Interleave-Division Multiple Access and Chip-by-Chip Iterative Multi-User Detection

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Abstract

This article outlines a multiple access scheme in which interleaving is the only means of user separation. As a special form of CDMA, the new scheme inherits many advantages of CDMA, such as dynamic channel sharing, mitigation of cross-cell interference, asynchronous transmission, ease of cell planning, and robustness against fading. Furthermore, it allows a low-cost interference cancellation technique applicable to systems with large numbers of users in multipath channels. Performance close to theoretical limits has been observed based on an unequal power control strategy.

Introduction

Direct-sequence code-division multiple access (DS-CDMA or simply CDMA) has been adopted in second- and third-generation cellular mobile standards. CDMA possesses many attractive features such as dynamic channel sharing, mitigation of cross-cell interference, asynchronous transmission, ease of cell planning, and robustness against fading.

In a CDMA system, many users share the same transmission media so that signals from different users are superimposed, causing the multiple access interference (MAI) problem. At the receiver side, it is necessary to separate the mixed signals. Multi-user detection (MUD) is a technique to improve performance by jointly processing the signals from all of the users [1, 2]. However, the complexity related to MUD has been a major concern for its practical application.

In this article we describe an interleave-division multiple access (IDMA) scheme in which interleavers are employed as the only means of user separation. As a special form of CDMA, IDMA inherits the advantages of CDMA mentioned earlier. Furthermore, it allows a low-complexity MUD technique applicable to systems with large numbers of users in multipath channels. Performance close to theoretical limits [3] has been observed based on an unequal power control strategy.

Background

MUD and Complexity Considerations

The use of signature sequences for user separation is a characteristic feature of conventional coded CDMA schemes [1, 2]. An illustrative CDMA scheme with K users is shown in Fig. 1. Let k be the user index. Each user k is assigned a unique signature sequence $\mathbf{s}_k$ (with length S). The elements in $\mathbf{s}_k$ are commonly called *chips*. Data from user k is first encoded by a rate-R binary forward error control (FEC) code followed by interleaving. Here interleaving is mainly to alleviate the fading effect. The spreader for user k then spreads a coded bit to a chip sequence (i.e., it transmits either $\mathbf{s}_k$ or $-\mathbf{s}_k$ to represent one bit). The spreading operation results in redundancy (and thus bandwidth expansion) since a single chip alone can carry one bit of information. The redundancy from spreading is introduced mainly to distinguish different users. From a coding theory point of view, however, this is not a good choice since it introduces redundancy without coding gain.[1] We return to this issue later.

MUD is a promising technique for the MAI problem mentioned above. A good tutorial on noniterative MUD can be found in [2]. Inspired by the success of turbo codes [4], iterative MUD has been extensively studied in recent years [5–8]. The principle of iterative MUD is illustrated in the lower part of Fig. 1. The received signal is first passed through K correlators based on K signature sequences. This provides coarse initial estimates. The turbo processor in Fig. 1 then resolves the residual cross-interference at the outputs of the correlators.

Two issues, FEC coding and MAI, must be considered here. Finding a joint optimal solution is usually computationally prohibitive. The turbo processor takes a suboptimal approach by decomposing the task into two parts. It involves an elementary multi-user detector (EMUD) and a bank of K decoders (DECs). The EMUD partially resolves MAI without considering FEC coding. The outputs of the EMUD are then passed to the DECs for further refinement using the FEC coding constraint. The DECs are based on the so-called soft-in soft-out principle [4–9], and their outputs are fed back to the EMUD to improve its estimates in the next iteration. This iterative procedure is repeated a preset number of times (or terminated if a certain stopping criterion is fulfilled). After the final iteration, the DECs produce hard decisions on the information bits.

In the turbo processor, each DEC handles the data for a particular user only and ignores the others. Therefore, the DEC complexity per user is independent of the user number K. The task of the EMUD, on the other hand, is to find a joint solution considering all users. The complexity involved (mainly for solving a size $K \times K$ correlation matrix) is $O(K^2)$ per user by the well-known iterative minimum mean square error (MMSE) technique [7]. This can be a serious concern when K is large. Hence, we focus on techniques to minimize the EMUD cost below.

Theoretical Considerations

Besides the cost issue, there is also a theoretical one. It is more difficult to achieve efficient information transmission in a multiple access channel than in a single-user channel, mainly due to the MAI problem. However, the discussions in [1, 3, 10] show that, at least theoretically, there is no penalty on spectral efficiency with CDMA even when MAI is considered. In [10] it is shown that channel capacity can be approached by

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[1] *Roughly speaking, coding gain refers to the reduction of the required* E_b/N_0 *to achieve the same performance as an uncoded scheme.*

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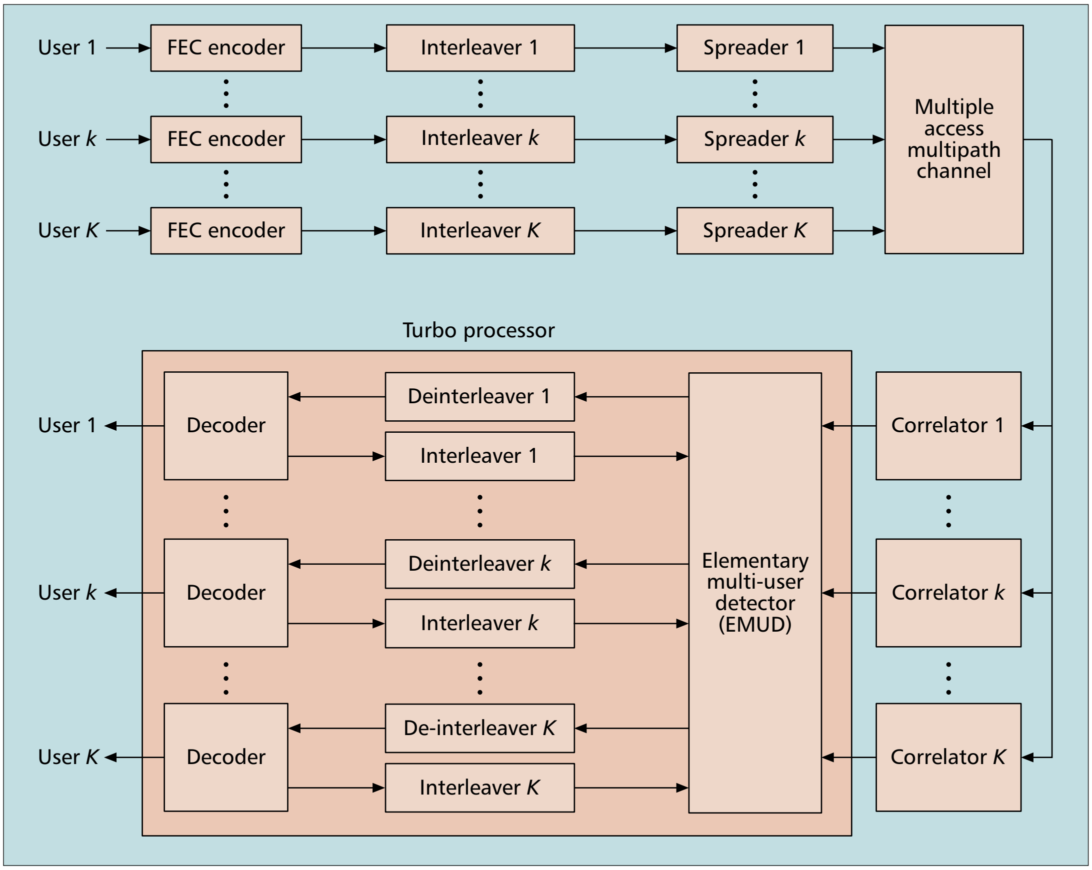

FIGURE 1. *Conventional coded CDMA transmitters and an iterative MUD receiver.*

devoting the entire bandwidth expansion to FEC coding and removing spreading. This is a sensible strategy since spreading introduces redundancy without coding gain. However, it is spreading that makes the signals from different users separable in CDMA. Clearly, some structural change is necessary if we want to make progress toward fully exploiting the available capacity. The question is, how can we achieve user separation within the CDMA framework without spreading?

Interleave-Division Multiple Access and Iterative Chip-by-Chip MUD

Interleaving-Based Multiple Access Techniques

First, some background is in order. The theoretical aspects of low-rate coded CDMA systems were studied in [10]. The use of multiple access techniques based on code structures and interleavers was studied in [5, 11] for narrowband systems. A low-rate coded CDMA scheme using scramblers for user separation was discussed in [12]. A CDMA scheme with chip-level interleavers and maximal ratio combining (MRC) detection was introduced in [13] to treat intersymbol interference (ISI). An IDMA principle was studied in [14] for high performance and low receiver cost.

Figure 2 illustrates the IDMA principle incorporating the work in [5, 11, 13, 14]. We can view Fig. 2 as a special case of Fig. 1 when all signature sequences reduce to a single chip (i.e., $S = 1$). Then spreaders and correlators become trivial and thus can be removed. This view is helpful: the elementary signal estimator (ESE) in Fig. 2 is in fact an extremely simplified version of the EMUD in Fig. 1.

For simplicity, we assume that all the encoders (with rate R) are same in Fig. 2. The total system throughput is $K \times R$ information bits per chip. (As a comparison, the system throughput of the conventional CDMA in Fig. 1 is $K \times R/S$.) Interleavers remain the only means to distinguish the signals from different users in Fig. 2. Each user is assigned a unique sequence of interleaving indexes. It is a special form of CDMA if we view each (uniquely) interleaved version of a code as a different code. We focus on wideband applications. The bandwidth expansion is entirely achieved by a low-rate FEC code. This code can be a simple repetition code if our goal is low cost, or a sophisticated turbo-type code [14] if our goal is high coding gain. We can also employ a combination of a repetition code (for bandwidth expansion) and a stronger code (for coding gain), which provides a trade-off between performance and complexity. Following the CDMA convention, we still call the elements in the transmitted sequences *chips*.

Chip-by-Chip MUD in Channels Without Memory

Recall our observation that Fig. 2 is a special case of Fig. 1 when all signature sequences reduce to a single chip. Consequently, the ESE in Fig. 2 works in a chip-by-chip manner. For illustration, we first consider a fully synchronized channel without memory. Let $x_k(j)$ be the jth chip transmitted by user k and h_k the channel coefficient for user k. We will assume that all h_k are known at the receiver. The received signal $r(j)$ is expressed as (after chip-matched filtering [2])

$$r(j) = \sum_{k=1}^{K} h_k x_k(j) + n(j), \qquad (1)$$

where $n(j)$ is a noise sample. For a particular user k, we rewrite Eq. 1 as

$$r(j) = h_k z_k(j) + \zeta_k(j), \qquad (2)$$

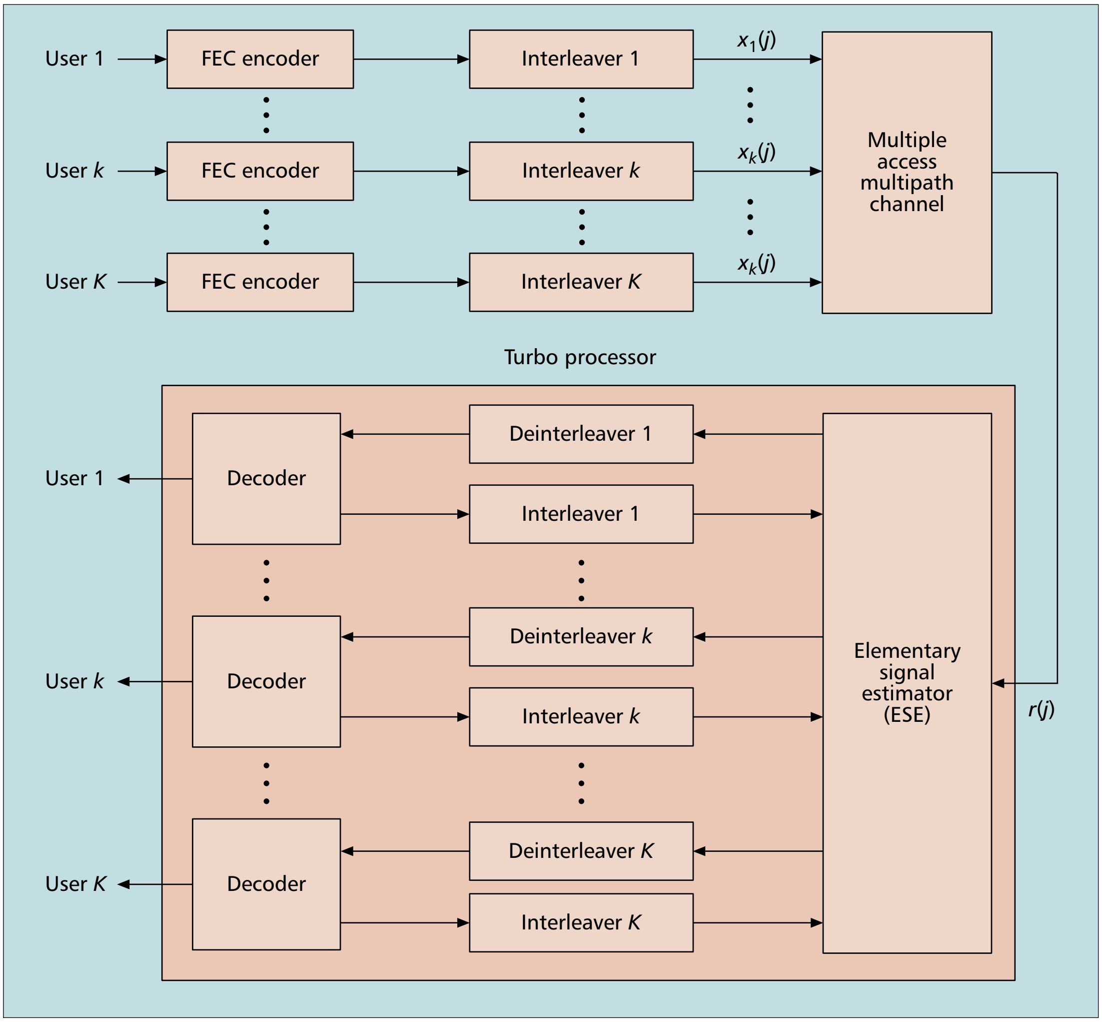

FIGURE 2. *IDMA transmitter and receiver structures.*

where $\zeta_k(j)$ is the distortion (including both interference and additive noise) contained in $r(j)$ with respect to $x_k(j)$. The ESE operations listed in Table 1 can be applied to estimate $x_k(j)$. The principles are rather straightforward. The distortion component $\zeta_k(j)$ in Eq. 2 is the summation of the received signals from other $K - 1$ users (except user k) plus noise. Assume that these signals are random and independent of each other. Then according to the central limit theorem, $\zeta_k(j)$ can be approximated by a Gaussian random variable for a large K. Assume that the means and variances of all $\zeta_k(j)$ are available. (We come back to this point later.) Let $E(\cdot)$ be the mathematical expectation. From Eq. 1, $E(r(j))$ in step 1 is the summation of $E(h_k x_k(j))$ over all k. From Eq. 2, $E(x_k(j))$ in step 2 is the difference between $E(r(j))$ and $E(h_k x_k(j))$. The variances of $r(j)$ and $\zeta_k(j)$ can be obtained similarly. Once the mean and variance of $\zeta_k(j)$ are obtained, step 3 is straightforward following the assumption that $\zeta_k(j)$ is Gaussian. (For detailed discussion see [14]. Similar methods were also studied in [6, 13].)

Step 1. Estimate the mean and variance of $r(j)$ using Eq. 1.
Step 2. Estimate the mean and variance of $\xi_k(j)$ using Eq. 2.
Step 3. Estimate $x_k(j)$ based on $r(j)$ using Eq. 2.

TABLE 1. *The chip-by-chip ESE operations in a fully synchronized channel*

The outputs of the ESE are noisy initially since they are estimated using only one chip observation. An iterative technique is applied to improve the estimation. The global process starts from the ESE. At the beginning, if no a priori information is available, we set the means and variances of all of the transmitted chips to zero and one, respectively. This simply says that each chip takes +1 and -1 with equal probability (assuming binary signaling over {+1, –1}). The ESE then produces coarse estimates as described above and delivers them to the DECs. The DECs calculate (based on the FEC coding constraint) the *a posteriori* probability (APP) of each transmitted chip being +1 and –1 [4], and update its mean and variance [14], which are fed back to the ESE for the next iteration.

The above iterative process heavily relies on the DECs to provide improved APP estimation. Codes of relatively low rate are necessary when K is large. Note that even simple repetition codes (without any coding gain) can efficiently suppress the MAI induced distortion, which is related to the processing gain [2]. However, if the FEC code is properly designed to exploit the advantage of reduced rate, improved coding gain comes as a bonus, which is vital if we want to converge toward capacity.

The complexity of step 1 in Table 1 is very low, only involving a summation over all K users who share the results and also the cost. The cost of step 1 per user is only several additions and multiplications. Steps 2 and 3 are very simple [14]. Overall, steps 1–3 together cost only several arithmetic operations per chip per user per iteration. No matrix operation is necessary. The complexity is independent of K.

When K reduces, the Gaussian approximation for the interference component becomes less valid, but then the ben-

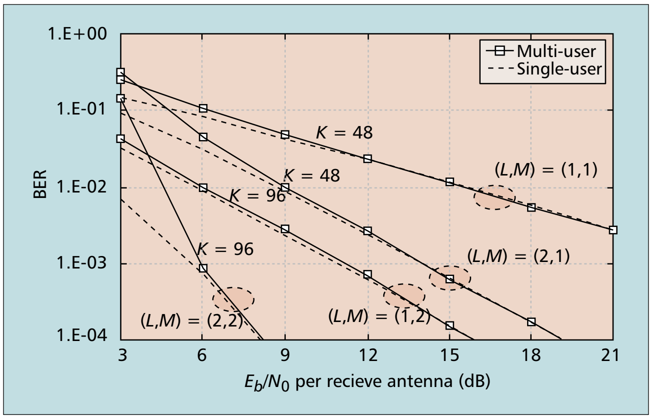

FIGURE 3. *The simulated performance of an IDMA scheme using a rate-1/16 FEC code consisting of a rate-1/2 (23, 35) convolutional code and a rate-1/8 repetition code. Iteration number = 10. Information length = 128/frame/user. Quasi-static Rayleigh fading multipath channels with equal average power per tap. The (*L, M*) values are marked in the figure with* L *the number of path taps and* M *the number of receive antennas.*

efit of less interference generally offsets the problem due to interference modeling.

Chip-by-Chip MUD in Channels with Memory and Multiple Receive Antennas

We now proceed to consider MUD in channels with memory due to multipath delay dispersion [13, 14]. Let a received sample be expressed using an L-tap model as

$$r(j) = \sum_{l=0}^{L-1}\sum_{k=1}^{K} h_{k,l}x_k(j-l) + n(j) \; = \; h_{k,l}x_k(j-l) + \zeta_{k,l}(j), \qquad (3)$$

where $h_{k,l}$ is the lth channel coefficient for user k (corresponding to a delay of l chip durations) and $\zeta_{k,l}(j)$ is the distortion (including additive noise, interference from other users as well as ISI from the same user) contained in $r(j)$ with respect to $x_k(j–l)$. The channel coefficients can be estimated using an overall joint channel estimation/detection process, but we omit the details in this article. We focus on detection below, assuming that all $h_{k,l}$ are known at the receiver side.

Following a similar principle as that for Eq. 2, we evaluate the mean and variance of the interference component $\zeta_{k,l}(j)$ in Eq. 3. A partial estimate of $x_k(j - l)$ can then be generated using $r(j)$. Notice from Eq. 3 that due to multipath delay, each transmitted chip will make a contribution to L received samples. Consequently, L estimates can be obtained for each transmitted chip. These estimates, usually expressed as log-likelihood ratios (LLRs), are combined using a simple summation. This is referred to as the *LLR combining* (LLRC) method and can also be applied to systems with multiple receive antennas [15]. The related computational complexity is $O(L)$ per user, regardless of user number K. A cost comparison of different MUD methods is provided in Table 2. The MMSE and MRC methods in Table 2 are discussed in [7, 13], respectively, for CDMA systems. (For very large K, [7] discussed an alternative method with cost per user $O((L+S)^2)$.) From Table 2, the LLRC method is advantageous when K is large.

Examples

We first consider a simple example. We construct the FEC code in Fig. 2 using a rate-1/2 convolutional code and a rate-1/8 repetition code (i.e., repeating each convolutionally coded bit eight times). The repetition coding can be viewed as a form of spreading, except that all of the users use the same sequence. The rate of the resulting FEC code is $R = 1/16$. For each user, two interleavers are used to produce two chip streams for in-phase and quadrature signaling. All of the interleavers are generated independently and randomly.

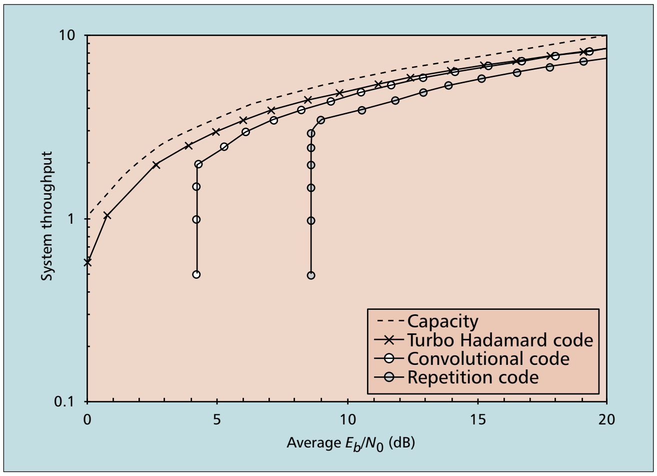

FIGURE 4. *IDMA system throughput with different coding methods. (With unequal power control,* E_b/N_0 *values can be different for different users. The abscissa above indicates the average* E_b/N_0 *over all users.)*

	LLRC	MMSE [7]	MRC [13]
Cost per user	$O(L)$	$O(K^2)$	$O(LK)$

TABLE 2. *Cost comparison of MUD algorithms in a multipath channel with memory length* L*. (Unit: operations per user.)*

Figure 3 shows the simulated performance of the above system in quasi-static Rayleigh fading multipath channels with different tap numbers and receive antenna numbers. The LLRC technique is employed. The corresponding single-user performance is also included for reference. System throughputs are $K \times R = 3$ b/chip for $K = 48$ and $K \times R = 6$ b/chip for $K = 96$. Even with such high throughputs, the system performance is still close to the single-user performance at bit error rate (BER) = 10^{-4}. Note that the performance in Fig. 3 improves with L, indicating that the IDMA scheme can efficiently exploit the advantage of path diversity [15].

By simulation, we observed that the MMSE algorithm [7] for an equivalent CDMA system (constructed using an $R = 1/2$ convolutional code and length 8 signature sequences according to Fig. 1) can achieve similar performance as IDMA for relatively small K. It is difficult to conduct simulations for large K due to the high complexity $O(K^2)$ involved. Low complexity is the key advantage of the IDMA scheme in this case.[2] With the computational burden eased, we are now able to demonstrate the full potential of the MUD technique, such as supporting nearly 100 users with only moderate computing power and a bandwidth expansion factor of merely 16.

Theoretically, the capacity of a random waveform CDMA system is power limited, meaning that it is only limited by signal-to-noise ratio (SNR), and information rate can be increased indefinitely provided SNR is sufficiently high [1, 3]. However, a practical CDMA system can be interference limited, meaning that increasing SNR may not improve system performance once interference reaches a certain level due to

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[2] *The following factors should also be considered in complexity comparison. The IDMA approach has a slightly higher DEC complexity due to use of the rate-1/8 repetition code. Also, although the ESE complexity is independent of* K*, it increases linearly with bandwidth expansion factor 1/*R*. Overall, the complexity advantage of IDMA is significant when* K *is large.*

too many simultaneous users [1–3, 15]. It has been shown in [10] that unequal power control can be a potential solution to this problem. The intuition here is that with unequal power control, the detection for strong power users can converge first and benefit weak power users (since then the interference from the former to the latter can be cancelled). This strategy is particularly effective for IDMA [14]. Figure 4 shows the IDMA system throughputs vs. average E_b/N_0 (at BER $\leq 10^{-4}$) based on different codes. The curves in Fig. 4 are generated using the so-called *SNR evolution method* [14], a fast technique to predict the performance of an IDMA receiver. We have also conducted simulation to verify these curves [14]. From Fig. 4, the spectral efficiency of IDMA is indeed power limited and can be quite close to that promised by information theory. Also from Fig. 4, a good FEC code (e.g., the turbo Hadamard code [14]) is essential in the low E_b/N_0 region. However, simple codes can be sufficiently good in the high E_b/N_0 region. For example, at E_b/N_0 = 15 dB, even repetition coded IDMA can achieve a rate of about 6 b/chip, compared to the capacity of approximately 8 b/chip. The relative difference is only (8 – 6)/8 = 25 percent. The APP decoding for a repetition code is extremely simple, involving only a summation of the input LLR values. This observation of good performance and low cost is quite striking.

Conclusions

In summary, we have outlined the basic principles of IDMA and the accompanying chip-by-chip iterative MUD algorithms. The schemes, although conceptually simple, offer very good performance. We have shown in Fig. 3 that the chip-by-chip detection algorithm can support a large number of users (e.g., nearly 100 users) in multipath environments. We have also demonstrated in Fig. 4 that the IDMA scheme can achieve performance close to theoretical limits. These features indicate the potential application of the new scheme in future wireless communication systems.

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References

[1] S. Verdú and S. Shamai, "Spectral Efficiency of CDMA with Random Spreading," *IEEE Trans. Info. Theory*, vol. 45, Mar. 1999, pp. 622–40.

[2] S. Moshavi, "Multi-user Detection for DS-CDMA Communications," *IEEE Commun. Mag.*, vol. 34, Oct. 1996, pp.124–36.

[3] T. Cover and J. A. Thomas, *Elements of Information Theory*, Wiley, 1991.

[4] C. Berrou and A. Glavieux, "Near Shannon Limit Error Correcting Coding and Decoding: Turbo-codes," *IEEE Trans. Commun.*, vol. 44, Oct. 1996, pp. 1261–71.

[5] M. Moher and P. Guinand, "An Iterative Algorithm for Asynchronous Coded Multiuser Detection," *IEEE Commun. Lett.*, vol. 2, Aug. 1998, pp. 229–31.

[6] M. C. Reed and P. D. Alexander, "Multiuser Detection using Antenna Arrays and FEC on Multipath Channels," *IEEE JSAC*, vol. 17, Dec. 1999, pp. 2082–89.

[7] X. Wang and H. V. Poor, "Iterative (Turbo) Soft Interference Cancellation and Decoding for Coded CDMA," *IEEE Trans. Commun.*, vol. 47, July 1999, pp. 1046–61.

[8] Z. Shi and C. Schlegel, "Joint Iterative Decoding of Serially Concatenated Error Control Coded CDMA," *IEEE JSAC*, vol. 19, Aug. 2001, pp. 1646–53.

[9] P. Hoeher, "On Channel Coding and Multiuser Detection for DS-CDMA," *Proc. IEEE Int'l. Conf. Univ. Pers. Commun.*, Oct. 1993, pp. 641–46.

[10] A. J. Viterbi, "Very Low Rate Convolutional Codes for Maximum Theoretical Performance of Spread Spectrum-Multiple-Access Channels," *IEEE JSAC*, vol. 8, May 1990, pp. 641–49.

[11] F. N. Brannstrom, T. M. Aulin, and L. K. Rasmussen, "Iterative Detectors for Trellis-code Multiple-Access," *IEEE Trans. Commun.*, vol. 50, Sept. 2002, pp. 1478–85.

[12] P. Frenger, P. Orten, and T. Ottosson, "Code-spread CDMA with Interference Cancellation," *IEEE JSAC*, vol. 17, Dec. 1999, pp. 2090–95.

[13] R. H. Mahadevappa and J. G. Proakis, "Mitigating Multiple Access Interference and Intersymbol Interference in Uncoded CDMA Systems with Chip-level Interleaving," *IEEE Trans. Wireless Commun.*, vol. 1, Oct. 2002, pp. 781–92.

[14] L. Ping et al., "On Interleave-division Multiple-Access," *Proc. IEEE ICC '04*, Paris, June 2004, pp. 2869–73.

[15] S. Heykin and M. Moher, *Modern Wireless Communications*, Pearson Prentice Hall, 2005.

Biography

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