

Channel Division Multiple Access Based on High UWB Channel Temporal Resolution

Raul L. de Lacerda Neto, Aawatif Menouni Hayar and M erouane Debbah

Institut Eurecom

B.P. 193

06904 Sophia-Antipolis Cedex - France

Email: {Raul.de-Lacerda, Menouni, Debbah}@eurecom.fr

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 Responses (CIR). Due to their large bandwidth, UWB systems enable high temporal resolution with long CIR. In this paper, we evaluate 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 framework is analyzed and validated by capacity assessments using UWB measurements performed at Eurecom and compared with classical CDMA schemes with random spreading codes. The analysis is focused on the impact of the user’s asynchronism and the period of symbol on system performance. Two structures are considered at the receiver: single-user matched filter and MMSE receiver with Gaussian and BPSK signaling schemes.

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

Until recently, the main focus of Ultra-WideBand (UWB) studies has been on the analysis of point to point communications. Hence, in [1], 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. An interesting feature is that this capacity can be achieved with any kind of orthogonal code set. In [2], [3], [4], these results are generalized to the case where the channel is not known at the receiver with different constraints on the input signal. In [2], 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 is an interesting 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). As consequence, low duty cycle signals are employed to mitigate the penalty factor due to channel estimation [5].

In multiuser setting, however, there has not been proposed any multiple access scheme able to provide benefits of using low duty cycle transmissions. For this reason, in this work, a signaling scheme for multi-user communications is proposed using low duty cycle transmissions, which we call it Channel Division Multiple Access (ChDMA). Benefiting from the fact that the coherence time T_c of UWB systems is large (typically about 100 μ s) whereas the delay spread T_d is very small (typically from 15-40 ns, depending on the user environment), each user sends a very modulating peaky signal every T_s ¹. 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 codes for which the capacity region is known [6]. Due to the fact that the power dedicated to the channel estimation is limited the channel estimation efficiency 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.

This paper is organized as follows. In Section II presents the system model, which includes a brief description of the

This work is part of the European Network of Excellence NEWCOM, Contract IST NoE 507325.

¹We suppose, for simplicity sake, that T_s is the same for all users and it is function of the maximum delay spread $T_d^{(max)}$. It is important to note that T_s is strongly related with the user’s synchronism.

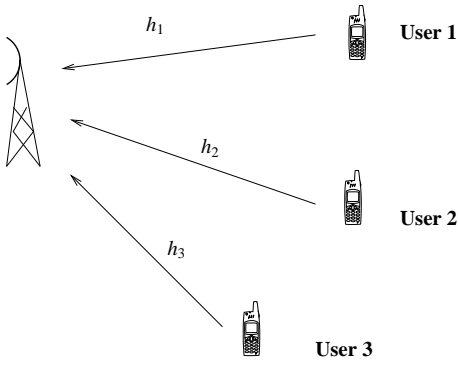


Fig. 1. Channel Impulse Division Multiple Access Scheme with three users.

channel model and the capacity equations. The simulation characteristics are detailed in Section III. After that, some performance results are shown in Section IV. Finally, in Section V, the conclusion and some perspectives are presented.

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 and each user transmits a low duty modulating signal every T_s . In this case, the symbol received at the access point is given by:

$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{n}, \quad (1)$$

where \mathbf{y} is a $N \times 1$ vector with $N = \frac{T_s}{T_r}$, which represents the relation between the delay between the transmission of symbols and the sampling rate at the receiver². $\mathbf{H} = [\mathbf{h}_1, \dots, \mathbf{h}_K]$ is a $N \times K$ matrix which contains the time response vector \mathbf{h}_i of each user i . \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. \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_s , which is greater than T_d . 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 others³. 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

² $\frac{1}{T_s}$ is the frequency resolution and $\frac{1}{T_r}$ is the bandwidth allocated for the ultra-wideband signal

³ See section II-A for a discussion on this issue.

user (although the total spectral efficiency decreases) as the number of users decreases. In all the following, we assume that for any i , $\mathbb{E}(|\mathbf{h}_i|^2) = 1$.

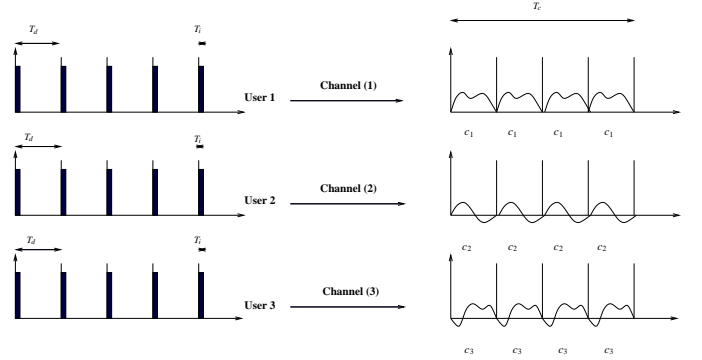


Fig. 2. Channel Division Multiple Access signaling.

A. Multipath Channel

We consider a time invariant channel $c^{(k)}$ of user k given by:

$$c^{(k)}(\tau) = \sum_{l=1}^{L^{(k)}} \lambda_l^{(k)} \delta(\tau - \tau_l^{(k)}), \quad (2)$$

where λ_l and τ_l represent respectively the gain and the delay of the l -th multipath. For simplicity sake, we suppose that all users are in the same environment, operating at the same bandwidth, and the number of paths is the same ($L^{(k)} = L$). Furthermore, because of the pulse signal \mathbf{g} employed for the transmission of the symbols on the environment, the channel $h^{(k)}(\tau)$ of the k -th user is given by

$$h^{(k)}(\tau) = \sum_{l=1}^L \lambda_l^{(k)} g(\tau - \tau_l^{(k)}), \quad (3)$$

where g is the transmit filter.

As consequence, the discrete channel matrix \mathbf{H} is given by the concatenation of the discrete channel vector of each user as show in the following:

$$\mathbf{H} = [h^{(1)} h^{(2)} \dots h^{(K)}]. \quad (4)$$

where the channel vector length is given by the ratio between the temporal resolution (T_r) and the symbol period (T_s).

B. 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 (MF) and the MMSE receivers:

$$\gamma = \frac{1}{N} \sum_{i=1}^K \log_2 (1 + \text{SINR}_i)$$

which the SINR value is respectively calculated by

$$\text{SINR}_{MF_i} = \frac{|\mathbf{h}_i^H \mathbf{h}_i|^2}{\sigma^2(\mathbf{h}_i^H \mathbf{h}_i) + \sum_{j=1, j \neq i}^K |\mathbf{h}_i^H \mathbf{h}_j|^2} \quad (5)$$

$$\text{SINR}_{MMSE_i} = \mathbf{h}_i^H (\tilde{\mathbf{H}}_i \tilde{\mathbf{H}}_i^H + \sigma^2 \mathbf{I})^{-1} \mathbf{h}_i, \quad (6)$$

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

For all receiver, the signal to noise ratio $\frac{1}{\sigma^2}$ is related to the spectral efficiency γ by: $\frac{1}{\sigma^2} = \frac{N}{K} \gamma \frac{E_b}{N_0}$. The spectral efficiency of these receivers with random spreading has been studied in [6].

The expression of the mutual information with BPSK signaling is given by:

$$\gamma = \frac{1}{N} \sum_{i=1}^K 1 - \int_{-\infty}^{+\infty} \frac{e^{-\frac{v^2}{2}}}{\sqrt{2\pi}} \log_2 \left(1 + e^{-2\text{SINR}_i - 2\sqrt{\text{SINR}_i} v} \right) dv, \quad (7)$$

where SINR_i for MF and MMSE receivers are already defined before.

III. SIMULATION CHARACTERISTICS

For the simulations, two different evaluations are employed. First, we will compare the performance of the ChDMA and the CDMA for synchronous and asynchronous users. In such simulations, we assume that the samples are in temporal domain with a fixed number of samples. The second kind of simulations are employed to estimate the impact of the symbol period (T_s) when the asynchronous case is employed by using a random delay retard⁴ for a fixed bandwidth.

To perform the simulation, some assumptions are considered:

Assumption 1: The considered channel bandwidth is 1GHz with resolution of 1MHz, which gives a channel vector with length equal to 50, due to the fact that the maximum delay spread of the indoor channel is limited on 50 ns.

Assumption 2: . 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 $\in \left\{ -\frac{1}{\sqrt{50}}, \frac{1}{\sqrt{50}} \right\}$.

Assumption 3: The asynchronous case are generated by the introduction of retards on the channel vectors. This retard ($\tau_i^{(k)}$) is given by a uniform variable generated between $[0, T_s]$.

IV. CAPACITY PERFORMANCE AND COMPARISON OF RESULTS

In Fig. 3, we show the spectral efficiency when synchronous and asynchronous modes are employed on a ChDMA system in terms of the relation between the number of the users and the resolution ($\frac{K}{N}$). In the same figure, we show the performance of the CDMA system when pseudo random codes are used. As we can see, the effect of the asynchronism maximizes the spectral efficiency of the system, given almost

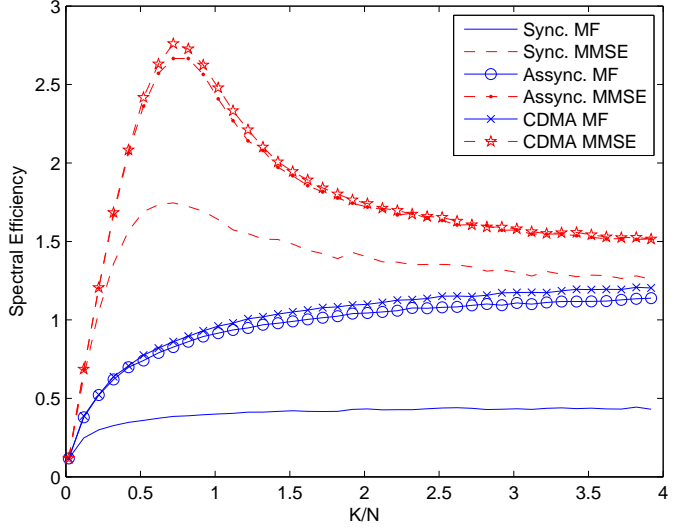


Fig. 3. Capacity analysis on the impact of the asynchronism when $\frac{E_b}{N_0} = 10\text{dB}$.

the same performance of the perfect CDMA capacity. This effect is generated by the fact that real channels have a typical power delay profile which spread the energy over only a few samples. When the asynchronism between users is considered, the interference is spread on all considered samples, avoiding the concentration of interference on the most important samples.

To evaluate the impact of the symbol period, we show in Figs. 4 and 5 the spectral efficiency curves when we employ asynchronous ChDMA and CDMA systems with matched filter receivers. The first figure shows the performance when Gaussian signaling is used. As we can see, the impact with respect to the ratio $\frac{K}{N}$ is not significative, but we can confirm our intuition that when we increase the symbol period, we decrease the spectral efficiency. We can conclude that the performance of the asynchronous ChDMA and the CDMA is the same when we employ the same system characteristics. In the same direction, Fig. 5 shows the performance when BPSK signaling is employed, and we confirm that the greatest spectral efficiency period of symbol is given when the symbol period is equal to the latest significative delay.

In Fig. 6 and 7, we show the spectral efficiency of the asynchronous ChDMA and CDMA when Gaussian and BPSK signaling are employed, respectively. As for the matched filter receiver, we see that the performance is almost the same, but as long as we decrease the period of symbol, we increase the spectral efficiency. Another interesting effect that we can see in this figure is that the classical peak found on the performance of the MMSE receiver in terms of the number of users is inversely related with the period of symbol. Again, the performance of the asynchronous ChDMA and the CDMA is the same.

The curves were simulated for a $\frac{E_b}{N_0}$ of 10dB. As we can see, the performance of the CDMA-based case is equal to the results of the asynchronous ChDMA case.

⁴The delay retard is limited between zero and the symbol period (T_s).

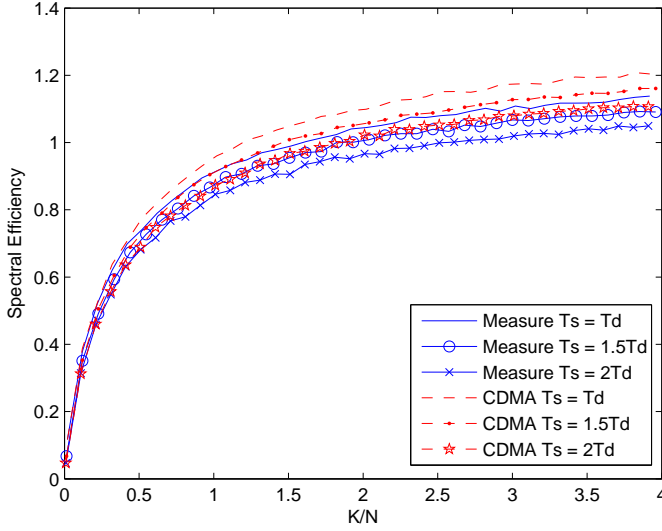


Fig. 4. Capacity analysis on the impact of T_s when a Match Filter receiver is employed at $\frac{E_b}{N_0} = 10\text{dB}$ with a Gaussian signaling.

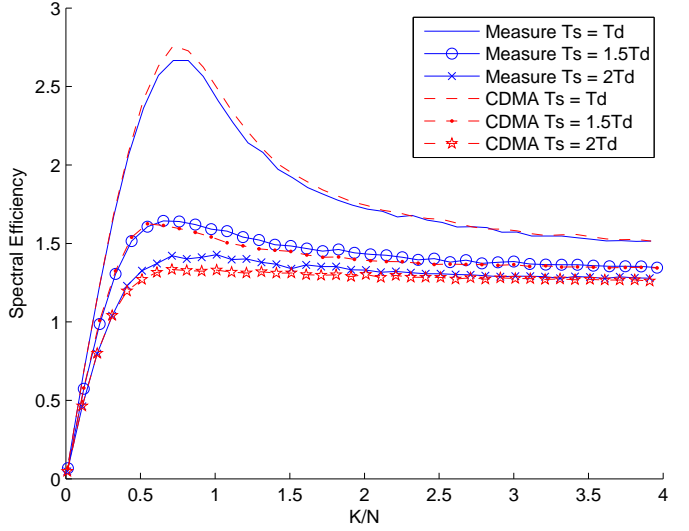


Fig. 6. Capacity analysis on the impact of T_s when a MMSE receiver is employed at $\frac{E_b}{N_0} = 10\text{dB}$ with a gaussian signaling.

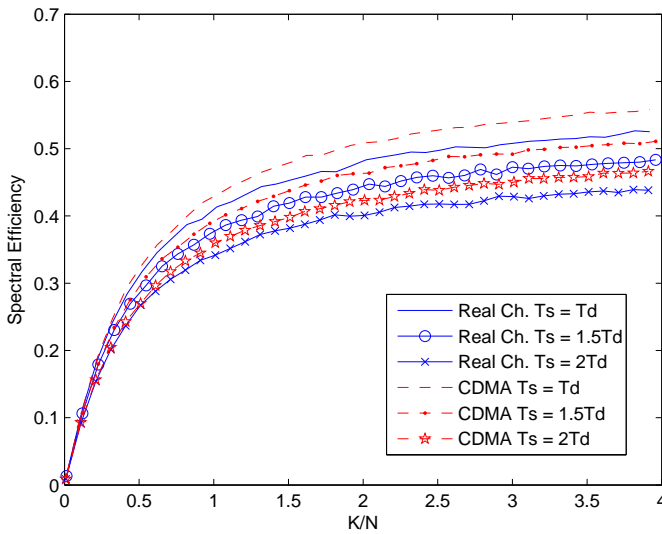


Fig. 5. Capacity analysis on the impact of T_s when a Match Filter receiver is employed at $\frac{E_b}{N_0} = 10\text{dB}$ with a BPSK signaling.

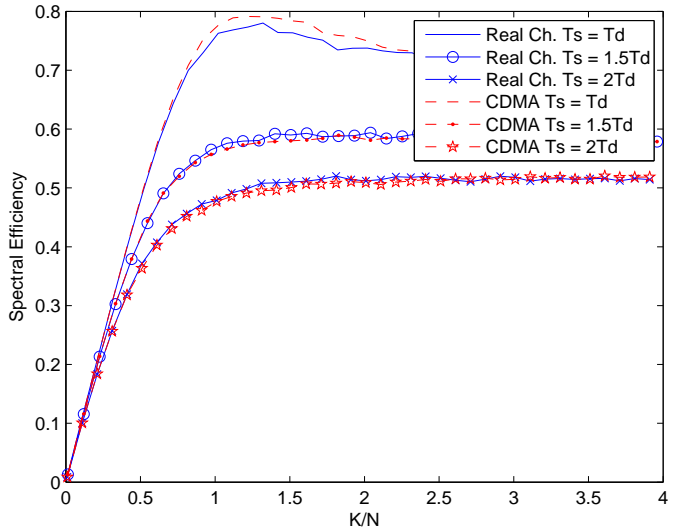


Fig. 7. Capacity analysis on the impact of T_s when a MMSE receiver is employed at $\frac{E_b}{N_0} = 10\text{dB}$ with a BPSK signaling.

It is important to note that the results presented for the CDMA case is for a perfect 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. For the CDMA case, as the channel profile is constant, the asynchronism will not change the performance.

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

For the synchronized case, the results are encouraging especially if we take into account the fact that the codes in ChDMA system are naturally provided by the channel estimation, they are location dependent which will increase the privacy. They also benefit from code hopping at each new channel realization which will increase the resistance against

inter-codes interference. Despite the slowest performance of the MF receiver, when we employ MMSE receivers, the ChDMA has almost the same performance as the CDMA-based case. This result implies that, even in a synchronous system, it is possible to build receivers for the ChDMA that is able to achieve a performance comparable to the CDMA capacity.

For the asynchronism case, it is possible to achieve the CDMA capacity for both receivers. Thanks to the exponential shape of the real channel, only a few paths will interfere which improve significantly the performance as we can see from the figures.

As future work, detailed analysis on the optimization of the symbol period should be done by the use of theoretic information tools. Furthermore, we know that the degrees of freedom plays an important role on the system modeling, and some studies are being conducted to analyze the impact of the degrees of freedom given by the channel model when high correlated channels are considered.

REFERENCES

- [1] R. S. Kennedy, *Fading Dispersive Communication Channels*. New York, USA: Wiley, 1969.
- [2] I. E. Telatar and D. N. C. Tse, "Capacity and Mutual Information of Wideband Multipath Fading Channels," *IEEE Trans. on Information Theory*, pp. 1384–1400, July 2000.
- [3] V. Subramanian and B. Hajek, "Broad-band Fading Channels: Signal Burstiness and Capacity," *IEEE Trans. on Information Theory*, pp. 809–827, Apr. 2002.
- [4] M. Médard and R. G. Gallager, "Bandwidth Scaling for Fading Multipath Channels," *IEEE Trans. on Information Theory*, pp. 840–852, Apr. 2002.
- [5] D. Porrat, D. N. C. Tse, and S. Nacu, "Channel uncertainty in ultra wideband communication systems," *IEEE Transactions on Information Theory*, 2005 (Submitted).
- [6] S. Verdú and S. Shamai, "Spectral Efficiency of CDMA with Random Spreading," *IEEE Trans. on Information Theory*, pp. 622–640, Mar. 1999.