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Controlling the Peak-to-Average Power Ratio in the Downlink of WiMAX Systems

Guilherme Guimares Mendes and Andr Noll Barreto
Microwave and Wireless Systems Lab (http://mwsl.unb.br)
Universidade de Braslia (UnB)
guigdes@yahoo.com.br, andrebarreto@ene.unb.br

***Abstract*— It is well known that one of the main implementation issues in multicarrier modulation schemes, like OFDM, is their high peak-to-average power ratio (PAPR). Power amplifiers that are employed in the transmitters of communications systems are highly non-linear devices, which present a saturation level, and typically show a higher power efficiency close to saturation. Therefore, the high peak amplitudes common in OFDM may cause severe non-linear effects, such as signal clipping, which result in out-of-band radiation and signal constellation distortion. Several techniques are proposed in the literature in order to reduce the PAPR of OFDM signals, such as clipping with additive or multiplicative windowing, use of virtual subcarriers, active constellation extension and partial transmit sequences, among others. In this contribution we demonstrate the use of some of these techniques in a WiMAX wireless system, based on the IEEE 802.16e, focusing on techniques that can be employed with no or little modifications to existing standards. The PAPR effects are investigated in terms of several different performance metrics, namely the adjacent channel power ratio (ACPR), the total degradation and data throughput, and we see that through the proper combination of different techniques significant performance gains can be achieved.**

Keywords*— *WiMAX, PAPR, PAPR reduction schemes, non linear amplifiers

I. INTRODUCTION

The next generation of wireless networks will rely mostly on techniques that employ frequency domain equalisation for broadband transmission transmission, such as orthogonal frequency domain equalisation (OFDM), which facilitate the equalisation of frequency-selective wideband channels.

In a single-carrier transmission scheme, modulation symbols are sent sequentially over a unique high-frequency carrier, which is digitally modulated at the symbol rate of the information source. With OFDM the data flow is divided into many different subchannels, which are modulated in distinct subcarriers [1], whose frequencies are chosen such that they are orthogonal over a symbol interval. The subchannels spectra may overlap, and, thus, optimise spectral usage. By splitting the data in different subchannels, we substantially increase the symbol interval, hence simplifying the equalisation process, which can be extremely complex in high-rate single-carrier transmission. To eliminate the intersymbol interference, a guard interval can be introduced between consecutive symbols, which is usually filled with a cyclic prefix.

OFDM is employed in nearly all major technologies for broadband wireless communications currently being developed. Among these technologies, WiMAX is one of the most promising, with many networks already deployed worldwide. The physical (PHY) and medium access control (MAC) layers of mobile WiMAX are based on the IEEE 802.16-2009 standard [2], [3], which relies on OFDMA to guarantee high spectral efficiency in frequency-selective wireless channels. WiMAX operates in frequency bands below 11GHz (but typically 2,5 or 3,5 GHz) with bandwidths from 1,25 to 20 MHz. The evolution of WiMAX is ongoing under IEEE 802.16m task group, which is in its final standardisation stage, but still employs OFDMA with very similar PHY parameters.

However, despite easing the equalisation process, OFDM also brings about some other problems. As a negative consequence of the OFDM modulation scheme, the time-domain signal is obtained as the sum of many subcarriers, which may add constructively or cancel out each other at each time sample, thus causing a large dynamic range of the signal amplitude. Due to the central limit theorem, when the number of subcarriers is large the complex signal envelope can be modelled as a Gaussian random variable, and the signal variation is usually measured in terms of its peak-to-average power ratio (PAPR). The high PAPR of an OFDM signal poses a substantial problem when nonlinear power amplifiers are employed. Amplifiers are linear up to a certain input level, and saturate at high levels. Thus, parts of the OFDM signal with high amplitude values are clipped or heavily distorted by the amplifier, causing out-of-band radiation and introducing signal distortion.

In view of this issue, several methods have been proposed in the literature to deal with this problem. Among the different techniques we can mention the use of coding [4]–[6], clipping and windowing [7], [8], partial transmit sequences (PTS) [9], [10], the use of virtual subcarriers [11]–[13] or dummy symbols [14], active constellation extension (ACE) [15]–[18] or even the combination of several different methods [19].

WiMAX standards do not specifically mention any PAPR reduction scheme, but some methods might be considered for use with little or no modifications to existing standards. Among these we can mention ACE, which does not require modifications to the physical layer (it might require though an adaptation of the transmitter requirements); the use of virtual subcarriers, as we can reserve some subchannels for the PAPR reduction. Even the PTS scheme, which was devised with extra signalling in mind, can be employed with little modifications by using the downlink pilot tones, as it was shown in [19]. In our contribution we investigate the performance of these methods in a mobile WiMAX system, considering several different figures of merit, namely the total degradation, the adjacent channel power ratio and the effective throughput, and see that by means of an appropriate combination of these schemes the PAPR can be effectively mitigated.

In Section II we briefly describe the investigated methods. In Section III the main WiMAX parameters relevant to our studies are reviewed. The performance metrics employed in this paper are described in Section IV, and simulation results are shown and analysed in Section V. Finally, some concluding remarks are made in Section VI.

II. PAPR Reduction Schemes

As already mentioned in the Introduction, the high PAPR of OFDM signals is a potential serious problem when non-linear amplifiers are employed, and several methods are proposed in the literature to reduce the PAPR. In this Section we briefly describe a few of these methods that could be used in existing WiMAX Systems.

A. Active Constellation Extension

One of the most promising PAPR reduction techniques is the active constellation extension method (ACE) proposed by Jones [15], [16], which consists in modifying the signal constellation without increasing its error rate. The effect of this modification is to add sinusoids in some frequencies that can lead to the cancellation of some signal peaks.

Figure 1 shows the constellation of a 16-QAM modulated signal after being modified by the method, where it is possible to see that the optimum decision regions, in terms of maximum likelihood detection, are not abandoned. It is clear to see that the method involves increasing the transmit signal power at some modulation symbols. However, this power increase is not significant when compared to the gains provided by the method [16], [18].

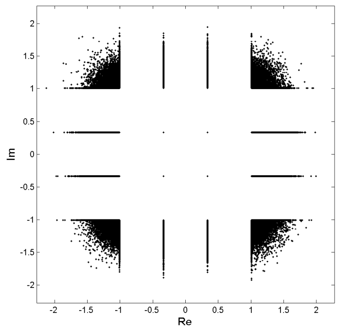

Fig. 1. 16 QAM constellation with the ACE method

The algorithm must modify only the data subcarriers, letting the pilot and guard subcarriers unchanged. It can be described by the following steps, which are executed for each OFDM symbol:

1) According to input data, designate the K constellation points X_k ;
2) By means of an IFFT, construct the sampled time domain signal x_l;
3) Compare the magnitude of all samples with $L_{\max}$, the maximum allowed amplitude;
4) For samples that exceeded $L_{\max}$, resize them, i.e, make $\tilde{x}_l = L_{\max}e^{j\theta_l}$, where $x_l = |x_l|e^{j\theta_l}$;
5) Regain the frequency domain signal via FFT;
6) Restore the pilot and zero subcarriers,as well as the interior constellation points to the original values;
7) Return to the second step until no time sample is resized or the maximum number of iterations is reached.

The algorithm complexity depends on the number of iterations, basically requiring one further IFFT for each iteration, but only a few iterations are usually enough to reach a satisfactory result. A particularly positive feature is that its application does not require extra signalling or any change in the receiver. This makes it acceptable for existing wireless technologies that employ OFDM. The only adjustable parameters are the maximum number of iterations and the value of L_{max}, whose impacts are analysed in [18].

B. Partial Transmit Sequences

The partial transmit sequences (PTS) [9], [10] scheme belongs to the class of selected mapping methods. These methods consist in generating several different possible transmit signals, all transmitting the same data and with same performance, and selecting the one with the lowest PAPR value. In order to make detection possible, the index of the selected sequence must be transmitted through a signalling side channel.

In PTS each data block, corresponding to an OFDM symbol, is divided into a few subblocks in the frequency domain. Each one of the N_b subblocks can be shifted by a different phase, which is chosen from a finite set with N_ϕ elements. Thus, there are $N_{wf} = N_\phi^{N_b}$ possible waveforms to choose from. The optimum algorithm requires an exhaustive search, such that all possible waveforms are tested, first by performing an IFFT and then measuring the PAPR for each possibility. The one with the lowest PAPR is chosen and signalled with $\log_2 N_{wf}$ bits for each OFDM symbol. Some algorithms are proposed in the literature to reduce the search space and minimise the method complexity [10]. The choice of the parameters N_b and N_ϕ is a trade-off between the complexity, which increases rapidly with these parameters, and the method efficiency, which is higher when there are more sequences to choose from.

The need for signalling can be overcome in some situations by using the pilot signals. In WiMAX systems the preamble is used for initial synchronisation and channel estimation. Beside the preamble, pilot tones are still foreseen in every OFDM symbol, and are mainly used for tracking the carrier frequency offset and the channel estimation. In situations where the channel changes slowly the pilots can be employed to convey the phase information, which is usually limited to only a few possible values.

It should be noticed that this technique would require substantial changes to existing standards, not to mention the increased complexity, particularly at the transmitter.

C. Virtual or Dummy Subcarriers

OFDM systems typically do not use all subcarriers at the input of the IFFT for data transmission. As long as the spectral mask is satisfied, this unused subcarriers may be loaded at each symbol with a specific signal that reduces the PAPR [11]–[13].

There are many proposals in the literature about how we choose this signal, and one of the most efficient and simple is the one proposed by Gatherer and Polley [11]. This algorithm performs an iterative projection onto convex sets, which is basically the same algorithm described in Section II-A for the ACE method. The difference is only in item 6, in that now we only allow modifications to the reserved subcarriers and return all data and pilot subcarriers to their original values.

As we shall see in Section III, in WiMAX the available data subcarriers are divided into many subchannels, each one consisting of several subcarriers spread along the whole spectrum. Here we propose that we reserve one or more of these subchannels not to transmit data, but to send a signal that reduces the overall PAPR.

This approach can be easily combined with ACE, as they both employ the same optimisation algorithms.

III. Mobile WiMAX

Mobile WiMAX makes use of scalable OFDMA, i.e., it supports different bandwidths from 1,25 to 20 MHz by having from 128 to 2048 subcarriers, while keeping the subcarrier spacing fixed and equal to 10,94 kHz.

A subchannel is defined as a set of subcarriers, which can be adjacent or distributed over the whole spectrum. Several different permutation schemes are defined in the standards, but the most commonly used is the partial usage of subcarriers (PUSC), which is the one considered in our work. In DL PUSC all subcarriers are pseudo-randomly divided into 6 different groups, which may be assigned to different sectors if needed. Subchannels are created from pseudo-random permutations within the data subcarriers of each group, with each subchannel consisting of 24 data subcarriers

IV. Performance Metrics

A. Input and Output Backoff

The definition of input backoff (IBO) and output backoff (OBO) is indispensable, and will be used in other metrics:

$$IBO_{dB} = 10log_{10}\left(\frac{P_{sat,in}}{P_{in}}\right) \quad (1)$$

$$OBO_{dB} = 10log_{10}\left(\frac{P_{sat,out}}{P_{out}}\right), \quad (2)$$

where P_{in} and P_{out} are the input and the output average power, respectively; and $P_{sat,in}$ and $P_{sat,out}$ are the input and the output saturation power, respectively, obtained from the amplifier AM/AM conversion function.

One important characteristic of power amplifiers is their efficiency, which is the proportion of their consumed power actually employed in irradiating the desired radio signal, instead of being dissipated as heat. In this regard, one should bear in mind that the efficiency increases as the operating point gets closer to the saturation level. If the signal amplitude is constant, it is possible to work closer to saturation region with high power efficiency, but if the signal amplitude varies a lot, we need a high backoff value if we want the amplifier to operate mostly in the linear region.

B. Total Degradation

Most contributions in the literature are concerned only with the PAPR reduction. However, reducing the PAPR is not necessarily enough. A good system performance also needs to be guaranteed. Therefore, when a non-linear amplifier is used, the analysis of an OFDM system needs to be done considering some metrics such as the bit error rate (BER), the backoff, the out of band radiation, among others.

The backoff must be included in the analysis of an amplified system, because it represents an available power that is being wasted. There is however no sense in analysing backoff only, we must also consider the BER performance loss. An intelligent analysis is to determine the Total Degradation (TD) of a system, which is defined by

$$TD_{dB} = OBO_{dB} + \left[EbN0_{(OBO)} - EbN0_{(linear)}\right]_{BER}, \quad (3)$$

where $EbN0_{(OBO)}$ and $EbN0_{(linear)}$ are, respectively, the required bit-energy to noise-spectral-density ratios E_b/N_0 in dB for the non-linear amplifier and for an ideal linear amplifier for a given output backoff OBO_{dB}. In other words, the first term indicates the decrease in power transmission in the amplifier, while the second term represents the degradation due to the non-linear distortion caused by the amplifier. This figure of merit is measured for a specific channel and for a specific BER. In the analysis done in this work we considered an AWGN channel and $BER = 10^{-3}$.

An analysis of a total degradation curve leads us to reach an optimum backoff value, which is the value for which we have the least degradation of the system.

C. Adjacent Channel Power Ratio

One of the main perturbations caused by non-linear distortions is the increase in the emission of out-of-band radiation. To assess the severity of this problem, one popular metric is the adjacent channel power ratio (ACPR), which can be defined in several different ways. Here it is considered to be the ratio between the mean power inside the allocated channel bandwidth and the mean power of the out-of-band radiation, which can be calculated by integrating the estimated power spectral density.

D. Throughput

One of the techniques investigated in this contribution is the dummy subcarriers approach, described in Section II-C. This technique requires the use of some subchannels for PAPR reduction, instead of carrying useful data. This causes some throughput reduction, which may be compensated by the improved performance due to the smaller PAPR. It is therefore essential for us to estimate the throughput in order to assess the algorithm efficiency.

Computer simulations, to be presented in Section V, were used to evaluate the achievable throughput. In our simulations we haven't considered the assembly of packets and frames, but only calculated the bit error rate of an uncoded WiMAX system. The achievable throughput can nevertheless be estimated. Let R_b be the channel gross bit rate:

$$R_b = \frac{(K_{data} - K_{dummy})\log_2(M)}{T_S + T_G}, \quad (4)$$

where K_{data} is the number of available data subcarriers, K_{dummy} the number of reserved dummy subcarriers, M the constellation size of the modulation scheme, T_S the OFDM symbol length and T_G the guard interval.

Data bits are transmitted with an uncoded bit error probability p_b, which can be obtained from simulations, and error-free transmission can theoretically be obtained by means of coding with a rate $C(p_b)$, which is the capacity of a binary symmetric channel:

$$C(p_b) = (1 - p_b)\log_2(2(1 - p_b)) + p_b \log_2(2p_b). \quad (5)$$

Hence, for a given error probability, the achievable throughput can be given by

$$Tput(p_b) = R_b C(p_b). \quad (6)$$

V. Simulation Results

In order to assess the effect of non-linear amplifiers, the downlink of a WiMAX system was modelled in a link-level simulator. We have considered a system with 10 MHz bandwidth (1024 subcarriers), cyclic prefix corresponding to 1/8 of the useful symbol length and 64-QAM modulation. PUSC-like subchannelisation is considered, with 24 randomly chosen subcarriers for each subchannel. We consider a solid-state amplifier, following Rapp's model [20].

In Figures 2 and 3 we investigate the performance of the dummy subcarriers scheme in terms of the total degradation and ACPR respectively. In the Figures, conventional transmission corresponds to a situation without any PAPR reduction scheme. We vary the number of PUSC subchannels reserved for PAPR reduction and load them according to Gatherer-Polley's (GP) algorithm, described in Section II-C.

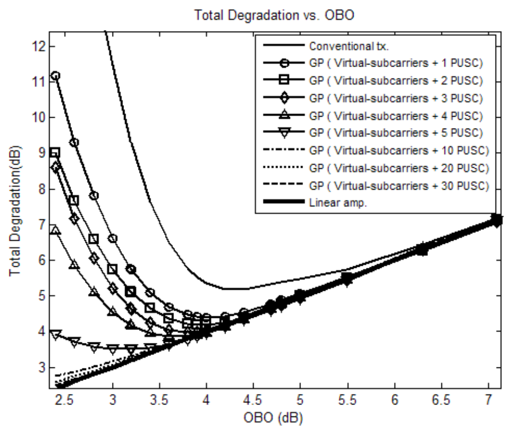

Fig. 2. Total degradation with the dummy subcarriers scheme

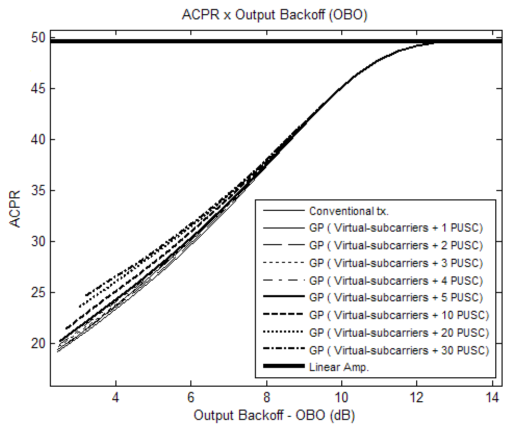

Fig. 3. ACPR with the dummy subcarriers scheme

As we can see, the use of dummy subcarriers can effectively reduce the total degradation and the emission of out-of-band radiation, and the more subchannels we use the better the results are. However, the reservation of subcarriers reduces the number of subcarriers that carry useful data, and, thus, reduce the gross bit rate. In some situations, this may be compensated by the positive effects of the PAPR reduction, such that the throughput is increased on account of the reduced BER. This can be seen in Figure 4, in which the achievable throughput is plotted for different E_b/N_0 and backoff values, varying the number of reserved dummy subchannels, according to the method described in Section IV-D. We see that for a high backoff value of 6 dB the non-linear distortion is not very significant. We can observe a very small throughput gain with one reserved PUSC subchannel, but for a higher number of subchannels, dummy subcarrier reservation for PAPR reduction is negative in terms of throughput. Nevertheless, when lower backoff values are chosen, the non-linear distortions become very important and increase the BER a lot. In this case the reservation of a few subchannels may bring about substantial throughput gains, despite the lower gross bit rate.

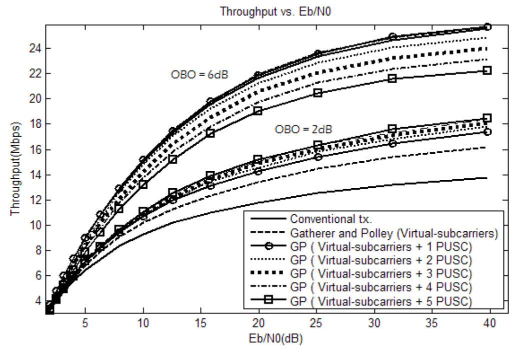

Fig. 4. Throughput with the dummy subcarriers scheme for different backoff values

In Figures 5 we show the total degradation when PTS scheme is applied to a WiMAX system. We can see that the method is more effective when the subcarriers are divided into more subblocks and there are more phases to chose from. Nevertheless, as explained in Section II-B, the complexity increases rapidly with this efficiency improvement.

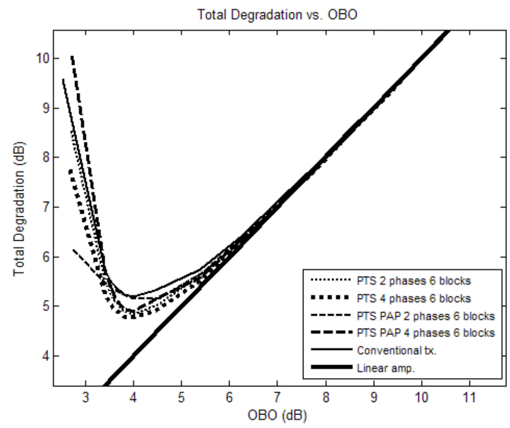

Fig. 5. Total degradation with PTS

We should bear in mind that the methods described here are not mutually exclusive, and can be employed together. Besides the virtual subcarriers and PTS schemes, Jones' ACE method can also be combined together. As we can see in Figure 6, the dummy or virtual subcarriers method is alone the most effective. It may cause however a throughput reduction, therefore we have limited the number of reserved subchannels to two. The best overall performance is achieved with the combination of all three methods, resulting in this case in about 1,5 dB performance gain.

VI. Conclusions

In this contribution we have investigated the PAPR issue in the downlink of WiMAX systems and analysed three different PAPR reduction methods, namely the use of virtual or dummy subcarriers in reserved subchannels, partial transmit sequences and the active

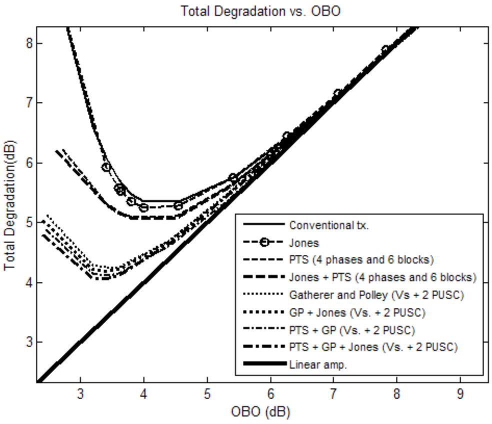

Fig. 6. Total degradation with the combination of several PAPR reduction methods

constellation extension (ACE) method. The use of of dummy subcarriers seems to be the most effective, but may incur in some throughput loss. We also saw that the methods are not mutually exclusive and their gains are cumulative, such that the combination of the three methods brings about the highest performance gains.

As future work, we may emphasise the need to investigate the problem in a more realistic scenario, including channel coding and a frequency-selective channel. Furthermore, the search for PAPR-reduction schemes is not exhausted, and less complex methods are still required.

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