmitter and the receiver. The distance d depends on the multicarrier scheme. Thus, we can write:

a) OFDM case:

$$d_{\text{OFDM}} = a^I_{m,n}\cos(\delta\varphi) - a^Q_{m,n}\sin(\delta\varphi) \tag{9}$$

where $a^I_{m,n}$ and $a^Q_{m,n}$ denote respectively the in-phase and the quadrature-phase components of the transmitted complex QPSK symbol.

b) FBMC case:

$$d_{\text{FBMC}} = a_{m,n}\cos(\delta\varphi) - u_{m,n}\sin(\delta\varphi) \tag{10}$$

where $u_{m,n}$ is given by (5).

We can observe that the respective distributions of $a^Q_{m,n}$ (i.e d_{OFDM}) and $u_{m,n}$ (i.e d_{FBMC}), depicted in Figure 2, are strongly different. This difference, can explain,later, the gap between the BERs of OFDM and FBMC.

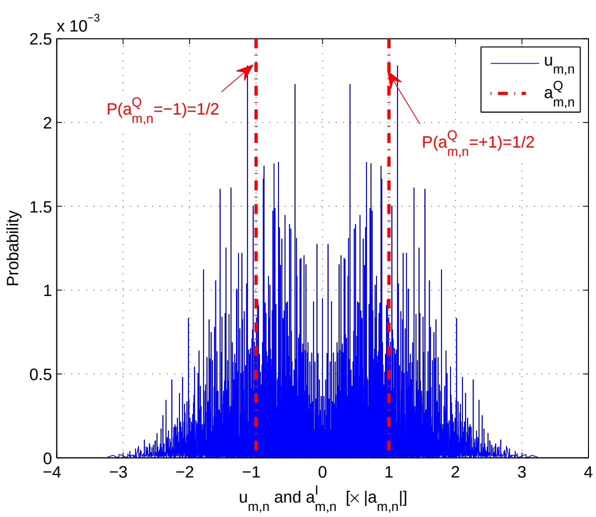

Fig. 2. The respective distributions of $u_{m,n}$ and $a^Q_{m,n}$

B. Predistortion technqiues

The concept behind predistortion calls for the insertion of a nonlinear device between the input signal and the power amplifier (Figure 1).

In adaptive predistortion, two important aspects needs to be considered for finding the coefficients of the predistorter : learning architecture and adaptation algorithm.

In this work, we deal with the indirect learning architecture (Figure 3) which is much more efficient than a direct one for predistortion systems [7]. This architecture uses two identical nonlinear functions for the predistorter and training. The coefficients of the predistorter are a copy of the coefficients of the training function connected as a post-distorter to the nonlinear HPA. The coefficients of the training function are estimated using the error signal and training algorithms. The training function could be modeled as a Volterra system [8], rational function [18], Wiener-Hammerstein system [16], [17], polynomial model [19], and neural network [7]. This approach can be classified into two schemes:

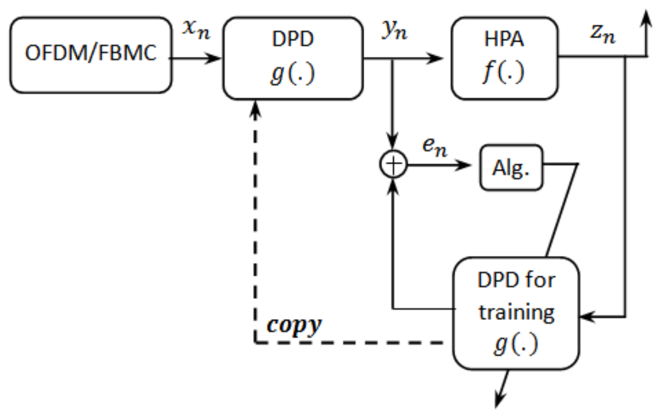

Fig. 3. First DPD scheme

1) First DPD scheme: Using the DPD scheme illustrated in Figure 3, we approximate simultaneously the inverse transfer functions of the nonlinear HPA (AM/AM and AM/PM).

2) Second DPD scheme: With that scheme (Figure 4), we aim to compensate separately amplitude distortion and phase distortion with two independent predistortion functions.

IV. Simulation Results

In this section, we present simulation results illustrating the performance in terms of the Symbol Error Rate (SER) of the FBMC-OQAM and OFDM systems in the presence of the HPA nonlinearities. The performance of the two mentioned predistortion schemes in the compensation of the nonlinear distortions are also presented. Herein, we consider the Salhe's model for the nonlinear HPA as described in section II-B.

A complex baseband FBMC-OQAM/OFDM with $N = 64$ subcarriers using 10^6 randomly generated symbols was considered. An Additive White Gaussian Noise channel model (AWGN) was used to clearly observe the effect of nonlinearity and performance improvement by the considered DPDs.

For the FBMC-OQAM system, we recall that we use the PHYDYAS prototype filter with an overlapping factor of 4 [13].

For illustration, within all possible nonlinear functions, we have chosen a DPD function based on feed-forward neural network as in [7]. This predistorter considered, named NNPD

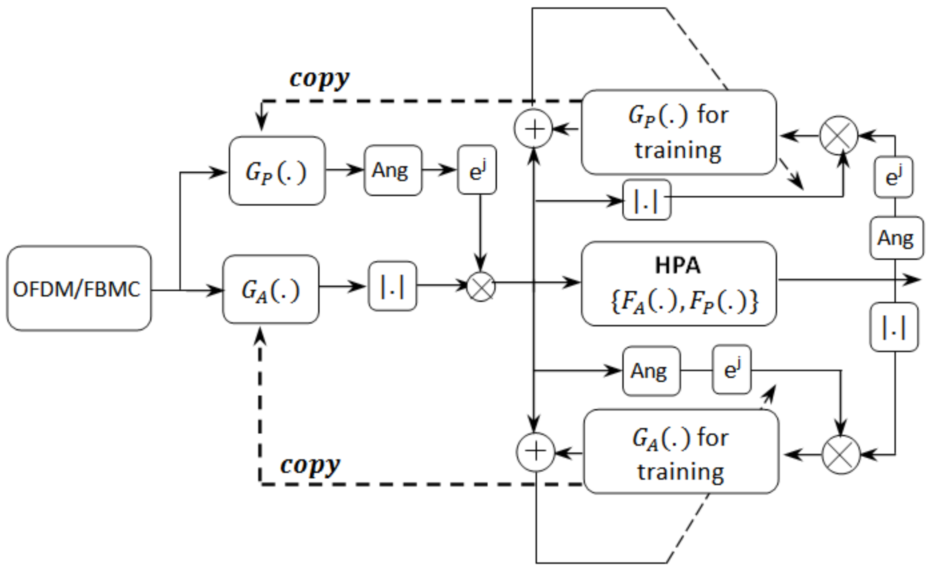

Fig. 4. Second DPD scheme

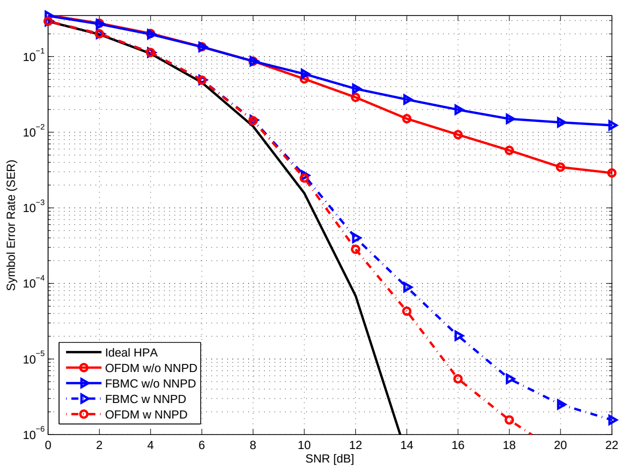

Fig. 5. SER vs SNR for OFDM/FBMC-OQAM systems with and without first DPD scheme : HPA, IBO=6dB, 64 subcarriers, AWGN channel

[7], was a multilayer perceptron, which has two inputs and two outputs, namely the I and Q components of the input and output signal, respectively. The NNPD has one hidden layer with N_h neurones. the Levenberg-Marquardt (LM) algorithm is used to evaluate its coefficients. This algorithm has been shown, in [7], to exhibit a very good performance at a low computation complexity, a low amount of required RAM and faster convergence than other algorithms used in literature. This work can be extended to any other method such as polynomial models, Volterra series.

A. First DPD scheme

In Figure 5, we investigate the performance of the first DPD scheme over OFDM and FBMC-OQAM systems in presence of amplitude and phase distortions with an IBO of $6dB$. We can notice from these results that the FBMC-OQAM performance is more affected by the HPA nonlinearities than OFDM. As demonstrated in section III-A, this observation is expected and it can be explained by the fact that the FBMC-OQAM system is more sensitive to the phase distortion than the OFDM system.

On the other hand, Figure 5 shows that the first DPD scheme can reduce considerably the SER, in the two considered systems, compared to the one without any predistortion. Nevertheless, it performs worse with the FBMC-OQAM system when compared to the OFDM one. Such degradation can be explained by the fact that this DPD, which aims to compensate simultaneously the amplitude and phase nonlinearities, is not able to compensate perfectly the phase error.

Indeed, AM/AM distortion can only be perfectly inverted as far as the input power is lower than the saturation power, and then the predistorted amplifier exhibits a residual AM/AM distortion that affects the correction of the AM/PM distortion.

B. Second DPD scheme

In relation with attempts to get efficient predistortion scheme, our efforts were deployed to build a new predistortion scheme around the concept of separating the compensation of the phase and amplitude distortions.

In this part, the simulation results of the performance of the second predistortion scheme are given in presence of the nonlinear HPA described in section II-B.

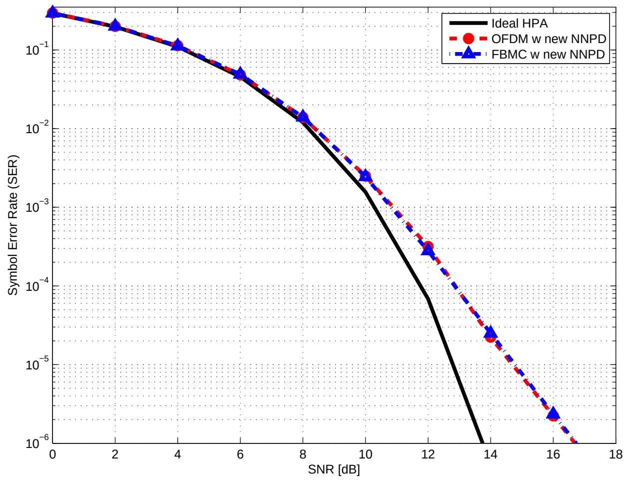

Fig. 6. SER vs SNR for OFDM/FBMC system with second DPD scheme, IBO=6dB, 64 subcarriers, AWGN channel

Figure 6 shows the OFDM and FBMC-OQAM SERs versus SNR for an IBO of $6dB$. Comparing the different curves, we clearly note an excellent match between the performance provided by the second predistortion scheme for both OFDM and FBMC-OQAM systems. we can note from these results that this DPD scheme arrive to compensate perfectly the phase error due to the nonlinear power amplifier.

V. Conclusion

In this paper, we have investigated the impact of HPA nonlinearity on the performance of OFDM and FBMC-OQAM systems. Herein, we consider the Saleh's model for the nonlinear HPA that exhibits amplitude and phase distortions. We first give an analysis showing that the FBMC-OQAM signal is more sensitive to phase error than OFDM signal. We then present two predistortion schemes, which are based on the indirect learning architecture. The first scheme aims to compensate simultaneously the amplitude and phase distortions induced by the nonlinear HPA, while the second one aims to compensate these distortions separately. An evaluation of the performance of these predistotions is made for OFDM and FBMC-OQAM systems. Through this evaluation, we have shown that the first predistortion scheme performs worse in FBMC-OQAM system than in OFDM one. This result is explained by the fact that the phase error correction depends on the correction of the amplitude distortion.

With the second DPD scheme where phase and amplitude preditortions are made separatly, OFDM and FBMC-OQAM systems reach the same performance showing that a higher attention must be paid for phase correction in FBMC.

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