CHIP-INTERLEAVED WCDMA WITH PARALLEL-INTERFERENCE-CANCELLATION RECEIVER IN MULTIPATH RAYLEIGH FADING CHANNELS

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ABSTRACT

Multiple access interference (MAI) is a major limiting factor of DS-CDMA system capacity. Parallel interference cancellation (PIC) is an effective means to mitigate MAI. However, if the initial decisions of which PIC is based on have high error probabilities, then PIC cannot perform well. To improve the performance of PIC, we propose chip-interleaving to provide intra-bit diversity. Then the initial decisions can be more accurate so as to enhance the PIC's performance. We design a chip-interleaving scheme based on some 3GPP WCDMA system features, such as the use of the Q-branch to transmit control bits and the I-branch to transmit data bits in a QPSK-like modulation scheme. Simulation results show that the proposed chip-interleaved WCDMA (CI-WCDMA) transmission can have significant performance advantage compared to simple WCDMA in transmission over fading multipath channels with MAI.

1. INTRODUCTION

Direct-sequence code division multiple access (DS-CDMA) has been employed in the second- and the third-generation mobile communication systems, and it has been envisioned for use in other contexts as well. Since it is hard to maintain orthogonality among simultaneously transmitting user signals, multiple access interference (MAI) has been a limiting factor to the capacity of DS-CDMA systems. Various multiuser detection (MUD) technologies have been proposed. Among them parallel interference cacellation (PIC) [1], [2] is an efficient yet practical choice due to its lower complexity. However, the performance of PIC is highly dependent on the correctness of tentative decisions in previous stages. In the transmission over fading channels, the decision signals may fluctuate enormously in magnitude, which hampers the interference cancellation capability of PIC.

Bit-interleaving is a common way to remedy channel fading in a channel coded system. However, most MUDs including PIC perform interference cancellation before channel decoding, for otherwise the complexity becomes overwhelming. In this case, the inter-bit diversity provided by bit-interleaving provides no help to the MUDs. Chip-interleaved DS-CDMA (CI-CDMA), which spreads out the chips of each single bit, has been proposed by several research groups recently. And some discussions of its performance in fading channels can be found in [3], [4]. Due to the resulting intra-bit diversity, chip-interleaving should provide great help to the performance of PIC.

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The wideband code division multiple access (WCDMA) wireless communication standard completed recently by the Third Generation Partnership Project (3GPP) is now entering the stage of commercial operation. Based on some features of 3GPP WCDMA, we propose a chip-interleaved WCDMA (CI-WCDMA) technique in this paper and examine its transmission performance in multipath Rayleigh fading channels both with and without use of PIC.

This paper is organized as follows. Section 2 describes the CI-WCDMA signals. Two receiving strategies, including a rake-like receiver and a PIC receiver, are discussed in Sec. 3. Some simulation results are presented in Sec. 4. They demonstrate the effectiveness of the proposed scheme in addressing the MAI. Finally, Sec. 5 is the conclusion.

2. CI-WCDMA SIGNALING

In a chip-interleaved DS-CDMA system, bits are first spread as in conventional DS-CDMA and are then transmitted with interleaved chips. Consider the spreading and modulation method defined in the FDD mode of 3GPP WCDMA [5]. Figure 1 shows the proposed CI-WCDMA signaling scheme. As in WCDMA system, the data and control bits are first spread by channelization codes and carried in I- and Q-branches, respectively. A scrambling code is applied after block interleaving of the complex output chips. Let M be the interleaving depth in number of data bits and N the spreading factor of each data bit. Then we have NM chips in one interleaving block. The interleaving output forms N chip-blocks, with M chips per chip-block, for each interleaving block. With this chip-interleaver, we send the chips of each data bit in different chip-blocks and hence increase the intra-bit diveristy. The control channel always uses 256 as the spreading factor and therefore $R = 256/N$ is the spreading factor ratio of data channel to control channel. And each interleaving block contains M/R control bits in addition to M data bits.

Consider one interleaving block. The transmitted signal by the kth user can be expressed as

$$\begin{aligned} s^{(k)}(t) \quad = \quad & \sum_{n=0}^{N-1}\sum_{m=0}^{M-1} \Big[\Big(b_d^{(k)}[m]C_I[n] \\ & + j\beta^{(k)} \cdot b_c^{(k)}[\lfloor \frac{m}{R} \rfloor]C_Q[(mN+n)\%256]\Big) \\ & \cdot c_s^{(k)}[nM+m]p(t-(nM+m)T_c)\Big]\,, \qquad (1) \end{aligned}$$

where $b_d^{(k)}[m]$ and $b_c^{(k)}[m]$ denote the mth data and control bits for the user, respectively, $C_I[n]$ and $C_Q[n]$ are the orthogonal

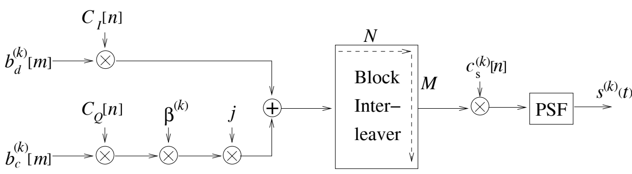

Fig. 1. The proposed CI-WCDMA signaling scheme.

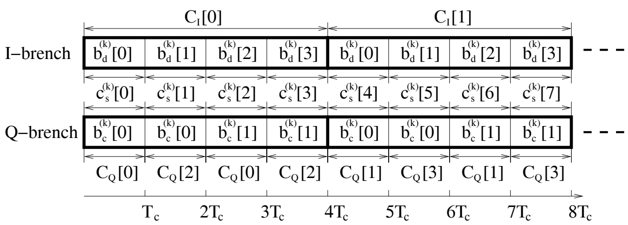

Fig. 2. An example of CI-WCDMA signal.

channelization codes for the data and the control channel, respectively, $c_s^{(k)}[n]$ is the scrambling code, T_c is the chip period, $p(t)$ is a square pulse of chip duration that is normalized so that $\int_0^{T_c} p^2(t)dt = 1$, and $\%$ denotes the modulo operation. The weighting factor $\beta^{(k)}$ usually should be less than 1 for power efficiency. The channelization codes are Walsh-Hadamard sequences and the scrambling code is a pseudo-random sequence with much longer period than the spreading factor. Figure 2 gives a illustrative example of the CI-WCDMA signal with $M = 4$ and $N = 2$, where each thick rectangle marks a chip-block.

In an asynchronous system, transmission over a multipath fading channel results in a received signal as

$$r(t) = \sqrt{2P}\sum_{k=0}^{K-1}\left\{\sum_{l=0}^{L-1}\alpha_l^{(k)}(t)s_k(t-\tau_k T_c - lT_c)\right\} + \eta(t), \tag{2}$$

where $\sqrt{2P}$ is the normalized signal amplitude of each user, K is the number of users in the system, L is the number of multipaths of each user, $\tau_k T_c$ is the relative signaling delay of the kth user, $\eta(t)$ is the additive noise (assumed white Gaussian), and $\alpha_l^{(k)}(t)$ are time-varying channel coefficients which, under a Rayleigh fading assumption, are zero-mean, complex-valued Gaussian random variables. In additon, let $\sum_{l=0}^{L-1} E\{|\alpha_l^{(k)}(t)|^2\} = 1$ for all k so that no user is at a disadvantaged position. Thus, we are considering a perfect slow power-controlled systems.

3. RECEVING OF CI-WCDMA SIGNALS

3.1. Rake-like Receiver

A PIC receiver is usually built on a rake receiver. Like in conventional DS-CDMA, a rake-type receiver which can provide multipath diversity is also an efficient receiver structure for CI-WCDMA signals. Figure 3 shows such a receiver, where z^{-M} denotes delay by M chips. Channel estimation is performed before chip deinterleaving using the control bits transmitted in the Q-branch. If the channel remains constant during each chip-block but varies independently randomly between chip-blocks, then with known control bits (pilot bits in 3GPP WCDMA language) and known channelization code, the maximum likelihood estimate of the channel coefficient in Gaussian noise and interference for each chip-block is the normalized correlation between the input signal samples and the product of the control bits and the channelization code in the chip-block. This is what shown in Fig. 3. Practical fading channels usually behave differently from the above and usually are not independent from chip-block to chip-block, and accordingly samples from several chip-blocks can be combined in a more complicated way to achieve better channel estimation. But such is not considered in the present work.

Without loss of generality, consider the detection of user 0's signal. After matched filtering and descrambling, the input signal to the lth finger of the rake-like receiver is given by

$$s_l^{(0)}[n] = c_s^{*(0)}[n]\cdot\int_{(n+\tau_0+l)T_c}^{(n+\tau_0+l+1)T_c} r(t)\cdot p(t-(n+\tau_0+l)T_c)dt. \tag{3}$$

The control bits $b_c^{(0)}[m]$ in 3GPP WCDMA may include pilot bits, power control bits and other control bits. In the following discussion, we treat them as only consisting of pilot bits (that is, all bits are known). The results can be easily extended to other situations. To estimate the channel coefficient of the lth path during the n_dth chip-block, we therefore calculate

$$\begin{aligned}\hat{\alpha}_l^{(0)}[n_d] &= \frac{1}{j2M\beta^{(0)}}\sum_{m=0}^{M-1}\Big(s_l^{(0)}[n_dM+m] \\ &\qquad \cdot b_c^{(0)}[\lfloor\frac{m}{R}\rfloor]C_Q[(mN+n_d)\%256]\Big) \\ &= \sqrt{2P}\cdot\alpha^{(0)}[n_d] + \sum_{l'\neq l}^{L-1}\zeta_{l,l'}^{(0)}[n_d] \\ &\quad + \sum_{k=1}^{K-1}\sum_{l'=0}^{L-1}\zeta_{l,l'}^{(k)}[n_d] + \hat{\eta}_l[n_d],\end{aligned} \tag{4}$$

where $\hat{\eta}_l[n_d]$ summarizes the effect of the AWGN (additive white Gaussian noise), and $\zeta_{l,l'}^{(k)}$ is the interference from user k's l'th path to the estimation of user 0's lth path coefficient. Thus, the second and third terms in (4) are the interpath interference (IPI) and MAI, respectively. It can also be shown that for channel estimation, the "processing gain" provided by chip-interleaving in reducing the effect of IPI and MAI is M. Therefore, a larger interleaving depth increases the robustness of the channel estimate. But this is on the condition that the channel stays relatively constant over the chip-block. For fast fading channels a large M may not be beneficial.

Unlike channel estimation, data detection is performed after chip deinterleaving. Let $\hat{b}_d^{(0)}[m] = \text{sign}\{\Re\{y^{(0)}[m]\}\}$ be the decision for $b_d^{(0)}[m]$, we have the decision signal $y^{(0)}[m]$ as

$$\begin{aligned}y^{(0)}[m] &= \sum_{l=0}^{L-1}\sum_{n_d=0}^{N-1}\left\{s_l^{(0)}[n_dM+m]\left(\hat{\alpha}_l^{*(0)}[n_d]C_I[n_d]\right)\right\} \\ &= 2P\cdot b_d^{(0)}[m]\cdot\left(\sum_{l=0}^{L-1}\sum_{n_d=0}^{N-1}2\cdot\hat{\alpha}_l^{*(0)}[n_d]\alpha_l^{(0)}[n_d]\right) \\ &\quad + \sum_{l=0}^{L-1}\sum_{l'\neq l}^{L-1}\xi_{l,l'}^{(0)}[m] + \sum_{l=0}^{L-1}\sum_{k=1}^{K-1}\sum_{l'=0}^{L-1}\xi_{l,l'}^{(k)}[m] \\ &\quad + \hat{\eta}^{(0)}[m],\end{aligned} \tag{5}$$

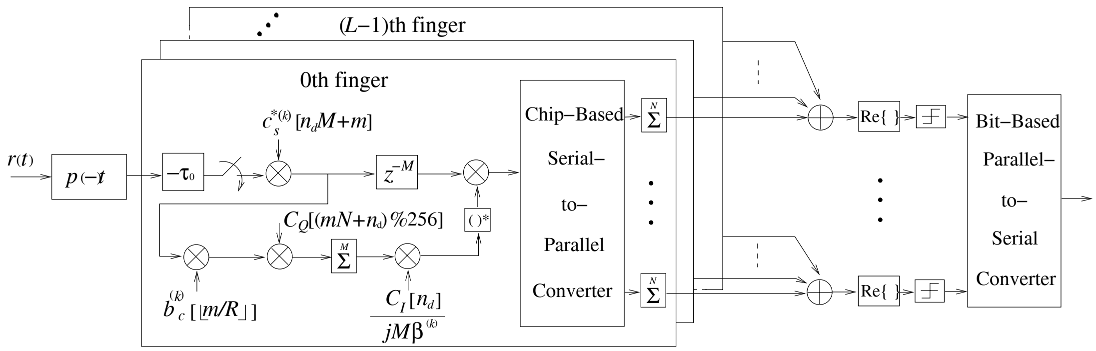

Fig. 3. A rake-like receiver for CI-WCDMA signals.

where $\xi_{l,l'}^{(k)}[m]$ has a similar interpretation as $\zeta_{l,l'}^{(k)}[m]$ but the processing gain here is $2N$. By (5), it is clear that the decision signal is the combination of NL independently faded coefficients $\alpha_l^{(0)}[n_d]$. Thus, there is an intra-bit diversity of order NL in CI-WCDMA systems.

3.2. PIC Detector

The basic idea behind PIC is quite simple: regenerate the interference to all received user signals from all others and substract such interference from the received signals simultaneously. For simplicity, only wideband hard-decision PIC is described here. In the first stage of PIC, the regenerated received signal of user k can be written as

$$\hat{r}^{(k)}(t) = \sum_{l=0}^{L-1} \hat{\alpha}_l^{(k)} \hat{s}^{(k)}(t - \tau_k T_c - lT_c), \tag{6}$$

where $\hat{s}^{(k)}(t)$ has the same expression as (1) except that $b_d^{(k)}[m]$ is replaced by $\hat{b}_d^{(k)}[m]$. Then for user 0, we pass the following signal again to the rake-like receiver: $r(t) - \sum_{k=1}^{K-1} \hat{r}^{(k)}(t)$. Subsequent PIC stages regenerate $\hat{s}^{(k)}(t)$ and $\hat{r}^{(k)}(t)$ using the respectively previous stages' output in a similar fashion, in hope that better detection results can be obtained with more repetitions.

Evidently, the correctness of the tentative decisions $\hat{b}_d^{(k)}[m]$ will affect the PIC performance greatly. With chip-interleaving, the output of rake receiver is more resistant to channel fading effects and hence the regenerated signals are more correct. An alternative to wideband PIC is narrowband PIC, which does not regenerate the received signals but the resultant interference in the despread signals directly [2]. That is, $\xi_{l,l'}[m]$ is regenerated and substracted from $y^{(0)}[m]$. Narrowband PIC has exactly the same performance as wideband PIC but with lower complexity especially when the spreading factor is high. Variants of these basic PIC schemes also exist. No matter what the kind of PIC is performed, CI-WCDMA can always help the interference cancellation ability.

4. SIMULATION RESULTS

We compare the performance of CI-WCDMA and nonchip-interleaved WCDMA by computer simulation. Similar to the 3GPP WCDMA, we let the chip rate be 3.84 Mcps. The interleaving depth M is set arbitrarily to 2560. Therefore, there are 10 control bits in each chip-block. (As indicated previously and will be touched on again in a later paragraph, a good choice of M has something to do with the channel's coherence time.) Let the data spreading factor be $N = 32$ and SNR be 13 dB. For the channel, let the number of multipaths be $L = 4$. And we perform only one stage of PIC.

Consider first quasi-static (or slow fading) channels, where the path coefficients remain constant during a chip-block and vary independently randomly from block to block. Figures 4 and 5 show some performance results for rake and PIC receivers, respectively. Clearly, CI-WCDMA has much better performance than simple WCDMA in both cases and the difference is more pronounced with PIC-based reception. The influence of β is also included in these simulations. It is interesting to note that, in the case of rake reception, the performance with $\beta = 4/15$ is worse than that with $\beta = 1$. This is due to the fact that the control channels also interfere with the data channel and a larger β induces a larger interference although it can facilitate a more accurate channel estimation. With PIC, however, the converse is true because the increased interference from having a larger β can be dealt with by its interference cancellation capability.

Next, we consider a more practical channel condition. We generate correlated Rayleigh fading channels by the baseband Doppler filtering method [6]. The coherence time of a fading channel can be defined as $B_c = 0.423/f_d$ where f_d is the maximum Doppler shift. In 3GPP WCDMA parameters, if the carrier frequency is equal to 2 GHz and if the coherence time is equal to the chip-block length $M = 2560$, then the corresponding mobile velocity is $v = 340$ km/h. Let $\beta = 1$. The performance of PIC is shown in Fig. 6. Again, CI-WCDMA has much better detection results than WCDMA. Another observation is that although the fading channel with velocity $v = 240$ km/h should yield a larger diversity order, its performance is inferior to that with $v = 120$ km/h. This is reasonable because our way of channel coefficient estimation by simple correlation does not yield very accurate results in relatively fast fading.

Additionally, we consider a channel with unequal path energies, where the path energies show exponential decay and are equal to 0, -3, -6, and -9 dB, respectively. The results are shown in Fig. 7. The performance of CI-WCDMA in this channel is quite similar to that in the equal-energy channel, but the performance of WCDMA is worse. This is because the main diversity exploited in WCDMA is path diveristy and hence the diversity gain is reduced when the paths have larger energy disparity. For CI-WCDMA, there is an additional time diversity and it is more robust.

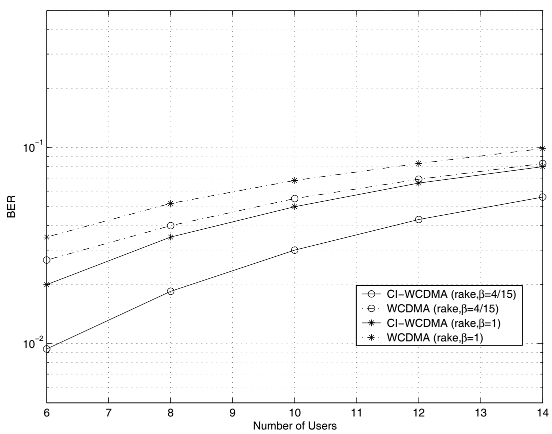

Fig. 4. Performance of rake receiver in multiple access communication over quasi-static channels for different systems and different choices of β with equal-energy multipaths.

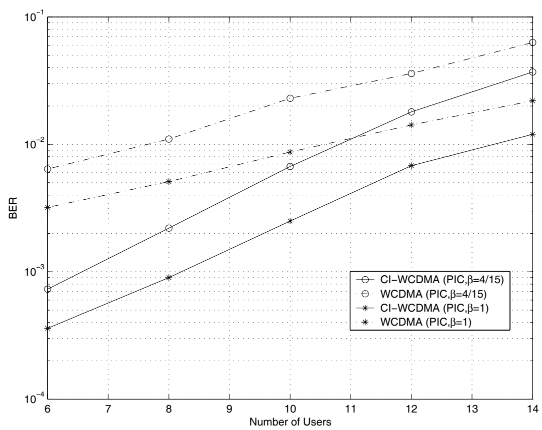

Fig. 5. Performance of PIC in multiple access communication over quasi-static channels for different systems and different choices of β with equal-energy multipaths.

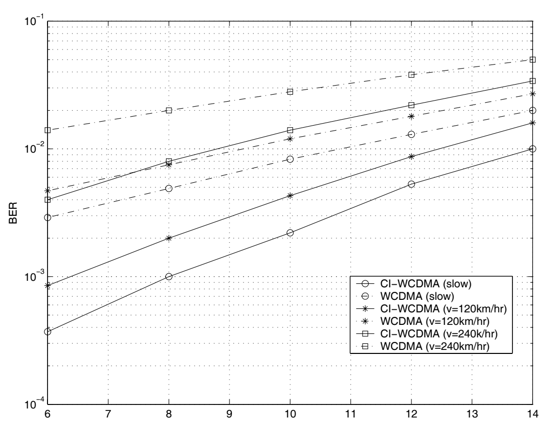

Fig. 6. Performance of PIC in multiple access communication over various fading channels for different systems with equal-energy multipaths.

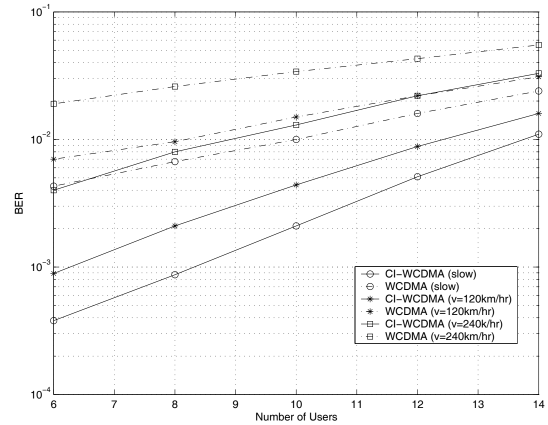

Fig. 7. Performance of PIC in multiple access communication over various fading channels for different systems with unequal-energy multipaths.

5. CONCLUSION

We proposed a chip-interleaved WCDMA (CI-WCDMA) transmission scheme and considered two ways of signal reception, namely, rake-like receiver and PIC. Due to the intra-bit diversity provided by chip-interleaving, CI-WCDMA is shown to have better performance than simple WCDMA in various conditions. The performance gain is especially significant with PIC reception. Essentially, the performance gain of CI-WCDMA comes from the increased time diversity due to chip-interleaving and, intuitively, more diversity is always beneficial to performance in multipath fading channels.

We have used a simple channel estimation scheme in the simulations. More sophisticated channel estimation methods should lead to even better performance of CI-WCDMA.

6. REFERENCES

[1] M. K. Varanasi and B. Aazhang, "Multistage detection in asynchronous code-division multiple-access communications," *IEEE Trans. Commun.*, vol. 38, pp. 509–519, Apr. 1990.

[2] A. Nahler, R. Irmer, and G. Fettweis, "Reduced and differential parallel interference cancellation for CDMA systems," *IEEE J. Select. Areas Commun.*, vol. 20, no. 2, pp. 237–247, Feb. 2002.

[3] P. Frenger, P. Orten, and T. Ottosson, "Coded-spread CDMA using maximum free distance low-rate convolutional codes," *IEEE Trans. Commun.*, vol. 48, no. 1, pp. 135–144, Jan. 2000.

[4] Y.-N. Lin and D. W. Lin, "Chip interleaving for performance improvement of coded DS-CDMA systems in Rayleigh fading channels," in *IEEE 58th Veh. Technol. Conf.*, Oct. 2003.

[5] 3GPP, *Technical Specification Group Radio Access Network; Spreading and Modulation (FDD)*. Doc. 3G TS 25.213 version 4.1.0, June 2001.

[6] T. S. Rappaport, *Wireless Communication: Principles and Practice, 2nd ed.* Upper Saddle River, NJ: Prentice-Hall, 2002.