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Overview of Nonlinear Distortion in OFDM Systems

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***Abstract* - OFDM is to be a very effective technique for high speed digital communications in environments affected by high interference and multipath propagation. However, the principle of OFDM that brings this advantage (the use of several sub-carriers resulting in a proportionally longer symbol period in each sub-carrier) brings also one of the major drawbacks of this technique.**

As the number of sub-carriers *Nc* increase, the OFDM signal dynamic becomes larger. This happens because for each sub-carrier there is a signal with random phase and amplitude. In other words, OFDM signals have a large Peak-to-Average Power Ratio (PAPR) [1]. This characteristic makes the OFDM system very sensitive to non-linear distortions.

Index Terms – Peak-to-Average Power Ratio (PAPR), Power Amplifiers (PA), High Power Amplifiers (HPA), Traveling-Wave Tube Amplifiers (TWTA), Soft Envelope Limiter (SEL), Solid State Power Amplifiers(SSPA), Power Amplifier Nonlinearity Cancellation (PANC), Output Back Off (OBO), High Power Amplifier (HPA).

I. Introduction

The PAPR is defined as:

$$PAPR_{OFDM} = \frac{max|x_i|^2}{\frac{1}{N_c}\sum_{i=0}^{N_c-1}|x_i|^2}, for\ i = 0,1,2,\ldots\ldots,N_c-1$$

Where x_i are the transmitted time samples of an OFDM symbol. Nonlinear distortions are mainly caused by the Power Amplifiers (PA). The nonlinear distortion at the transmitter causes interference both inside and outside the signal bandwidth. The in-band component affects the system BER [8] while the out-of band component affects adjacent frequency bands [2].

The high PAPR in OFDM systems brings an additional condition in order to maintain their performance in an acceptable range. The nonlinear distortions have to be kept as low as possible. A linear behavior is achieved when operating the amplifier sufficiently below its saturation point. As a result, a high output back off (OBO) is required in the power amplifiers. The OBO is the ratio between the saturation power and the actual output power, which is the power at which the amplifier is operating [3].

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This can be expressed as

$$OBO = \frac{P_{sat}}{P_{out}} = \frac{V_{sat}^2}{E\{|y(t)|^2\}}$$

Where V_{sat} is the saturation voltage and *y(t)* is the output of the amplifier. Generally High Power Amplifiers (HPA) show better power efficiency when driven close to their saturation point. Therefore, a higher OBO results in lower power efficiency. Power efficiency is especially valuable in the cases, for example, of portable devices (mobile phones) and satellite systems, where power is indeed a very limited and expensive resource. Therefore a preliminary study of the system is required for finding a good trade-off between transmitted power and degradation [4].

II. THE OFDM RF SUB-SYSTEM

The Power Amplifier is part of the RF sub-system of OFDM systems. The RF sub-system consists of the In-phase and Quadrature (IQ) modulator, a baseband converter, a spectral filter and the power amplifier. Figure 1 shows a block diagram of an RF sub-system [5].

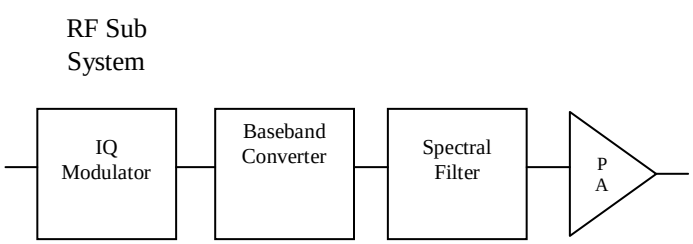

Figure 1: Block diagram of the RF Sub System.

The IQ modulator splits the input data stream into two separate streams x_I and x_Q. Then it multiplies these streams by a sine and a cosine waveforms respectively. The resulting signals are later summed together to form a modulated intermediate frequency (IF) carrier. The envelope of the IF carrier A is given by:

$$A = \sqrt{x_I^2 + x_Q^2}$$

The modulated IF carrier is then converted to the RF carrier frequency via the baseband converter. The baseband converter is built up of a multiplier and a local oscillator of frequency fc which is the carrier frequency or central frequency. The output of the baseband converter is then filtered by the spectral filter to limit the bandwidth of the RF carrier. This filtered signal is then amplified by the PA to an adequate power level for the RF transmission [6].

The amplifier introduces most of the nonlinear distortion in the system and therefore it is the main element to be analyzed in this paper. The following section describes the characteristics and models of power amplifiers used in OFDM systems.

III. POWER AMPLIFIERS IN OFDM APPLICATIONS

Ideally, a power amplifier produces a scaled version of the input signal. Therefore, the output an ideal amplifier can be described as

$$V_{out} = GV_{in}$$

Where G is the voltage gain of the amplifier. The output signal has the same waveform as the input signal and no new frequencies are introduced [7].

However, real amplifiers do not behave in this way. They act on the signal in an uneven way depending on the magnitude and frequency of the signal. This results in a distortion of the waveform that does not follow the superposition principle and therefore is not linear.

$$f(Cx_1) = C(f(x_1))$$
$$f(x_1 + x_2) = f(x_1) + f(x_2)$$

Nonlinearities in amplifiers can be described by their amplitude transfer characteristics - also referred as Amplitude Modulation/Amplitude Modulation (AM/AM) conversion - and phase transfer characteristics

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or Amplitude Modulation/Phase Modulation (AM/PM) conversion. The AM/AM conversion (FA[ρ]) describes the amplitude of the output signal for a given input amplitude (ρ) and the AM/PM conversion (FA[ρ]) describes the phase of the output for a given input amplitude (ρ)[8].

Both AM/AM conversion and AM/PM conversion can either depend on the frequency at which the amplifier is operating or be the same for all frequencies. Therefore, amplifiers can be classified, in terms of nonlinearity, into frequency-dependent and frequency-independent [10]. Frequency independent amplifiers can either be memory less system or systems with memory. Frequency-dependent amplifiers are systems with memory.
In table 1 a summary of the classification and different distortion effects of nonlinear amplifiers is presented.

In a memory less system there are no energy storing components, and any change in the input occurs instantaneously at the output. In other words, the output and the input are in-phase and there is only AM/AM conversion. In a system with memory there are energy storing devices, therefore the output depends on the previous inputs values. This results in phase distortion in addition to the amplitude distortion. Detailed information about nonlinearities with and without memory are presented in [9] and [10].

For the analysis of nonlinear distortion in OFDM systems, amplifiers are often considered frequency-independent. In addition, even considering that in general the overall system is considered to have memory1, there is no ISI between OFDM symbols. Furthermore, in [12] the analysis is performed for Traveling-Wave Tube Amplifiers (TWTA) and solid-state power amplifiers (SSPA). In addition, [11] uses the Soft Envelope Limiter (SEL). An overview of the models for these amplifiers is presented below. Models for other amplifiers as well as a deeper discussion about amplifier nonlinearities is available in [11].

IV. High Power Amplifiers

Today, the most commonly used devices are the ones based on electron beam tubes, usually Travelling Wave Tube Amplifiers (TWTA), and the Solid State Power Amplifiers (SSPA) as shown in table 3.2, for different microwave bandwidths.

TWTA operation is based on the same principle of the incandescent electric light bulb: making an electric current flow through a glass tube surrounding a vacuum.

An electron emitter, which mainly consists of a heater, a cathode and an anode, starts the stream of electrons by heating the cathode. The stream passes through the anode and travels through the helix. At this point the energy is transferred to the signal travelling around the helix thus amplifying it. Because of their construction, TWTAs offer large currents and therefore, high output powers can be obtained [13].

TWTAs can be modeled, for the non-frequency selective case, using the model proposed by Saleh in [12] as:

$$F_A[\rho] = \frac{v\rho}{1 + \beta_a \rho^2}$$

$$F_P[\rho] = \frac{\alpha_p \rho^2}{1 + \beta_p \rho^2}$$

$F_A[\rho]$ and $F_P[\rho]$ are the AM/AM and AM/PM conversion functions respectively, v is the small-signal gain of the amplifier, β_a depends on the input saturation voltage and α_p and β_p depend on the maximum phase displacement that can be introduced by the amplifier.

V. Characterisation of Nonlinear Effects in OFDM systems

The distortions caused by nonlinearities can be classified into two components: the in-

band component and the out-of-band component. The last causes mainly adjacent-channel interference (ACI) [9] affecting other systems in adjacent bands but has no effects on the performance of the actual system. The in-band component, on the other hand, affects the performance of the system.
The effects of these distortions are:

- Interference between the in-phase and quadrature (I/Q) components due to AM/PM conversion (if present).
- Intermodulation effects on the sub-carriers.
- Wrapping of the signal constellation in each sub-channel.

Degradation in the performance of a communication system generally results in an increase in the BER. The following analysis explains, quantitatively, the impact of the nonlinearities in the BER.

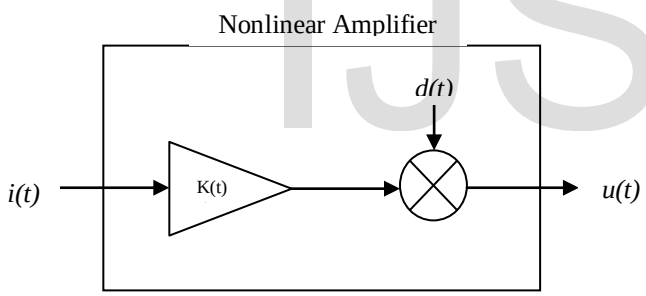

Figure 2: Alternative model of a nonlinear amplifier.

VI. Power Amplifier Nonlinearity Cancellation

Power Amplifier Nonlinearity Cancellation (PANC) is introduced in [13]. This technique attacks the nonlinearity problem from the receiver point of view. It requires the knowledge of the channel coefficients and the characteristics of the amplifier.
The main idea of this technique is, based on the received symbols, to estimate the NLD noise term caused by the amplifier and subtract it from the received signal. By repeating this process for several times, a better estimation of the received signal is achieved.

Figure 3 presents a block diagram of the PANC. An IFFT is applied to the decoded symbols and then passed through the amplifier model. The input of the amplifier is then subtracted from the output to obtain an estimation of the NLD noise term. The result is then transformed to the frequency domain by the FFT block and subtracted from the received signal. Since the distortion term is subtracted in the frequency domain, this is equivalent to a symbol-by-symbol subtraction.

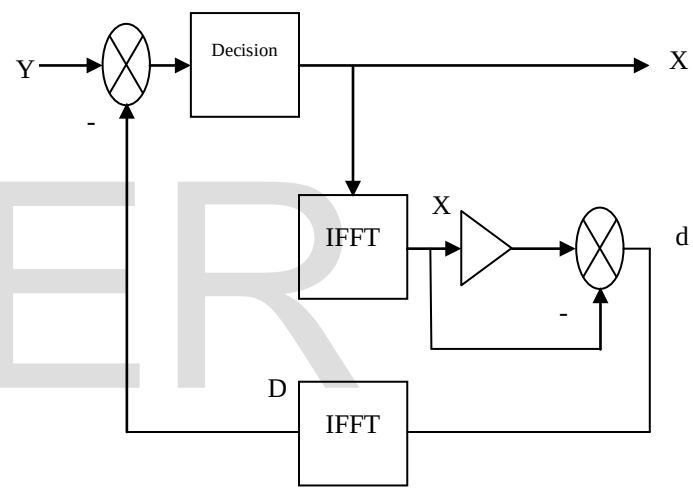

Figure 3: Power Amplifier Nonlinearity Cancellation (PANC).

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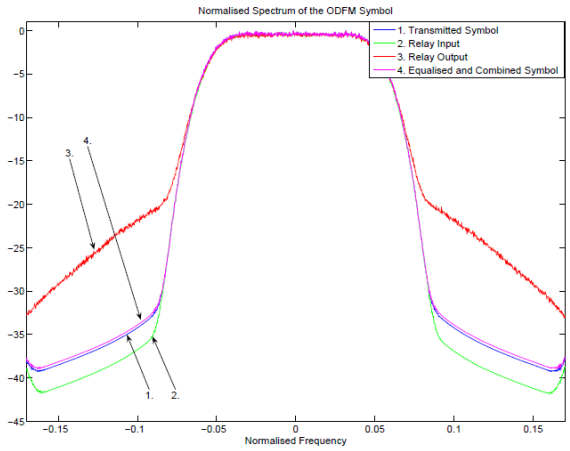
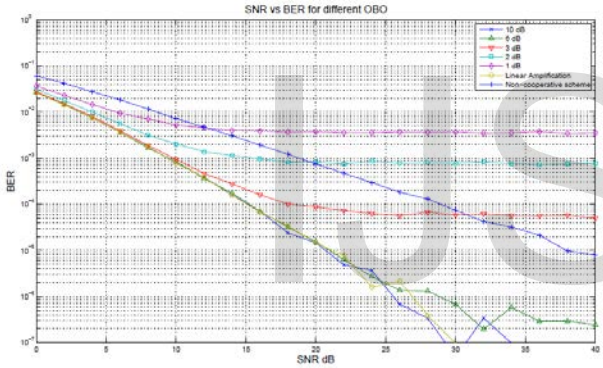
VII. RESULTS



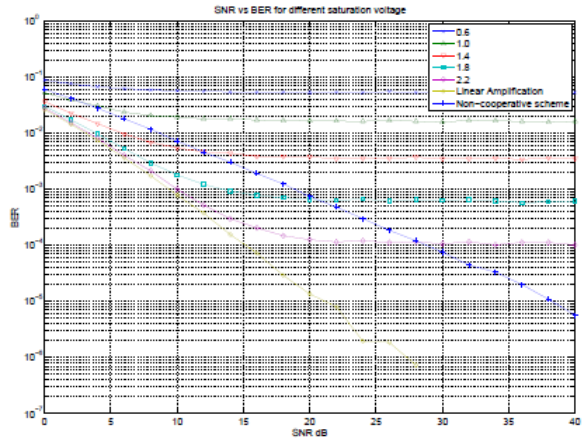
a. Different Spectra of the OFDM symbol

Non Linear Distortion (NLD) affects the spectrum of the OFDM symbol.



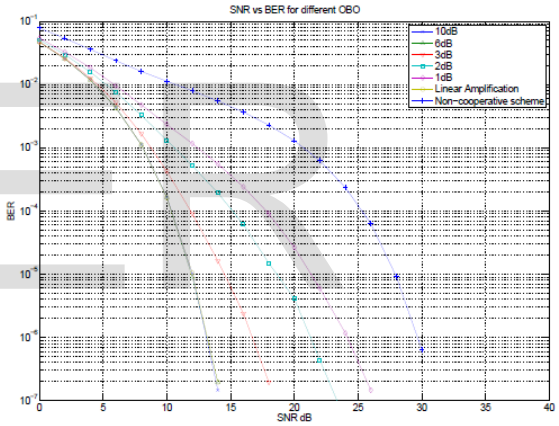
b. BER for different levels of Output Back Off (OBO).

Increasing the OBO results in an inefficient use of resources because the High Power Amplifier (HPA) s' maximum efficiency is achieved when they are operating close to their saturation point.



c. BER for different levels of Saturation Voltage

Increase in BER even for large values of saturation voltage results in isolate the cause of such distortion.



d. BER for different OBO with optimised MRC and Slow Fading Channel.

Slow fading channel, using 512 OFDM symbols as training sequence. The Doppler spread of the channel is $f_d \approx 10$ Hz.

VIII. CONCLUSION

In this paper, nonlinear amplifier distortion in OFDM systems is described. The OFDM RF sub-system is described. The characteristics and models of the most common power amplifiers used in telecommunications are also briefly introduced. A method for characterization of the NLD effects as well as a

method for performance evaluation is explained. Finally, some techniques for mitigating the effects of NLD are briefly presented.

OFDM systems are highly sensitive to NLD because of the high PAPR inherent to this modulation technique. Unfortunately, HPAs are more efficient when operated close to their saturation point, where the nonlinearities increase. The NLD term can be modeled as an additive Gaussian noise in the system. Several techniques exist for mitigating the effects of NLD noise; specifically PANC technique can be applied at the receiver in cases where other techniques are not available at the transmitter [13].

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Frequency-Independent System	Frequency-Dependent System
Memory less systems – gain distortion	System with memory
System with memory gain distortion phase distortion	Frequency dependent gain distortion Frequency dependent phase distortion

Table 1: Classification of distortion effect in Nonlinear Amplifiers.