Channel division multiple access: The access solution for UWB networks

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***Abstract*—In this paper we study a promising multiple access scheme entitled Channel Division Multiple Access (ChDMA). ChDMA was developed to cope with the particularities of low duty cycle Impulsive Radio Ultra Wideband systems (IR-UWB). The idea is based upon the fact that Channel Impulse Responses (CIR) could be exploited as users signatures. Based on the knowledge of the CIRs at the receiver, transmitted signals can be detected and estimated in a very similar approach as performed by DS-CDMA systems. We present in this contribution initial analysis of the spectral efficiency performance of ChDMA systems. As a matter of fact, ChDMA overcomes the multiple access paradigm of impulsive-radio signaling and provides an efficient and low complex technique to exploit the diversity of UWB communications. For the study, we consider three different receiver structures: optimal receiver, matched filter (MF) and linear minimum mean square error receiver (l-MMSE). As a result, it is shown that under certain conditions ChDMA can even outperform CDMA in terms of Shannon's capacity, providing a real option for future communication systems.**

Keywords*—*ChDMA, IR-UWB, Multiple Access, Wideband Channels, Spectral Efficiency.

I. Introduction

Ultra-Wideband (UWB) communication has received a lot of attention because it can coexist with legacy systems on the same band while delivering very high data rates [1]–[3]. Foreseen as a cheap short-range high data rate solution, UWB is an attractive technology for applications such as localization, security, emerging wireless automotive communications and home-based "location awareness" [4].

The idea of UWB technology is to transmit signals across a much wider frequency band than conventional systems. A traditional UWB transmitter works by sending pulses across a very wide bandwidth, generally pulses of few hundred picoseconds. By spreading its power across a broad spectrum, UWB system can potentially improve rate and reduce interference.

Standardized by the American Federal Communications Commission (FCC) and the International Telecommunication Union Radiocommunication Sector (ITU-R) as a system whose bandwidth exceeds the lesser of 500MHz or at least 20% of fractal bandwidth [1]–[3], in the United States, the FCC has mandated that UWB radio transmissions can legally operate in the range from 3.1 GHz up to 10.6 GHz, at a limited transmit power of -41dBm/MHz. Some studies have demonstrated that UWB systems offer their greatest promise for very high data rates when the range is less than approximately 10m, due to the FCC's current power limitation on UWB transmissions.

It is common knowledge that increasing the bandwidth enables higher data rates. However, for limited power transmissions, the increase of the bandwidth represents higher noise power, which degrades system performance. Golay [5] showed that employing on-off keying (pulse position modulation) with very low duty cycles mitigates the noise effect. Kennedy [6] proved that over an infinite bandwidth Rayleigh fading multipath channel with perfect channel knowledge at the receiver, the use of frequency shift keying signals together with low duty cycle transmissions achieves maximum rate, the same as the infinite bandwidth non-fading additive white Gaussian channel with Gaussian signaling. Telatar and Tse extended the proof for multipath channels with any number of paths. Assuming no inter-symbol interference (ISI), they show that the achievable rate is

$$\gamma = \left(1 - 2\frac{T_d}{T_c}\right)\rho, \tag{1}$$

where ρ is the signal to noise ratio (SNR) at the input of the receiver and T_d and T_c are, respectively, the channel delay spread and the channel coherence time. In particular, by transmitting at very low duty cycles, the capacity of the infinite-bandwidth AWGN channel can be achieved in a fading multipath channel with any number of paths. Consequently, low duty cycle signals represent a solution to cope with the particularities of wireless environments [7].

There are two methods to generate UWB signaling [1]: *single-band* and *multiband*. In the single-band case, all users employ the same pulse to transmit signals. Also known as impulse radio UWB (IR-UWB), the transmitted signal is spread over the whole UWB spectrum. In the multiband case, however, the spectrum is divided in channels of at least 500MHz. Then, users have to employ different pulses to access different wideband channels [8], [9], requiring more complex receivers.

In this paper, we focus on the IR-UWB method. The results presented herein can also be easily extended to the multiband case. In the following, we present in Section II the IR-UWB technology and discuss about the limitations of the implementation of the various multiple access schemes. In Section III, we introduce the ChDMA concept. We present in Section IV assumptions and considerations that allow the performance evaluation presented on Section V.

II. Impulsive Radio Signaling and Multiple Access

In IR-UWB systems, transmitters radiate low duty cycle waveforms created by very short baseband electrical pulses. Such signals are free of sine-wave carriers and do not require the use of local oscillators or mixers, so IR-UWB transceivers are simpler and cheaper than conventional narrow-band transceivers. The system bandwidth is determined by the shape and duration of the pulse employed. Typically, Gaussian monocycle and Hermitian pulses [10] are employed.

Due to high channel resolution of UWB systems, multiple paths can be resolved, improving the signal's immunity to interference effects and robustness to multi-path fading. Moreover, for the same SNR, the coverage of UWB is larger than conventional narrow-band systems because its low frequency components have good penetration properties. This is one of the reasons why UWB technology is also largely used in radar applications [11], [12].

Despite the many aforementioned advantages, the issue of multiple access in IR-UWB systems has proved to be challenging. There has not been any proposal to provide a multiple access scheme in the multi-user setting that benefit from low duty cycle regime. All techniques thus presented were developed to provide orthogonal communication channels to enable simultaneously connected terminals. However, all of those approaches were designed under almost ideal environments. Under Wireless UWB condition, conventional multiple access schemes suffer from great inadaptability when employed on IR-UWB systems:

- **FDMA:** Due to the absence of carriers, FDMA can only be employed on multi-band UWB, when different users use different pulses (shapes and length) [8], [9] to transmit.
- **TDMA:** TDMA is highly sensitive to asynchronism, which is inherent to IR-UWB communication. Furthermore, the high dispersion of the UWB channel requires large guard intervals between different user access, which cause low spectral efficiency.
- **SDMA:** SDMA requires the use of antenna arrays, which means the use of multiple antennas on at least one side of the communication. This implies that terminals must be bigger and more expensive, which goes against the goal of UWB.
- **CDMA:** In spread spectrum techniques, information bits are broken into chips and the chips are modulated with either a fixed carrier frequency (DS-CDMA) or in a set of carrier frequencies (FH-CDMA). Over UWB channels, the data rate goes to zero for very high bandwidths [13]. Consequently, CDMA provides a very inefficient technique for UWB communications.

In a trial to provide a solution for IR-UWB systems, we introduce in the following a multiple access scheme that exploits the benefits of low duty cycle transmissions without adding guard intervals while still offering a low interference level between simultaneous communications.

III. Channel Divisition Multiple Access (ChDMA)

Channel division multiple access (ChDMA) is a scheme where each user transmits its own signal through modulated short pulses and the wireless channel acts as user signatures [14], [15]. As a result, channels can be seen as user codes that enable the receiver to separate the simultaneous transmitted sequences of different users.

A. ChDMA Principle

Equivalent to DS-CDMA, but with the wireless channel employed as signaling codes, ChDMA benefits from the intrinsic statistical properties of the wireless environment, that are often considered as obstacles. The codes are naturally generated by the environment. Due to wireless channel effects (path loss, shadowing, multipath, *etc.*), the channels are position-dependent and have a very strong random component. Combined with the wideband nature of UWB channels and the highly dispersive nature of indoor environments, the signaling codes are long and uncorrelated which provide good separation capabilities. System bandwidth and duty cycle are the main parameters that define the degrees of freedom to separate the various transmitted signals.

B. System Model

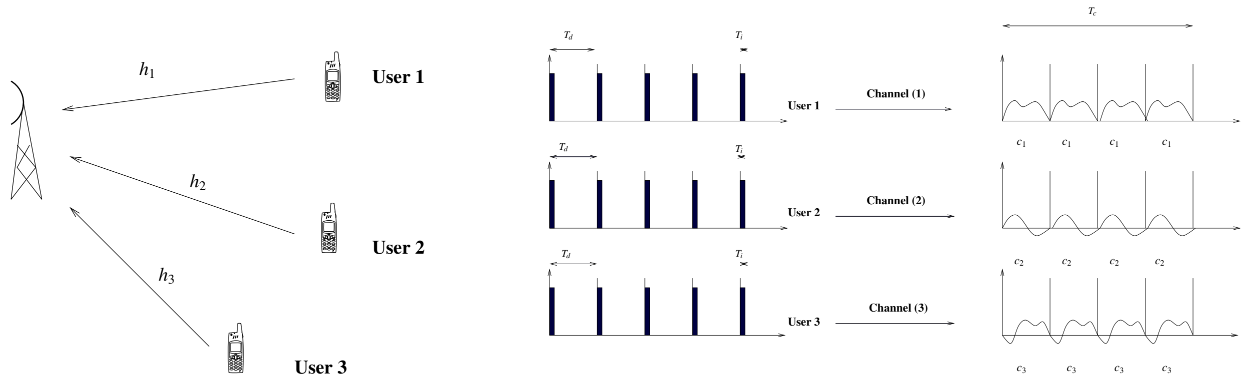
Let us consider a multi-user single-band IR-UWB system with K single antenna users. Each uplink channel between user k and the base station (BS) is considered to be frequency selective and suffers from additive white Gaussian noise. Transmissions are carried by very short electric pulses of length T_i. These pulses define the system bandwidth ($W \cong T_i^{-1}$) and the sampling rate. The interval between consecutive transmissions is denoted as T_s, and it provides the symbol rate ($f_s = T_s^{-1}$). It is important to note that, since the duty cycle is low, the pulse length T_i employed by the pulse signaling is only a small fraction of T_s ($T_i \ll T_s$).

The basic system scheme is presented in Fig. 1(a). In the example, three mobiles are transmitting to the same destination across the same wireless medium. Each mobile sends a modulated pulse. Transmitted through the channel, the signal is distorted by the wireless environment, as illustrated in Fig. 1(b). This distortion can be regarded as a modulation scheme. At the receiver, under the assumption that the BS knows the channels of different users, it is able to detect and demodulate the received signals by using the channel as a code. Since the users have different locations, each transmitted signal is affected by a different channel, and the signaling scheme provides enough diversity to separate the information sent by different users.

For the sake of simplicity, the system is considered to be symbol-synchronous[1], which means that the maximum delay between all user paths is bounded by T_s and the ISI is avoided. Since the model does not change whether one is in frequency or time (since the Fourier transform is unitary), we will keep the same notation. Then, at the BS, the received signal can be represented as

$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{n}, \tag{2}$$

[1] Symbol synchronization means that all users transmit their symbols during a fixed interval. Under typical low-duty cycle UWB communication, ($T_d \ll T_s$), so the symbol-synchronous assumption does not restrict our model.



(a) Multiple access of 3 users.

(b) Transmitted and received signals.

Fig. 1. Illustration of the Channel Division Multiple Access Scheme of a system with three users.

where $\mathbf{y}$ is a N-dimensional complex vector that represents the received signal; $\mathbf{H}$ is an $N \times K$ complex matrix that represents the wireless channel; $\mathbf{s}$ is a K-dimensional complex vector that contains the transmitted symbols of the K users; and $\mathbf{n}$ is an N-dimensional complex additive white Gaussian noise vector with entries of variance σ^2.

C. Spectral Efficiency and Capacity of ChDMA Systems

For the ChDMA, the mutual information between input and output of our model (see Eq. 2) is

$$\begin{aligned} \mathcal{I}(\mathbf{s};(\mathbf{y},\mathbf{H})) &= \mathcal{I}(\mathbf{s};\mathbf{H}) + \mathcal{I}(\mathbf{s};\mathbf{y} \mid \mathbf{H}) && (3)\\ &= \mathcal{H}(\mathbf{y} \mid \mathbf{H}) - \mathcal{H}(\mathbf{n} \mid \mathbf{H}), && (4) \end{aligned}$$

where $\mathcal{I}(\cdot,\cdot)$ and $\mathcal{H}(\cdot,\cdot)$ represent respectively the mutual information operator and entropy operator.

In the case of zero mean Gaussian signaling, the entropy can be written in terms of the covariance matrix, *i.e.*,

$$\mathcal{H}(\mathbf{s}) = \log_2 \det(\pi e \mathbf{Q}), \quad (5)$$

for $\mathbf{Q} = \mathbb{E}\{\mathbf{s}\mathbf{s}^H\}$. Since $\mathbb{E}(\mathbf{n}\mathbf{n}^H) = \sigma^2 \mathbf{I}_N$ and $\mathbb{E}(\mathbf{y}\mathbf{y}^H) = \sigma^2 \mathbf{I}_N + \mathbf{H}\mathbf{H}^H$, the spectral efficiency is then

$$\begin{aligned} \gamma_{Gauss} &= \frac{1}{T_s W}\left[\mathcal{H}(\mathbf{y} \mid \mathbf{H}) - \mathcal{H}(\mathbf{n} \mid \mathbf{H})\right] \\ &= \frac{1}{N}\log_2 \det\left(\mathbf{I}_N + \frac{1}{\sigma^2}\mathbf{H}\mathbf{H}^H\right). && (6) \end{aligned}$$

The signal to noise ratio $\frac{1}{\sigma^2}$ is related to the spectral efficiency γ by $\frac{1}{\sigma^2} = \frac{N}{K}\gamma\frac{E_b}{N_0}$ [16]. Assuming channel state information at the receiver side, γ_{Gauss} can be decomposed as

$$\gamma_{Gauss} = \frac{1}{N}\sum_{i=1}^{K}\log_2\left(1 + \mathrm{SINR}_i\right), \quad (7)$$

being SINR_i the signal to interference plus noise ratio of user i.

IV. System Assumptions and Considerations

For the rest of the paper, the following assumptions are made:

Assumption 1: Users are symbol-synchronous and the receiver has full knowledge of the environment.

Assumption 2: The channels are complex random matrices whose entries come from a zero-mean Gaussian distribution such that $\mathbb{E}(\mid \mathbf{h}_i \mid^2) = 1$. We assume that the entries are i.i.d. with variance $\frac{1}{N}$, which implies that energy is uniformly distributed over the channel taps.

Assumption 3: DS-CDMA system is simulated and compared in performance with ChDMA. To create a fair comparison between both systems, the spreading code length N for DS-CDMA is $N = \frac{T_s}{T_i}$. Each spreading code word is equally likely and chosen independently by each user; equivalently each chip is independently picked from the finite set $\{-\frac{1}{\sqrt{N}}, \frac{1}{\sqrt{N}}\}$. The performance of DS-CDMA is evaluated in a *flat-fading* white Gaussian channel, which is the scenario that offers an *upper bound* of the DS-CDMA's performance.

Assumption 4: For sake of objectivity, the results are limited to the analysis of Gaussian signaling spectral efficiency expressions. The conclusion is also valid to the BPSK and QPSK signaling, respecting the performance differences of each signaling scheme.

Assumption 5: The asynchronism considered in the simulations is generated by the introduction of delays d_i on the CIRs. At the first moment, we assume symbol synchronism and these delays are bounded by the delay spread, *i.e.*, each delay d_i is randomly generated, following a uniform distribution on $[0, T_s - T_d]$.

To simplify notations, we express the time interval between consecutive transmissions T_s and the delay spread of the channel T_d in terms of sampling frequency f_i. This allows us to generalize the results for any case where the relations between T_s, T_d and T_i are satisfied.

A. Receiver Structures

For the performance evaluation of ChDMA, we consider three different receiver structures: the optimal receiver, the matched filter (MF), and the linear minimum mean square error receiver (MMSE).

1) Optimal Receiver: The optimal receiver is the receiver that minimizes the probability of symbol error among all receiver structures. It is based on the analysis of the posterior probabilities of the transmitted signal [17], *i.e.*, given the received signal and the channel matrix, the optimal receiver estimates the transmit signal $\hat{\mathbf{s}}$ such that:

$$\hat{\mathbf{s}} = \underset{\mathbf{s}}{\operatorname{argmin}}(|\mathbf{y} - \mathbf{H}\mathbf{s}|). \tag{8}$$

Although implementing the optimal receiver is generally not feasible in practice, it provides an upper bound of ChDMA's achievable performance. The analytical expression for the spectral efficiency of the optimal receiver is known and presented in Section III-C, Eq. (6).

2) Matched Filter (MF): The MF is the best linear receiver for estimating the transmitted signal in the presence of additive Gaussian noise. As shown in [18], [19], when employing the MF, the signal-to-interference plus noise ratio (SINR) of each user is given by

$$\text{SINR}_{\text{MF}_i} = \left\{ \frac{|\ \mathbf{h}_i^H \mathbf{h}_i\ |^2}{\sigma^2(\mathbf{h}_i^H \mathbf{h}_i) + \sum_{j=1, j\neq i}^{K} |\ \mathbf{h}_i^H \mathbf{h}_j\ |^2} \right\}. \tag{9}$$

Then, the spectral efficiency of the MF is calculated by substituting Eq. (9) in Eq. (7).

3) Linear Minimum Mean Square Error (MMSE) Receiver: The linear MMSE receiver [20]–[24] is also a linear filter that differs from the MF due to the fact that it minimizes the mean square error:

$$G_{\text{MMSE}} = \underset{\mathbf{f}}{\operatorname{argmin}}\ \mathbb{E}\{|\ \mathbf{s} - \mathbf{f}\mathbf{y}\ |^2\}. \tag{10}$$

The MMSE maximizes the SINR over all linear receivers [25] but at a price of higher complexity, due to the fact that the filter considers the interference level, which requires the knowledge of all channels. The linear MMSE filter of user i is given by [21],

$$\mathbf{f}_i = \left(\tilde{\mathbf{H}}_i \tilde{\mathbf{H}}_i^H + \sigma^2 \mathbf{I}\right)^{-1} \mathbf{h}_i, \tag{11}$$

where $\tilde{\mathbf{H}}_i$ is $(N \times (K-1))$ matrix which contains all time response vectors $\mathbf{h}_j$ for all $j \neq i$.

The SINR_i of each user after linear filtering is given by

$$\text{SINR}_i = \left\{ \frac{|\ \mathbf{f}_i^H \mathbf{h}_i\ |^2}{\sigma^2(\mathbf{f}_i^H \mathbf{h}_i) + \sum_{j=1, j\neq i}^{K} |\ \mathbf{f}_i^H \mathbf{h}_j\ |^2} \right\}. \tag{12}$$

Hence, the $\text{SINR}_{\text{MMSE}_i}$ is obtained by substituting Eq. (11) into Eq. (12). Tse and Hanly [26] simplified the expression and proved that we can represent the linear MMSE SINR as

$$\text{SINR}_{\text{MMSE}_i} = \left\{ \mathbf{h}_i^H (\tilde{\mathbf{H}}_i \tilde{\mathbf{H}}_i^H + \sigma^2 \mathbf{I})^{-1} \mathbf{h}_i \right\}. \tag{13}$$

As in the MF case, the spectral efficiency of the linear MMSE receiver is calculated with Eq. (7).

V. Numerical Performance Evaluation (ChDMA vs Ideal DS-CDMA)

In this section, we compare the spectral efficiency of the ChDMA scheme with the flat-fading synchronous DS-CDMA scheme employing two different codes: orthogonal Hadamard codes and random binary codes. The analysis is performed by using three different receiver architectures and evaluated through Monte Carlo simulations.

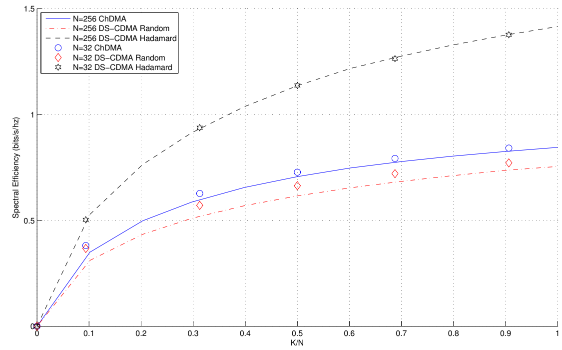


Fig. 2. Performance of MF ($E_b/N_o = 5$dB and $T_d = T_s$).

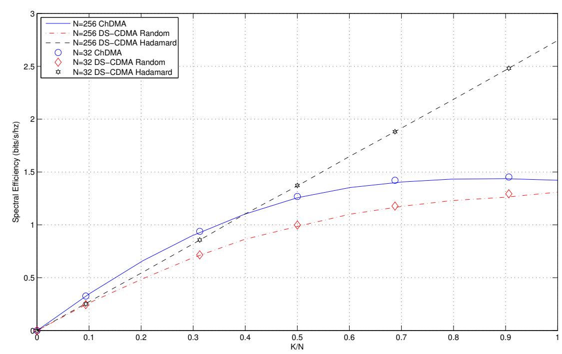


Fig. 3. Performance of linear MMSE ($E_b/N_o = 5$dB and $T_d = T_s$).

A. Number of Users to Spreading Factor Ratio (K/N)

We first analyze the impact of the number of users K and the spreading factor N on the ChDMA performance. We focus our analysis on the region where the K/N ratio is smaller than one, consistently with the fact that UWB systems are short range networks, which implies that there are few users compared to the large spreading factor currently employed in IR-UWB technique.

In the CDMA case, Verdú and Shamai [16] have shown that when the number of users and the spreading factor both go to infinity, but at a constant ratio, the spectral efficiency depends only on the K/N ratio. The results from this asymptotic regime provide good approximations for finite values of K and N. We consider here a similar condition for the ChDMA.

Considering a delay spread equal to the interval between consecutive transmissions ($T_s = T_d$), we analyze the spectral efficiency of the ChDMA for two different spreading factor values $N = 32$ and $N = 256$. In Fig. 2 and Fig. 3, the performance of the MF and the linear MMSE receiver is evaluated for an energy per bit to noise spectral density ratio (E_b/N_o) of 5dB. The figures show the performance of the ChDMA, the DS-CDMA with random codes and the DS-CDMA with orthogonal codes for the two values of N. The spectral efficiency does not change when different spreading factor values are employed. For a very high ratio K/N, DS-CDMA considerably outperforms ChDMA due to the

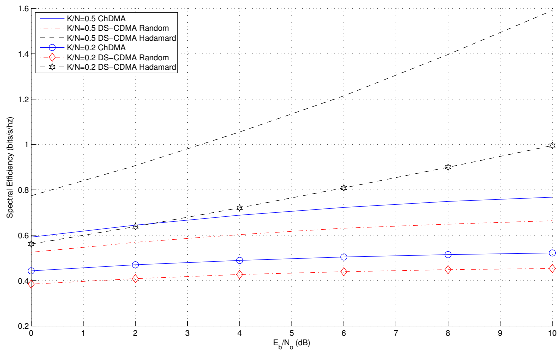


Fig. 4. Performance of MF ($T_d = T_s$).

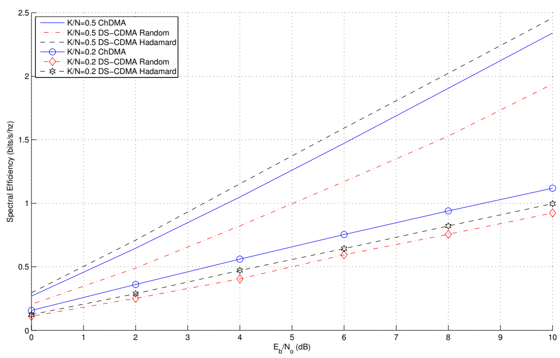


Fig. 5. Performance of linear MMSE Receiver ($T_d = T_s$).

properties of orthogonal codes, whereas ChDMA does suffer from multi-user interference. The MF is more sensitive to the spreading factor, but both receivers depend only slightly on the spreading factor. Using a MF receiver, DS-CDMA with orthogonal codes always outperforms ChDMA even for a very small number of users. This is because the MF is not designed to cope with the interference. On the other hand, the linear MMSE receiver performs nicely as well as the optimal receiver. Actually, for DS-CDMA with orthogonal codes, the linear MMSE presents the same results of the optimum receiver. For ChDMA, the linear MMSE receiver does not achieve the same performance as the optimal receiver, but it still outperforms DS-CDMA when only few users are connected.

The results in this section can provide insights for system design. Even though DS-CDMA with orthogonal codes could present better spectral efficiency than ChDMA, as has been seen so far in this section, when effects like time-offset and channel multipath are considered, ChDMA achieve better performance relatively.

B. Energy per Bit to Noise Ratio (E_b/N_o)

As shown in the previous section, for $N > 100$, the spectral efficiency depends almost exclusively on the ratio K/N. For this section, we will assume that $N = 128$ and we will consider two values of the ratio: $K/N = 0.2$ and $K/N = 0.5$).

In Fig. 4 and Fig. 5, we present the performance of the

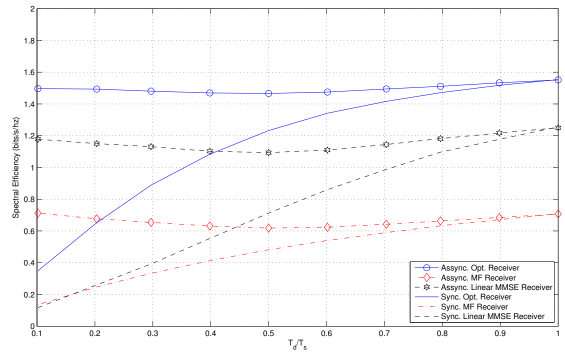


Fig. 6. Impact of asynchronism ($K/N = 0.5$ and $E_b/N_o = 5dB$).

MF and the linear MMSE receiver, respectively. The spectral efficiency of ChDMA using the MF is almost constant with the increase of E_b/N_o, whereas the performance of DS-CDMA grows more than linearly. The reason for this is that the MF does not counteract interference, so the ChDMA performance is limited by the interference level; increasing E_b/N_o will not ameliorate it. However, the linear MMSE receiver performs much better than the MF, similar to the optimal receiver, presenting an almost linear gain for the spectrum efficiency with the increase of E_b/N_o.

C. Channel Delay Spread and User's Asynchronism

Previously, the delay spread T_d was equal to the interval between consecutive symbols T_s. This is because we would like to compare the ChDMA and the DS-CDMA under the same system configuration. However, in a realistic environment, the delay spread should be shorter than the interval between consecutive symbols. Here, we would like to show some of the real improvements that ChDMA has to offer to IR-UWB systems.

Usually, IR-UWB systems are designed to operate over different channel conditions. Even if the channel delay spread of the users is the same, it is difficult to perfectly synchronize all transmit signals at the receiver. For this reason, we evaluate the performance of ChDMA when users are symbol-synchronous and the delay spread is only a fraction of the interval between consecutive transmissions. If the users are perfectly synchronized, by decreasing T_d, the spectral efficiency will decrease because the channel energy will be concentrated in few channel taps, resulting in smaller signatures and a higher interference level. However, if the messages of different users arrive at different times asynchronously, the receiver will be able to exploit this feature to increase the degree of interference cancelation.

In Fig. 6, we present the spectral efficiency as a function of the delay spread. For perfectly synchronized ChDMA, decreasing the spread spectrum length (or increasing the symbol interval) results in a loss of performance when the system uses any of the three receivers. However, if the system is asynchronous, the performance is nearly independent of the ratio T_d/T_s. The same effect was also observed for different values of K/N and E_b/N_o.

Asynchronism is beneficial to ChDMA and provides robustness against low dispersive environments, allowing increased inter-symbol intervals without a corresponding spectral efficiency loss. The results presented here assume symbol synchronism, which is often employed in wireless networks through the use of beacon signals. The assumption of symbol-synchronization can be relaxed when there are many transmitters and a large interval between consecutive transmissions. Due to the different location of the transmitters, resulting in different signal delays and channel delay spreads, synchronism at the receiver is an unrealistic assumption.

VI. Conclusions

UWB radio is an emerging technology bringing major advances in wireless communications, networking, radar, imaging, and positioning systems. The large bandwidths enable very high achievable capacities. The FCC and the ITU-R have already standardized UWB and restricted the technology to very low output energy levels for short-range communications. None of the conventional multiple access techniques are adapted to the highly dispersive nature of UWB environments. For this reason, we proposed a new concept that provides a multiple access scheme that explores the low duty cycle characteristic of IR-UWB systems to guarantee simultaneous communications. This scheme is the channel division multiple access.

The ChDMA proposal is, in many ways, similar to the CDMA scheme. They share the same concept but the signatures of ChDMA are designed naturally by the wireless environment. This simplifies the transmitter architecture and provide a natural multiple access scheme for IR-UWB systems to cope with the highly dispersive nature of the UWB channel. Nevertheless, the system cannot control the degree of separability between different users' "codes," which can be a problem if two users have very correlated channels. However, in very dense environments, even if the users are very close, the channel resolution of UWB systems is high and we expect a low degree of correlation between different channels.

The results presented herein show that ChDMA performs quite well under various system configurations and we can conclude that it really is an interesting option for IR-UWB systems. We observe that the number of users per spreading factor is an important parameter for ChDMA (as it is for the CDMA case [16]). Furthermore, the performance of the scheme is directly related to the kind of receiver that is employed, and the performance under the same conditions is very close to the one achieved by CDMA systems transmitting over *flat-fading channels*. Nevertheless, in some cases ChDMA performs better than CDMA, even when orthogonal codes were employed. We also observed that asynchronism is beneficial for ChDMA and provide some gain when the delay spread is low relative to the interval between consecutive transmissions.

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