Channel Division Multiple Access

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***Abstract*— Ultra-WideBand (UWB) has been recently presented as a promising radio technology due to the large bandwidth available. This feature enables point to point high data rates at short range as well as high temporal resolution with long channel impulse reponses (CIR). In this paper, we present an original multiple access scheme called Channel Division Multiple Access (ChDMA), where we use the CIR as a user signature. The signature code is given by the channel and the users are separated by their position: this signature is uniquely determined by the user's position, which changes from one position to another. This signature location-dependent property provides decentralized flexible multiple access as the codes are naturally generated by the radio channel. The results derived can be straightforwardly applied to UWB ad-hoc networks. To analyze the multiple access scheme performance, we evaluate the channel capacity in a wideband power limited regime by the tradeoff of the spectral efficiency (b/s/hz) versus the ratio between the number of users and the system resolution. The framework is analyzed and validated by capacity assessments using UWB measurements performed at Eurecom and compared with classical CDMA schemes with random spreading. The following receivers are considered: optimal joint processing, single-user matched filter and MMSE receiver.**

***Index Terms*— Multiple access schemes, multi-user systems, channel signatures, channel division multiple access, code division multiple access, channel capacity, fading channels, noisy channels, spectral efficiency, multiuser detection, multiuser information theory, spread spectrum, wideband regime.**

I. INTRODUCTION

Ultra-WideBand (UWB) signalling techniques are being considered for indoor short-range high data rate radio links overlaying with other existing wireless systems. Such techniques, as well as others are being considered in the standardization process of IEEE 802.15a Wireless Personal Area Networks (WPAN) proposal. FCC's ”Report and Order” allows for a UWB system bandwidth that extends from 3.1-10.6 GHz. This large bandwidth represents a high potential regarding capacity and flexibility issues and makes UWB systems attractive for applications such as localization, security systems, emerging automotive and home based ”location awareness” systems. Thanks to their large bandwidth, these systems present a very high temporal resolution. This results in long channel impulse response (CIR) sequences, with a high number of degrees of freedom [1] which can be used as a user signature. The benefit from this proposal is that the codes are naturally provided by the radio channel and differ from one location to another. This last property can be used for flexible code allocation in decentralized networks such as UWB ad-hoc networks.

Until recently, the main focus of ultra-wideband studies has been on the analysis of point to point communications. Hence, in [2], Kennedy showed that the infinite bandwidth capacity of a Rayleigh fading multipath channel with perfect channel knowledge at the receiver is the same as the infinite bandwidth capacity of the non-fading additive white gaussian noise (AWGN) channel with the same average received power (the asymptotic bandwidth capacity in this case is equal to $\frac{P}{N_0}$ in nats/s, where P is the average received power while $\frac{N_0}{2}$ is the power spectral density of the additive white gaussian noise). An interesting feature is that this capacity can be achieved with any kind of orthogonal code set. In [3], [4], [5], these results are generalized to the case where the channel is not known at the receiver with different constraints on the input signal. In [3], the infinite bandwidth capacity is shown to be equal to : $\left(1-2\frac{T_d}{T_c}\right)\frac{P}{N_0}$, where T_d and T_c are respectively the delay spread and the coherence time interval in the case of no inter-symbol interference (ISI). Surprisingly, the result in this case is not valid for any code set, but it depends crucially on the type of the orthogonal signaling. In particular, by transmitting at very low duty cycle, capacity of the infinite-bandwidth AWGN channel can be achieved independently of the number of paths and code sets, which is not the case for spread spectrum signals. Spread spectrum signals (which could be good candidate for multi-user communications) were shown to suffer a dramatic loss in terms of mutual information unless the channel varies very slowly almost in a quasi-static way. The basic guidance behind this fact is that as the bandwidth increases, the power available to estimate each path is too small for accurate channel detection techniques to work well. This effect degrades significantly the signal to noise ratio (SNR). Low duty cycle signals are interesting as they reduce the penalty factor due to channel estimation [6].

In the multiuser setting, however, there has not been any proposal to provide a multiple access scheme benefiting from low duty cycle transmissions. In this work, a signaling scheme for multi-user communications is proposed using low duty cycle transmissions called Channel Division Multiple Access (ChDMA). Benefiting from the fact that the coherence time T_c of UWB systems is large (typically about 100 μs) whereas the delay spread T_d is very small (typically about 15 ns), each users sends a very modulating peaky signal every ${T_d}^1$.

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[1] We suppose, for simplicity sake, that all the users have the same delay spread T_d. Otherwise, users send a peaky signal every $T_d^{\max}$ where $T_d^{\max} = \max_i(T_d^i)$

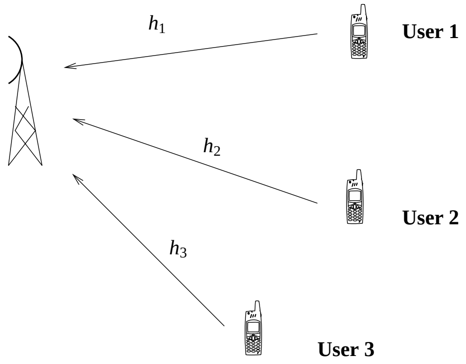

Fig. 1. Channel Impulse Division Multiple Access Scheme with three users.

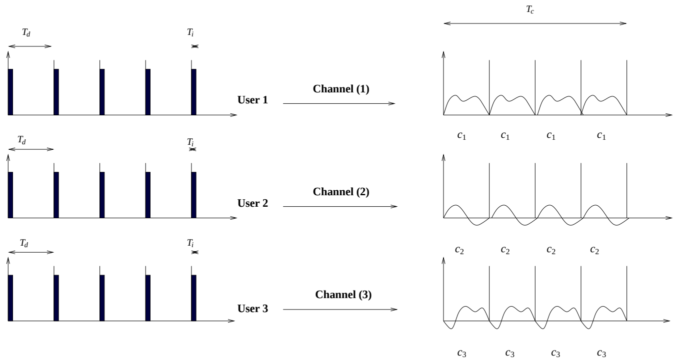

Fig. 2. Channel Division Multiple Access signaling.

The resulting impulse response modulates the signal of interest and is decorrelated of any other user sending information at the same time and in the same band. The system is equivalent to an uplink code division multiple access (CDMA) with random spreading system for which the capacity region is known [7]. Due to the fact that $\frac{T_d}{T_c}$ is small, the channel estimation occurrence will be limited and the power dedicated to estimate the channel when the bandwidth increases is bounded. Moreover, the high number of degrees of freedom of the channel provide enough uncorrelated random spreading codes to separate the users. Note finally that the low spectral efficiency typical of wideband systems does not imply that the communication is wasteful of channel resources or that the system operates far from channel capacity. In multiuser channels, the spectral efficiency achieved by any user may be small but the sum of the data rates may actually be near the channel capacity.

The remainder of this paper is organized as follows. In Section II, we describe the system model of the ChDMA architecture and provide the capacity expressions for the system. In Section III, we detail the measurement campaign performed at Eurecom Institute in a typical office environment. In Section IV, the capacity results of the ChDMA proposal are evaluated and compared with the capacity of the CDMA system with random spreading in a non-fading AWGN channel. The Section V is dedicated to a brief discussion about the ChDMA proposal and our perspectives.

II. SYSTEM MODEL

To build the system model, we consider a fading channel with additive white gaussian noise, like typical ultra-wideband wireless environments. Furthermore, considering the uplink case, we assume that the system employs K users, where each user wants to communicate towards the same destination as shown in Fig. 1. Each user transmits a low duty modulating signal as presented in Fig. 2. The signal is transmitted every T_d. In this case, the symbol received at the access point is given by:

$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{n}, \tag{1}$$

where $\mathbf{y}$ is a $N \times 1$ vector with $N = \frac{W}{W_c}$, which W is the bandwidth allocated for the ultra-wideband signal and W_c is the frequency resolution. $\mathbf{H} = [\mathbf{h}_1, ..., \mathbf{h}_K]$ is a $N \times K$ matrix which contains the frequency response vector $\mathbf{h}_i$ of each user i. $\mathbf{n}$ is a $N \times 1$ additive white gaussian noise vector of variance σ^2.

In the system employment, the ISI is avoided due to the fact that users transmit only every T_d. $\mathbf{s}$ is a $K \times 1$ vector which contains the transmitted symbols of the various users, typically $\{+1, -1\}$ due to the low spectral efficiency of wideband signals. As a consequence, we can consider that the channel impulse responses works as users signatures to access the environment, like a multiple access scheme as CDMA. It is important to note that the impulse radio has long been seen as a modulation scheme and never as a multiple access scheme.

Note that each user has a particular channel $\mathbf{h}_i$, and we suppose that each channel is independent from the others[2]. Because of this assumption, it is possible to use the channel signature to separate the signals that come from different users. The system can achieve very good spectral efficiency as long as the number of users is high compared to the delay spread and the coherence time is quite long. Moreover, the system is flexible in the sense that the spectral efficiency of the system depends mainly on the number of users and increases for each user (although the total spectral efficiency decreases) as the number of users decreases. In all the following, we assume that for any i, $\mathbb{E}(\mid \mathbf{h}_i \mid^2) = 1$.

A. Spectral Efficiency expressions

Assuming Gaussian signaling, the instantaneous spectral efficiency is given by:

- For the optimum receiver:

$$\gamma_{\text{opt}} = \frac{1}{N} \log_2 \det \left(\mathbf{I}_N + \frac{1}{\sigma^2} \mathbf{H}\mathbf{H}^H \right)$$

- For the matched filter:

$$\gamma_{\text{MF}} = \frac{1}{N} \sum_{i=1}^{K} \log_2 \left(1 + \frac{\mid \mathbf{h}_i \mid^4}{\sigma^2 \mid \mathbf{h}_i \mid^2 + \sum_{j=1, j \neq i}^{K} \mid \mathbf{h}_i^H \mathbf{h}_j \mid^2} \right)$$

- For the MMSE receiver:

$$\gamma_{\text{MMSE}} = \frac{1}{N} \sum_{i=1}^{K} \log_2 \left(1 + \mathbf{h}_i^H (\tilde{\mathbf{H}}_i \tilde{\mathbf{H}}_i^H + \sigma^2 \mathbf{I})^{-1} \mathbf{h}_i \right)$$

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[2] See section II-B for a discussion on this issue.

where $\tilde{\mathbf{H}}_i$ is an $N \times K - 1$ matrix, without column $\mathbf{h}_i$.

For all receiver, the signal to noise ratio $\frac{1}{\sigma^2}$ is related to the spectral efficiency γ by: $\frac{1}{\sigma^2} = \frac{N}{K}\gamma\frac{Eb}{N0}$. The spectral efficiency of these receivers with random spreading has been studied in [7]. In the following, we extend the analysis for real measurement data for which the spreading corresponds to different channels measured and asses the multiple access separability of the system with respect to the bandwidth. Note that Gaussian inputs in the UWB setting are not mandatory to achieve the previous spectral efficiencies. Indeed, for low signal to noise ratios, binary antipodal inputs are as good as Gaussian inputs in the sense that the ratio of mutual information (with BPSK signaling) to capacity approaches unity.

In section IV, comparisons are made with the optimum receiver, the matched filter and the MMSE receiver to the case where we employ a ratio $\frac{E_b}{N_0}$ equal to 5dB and 10dB. The curves have been plotted only for Gaussian signaling as capacity and mutual information are similar in the low SNR regime (typical of UWB systems and which provides a practical framework for Channel Division Multiple Access as the transmitter sends either positive or negative peaks). To compare the spectral efficiency of our proposal, we simulated a CDMA system where signature waveforms are assigned at random. In this case, each code word is chosen equally like and independent for each user, where each chip corresponds to $\in \{-\frac{1}{\sqrt{N}}, \frac{1}{\sqrt{N}}\}$.

B. Degrees of freedom versus number of users

For a given environment, the problem that arises concerns the maximum number of users that the system can incorporate. Indeed, the environment provides different channel signatures. However, as the number of users increases, the different signatures become more and more correlated as they are generated by the same filter environment. In particular, the number of scatterers and their relative positions will undoubtly determine the maximum number of users. To better understand this effect, consider the matrix $\mathbf{H}$ of size $N \times K$ which contains the different signatures of the users. We have,

$$\lim_{N\to\infty} \frac{1}{K}\mathbf{H}\mathbf{H}^H = \mathbf{R} \tag{2}$$

which is the covariance matrix of the channel. The L non-zero eigenvalues of the matrix $\mathbf{R}$ determine the scaling of the spectral efficiency with the optimal receiver. Indeed, for $K \to \infty$ (and supposing the non-zero eigenvalues equal to λ_i with $1 \leq i \leq L$):

- At high SNR:

$$\frac{1}{N}\log_2 \det\left(\mathbf{I}_N + \frac{1}{\sigma^2}\mathbf{H}\mathbf{H}^H\right) \to_{\sigma^2 \to 0} \frac{1}{N}\sum_{i=1}^{L}\log_2(\frac{\lambda_i}{\sigma^2})$$

- At low SNR (typical of UWB) :

$$\frac{1}{N}\log_2 \det\left(\mathbf{I}_N + \frac{1}{\sigma^2}\mathbf{H}\mathbf{H}^H\right) \to_{\sigma^2 \to \infty} \frac{\sum_{i=1}^{L}\lambda_i}{N\sigma^2}$$

which shows that there is a limit in the number of users since the system depends only on L and not K anymore for high number of users. The number L has already been characterized before as the number of degrees of freedom of the wideband channel [8] and this contribution shows once again its key role in the channel division multiple access realm. Studies are still being conducted to characterize the number of degrees of freedom with respect to the spatial position and geometry of the scatterers. Interestingly, one should note that for UWB systems, the spectral efficiency scales with the energy provided by the channel and not the multiplexing gain since one operates at t very low signal to noise ratios.

III. MEASUREMENT CAMPAIGN

A. Equipment and Measurement Setup

The measurement device used in this study is a wideband vector network analyzer (VNA) which allows complex transfer function (e.g. S_{21}) parameter measurements in the frequency domain extending from 10 MHz to 20 GHz. This instrument has low inherent noise (<-110 dBm for a measurement bandwidth of 10 Hz) and high measurement speed (<0.5 ms/point). The maximum number of equally-spaced frequency samples (amplitude and phase) per measurement is 2001. The measurement data are acquired and controlled remotely using the RSIB protocol over an Ethernet network permitting off-line signal processing and instrument control in MATLAB.The measurement system is shown in Fig. 3.

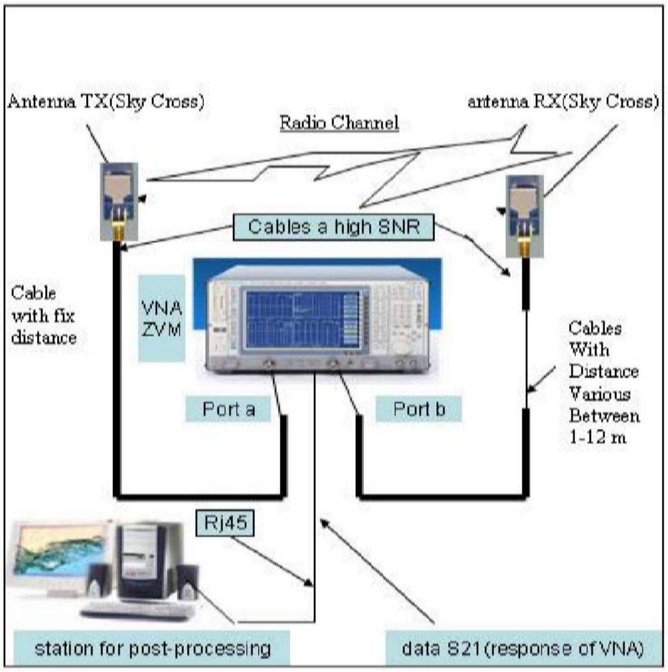

Fig. 3. Channel measurement setup.

In order to perform truly wideband measurements with sufficient resolution several bands can be concatenated using consecutive measurements. In this study we performed measurements from 3 to 9 GHz by concatenating 3 groups of 2001 frequency samples per 2 GHz sub-band (3-5 GHz, 5-7 GHz, 7-9 GHz). This yields a 1 MHz spacing between frequency

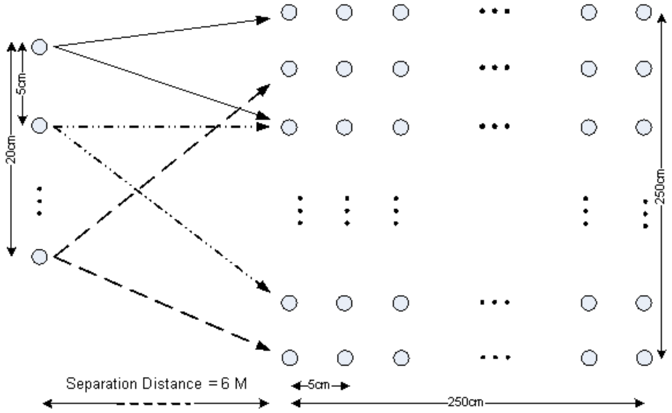

Fig. 4. Transmitter/Receiver positioning.

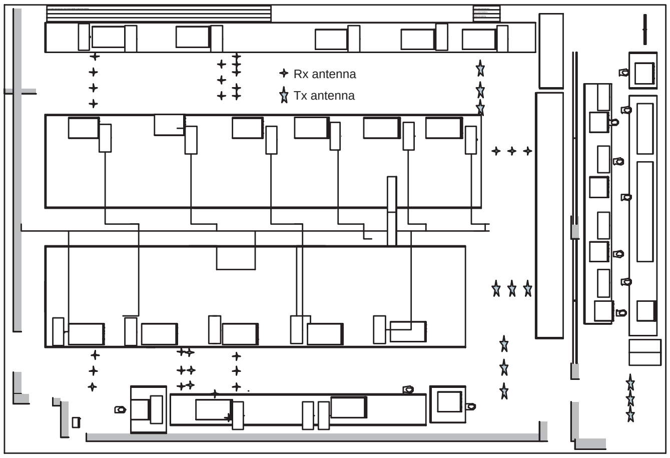

Fig. 5. Channel measurement environment.

samples. As discussed in the following section, this resolution was found to be sufficient for the analysis of the second order statistics of the channel impulse response. The corresponding maximum time domain resolution is $T = 167\ p$s in a 1μs time-interval. The use of passive elements in the measurement apparatus (cables, SMA connectors, etc.) imposed a systematic and frequent calibration measurement (which was controlled remotely), in order to compensate undesirable frequency-dependent attenuation factors that could affect the collected data. Following the VNA's manual recommendations, the calibration ”through response” type was selected, and the cables and the connectors were included in this calibration.

The wideband antennas employed in this study are omnidirectional in the vertical plane and have an approximate bandwidth of 7.5 GHz (varying from 3.1 to 10 GHz). They are not perfectly matched across the entire band, with a VSWR (Voltage Standing Wave Ratio, $VSWR = \frac{1+|\rho|}{1-|\rho|}$, where ρ is the wave's coefficient of reflection) varying from 2 to 5 (as an example the antenna has an efficiency of about 82% at 5.2 GHz).

B. Measurement Environment

Measurements were performed at spatially different locations for both Line-Of-Sight (LOS) and Non-Line-Of-Sight (NLOS). The experiment area is set by fixing the transmitting antenna on a mast at 1 m above the ground on a vertical linear grid (20 cm) close to the VNA and moving the receiver antenna to different locations on a square grid (50 cm x 50 cm) in $\frac{\lambda_{\max}}{2} = 5$ cm steps. The transmitter/receiver positioning is depicted in Fig. 4. The height of the receiver antenna was also 1m above the ground. This type of propagation scenario clearly targets peer-to-peer applications.

A measurement scenario is described by the transmitter/receiver separation and the presence or lack of a LOS component. The latter was achieved by inserting a large obstacle between the transmitter and receiver in order to block the LOS path. Because of the proximity of the transmitter and receiver, this also has the effect of reducing the amount of scattered paths which reach the receiver and thus the richness of the propagation channel. For the two measurement scenarios with transmitter/receiver separation of 6m representing NLOS and LOS communications, we acquired 400 different complex frequency responses each. Similar experiments with fewer measurements were also made for transmitter/receiver separations varying from 1-12 m in both LOS and NLOS configurations. The measurements were carried out in Eurecom Institute Mobile Communication Laboratory, which is a typical laboratory environment (radio frequency equipment, computers, tables, chairs, metallic cupboard, glass windows,...), as shown in Fig. 5, rich in reflective and diffractive objects. For simplicity, all numerical results reported in this paper refer to the 6m LOS scenarios.

IV. CAPACITY PERFORMANCE AND COMPARISON RESULTS

In this section, we analyze some of the results obtained by using the measurements of a real environment. Considering the measurements carried at a typical laboratory environment, we assumed that each user channel is given by the channel reponse of a measured transmitter-receiver with fixed positions separated by $\frac{\lambda_{max}}{2} = 5$ cm, which gives a total of 400 users. It is important to note that this assumption does not represent a real case, because all the users are close to each other, implying in a higher correlation between the signals from different users when compared with the case where the users are spread in the hole environment. Furthermore, a pretreatment in the measured data was done with the objective to be fair with the comparison. This treatment was employed to guarantee that the total system power was constant, by normalizing the channel impulse response of each user, i.e., each channel column vector $\mathbf{h}_i$ was assumed to have norm equal to 1[3]. In the same vein, the CDMA codes were generated in the way that each code word has norm $\|\mathbf{c}_i\|$ equal to 1.

In Fig. 6 and 7, we show the spectral efficiency of two systems when Gaussian signaling is employed. One of the systems is the ChDMA, which uses the CIR of each user, and the other is a CDMA-based system with random pseudo-noise codes. The spectral efficiency is evaluated in terms of

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[3] We normalized the channel by dividing all the elements of the vector $\mathbf{h}_i$ by $\|\mathbf{h}_i\|$.

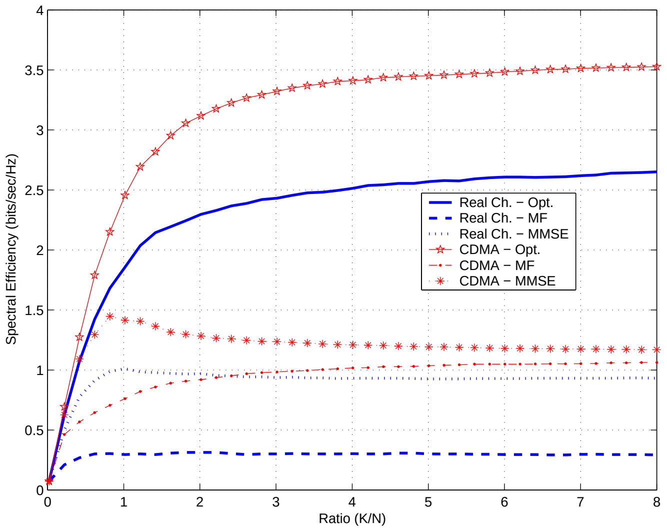

Fig. 6. Capacity comparison in a Gaussian signaling assumption with $\frac{E_b}{N_0} =$ 5dB.

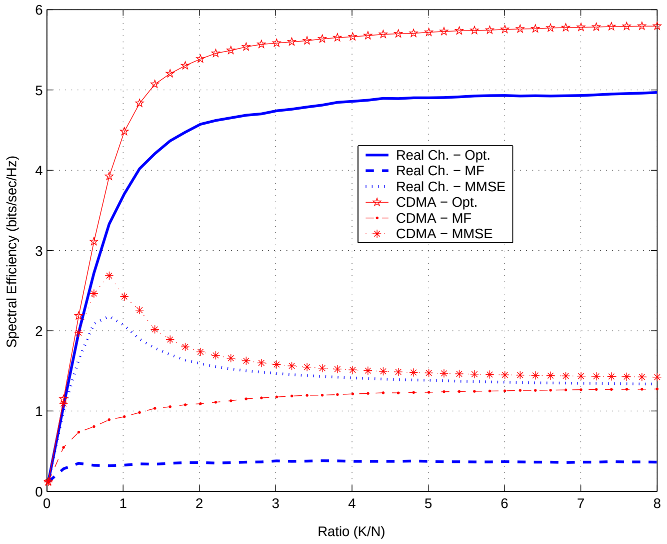

Fig. 7. Capacity comparison in a Gaussian signaling assumption with $\frac{E_b}{N_0} =$ 10dB.

the ratio between users/chips, or users/resolution, of three different receivers (Optimal receiver, Match Filter receiver and Minimum Mean Square Error receiver).

The curves presented in Fig. 6 were simulated for a $\frac{Eb}{No}$ of 5dB. As we can see, the performance of the CDMA-based case presents better results than the ChDMA case. Despite this, when we employ MMSE receivers, the gain is not very significative, showing almost the same performance as the CDMA-based case. This result imply that it is possible to build receivers for the ChDMA that is able to achieve a performance comparable to the CDMA capacity.

In Fig. 7, we present the curves for a $\frac{Eb}{No}$ of 10dB. As said before, the performance of the CDMA-based case presents better results than the ChDMA case, but when we employ optimal or MMSE receivers, the gain is not very significative.

It is important to note that the results presented for the CDMA case is for a AWGN channel, i.e., the channel does not have multipaths, which is an unfair assumption when we consider real channels. Actually, when we employ CDMA systems in real channels, it is necessary to add some complex structures like scrambling codes, which increases the code length and the computational complexity of the receiver. In this cases, the CDMA system needs to know the channel information to adapt the transceiver architecture with the objective to maximize the system capacity and to ameliorate the spectral efficiency to be able to achieve high data rates.

The only assumption that we need to consider to employ the ChDMA is the knowledge of the channel at the receiver. Moreover, the natural codes generated by the environment introduces a natural privacy, which can be exploited without additional complexity.

V. CONCLUSION

In this paper, we have provided a constructive scheme for multiple access using low duty cycle nicknamed Channel Division Multiple Access. The genuine idea is to benefit from the richness of the channel which provides code separability of the users in a natural way. Some performance results have been presented to illustrate the capacity that this scheme can achieve. Despite the unfair comparison, where the considered channel was built without considering the spread of the users all over the environment, the ChDMA scheme have shown to be able to achieve close to CDMA performance without centralized code allocations. Furthermore, in the simulations, we could note that the performance of the ChDMA scheme is critically dependent of the receiver structure, but the analyzed receivers were not able to achieve the optimal performance.

Focusing almost completely on the description of the ChDMA scheme, we have shown only some performance results of this scheme when a Gaussian signature is employed in a LOS environment. As future work, a detailed evaluation of the impact of the modulation and the environment should be done. Furthermore, it is also of interest to evaluate and to propose other types of receivers, where are more adapted for this multiple access scheme. Further studies are being conducted taking account mutual information criteria as well channel estimation mismatches.

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