A NOVEL CARRIER ALLOCATION METHOD FOR MULTIUSER OFDM SYSTEM WITH AMPLIFIER NONLINEARITIES

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ABSTRACT

Amplifier nonlinearities affect drastically the performance of OFDM systems. A new carrier allocation method that reduces the intermodulation distortion between different carriers for multiuser OFDM system is presented. Using this allocation technique and transmit beamforming a bit error rate improvement is obtained in a low or medium load system. Comparison of this proposal with Block and Interleaved OFDM allocation methods is performed. Applying the novel allocation technique, the values of Input Back Off (IBO) that can be applied in order to obtain an adequate bit error rate are smaller than with conventional allocation techniques.

1. INTRODUCTION

The introduction of array antenna systems in base stations of mobile communication systems increases the spectral efficiency, reducing the co-channel interference and increasing the number of users in a geographic area.

Orthogonal Frequency Division Multiplexing (OFDM) is a promising technique for achieving high data rate and combating multipath fading in wireless systems. Multiple transmit antennas usually conform a beamforming function to direct efficiently the transmitted power to receiving users. Antenna array systems are used with Multicarrier Power Amplifier in order to reduce the number of amplifiers placed in the base station. 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.

The nonlinear amplifier distortion can seriously harm the beamforming performance [1]. 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.

In multiuser OFDM, a group of carriers is assigned for each user. Different access techniques can be used, like TDMA, Block OFDM and interleaved OFDM [2].

In this paper a new access technique is proposed which considers the interference created by the nonlinear power amplifier. The carriers are assigned to minimize the interference over other users created by second and third-order

distortion. Beamforming in the frequency domain, *Pre-IFFT* is included in our transceiver.

Joint carrier allocation and beamforming calculation can reduce significantly the effect of power amplifier nonlinearity. A comparison with conventional carrier allocation is carried in order to verify the improvements generated by the new technique using power amplifier models with more or less severe nonlinearities.

The paper is organized as follows. Model amplifier and clipping concepts are reviewed in Section 2. The new multiuser access technique is presented in Section 3. Section 4 include beamforming design for multiuser OFDM systems. Simulation results are presented and discussed in Section 5. Conclusions are drawn in the last section.

2. OFDM AND NONLINEAR POWER AMPLIFIER

An ideal power amplifier has linear gain characteristics, i.e the output signal is a scaled version of the input signal. In the ideal case, the output and input signal will have the same shape.

2.1 Distortion in power amplifiers

In real systems, distortion due to an power amplifier occurs when adding second, third or higher order terms to the linear transfer function. When more than one frequency signal is applied in the nonlinear amplifier with N_{PA} order distortion, Intermodulation Distortion IMD is generated. The frequency components of the distortion appear in the signal band which are difficult to remove using filters.

When a two-tone signal is applied to nonlinear amplifier, intermodulation products are generated. The new frequency components can be expressed as

$$f_{IMP} = mf_1 \pm nf_2 \qquad (1)$$

where f_1 and f_2 are the input signal frequencies and m,n are positive integer that verify $m + n = N_{PA}$.

OFDM systems are known to be more sensitive to nonlinear distortion caused by a high-power amplifier than single carrier systems. Therefore, in order to reduce performance degradation in OFDM systems, compensation of nonlinear distortion is required [3]. Peak to Average Ratio is an important factor of a communication system. A low PAR allows the transmit power amplifier to operate efficiently. On the other hand, a high PAR forces the power amplifier to have a large backoff in order to ensure linear amplification of the signal.

Low PAPR techniques like Clustered OFDM and Antenna Interleaving OFDM are other options [4] that can be considered in order to reduce the nonlinear effects. When input signal peak value is close to the average value, the power

amplifier can operate in the linear region with maximum efficiency [5].

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 the expected value $E\{|x(t)|\} = N\mu$ and variance $Var\{|x(t)|\} = N\sigma^2$. Therefore, the probability density function (PDF) of the OFDM signal can be expressed as a Gaussian distribution $N(N\mu, N\sigma^2)$.

The gain characteristics for a power amplifier can be approximated by a nth-order polynomial. A third-order distortion model for the power amplifier can be written as

$$v_{out}(t) = a_1 v_{IN}(t) + a_3 v_{IN}^3(t) \tag{2}$$

Considering an input signal $v_{IN} = A_1 cos(f_1 t) + A_2 cos(f_2 t)$, the power amplifier will generate the following frequency components: $3f_1, 3f_2, 2f_1 + f_2, 2f_1 - f_2, f_1 + 2f_2, 2f_2 - f_1$ [6]. In an OFDM system N different carriers are amplified generating a huge number of intermodulation products. 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 [7].

2.2 Input Backoff and power efficiency

To reduce the distortion, the symbols to be amplified are scaled by a factor $\varepsilon < 1$ 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. The Input Backoff (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

$$IBO_{dB} = 10\log\varepsilon^2\sigma_s^2 - 10\log A^2 \tag{3}$$

If $A^2 = \sigma_s^2$, $IBO_{dB} = 10\log\varepsilon^2$.

The backoff determines the power consumption of the power amplifier and also its dynamic range directly related with the distortion. Larger values of IBO reduce the clipping probability and decreases the BER degradation decreasing the power efficiency. For OFDM signals (non-constant envelope), a Class A amplifier with power back-off is necessary to consider. Figure 1 shows the power efficiency of a class A power amplifier as a function of IBO [8].

3. INTERMODULATION MINIMIZING ALLOCATION TECHNIQUE (IMAT)

In multiuser OFDM systems multiple carriers are assigned to each user. Considering U users and N_c data carriers, a each user a set of N_c/U carriers are alloted. In the other hand, the PAPR of the OFDM signal is proportional to the number of carriers utilized. In low load system, with only few active carriers, the effect of the nonlinearity is less significant than in a high or medium load system. Increasing the number of users, increases the signal levels that drive the power amplifier near to the saturation region generating distortion.

There are several access techniques that can be applied in multiuser OFDM systems. Like Block OFDM, Interleaved OFDM and TDMA-OFDM are the most commons methods [2].
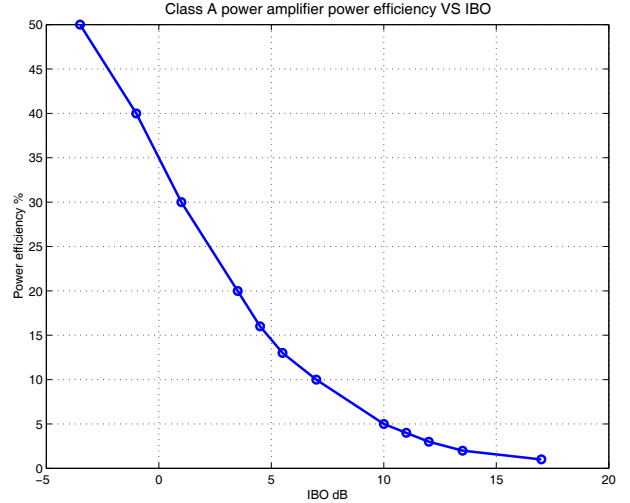

Fig. 1. Typical class A power amplifier - Power efficiency Vs. Input Backoff

In order to consider the effects of nonlinear amplifiers , a new user allocation technique is proposed. An OFDM system with N_c carriers and a maximum of U users is considered. The first user is allocated in random carriers distributed across the spectrum. If a new user is connected at the system, it is necessary to assign a new group of carriers to it. The allocation criterion for each new carrier f_i can be written as:

$$\text{Find } \mathbf{f_i} \in \mathbf{F} := \min \left| \sum_{\mathbf{j=1}}^{\mathbf{J}} \mathbf{P_{IM}(f_i)} \right| \tag{4}$$

where $F = \{f_1, f_2, \cdots, f_N\}$ and $P_{IM}(f_i)$ is the power of the IMP generated between the carrier f_i with the J combinations of active carriers that generate IMP inside the OFDM bandwidth. IMP is calculated combining the previously assigned carriers with all the possible new carriers allowing no more than one user per carrier. The new $N_u = N_c/U$ carriers that give the minimum IMP power affecting at active users are chosen. The computational complexity of IMP would be relatively high, however it is possible to calculate a reduced number of IMP without affecting the method performance. In our implementation only the combination of 3 or fewer carriers is considered. The IMP for two carries is given by $f_{IMP} = mf_1 \pm nf_2$ with $m + n = 3$. If three carriers are considered, the IMP appears at the frequencies $f_{IMP} = mf_1 \pm nf_2 \pm kf_2$ with $m, n, k \leq 0$ so $m + n + k = 3$.

The bit rate for each users is given by $R = N_u b$, where N_u is a number of carries per user and b is the constellation size. Both values are considered fixed in this implementation.

If a new user becomes active, the selection process is carried out again with the free carriers. The advantage of this method is evident in medium or low load systems. In the case of full load systems, the results are the same as for conventional block OFDM or interleaved OFDM methods.

The system carrier allocation can be represented for a matrix V of $N_c \times U$ size, where each row represent the assignation for each user. If the element $V_{i,j} = 1$, the carrier i is assigned to the user j.

4. TRANSMIT BEAMFORMING

Let us consider a base station with L transmit antennas that cover a group of U mobile stations with a single antenna. A
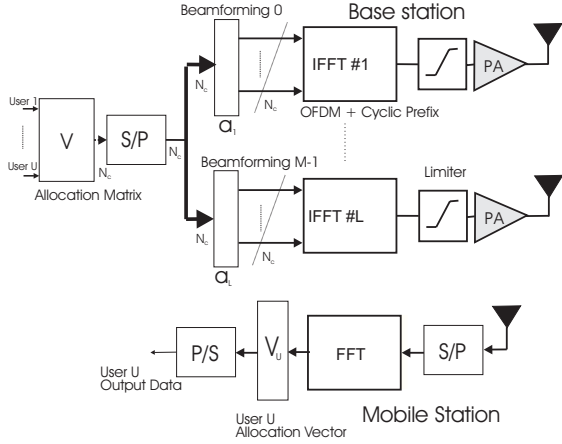
Fig. 2. Multiuser OFDM Transceiver

beamforming is applied before the IFFT in the frequency domain. Figure 2 shows the diagram of the multiuser OFDM system with pre-IFFT beamforming. The beamforming is represented by $\mathbf{a}_k = [a_1(k)\ldots a_L(k)]^T$, where $a_l(k)$ is the weight for the antenna l at the carrier k. The signal transmitted for user u trough antenna l can be written as

$$x^l(t) = \frac{1}{\sqrt{N_c}} \sum_{k=0}^{N_c-1} s_k(t)V_u(k)a_l(k)e^{(j\frac{2\pi}{N_c}k)} \qquad (5)$$

where $V_u(k)$ is the allocation vector for the user u and $a_l(k)$ is the transmit beamforming weight at frequency k at the l antenna. The received signal for user u in frequency domain considering a system with cyclic prefix longer than the channel impulse response is expressed as

$$Y_u(k) = \sum_{l=1}^{L} X_l(k)H_{l,u}(k) + n(k) \qquad (6)$$

where $X_l(k)$ is the signal transmitted for the antenna l in frequency domain and $H_{l,u}(k)$ is the channel frequency response between user u and antenna l at carrier k. The beamforming weights are calculated in order to maximize the SIR for each user. The SIR at carrier k, if IMP is not considered, is:

$$SIR(k) = \frac{E\{|\sum_{l=1}^{L} s_k(t)a_l(k)H_{l,u}(k)|^2\}}{E\{|n_k(t)|^2\}} \qquad (7)$$

Considering that all the users must receive the same power P and the interference is AWGN, the weights for antenna l and carrier k assigned to user u can be obtained as $a_l(k) = \frac{\sqrt{p}}{H_{l,u}(k)}$.

5. SIMULATIONS

The proposed multiuser OFDM system with a new allocation technique is evaluated and compared with Interleaved Allocation Technique (IAT). The number of user is varying between 1 to 7 with 8 carriers per user. A system with $N_c = 64$ carriers and 2 transmit antennas is implemented. Convolutional coding and hard Viterbi decoder is included. OFDM system is implemented using 64 carrier with cyclic prefix length equal to 4. Each carrier is modulated using QAM constellation. The carrier frequency is $f_c = 2.4$ GHz. Frequency domain equalization is not applied.

A four-path Rayleigh fading channel with independent propagation paths is implemented. The paths are generated using Jake's Doppler spectrum. The power loss of the channel taps are [0,-1,-3,-9] dB with the delay profiles equal to [0,1,2,3] μs. This model corresponds to the Typical Urban scenario. AWGN noise is included. A clipping ratio CR is defined in 1.8 and a third-order power amplifier is implemented. Bit Error rate (BER) is evaluated for a particular user when different number of users are actives. Figure 3 shows the BER for user 1 when 4 users are active. The results for 7 users active are shown in Figure 4. Both simulations were carried out using a power amplifier model with a1 = 1 and a3 = 0.001.

From these results, we can conclude that the best results are obtained using the novel carrier allocation technique (IMAT) with 3-4 active users which corresponds to a medium-load system. Similar performance is achieved for both allocation methods when a full-load system is evaluated.

Power amplifier efficiency for both methods are evaluated for a fixed BER. In this evaluation, IBO value is adjusted in order to reach a BER equal to 10^{-4} considering different number of active users. Class A power amplifier, typical for nonconstant envelope signal, is considered in the efficiency evaluation. Class A amplifier has a theoretical maximum efficiency of 50 that drops rapidly with increasing backoff.

Figure 5 shows the IBO values using both methods in function of the number of active users with $SNR = 10, 15, 20$ dB. In this figure, a significant reduction of the IBO was obtained when the novel technique IMAT is used giving an improvement in the efficiency of the power amplifier. This advantage is shown in Figure 6, in which the power amplifier efficiency in function of the number of user is presented considering the efficiency curve given in Figure 1. Table 1 resumes the power amplifier efficiency obtained with both methods that show levels of improvement in the order of 10% using the novel technique in medium load system. In order to evaluate the relative improvement obtained using the novel allocation method, the normalized efficiency is defined that is given by $\bar{\eta} = \eta / \eta_{max}$, where $\eta_{max} = 50\%$ in class A amplifier.

6. CONCLUSIONS

A new multiuser allocation technique was presented. Better performance compared with other allocation method was obtained when the number of active users are evaluated near to medium load of the system. Using the novel carrier allocation method, the IBO factor was reduced for an equal value of BER, increasing the amplifier efficiency. So the power consumption can be reduced, increasing the battery life that is a critical resource in mobile implementations. Levels of 10% of power efficienccy improvements was obtained.

In MIMO and MISO transmit-receive beamforming design, it is possible to consider the intermodulation distortion generated by nonlinearities in order to reduce their effect over other users and systems that are distributed in the same band of frequency.

In multiuser OFDM systems in which several carriers are assigned to each users, it is essential that a beamforming design considers intermodulation distortion reducing in-band (that affect other users sharing the same base station) and out-band interfering signals. By adding some constraints that consider nonlinear effects it will be possible to find good solutions that combat the nonlinearity problem. This subject is currently being investigated.
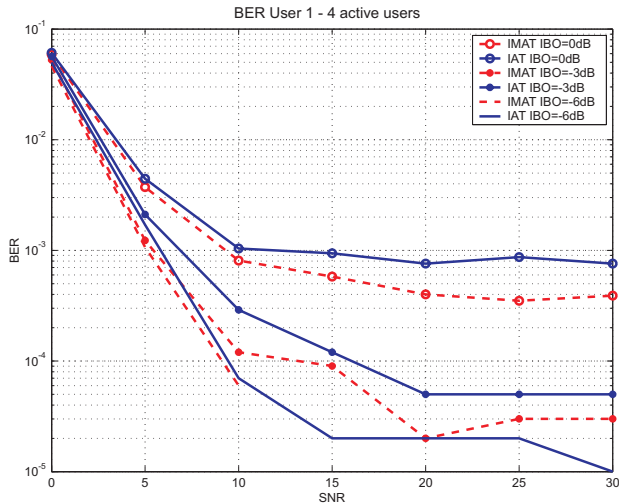
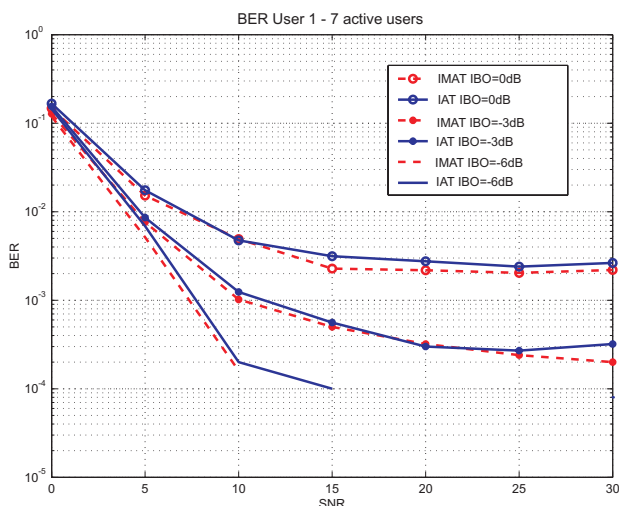**Fig. 3**. Bit error rate User 1 when 4 users are active (medium load)

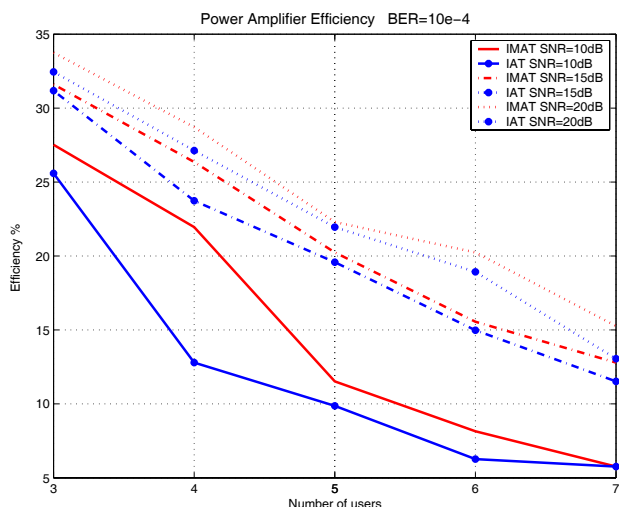**Fig. 4**. Bit error rate User 1 when 7 users are active (high load)

Fig. 5. Input Backoff values obtained with a fix $BER = 10^{-4}$ for IMAT and IAT methods
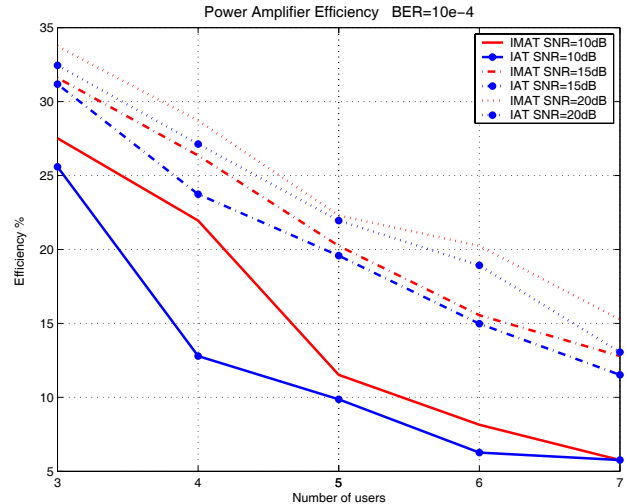

Fig. 6. Power Amplifier efficiency obtained with a fix $BER = 10^{-4}$ for IMAT and IAT methods

	η_{IMAT}	η_{IAT}	$\bar{\eta}_{IMAT}$	$\bar{\eta}_{IAT}$
Medium Load SNR=10dB	22.5%	12.8%	0.45	0.256
High Load SNR=10dB	8.4%	6.3%	0.168	0.126
Medium Load SNR=20dB	29.7%	26.9%	0.594	0.538
High Load SNR=20dB	20.3%	18.2%	0.406	0.364

Table 1. Power amplifier efficiency with a fix $BER = 10^{-4}$ for IMAT and IAT methods

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