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COMPARISON OF CLUSTERED AND ANTENNA INTERLEAVING OFDM IN MULTIPLE-ANTENNA SYSTEMS WITH AMPLIFIER NONLINEARITIES

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ABSTRACT

The transmit power requirements are one of the key issues in future Wireless Orthogonal Frequency Division Multiplexing (OFDM) systems.

Diversity techniques applied in OFDM systems help to reduce nonlinear effects produced by the power amplifier.

In this paper, low Peak to Average Power Ratio (PAPR) techniques Clustered OFDM (COFDM) and Antenna Interleaving OFDM (AIOFDM) applied in a Wireless LAN systems are evaluated under nonlinear power amplifier.

This paper shows that the Bit Error Rate (BER) obtained using Antenna Interleaving OFDM is lower compared to the BER obtained applying Clustered OFDM and conventional OFDM in fading channels subject to amplifier nonlinearities. The implementation of these low PAPR techniques can help to reduce the power amplifier linearity restrictions increasing the power efficiency. Power amplifier efficiency is crucial in mobile systems since it has a dominant effect on the battery charge life.

1. INTRODUCTION

The introduction of antenna arrays in base stations of mobile communication systems increases the spectral efficiency, reducing the co-channel interference and increasing the number of users placed in the same spectral portion [1].

Orthogonal Frequency Division Multiplexing (OFDM) is a promising technique for achieving high data rate and combating multipath fading in wireless systems. OFDM is applied in Wireless Networks (WLAN) and other applications.

Common to all OFDM systems is the large peak-to-average-power ratio (PAPR) problem, which can lead to low power efficiency and nonlinear distortion at the transmit power amplifier [2].

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Multiple transmit antennas usually implement a beamforming function to direct efficiently the transmitted power into receiving users. The nonlinear amplifier distortion can seriously harm the beamforming performance. One reason for this is that the nulls and the main beam pointing direction obtained with beamforming will change due to the nonlinear amplifier distortion, increasing the interference level for mobiles using the same frequency channel. Other reason to reduce nonlinear amplifier distortion is that it produces intermodulation beams that radiate intermodulation products in different directions [3].

The performance of Clustered OFDM and Antenna Interleaving OFDM was evaluated in [4] in a linear context. In our paper, COFDM and AIOFDM compared with conventional OFDM when nonlinearities are introduced by the power amplifier will be evaluated .

The concepts of Peak to Average Power Ratio (PAPR), clipping and input backoff (IBO) are presented in the second section, MIMO OFDM is introduced in the third section. Clustered OFDM and Antenna Interleaving OFDM systems are studied in the fourth section. Finally both methods are evaluated and compared with conventional OFDM under nonlinear power amplifier in terms of Bit Error rate.

2. NONLINEAR AMPLIFIER MODELS

Peak to Average Power Ratio is an important factor of a communication system. A low PAPR allows the transmit power amplifier to operate efficiently. On the other hand, a high PAPR forces the power amplifier to have a large backoff in order to ensure linear amplification of the signal.

Power amplifier response characteristics is illustrated in Figure 1. Signals that drive the amplifier close to the cut-off region or near saturation will result in more Intermodulation Distortion (IMD) than signals that drive the amplifier in the mid-region of its characteristic.

When input signal peak value is close to the average value, the power amplifier can operate in the linear region with maximum efficiency [5].

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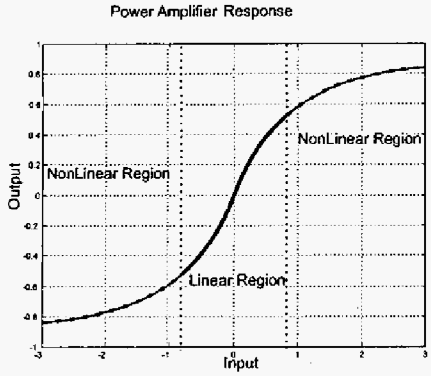

Fig. 1. Power Amplifier Response Characteristics

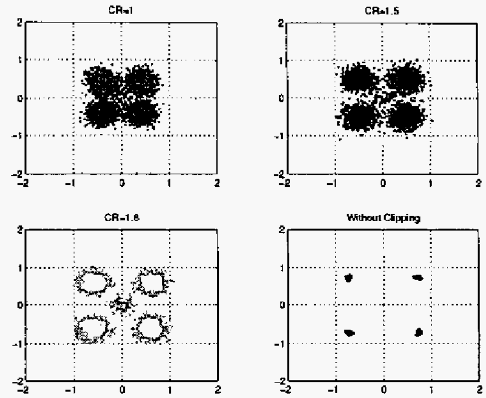

Fig. 2. Constellation OFDM $CR = 1, CR = 1.3, CR = 1.8, CR = \infty$

The PAPR is defined as

$$PAPR = \frac{max\,|x[n]|^2}{E_n[|x[n]|^2]} \quad (1)$$

Considering L Gaussian i.i.d random variables, with unit amplitude, the average signal power is equal to 1 and the peak value can easily be shown to be max $|x[n]|^2 = L$. The maximum PAPR is L for L subcarriers, although in practice, fully coherent addition for the maximum value is highly improbable.

An OFDM signal can be seen as a sum of N independent and identically distributed random variables. In this case, The Central Limit Theorem states that the probability density function of the sum of N random variables is Gaussian, with expected value $E[|x(t)|] = N\mu$ and variance $Var[|x(t)|] = N\ ^2$. Therefore, the Probability Density Function (Pdf) of the OFDM signal can be expressed as a Gaussian distribution $\mathrm{N}(N\mu, N\ ^2)$.

The effects of a nonlinear amplifier on the performance of an OFDM system can be evaluated using a single clipping amplifier which limits the amplitude of the transmitted signal to a given level, without perturbing the phase information [2]. Transfer characteristics of a clipping amplifier are expressed as

$$HPA(x) = \begin{cases} x & |x| < A \\ A & |x| > A \end{cases} \quad (2)$$

where A is defined as the clipping level. The clipping ratio CR is the relation between the clipping level A to the root mean square value of the OFDM signal.

$$CR = \frac{A}{\sqrt{E_n[|x[n]|^2]}} \quad (3)$$

For example, with a $CR = 1$, the signal is limited at the root mean square value of the OFDM signal. In this case, the distortion generated by the clipping is very important but the power amplifier will be working in a high efficient region. If the level of clipping is increased, the distortion is reduced but the power amplifier has to work with big levels of the input signals in a low efficiency region.

Figure 2 shows the constellation of the received signal in a OFDM system with different Clipping Ratio without noise.

Nonlinear effects on the transmitted OFDM symbols can be observed as spectral spreading, intermodulation, and signal constellation distortion. Nonlinear distortion causes both in-band and out-of-band interference to signals. In-band interference increases the BER of the received signal through warping of the signal constellation and intermodulation while the out-of-band interference causes adjacent channel interference through spectral spreading.

To reduce the in-band distortion the symbols to be amplified are scaled by a factor $\epsilon < 1$ that reduce the clipping probability limiting the in-band distortion. The size of ϵ is used as a figure of merit in order to evaluate the performance of different implementations. This is called Input Backoff (IBO).

IBO is defined as the ratio of the mean power at the PA input over the input saturation power A^2. IBO can be represented in decibels as

$$IBO_{dB} = 10log\epsilon^2 \ {}^2_s \quad 10logA^2 \quad (4)$$

If $A^2 = \ {}^2_s, IBO = 10log\epsilon^2$.

Larger values of IBO reduce the clipping probability and decreases the BER degradation but decrease the power efficiency. In order to minimize the efficiency degradation and optimize the BER performance, it is imperative to implement Low PAPR OFDM techniques.

3. MIMO OFDM SYSTEMS

An increasing interest has been put on array antenna technology for exploiting the capacity of the scatterer wireless channel[1]. Initial works introduced beamforming techniques in the receiver. However, the introduction of antenna array in the transmitter has been considered in the last years creating a Multi-Input-Multi-Output (MIMO) channel [6].

The combination of antenna array with OFDM is undoubtedly advantageous for future generation of mobile cellular communication systems. Power amplifier nonlinearity is one important topic that will be considered in the combination of OFDM and MIMO techniques if a communication system with good performance is desired.

OFDM systems are known to be more sensitive to nonlinear distortion caused by a High Power Amplifier [7] than single-carrier systems. Therefore, in order to reduce performance degradation in OFDM systems, compensation of nonlinear distortion is required [8]. Other option to improve the performance of the systems is to use predistortion techniques. This techniques attempt to compensate nonlinear distortions by modifying the input signal characteristics. The more common technique is *amplitude clipping*, presented in the previous section [9]. Other options are coding and selective mapping [10].

In multiantenna systems transmitting multiple beams, the Intermodulation Products (IMP) created by nonlinearities are radiated in different directions decreasing the Signal to Interference Ratio (SIR) of other users, reducing the system capacity [11], [3].

Several diversity techniques can be applied in Multiple antennas OFDM systems. The space-time diversity techniques like delay diversity, phase diversity and cyclic delay diversity are applied with good results in OFDM systems with fading channels. Signals at the individual beams are transmitted delayed to each other according to the principle of delay diversity [12].

In these schemes, multiple antennas transmit delayed versions of the original signals. Each Power Amplifier works with signal levels similar to conventional OFDM systems, so that the requirements for the power amplifier linearity are the same.

4. LOW PAPR OFDM TECHNIQUES

By reducing the peak-to-average power ratio of the multicarrier signals the power amplifier linearity restrictions can be reduced.

Clustered OFDM (COFDM) and Antenna Interleaving OFDM (AIOFDM) techniques provide low PAPR overcoming with nonlinearity effects that reduce the performance in conventional OFDM approach.

4.1. Clustered OFDM

One interesting approach to reduce the amplifier linearity requirements is to split an OFDM symbol into groups of subcarriers which are processed, amplified and transmitted over separate antennas. This technique receives the name of

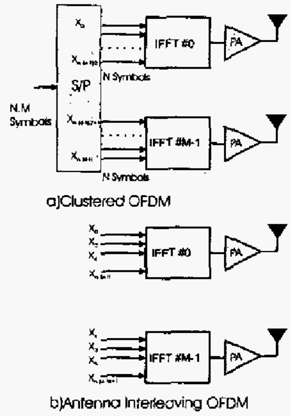

Fig. 3. a) Clustered OFDM transmitter b) Antenna Interleaving OFDM transmitter

Clustered OFDM (COFDM) or Subcarrier Diversity [13], [14].

Considering an OFDM system with 64 carriers, it is possible to split this symbol in two blocks of 32 carriers and then transmit for two different antennas. In this case, the Peak Value for each block will be 32, in place of 64 compared with the original system.

Using a reduced number of carriers results in less spectral spreading and less backoff for each power amplifier [15].

The structure of COFDM transmitter is shown in Figure 3(a). After Serial-to-Parallel (SP) conversion, each IFFT block processes N complex-valued data symbols out of a sequence of $L = NM$. Each of the M IFFT blocks maps its N data symbols on its assigned set of subcarriers.

In clustered OFDM the input symbols $x(n)$ are divided in M disjunct subset which are assigned to different antennas and transmitted at the respective subcarriers. In this system, the antenna m only transmits the subcarriers mN $k_m < (m+1)N$ 1. The neighboring channels are transmitted from the same antenna, so that if the channel has deep fades several subcarriers will be affected.

4.2. Antenna Interleaving OFDM

Antenna Interleaving OFDM (AIOFDM) [4] is a variation of clustered OFDM.

In Antenna Interleaving OFDM the input symbols x are divided in M disjunct subset which are assigned to different antennas and transmitted at the respective subcarriers. Antenna m only transmits the subcarriers $k_m \in \{m, m + M, m + 2M, ..., m + (N \quad 1)M\}$.
Considering two antennas $M = 2$ and N carriers, the first antenna transmits carriers $k_{A1} = 1, 3, \ldots N$ 1 and the second antenna carriers $k_{A2} = 2, 4, \ldots N$.

The subcarriers transmitted for each antenna are thus spread over the whole frequency bandwidth, maximizing

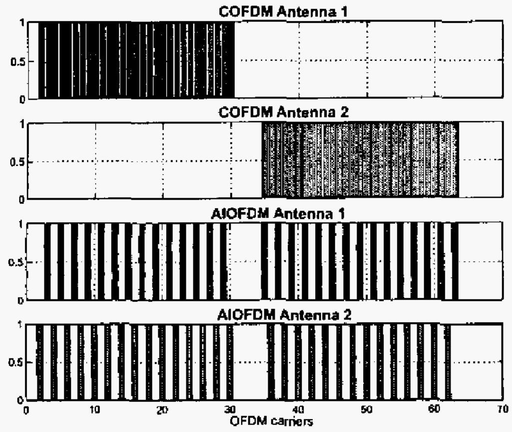

Fig. 4. Carrier allocation for COFDM and AIOFDM

the frequency diversity which is beneficial in frequency-selective channels.

Antenna interleaving reduces the PAPR in the same way that clustered OFDM so that both techniques are feasible for OFDM multiple antenna system affected by power amplifier's nonlinearities.

AIOFDM structure is shown in Figure 3(b). Figure 4 shows the carrier's assignation for each technique using 64 carriers and 2 antennas.

The main disadvantage of these approaches is that the number of antennas, power amplifiers and transmit chains is increased. For this reason, the number of clusters must be selected looking for a good compromise between implementation complexity and performance improvement.

5. SIMULATIONS AND DISCUSSION

In order to evaluate the performance of Clustered OFDM and Interleaving Antenna OFDM systems, simulations are implemented and the results are compared with a conventional OFDM system results in terms of Bit Error Rate (BER).

A simplified WLAN IEEE802.11 [16] system is implemented with $N = 64$ carriers using 2 transmit antennas. The transfer function of the clipping power amplifier is defined by eq.(2). QAM modulation is defined for each subcarrier. Clustered OFDM is implemented with two IFFT blocks by using carriers $1 : 32$ in the first block and $33 : 64$ in the second block. In Antenna Interleaving OFDM two blocks are used with subcarriers $k = 2m$ with $0 < m < 32$ in the first block and $k = 2m + 1$ in the second block. Table 1 summarizes implementation parameters.

The evaluation was carried out using a Gaussian channel and Rayleigh fading channel in order to verify the performance of both structures.

Antenna Interleaving OFDM is supposed to have better performance in multipath channels than the Clustered OFDM due to Antenna Interleaving OFDM maximizes the frequency diversity. Even for static users, the WLAN channel is frequency-selective due to multipath propagation.
In Gaussian channels it is expected that both systems give similar results.

Parameters	
No. of carriers	64
Channel model	Rayleigh Fading channel
Channel delay spread	$50ns$ rms
Convolutional Encoder	$[133_8 171_8]$
CR	$1.1, 3, \infty$
IBO	$0, \quad 3\,dB$
Sampling Frequency	20 MHz
Cyclic Prefix Length	12

Table 1. Simulation Parameters

Figure 5 shows the BER results with $CR = 3$ for the three systems in a channel with Delay Spread $50ns\ rms$ with $IBO = 0, \quad 3\,dB$. Using Antenna Interleaving OFDM technique the best performance is achieved. Using AIOFDM and COFDM without IBO reach smaller values of BER than conventional OFDM with $IBO = \quad 3\,dB$. In this case, the power efficiency is increased meaningfully. In a Gaussian Channel (Figure 6) with $IBO = 0\,dB$ and a severe clipping $CR = 1.1$, the performance is similar using AIOFDM and COFDM.

6. CONCLUSIONS

Combining antenna arrays with OFDM is undoubtedly advantageous for future generations of mobile cellular communication systems. The application of diversity and beamforming techniques give good results in linear environment. But, when nonlinearities appear, this performance is degradated significantly. In this paper Low PAPR techniques as Clustered OFDM and Antenna Interleaving OFDM were analyzed under power amplifier nonlinearities. Results show that the introduction of Clustered OFDM and Antenna Interleaving OFDM helps to reduce the linearity constraints in the power amplifier increasing the power efficiency.

The performance of COFDM and AIOFDM can be improved by optimally allocating a given cluster to a particular antenna. Cluster switching [14] can be applied in order to select the best carriers if a feedback channel is available. With channel information, it is possible to learn which carriers are bad and switch a bad cluster to the other antenna [13].

If the number of antennas is increased,a hybrid solution that include both approaches, COFDM and AIOFDM, is a good option to be evaluated in the future for an optimal carrier assignment over frequency selective channels.

An hybrid OFDM system must be integrated by a low PAPR OFDM transceiver in which coding, selective map-

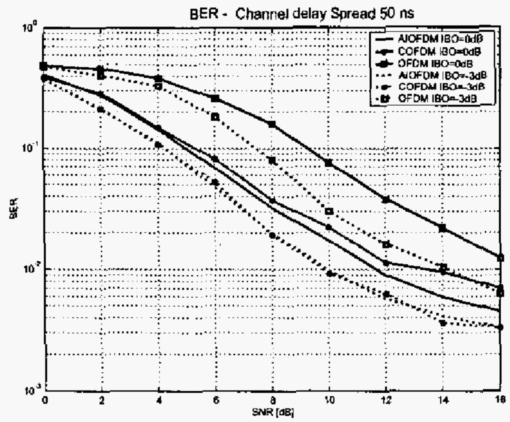

Fig. 5. BER with $CR = 3$ and $IBO = 0, \quad 3\,dB$ in **Multipath Channel** with Delay Spread $50ns\ rms$

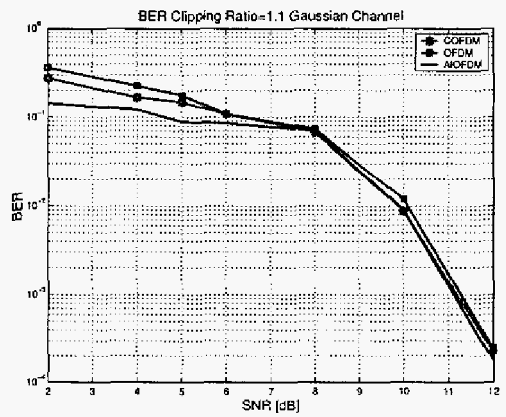

Fig. 6. BER with $CR = 1.1$ and $IBO = 0\ dB$ in **AWGN Channel**

ping, and nonlinearity compensation techniques should be added. Also, a beamforming structure can be included in order to reduce the residual intermodulation distortion radiation.

Both the beamforming design and the hybrid solution are currently being investigated.

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