PEAK-TO-AVERAGE POWER-RATIO REDUCTION VIA CHANNEL HOPPING FOR DOWNLINK CDMA SYSTEMS

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ABSTRACT

The effect of Walsh code assignment and data correlation on the peak-to-average power-ratio (PAPR) of a downlink CDMA signal is investigated. A PAPR-reduction algorithm is proposed using data reversal and channel hopping. Simulations show that improved PAPR reduction and bit-error rate performance can be achieved by the proposed algorithm.

1. INTRODUCTION

In the field of personal communications, high data-rate wireless applications have attracted a great deal of attention, and one of these applications is code-division multiple-access (CDMA). It is well known that the capacity of a CDMA system is limited by multiple-access interference (MAI). Since the peak-to-average po-wer-ratio (PAPR) of the transmit signal in CDMA systems is usually quite high, the signal may be distorted if the transmitter contains nonlinear components such as power amplifiers (PAs). As a result, nonlinear distortion becomes another interference source that further degrades system performance. In order to mitigate the nonlinear distortion, the PAs can be operated with a large backoff but such operation makes the PAs inefficient. Recently, several algorithms for the reduction of nonlinear distortion for downlink CDMA systems have been proposed [1]-[3]. In [1][2], Walsh code selection algorithms to reduce the PAPR of the transmit signal were described, but the effects of data correlation on PAPR were not considered. In [3], an algorithm using deliberate data reversal to reduce the power variance of the transmit signal at the cost of bit-error rate (BER) performance degradation was reported. In this paper, we propose a new PAPR reduction algorithm based on data reversal and channel hopping for downlink CDMA systems. Computer simulations demonstrate that considerable improvement in PAPR reduction as well as BER performance can be achieved.

2. WALSH CODE BASICS

The $N \times N$ Hadamard matrix can be generated recursively as follows:

$$\mathbf{H}_1 = [1]; \quad \mathbf{H}_N = \begin{bmatrix} \mathbf{H}_{N/2} & \mathbf{H}_{N/2} \\ \mathbf{H}_{N/2} & -\mathbf{H}_{N/2} \end{bmatrix} \quad \text{for } N \geq 2. \tag{1}$$

The Walsh code $\mathbf{W}_i$ $(0 < i < N-1)$ of length N is obtained as the $(i+1)$th row of $\mathbf{H}_N$, and subscript i will be used as the index of Walsh code $\mathbf{W}_i$. Several useful properties of the Walsh code are listed below.

Property 1 The component-wise product of two Walsh codes of the same length is also a Walsh code. For example, if $\mathbf{W}_i$ and $\mathbf{W}_j$ are both Walsh codes of length N, then $\mathbf{W}_{<i,j>} = \mathbf{W}_i \cdot \mathbf{W}_j$ forms a new Walsh code of length N.

Property 2 For a given Walsh code $\mathbf{W}_i = [\mathbf{W}_i(0 : N/2-1)\ \mathbf{W}_i(N/2 : N-1)]$, the component-wise product of $\mathbf{W}_i$ and $\mathbf{W}_{N/2}$ can be expressed as $\mathbf{W}_{<i,N/2>} = [\mathbf{W}_i(0 : N/2-1)\ -\mathbf{W}_i(N/2 : N-1)]$.

Property 3 Walsh codes with indices of 2^k, especially for $k \geq 3$, have a large runlength, where the runlength is the maximum number of continuous 1's or -1's in the codeword.

3. SYSTEM DESCRIPTION

In this section, the models of a nonlinear PA and the downlink CDMA transmitter are briefly described.

3.1. Nonlinear PA model

A memoryless model for a nonlinear PA is described in [4] where only amplitude-modulation/amplitude-modulation (AM/AM) conversion is considered. The input-output relationship is given by

$$A(X) = \frac{X}{[1 + X^{2p}]^{1/2p}} \tag{2}$$

where $A(X)$ and X represent the amplitude of the output and input signals, respectively. Parameter p in (2) is a positive number to control the smoothness of the nonlinear curve, and a good approximation of a solid-state PA can be obtained by selecting p in the range 2 to 3. The nonlinear characteristic for various values of p is illustrated in Fig. 1.

3.2. Transmitter model

The generation of a downlink CDMA signal is illustrated in Fig. 2. For the kth user, the traffic bits are modulated using quatrature phase-shift modulation (QPSK), where $d_k^I(n)$ and $d_k^Q(n)$ represent the nth traffic bit in inphase (I) and qudrature (Q) branch, respectively. After being scaled by the power-control factor G_k, the QPSK-modulated symbol is spread by an assigned Walsh code $\mathbf{W}_k$. The spread signals for different users are combined before being multiplied by the chip-rate complex scrambling sequence $\mathbf{P}_n$, namely, $\mathbf{P}_n^I + j\mathbf{P}_n^Q$. The scrambled signal is then passed through a root raised-cosine rolloff filter, with impulse response $h(t)$. Owing to the band-limited property of the channel, the pulse width of $h(t)$ would span over several chip intervals. At the last stage, the output of the filter is fed into the

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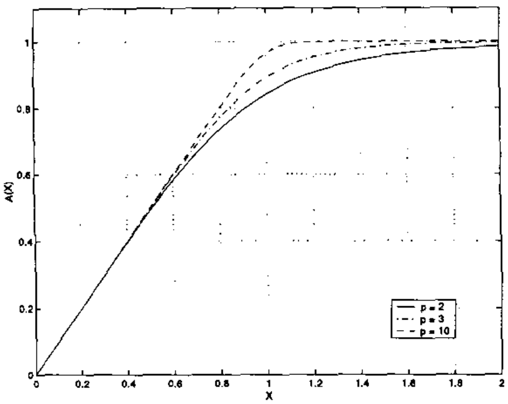

Figure 1: Nonlinear characteristic of a PA for various values of p.

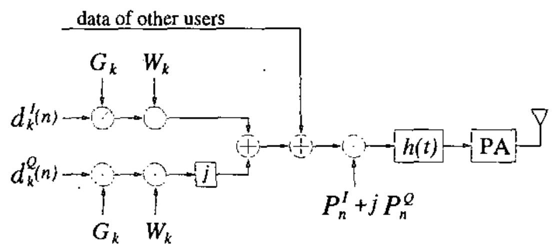

Figure 2: Configuration of transmitter at the base station.

power amplifier.

For convenience, waveforms are represented only for a symbol period T_s and the subscript/index n will be ommitted hereafter. The transmit CDMA signal $s(t)$ can be expressed as

$$s(t) = \sum_{l=1}^{L}\sum_{k=1}^{N_u} G_k \mathbf{W}_k(l) d_k \mathbf{P}(l) h(t - lT_c) \tag{3}$$

where T_c is the chip duration, L is the number of chips per symbol duration, N_u is the number of active users in the system, $W_k(l)$ represents the lth chip of Walsh code $\mathbf{W}_k$, and the complex data symbol d_k and scramble sequence $\mathbf{P}(l)$ are given by

$$d_k = d_k^I + j d_k^Q \tag{4}$$

and

$$\mathbf{P}(l) = \mathbf{P}^I(l) + j\mathbf{P}^Q(l). \tag{5}$$

respectively. For simplicity, (3) is expressed as

$$s(t) = I(t) + jQ(t) \tag{6}$$

where

$$I(t) = \sum_{l=1}^{L}\sum_{k=1}^{N_u} G_k \mathbf{W}_k(l) \mathrm{Re}\left[d_k^I \mathbf{P}(l)\right] h(t - lT_c) \tag{7}$$

$$Q(t) = \sum_{l=1}^{L}\sum_{k=1}^{N_u} G_k \mathbf{W}_k(l) \mathrm{Im}\left[d_k^I \mathbf{P}(l)\right] h(t - lT_c). \tag{8}$$

Functions $\mathrm{Re}\,[\cdot]$ and $\mathrm{Im}\,[\cdot]$ in (7) and (8) represent the real and imaginary components of the signal, respectively.

4. DEPENDENCE OF PAPR ON WALSH CODE SELECTION AND DATA CORRELATION

Generally, the PAPR of a transmit signal is defined as the ratio of its peak and average power. If we denote the envelope of the transmit signal $s(t)$ as $E(t)$, then the PAPR of signal $s(t)$ is defined as

$$\mathrm{PAPR}\,[s(t)] = \frac{\max\left[E^2(t)\right]}{\mathcal{E}\left[E^2(t)\right]} \tag{9}$$

where $\max\,[\cdot]$ and $\mathcal{E}\,[\cdot]$ denote maximum and expectation, respectively. From Eqs. (3)-(8), we have

$$\begin{aligned} E^2(t) &= I^2(t) + Q^2(t) \\ &= \sum_{l_1,l_2}\sum_{k_1,k_2} \{G_{k_1} G_{k_2} W_{k_1}(l_1) W_{k_2}(l_2) \mathrm{Re}\,[d_{k_1}\mathbf{P}(l_1)] \\ &\quad \cdot \mathrm{Re}\,[d_{k_2}\mathbf{P}(l_2)]\, h(t - l_1T_c) h(t - l_2T_c)\} \\ &\quad + \sum_{l_1,l_2}\sum_{k_1,k_2} \{G_{k_1} G_{k_2} W_{k_1}(l_1) W_{k_2}(l_2) \mathrm{Im}\,[d_{k_1}\mathbf{P}(l_1)] \\ &\quad \cdot \mathrm{Im}\,[d_{k_2}\mathbf{P}(l_2)]\, h(t - l_1T_c) h(t - l_2T_c)\} \end{aligned} \tag{10}$$

Eq. (10) can be further simplified as

$$E^2(t) = E_1 + E_2 \tag{11}$$

where

$$\begin{aligned} E_1 &= \sum_{k_1,k_2} 2G_{k_1} G_{k_2} \left[d_{k_1}^I d_{k_2}^I + d_{k_1}^Q d_{k_2}^Q\right] \\ &\quad \cdot \sum_{l} W_{<k_1,k_2>}(l) [h(t - lT_c)]^2 \end{aligned} \tag{12}$$

and

$$\begin{aligned} E_2 &= \sum_{l_1 \neq l_2}\sum_{k_1,k_2} \{G_{k_1} G_{k_2} W_{k_1}(l_1) W_{k_2}(l_2) \mathrm{Re}\,[d_{k_1}\mathbf{P}(l_1)] \\ &\quad \cdot \mathrm{Re}\,[d_{k_2}\mathbf{P}(l_2)]\, h(t - l_1T_c) h(t - l_2T_c)\} \\ &\quad + \sum_{l_1 \neq l_2}\sum_{k_1,k_2} G_{k_1} G_{k_2} W_{k_1}(l_1) W_{k_2}(l_2) \mathrm{Im}\,[d_{k_1}\mathbf{P}(l_1)] \\ &\quad \cdot \mathrm{Im}\,[d_{k_2}\mathbf{P}(l_2)]\, h(t - l_1T_c) h(t - l_2T_c) \end{aligned} \tag{13}$$

Therefore, Eq. (9) can be express as

$$\mathrm{PAPR}_0 = \frac{\max\left[E_1 + E_2\right]}{\mathcal{E}\left[E^2(t)\right]} \tag{14}$$

From (14) it follows that in order to reduce the PAPR of the transmit signal, the peak value of $E_1 + E_2$ must be reduced. As can be seen from (13), the value of E_2 is randomly distributed due to the complex scrambling code $\mathbf{P}$. Therefore, E_1 dominates the value of $E_1 + E_2$. From Eq. (10), it can be observed that the peak value of E_1 depends on two factors. First, its peak value depends on the product of each pair of assigned Walsh codes. If the runlength of $W_{<k_1,k_2>}$

is large, then the peak value of E_1 can be large since the pulse width of $h(t)$ spans over several chips. If the product of the power-control factors G_{k_1} and G_{k_2} is large, then the peak value of E_1 can be large. Second, if vectors $\left[d_{k_1}^I\ d_{k_1}^Q\right]$ and $\left[d_{k_2}^I\ d_{k_2}^Q\right]$ are correlated, then the peak value of E_1 may be large. In the next section, a PAPR-reduction algorithm is proposed based on these observations.

5. PAPR-REDUCTION ALGORITHM

First, we follow [1] to determine the Walsh code allocation. At the base station (BS), the whole Walsh code space is divided into 8 bins, i.e., $V_1, V_2, \cdots, V_8$. A Walsh code falls into bin V_i if its index modulo by 8 is equal to i. At the stage of call origination, the BS counts the number of assigned Walsh codes in each bin and an available Walsh code in the lowest bin will be allocated to the new user. In this way, the occurrence of a $W_{<k_1,k_2>}$ with large runlength is reduced. Next, the correlation between the data of users in the same bin is considered. If users k_1 and k_2 are in the same bin and vectors $\left[d_{k_1}^I\ d_{k_1}^Q\right]$ and $\left[d_{k_2}^I\ d_{k_2}^Q\right]$ are correlated, then the sign of $d_{k_2}^Q$ is reversed. Such operation makes vectors $\left[d_{k_1}^I\ d_{k_1}^Q\right]$ and $\left[d_{k_2}^I\ -d_{k_2}^Q\right]$ uncorrelated and the peak value of E_1 is reduced. However, this deliberate data reversal can cause detection error if no proper scheme is adopted at the receiver. To avoid such error, a channel hopping scheme can be applied. When data reversal occurs for user k_2, the Walsh code associated with user k_2 will hop from W_{k_2} to $W_{k_2+N/2}$, which does not change the bin distribution. At the mobile station (MS), the received signal is passed through the root raised-cosine rolloff filter, and then descrambled, as shown in Fig. 3. Next, the chip-rate signal is demodulated using both of the assigned Walsh codes W_{k_2} and $W_{k_2+N/2}$, and the output signals of correlators are denoted as $r_{k_2}^{I(Q)}$ and $r_{N/2+k_2}^{I(Q)}$. Based on this knowledge, a hard decision can be made using the following criterion.

$$
\begin{aligned}
\text{If } |r_{k_2}^I| > |r_{N/2+k_2}^I|, \text{ then } d_{k_2}^I &= \text{sign}(r_{k_2}^I);\\
\text{else } d_{k_2}^I &= \text{sign}(r_{N/2+k_2}^I);\\
\text{If } |r_{k_2}^Q| > |r_{N/2+k_2}^Q|, \text{ then } d_{k_2}^Q &= \text{sign}(r_{k_2}^Q);\\
\text{else } d_{k_2}^Q &= \text{sign}(-r_{N/2+k_2}^Q);
\end{aligned}
$$

where sign($\cdot$) represents the sign function. In particular, if $r_{N/2+k_2}^{I(Q)}$ has more power, the sign of $r_{N/2+k_2}^Q$ is reversed before final decision and, therefore, the potential detection error caused by the deliberate data reversal is avoided.

The complexity of the above algorithm seems to be quite high since the MS must demodulate two Walsh channels simultaneously. In practice, the demodulation procedure can be simplified as shown in Fig. 4. After descrambling, the chip-rate signal is demodulated using only Walsh code. The correlations of the descrambled signal and W_{k_2} in the time intervals $[0, T_s/2]$ and $[T_s/2, T_s]$ are performed and the output signals are denoted as $r_{k_2,1}^{I(Q)}$ and $r_{k_2,2}^{I(Q)}$, respectively. Based on *Property 2* of the Walsh code, it can be seen that the correlator output signals for channels W_{k_2} and $W_{k_2+N/2}$ can be obtained as $r_{k_2}^{I(Q)} = r_{k_2,1}^{I(Q)} + r_{k_2,2}^{I(Q)}$ and $r_{N/2+k_2}^{I(Q)} = r_{k_2}^{I(Q)}(1) - r_{k_2}^{I(Q)}(2)$, respectively. Thus, demodulation of two Walsh channels at MS is avoided. Compared with the receiver structure in Fig. 3, the complexity of the receiver in Fig. 4 is dramatically reduced.

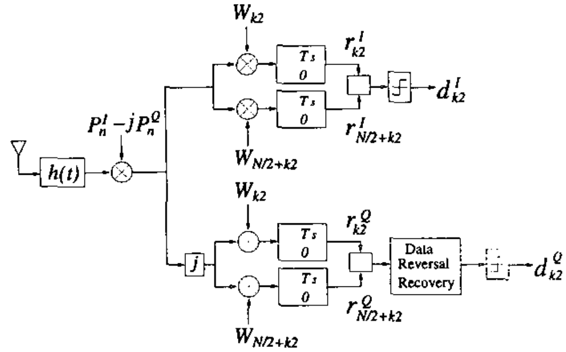

Figure 3: Structure of receiver at the mobile station.

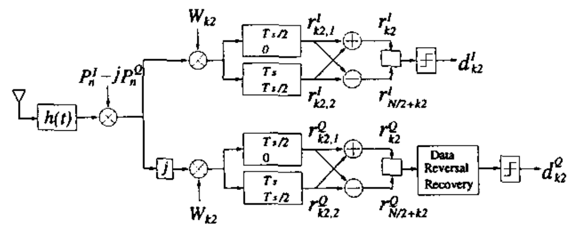

Figure 4: Simplified structure of receiver at the mobile station.

6. SIMULATIONS

Simulations were carried out for a downlink CDMA system with 14 active users in which Walsh codes 0, 1, and 32 were assigned to the pilot, paging, and sync channels, respectively. The power-control factors for the pilot, paging, and sync channels were set to 1, and that of each traffic channel was set to 0.8. Two different bin configurations for active users were considered with Walsh code indices $\mathcal{I}_1 = \{4, 8, 12, 16, 20, 24, 28, 36, 40, 44, 48, 52, 56, 60\}$ and $\mathcal{I}_2 = \{2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15\}$. Note that configuration 2 had a more balanced distribution than configuration 1. The rolloff factor of the square-root raised-consine filter was chosen as 0.22 and the pulse width of its impulse response spanned 12 chip intervals. The long PN sequence was a randomly generated code with length 2^{41}. The proposed algorithm was applied to the case of configuration $\mathcal{I}_2$, and the complementary cumulative distribution function (CCDF) of the PAPR of the transmit signal is plotted as a solid line in Fig. 4. For comparison purposes, the CCDFs of the PAPRs of the transmit signals using configurations $\mathcal{I}_1$ and $\mathcal{I}_2$ are plotted in the same figure as dash-dot and dashed lines, respectively. It can be observed that at the clipping level of 10^{-6}, the PAPR of the transmit signal using the proposed algorithm is 1.4 dB and 1.7 dB less than that with configurations 2 and 1, respectively.

The BER performance of the CDMA system using the proposed algorithm was evaluated in an additive white Guassian noise (AWGN) channel. In the simulations, the nonlinear PA had the characteristic shown in Fig. 1 with $p = 3$. The BER performance achieved is plotted in Fig. 5 as a solid line. The BER performance of the systems with configurations 2 and 1 is plotted in the same figure with

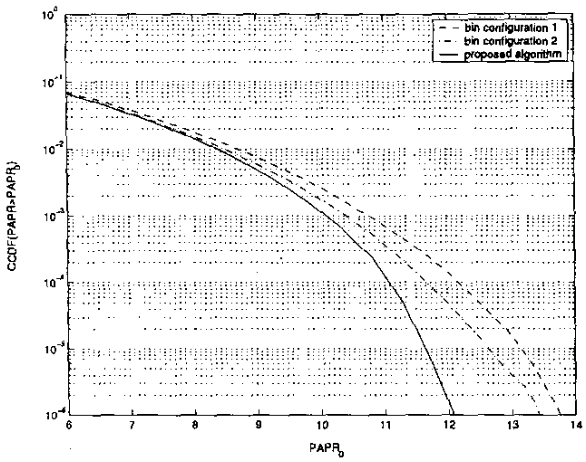

Figure 5: CCDFs for PAPRs of transmit signals for various configurations.

dash-dot and dashed lines, respectively, as reference. As can be seen from the figure, in the range of high SNR, the BER performance of the system using the proposed algorithm is better than that of the systems with configurations 2 and 1. For example, at the level of BER $= 10^{-6}$, the SNR required by the proposed algorithm is 1 dB and 1.5 dB less than that required by configurations 2 and 1, respectively. On the other hand, in the range of low SNR, the BER performance of these systems is comparable. The performance degradation of the proposed algorithm for low SNR is due to the fact that AWGN dominates the nonlinear distortion when the SNR is low.

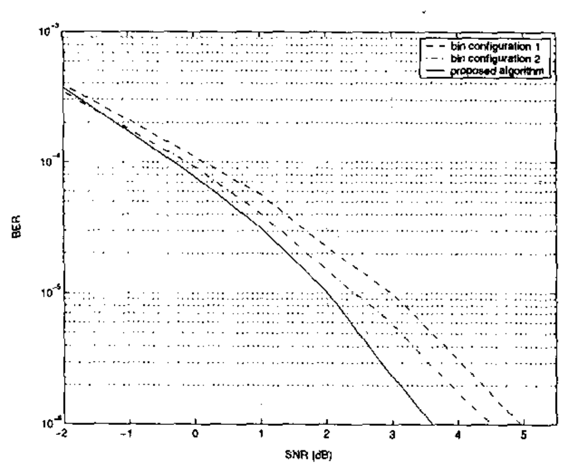

Figure 6: Comparison of BER performance for various system configurations.

7. CONCLUSIONS

The effect of Walsh code assignment and data correlation on the PAPR of the downlink CDMA signal has been investigated. Based on our analysis, a new PAPR-reduction algorithm using data reversal and channel hopping has been proposed. Simulations show that at the clipping level of 10^{-6}, approximately 1.4 dB improvement can be achieved by the proposed PAPR-reduction algorithm. The system performance of the CDMA system in term of bit-error-rate was evaluated in an AWGN channel. It is observed that at the level of BER $= 10^{-6}$, the SNR required by the proposed algorithm is approximately 1 dB less than that required by the algorithm in [1].

ACKNOWLEDGEMENT

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