RECENT PROGRESS IN INTERLEAVE-DIVISION MULTIPLE-ACCESS (IDMA)

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ABSTRACT

In this paper, we outline several new developments related to interleave-division multiple-access (IDMA). Our discussion encompasses analysis and optimization techniques, superposition-coded modulation, frequency domain processing schemes and the applications of IDMA in multiple-input multiple-output, relay and ad hoc environments. We demonstrate the flexibility and robustness provided by IDMA. We show that the IDMA principle can be applied to realize many potential performance gains highlighted by information theory, including coding gain, diversity gain and multi-user gain. We demonstrate that these gains can be very high, ranging from a few to tens of dBs, compared with conventional approaches.

INTRODUCTION

Additive white Gaussian noise (AWGN) and interference are two main hazards in communication systems. After decades of research effort, we are now quite confident in handling AWGN using forward error correction (FEC) codes, such as turbo [1] and low-density parity-check (LDPC) codes [2]. Interference still remains a problem, but progress is being made steadily [3]-[15].

Interference may come in many different forms, e.g.,

- multiple-access interference (MAI);
- inter-symbol interference (ISI) in multipath channels;
- cross-antenna interference (CAI) in multiple transmit antenna systems; and
- cross layer interference (CLI) in systems involving several singling layers (such as the superposition coded modulation (SCM) scheme to be discussed below).

Many techniques, such as time-division multiple-access (TDMA), frequency-division multiple-access (FDMA) and orthogonal frequency-division multiplexing (OFDM) have been developed to avoid interference during transmission. We can also treat interference as additive noise, which is the principle taken in, e.g., single-user detection (SUD) for random waveform CDMA systems. However, these methods are mostly sub-optimal from the information theory point of view.

The use of random sequences (i.e., random coding) for communication forms the core of information theory. Interestingly, interference is an inevitable consequence here, since orthogonality is not essential in an optimal communication system as envisaged by Shannon. For many years, random coding was regarded as an ingenious but only theoretical tool for the proof of channel capacity. The invention (and the re-invention) of pseudo-random codes such as turbo and LDPC codes [1][2], however, demonstrates the important practical impact of random coding principles. The capacity of an AWGN channel can now be approached to within a fraction of a dB using various pseudo-random codes.

The framework of interleave-division multiple-access (IDMA) [3], [10]-[15] is closely related to random coding. With IDMA, different users are solely distinguished by user-specific interleaves. These interleavers can be selected randomly (or deterministically for practical convenience) and orthogonality is not essential. Interference among users is inevitable in IDMA but can be suppressed by a low-cost iterative multi-user detection (MUD) procedure [14]. Although IDMA was originally proposed for multiple access channels (MACs), similar principles have been studied for many other applications, e.g., broadcast systems, coded modulation, multiple antenna systems, relay and ad hoc networks.

In this paper, we outline several new developments related to IDMA. In particular, we focus on the following issues:

- the analysis and optimization of IDMA systems;
- superposition-coded modulation for high rate systems;
- single-carrier and multi-carrier IDMA systems and frequency domain processing techniques;
- IDMA in multiple-input multiple-output (MIMO), relay and ad hoc environments.

We demonstrate the flexibility and robustness provided by IDMA. We show that the IDMA principle can be applied to realize many potential performance gains highlighted by information theory, including coding gain, diversity gain and multi-user gain. We demonstrate that these gains can be very high, ranging from a few to tens of dBs, compared with conventional approaches.

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BASIC IDMA PINCIPLES

Fig. 1 below shows an IDMA system over a MAC. At the transmitter for user *k*, the information sequence for user *k* is first encoded by an FEC encoder (ENC_k) with rate *R* and then interleaved by an interleaver π_k into a chip sequence $\{x_k(j)\}$. A power control factor $\sqrt{p_k}$ is used before transmission, which will be discussed in the next section. Note that in Fig. 1, the conventional spreading operation in CDMA is not necessary and user separation is solely guaranteed by user-specific interleavers $\{\pi_k\}$.

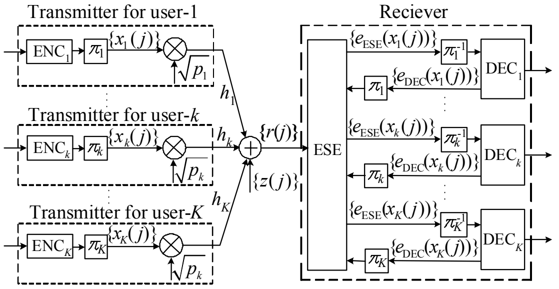

Figure 1. The system model of an IDMA multiple access scheme.

Initially, let us assume perfect synchronization and no ISI. These assumptions will be relaxed later. Suppose that the channel is perfectly known at the receiver. (For channel estimation issues, see [12].) The received signal can be written as

$$r(j) = \sum_{k=1}^{K} \sqrt{p_k}\, h_k x_k(j) + z(j) \tag{1}$$

where h_k is the channel coefficient for user-*k* and z(*j*) an AWGN with zero-mean and variance $\sigma^2 = N_0/2$.

The key to the low-cost detection strategy is the Gaussian approximation below [9][14]. Focusing on user-*k*, we rewrite (1) as

$$r(j) = \sqrt{p_k}\, h_k x_k(j) + \xi_k(j) \tag{2}$$

where $\xi_k(j)$ is the noise-plus-interference component in $r(j)$ in (1) with respect to $x_k(j)$. We approximate $\xi_k(j)$ by a Gaussian random variable, which greatly simplifies the detection model. This crucial approximation is a direct consequence of the chip-level random interleaving in IDMA. Based on (2), the log-likelihood ratio (LLR) estimate of $x_k(j)$ is calculated as (assuming BPSK modulation)

$$e_{ESE}(x_k(j)) = \frac{\Pr\left(x_k(j)=+1\right)}{\Pr\left(x_k(j)=-1\right)} = \frac{2\sqrt{p_k}\, h_k\left(r(j) - \mathrm{E}\left(\xi_k(j)\right)\right)}{\mathrm{Var}\left(\xi_k(j)\right)}. \tag{3}$$

The estimation in (3) is very coarse at the beginning (when $\mathrm{E}(\xi_k(j))$ and $\mathrm{Var}(\xi_k(j))$ are initialized by some poor estimates). However, it can be gradually refined by iteratively updating $\mathrm{E}(\xi_k(j))$ and $\mathrm{Var}(\xi_k(j))$ based on the feedback information $\{e_{\mathrm{DEC}}(x_k(j))\}$ from the decoders $\{\mathrm{DEC}_k\}$ in Fig. 1 [14].

Although the above detection technique is rather simple and straightforward, it works very well, usually converging to satisfactory results within several iterations. Early work on this technique was mostly based on simulation results. Recently, a semi-analytical tool has been developed to provide faster and more convincing performance evaluation for IDMA systems. This is the signal to noise-plus-interference ratio (SNIR) evolution technique, which is discussed in detail in the next section.

We note that the above process is MUD, not SUD, since the updating of $\mathrm{E}(\xi_k(j))$ and $\mathrm{Var}(\xi_k(j))$ in (3) involves feedback information from all users' decoders [14].

ANALYSIS AND OPTIMIZATION OF IDMA

An interesting feature of IDMA is that its performance can be quickly predicted by tracking the average SNIR of each user during the iterative process. This also leads to a fast (searching-based) design strategy for IDMA based on repeated performance evaluations.

The SNIR Evolution Technique

Denote by $\{SNIR_k^{(l)}\}$ the average SNIRs for the outputs of (3) after the *l*-th iteration. Let $f_k(SNIR_k^{(l)})$ be the average variance of the outputs of DEC_k driven by an input sequence with SNIR $SNIR_k^{(l)}$. In [14], it is shown that $\{SNIR_k^{(l)}\}$ can be approximately tracked by the following recursion:

$$SNIR_k^{(l)} = \frac{p_k \,|\, h_k \,|^2}{\sum_{i \neq k} p_i \,|\, h_i \,|^2\, f_i(SNIR_i^{(l-1)}) + \sigma^2}, \quad \forall k, l = 1, 2, \cdots L\,. \tag{4}$$

In (4), the $f_i(\cdot)$ function is determined by the decoder and can be obtained using a Monte Carlo method. At the beginning, we initialize $f_i(SNIR_i^{(0)}) = 1$, $\forall i$, indicating that there is no feedback from the decoders. By tracking (4) recursively, we can obtain the final SNIRs of all users and thus the system performance is predicted. The detailed derivation of (4) is omitted here.

Intuitively, (4) is quite easy to understand. The numerator $p_k|h_k|^2$ is simply the received signal power for user *k*. When $f_i(SNIR_i^{(0)}) = 1$, $\forall i$, the denominator $\Sigma_{i\neq k} p_i|h_i|^2 + \sigma^2$ is the total noise-plus-interference seen by user *k*. Otherwise, each interference component in the denominator is reduced by a factor of $f_i(SNIR_i^{(0)})$ that represents the noise-suppressing effect of decoder *k*. In particular, $f_i(SNIR_i^{(0)}) = 0$ implies error-free decoding at decoder *k* and hence no interference from user *k*.

Power Optimization

Suppose that we want to minimize the total transmitted power $\Sigma_k p_k$ in Fig. 1. Based on (4), the power optimization problem can be formulated as follows.

$$\text{Minimize} \qquad \sum_{k=1}^{K} p_k \tag{5a}$$

$$\text{Subject to} \qquad SNIR_k^{(L)} \geq \Gamma_k, \quad \forall k \tag{5b}$$

where $\{SNIR_k^{(L)}\}$ are obtained based on (4) with initial conditions $f_k(SNIR_k^{(0)}) = 1$, $\forall k$ and Γ_k is a pre-specified SNIR threshold for user k, $\forall k$.

Several algorithms have been proposed to solve problem (5) based on linear programming and interior-point methods [14][15]. The linear programming approach is fast but the interior-point one is more versatile and accurate. Fig. 2 below shows the optimized BER performance of IDMA systems with different number of users K over AWGN channels. A rate ½ convolutional code followed by a length-8 repetition code and QPSK modulation is used by all users. The corresponding evolution performance and capacity limits are also plotted for reference. From Fig. 2, we can see that the simulation and evolution performance is in good agreement. It appears that the throughput of an optimized IDMA system is power limited, not interference limited (as in traditional CDMA systems).

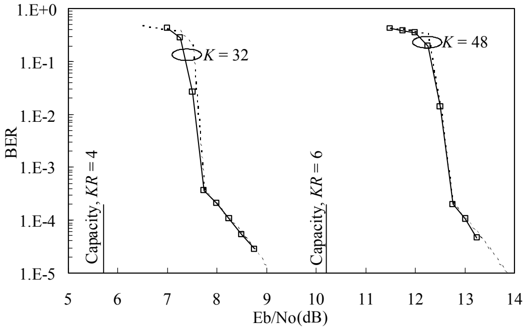

Figure 2. The performance of IDMA systems obtained by simulation (solid lines) and SNIR evolution (dashed lines).

The IDMA performance shown in Fig. 2 is about 3~4 dB away from the capacity, which is generally in line with a convolutionally coded system in a single-user AWGN environment. In this case, IDMA can offer several additional advantages such as asynchronous transmission and mitigation of cross-cell interference. Also note that IDMA is considerably better than CDMA with SUD. The latter cannot work at the high throughputs in Fig. 2 [16].

Fading Channels and MUG

The advantages of IDMA become more substantial in fading channels. This is illustrated in Fig. 3 using a convolutionally coded IDMA system with different numbers of users K over a single-cell fading channel containing path loss, lognormal fading and Rayleigh fading. The system throughput is fixed at 4 bits/chip. The performance of a TDMA system with trellis coded modulation (TCM) and their corresponding channel capacities are also plotted for reference. From Fig. 3 we can see that the performance of an optimized IDMA system can be very close to the fading channel capacity (with a gap caused by the non-ideal convolutional code used) and can be improved by increasing the number of users K. When K is large, IDMA can significantly outperform TDMA. This advantage is referred to as multi-user gain. The theoretical rationale and practical impact of multi-user gain is analyzed in [16][17].

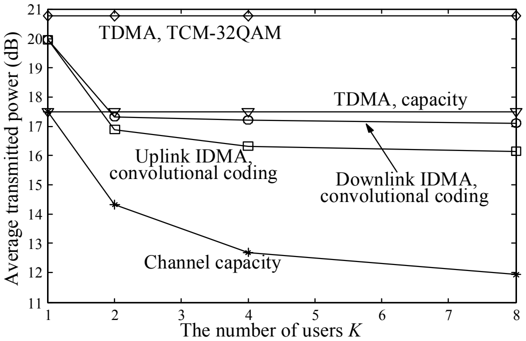

Figure 3. The average transmitted power versus the number of users K for an IDMA system over a single-cell fading channel. The outage probability is 0.01. The desired BER = 10^{-4}. The performance of a downlink IDMA scheme to be discussed is also included here.

DOWNLINK CHANNELS

A downlink IDMA system is, in many respects, similar to the uplink system shown in Fig. 1. At the transmitter, the signals for different users are interleaved by user-specific interleavers and transmitted over a common broadcast channel. Unlike the uplink where a common MUD is shared by all users, an individual MUD is required for each user in the downlink. Therefore, the MUD cost can be a serious concern here. Nevertheless, significant multi-user gain is also achievable in the downlink, as shown in Fig. 3. This can be proved using the duality principle [18] and has been confirmed by simulation. (Note that in Fig. 3, the convolutionally coded downlink IDMA performs slightly worse than the uplink one. This is caused by different searching methods used in the uplink and downlink power allocations.) Since the gain is quite significant, it may justify the use of MUD in the downlink even at the cost of increased complexity, at least for a small K (for which the cost increase is moderate).

SUPERPOSITION CODED MODULATION

For single-user high rate applications, we can assign all of the resources to a single user in Fig. 1. This leads to superposition-coded modulation (SCM) [19] in which several binary coded sequences, each referred to as a layer and independently encoded and interleaved, are linearly superimposed prior to transmission. A layer in SCM is roughly equivalent to a user in IDMA.

SCM has several advantages over conventional coded modulation schemes such as TCM and bit-interleaved coded-modulation with iterative decoding (BICM-ID). First, with the detection method introduced above, the detection complexity of a K-layer SCM is linear with K, while that of TCM or BICM-ID with the same constellation size (2^K) may grow exponentially with K. Thus SCM is cost effective for high throughput systems.

Another advantage of SCM is its flexibility in adaptive modulation. In many scenarios including frequency-selective and MIMO channels, the channel can be decomposed into a set of parallel sub-channels, of which the capacity is theoretically achieved by the water-filling strategy. Adaptive adjustment of the coding rate in each sub-channel is needed to realize this in practical systems. With traditional coded-modulation schemes, a bank of encoders/decoders with different rates is required for this purpose, which makes the system very complicated. While with SCM, rate adaptation can be simply achieved by adjusting the number of layers [13].

A third advantage of SCM is its robustness in fast fading channels. This can be achieved by employing a relatively low-rate code for each layer to provide a high diversity order. Note that for a fixed throughput KR, a lower single-layer rate implies more layers, which may result in increased receiver cost.

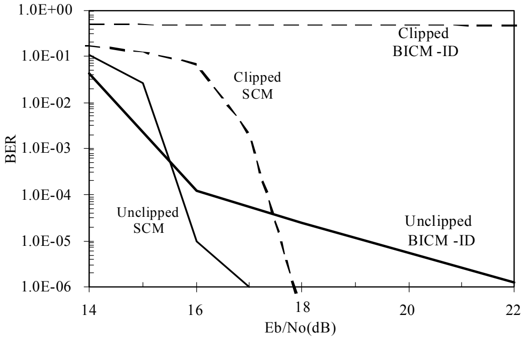

Figure 4. Performance of unclipped and clipped OFDM systems based on SCM and BICM-ID at $KR\psi = 5$ bits/symbol.

Due to the superposition operation, SCM in its straightforward form has a relatively high peak-to-average power ratio (PAPR). This issue can be effectively alleviated by amplitude clipping together with soft compensation [19]. Interestingly, it turns out that SCM is advantageous with respect to PAPR when it is used in OFDM. High PAPR is an inherent problem of all OFDM systems, whether using SCM or not. However, the soft compensation method performs the best when signaling is based on SCM. For illustration, the BER performance of SCM and BICM-ID based OFDM schemes at $KR\psi = 5$ bits/symbol are compared in Fig. 4. It is seen that the SCM significantly outperforms BICM-ID when applied to OFDM. We are currently working on a theoretical proof for this interesting observation.

IDMA IN ISI CHANNELS

The use of random interleaving in IDMA also facilitates detection in ISI channels [20], as discussed below.

Time Domain Detection

For an IDMA system over an ISI channel, the received signal model (1) can be modified to

$$\boldsymbol{r} = \sum_{k=1}^{K} \sqrt{p_k}\, \boldsymbol{h}_k \otimes \boldsymbol{x}_k + \boldsymbol{z} \qquad (6)$$

where $\boldsymbol{r}$ is the received signal vector, $\boldsymbol{h}_{k,} \equiv \{h_{k,0}, \ldots, h_{k,L-1}\}$ a vector of the fading coefficients related to user k, $\boldsymbol{x}_k \equiv \{x_k(j)\}$ the transmitted signal vector from user k, $\boldsymbol{z}$ a AWGN sample vector and $\otimes$ the convolution operation.

There are several options for detection based on (6). The first is to apply the detection rule in (3) to (6) for every delayed version of a transmitted chip and then combine the resultant LLR values afterwards. (In this approach, $\xi_k(j)$ in (3) should include the contributions of the delayed versions of the interfering signals.) This LLR combining technique is simple and works well when the coding rate of each user is relatively low. The complexity is $O(L)$ per chip where L is the length of channel delay.

If the rate of each user is relatively high, the joint-Gaussian approach described in [20] provides improved performance compared with LLR combining. This method models the interference-plus-noise samples by a joint Gaussian vector so as to handle the correlation introduced by multipath delay. The complexity related to this method is $O(L^2)$ per chip.

The above two methods do not require frame level synchronization and are very flexible. However, if frame level synchronization is possible (at least loosely), the following frequency domain method [21] can lead to lower complexity for a large L.

Frequency Domain Detection

We apply a cyclic prefixing technique at the transmitter and assume that the frames from different users can be approximately aligned when they arrive at the receiver. At the receiver, we first remove the cyclic prefix and perform the fast Fourier transform (FFT) on $\boldsymbol{r}$, producing

$$R(m) = \sum_{k=1}^{K} H_k(m) X_k(m) + Z(m) \qquad (7)$$

where the variables involved in (7) are the Fourier transforms of those in (6).

Similar to (2) and (6), we again rewrite (7) in a signal plus distortion form and approximate the distortion term by a Gaussian random variable. Note that even if $\{x_k(j)\}$ in the time domain carry binary information, after Fourier transform, $\{X_k(m)\}$ are no longer binary. Instead, $\{X_k(m)\}$ can be approximated by Gaussian random variables according to the central limit theorem. Therefore, we can apply minimum mean square error estimation to $\{X_k(m)\}$. The results are then transformed back to the time domain to produce LLR estimates. The complexity of frequency domain detection is dominated by FFT and is independent of the channel memory length *L*.

OFDM-IDMA

The OFDM-IDMA scheme was first introduced in [22][23]. The basic principle of an OFDM-IDMA system is similar to that in Fig.1, except for an additional inverse FFT operation at the transmitter and an FFT operation at the receiver. These two operations transform the convolution effect of the ISI channel in the time domain into a fluctuation effect in the frequency domain (due to frequency selectiveness). The key advantage of OFDM-IDMA is that MUD can be realized efficiently with complexity per user independent of the channel length and the number of users, which is significantly lower than that of other alternatives.

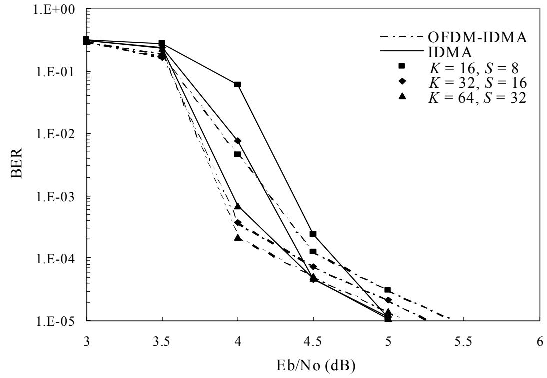

Figure 5. Performance comparison between IDMA and OFDM-IDMA systems over ISI channels. The system throughput is *KR* = 2.

Fig. 5 shows the performance of a single-carrier IDMA system with frequency domain detection and an OFDM-IDMA system over an ISI channel. An un-correlated Rayleigh fading among the sub-carriers is assumed. The coding scheme for each user in both systems is a rate-1/2 convolutional code followed by a length-*S* repetition code and QPSK modulation. The system throughput is fixed at *KR* = 2 bits/symbol. From Fig. 5, we can see that both systems have similar performance. For the OFDM-IDMA system, the performance can be slightly improved by increasing *K* (and *S* as well). This is because longer spreading length *S* is more effective to combat the frequency selectiveness among different sub-carriers.

Multi-user gain can also be achieved in OFDM-IDMA systems when near-far effect is involved. Fig. 6 below considers an OFDM-IDMA system over a single-cell fading channel. In addition to Rayleigh fading, path loss and lognormal fading are also considered here. In Fig. 6, a rate-1/2 convolutional code followed by a length-8 repetition code and QPSK modulation is used by all users. The system throughput is fixed at 3 bits/symbol and hence 24 code streams are involved here. When *K* < 24, multiple code streams are assigned to each user based on SCM. A single-user BICM-ID scheme with the same throughput is also considered, which has similar performance to that of the OFDM-IDMA scheme with *K* = 1. A multi-user BICM-ID scheme (not shown in Fig. 6) with orthogonal frequency-division multiple-access (OFDMA) always performs slightly worse than the single-user one because the block length of each user is decreased when *K* increases. However, we can see from Fig. 6 that the performance of the OFDM-IDMA system can be improved by increasing the number of users *K* and a large portion of power saving can be achieved at *K* = 2. This again indicates that the near-far effect is advantageous in IDMA-based systems and multi-user gain can be achieved by multi-user simultaneous transmission.

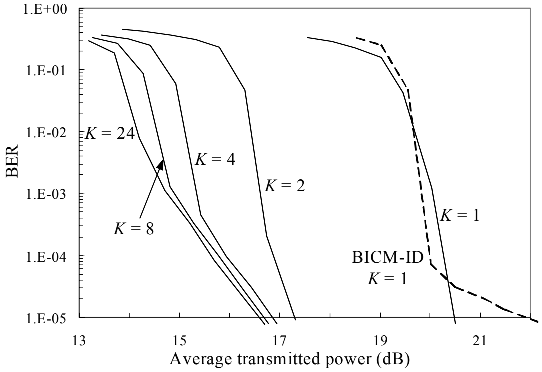

Figure 6. Simulation performance of an OFDM-IDMA system over an ISI channel containing path loss, lognormal fading and Rayleigh fading. The throughput is fixed at *KR* = 3. The transmitters know the path loss and lognormal fading but don't know Rayleigh fading.

IDMA IN MIMO CHANNELS

IDMA is also a promising technique for applications over MIMO channels. Two methods are outlined below for situations with and without channel state information (CSI) at the transmitter, respectively.

Interleave-Division-Multiplexing Space-Time Coding

If the transmitter has no CSI, the interleave-division-multiplexing space-time (IDM-ST) scheme [24] shown in Fig. 7 can be employed to exploit the diversity provided by the use of multiple antennas. In Fig. 7, the information is first encoded by SCM and then segmented in a serial-to-parallel converter into *N* equal-length sections to be transmitted from *N* antennas simultaneously. The layer-specific random interleaving in SCM ensures that the signal can be detected using an iterative receiver [24].

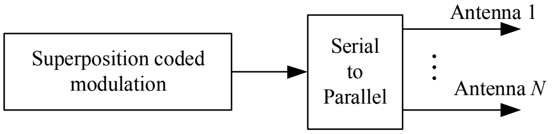

Figure 7. Transmitter structure of a superposition IDM-ST code.

Fig. 8 below shows the performance of such IDM-ST schemes with 2, 4 and 8 transmit antennas. A turbo-SPC code is used for all layers and the transmission rate is fixed at 1 bit per channel user. From Fig. 8 we can see that the performance gaps between IDM-ST schemes and their corresponding outage capacities are only about 1dB.

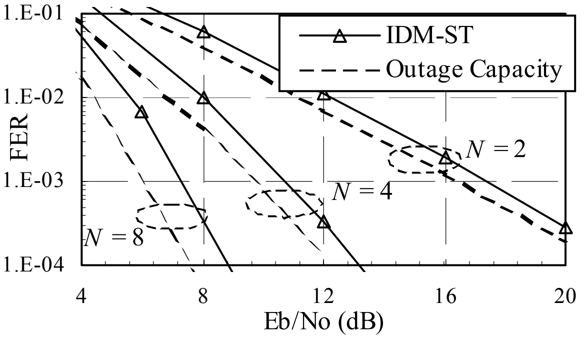

Figure 8. Performance of 2×1, 4×1 and 8×1 turbo-SPC coded IDM-ST scheme with $R = 1$ bits per channel use.

Maximum Eigenmode Beamforming

For a multi-user MIMO channel with full CSI at the transmitters, the optimal transmission scheme involves the joint optimization of the transmission power (or rates) and the input covariance matrices for all users, which is rather complicated. A simplified approach is the so-called maximum eigenmode beamforming (MEB) method [17], in which each user is only allowed to transmit in the direction of its maximum eigenmode. This method, though sub-optimal, greatly reduces the complexity of the system. It has been proved that the MEB approach is asymptotically optimal when the number of users in the system is sufficiently large. Fig. 9 compares the required average transmitted sum-power of an optimal MIMO system with equal rate constraint for each user and that achieved by the MEB approach. The channel condition is the same as that in Fig. 3 and the system throughput is fixed at 4 bits/symbol. From Fig. 9, we can see that when $K \geq 2$, the performance loss of the MEB approach is negligible. Fig. 9 also indicates that significant power saving can be achieved due to multi-user gain.

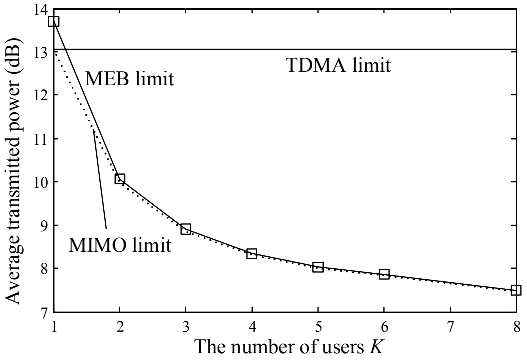

Figure 9. Comparison between the power efficiencies of optimal transmission and the MEB approach in a 2×2 MIMO channel. The system throughput is 4 bits/symbol. The outage probability is 0.01.

IDMA provides a convenient platform for the implementation of the MEB strategy. Fig. 10 shows the performance of a convolutionally coded MIMO system in which users are separated solely by user-specific interleavers and each user is only transmitting in the direction of the maximum eigenvalue of the channel seen by this user. From Fig. 10, we can see that about 6 dB power saving is achievable with 8-user simultaneous transmission compared with a single-user system with the same throughput. This is in good agreement with the theoretical prediction shown in Fig. 9.

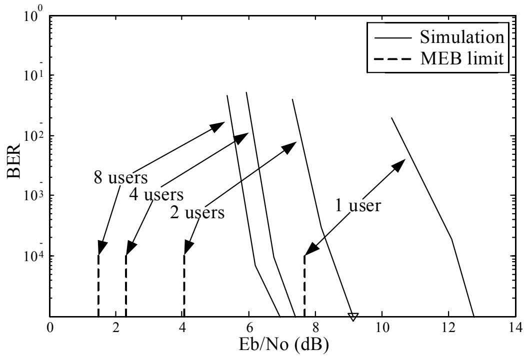

Figure 10. Simulation performance of an MEB-IDMA system over a 2×2 single-cell fading channel for $K = 1, 2, 4$, and 8, respectively. The system throughput is $KR = 4$ bits/symbol. The outage probability is 0.01. The corresponding MEB limits are also plotted for reference.

OTHER APPLICATIONS

Besides cellular systems, IDMA can be applied to many other applications including those mentioned below.

Ultra Wideband (UWB) and Sensor Systems

IDMA is advantageous in many low-rate systems, such as UWB and sensor systems. The main advantage of IDMA in such applications is the high coding gain achievable if traditional spreading (as used in CDMA) is replaced by low-rate coding. For this purpose, the simple low-rate zigzag-Hadamard code [25] can be employed. Significant coding gain can be achieved as reported in [26] for UWB systems. We expect that the same principle is applicable to sensor systems where low-power transmission is crucial to save battery life.

Relay and Ad Hoc Networks

An interesting concept related to IDMA is described in [27] to separate different replicas of a common signal that arrive at a destination through different relays. Suppose that the signal from a transmitter is randomly delayed before transmission and its replicas experience different delay factors through different transmission paths. If the delay difference among these paths is relatively small, then Rayleigh fading may result. However, if the delay difference is sufficiently large, these replicas may look as if they are produced using different interleavers. (Note: The delayed version of a random interleaver is almost random to itself.) Using this principle, it is shown in [27] that random delay can be deliberately introduced at the relay nodes to avoid Rayleigh fading and to facilitate IDMA-type detection at the destination. This provides an efficient way to exploit the diversity provided by different transmission paths.

Optical Networks

IDMA can also be applied in optical networks [28]. In the OR channel of an optical network, the linear summation operation in (1) is replaced by nonlinear OR operation, which makes it difficult to support uncoordinated multiple access. The IDMA principle provides a solution to this problem while maintaining high optical transmission rates. An IDMA architecture allowing transmission rate as high as 5.4Gbps has been proposed in [28].

CONCLUSIONS

In this paper, we have outlined the recent progress of IDMA in various applications. IDMA provides many desired features for modern communications systems, in particular, robustness against interference and both high power efficiency and spectral efficiency. IDMA is also very flexible, allowing low-cost iterative detection in various channel conditions. We have used both theoretical arguments and simulation results to demonstrate these features of IDMA.

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