EXTENDING THE CAPACITY OF MULTIPLE ACCESS CHANNELS

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ABSTRACT

Multiple access techniques which allow a communication medium to be shared between different users represent one of the most challenging topics in digital communications. In terms of the number of users that can be accommodated on a given channel, there are two distinct classes of multiple access techniques. The first class includes the well-known FDMA, TDMA, and OCDMA. On a channel whose bandwidth is N times the bandwidth of the individual user signals, these techniques can accommodate N users without any mutual interference, but not a single additional user can be supported beyond this limiting number. The second class includes CDMA with pseudo-noise spreading sequences (which we refer to as PN-CDMA) and some other related schemes. PN-CDMA does not have a hard limit on the number of users that can be accommodated, but is subject to multi-user interference which grows linearly with the number of users. In this article, after reviewing the capacity limits of existing multiple access techniques, we describe some newly introduced concepts which allow us to accommodate N users without any interference while also accommodating additional users at the expense of some SNR penalty.

INTRODUCTION

Multiple access techniques represent one of the most essential functions of access networks, whether based on coaxial cable, fiber, radio, or satellite. The three basic multiple access techniques are frequency-division multiple access (FDMA), time-division multiple access (TDMA), and code-division multiple access (CDMA) [1]. The oldest of these, FDMA, has been in use since the early days of telecommunications. Today, there is also a modern version of this technique called orthogonal FDMA (OFDMA), principally introduced for cable networks which suffer from narrowband interference [2]. A basic question in any access network is the number of users that can be accommodated per cell, and in addition to other physical-layer functions this parameter is closely related to the multiple access technique used.

From the standpoint of the number of users that can be accommodated on a given channel, multiple access techniques can be separated into two basic categories with distinct operating principles: The first category, which can be referred to as orthogonal-waveform multiple access (OWMA), includes FDMA, TDMA, CDMA with orthogonal spreading sequences (called orthogonal CDMA, or OCDMA), OFDMA, and any other multiple access scheme which assigns orthogonal signal waveforms. On a channel whose bandwidth is N times the bandwidth of the individual user signals, these techniques can accommodate N users without any mutual interference, but N appears as a hard limit which cannot be exceeded without reducing user bit rates. The other category includes CDMA with pseudonoise (PN) spreading sequences (PN-CDMA) and multiple access techniques based on frequency hopping. Here, we will ignore frequency hopping and focus on PN-CDMA. In this technique, different user signals interfere with each other, and the amount of interference grows linearly with the number of simultaneous users. Consequently, the capacity of PN-CDMA is not a fixed number; it depends on the receiver used on one hand, and on the tolerable performance degradation on the other.

In this article, we begin with a brief review of different multiple access techniques and analyze their capacity. Throughout the article, N will designate the ratio of the total bandwidth of the multiple access channel to the bandwidth of the individual user signals, and we will assume an ideal additive white Gaussian noise (AWGN) channel. Then, after observing that:

- OWMA techniques are not subject to any interference up to N users but have a hard capacity limit at that point
- PN-CDMA has a soft capacity that depends on the desired performance but is subject to interference as soon as there are two active users

we describe two newly introduced concepts [3, 4] which allow to significantly increase the number of users K beyond N while guaranteeing interference-free transmission for $K \leq N$. The first consists of augmenting OCDMA with PN sequences when the N orthogonal sequences are all assigned. The excess users which use PN spreading sequences are subject to mutual interference in addition to interference from the set of

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orthogonal sequences, while orthogonal sequence users only get interference from PN sequence users. The second concept consists of using two sets of orthogonal signal waveforms. In this technique, there is no interference between users with spreading sequences from the same set, but of course there is interference between users from different sets. In both techniques, iterative multistage detection is used at the receiver to cancel multi-user interference. Throughout the article, we focus on the single-cell case. This may represent a standalone tree-structured cable network, a satellite beam spot, or an isolated cell in a radio network. Interference analysis in cellular networks requires, of course, taking into account the interference from users located in other cells.

The article is organized as follows. First, we give a brief state-of-the-art review of existing multiple access techniques. Next, we give a preliminary discussion on the sensitivity to narrowband interference and the achievable cell capacity in cellular CDMA and TDMA. Then, we present a CDMA scheme which uses a combination of orthogonal and PN spreading sequences along with an iterative multistage detection technique. That secction then describes a general multiple access concept that uses two sets of orthogonal signal waveforms. Finally, we summarize our main results and give our conclusions.

A BRIEF REVIEW OF MULTIPLE ACCESS TECHNIQUES

FDMA

FDMA is the most classic multiple access technique, widely used today in satellite, cable, and radio networks to multiplex analog or digital signals. It consists of assigning a separate carrier frequency to each user. The available bandwidth is split into a set of N channels, each assigned to one active user. Frequency spacing of the individual channels is such that there is no overlap between adjacent spectra. Furthermore, a sufficient guard band is left between two adjacent spectra in order to cope with frequency uncertainty of the oscillators used and to minimize interference from adjacent signals after the receive filter. Neglecting the guard bands, a frequency multiplex of N modulated carriers with an individual bandwidth of W Hz occupies NW Hz. The basic problem of classic FDMA is that N modulators and demodulators need to be implemented at the base station if N users are to be accommodated simultaneously. This leads to excessive complexity and cost in a broadband access system where the base station must handle hundreds or thousands of users. On the positive side, one advantage of FDMA is that since each user occupies $(1/N)$th of the total bandwidth, channel equalization is either not needed or simpler than in other multiple access techniques in which user signals are spread over the entire channel bandwidth.

TDMA

TDMA is a very popular multiple access technique used in numerous international standards and proprietary systems. For example, the Global System for Mobile Communications (GSM), which counts today more than 200 million subscribers worldwide, as well as the technical specifications of several international forums including the Digital Video Broadcasting (DVB) project and the Digital AudioVisual Council (DAVIC) for cable networks, microwave multipoint distribution services (MMDS), and local multipoint distribution services (LMDS) employ time-division multiplexing (TDM) on the forward channel and TDMA on the return (reverse) channel [5, 6]. These are only a few well-known examples. In what follows, we will not make any distinction between multiplexing and multiple accessing. The first refers to the function performed at the base station (or cable network head-end) for the forward link, and the second refers to the function performed by user terminals to communicate with the base station. The difference is that in multiplexing all signal components are available locally, whereas signal components in multiple access originate from separate geographical locations, and their timing and amplitude differences need to be compensated. When this compensation is perfect, multiple access essentially coincides with multiplexing.

TDMA consists of assigning time slots from the composite signal occupying the entire channel bandwidth. In what follows, we consider a simple TDMA scheme which formats the composite wideband signal into frames of N time slots and assigns the kth time slot of each frame to the kth user. The composite bit rate in this system is evenly shared between the N users. Neglecting the overhead needed for framing, the multiplexed signal bandwidth is N times the bandwidth of the individual user signals in the single-user case. This example shows that, as can ideal FDMA, TDMA can support N users on a channel whose bandwidth is N times the bandwidth of the individual user signals.

CDMA

CDMA is a multiple access technique that derived from direct sequence spread spectrum (DS-SS) systems originally developed for military communication systems [7]. DS-SS systems have two interesting properties which make them extremely attractive for those applications. The first is that after spreading, the useful signal becomes virtually buried in the background noise in both the time and frequency domains. This leads to discreteness and low intercept probability. The second is the robustness of the transmitted signal to intentional or unintentional jamming. The despreading operation at the receiver improves the signal-to-interference ratio (SIR) by a factor of $10\log(N)$, where N denotes the spreading factor. It is, of course, essential in this application to use long PN sequences which are difficult to detect, because the whole process becomes useless if an unauthorized user is able to replicate the spreading sequence.

PN-CDMA makes use of the second property of DS-SS systems to share a communication channel among different users. (Note that the first property is in principle irrelevant to multiple access, because discreteness is not an issue.) Each user is given a PN sequence for spreading the transmitted signal and despreading it at the

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receiver. All users transmit in the same band, and other user signals are regarded as co-channel interference [1]. If the useful signal power is normalized by 1 and the spreading factor is N, the interference power from each other user is $1/N$ after despreading at the receiver. The total interference power is proportional to the number of interfering users, and the cell capacity depends on the performance degradation that can be tolerated. If we assume that there are N active users (as in a fully loaded TDMA cell), the interference power is $(N-1)/N \cong 1$, which is clearly prohibitive for a single-user detector. With such a detector, the cell capacity in PN-CDMA is only $N/4$ if the interference level is to be kept 6 dB below the signal level. Of course, capacity can be increased by multi-user detectors [8] which cancel interference from other users, but it is still to be demonstrated that PN-CDMA can reach a capacity of N users per cell with practically realizable detectors and acceptable performance.

OCDMA is similar to PN-CDMA except that it employs a set of orthogonal sequences, such as Walsh-Hadamard (WH) sequences [9], for spectral spreading. The WH sequence length is equal to the spreading factor N, which in turn is equal to the number of chips per transmitted symbol. That is, unlike PN-CDMA, in which the spreading sequences look random, spreading sequences in OCDMA are fully deterministic and repeat from one symbol to the next. Provided the user signals are well synchronized in terms of symbol timing, orthogonality of the spreading sequences guarantees that there is no mutual interference between users. But the maximum number of orthogonal sequences of length N being exactly N, this is also the maximum number of users that can be accommodated (assuming again that all users require a fixed bit rate equal to the chip rate divided by N). This implies that in terms of the number of users which can be accommodated on a given channel, OCDMA is equivalent to TDMA and FDMA.

OFDMA

This multiple access technique, described in [2], was proposed for cable networks which suffer from narrowband interference. It directly derives from the multicarrier transmission technique called orthogonal frequency-division multiplexing (OFDM) which has become a standard for digital terrestrial audio and video broadcasting, and is pursued today by several standardization groups as a serious candidate for wireless indoor communications. With channel coding and interleaving, OFDM is an attractive transmission technique on dispersive channels, particularly if the channel impulse response is long and/or the transfer function has deep notches [10]. The two basic problems of OFDM are the large peak-to-average power ratio of the transmitted signal, which requires costly transmit power amplifiers, and its strong requirement for oscillators with very low phase noise.

In its simplest form, OFDMA consists of assigning a single carrier to each user. The carrier spacing is $1/T$, where T designates the symbol period. The transmitted signal is an unfiltered single-carrier signal, and the $\sin(x)/x$-shaped spectra of adjacent carriers overlap, but modulated carriers are still orthogonal thanks to the carrier spacing of $1/T$ and the symbol timing control which ensures that different user signals arrive at the cable network head-end in phase. Although the transmitted user signals are single-carrier in the basic OFDMA scheme, their sum which is received by the cable network head-end is an OFDM signal. Therefore, a single receiver (an OFDM receiver) is all that is needed to detect the N user signals as opposed to N demodulators in classic FDMA. From the capacity standpoint, there is no difference between this multiple access technique and FDMA, TDMA, and OCDMA, because to accommodate N users requires N times the bandwidth of the individual user signals.

SOME PRELIMINARIES

Before proceeding further, it is instructive to briefly discuss two interesting issues. The first concerns the sensitivity of multiple access techniques to narrowband interference, on which quite erroneous ideas are widespread within the engineering community. The second is the achievable cell capacity in cellular systems, about which there has been a long-standing controversy.

SENSITIVITY TO NARROWBAND INTERFERENCE

As mentioned earlier, narrowband interference was the basic reason for one of the present authors to propose OFDMA for the reverse channel in cable networks. Beyond any doubt, FDMA and OFDMA are the most suitable multiple access techniques to operate on a channel with static narrowband interference. Since the channel is split into N separate bands, the few bands that are corrupted by interference can easily be discarded in the resource allocation process. If the interference affects L carriers of the N carriers available, there are still $N - L$ carriers usable, and $N - L$ users can be supported without any performance degradation. This is true in the strict sense in FDMA with nonoverlapping carrier spectra and is also a good picture of OFDMA although more than M carriers will be unusable in the latter case.

In contrast to FDMA and OFDMA, the impact of narrowband interference is the same for all users in TDMA and CDMA with PN sequences. All users suffer from signal-to-noise ratio (SNR) degradation that grows with the interference power, and the channel becomes entirely unusable beyond some threshold value of the interference power. An interesting question concerns the relative sensitivity of TDMA and CDMA to narrowband interference. Since CDMA is based on DS-SS techniques, it is commonly perceived as more robust than TDMA. To the question of which of these two multiple access techniques is more robust to narrowband interference, it is quite unlikely that someone would answer either that TDMA is more robust or that the two techniques are equivalent. One possible reason for this perception is that the CDMA vs. TDMA issue is erroneously assimilated into DS-SS vs. narrowband transmission. Yet, using continuous-wave (CW) interference, it is clearly demonstrated in [11] that for a given interference power, the SIR at the threshold detector input is identical in TDMA and CDMA. It is also shown that in terms of the resulting bit error rate (BER) degradation, TDMA is in fact slightly superior to CDMA. These results may seem counterintuitive, but they are hardly surprising and are easily explained as follows.

It is true that CDMA benefits from a factor of N in the despreading process, but the same factor is also valid for TDMA since only $(1/N)$th of the interference energy affects a given user. In other words, the performance of TDMA is determined by the ratio of the interference power to the power of the multiplexed signal with N users rather than to the power of the individual signals. Another way to see this is to recognize that TDMA is in fact a special form of CDMA in which the (orthogonal) spreading sequences are composed of a single 1 and $N - 1$ zeros, the position of the nonzero element determining a particular spreading sequence. Signal detection can be viewed as windowing the desired symbol position, rejecting the other $N - 1$ symbols of the frame along with the interference energy affecting them, and then stretching the windowed symbol to the frame length. This process obviously gains a factor of N against the interference power, as does the despreading operation in standard CDMA receivers.

Once it becomes clear that TDMA and CDMA are equivalent in terms of SIR at the threshold detector input, it is easily shown that CDMA suffers a higher BER degradation. Since there is no special processing of the received signal in TDMA, the interference at the threshold detector input has a fixed amplitude and uniform phase. In contrast, the interference at the correlator output in a CDMA receiver is a linear combination of a large number of segments from the original interference which is closely approximated by a Gaussian process. Recognizing that for a given noise (or interference) power, the Gaussian process leads to a higher BER than does a constant-amplitude process, one realizes that the impact of narrowband interference on the BER is stronger in CDMA.

CELL CAPACITY IN CELLULAR SYSTEMS

The comparison of CDMA and TDMA in terms of the achievable cell capacity in cellular systems has been a subject of strong and long-standing controversy. Rarely (if ever) in telecommunications history have technical issues created such heated debates. There are several reasons for this controversy. First, commercial interests, which often dominate the work of standardization groups, tend to obscure technical aspects, and it is not unfair to say that this has been particularly strong in digital mobile radio. Second, most existing comparisons are between systems in which TDMA and CDMA are only one ingredient among many others, and meaningful conclusions are quite hard to draw from them as to the true capacity of the multiple access techniques themselves. Finally, the problem does not have a unique answer, because it consists of comparing one method with a clearly understood hard capacity limit to another that has a soft capacity which depends on the receiver used and other assumptions made.

The ultimate solution will therefore depend on the particular application, but analyzing cellular TDMA and CDMA with the same maximum capacity and bandwidth occupancy, the present authors found [12, 13]) that in a cellular network with hexagonal cells, assuming that signal attenuation is proportional to the fourth power of the propagation distance, multiple access interference is approximately 10 dB higher in CDMA than in TDMA when the cells are fully loaded. In turn, this means that CDMA must virtually use 10 times more bandwidth than TDMA to achieve the same interference level, which may seem surprising given the common perception that CDMA has substantially higher capacity than TDMA. The cellular TDMA considered in this study has a frequency reuse factor of 4 and a capacity of N users/cell. The CDMA scheme was a two-layer CDMA in which the transmitted signal is first spread by a user-specific length-$4N$ WH sequence and then multiplied by a cell-specific PN sequence without further spreading. The maximum number of spreading sequences in CDMA was N, so both cellular schemes had the same maximum cell capacity and total bandwidth occupancy. Our analysis of CDMA in a number of other situations led us to the conclusion that capacity is precisely the price paid in general for the ease of network planning which is the chief virtue of this multiple access technique.

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NEW MULTIPLE ACCESS CONCEPTS

After the brief review of the principal existing multiple access techniques presented above and in the following discussion, we can now summarize the capacity issues: As sketched in Fig. 1 for $N = 8$, all multiple access techniques which use orthogonal signal waveforms (FDMA, TDMA, OCDMA, OFDMA, etc.) can support N users without any interference (on a channel whose bandwidth is N times that of the individual user signals), but they reach a hard limit at that point. On the other hand, PN-CDMA has a soft capacity but is subject to interference and BER degradation as soon as there are two simultaneous users on the channel. Once these observations are made, it becomes strongly desirable to ensure interference-free transmission for up to N users while also supporting additional users at the expense of some SNR penalty. This would combine the best virtues of existing multiple access techniques while avoiding their shortcomings. In an attempt to achieve this goal, two new multiple access concepts were devised recently [3, 4]. We describe them in the following subsections.

COMBINING OCDMA WITH PN-CDMA

The first idea for extending cell capacity beyond the spreading factor N while maintaining interference-free transmission when the number of users K is less than or equal to N is to use OCDMA and augment it with PN-CDMA when K exceeds N [3]. More specifically, the base station in this scheme assigns WH sequences to the first N users and PN sequences to the additional users. With $K = N + M$ users, a set of M users will employ PN sequences. Signal detection is carried out iteratively, each iteration consisting of two separate stages, The performance difference that was observed between the two sets of users in this technique motivated us to use two sets of orthogonal signal waveforms.

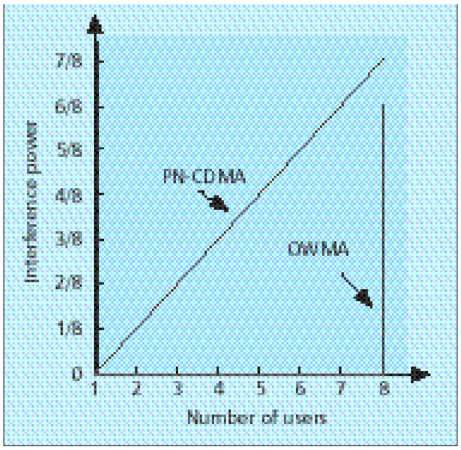

Figure 1. *Multi-user interference power in OWMA and PN-CDMA for* N = *8.*

one for the set of users with WH sequences and one for the set of users with PN sequences.

First Iteration

Stage 1 — Remember that the first set of N users do not have any mutual interference. They only get an interference power of M/N from the second set of users. As long as M remains small, the correlator output for these users can be sent to a threshold detector to make symbol decisions with some good reliability. For example, $M = N/4$ leads to an SIR of 6 dB, and since the interference is the sum of a large number of random variables, it tends to be Gaussian. This is equivalent to operating the receiver at an SNR of 6 dB on an AWGN channel. For binary phase-shift keying (BPSK) modulation, this leads to a BER on the order of 10^{-3}. This BER is not sufficiently low to consider the first-stage decisions as final, but they can be used as preliminary decisions in the next stage for interference cancellation.

Stage 2 — Considering next the set of M users with PN sequences, they get an interference power of $N.1/N = 1$ from the first set of users in addition to their mutual interference power which amounts to $(M - 1)/N$. The total interference power for these users is therefore $1 + (M - 1)/N$ which is clearly prohibitive for a threshold decision device, but the preliminary decisions of the first stage can be used to synthesize and subtract the WH sequence users. Interference synthesis and cancellation are as follows:

Let $W_1, W_2, \ldots, W_N$ designate the N orthogonal sequences assigned to the first set of users. We write $W_i = (w_{i,1}, w_{i,2}, \ldots, w_{i,N})$ for $i = 1, 2, \ldots, N$. That is, $w_{i,j}$ designates the jth chip of the sequence W_i. Next, suppose that $P_1, P_2, \ldots, P_M$ designate the portion corresponding to the current symbol of the PN sequences allocated to the second set of users. Note that the W_i sequences are independent of the symbol index, and although the PN sequences do not repeat from one symbol to the next, we also drop their symbol index, because the signal processing we consider in the receiver is memoryless. That is, detection of the current symbol does not involve signal samples from previous and future symbols. Consequently, we write $P_i = (p_{i,1}, p_{i,2}, \ldots, p_{i,N})$ for $i = 1, 2, \ldots, M$. Also, rather than using real-valued WH and PN sequences which take their values from the set $\{\pm 1\}$, we assume in what follows complex spreading sequences [14] taking their values from the set $\{\exp(\pm j\pi/4), \exp(\pm j3\pi/4)\}$. Furthermore, to avoid using two real-valued WH sequences to generate a complex WH sequence and divide by two the number of orthogonal spreading sequences of a given length, we assume that a complex WH sequence consists of multiplying a real-valued WH sequence by a complex PN sequence. In the sequel, W_i ($i = 1, 2, \ldots, N$) will designate the complex WH sequences generated in this way rather than the original binary WH sequences.

After the despreading operation at the receiver,, the total interference from the WH sequence users on the kth PN sequence user (the user with index $N + k$) signal is

$$\begin{aligned} I_{N+k} &= \sum_{i=1}^{N} a_i \sum_{j=1}^{N} p^*_{k,j} w_{i,j} \\ &= \sum_{i=1}^{N} a_i P_k^* W_i^T \end{aligned} \qquad (1)$$

where a_i is the data symbol transmitted by the ith user during the current symbol interval, and where the superscripts * and T denote complex conjugate and transpose, respectively. Each term in this sum represents the interference from one user.

Since P_k and W_i, $i = 1, 2, \ldots, N$ are known to the receiver, I_{N+k} can be estimated once the symbol decisions are made by the receivers of users 1 to N. This estimate of I_{N+k} is then subtracted from the corresponding correlator output before sending this signal to the threshold detector. If all decisions are correct, interference cancellation is perfect, and the only remaining interference is the mutual interference of PN sequence users. The power level of this interference is $(M - 1)/N$, and as for the first set of users, signal detection is possible at least to obtain some preliminary decisions. As long as the first-stage decision error probability is small, reliability of the second-stage decisions is similar to that of the first-stage decisions.

Second Iteration — The symbol decisions made for PN sequence users in the first iteration are used to synthesize and subtract their interference from the WH sequence users signals. The interference corrupting the kth user signal ($k = 1, 2, \ldots, N$) is given by

$$\begin{aligned} I_k &= \sum_{i=1}^{M} a_{N+i} \sum_{j=1}^{N} w^*_{k,j} p_{i,j} \\ &= \sum_{i=1}^{M} a_{N+i} W_k^* P_i^T. \end{aligned} \qquad (2)$$

This interference is synthesized by substituting the second-stage decisions of the first iteration for the symbols actually transmitted. Since the decisions are correct with a probability close to 1, the synthesized replica is virtually identical to the actual interference. The synthesized interference is subtracted from the kth WH sequence user signal at the correlator output, and the resulting signal is passed to the threshold detector. This process is repeated for all WH sequence user signals.

The second-iteration decisions for PN sequence users are made after subtracting their mutual interference based on the first-iteration decisions in addition to subtracting the interference of WH sequence users based on the second-iteration decisions. The total interference corrupting the *k*th PN sequence user is given by

$$\begin{aligned} I'_{N+k} &= I_{N+k} + \sum_{k' \neq k} a_{N+k'} \sum_{j=1}^{N} p^*_{k,j} p_{k',j} \\ &= I_{N+k} + \sum_{k' \neq k} a_{N+k'} P_k^* P_{k'}^T . \end{aligned} \qquad (3)$$

The first term in this expression is the interference from the set of WH sequence users given by Eq. 1, and the second represents the interference from the other PN sequence users. After subtracting the best available estimate of this interference, the correlator output for the *k*th PN sequence user is sent to the threshold detector, which makes the second-iteration decision for that user. The results indicate that if the number of excess users M is not too large, the second iteration gives sufficiently good performance and the detection process stops at this iteration. But for larger values of M, further improvements are still possible from additional iterations.

Figure 2 shows the simulated BER performance of this multiple access technique using BPSK modulation, a spreading factor $N = 64$, and a number of PN sequence users $M = 12$. The first (resp. the second) plot gives the BER curves corresponding to the WH sequence users (resp. the PN sequence users) after the first, second, and third iterations. The figure also gives the analytic results which were obtained assuming no decision errors in the interference cancellation steps. We observe that (as expected) the first iteration does not give sufficiently reliable decisions, but convergence quickly occurs after the second or third iteration. We can also see that at all iterations, performance is slightly better for WH sequence users which are free of mutual interference. After the third iteration, the SNR degradation from ideal BPSK at the BER of 10^{-4} due to residual interference is virtually zero for WH sequence users and approximately 0.3 dB for PN sequence users. The performance difference between the two sets of users is not surprising, because in the example at hand WH sequence users are only corrupted by interference from 12 users, while PN sequence users are corrupted by interference from 74 users.

USING TWO SETS OF ORTHOGONAL SIGNAL WAVEFORMS

The multiple access technique described in the previous section makes use of two sets of signal waveforms, but only one is orthogonal, the other being a set of uncorrelated PN sequences. The performance difference that was observed between the two sets of users in this technique motivated us to use two sets of orthogonal signal waveforms [4]. In such a multiple access scheme, a given user will not interfere with other users which make use of resources from the same set, but only with users whose resources are from the other set.

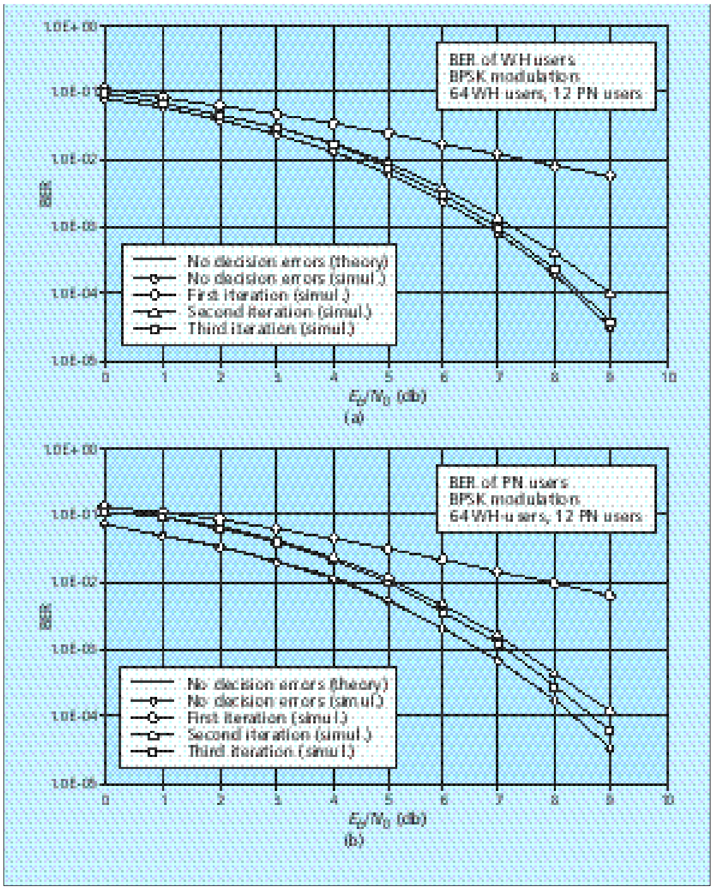

Figure 2. *The BER performance of OCDMA augmented with PN-CDMA: a) BER of WH sequence users; b) BER of PN sequence users.*

We will now describe this general concept using OCDMA and TDMA as the two sets of orthogonal signal waveforms. For the sake of simplicity, we assume that the TDMA frame consists of N time slots of one symbol each. (This is of course not a practical situation in itself, because TDMA time slots typically comprise a large number of symbols, including both information symbols and overhead. But a TDMA signal with L symbols/time slot and N users/frame gives L isolated symbols with a separation of $N - 1$ symbols when input to a block interleaver with L rows and N columns in which the input data are written row by row, and the output data are read column by column. In other words, the assumption made about the TDMA time slots is satisfied provided that an appropriate interleaver is employed.) Suppose next that resource allocation starts with length-N WH sequences. Up to N users, the multiple access scheme at hand thus coincides with OCDMA. But once all WH sequences are used, the base station assigns TDMA time slots to additional users. All signal waveforms are assumed to have equal energy. Figure 3 shows the instantaneous

The presented multiple access concepts thus significantly increase the number of users that can simultaneously operate on a multiple access channel and open up some interesting perspectives in the fields of cable networks, fixed wireless access, and mobile radio.

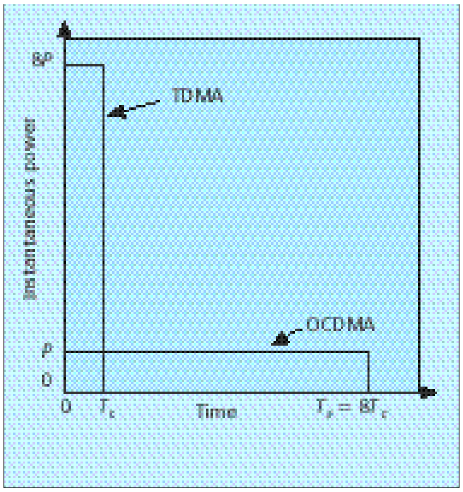

Figure 3. *Instantaneous power of OCDMA and TDMA pulses for* N = 8.

power of the waveforms used for $N = 8$. The energy of OCDMA waveforms is uniformly distributed over the symbol period $T_S = 8T_C$, where T_C is the chip period (which is also the TDMA symbol period). The TDMA waveform in this figure interferes with the first chip of all OCDMA users, but all other chip periods are free of interference. Since all users have the same symbol energy, the interference at the correlator output in the OCDMA receivers is $1/N$ when only one TDMA user is active. With M TDMA users, the interference power is M/N. Clearly, $1/N$ is also the interference power caused by each OCDMA user on TDMA users, because only $(1/N)$th of the OCDMA pulse energy affects a given TDMA pulse.

First Iteration — Provided that M remains moderately small with respect to N, the correlator output in the N OCDMA receivers can be directly sent to a threshold decision circuit to make preliminary decisions. This is the first stage of the detection process. The second stage starts with the synthesis of the interference of OCDMA users on TDMA users using the preliminary decisions obtained from the first stage. Omitting the time index as previously, the interference on the kth TDMA user (the user with index $N + k$) can be written as follows:

$$I_{N+k} = \sum_{i=1}^{N} a_i w_{i,k} \qquad (4)$$

where a_i is the present symbol of the ith OCDMA user, and $w_{i,k}$ is the kth chip of the WH sequence assigned to that user. This interference is estimated by simply substituting the first-stage decisions $\hat{a}_i$ ($i = 1, 2, ..., N$) for the symbols actually transmitted a_i ($i = 1, 2, ..., N$). The estimated interference is subtracted from the received TDMA signals, and after this operation the TDMA signals are passed to a threshold detector. As in the previous technique, $M = N/4$ leads to an SIR of 6 dB and a BER of approximately 10^{-3} for the first-stage preliminary decisions assuming BPSK signaling. This means that interference cancellation in stage 2 is close to ideal even with such a high value of M. In other words, the second-stage decisions on the transmitted TDMA symbols will be very reliable, and the corresponding BER curve will be close to the ideal curve corresponding to interference-free transmission.

Second Iteration — In the second iteration, the interference of TDMA users on OCDMA users is synthesized using the first-iteration symbol decisions for these users. The interference from M TDMA users at the correlator output of OCDMA receivers is expressed as

$$I_k = \sum_{i=1}^{M} w_{k,i} a_{N+i} \qquad (5)$$

for the kth user. The estimated interference is subtracted from the correlator output, and an improved decision is made for the symbol transmitted by each of the N OCDMA users. Since most TDMA symbol decisions made in the first iteration are correct, interference cancellation from OCDMA user signals in the second iteration is close to perfect, and this step hopefully gives the final receiver decisions for these symbols. Also, there is little need in the second iteration to use these decisions for canceling in a second stage the interference caused by the OCDMA users on the TDMA users since most of the TDMA user signals have been detected correctly during the first iteration. The simulation results indicate that this is indeed the case for small values of M, but further iterations are required in the detection process for larger values of this parameter.

Performance of this multiple access technique is illustrated in Fig. 4, which shows the simulation results obtained using BPSK modulation, $N = 64$, and $M = 12$, as previously. Here too, we give the theoretical results obtained in the absence of decision errors in the interference cancellation steps. The first (resp. the second) plot gives the results corresponding to the OCDMA users (resp. TDMA users) after one and two iterations. We observe that the first iteration decisions are not reliable for OCDMA users because these decisions are made in the presence of interference from 12 TDMA users. In contrast, the first-iteration decisions of TDMA users are much more reliable since they are made after subtracting the (estimated) interference from the 64 OCDMA users. But the most remarkable result is that for both sets of users, the BER curve after the second iteration virtually coincides with the ideal curve, which corresponds to interference-free transmission. This result implies that no further iterations are needed, at least with this number of excess users.

GENERALIZATIONS

First, instead of assigning WH sequences to the first set of N users and TDMA time slots to the additional users, exactly the opposite can be done. In this case, the first N users get TDMA time slots and the additional users get length-N WH sequences. The interference problem and its cancellation remain the same as previously, although performance may differ. Specifically, each TDMA symbol in this scheme is corrupted by one chip of OCDMA symbols, and the total interference power from the set of M OCDMA users is M/N. Again, as long as M does not take excessive values (close to N), preliminary decisions can be made on the symbols transmitted by the N TDMA users. Next, those decisions are used to synthesize and cancel the interference of TDMA users on OCDMA users and make intermediate decisions on the symbols transmitted by the latter. Further iterations continue as described above.

The TDMA and OCDMA waveform sets are only one example, and any other sets of orthogonal signal waveforms can be used. First, note that both TDMA and OCDMA are time-domain techniques. Their frequency-domain counterparts are OFDMA and multicarrier OCDMA (MC-OCDMA) [15]. MC-OCDMA consists of spreading the transmitted signal spectrum in the frequency domain instead of in the time domain. This is performed by entering to an inverse discrete Fourier transform the baseband signal after spectral spreading using WH sequences. The combination of OFDMA with MC-OCDMA has exactly the same power density representation as that shown in Fig. 3 for combined TDMA/OCDMA except that the time axis in the abscissa must be replaced by the frequency axis. This reflects the fact that an OFDMA signal occupies only $(1/N)$th of the channel bandwidth, while an MC-OCDMA signal occupies all of it. When the same symbol energy is used in both of these multiple access techniques, the power density is obviously N times larger in OFDMA. The bottom line is that the interference between an OFDMA user and an MC-OCDMA user has a power of $1/N$ at the threshold detector input, and the general resource assignment concept and multistage detection technique described earlier are readily applicable.

It is also possible to use a combination of time-domain and frequency-domain signal sets, for example, combine TDMA with OFDMA. A number of those combinations are discussed in [3].

SUMMARY AND CONCLUSIONS

After analyzing the capacity of conventional multiple access techniques and highlighting their respective virtues and shortcomings, we have described two newly introduced concepts which extend the number of users beyond the spreading factor N (the channel bandwidth divided by the bandwidth of the individual user signals) and ensure an interference-free transmission for $K \leq N$. The first one is a full CDMA which assigns orthogonal sequences to the first N users and PN sequences to the additional users. When K is larger than N, interference appears within the set of PN sequence users on one hand, and between the two sets of users on the other hand. A multistage iterative detection technique is used to cancel this multi-user interference and obtain reliable receiver decisions. At each stage, the interference corrupting the set of users of interest is synthesized based on the receiver decisions available from the previous stages and subtracted from the correlator output before passing this signal to a threshold detector.

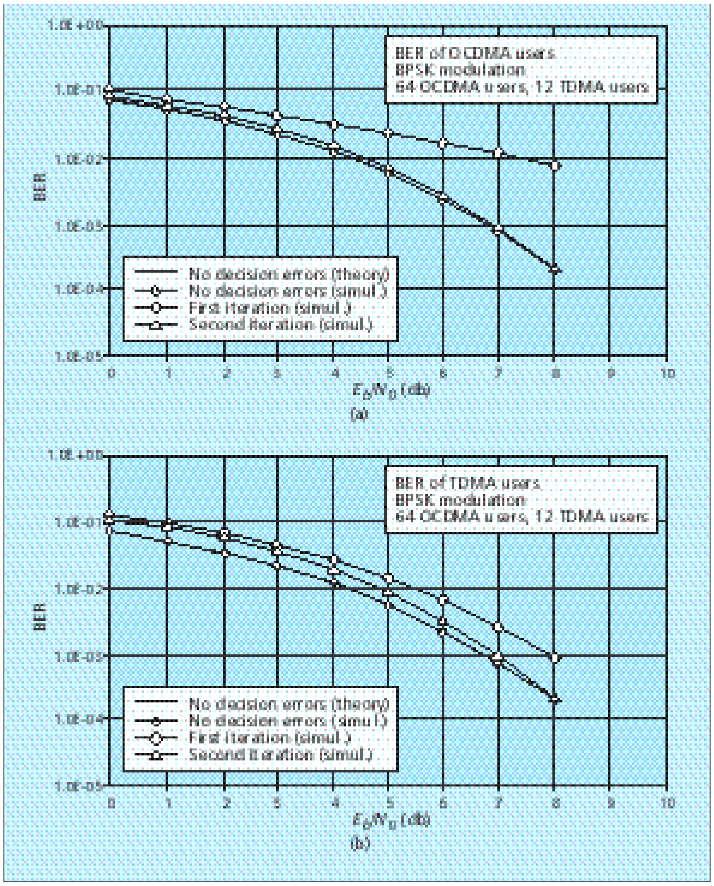

Figure 4. *The BER performance of OCDMA augmented with TDMA: a) BER of OCDMA users; b) BER of TDMA users.*

The second technique is similar to the first except that the two sets of signal waveforms used are both orthogonal, and therefore it avoids any interference between users with resources from the same set. The only interference in this case is that between users with resources from different sets of signal waveforms, and therefore detection requires a smaller number of iterations than the first technique, and the BER performance is superior. Description of this technique is performed using a combination of TDMA and OCDMA, but its generalization to other signal sets is also briefly outlined. Using BPSK modulation, it was shown that a 20 percent increase in user capacity in this technique is achieved with virtually no SNR degradation.

The presented multiple access concepts thus significantly increase the number of users that can simultaneously operate on a multiple access channel and open up some interesting perspectives in the fields of cable networks, fixed wireless access, and mobile radio. Before closing, we point out that the reviewers of this article brought to our attention that similar attempts to increase cell capacity are currently being made within the framework of standardization groups for the third-generation cellular systems based on CDMA. The need to allocate more than N

spreading sequences/cell is indeed discussed in the CDMA2000 standard draft [16] and in a contribution to the Universal Mobile Telecommunications System (UMTS) standard [17]. But in both standardization groups, current documents only describe how these sequences can be generated and, to the authors' knowledge, the resulting interference problem is not addressed.

> The need to allocate more than N spreading sequences per cell is discussed in the CDMA2000 standard draft and in a contribution to the UMTS standard. But in both standardization groups, current documents only describe how these sequences can be generated.

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