PAPR reduction in orthogonal MC and MC-SS systems

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Abstract

Several Multi-Carrier (MC) and Multi-Carrier Spread Spectrum (MC-SS) schemes have been proposed for the downlink of the next generation of wireless systems (4G). One of the major drawbacks with MC modulations is the large Peak-to-Average Power Ratio (PAPR) of the transmitted signal which reduces the D/A and A/D effective mean resolution, the power amplifier efficiency and the battery life. In this paper the effects of the PAPR in OFDM and MC-CDMA as well as the consequences of using determined PAPR reduction methods are studied. Appropriate PAPR reduction methods from those that can be found in the literature have been selected in order to guarantee the compatibility with current 4G downlink proposals.

I. Introduction

The choice of appropriate modulation schemes is an important key to guarantee the success of the next generation of wireless systems. Current proposals suggest the use of OFDM [1] and OFCDM [2] for the future 4G downlinks due to their high spectral efficiency and robustness against multipath fading channels. One of the major negative aspects with MC modulations is that when the sinusoidal signals of the n carriers add mostly constructively the peak envelope power is as much as n times the mean envelope power. The ratio between the instantaneous power of these peaks and the average power of the signal (PAPR) is too large and so it reduces the A/D and D/A converters effective mean resolution. Furthermore, it requires the use of power amplifiers that behave linearly up to the peak envelope power of the transmitted signal. Several methods that reduce the high PAPR of the orthogonal MC modulations have been proposed during the last few years; those might be put into two different groups depending on whether they introduce some distortion to the transmitted signal or not. Distortion type methods directly modify the time domain transmitted signal in order to reduce its PAPR below a given threshold; this generally results in an increase of the Out-of-Band Radiation (OBR) and the BER. On the other hand, non-distortion type methods try to reduce the PAPR of each OFDM symbol without neither increasing the BER nor the OBR. However, in general, these methods can not assure that the PAPR will never exceed a given threshold and hence, in a practical implementation, they must be combined with distortion type methods to assure a predefined maximum PAPR with low BER and OBR; furthermore, in some non-distortion type methods, the transmission of additional information for a correct demodulation is required. Distortion type methods include Clipping [3], Windowing [3][4] and Peak Canceling [5][6]; non-distortion type methods include Coding [7], Peak Reduction Carriers [8], Selected Mapping [9] and Partial Transmit Sequences [10]. Most of the methods that were first designed for OFDM can also be used in MC-SS systems [9] [11]; on the other hand, the use of the appropriate spreading codes can be exploited in order to further reduce the PAPR [12]. For large number of subcarriers, where the appropriate spreading codes can not be determined, different methods such as [13] propose to assign several spreading codes to each user, evaluate all combinations and transmit the one with lowest PAPR.

In this paper the effects of the PAPR in OFDM and MC-CDMA as well as the consequences of using determined PAPR reduction methods are studied. In order to obtain a fair comparison the same parameters will be used for both systems; parameter specification is based on the 4G downlink physical layer proposed in [1].

II. The Peak Power problem in 4G downlinks

In MC-based 4G downlink scenarios where a large number of subcarriers is used, a high PAPR of the transmitted signal may be appreciated. The system proposed in [1] uses 500 subcarriers which results in a 27 dB PAPR; this implies an average resolution loss of 4.5 bits in the D/A converter and requires a power amplifier with a linear margin much larger than 27dB. Furthermore, assuming that the PAPR characteristics of the transmitted signal are not affected by the channel, this implies that the average received power in the mobile terminal would be 27dB lower compared to a constant envelope system such as DS-CDMA. However, the high spectral efficiency and robustness against multipath fading channels offered by orthogonal MC and MC-SS systems gives a clear motivation to find ways of controlling the PAPR of the transmitted signal in order to be able to take advantage of the benefits of using MC systems in the future 4G downlinks.

In other scenarios, such as very large distance HF communications, the problem of the PAPR in MC and MC-SS modulations becomes much more critical since the signal-to-noise ratio is very low and the interference level is usually higher than the level of the desired signal [14]. In this environment, any way of increasing the average transmitted power is very welcomed; particularly when expensive linear high power amplifiers are used.

4G downlink proposals presented in [1] and [2] are designed to maximize the spectral efficiency while assuring a low BER. Those restrictions suggest that the PAPR reduction methods to be used should have a minimum effect over the BER and the OBR. Therefore, methods that require the transmission of additional information such as Partial Transmit Sequences and Selected Mapping are not suitable since an error on the additional information would result in a high increase of the BER. On the other hand, methods that exploit the use of coding and interleaving can neither be used since a change on the proposed physical layers would be required. As a result, we propose to use Peak Reduction Carriers (PRC) for the PAPR reduction in [1] and an hybrid system with PRC and appropriate spreading codes in [2].

III. System description

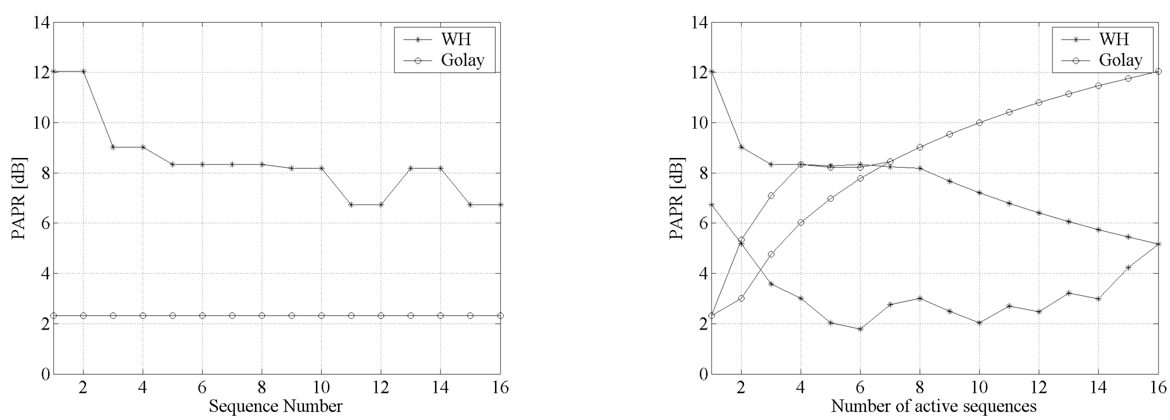
A. OFDM system description

OFDM symbols are designed to have a cyclic prefix of $11\mu s$ and a symbol period (including cyclic prefix) of $111\mu s$ [1]. In order to assure orthogonality among the different subcarriers, a subcarrier spacing of 10KHz is chosen. In [1] a total transmission bandwidth of 5MHz is assumed which results in 500 subcarriers per OFDM symbol. Furthermore, resource allocation among the different users and adaptive modulation are implemented through the definition of time-frequency bins to maximize the throughput of the base station while assuring a low BER. For sake of simplicity, in this paper only 32 subcarriers are used (which results in a 320KHz transmission bandwidth) and no resource allocation, coding, interleaving, neither adaptive modulation is performed. Each subcarrier is mapped with a BPSK information symbol; therefore, neither control information nor pilot subcarriers are transmitted. In the receiver, perfect channel estimation is assumed and zero forcing equalization with hard decision data detection is performed.

The PAPR of the transmitted signal is limited to a maximum level of 3dB. This might represent an extremely severe threshold for 4G downlinks since high resolution D/A converters and high linear power amplifiers might be used. However, as only 32 subcarriers are used, limiting the PAPR to 3dB represents a PAPR reduction of approximately 12dB; assuming that the same PAPR reduction is done in the 500 subcarrier system in [1], this would represent that a maximum PAPR of 15dB is allowed. As stated in Section II, the following PAPR reduction methods will be evaluated: Clipping, PRC and PRC + Clipping. Clipping directly clips the transmitted signal so that the PAPR does not exceed the 3dB threshold. PRC reduces the PAPR of each OFDM symbol by adding several subcarriers with appropriate amplitudes and phases; in this paper, 6 subcarriers with only one amplitude (1) and two phases (0 and π) are used which requires the evaluation of 64 combinations for each OFDM symbol. Since PRC can not assure that the PAPR will never exceed a given threshold Clipping at 3dB is done after PRC.

B. MC-CDMA system description

MC-CDMA symbol design is based on the previously described OFDM symbol: a symbol period of $111\mu s$ which include the $11\mu s$ for cyclic prefix and 32 subcarriers 10KHz separated. Each information bit is BPSK mapped and spread over the 32 subcarriers; 32 bits are transmitted in parallel using different spreading codes, which represents a fully loaded MC-CDMA system, to achieve the same spectral efficiency of the OFDM case. Perfect channel estimation is also assumed in the receiver and zero forcing equalization with conventional single user detection and hard decision is performed. A maximum PAPR of 3dB is also allowed and the same PAPR reduction methods than in the OFDM system are used.



(a) Uplink

(b) Downlink

Fig. 1. PAPR in MC-CDMA using different spreading sequences

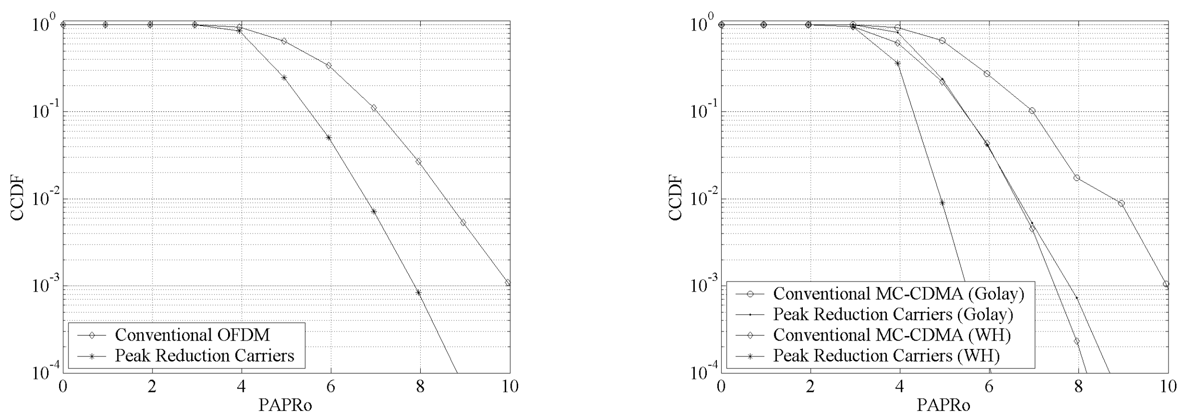
In order to reduce the multiple access interference in synchronous downlinks orthogonal spreading codes shall be used. Moreover, it must be taken into account that the selection of the spreading code has influence on the PAPR of the transmitted signal. Figure 1 shows the PAPR of a 16 subcarrier MC-CDMA system obtained using different spreading codes: Walsh-Hadamard (WH) and Golay. In Figure 1(a) the PAPR of each sequence in an uplink scenario is shown; only one sequence per user is assumed. Figure 1(b) shows the maximum and minimum PAPR obtained in a downlink scenario for a given number of active users. As it can be appreciated Golay spreading codes have a much lower PAPR when only one sequence is used (uplink PAPR); however, in a downlink scenario with more than two users WH spreading codes achieve lower PAPR. The choice of the appropriate spreading codes in a downlink case, so that PAPR is minimized for a given number of users, can only be done for few number of subcarriers since, assuming an m-ary modulation, an spreading factor of l and k active users, the number of OFDM symbols to be evaluated is $\binom{k}{l} \cdot m^k$. That is, around 43 million OFDM symbols in the 16 subcarrier case and more than $18.5 \cdot 10^{15}$ OFDM symbols in the 32 subcarrier case. Therefore, WH spreading sequences with no appropriate codes will be used.

IV. Simulations results

Three different results are shown in order to compare the effects of the PAPR reduction in OFDM and MC-CDMA systems: the Complementary Cumulative Density Function (CCDF) of the transmitted signal's PAPR, the OBR and the BER. Both the measurement of the CCDF and the OBR are done at the output of the transmitter. The BER performance has been evaluated using AWGN and COST207+AWGN channels. Typical Urban (TU), Hilly Terrain (HT) and Rural Area (RA) COST207 channel models have been used; however, since similar results have been appreciated only the HT case is shown.

A. Effects on the PAPR reduction

Figure 2 shows the CCDF of the transmitted signal's PAPR for OFDM and MC-CDMA using Golay and WH spreading codes. Two conclusions should be noted. First, conventional OFDM and MC-CDMA with Golay codes have a similar performance, even if PRC is used. Second, the use of WH codes in a conventional MC-CDMA system has a very important influence on the PAPR reduction. In fact, a MC-CDMA system with WH spreading codes has better CCDF curves of the transmitted signal's PAPR than a MC-CDMA system with Golay spreading codes and 6 peak reduction carriers. If further PAPR reduction is needed, PRC can be added to the conventional WH based MC-CDMA system.

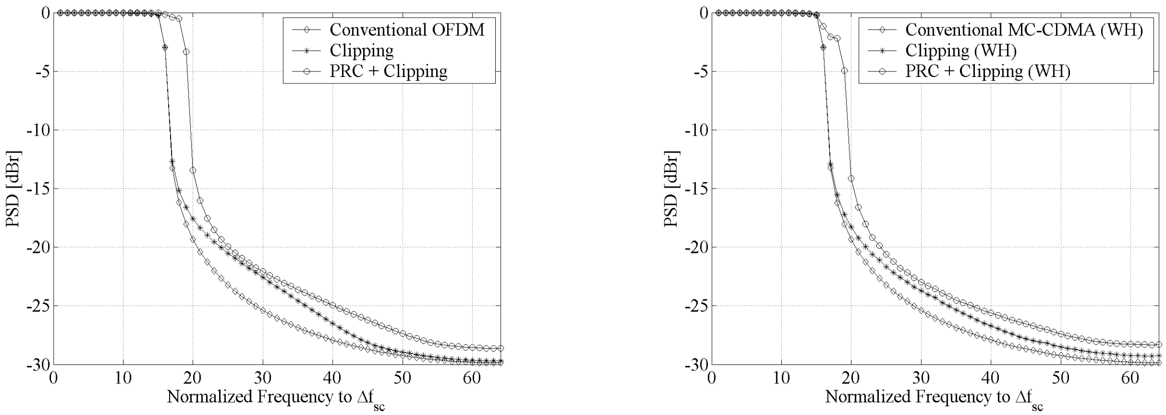


(a) OFDM (b) MC-CDMA

Fig. 2. PAPR reduction

B. Effects on the OBR

Figure 3 shows the Power Spectral Density (PSD) of the transmitted signal. As it can be appreciated, conventional OFDM and conventional MC-CDMA have the same OBR; however, when PAPR is limited the OBR of the OFDM system increases more than in MC-CDMA. This phenomenon is completely understandable since the MC-CDMA system with WH spreading codes has lower PAPR. It is interesting to notice that the OBR of a PRC+Clipping system is not only larger in the peak reduction carriers but also on the rest of the spectrum. The ratio between the OBR and the in-band Radiated power of the conventional OFDM and MC-CDMA systems shown in Figure 3 is -18.89dB; when Clipping is applied this ratio slightly decreases to -17.39dB in OFDM and -17.94dB in MC-CDMA; however, if PRC+Clipping is used it decreases to -8.0dB in OFDM and -9.51dB in MC-CDMA. Hence, the ratio between the OBR and the in-band radiation is slightly increased when Clipping is used but significantly increased when PRC is also used.

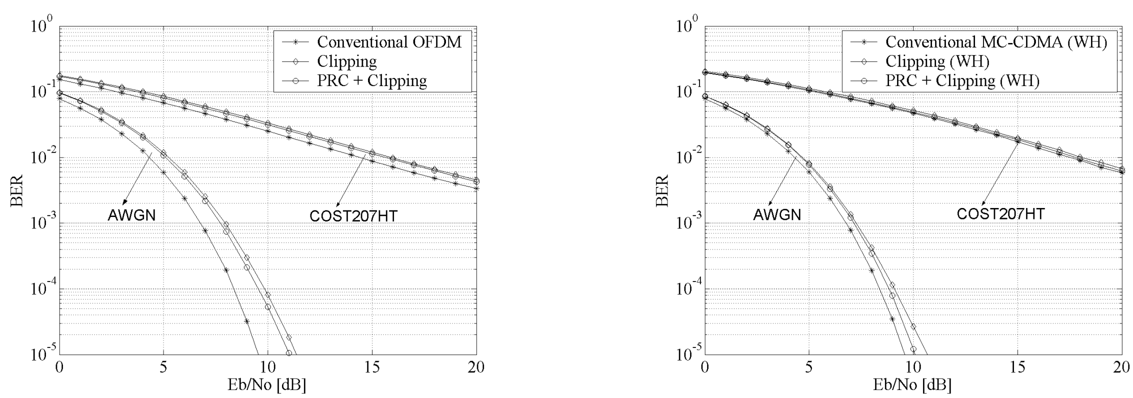


(a) OFDM (b) MC-CDMA

Fig. 3. Out-of-Band Radiation

C. *Effects on the BER*

Figure 4 shows the BER performance of the OFDM and MC-CDMA (with WH spreading codes) systems over AWGN and COST207HT+AWGN channels. If only the AWGN channel results are taken into account it can be appreciated that the BER performance of both, conventional OFDM and conventional MC-CDMA systems, are identical. However, when the PAPR of the transmitted signal is limited to a maximum threshold (3dB), as previously observed for the OBR, the BER performance of the OFDM system becomes worse than the one achieved with MC-CDMA. When simulations are done over multipath fading channels the BER performance of the MC-CDMA systems becomes slightly worse than the achieved with OFDM. These results are due to the fact that single-user detection techniques are used; however, if multiuser detection techniques were used much better results in MC-CDMA would be appreciated. Table I shows which increment of the SNR is required so that the BER performance of a PAPR limited OFDM/MC-CDMA system becomes the same to the BER performance of the conventional system. Two observations must be done: first, the worst BER degradation in multipath fading channels when PAPR reduction methods are used is lower than 2dB in OFDM and lower than 1dB in MC-CDMA and second, the worst BER degradation between using PRC+Clipping or Clipping directly is 0.36dB in OFDM and 0.42dB in MC-CDMA. Therefore, it seems that the use of PAPR reduction methods that require a high computational complexity is not necessary neither in OFDM nor in MC-CDMA since it has a minor effect on the BER degradation; on the contrary, low computational complexity PAPR reduction methods should be used.



(a) OFDM (b) MC-CDMA

Fig. 4. Bit Error rate in AWGN and COST207HT+AWGN channels

V. Conclusion

In this paper we have studied the effects of the PAPR in OFDM and MC-CDMA as well as the effects of using appropriate PAPR reduction methods. The implemented methods have been selected so that the compatibility with the current 4G downlink

TABLE I

BER DEGRADATION

	High SNR		Low SNR	
	OFDM	MC-CDMA	OFDM	MC-CDMA
Clipping	1.68	0.7	1.25	0.57
PRC+Clipping	1.32	0.29	0.94	0.15

proposals is guaranteed. Clipping and PRC + Clipping have been studied in OFDM while appropriate spreading + Clipping and appropriate spreading + PRC + Clipping have been studied for MC-CDMA.

Focusing on OFDM based downlinks, it has been appreciated that lower CCDF of the transmitted signal's PAPR is achieved when PRC is used. Therefore, lower BER is appreciated when maximum PAPR thresholds are defined; however, although the BER reduction is significant on AWGN channels it is not that much significant on multipath fading channels. As a result, we believe that low complexity PAPR reduction methods should be used in OFDM. However, further simulation using large number of subcarriers, error correcting codes, models of power amplifier's non-linearities, etc. should be done in order to determine the relationship between the useful computational complexity increase and the BER decrease when maximum PAPR thresholds are defined.

In MC-CDMA it has been appreciated that the spreading codes have an important influence on the PAPR of the transmitted signal. Although Golay spreading codes achieve low PAPR MC transmissions in single user environments, WH spreading codes offer better performance when there are several active users. This property makes the WH codes appropriate for MC-CDMA based downlinks. Furthermore, it must be taken into account that WH easily allows the use of variable spreading factors as it is proposed in [2]. Lower BER degradation is observed in WH based MC-CDMA systems when PAPR is limited; therefore we also believe that only low complexity PAPR reduction methods should be used in MC-CDMA.

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