WIRELESS COMMUNICATIONS AND MOBILE COMPUTING
Wirel. Commun. Mob. Comput. 2007; **7**:311–318
Published online 2 March 2006 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/wcm.327

A study on the PAPRs in multicarrier modulation systems with different orthogonal bases

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Summary

This paper studies the peak-to-average power ratios (PAPRs) in multicarrier modulation (MCM) systems with seven different orthogonal bases, one Fourier base and six wavelet bases. It is shown by simulation results that the PAPRs of the Fourier-based MCM system are lower than those of all wavelet-based MCM (WMCM) systems. A novel threshold-based PAPR reduction method is then proposed to reduce the PAPRs in WMCM systems. Both numerical and simulation results indicate that the proposed PAPR reduction method works very effectively in WMCM systems. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: multicarrier modulation (MCM); Fourier base; wavelets; OFDM; peak-to-average power ratio (PAPR)

1. Introduction

The principle of multicarrier modulation (MCM) is to split the data stream into multiple subcarriers and hence, capable of reducing the frequency-selective fading into flat fading. This provides a great immunity to multipath dispersion and can easily handle high data rate transmissions by increasing the number of subcarriers [1]. Thanks to these advantages, MCM systems have been considered as a potential candidate for the next generation wireless communications. One of the most important MCM schemes is to employ the Fourier base as the orthogonal base, resulting in the well-known orthogonal frequency division multiplexing (OFDM). OFDM has widely been used in wireless communication systems, such as digital video broadcasting (DVB), digital audio broadcasting (DAB), and wireless local area networks (WLANs). The following questions may arise: Is the Fourier base the best orthogonal base? Is there any other

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Contract/grant sponsor: National Natural Science Foundation of China; contract/grant number: 60372030.
Contract/grant sponsor: Provincial Scientific Foundation of Shandong (Key Project); contract/grant number: Z2003G02.
Contract/grant sponsors: National Mobile Communications Research Laboratory, Southeast University; State Key Laboratory of Integrated Services Network, Xidian University.

orthogonal base that performs better? Recently, MCM schemes with different orthogonal bases were studied in References [2–5], where it was believed that the wavelet packet bases can be a good alternative to the Fourier base. According to Reference [3], discrete wavelet transform-based OFDM (DWT-OFDM) provides much higher spectrum efficiency than discrete Fourier transform-based OFDM (DFT-OFDM). This is due to the fact that DWT-OFDM does not need guard intervals and pilot tones, as required by DFT-OFDM. It was shown in Reference [4] that the bit error rate (BER) performance of a DWT-OFDM system can be better than that of a DFT-OFDM system under certain channel conditions.

The occurrence of high peaks in transmitted signals is often a major problem in MCM systems. To mitigate this problem, we can possibly either increase the dynamic range of corresponding parts of the communication system or clip the signals. The latter yields an undesirable intercarrier and out-of-band radiation [6]. From this perspective, it is desirable to avoid using signals with high peaks. The peak-to-average power ratios (PAPRs) of MCM signals with different orthogonal bases can be quite different. To the best of authors' knowledge, however, the comparison of the PAPRs for Fourier-based MCM systems and wavelet-based MCM (WMCM) systems has not been done so far. The motivation of this paper is to fill the gap.

In the present paper, we first compare the PAPRs of MCM systems with the Fourier base and six wavelet bases. Simulation results show that the PAPRs of the Fourier-based MCM system are always lower than the PAPRs of the WMCM systems. This observation holds regardless of the wavelet types and the digital modulation schemes. In order to reduce the PAPRs of WMCMs, we further propose a novel threshold method. Both numerical and simulation results justify that the proposed PAPR reduction method is very effective in reducing the PAPRs of WMCM systems, with only a slight degradation of the BER performance.

The rest of this paper is organized as follows. Section 2 briefly reviews the Fourier and wavelet bases of MCM systems. In Section 3, the definition of the PAPR is given. Section 4 demonstrates the PAPR comparisons of MCM systems with different orthogonal bases. The influence of digital modulation schemes and subcarrier numbers on the PAPRs in MCM systems is also studied in this section. Section 5 presents a novel PAPR reduction method. Finally, the conclusions are drawn in Section 6.

2. Orthogonal Bases of MCM Systems

The Fourier base is a commonly used orthogonal base in MCM systems, while wavelet packet bases have attracted attention only recently. It is well known that a wavelet transform stems from a Fourier transform. Therefore, these two different kinds of transforms also share some common properties.

2.1. Fourier Base

Fourier's representation of functions as a superposition of sines and cosines has become ubiquitous for both the analytical and numerical solutions of differential equations. This also applies to the analysis and treatment of communication signals. The Fourier transform works by translating a function in the time domain into a function in the frequency domain. The signal can then be analyzed for its frequency contents. The Fourier transform is applicable to slowly changing signals. The DFT and the inverse DFT functions can be expressed as:

$$A_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} B_n \mathrm{e}^{-jwnk} \quad (k = 0, 1, \ldots, N-1) \tag{1}$$

$$B_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} A_k \mathrm{e}^{jwkn} \quad (n = 0, 1, \ldots, N-1) \tag{2}$$

respectively.

It has been shown that the inverse DFT can be considered as an orthogonal modulation of MCM, since they have the same expression [1]. The transmitted MCM signal with a Fourier base $s(n)$ can be expressed as:

$$s(n) = \frac{1}{\sqrt{N}} \sum_{m=1}^{N} \sum_{z=0}^{N-1} x_z(m) \mathrm{e}^{jwnz} \tag{3}$$

where N denotes the total number of subchannels and $x_z(m)$ represent the transmitted symbols (BPSK or 8ASK symbols in this paper) in the zth subchannel.

2.2. Wavelet Base

Wavelet transforms can be derived from Fourier transforms. The most interesting dissimilarity between these two kinds of transforms is that the individual wavelet functions are localized in space, while

Fourier's sine and cosine functions are not. The space localization feature, along with wavelets' localization of frequency, makes many wavelet functions perform better in impulse interference cancellation scenarios. This is also a part of the important reasons why we prefer using wavelet bases to modulate symbols in MCM systems.

In the following, let us denote the nonnegative integers by $Z_+ = \{0, 1, 2, \ldots\}$. The wavelet packet functions $w_n(t)$ ($n \in Z_+$) are defined by the following recursive functions:

$$w_{2n}(t) = \sqrt{2}\sum_{k\in Z_+} h(k)w_n(2t-k) \tag{4}$$

$$w_{2n+1}(t) = \sqrt{2}\sum_{k\in Z_+} g(k)w_n(2t-k) \tag{5}$$

where $h(k)$ and $g(k) = (-1)^k h(L-1-k)$ stand for a pair of quadrature mirror filters (QMFs) of length L. This means that the sequences $h(k)$ and $g(k)$ correspond to the discrete impulse responses of a QMF bank with perfect reconstruction. The function $w_0(t)$ is the unique fixed point of the two-scale Equation (4) with $n = 0$ and is exactly the scaling function from a multiresolution analysis (MRA). Similarly, the wavelet function $w_1(t)$ can be obtained from Equation (5) with $n = 0$. The wavelet packets $\{w_n(t)\}$, $n \in Z_+$, have the following two useful properties:

$$\langle w_n(t-j), w_n(t-k)\rangle = \delta_{j,k}; \quad j,k \in Z_+ \tag{6}$$

$$\langle w_{2n}(t-j), w_{2n+1}(t-k)\rangle = 0; \quad j,k \in Z_+ \tag{7}$$

Equation (6) indicates that each individual wavelet packet function is orthogonal with all its nonzero translations. This feature is actually utilized to eliminate inter-symbol interference (ISI). From Equation (7), it is clear that every pair of packets from the same parent packet is orthogonal at all translations. Therefore, the wavelet packets $\{w_n(t)\}$ ($n \in Z_+$) are a set of orthogonal functions.

In WMCM, the baseband signal $\{c_k\}$ is obtained from the wavelet reconstruction algorithm and can be given by:

$$c_k^{(j)} = \frac{1}{\sqrt{2}}\sum_l \left[g(n-2l)c_l^{(j-1)} + h(n-2l)d_l^{(j-1)}\right] \tag{8}$$

where $\{c_k^{(j)}\}$ and $\{d_k^{(j)}\}$ are the kth symbols in the jth subband. If the Haar wavelet is used, then the following relations hold:

$$g(0) = g(1) = 1, \quad g(k) = 0, \quad k > 1 \tag{9}$$

$$h(0) = -h(1) = 1, \quad h(k) = 0, \quad k > 1 \tag{10}$$

The transmitted baseband signals are again transformed into subband signals using the wavelet decomposition algorithm and can be expressed as:

$$c_k^{(j-1)} = \frac{1}{\sqrt{2}}\sum_l r(2k-l)c_l^{(j)} \tag{11}$$

$$d_k^{(j-1)} = \frac{1}{\sqrt{2}}\sum_l \eta(2k-l)c_l^{(j)} \tag{12}$$

where $\{r(k)\}$ and $\{\eta(k)\}$ are the decomposition sequences of wavelets. Similarly, in case of the Haar wavelet, we have

$$r(-1) = r(0) = -\eta(-1) = \eta(0) = 1 \tag{13}$$

$$r(k) = \eta(k) = 0, \quad k = \text{others} \tag{14}$$

The decomposition and reconstruction processes of wavelet functions are shown in Figure 1, where '↓' means the decomposition and '↑' indicates the reconstruction.

3. The PAPR

Figure 2 demonstrates a simple MCM system. The high PAPR of uncoded MCM signals is a major barrier to the widespread acceptance of MCM. It is well known that the peak transmit power is often limited, either by regulatory or application constraints. This has the effect of reducing the average

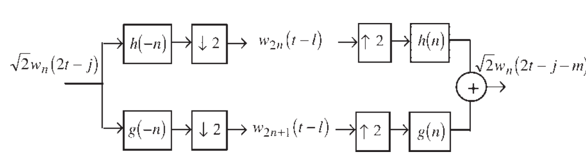

Fig. 1. The decomposition and reconstruction of wavelet functions.

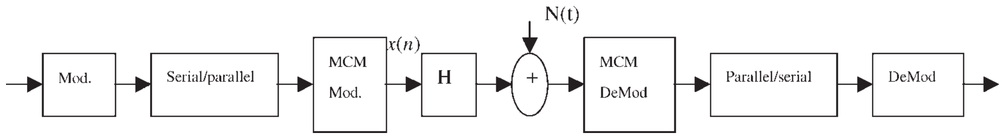

Fig. 2. A multicarrier modulation (MCM) system.

power allowed by MCM, which in turn reduces the range of MCM transmissions [7]. Thus, to maintain spectral efficiency, a linear amplifier with a large dynamic range is required. As a result, however, the power efficiency which influences the BER performance of MCM systems will be degraded significantly. Therefore, we must find a good tradeoff between the PAPRs and the BER performance of MCM systems.

Assume $x(n)$ is a signal obtained after an orthogonal modulation. Then, the PAPR is defined as:

$$\begin{aligned}\text{PAPR (dB)} &= 10\log_{10}\frac{\max_n\{|x(n)|^2\}}{E\{|x(n)|^2\}}\\ &= \frac{\max(|x(n)|^2, \quad n = 0, 1, \ldots, K-1)}{\frac{1}{K}\sum_{n=0}^{K-1}|x(n)|^2}\end{aligned} \tag{15}$$

where E denotes the statistical average operator.

4. PAPR Simulation Results and Discussions

In this section, the PAPRs of MCM systems with seven different orthogonal bases are investigated. One is a Fourier base. The other six are all wavelet bases with different types and parameters, that is, the Haar wavelet, the Daubechies wavelets (db4 and db10), the Biorthogonal wavelets (bio3.3 and bio5.5), and the Symlets wavelet (sym10). Note that we have denoted the Daubechies wavelets by dbα, where α represents the order. We chose $\alpha = 4$ and $\alpha = 10$ in this paper. Analogously, the Biorthogonal wavelets are denoted as bio$N_\text{r}N_\text{d}$, where r and d stand for reconstruction and decomposition, respectively. Here, we selected two cases: $N_\text{r} = N_\text{d} = 3$ and $N_\text{r} = N_\text{d} = 5$.

It is widely accepted that different digital modulation schemes can result in different PAPRs. Figure 3 shows the comparison of the PAPRs of MCM systems employing the seven different orthogonal bases by using the BPSK modulation scheme. The corresponding PAPR results of MCM systems with the 8ASK modulation scheme are illustrated in Figure 4. In both figures, the total number of subcarriers was fixed to be $N = 64$. It is obvious from Figures 3 and 4 that the PAPRs of the Fourier-based MCM system are always the lowest, no matter of the chosen digital modulation scheme. Among the six kinds of wavelet bases, the

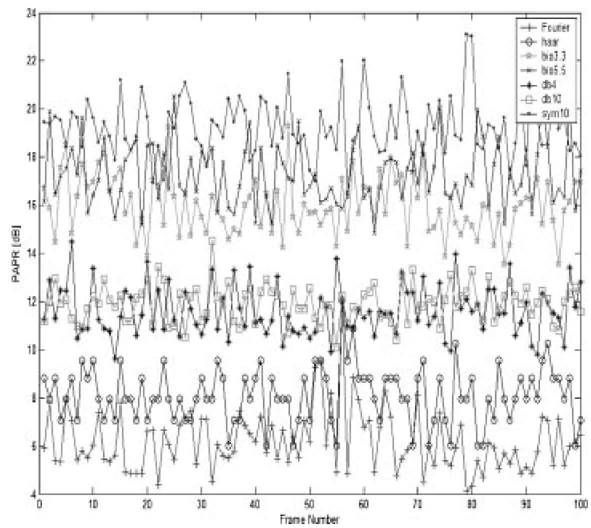

Fig. 3. The peak-to-average power ratio (PAPR) comparison of MCM systems with BPSK when the subcarrier number is 64.

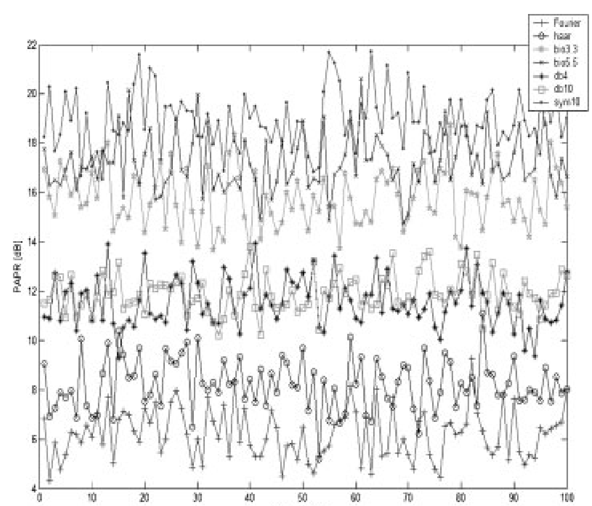

Fig. 4. The PAPR comparison of MCM systems with 8ASK when the subcarrier number is 64.

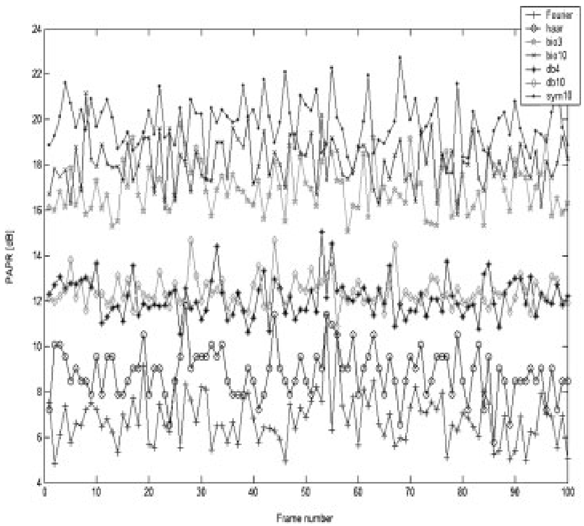

Fig. 5. The PAPR comparison of MCM systems with BPSK when the subcarrier number is 128.

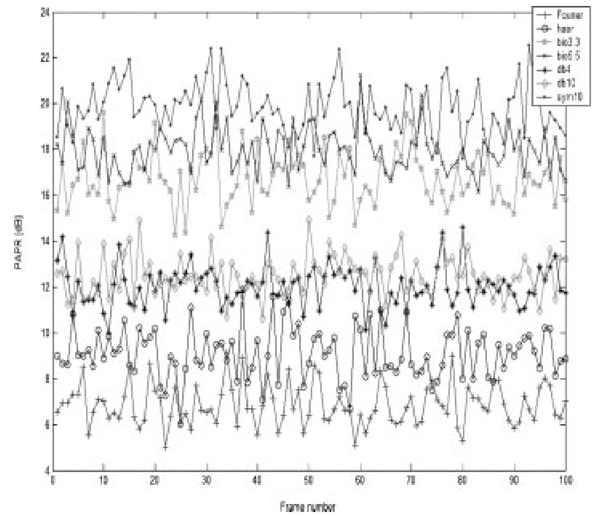

Fig. 6. The PAPR comparison of MCM systems with 8ASK when the subcarrier number is 128.

Haar wavelet results in the lowest PAPRs, while the Symlets wavelet the highest. The PAPRs for the Daubechies wavelets are even lower than those for the biorthogonal wavelets. For the Daubechies wavelets, db*K*, the bigger the value of *K*, the higher the PAPRs. For the Biorthogonal wavelets, the PAPRs of bio3.3 are in average higher than those of bio5.5. According to Reference [8], however, the MCM system with the Haar wavelet has the worst BER performance if the PAPRs cannot exceed the dynamic range of the linear amplifier. For the Daubechies wavelets, dbα, the bigger the value of α, the better the BER performance we get.

Figures 5 and 6 show us the PAPR curves of MCM systems with BPSK and 8ASK, respectively, when the subcarrier number $N = 128$. From both figures, similar conclusions to those obtained from Figures 3 and 4 can be drawn by comparing the PAPRs for different orthogonal bases. The comparison of Figure 3 and Figure 5 tells us that the larger number N of subcarriers in average increases the PAPRs in MCM systems with the BPSK scheme. By comparing Figures 4 and 6, we can also conclude that the PAPRs are in average increased with the increase of the subcarrier number in MCM systems with 8ASK.

5. A Novel PAPR Reduction Method

Wavelet transforms have a property that they always concentrate energies on parts of signals with sharp changing rates. This property has widely been used in image processing, such as wavelet de-noising [9–11]. Next, we will show how to utilize this property to reduce the PAPRs in WMCM systems with a little reconstruction lost.

By taking the advantage of the fact that the wavelet transforms concentrate energies on only a certain number of bases, we can choose an energy threshold T and define a new sequence $y(n)$ with the relation to the signal sequence $x(n)$, $n = 0, 1, \ldots, K-1$, as follows:

$$y(n) = \begin{cases} 0, & \text{if} \quad |x(n)|^2 < T \\ x(n), & \text{if} \quad |x(n)|^2 \geq T \end{cases} \tag{16}$$

Assume the energies of M bases are smaller than the given threshold T. Then, let us define another new sequence $x_1(i)$:

$$x_1(i) = y(n), \quad \text{when} \quad y(n) \neq 0 \tag{17}$$

for $i = 0, 1, \ldots, K-M-1$ and $n = 0, 1, \ldots, K-1$. It follows that the new PAPR can be calculated, similarly to Equation (15), as follows:

$$\begin{aligned} \text{PAPR}'(\text{dB}) &= 10 \log_{10} \frac{\max_i\{|x_1(i)|^2\}}{E\{|x_1(i)|^2\}} \\ &= \frac{\max(|x_1(i)|^2, \quad i = 0, 1, \ldots, \ K-M-1)}{\frac{1}{K-M}\sum_{i=0}^{K-M-1} |x_1(i)|^2} \end{aligned} \tag{18}$$

Let us choose the threshold T in such a way that it is less than the average signal power, that is,

$T < (1/K) \sum_{n=0}^{K-1} |x(n)|^2$ holds. Obviously, we have the following relation

$$\frac{1}{K}\sum_{n=0}^{K-1}|x(n)|^2 < \frac{1}{K-M}\sum_{n=0}^{K-M-1}|x_1(n)|^2 \tag{19}$$

The comparison of Equations (15), (18), and (19) makes clear that

$$\text{PAPR} > \text{PAPR}' \tag{20}$$

holds. Therefore, the PAPR value is effectively reduced by using this threshold method. The confronted task now is to choose a proper value for the threshold T. From Equations (16) and (17), it is obvious that the higher the value of T, the larger the value of M. This implies that the PAPRs will be reduced more. On the other hand, the higher value of T results in more distortions on transmission signals. Consequently, much more information will get lost and the BER performance will be degraded. Given a value of T, different wavelet bases perform differently in reducing PAPRs due to their own characteristics. In this paper, we chose the Haar wavelet as an example to investigate the PAPRs and BER performance of MCM systems employing the above described PAPR reduction method.

It is relatively simple to design the receiver side of MCM systems with the proposed PAPR reduction method. Only an additional forward transfer channel is required to carry the label information of subspaces whose energies were set to be zero. Then, we have to pad zeros to the subspaces which are made zero at the transmitter side. After the serial to parallel transformation, the DWT can be proceeded to get deorthogonal signals.

In our simulation, the average power of one multicarrier symbol was set to be 1. Additionally, BPSK was used as a digital modulation scheme. Then, choosing the threshold $T = 0.3$, we compare the PAPRs of the Haar WMCM systems with and without the PAPR reduction method in Figure 7. In the employed WMCM system, the total number of subchannels was set to be $N = 512$. Figure 7 clearly illustrates that the PAPRs are reduced greatly by using the proposed threshold method. In the figure, $R1 = 1.1$ dB and $R2 = 1.4$ dB were chosen as two examples to show us the possible reduction values of PAPRs. Figure 8 demonstrates the BER performance comparison of the Haar WMCM systems with and without the PAPR reduction method. We have assumed that the

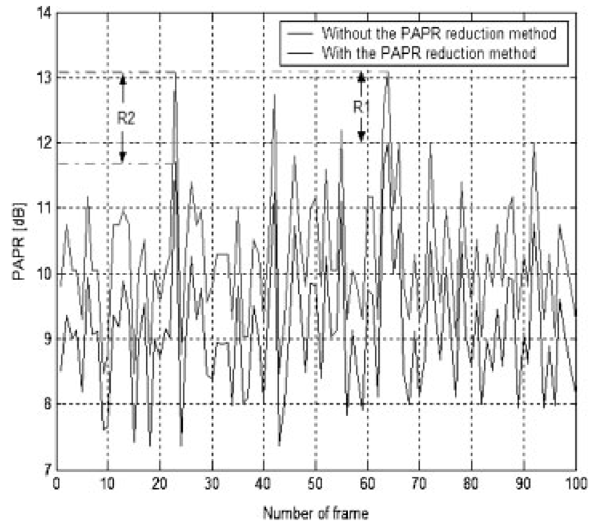

Fig. 7. The PAPR comparison of Haar WMCM systems with and without the PAPR reduction method.

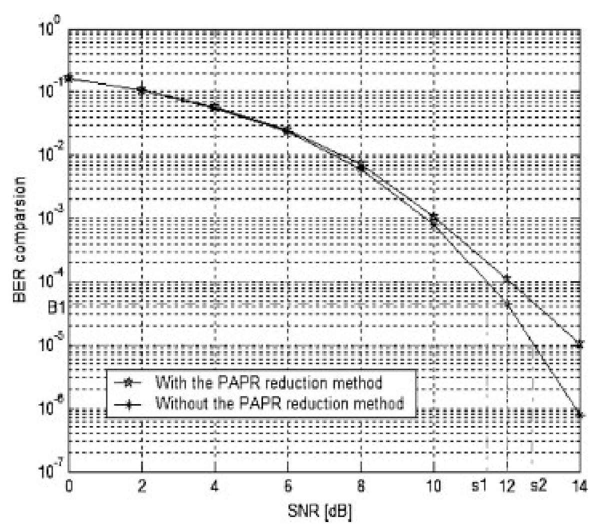

Fig. 8. The BER comparison of Haar WMCM systems with and without the PAPR reduction method.

power amplifier always works in its linearity range. From this figure, we can find that the BER performance is degraded only slightly by employing the threshold method to reduce PAPRs in the WMCM system. For example, the BER only increases from 0.6×10^{-4} to 10^{-4} when the signal-to-noise ratio (SNR) is 12 dB. At the BER $= 10^{-4}$, we need to pay an extra 0.5 dB power by using the PAPR reduction method. It is important to mention that the BER is increased with the increase of the SNR. Therefore, we must find a good tradeoff between the PAPRs and the BER performance. A further study is performed concerning the influence of different values of T on the

PAPRs and the BER performance of WMCM systems. Detailed investigations show that the larger value of T will result in smaller PAPRs and higher BERs. Nevertheless, the proposed threshold method turned out to be a promising and effective method to reduce the PAPRs in WMCM systems.

6. Conclusion

In the present paper, we have studied the PAPRs in MCM systems with seven different orthogonal bases. One orthogonal base is the well-known Fourier base and the other six are all based on wavelet packets with different wavelet types and parameters. Simulation results show that the Fourier-based MCM outperforms the WMCM in terms of the PAPRs.

A novel PAPR reduction method has been proposed to reduce the PAPRs of WMCM systems. We have also investigated the BER performance difference of the WMCM systems with and without the PAPR reduction method assuming that the power amplifier works in the linearity range. Simulation results show that the proposed threshold method can significantly reduce the PAPRs of WMCM systems by paying the price of slight BER performance degradation. It is important to stress here that the power amplifier has been assumed to work in the linearity domain. If the values of the original PAPRs exceed the dynamic range of the power amplifier, we will get much worse BER performance, which may be even worse than the BER performance using the proposed threshold method. In this case, we can gain even more from the PAPR reduction method. This highlights the advantage of the proposed threshold method in WMCM systems.

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Cheng-Xiang Wang received his B.S. and M.Eng. degrees in Communication and Information Systems from Shandong University, Shandong, China, in 1997 and 2000, respectively, and the Ph.D. in Wireless Communications from Aalborg University, Aalborg, Denmark, in 2004. From 2000 to 2001, he was a student research assistant with the Department of Communication Networks, Technical University of Hamburg-Harburg, Hamburg, Germany. From 2001 to 2005, he was a research fellow of mobile communications with Agder University College, Grimstad, Norway. From January to April 2004, he was on leave at Baseband Algorithms & Standardization Lab of Siemens AG-Mobile Phones, Munich, Germany, conducting research and development of error models for EGPRS systems within the framework of the 3GPP GERAN System Concept R&D Project. Since 2005, he has been a lecturer in Electrical, Electronic, and Computer Engineering, School of Engineering & Physical Sciences, Heriot-Watt University, Edinburgh, U.K. He has published more than 40 papers in international journals and conference proceedings. His current research interests include mobile radio channel modeling, error models, smart antennas and MIMO systems, OFDM, UWB, space-time coding techniques and cross-layer optimization of wireless networks. He was the recipient of the '2001 Excellent Master Thesis Award of Shandong Province.' Also, he received the '1999 Excellent Paper Award' for two of his papers from the sixth National Youth Communication Conference of China, Beijing, China. He is a member of the IEEE.