Optimized Spreading Code Reallocation Technique for PAPR Reduction in MC-CDMA systems

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***Abstract*— Multicarrier code division multiple access (MC-CDMA) is one of the most promising techniques considered for future broadband mobile services. However, the high peak to average power ratio (PAPR) problem associated with multicarrier systems significantly degrades the power efficiency and makes it less preferred by the industry. In this paper, we exploit the order of the CDMA spreading codes as an extra degree of freedom to devise an efficient PAPR reduction scheme for the downlink of MC-CDMA systems. Both lightly loaded and fully loaded systems are considered when using the orthogonal sets of Walsh-Hadamard and Golay complementary sequences. The proposed technique requires only slight modification to the MC-CDMA base station and negligible complexity to the mobile terminals. It will be demonstrated that it achieves significant PAPR reduction with low system complexity at both transmitter and receiver.**

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) has been adopted for high-speed wireless data transmission systems [1] due to its inherent robustness against multipath fading channels. By combining OFDM and Code Division Multiple access (CDMA), multicarrier code division multiple access (MC-CDMA or OFDM-CDMA) inherits the advantages of both OFDM and CDMA techniques. In such systems, the CDMA part provides multiple access ability as well as to spread each user's data across the entire available frequency band The spreading code's chips are then modulated on orthogonal subcarriers and spread across the time domain via the OFDM modulation which provides protection against the delay spread of the multipath channel. Therefore MC-CDMA technique can achieve high data rate transmission with protection against both frequency selective fading and time dispersion channel while at the same time offers a spectrum efficient multiple access strategy [2].

However MC-CDMA systems suffer from high peak to average power ratio (PAPR) which is one of the major drawbacks of all multicarrier transmission schemes. A wide dynamic range is required in the linear Power Amplifiers (PA) at the transmitter in order to transmit a signal with large PAPR. If the dynamic range of PA is insufficient, the signal could be distorted from the resulting nonlinearity which degrades the signal quality and leads to out of band (OoB) radiations and hence interfere with adjacent frequency bands.

Various PAPR reduction schemes have been proposed in literature, such as the most extensively studied multiple signal representation (MSR) techniques including partial transmit sequence (PTS) and selected mapping (SLM) [3]. Although these OFDM based schemes can be transplanted to MC-CDMA system [4][5], more efficient MC-CDMA specific algorithms have been developed by exploiting the spreading codes of the MC-CDMA systems. For instance, [6] proposed to assign two spreading codes for each user and use two chip-matched correlators to identify which spreading code has been used at the transmitter, and [7] provided a scheme for generating new spreading sequences with low PAPR.

In this paper, we propose a practical optimized spreading codes reallocation (SCR) technique suitable for the downlink MC-CDMA systems to achieve significant PAPR reduction with low system complexity [8]. Rather than randomizing the transmitted symbols as the SLM technique and sharing or creating new spreading codes as in [6][7], we dynamically redistribute spreading codes between users for each downlink MC-CDMA symbol in order to produce a set of alternative MC-CDMA symbol representations and increase the possibility of obtaining a low PAPR symbol. Both Walsh-Hadamard (WH) and Golay complementary sequences (CS) are considered in the study. Since WH sequences can cause extremely high PAPR values in low-traffic downlink MC-CDMA system [9], we also propose a sequence optimizing (SO) scheme to aid the SCR technique to achieve stable performance for both lightly and fully loaded systems. It will be shown in the results section that the proposed technique achieves comparable PAPR reduction ability to that of the SLM technique while requiring same amount of side informantion (SI) as the SLM technique. Moreover since mobile terminals only need to recognize their corresponding spreading codes and despread the signal as in all CDMA systems, it is unnecessary to de-randomise the received symbol as in the SLM and PTS techniques.

II. SYSTEM DESCRIPTION

Let's assume the MC-CDMA system has K active users with the vector $s^{(k)} = [s_1^{(k)}, s_2^{(k)}, ..., s_M^{(k)}]$ denotes M data symbols of the k^{th} user, where $k = 1, 2, ..., K$. The symbols are converted from serial to parallel and then spread by the specific spreading sequence $c^{(k)} = [c_1^{(k)}, c_2^{(k)}, ..., c_J^{(k)}]$, where J is the Spreading Factor (SF). The spread data symbols of K

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users are added and then interleaved in the frequency domain to achieve good frequency diversity. After interleaving and S/P conversion the $M \cdot J$ parallel data samples are input to the Inverse Fast Fourier Transform (IFFT) of size $N = M \times J$. The resultant baseband transmission signal for one MC-CDMA block can be mathematically written as

$$x[n] = \frac{1}{\sqrt{N}} \sum_{m=1}^{M} \sum_{j=1}^{J} \sum_{k=1}^{K} s_m^{(k)} c_j^{(k)} e^{i2\pi\{M\cdot(j-1)+(m-1)\}\Delta f \frac{nT}{L}} \tag{1}$$

where $\Delta f = 1/NT$ is the subcarrier spacing, L is the oversampling factor, and NT denotes the symbol period of one MC-CDMA symbol.

The MC-CDMA signal consists of the sum of several subcarriers, which may result in a large dynamic transmitted signal. The envelope variation of a multicarrier signal can be estimated by the PAPR:

$$PAPR(x[n]) = \frac{\max\limits_{0 \leq n \leq NL-1} |x[n]|^2}{E[x[n]^2]} \tag{2}$$

where $E[\cdot]$ stands for expectation function.

With a large number of subcarriers the large peaks of approximately Rayleigh distributed signal amplitude happen only with a very small probability. Therefore, the absolute PAPR is not meaningful for characterizing the PAPR property. The most intuitionistic way to measure the PAPR performance is to investigate the statistical probability that the PAPR of a block is larger than a certain level $PAPR_0$. This is represented by the Complementary Cumulative Distribution Function (CCDF) of PAPR, a random variable expressed as $P = \Pr(PAPR(x[n]) > PAPR_0)$.Assuming that the absolute values of the time-domain OFDM signal samples are distributed according to the Rayleigh function

$$f(x) = \frac{2x}{\sigma_x^2} e^{-\frac{x^2}{\sigma_x^2}}; \tag{3}$$

where $E(|\operatorname{Re}(x(n))|^2) = \sigma_x^2$. In order to evaluate which is the probability that an OFDM symbol exhibits a peak whose absolute value $|x_n|$ exceeds a certain value $|\bar{x}|$, or equivalently the probability that the normalized power exceeds the value$\frac{|\bar{x}|}{\sigma_x} = \sqrt{\mathrm{PAPR}_0}$, integrating 3 we obtain

$$\Pr(|x(n)| < |\bar{x}|) = 1 - \int_{|\bar{x}|}^{\infty} f(x)dx = 1 - e^{-\mathrm{PAPR}_0} \tag{4}$$

Thus the complementary CDF (CCDF) can be expressed as

$$P = 1 - (1 - e^{-\mathrm{PAPR}_0})^N. \tag{5}$$

III. SPREADING CODE REALLOCATION AND SEQUENCE OPTIMIZATION

In this section, the proposed technique will be systematically presented in three stages. After a briefly introduction of the Walsh-Hadamard (WH) and Golay complementary sequences (CS) in the first section, the dynamic spreading code reallocation (SCR) is discussed in detail with illustrative examples. Finally a scheme for sequence optimizing (SO) is proposed in order to aid the SCR technique to alleviate the serious impact of WH sequences on the PAPR in lightly loaded MC-CDMA systems.

A. Spreading Codes and PAPR

Walsh-Hadamard orthogonal spreading sequences are the rows of WH transform matrix, which is recursively defined as

$$\mathrm{H}_{2N}^{WH} = \frac{1}{\sqrt{2}} \begin{bmatrix} \mathrm{H}_N^{WH} & \mathrm{H}_N^{WH} \\ \mathrm{H}_N^{WH} & \text{-}\mathrm{H}_N^{WH} \end{bmatrix}; \ \mathrm{H}_2^{WH} = \frac{1}{\sqrt{2}} \begin{bmatrix} + & + \\ + & - \end{bmatrix} \tag{6}$$

Another set of orthogonal codes, frequently proposed for spreading, is the set of Golay complementary sequences which has also a recursive structure

$$\mathrm{H}_{2N}^{CS} = \frac{1}{\sqrt{2}} \begin{bmatrix} \mathrm{H}_N^{CS} & \bar{\mathrm{H}}_N^{CS} \\ \mathrm{H}_N^{CS} & \text{-}\bar{\mathrm{H}}_N^{CS} \end{bmatrix}; \ \mathrm{H}_2^{CS} = \frac{1}{\sqrt{2}} \begin{bmatrix} + & + \\ + & - \end{bmatrix} \tag{7}$$

where $\bar{\mathrm{H}}_N^{CS}$ is composed of H_N^{CS} as follows: if H_N^{CS} = [A_N B_N], then $\bar{\mathrm{H}}_N^{CS}$ = [A_N -B_N].

As defined in [11], the upper bound of PAPR of orthogonal sequences can be given by:

$$PAPR \leq \frac{\max\left\{|C_k[n]|^2\right\}}{J/2} \tag{8}$$

where

$$C_k[n] = \sum_{j=1}^{J} c_j^{(k)} e^{i2\pi jt/T_s} \tag{9}$$

For Walsh-Hadamard sequences, the maximum $C_k[n]$ appears $\max\{C_k[n]\} = J^2$ when the WH sequences are only composed of elements +1 [11]. Consequently, the PAPR upper bound for WH codes can be expressed as: $PAPR_{WH} \leq 2 \times J$. While in the case of Golay complementary sequences, its PAPR upper bound can be obtained by applying $\max\{C_k[n]\} = 2 \times J$ to expression (8), thus $PAPR_{CS} \leq 4$. These analytical results clearly indicate WH sequences have a higher PAPR upper bound than complementary sequences for $J > 2$.

B. Spreading Codes Reallocation (SCR)

Unlike other MSR techniques such as SLM and PTS, the proposed SCR technique shuffles the same set of spreading codes among users on a symbol by symbol basis, such that a number of new symbol representations are generated with the possibility of attaining one with a low PAPR value. The PAPR reduction ability of the SCR technique is mainly determined by the number of alternative signal representations while not so much by how they are generated. The maximum number of possible symbol representation is determined by the number of spreading sequences K: $\max\{N_s\} = K!$, where N_s indicates the number of signal representations. However, in this paper

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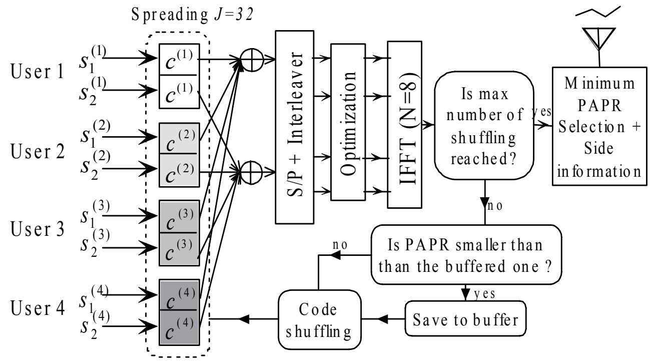

Fig. 1. MC-CDMA downlink transmitter with 4 users applying spreading code reordering technique.

the N_s is limited as $N_s \in [0, J]$. It will be shown in the simulation results that J signal representations can effectively achieve sufficient PAPR reduction (≈3dB). Although increasing the limit of N_s beyond J may achieve slightly better PAPR performance, it costs much higher computational complexity.

1) Cyclic Shifting: In order to produce N_s signal representations, the proposed SCR technique must shuffle the spreading codes N_s times. Considering the PAPR reduction performance is not affected by the shuffling process but the number of signal representations, it is preferred to use a simple shuffling mode to produce diverse signal representations at the lowest computational cost. Bear in mind that we are only interested in maximum J different representation as stated above, we can easily obtain the N_s shuffles by shifting the order of the spreading sequences cyclically. In the rest of the paper, shifting mode SCR$_{shift}$ is assumed to be the default mode applied with SCR technique. The redistributed spreading sequences for user i can be expressed as

$$c_{SCR_{shift}}^{(i)} = \begin{cases} c^{(i+N_s)} & \text{when } i + N_s < J \\ c^{(i+N_s-J)} & \text{when } i + N_s > J \end{cases} \tag{10}$$

Consequently the side information should contain the number of shifts so that all the users can identify their own spreading codes. The SI can be sent either within the data package or through dedicated channel. It is noteworthy to mention that since such information is common to all users, the associated data loss is not going to be excessive. In fact for Q-ary modulated MC-CDMA symbols the data rate efficiency can be expressed as

$$\eta = 1 - \frac{\log_2(N_s)}{N_c \times \log_2 Q} \tag{11}$$

where N_c is the number of subcarriers.

This proposed scheme can be regarded as a binomial distribution, the probability of at least 1 symbol having PAPR values larger than the threshold PAPR$_0$, $\Pr(A)$, can be expressed as

$$\begin{aligned} \Pr(A) &= 1 - \Pr\left(B_k | k = 0\right) & (12) \\ &= 1 - (1 - P)^R & \\ &= 1 - (1 - e^{-\text{PAPR}_0})^{NR} & (13) \end{aligned}$$

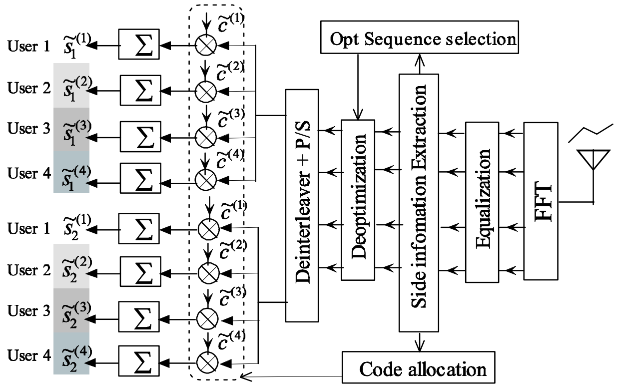

Fig. 2. MC-CDMA receiver with spreading code shuffling technique. K=J=4,M=2

where B_k is the event when there are k symbols with values larger than PAPR$_0$.

In the rest of this section, the transmitter and receiver models will be depicted with illustrative examples to further explain the operation of SCR technique. For simplicity but without loss of generality, we assume $K = 4; M = 2; J = 4$ which implies all the 4 users are active in the system with 2 CDMA symbols interleaved and input to the IFFT processor thus forming a MC-CDMA symbol with $N = M \times J = 8$ subcarriers.

2) Transmitter Model: The flow chart of SCR transmitter is described in figure 1, where $s_1^{(1)}, s_1^{(2)}, s_1^{(3)}, s_1^{(4)}$ indicate the first symbol from user 1 to user 4 respectively and $c^{(1)}, c^{(2)}, c^{(3)}, c^{(4)}$ are the default spreading codes allocated to the four users. Let us assume Golay complementary sequences are employed in the system, from equation (7) we can express it as

$$H_4^{CS} = \begin{bmatrix} c^{(1)} \\ c^{(2)} \\ c^{(3)} \\ c^{(4)} \end{bmatrix} = \frac{1}{\sqrt{4}} \begin{bmatrix} + & + & + & - \\ + & - & + & + \\ + & + & - & + \\ + & - & - & - \end{bmatrix}$$

The two information symbols of different users can be also written in the form of matrix: $\begin{bmatrix} s_1^{(1)} & s_1^{(2)} & s_1^{(3)} & s_1^{(4)} \\ s_2^{(1)} & s_2^{(2)} & s_2^{(3)} & s_2^{(4)} \end{bmatrix}$, therefore the input to the interleaver can be defined as:

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} s_1^{(1)} & s_1^{(2)} & s_1^{(3)} & s_1^{(4)} \\ s_2^{(1)} & s_2^{(2)} & s_2^{(3)} & s_2^{(4)} \end{bmatrix} \times \frac{1}{\sqrt{4}} \begin{bmatrix} + & + & + & - \\ + & - & + & + \\ + & + & - & + \\ + & - & - & - \end{bmatrix}$$

After S/P conversion, $[u_1, u_2]^T$ would be modulated by IFFT processor. If the resulting PAPR value is below the predetermined threshold, then it is transmitted directly without performing the MSR technique. Otherwise we shift the sequence of spreading codes circularly by one which means $c^{(2)}$ is allocated for user 1, $c^{(3)}$ for user 2 and so on. Consequently

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a new $[u_1', u_2']^T$ can be obtained as

$$\begin{bmatrix} u_1' \\ u_2' \end{bmatrix} = \begin{bmatrix} s_1^{(1)} & s_1^{(2)} & s_1^{(3)} & s_1^{(4)} \\ s_2^{(1)} & s_2^{(2)} & s_2^{(3)} & s_2^{(4)} \end{bmatrix} \times \frac{1}{\sqrt{4}} \begin{bmatrix} + & - & - & - \\ + & + & + & - \\ + & - & + & + \\ + & + & - & + \end{bmatrix}$$

It can be deduced by analogy that another two alternative MC-CDMA symbols can be obtained before $c^{(1)}$ is cyclically shifted back to user 1. By applying the SCR technique, we hope to get an alternative MC-CDMA symbol with a low PAPR factor. From the four MC-CDMA symbols carrying the same information, the one with minimum PAPR will be chosen for transmission together with the side information (SI) which should indicate the number of shifting performed to the spreading codes. For instance if the spreading codes are shifted once, the SI needs only one bit, either 1 or 0. In this particular case there are four active users and four possibilities for the total number of code shifts. Therefore the SI should be $\log_2 4 + \log_2 4 = 4$ bits.

3) Receiver Model: Figure 2 shows the receiver block diagram corresponding to the transmitter shown in figure 1. In order to recover the original data, the receiver must know how many shuffling operation were performed at the transmitter. Let us assume the SI $('10')$ indicates two cyclic shifts. Then based on this available information, the receiver for each user can determine its correct despreading code for the received symbol according to equation (10). The despreading sequences for all the users become

$$\tilde{c}^{(i)} = \begin{cases} c^{(i+2)} & \text{when } i \leq 2 \\ c^{(i-2)} & \text{when } i > 2 \end{cases}$$

Suppose $\tilde{u}_1$ and $\tilde{u}_2$ are the received MC-CDMA symbols after the de-interleaving process, the estimates for the data symbols of the different users can be produced by:

$$\begin{bmatrix} \tilde{s}_1^{(1)} & \tilde{s}_1^{(2)} & \tilde{s}_1^{(3)} & \tilde{s}_1^{(4)} \\ \tilde{s}_2^{(1)} & \tilde{s}_2^{(2)} & \tilde{s}_2^{(3)} & \tilde{s}_2^{(4)} \end{bmatrix} = \begin{bmatrix} \tilde{u}_1 \\ \tilde{u}_2 \end{bmatrix} \times [\tilde{c}^{(1)^T} \tilde{c}^{(2)^T} \tilde{c}^{(3)^T} \tilde{c}^{(4)^T}]$$

C. Sequence Optimization (SO)

Figure 3 shows PAPR λ_0 (where $Prob(\lambda > \lambda_0) = 10^{-3}$) with respect to the number of active users K. It clearly indicates that as the number of active users decreases in the MC-CDMA system using WH codes, the PAPR upper bound of downlink MC-CDMA signal increases dramatically. This is because when the MC-CDMA system is lightly loaded, the PAPR of the signal becomes highly dependent to the PAPR of the WH sequences. And since WH sequences inherently have very high PAPR upper bound when J is large as discussed in section A (eq.8), very likely the resultant symbols will suffer from high PAPR. However the PAPR performance with complementary sequences remains fine because they have much lower PAPR upper bound $(4 \times M)$ than WH sequences $(2 \times M \times J)$ while $J >> 2$.

In order to reduce the extremely high PAPR factor caused by WH sequences in light-loaded downlink MC-CDMA systems, a simple sequence optimizing (SO) scheme is introduced below before applying the SCR process.

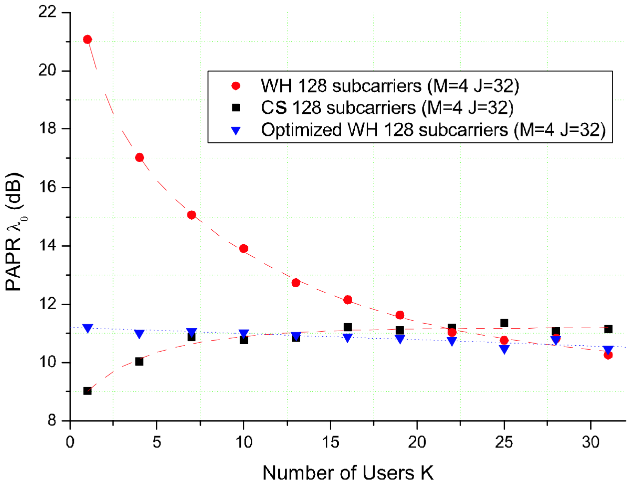

Fig. 3. Relationship between PAPR λ_0 and active number of users with WH and CP sequences where Prob($\lambda > \lambda_0$)=10^{-3}

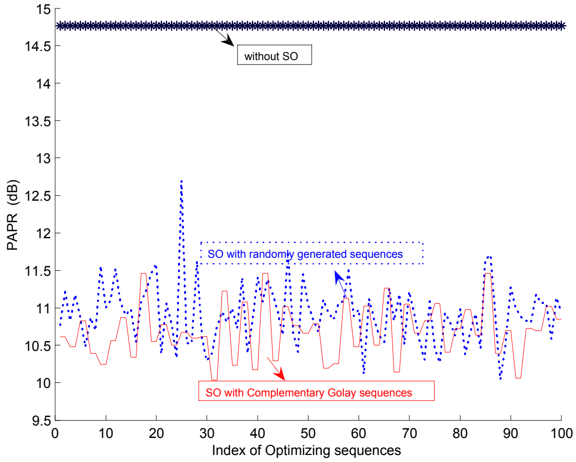

Fig. 4. PAPR λ_0 of symbols with /without optimization of 100 ramdom/CS sequences, Prob($\lambda > \lambda_0$)=10^{-3}

The result shown in figure 4 is obtained by transmitting 1000 CDMA symbols in a 32-user-system with 8 active users. We can see that without SO, the maximum PAPR of these 1000 symbols is almost $15dB$, which is consistent with the result shown in figure 3. Since such high peak values are caused by the WH codes, it is possible to reduce the influence of WH codes by multiplying the CDMA symbol with another sequence so that the resulting PAPR value can be maintained at a reasonable level. In order to validate this, we transmit the 1000 symbols again by multiplying them with an fixed optimizing sequence and record the maximum PAPR. This process is repeated with 100 different randomly generated optimizing sequences. It is clearly shown in the figure that with such optimization process, the maximum PAPR is effectively reduced to roughly $11dB$.

Since all optimizing sequences provide similar PAPR dis-

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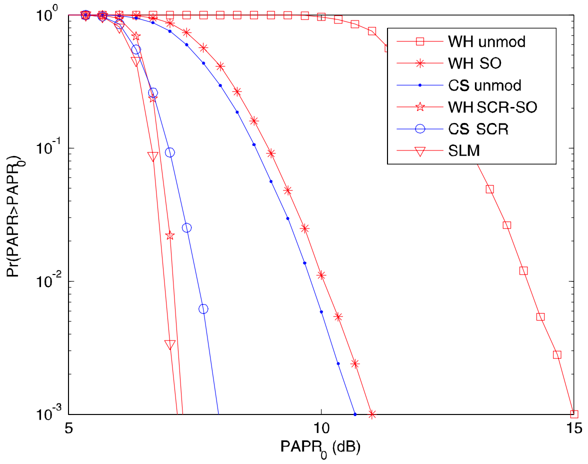

Fig. 5. PAPR performance of a light-loaded 32 users and 128 carriers MC-CDMA downlink system. (K=8,M=4,J=32) with our proposed technique.

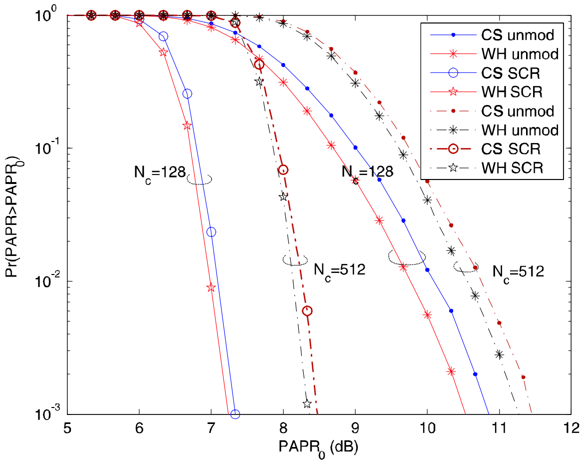

Fig. 6. PAPR performance of full-loaded 32 users and 128/512 carriers MC-CDMA downlink systems using SCR with WH and CS codes

tributing between $10dB$ to $11.5dB$, it is unnecessary to search for the best optimizing sequence for each data symbol, we can simply specify any complementary sequence to optimize the PAPR and then reverse the process at the receiver. By doing this, the high PAPR of light-loaded systems can be significantly reduced. Figure 3 clearly shows that by applying SO, stable PAPR performance can be obtained in both full-loaded and light-loaded MC-CDMA systems. It is also feasible to search for the best optimizing sequence in order to achieve slightly better PAPR performance, however this requires extra side information and computational complexity.

IV. NUMERICAL RESULTS AND DISCUSSIONS

In this section, we will report on several simulation results to evaluate the performance of the proposed PAPR reduction technique. The complementary cumulative density function (CCDF) of PAPR is used as the measure of performance. The transmitted signal is oversampled by a factor of four in the IFFT process in order to achieve an accurate measure of the PAPR as recommended by [10]. The simulation parameters used are summarized in Table 1 below. As can be seen from this table the PAPR performance for the SCR technique is evaluated for both light-loaded and full-loaded system scenarios. All the simulations were performed for a downlink scenario.

	Fig 5	Fig 6	Fig 7
Modulation	BPSK	QPSK	QAM-16
Number of users	8	32	32
Number of carriers	128	128/512	128/512
Spreading factor	32	32	32
Spreading code	WH/CS		WH

Table 1. Simulation parameters

The PAPR performance of a light-loaded MC-CDMA downlink system is illustrated in figure 5. Only 8 users are active in a 32-user-system ($K = 8, J = 32$) and 4 symbols are transmitted each time ($M = 4$), therefore the number of subcarriers is $M \times J = 128$. Since the system is lightly loaded, it can be seen from both figure 5 and previous figure 3 that the WH codes cause very high PAPR. For only 0.1% of the possible unmodified symbols, the PAPR value is $15dB$ which is highly unacceptable. However, by using sequence optimizing (SO) process, the maximum PAPR can be reduced to $11dB$. Moreover, when applying our proposed spreading codes reallocation (SCR) technique, the PAPR is further reduced to $7.3dB$, which is a significant reduction of $7.7dB$. For complementary sequences, no SO process is needed because the PAPR value of 0.1% of the spread signal is only $10.8dB$ which is close to the optimized WH spread signal. With SCR, the 0.1% PAPR value of modified signal is $8dB$ which is a $2.8dB$ reduction. Bear in mind that the SCR technique needs no extra randomizers, the $0.2dB$ loss,when comparing with the SLM technique is still acceptable. It will be shown later that for full-loaded systems, our technique has almost the same performance as SLM technique.

Full-loaded MC-CDMA downlink system scenario is considered in figure 6. Optimization is not used because the PAPR performance of WH and CS codes are fairly good in full-loaded system as shown in figure 3. Figure 6 clearly indicates that for 128 subcarriers MC-CDMA system, 0.1% unmodified signals spread by WH/CS codes have a PAPR value of $10.5dB/10.8dB$. By shuffling 32 spreading codes cyclically between the users, the PAPR is reduced to $7.3dB$ for WH codes, which is a reduction of $3.2dB$. For complementary sequences the reduction is 3.4dB. Similar reduction performance can be observed in the case of 512 subcarriers.

In figure 7, full-loaded MC-CDMA system with different number of shuffles (N_s) is considered. The number of carriers is fixed at 128 for the group of dashed lines and the number of cyclic shuffles is varied among 8, 16 and 32. It is shown that 0.1% of the modified symbols have PAPRs of 7.3dB, 7.5dB and 7.9dB for $N_s = 8$, 16 and 32 respectively. Same

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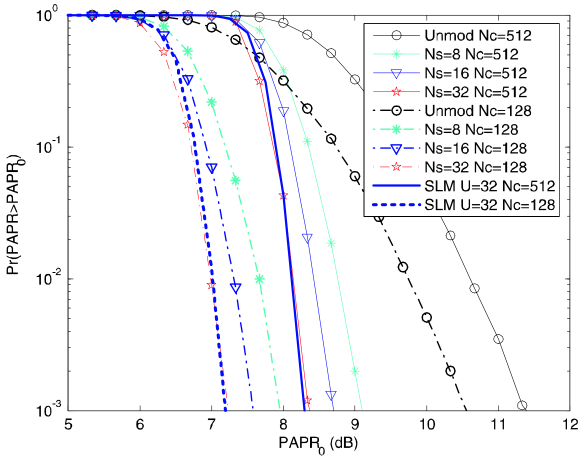

Fig. 7. PAPR performance of full-loaded 32 users and 128/512 carriers downlink MC-CDMA with SCR Ns=8/16/32.

simulation is performed to MC-CDMA downlink system with 512 carriers and shown with the group of real lines. When comparing with the traditional SLM technique using same amount of randomizing process, the performance of both techniques are almost identical.

V. CONCLUSION

This paper proposed a new spreading code reallocation PAPR reduction technique for MC-CDMA system. This technique utilizes the order of spreading codes to minimize the systems PAPR without the need of extra randomizers and therefore achieves much lower complexity than the traditional SLM technique. The problem of high PAPR factor raised by WH codes in lightly loaded system is solved by using an optimizing sequence. With the proposed technique, significant PAPR reduction can be achieved for both light-loaded and full-loaded MC-CDMA systems with only a slight complexity increase in the base station but hardly any complexity increase to the mobile terminals.

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