Comparison of Orthogonal and Non-Orthogonal Approaches to Future Wireless Cellular Systems

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Abstract

This article provides a comparative study of different multiple access techniques. It is demonstrated that non-orthogonal approaches have a spectral-power efficiency advantage over orthogonal ones for delay-sensitive applications in fading environments, and that this theoretical advantage can be realized in practice by exploiting recent progress in transmission and detection techniques. The practical aspects of these multiple access techniques are also discussed and compared.

Introduction

Multiple access (MA) is a basic function in wireless cellular systems. Generally speaking, MA techniques can be classified into orthogonal and non-orthogonal approaches. In orthogonal approaches, signals from different users are orthogonal to each other, i.e., their cross correlation is zero, which can be achieved by time-division multiple-access (TDMA), frequency-division multiple-access (FDMA) and orthogonal-frequency-division multiple-access (OFDMA). Non-orthogonal schemes allow non-zero cross correlation among the signals from different users, such as in random waveform code-division multiple-access (CDMA) [1], trellis-coded multiple-access (TCMA) [2] and interleave-division multiple-access (IDMA) [3].

First and second generation cellular systems are dominated by orthogonal MA approaches (with the exception of the American IS-95). The main advantage of these approaches is the avoidance of intra-cell interference. However, careful cell planning is necessary in these systems to curtail cross-cell interference. In particular, sufficient distance must exist between re-used channels, resulting in reduced cellular spectral efficiency.

Non-orthogonal CDMA techniques have been adopted in second and third generation cellular systems (e.g., IS-95, CDMA2000 and uplink WCDMA). Compared with its orthogonal counterparts, CDMA is more robust against fading and cross-cell interference, but is prone to intra-cell interference. Due to its spread-spectrum nature, CDMA is inconvenient for data services (e.g., wireless local area networks (WLANs) and 3GPP high speed uplink/downlink packet access (HSUPA/HSDPA) standard) that require high single-user rates.

This article presents a comparative study of orthogonal and non-orthogonal MA schemes. We will illustrate that non-orthogonal approaches have a spectral-power efficiency advantage over orthogonal ones for delay-sensitive applications in fading environments. This advantage is referred to as multi-user gain (MUG) below. We will also illustrate that MUG is realizable in practice by exploiting recent progress in interleave-division multiple-access (IDMA) and the related low-cost chip-by-chip (CBC) multi-user detection (MUD) algorithm. The gain is significant for high-rate applications.

It is envisaged that delay-sensitive applications (such as speech and video services) will contribute a considerable part of the traffic demand in the future, and so the discussion in this article may provide useful guidelines on the evolution path for future wireless cellular systems.

Our focus is mainly on uplink multiple access channels (MACs), but most findings in this article can be applied to downlink broadcast channels (BCs) based on the uplink-downlink duality principle [4]. Thus significant gain is available for both uplink and downlink applications, which deserves further research effort.

Spectral-Power Efficiency of MA Systems

Spectral-power efficiency is one of the fundamental topics of information theory. The limits on spectral-power efficiency are usually expressed in two equivalent forms:

i. The maximum information rate per unit spectrum at a given power level;
ii. The minimum power to support a given rate (or a set of rates for a multi-user system) per unit spectrum.

The discussion in this article is from the power minimization point of view.

Information theory indicates that orthogonal and non-orthogonal alternatives have the same fundamental limits in MACs where the only distortion is caused by additive white Gaussian noise (AWGN). However, if fading is also involved, the conclusion can be very different [4].

Communication services can be classified into delay-sensitive and insensitive ones. A typical example of a delay-insensitive service is email. Typical examples of delay-sensitive services include speech and video applications. For delay-insensitive services, rate constraints are relatively relaxed for individual users and maximizing the throughput by orthogonal methods[1] is a common strategy. For example, consider a power limited system over a static fading MAC with a single antenna at each transmitter. The maximum throughput can be achieved by a one-user transmission policy, where only the user with the largest channel gain is allowed to transmit. This implies time domain orthogonality as adopted in many WLANs. For delay-sensitive services, on the other hand, each user must transmit a certain amount of information within a certain period and maximizing the throughput is no longer an appropriate strategy. Rate constraints must be considered in this case.

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[1] This is not true in multiple-input multiple-output (MIMO) systems. In general, non-orthogonal schemes are necessary to achieve MIMO channel capacities [4]. Since the discussion of MIMO systems is rather involved, we will not include this topic in the present paper.

Assume that a user can transmit at different *instantaneous rates* and *instantaneous power* levels in different time slots. (The instantaneous rate and power level are both zeros in an idle period). *Average rate* and *average power* are the arithmetic means of instantaneous rates and instantaneous power levels over a certain period, respectively. For example, let a user transmit information in a time slot with duration T_1 at an instantaneous rate r_1 and an instantaneous power level p_1. It is idle in the next time slot with duration T_2. Then its average rate is $r_1T_1/(T_1+T_2)$ over the two time slots considered, and the corresponding average power level is $p_1T_1/(T_1+T_2)$. Throughput and average-sum-power refer to the sums of the average rates and average power levels of the two users, respectively. These definitions can be directly generalized to a multi-user system with an arbitrary number of users.

Next, for the purpose of illustration, we consider an MA system involving only two users with the same required average rate R. The distortion is caused by AWGN with power density N_0 and fading coefficients h_1 and h_2 for user 1 and user 2, respectively. We assume that h_1 and h_2 are known at both the transmitters and the receiver and remain unchanged within a frame.

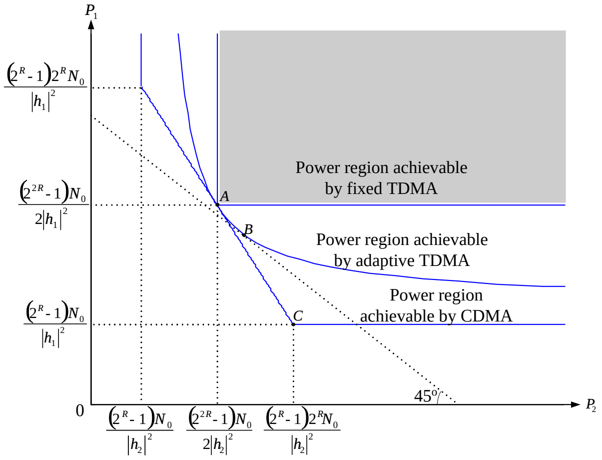

Fig. 1. The theoretical average transmitted power region for a two-user MA system with a fixed average rate R for each user. A, B and C indicate the points where the minimum transmitted average-sum-powers are achieved for fixed TDMA, adaptive TDMA and CDMA, respectively.

For orthogonal MA techniques, we consider two TDMA options: fixed TDMA and adaptive TDMA, as explained below. In both cases, each frame is divided into two time slots for two users. Their instantaneous and average transmitted power levels are denoted by p_1, p_2, P_1 and P_2, respectively.

- With fixed TDMA, the lengths of the two time slots are the same. As a consequence, the corresponding instantaneous rates are also identical.
- With adaptive TDMA, the instantaneous rates and slot lengths are optimized based on channel conditions (see discussion below). They can be different for the two users and vary frame by frame.

Fig. 1 illustrates the theoretical average transmitted power regions achievable by fixed TDMA, adaptive TDMA and CDMA. For example, any point (P_1, P_2) in the shadowed area represents a feasible pair of average transmitted power levels using fixed TDMA and the minimum average-sum-power is achieved at the corner point A. Similarly, the areas on the up-right of the other two curves represent the sets of valid power levels for adaptive TDMA and CDMA, respectively. The detailed calculation of these limits is explained below.

Fixed TDMA

For each user, the instantaneous rate in this case is constrained to be $2R$ to achieve the average rate R. From the Shannon capacity formula (i.e., $C = \log_2(1+SNR)$) and channel inversion principle, the minimum instantaneous transmitted power level for each user is

$$p_k = \frac{(2^{2R} - 1)N_0}{|h_k|^2}, \quad k = 1,2\,. \tag{1}$$

The corresponding average power levels are $P_k = p_k/2$, $k = 1,2$.

Adaptive TDMA

Let the instantaneous rates constraints be r_1 and r_2 for users 1 and 2, respectively. The time slot lengths t_1 and t_2 for the two users are then constrained by $r_1t_1/(t_1+t_2) = r_2t_2/(t_1+t_2) = R$. The minimum instantaneous power level for each user is given by

$$p_k = \frac{(2^{r_k} - 1)N_0}{|h_k|^2}, \quad k = 1,2\,. \tag{2}$$

The average power levels are $P_k = t_k p_k/(t_1+t_2)$, k=1, 2. The average-sum-power $P_1+P_2 = (t_1p_1+t_2p_2)/(t_1+t_2)$ can be minimized through a Lagrange multiplier technique [4], as indicated by the point B in Fig. 1.

CDMA

In this case, both users have the same instantaneous rate constraint R. Assume $|h_1|^2 \leq |h_2|^2$ and consider the successive cancellation principle [4]:

- User 2’s signal is decoded first by treating user 1’s signal as additive noise.
- User 1’s signal is decoded after stripping off the estimated signal of user 2 from the received signal.

The minimum average-sum-power is achieved at point C in Fig. 1 with the following power levels.

$$P_1 = p_1 = \frac{(2^R - 1)N_0}{|h_1|^2} \text{ and } P_2 = p_2 = \frac{(2^R - 1)2^R N_0}{|h_2|^2}\,. \tag{3}$$

Generally speaking, for an MA system with an arbitrary number of users, different decoding orders will lead to different average-sum-power, and the minimum average-sum-power is achieved by decoding the signal of the user with larger channel gain first [5].

The better performance of adaptive TDMA over fixed TDMA is evident in Fig. 1, and has motivated the recent research interest in adaptive modulation. Similar adaptive principles can also be applied to FDMA/OFDMA systems. For example, for a two-user OFDMA system, we can devise an adaptive scheme by dividing the spectrum for the two users according to their channel conditions. Such adaptive schemes lead to power saving compared with fixed FDMA/OFDMA in which each user occupies equal half of the total spectrum.

A heuristic reason for the advantage of CDMA over TDMA is the lower instantaneous rate for CDMA. As we know from the Shannon capacity formula, the required transmitted power grows exponentially with the increased coding rate R. Thus by comparing Eqns. (1) and (3) we can see that lower rate for user 1 in CDMA implies power reduction compared with that in TDMA. On the other hand, interference cancellation for CDMA causes power increase for user 2 since the first decoded user requires more power. When $|h_1|^2 = |h_2|^2$, these two opposite effects (power reduction for user 1 and power increase for user 2) cancel each other exactly. When $|h_1|^2 < |h_2|^2$, however, the power saving for user 1 surpasses the power increase for user 2. In this case, CDMA can take advantage of the difference between $|h_1|^2$ and $|h_2|^2$ and achieve higher power efficiency than TDMA. Note that this advantage is attainable only by MUD.

The minimum average-sum-power for CDMA with MUD is also the theoretical limit [4] on the average-sum-power for all possible transmission schemes. We refer to this as the "theoretical power limit" below. In general, when $|h_1|^2 \neq |h_2|^2$, the theoretical power limit can only be achieved by non-orthogonal schemes such as CDMA [1] and IDMA [3] and cannot be achieved by orthogonal ones [4]. Therefore non-orthogonal schemes have a power efficiency advantage for delay-sensitive applications in fading channels. A similar statement can also be made for more general channels as discussed below.

As a remark, FDMA/OFDMA and orthogonal CDMA have the same disadvantage of reduced coding gain as TDMA. In principle, an orthogonal scheme divides the entire signal space into orthogonal sub-spaces and the signal of each user is restricted within a sub-space. This implies reduced degrees of freedom for each user's signal and so reduced coding gain. Therefore, generally speaking, orthogonal schemes cannot achieve the channel capacities in fading environments [4].

Single Cell Uplink Scenario

We now consider more general uplink channel conditions. We first ignore Rayleigh fading and focus on path loss that produces the so-called "near-far effect". To be more practical, we will also include lognormal fading. We will show that CDMA is favorable in transmission environments with the near-far effect. We emphasize that MUD is assumed for CDMA in this section.

Let K be the number of users to be supported. We assume that all users are uniformly distributed in a single hexagon cell. We normalize the path loss factor from the farthest corner of the cell to the base station to unity and the path loss factors in other positions in the cell are computed proportionally using the fourth power loss law. The channel gain for user-k is then given by $|h_k|^2 = A \cdot d_k^{-4} 10^{x_k/10}$, where d_k is the normalized distance from user-k to the base station, x_k is a real Gaussian random variable with zero mean and variance s_s^2 ($s_s = 8$ in this article) that characterizes lognormal fading, and the normalization factor A is used to ensure that the mean of the lognormal fading part equals 1. At the base station, the received signal is distorted by a complex AWGN with power density $N_0 = 1$. We allow an outage probability of 0.01, i.e., user-k will not transmit when $|h_k|^2 < G_{\mathrm{out}}$ with $\Pr(|h_k|^2 < G_{\mathrm{out}}) = 0.01$.

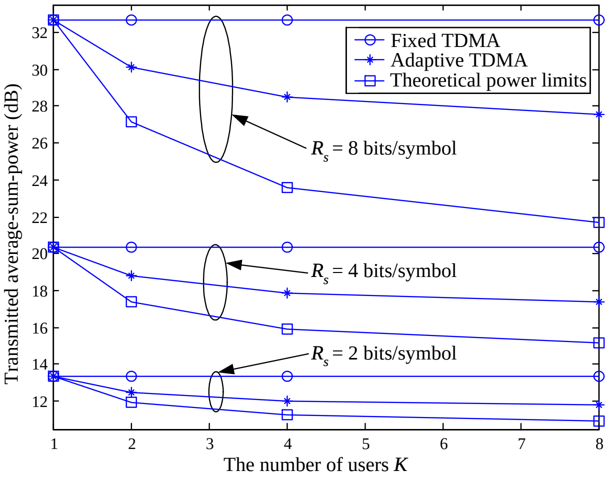

Fig. 2. The transmitted average-sum-power versus the number of users K for a multiple access system with different MA techniques. The channel coefficient for each user consists of path loss and lognormal fading. All users have the same average rate and are assumed to be uniformly distributed in a normalized single hexagon cell with edge length 1.

As mentioned above, only non-orthogonal schemes (such as CDMA with MUD) can achieve the theoretical power limits of fading channels. However, the performance of different MA schemes is quite close when the throughput $R_s = KR$ is relatively low (e.g., 2 bits/symbol or less). The difference becomes more significant when R_s increases. This is illustrated in Fig. 2 for R_s = 2, 4 and 8 bits/symbol. The curves are produced using methods similar to those in the last section, taking averages over the distribution of $\{|h_k|^2\}$. (Eqns. (1)-(3) can be easily generalized to systems with an arbitrary number of users [4].) The theoretical power limits are computed based on CDMA with MUD.

Some comments regarding Fig. 2 are in order.

- Power saving can be achieved by adaptive TDMA and CDMA relative to fixed TDMA. We refer to this power advantage as multi-user gain (MUG). This gain is, in principle, similar to the performance advantage of opportunistic techniques [4][2], although here only a single antenna at each transmitter is considered. (We consider multiple antennas later).
- As we explained in the last section, MUG is achieved for CDMA by taking advantage of the near-far effect.
- MUG increases when the number of users K or the throughput R_s increases.
- A significant portion of MUG is achievable with a small number of users (such as 2 or 4).
- The theoretical power limits can only be achieved by non-orthogonal schemes. MUD [6] is necessary to achieve these limits [4].

Clearly, the potential MUG is significant and very attractive. For example, at R_s = 8 bits/symbol and K = 8, about 11 dB gain is available compared with fixed

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[2] A subtle difference between the multi-user gain in this article and the multi-user diversity gain discussed in [4] for opportunistic techniques is that the later is focused on the advantage of adaptive TDMA over fixed TDMA.

TDMA. Such a large power saving offers considerable performance improvements in future wireless systems.

It can be shown that similar MUG is also available in other (such as Rayleigh) fading environments. As an example, let us include Rayleigh fading and consider the situation when the base station is equipped with two receive antennas. A single transmit antenna is still used by each user. The channel coefficients from a given user to different receive antennas have the same path loss and lognormal fading factor but different independently and identically distributed (i.i.d.) Rayleigh fading factors, then the fading coefficient from user-*k* to the *i*-th antenna at the base station is given by $h_{k,i} = (Ad_k^{-4}10^{x_k/10})^{1/2} c_{k,i}$, where c_k is a complex Gaussian variable with zero-mean and unit variance. The other conditions are as in Fig. 2. The theoretical limits are computed based on the methods outlined in [7]. The results are shown in Fig. 3 where the MUG is clearly seen. The relative differences between different strategies become even larger than those in Fig. 2 (e.g., at R_s = 8 bits/symbol and K = 8, about 14 dB gain is available compared with fixed TDMA).

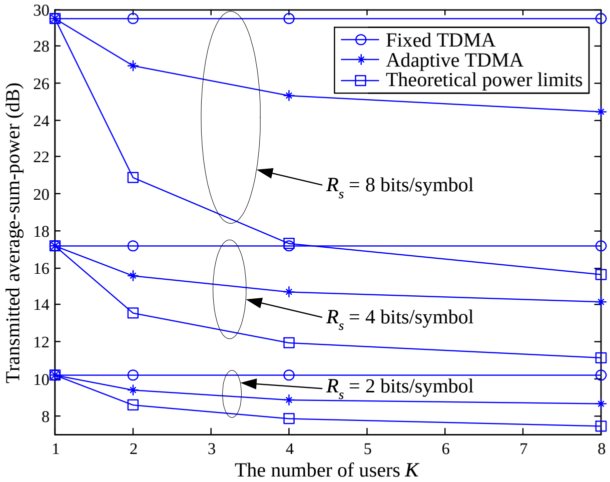

Fig. 3. The transmitted average-sum-power versus the number of users *K* for a multiple access system with different MA techniques. The base station is equipped with two antennas. The channel coefficients for each user consist of path loss, lognormal fading and Rayleigh fading. All users have the same average rate and are assumed to be uniformly distributed in a normalized single hexagon cell with edge length 1.

Although Figs. 2 and 3 are for systems with equal average rates for all users, the similar observation can be made if different users have different average rates [4]. A general conclusion is that non-orthogonal schemes have higher power efficiency than orthogonal ones for delay-sensitive applications in fading channels. [4]

The theoretical power limits achieved by CDMA above implicitly involve MUD [6] that resolves the intra-cell interference problem. With MUD, the CDMA performance is no longer interference-limited, at least theoretically [8]. Later we will show that this theoretical assertion can be turned into reality using recently developed iterative MUD techniques.

Single Cell Downlink Scenario

The discussion so far is for uplink MACs, but the results shown in Figs. 2 and 3 are also applicable to downlink BCs based on the uplink-downlink duality principle [4]. (Note that the dual of Fig. 3 is a downlink broadcast system with two transmit antennas at the base station.) Again, MUD is necessary if we want to fully exploit the advantage of MUG in downlink BCs. However, MUD in the downlink can raise serious concern in practice due to the high receiver cost at mobile units.

With the low-cost CBC detection technique for IDMA, the total receiver complexity increases only linearly with the number of users *K* [3]. An interesting observation from Figs. 2 and 3 is that a major portion of MUG can be achieved with a very small number of users, such as $K = 2$ (i.e., by applying MUD to only 2 users). For example, at $K = 2$ in Fig. 3, an optimal scheme can achieve about 4dB and 9 dB power reduction at R_s = 4 and 8 bits/symbol compared with fixed TDMA, respectively. The MUD cost for $K = 2$ is only modestly higher than the corresponding single user detection cost for TDMA (e.g., double[3]). The question is thus whether the gain is worth the cost. Recall that a turbo code can provide about 3dB more coding gain than a convolutional code at more than double decoding cost. It seems, therefore, that the potential gain shown in Figs. 2 and 3 can justify the complexity increase for introducing MUD in downlink applications.

Multiple Cells Scenario

Assume that cross-cell interference is treated as additive noise, i.e., MUD is not applied to other-cell users. Due to spectrum re-use, interference from other-cell users is inevitable in both orthogonal and non-orthogonal schemes. The performance of a cellular system is mainly determined by the carrier to interference ratios (CIRs) of the users. Lower transmitted average-sum-power implies higher average CIRs and thus more users can be supported. Higher power efficiency may therefore lead to higher cellular spectral efficiency.

Non-orthogonal systems like CDMA also have the advantage of the so-called mitigation effect on the worst-case cross-cell interference by means of the spreading gain. In a TDMA or FDMA system, interference is dominated by one (or a few) strong interferer from the nearby cells. In this case, the worst-case interference power is the limiting factor on system performance. In a random waveform CDMA, all users interfere with each other. After de-spreading, the total interference power is divided by the spreading ratio. This “accumulate and divide” operation results in an average effect on strong and weak interferers, i.e., it mitigates the worst-case damage from the strong interferers. Such mitigation is usually preferable, since it can minimize the adverse effect suffered by users.

It is interesting to note that orthogonal CDMA systems may provide both intra-cell interference avoidance and cross-cell interference mitigation [11]. However,

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[3] Here is a brief complexity comparison. Assume $K = 2$ and *N*-layer superposition coded modulation (SCM) [9] for both TDMA and IDMA. With TDMA, each user occupies all *N* layers in half the time and is idle in the other half. With IDMA, each user occupies *N*/2 layers at all time. Then the complexity of IDMA is two times that of TDMA since each TDMA receiver only operates in half the time. The use of SCM for comparison here is based on the consideration that SCM has comparable performance and complexity as the best known coded modulation schemes such as bit-interleaved coded modulation (BICM) [10].

orthogonal CDMA systems do not provide the MUG mentioned above due to the fact that the signal space for each individual user is reduced in such systems to maintain orthogonality.

Other Considerations

We now provide a brief comparison of some practical aspects of different MA techniques.

Orthogonal Schemes

Orthogonal schemes have the following common advantages.

- They can employ high-order modulation techniques to increase single-user rate.
- They can avoid intra-cell interference by assigning orthogonal signal sub-spaces to different users.
- They are not sensitive to the near-far effect.

On the other hand, orthogonal schemes have some common disadvantages (besides the spectral-power efficiency disadvantage discussed earlier).

- They are sensitive to cross-cell interference. This has been discussed in the previous section.
- Frame synchronization is usually necessary to maintain orthogonality.

Comments on individual orthogonal techniques include the following.

- In a multipath channel, the cost of inter-symbol interference (ISI) equalization in TDMA increases rapidly with the number of paths [4].
- The ISI problem can be avoided in OFDMA by a cyclic prefix technique [4].
- FDMA is prone to fading effects due to its narrow band nature.

Non-Orthogonal Schemes

CDMA is the most well known non-orthogonal technique. The main advantages of CDMA are its robustness against fading and cross-cell interference, and its flexibility in asynchronous transmission environments.

A main concern for CDMA is intra-cell interference. This can be treated by MUD [6]. However, the application of MUD has been limited by its high computational cost (complexity may increase in an exponential or polynomial order with K, the number of users involved). It is also difficult to support high single-user rate with CDMA.

With recent progress in iterative detection techniques, MUD complexity can be reduced to a level comparable to single-user detection for orthogonal schemes. A potential solution is IDMA that relies on the user-specific interleavers for user separation. The spreading operations in CDMA can be replaced by low rate forward error correction (FEC) codes in IDMA to provide increased coding gain. As a special case of CDMA, IDMA inherits most of the advantages of CDMA mentioned above. Furthermore, the iterative CBC detection algorithm for IDMA [3] has per-user complexity independent of K and can be incorporated in the overall iterative decoding process for turbo or low-density parity-check (LDPC) codes. Consequently, the cost of an IDMA receiver for K users is only modestly higher than the total cost of K single-user receivers (assuming iterative decoders are involved in both cases). There is also no need for frame-level synchronization in IDMA. Inaccuracy in chip-level synchronization can be treated in the same way as ISI.

The performance of some illustrative IDMA systems is shown in Fig. 4. The channel conditions are the same as in Fig. 2 with both path loss and lognormal fading in a single Hexagon cell setting. At the transmitter for user-k, a rate 1/2 convolutional code with generator $(23, 35)_8$ is used. The signal for each user is randomly and independently interleaved and QPSK modulated. For $K = 1$, all eight code streams (each independently interleaved) are assigned to one user. The power level of each code stream is optimized based on the method outlined in [3]. Similarly, four, two and one code streams are allocated to each user for $K = 2$, 4, and 8, respectively. The throughput (i.e., $R_s = 8$ bits/chip[4]) shown in Fig. 4 is higher than those reported for CDMA in the literature. The advantage of MUG can be clearly seen here by noting power saving for increased K.

Interestingly, the results in Fig. 4 also suggest an alternative coded modulation method: We can increase single-user rate by allocating multiple code streams to a user. This is the so-called superposition coded modulation (SCM) scheme that provides a flexible means for rate adaptation [9][12]. SCM is useful for many applications. For example, it can be used in MIMO systems together with the singular value decomposition and water-filling techniques [4]. The iterative decoding technique for SCM can also be conveniently implemented together with IDMA-type iterative MUD [9] and so it is particularly useful in applications involving MUG.

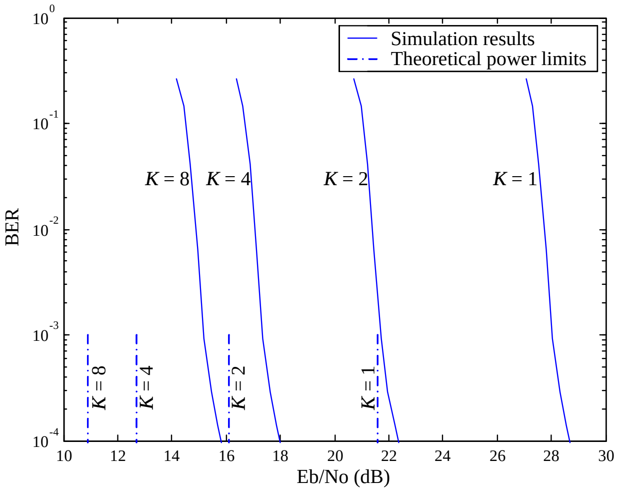

Fig. 4. Performance of IDMA systems in a multiple access channel. The throughput is $R_s = 8$ bits/chip. The information length of each code stream is 4096. The channel conditions are the same as those in Fig. 2. The outage probability is 0.01.

In a multi-path environment with ISI, the detection costs for CDMA and IDMA increase at least linearly with the number of paths (using a Rake receiver [4] or an iterative detector [3]). This may still be a concern for a wideband system when delay dispersion is large. Some solutions for this problem are outlined below.

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[4] Note that the basic unit is chip here, which follows the tradition of conventional CDMA. However, “chip” has the same meaning as “symbol” used in Figs. 2 and 3.

Table I. Comparison of different multiple access techniques.

	FDMA/OFDMA	TDMA	CDMA with SUD	IDMA	OFDM-CDMA	OFDM-IDMA
Intra-cell interference	No	No	Sensitive	Suppressed by MUD	Sensitive	Suppressed by MUD
Cross-cell interference	Sensitive	Sensitive	Mitigated	Mitigated	Mitigated	Mitigated
To achieve high single-user rate	High-order modulation	High-order modulation	Difficult	SCM	Difficult	SCM
Near-far effect	Insensitive	Insensitive	Sensitive	MUG	Sensitive	MUG
Treatment for ISI	Cyclic prefix	Equalization	Rake receiver	CBC detection	Cyclic prefix	Cyclic prefix
Synchronization	Yes	Yes	No	No	Yes	Yes

Hybrid Schemes

To combine the advantages of both orthogonal and non-orthogonal schemes, one possible approach is the hybrid OFDM-CDMA scheme [13]. Its basic principle is that each user is allocated with several OFDM sub-carriers and CDMA is used for user separation if multiple users share a common set of OFDM sub-carriers. OFDM-CDMA has the advantages listed below.

- CDMA is robust against fading and cross-cell interference.
- OFDM provides a simple treatment of ISI.

However, this hybrid scheme also has the following disadvantages:

- Intra-cell interference is induced due to the use of CDMA.
- Frame synchronization is required for OFDM.

OFDM-IDMA has been recently proposed as an alternative to plain IDMA in ISI channels [14][15]. In an OFDM-IDMA transmitter, the signal stream of a user is first FEC encoded and then permuted by a user-specific chip-interleaver. The resultant signal is then transmitted over selected OFDM sub-carriers with good channel conditions. At the receiver side, OFDM operations resolve ISI and IDMA operations resolve intra-cell interference. The main advantage of OFDM-IDMA over OFDM-CDMA is that low-cost iterative MUD becomes more effective when user-specific chip-interleaving is used. OFDM-IDMA also has lower receiver cost than plain IDMA in a multi-path environment where delay dispersion is large, since the complexity of OFDM operations is independent of path number. OFDM-IDMA appears to be a very promising solution for applications where frame synchronization is possible.

The features of different MA techniques are summarized in Table I.

Conclusions

The following is a summary of our findings so far.

- Non-orthogonal approaches can fully exploit the advantage of MUG for delay-sensitive applications in fading environments.
- MUG is significant (e.g., more than 10 dB) when the throughput is high.
- The potential gain can also justify the complexity increase for MUD in downlink applications.
- SCM provides a flexible implementation technique for MIMO systems.
- Hybrid schemes can combine the advantages of both orthogonal and non-orthogonal techniques and provide promising solutions for future wireless cellular communications.

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