# Chip-Spread CDMA Transmission: A Comparative Analysis

Darwin Pereira, Leonel Arévalo, Rodrigo Pereira David and Raimundo Sampaio-Neto.

*Abstract*— **In this paper a detailed study of an efficient transmission technique, recently proposed, which combines the single carrier (SC) block transmission, and the code division multiple access (CDMA), referred to as chip spread CDMA (CS-CDMA), is performed. The main feature of CS-CDMA is that, unlike the tradicional direct sequence (DS-CDMA) transmission system, the code orthogonality between users is maintained even when the transmissions, are made through a multipath frequency selective time-invariant channels. Thus, CS-CDMA allows the decoupling of user signals at the reception side. However, existing comparisons between CS-CDMA and DS-CDMA only consider the *up-link* scenario and particular conditions, which include orthogonal user codes and time invariant channels. In this scenario the CS-CDMA technique has shown a significant superiority when compared with the traditional DS-CDMA transmission. A detailed analisys of the CS-CDMA techique in more general conditions is presented in this work. We consider different environments such as, time invariant and time varying transmission channels, both orthogonal and non-orthogonal users' codes and *up-link* and *down-link* scenarios. We adopt frequency domain equalization with MMSE (*Minimum Mean Squared Error*) detection. Numerical results with performance comparisons indicate that, despite the effects of non-ideal conditions, CS-CDMA maintains a clear superiority over the DS-CDMA transmission.**

*Index Terms*—**Block Transmission; Single carrier systems; CS-CDMA; DS-CDMA; Non-orthogonal codes; Time varying channels.**

## I. INTRODUCTION

The growing demand for communications services with high reliability, high data rates and energy efficiency, indicates a need for the development of advanced and efficient digital systems. In this direction, many chalenges have to be adressed to improve the efficienty of wireless communications systems. For these reason, wireless communications have become an important research topic [1]. New trends provide that wireless communications systems must be: easily implemented and with tolerance to frequency selective channels and interferences [2]. The biggest source of interference in CDMA systems is the MAI (Multiple Access Interference), which is the result of the inability to maintain the orthogonality between the signals of users at the receiver side. In particular, the channel transmission effects and timing mismatches between signals can also enhance the MAI. Other deletorious effect is related to the multipath channel where the signal reaches the destination through multiple paths in different times. The presence of multipath channels in a cellular system, limits severely their performance. One of the deleterious effects when conventional serial transmission of information symbols are used, is the rise of intersymbol interference (ISI). One alternative for dealing with this problem is the adoption of block transmission with the resulting inter-block interference (IBI) being avoided by the insertion of a guard interval [3], [4]. The insertion of an appropriate guard interval also allows significant simplification of the process of channel estimation and equalization, with these procedures being performed in the frequency domain [3], [4].

To mitigate the MAI effects in DS-CDMA when the transmission is performed in frequency selective transmission channel, the CS-CDMA (*Chip - Spread Code Division Multiple Access*) has been proposed [5]. This technique combines the single carrier block transmission and an inversion between chips and information symbols in the traditional block CDMA. Studies have demonstrated that CS-CDMA can eliminate the MAI even when the transmission is made through frequency selective multipath channels, assumed time-invariant [5].

This paper presents a detailed analysis of the CS-CDMA scheme and a comparative study with the tradicional DS-CDMA in more general conditions where the systems operate in time invariant and time varying environments with both orthogonal and non-orthogonal codes and in two different scenarios, *down-link* and *up-link*. The results consider frequency domain MMSE (*Minimum Mean Squared Error*) equalization.

Notation: Uppercase characters in bold represent matrices; lowercase bold denote vectors. The operators $(.)^{\mathcal{T}}$, $(.)^{\mathcal{H}}$ denote transpose and hermitian, respectively, $(.)^{-1}$ represents matrix inversion and the operator $\mathbb{E}[.]$ denotes the expected value.

## II. SINGLE CARRIER CDMA SYSTEM

In this section we consider single carrier block transmission in the up-link of a CDMA system with K active users. The discrete channel that connects the user $k$ transmitter to the radio base station is modeled as a *Finite Impulse Response* (FIR) filter with size P. It is also assumed that a Cyclic Prefix (CP) [4] type of guard interval of sufficient size (not less than $P-1$) is inserted prior to block transmission to allow inter-block interference suppression at the receiver side.

### A. SC DS-CDMA Signal Model

Synchronous transmission in an *up-link* channel with K active users is assumed. The *kth* user transmits sequentially

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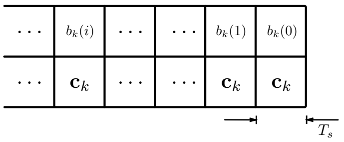

Fig. 1. Sequence of blocks transmitted by $k$-th user (DS-CDMA) ($T_s$ is the data symbol duration).

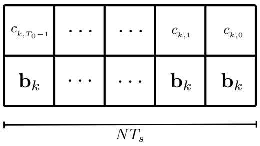

Fig. 2. Sequence of $T_0$ blocks transmitted by $k$-th user (CS-CDMA) ($T_s$ is the data symbol duration).

data symbols $b_k(i)$ drawn from a complex signal constellation. Each symbol is spread by a code sequence of length T, $\mathbf{c}_k = [c_{k,0} \dots c_{k,T-1}]^{\mathcal{T}}$ ($\| \mathbf{c}_k \|^2 = 1$). The block transmitted in a DS-CDMA scheme by $k$-th user in the $i$-th transmission is given by $\mathbf{c}_k b_k(i)$, ($i = 1, 2, \dots$). The sequence of blocks transmitted in the considered DS-CDMA system is illustrated in Figure 1. A cyclic prefix of size $L$ is added to each block prior to transmission resulting in a transmitted block of size $M = T + L$. Transmissions are made through the multipath channel $\mathbf{h}_k(i)$ of length P: $\mathbf{h}_k = [h_{k_0}(i), h_{k_1}(i), \dots, h_{k_{P-1}}(i)]^{\mathcal{T}}$, $\mathbb{E}[\|\mathbf{h}_k(i)\|^2] = 1$. It is assumed here that the channel is assentialy constant during the transmission of the block $\mathbf{c}_k b_k(i)$ but may vary from one transmission to the next. The transmission through the channel can be represented by a Toeplitz convolution matrix $\mathbf{H}_k(i)$ of dimension $M \times M$, where the first column is the channel response concatenated with zeros: $[\mathbf{h}_k(i), 0 \dots 0]^{\mathcal{T}}$. At the base station, the CP guard interval is removed from the block received, thus eliminating the IBI. Also the convolution matrix $\mathbf{H}_k(i)$ becomes a circulant matrix $\mathbf{H}_k^{(c)}(i)$, of dimension $T \times T$ with the first column given by:

$$\mathbf{h}_{k,ext} = [h_{k_0}(i), h_{k_1}(i), \dots, h_{k_{P-1}}(i), \mathbf{0}_{(1,T-P)}]^{\mathcal{T}}, \tag{1}$$

where $\mathbf{0}_{(1,T-P)}$ denotes $(T-P) \times 1$-dimensional vector full of zeros. The composite signal received at the radio base station corresponding to $i$-th block is then given by:

$$\mathbf{r}(i) = \sum_{k=1}^{K} \mathbf{H}_k^{(c)}(i)\mathbf{c}_k b_k(i) + \mathbf{n}(i), \tag{2}$$

where $\mathbf{n}(i)$ is complex Gaussian noise with zero mean and covariance matrix $\mathbf{K}_n = \sigma^2 \mathbf{I}_T$; $b_k(i)$ is the $k$-th user, $i$-th transmitted symbol with $\mathbb{E}[| b_k(i) |^2] = 1$ and $\mathbb{E}[b_k(i)] = 0$.

### *B. SC CS-CDMA Signal Model*

In the system analysed here an interchange between the information symbols and chips of the spreading code in the structure shown in Figure 1 is considered: a block of N data symbols, $\mathbf{b}_k = [b_k(0), b_k(1), \dots, b_k(N)]^{\mathcal{T}}$, is formed and replaces in the structure of Figure 1 the block $\mathbf{c}_k$, while the symbol $b_k(i)$ in this structure is replaced by the chip $c_{k,i}$ of $k$-th user code. This transmission structure is illustrated in Figure 2. As shall be seen later, in a time-invariant scenario the proposed scheme enables the orthogonality between the codes of different users to be preserved despite transmission through a frequency selective multipath channel. The block transmitted in a CS-CDMA scheme by the $k$-th user in the $i$-th transmission is then given by $\mathbf{b}_k c_{k,i}$ ($i$=0,1,2…$T_0$-1) where $c_{k,i}$ is the $i$-th chip of the length $T_0$ in the code sequence $\mathbf{c}_k$. After the insertion of a CP guard interval of size $L_0$ in the block $\mathbf{b}_k c_{k,i}$, the elements of the resulting block of size $L_0$+N are sequentially transmitted through the multipath channel. As in the DS-CDMA case, it is assumed here that the channel $\mathbf{h}_k(i)$ is essentially constant during block transmission $\mathbf{b}_k c_{k,i}$ but may vary from one transmission to the next. At the base station, the cyclic prefix is removed from the received block. Thus, by analogy with the results in the previous section and considering (2), we have that the signal received at the base station can be expressed as:

$$\bar{\mathbf{r}}(i) = \sum_{k=1}^{K} \bar{\mathbf{H}}_k^{(c)}(i)\mathbf{b}_k c_{k,i} + \bar{\mathbf{n}}(i),\ i = 0, 1 \dots T_0 - 1, \tag{3}$$

## III. FREQUENCY DOMAIN EQUALIZATION AND DETECTION IN SC DS-CDMA

In the SC DS-CDMA receiver, a normalized DFT (*Discrete Fourier Transform*) is applied to the signal given by (2) thus converting $\mathbf{r}(i)$ from the time domain to the frequency domain. The normalized DFT is represented by a matrix $\mathbf{W}_T$ such that $\mathbf{W}_T^{\mathcal{H}} \mathbf{W}_T = \mathbf{W}_T \mathbf{W}_T^{\mathcal{H}} = \mathbf{I}_T$. Its components are given by: $[\mathbf{W}_T]_{m,v} = \frac{1}{\sqrt{T}} e^{-j\frac{2\pi}{T}mv}$; $\quad 0 \le m, v \le T - 1$. The resulting signal in the frequency domain is

$$\tilde{\mathbf{r}}(i) = \mathbf{W}_T \mathbf{r}(i) = \sum_{k=1}^{K} \mathbf{W}_T \mathbf{H}_k^{(c)}(i)\mathbf{c}_k b_k(i) + \mathbf{W}_T \mathbf{n}(i). \tag{4}$$

Being a circulant matrix, the $T \times T$ matrix, $\mathbf{H}_k^{(c)}(i)$ in (4) can be decomposed in the form $\mathbf{H}_k^{(c)}(i) = \mathbf{W}_T^{\mathcal{H}} \mathbf{H}_k^{(d)}(i)\mathbf{W}_T$, where $\mathbf{H}_k^{(d)}(i)$ is a diagonal matrix whose inputs are the elements of the frequency response of the discrete channel, given by the $T \times 1$ vector $\mathbf{q}_k = \sqrt{T}\mathbf{W}_T \mathbf{h}_{k,ext}$, where $\mathbf{h}_{k,ext}$ is the impulse response of the channel discrete extended with zeros, given in (1). Substituting, we have

$$\tilde{\mathbf{r}}(i) = \sum_{k=1}^{K} \mathbf{H}_k^{(d)}(i)\mathbf{W}_T \mathbf{c}_k b_k(i) + \tilde{\mathbf{n}}(i), \tag{5}$$

where the complex Gaussian noise vector $\tilde{\mathbf{n}}(i) = \mathbf{W}_T \mathbf{n}(i)$ has zero mean and covariance matrix $\mathbf{K}_{\tilde{\mathbf{n}}} = \sigma^2 \mathbf{I}_T$.

### *A. SC DS-CDMA with MMSE equalization.*

The MMSE equalizer applied prior to the detection of $m$-th user is given by:

$$\mathbf{w}_m = \arg\min_{\mathbf{w}} \mathbb{E}[\| b_m(i) - \mathbf{w}^{\mathcal{H}} \tilde{\mathbf{r}}(i) \|^2], \tag{6}$$

whose solution is the $T \times 1$ vector $\mathbf{w}_m = \mathcal{R}^{-1}\mathbb{E}[\tilde{\mathbf{r}}(i)b_m(i)]$, where $\mathcal{R}^{-1}$ is the inverse of the autocorrelation matrix of $\tilde{\mathbf{r}}(i)$ in (6) given by:

$$\mathcal{R} = \sum_{k=1}^{K} \mathbf{H}_k^{(d)}(i)\mathbf{W}_T\mathbf{c}_k\mathbf{c}_k^{\mathcal{H}}\mathbf{W}_T^{\mathcal{H}}[\mathbf{H}_k^{(d)}(i)]^{\mathcal{H}} + \sigma^2\mathbf{I}_T, \qquad (7)$$

and the cross-correlation vector is given by $\mathbb{E}[\tilde{\mathbf{r}}(i)b_m(i)] = \mathbf{H}_m^{(d)}(i)\mathbf{W}_T\mathbf{c}_m$. After equalization the *m*-th user data symbol is detected through $\hat{b}_m(i) = \text{Disc}(\mathbf{w}_m^{\mathcal{H}}\tilde{\mathbf{r}}(i))$. Where $\text{Disc}(x)$ returns the point of the complex signal constellation closer to $x$.

## IV. FREQUENCY DOMAIN EQUALIZATION AND DETECTION IN SC CS-CDMA

At the receiver side a normalized DFT, $\mathbf{W}_N$, is applied to the signal CS-CDMA in (3). Considering the decomposition of the $N \times N$ circulant matrix, $\bar{\mathbf{H}}_k^{(c)}(i)$, we have by analogy with (5)

$$\tilde{\mathbf{r}}(i) = \sum_{k=1}^{K} \bar{\mathbf{H}}_k^{(d)}(i)\mathbf{W}_N\mathbf{b}_k c_{k,i} + \tilde{\mathbf{n}}(i),\ i = 0, 1 \ldots T_o - 1 \qquad (8)$$

The received vector $\tilde{\mathbf{r}}(i)$ is multiplied by the i-th code chip of the m-th active user, the signal to be equalized corresponding to the m-th user is obtained after the reception of T chips and is given by

$$\tilde{\mathbf{z}}_m = \sum_{i=0}^{T_o-1} \tilde{\mathbf{r}}(i)c_{m,i} = \underbrace{\frac{1}{T_o}\sum_{i=0}^{T_o-1} \bar{\mathbf{H}}_m^d(i)}_{\mathbf{D}_{m,m}}\mathbf{W}_N\mathbf{b}_m +$$

$$+ \sum_{\substack{j=1 \\ j\neq m}}^{K} \underbrace{\frac{1}{T_o}\sum_{i=0}^{To-1} \bar{\mathbf{H}}_j^d(i)T_o c_{j,i}c_{m,i}}_{\mathbf{D}_{j,m}}\mathbf{W}_N\mathbf{b}_j + \underbrace{\sum_{i=0}^{T_o-1} \tilde{\mathbf{n}}(i)c_{m,i}}_{\tilde{\mathbf{n}}_m}.$$

$$\tilde{\mathbf{z}}_m = \mathbf{D}_{m,m}\mathbf{W}_N\mathbf{b}_m + \sum_{\substack{j=1 \\ j\neq m}}^{K} \mathbf{D}_{j,m}\mathbf{W}_N\mathbf{b}_j + \tilde{\mathbf{n}}_m \qquad (9)$$

where $\mathbf{D}_{m,m}$ is a diagonal matrix associated to the desired user given by the mean of the user *m* time-varying channel matrix along the $T_o$ transmissions, $\mathbf{D}_{j,m}$ is a the diagonal matrix associated with the interfering users obtained by the weighted mean of the their channel matrices (weighted by the ±1 values of the product $T_o c_{j,i}c_{m,i}$) and $\tilde{\mathbf{n}}_m$ is a zero mean Gaussian noise vector with covariance matrix $\mathbf{K}_{\tilde{\mathbf{n}}_m} = \sigma^2\mathbf{I}_N$. Thus, the vector to be equalized, $\tilde{\mathbf{z}}_m$, corresponding to the desired user, is given by:

$$\tilde{\mathbf{z}}_m = \mathbf{D}_{m,m}\mathbf{W}_N\mathbf{b}_m + \mathbf{I}_{MAI} + \tilde{\mathbf{n}}_m. \qquad (10)$$

Where $\mathbf{I}_{MAI}$ represents the multiple access interference. For the particular case of transmission through time invariant channels, i.e., $\bar{\mathbf{H}}_k^d(i) = \bar{\mathbf{H}}_k^d$, we have that $\mathbf{D}_{m,m} = \bar{\mathbf{H}}_m^d$ and $\mathbf{D}_{j,m} = \bar{\mathbf{H}}_j^d\mathbf{c}_j^T\mathbf{c}_m$. If in addition, we have orthogonal codes, then $\mathbf{D}_{m,m} = \bar{\mathbf{H}}_m^d$ and $\mathbf{I}_{IMA} = 0$. In time-varying channels or with non-orthogonal user codes, however, the CS-CDMA receiver does not eliminate completely the IMA.

### A. *SC CS-CDMA with MMSE equalization.*

The MMSE equalizer for the signal in (16) is given by

$$\mathbf{E}_m = \arg\min_{\mathbf{E}} \mathbb{E}[\|\ \mathbf{b}_m - \mathbf{E}\,\tilde{\mathbf{z}}_m\ \|^2], \qquad (11)$$

whose solution is $\mathbf{E}_m = \mathbf{W}_N^{\mathcal{H}}\mathbf{D}_{m,m}^{\mathcal{H}}[\mathcal{R}_m]^{-1}$. Where $\mathcal{R}_m$ is the autocorrelation matrix of $\tilde{\mathbf{z}}_m$ given by

$$\mathcal{R}_m = \mathbf{D}_{m,m}[\mathbf{D}_{m,m}]^{\mathcal{H}} + \sum_{\substack{j=1 \\ j\neq m}}^{K} \mathbf{D}_{j,m}\mathbf{D}_{j,m}^{\mathcal{H}} + \sigma^2\mathbf{I}_N.$$

The data block $\mathbf{b}_m$ is then recovered by $\hat{\mathbf{b}}_m = \mathbf{Disc}(\mathbf{E}_m\tilde{\mathbf{z}}_m)$. When the environment is time-invariant and the codes are orthogonal, CS-CDMA can ideally detect in the absence of MAI and the matrix $\mathcal{R}_m$ is simpliffied to, $\mathcal{R}_m^o = [\mathbf{D}_{m,m}\mathbf{D}_{m,m}^{\mathcal{H}} + \sigma^2\mathbf{I}_N]$. When matrix $\mathcal{R}_m^o$ is used, even in cases where the MAI is present, the equalizer is referred as MMSE Simplified.

## V. NUMERICAL RESULTS AND COMPARISONS

For comparisons purposes, we note that for the two systems to have the same equivalent discrete channel impulse response (in this case $L = L_0$) and the same transmission bandwidth, the time duration of the chips in the block $\mathbf{c}_k$ in Figure 1 (SC DS-CDMA) must equal the time duration associated to the components of block $\mathbf{b}_k$ in Figure 2 (SC CS-CDMA). Under this assumption it can verified that the spectral efficiency, (bits/s/Hz), of the CS-CDMA system relates to that of the SC DS-CDMA by factor $\eta = T(1 + L/T)/T_0(1 + L/N)$. Furthermore, if one assumes equal lengths for the codes used by the two systems, then $T = T_0$. Thus, for a fair comparison ($\eta = 1$), the SC CS-CDMA system was assumed to operate with $N = T_0 = T$. Note that in this case the durations of the blocks $\mathbf{c}_k b_k(i)$ and $\mathbf{b}_k c_{k,i}$ transmitted by the DS-CDMA and CS-CDMA, respectively, are both igual to $T_s = 1/R_s$, where $R_s$ is the data symbol rate. Numerical results are presented for synchronous DS-CDMA and SC CS-CDMA systems using BPSK modulation and binary Hadamard orthogonal codes and pseudonoise (PN) non-orthogonal codes of length $T$. The channels associated to the active users in the system are random, identically distributed, statistically independent and modeled by a filter FIR with P coefficients. Considering the time-invariant case, the coefficients of the *k*-th user channel, $\mathbf{h}_k$, are given by $h_{k_i} = p_i\alpha_{k_i}$, where $\alpha_{k_i}$, *i*=0, 1 …, P-1, are statistically independent complex Gaussian random variables with zero mean and $\mathbb{E}[|\alpha_{k_i}|^2] = 1$ and . The values of $\alpha_{k_i}$ are randomly drawn and kept fixed throughout each simulation run. The weights $p_i$ satisfy $\sum_{i=0}^{P-1}|p_i|^2 = 1$, so that $\mathbb{E}[\|\ \mathbf{h}_k\ \|^2] = 1$. The CP guard interval is assumed large enough to allow IBI-free detection i.e. $L \geq P - 1$ The simulation results are an average of 2,000 simulations runs. For each run $500 \times N$ information symbols are transmitted. The results in Figure 3 and Figure 4 are for $N = T = 16$ and a channel with P=4 coefficients and weights $p_0 = 0.8671$, $p_1 = 0.4346$, $p_2 = 0.2178$, $p_3 = 0.1092$.

Figure 3 shows bit error rate curves versus $E_b/N_0$ for the two systems considered, obtained with MMSE equalization and *up-link* channel with 16 active users. In this experiment, we consider Hadamard orthogonal codes of length ($T = 32$) and PN non-orthogonal codes of length ($T = 31$).It's important to note that, unlike the SC DS-CDMA system, due to the elimination of MAI, in the orthogonal code case the SC CS-CDMA curves do not change with the number of users in the system (up to a maximum of $K = T = 32$). The performance of the CS-CDMA system is significantly superior than that of the DS-CDMA system, when orthogonal codes are used.

Figure 4 shows bit error rate curves versus $E_b/N_0$ for the two systems in the *down-link* scenario with $K = 16$ active users. We consider orthogonal codes ($T = 32$) and non-orthogonal codes ($T = 31$), the channels associated to each user is modeled by the time-invariant channel model described above.

Note that in the *down-link* scenario the signals transmitted by the BS (Base Station) to the active users reach a given user receiver through the same channel, the channel linking the BS to that user. The performance results for the *down-link* were obtained with we same expressions considered in the *up-link* but with the same channel associated to all users. The signal received by user $m$ ( $m$ = 1, 2, ...K) is given by (2) with $\mathbf{H}_k^{(c)} = \mathbf{H}_m^{(c)}$, for all $k$, in the DS-CDMA case and by (3) with $\bar{\mathbf{H}}_k^{(c)} = \bar{\mathbf{H}}_m^{(c)}$, for all $k$, in the CS-CDMA case.

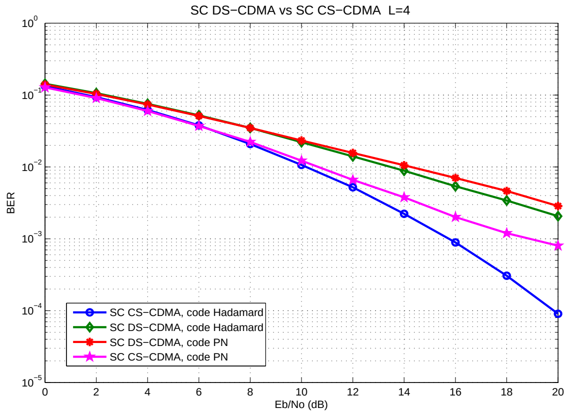

Fig. 3. BER versus $E_b/N_0$ for SC CS-CDMA and for the SC DS-CDMA system operating with $K = 16$, (Hadamard code: T=32, PN code T=31), *up-link*.

Figures 5, and 6 show bit error rate curves versus $E_b/N_0$ for the DS-CDMA and CS-CDMA systems in a time-varying enviroment. We consider both MMSE and MMSE Simplified equalization in the CS-CDMA case and *up-link* channel scenario with 16 active users in both systems. We also consider Hadamard orthogonal codes of length $T = 32$ and PN non-orthogonal codes of length $T = 31$, the channels associated to the active users are modeled by a time-varying channel with channel coefficients given $h_{k,l}(i) = q_l \alpha_{k,l}(i)$, where $\alpha_{k,l}(i)$ $(l = 1, \ldots, 4)$ are now independent zero mean, unit power, complex Gaussian processes with an auto-correlation fuction $\mathbf{E}[\alpha_{k,l}(i + \tau).\alpha_{k,l}^*(i)] = J_0(2\pi f_d.T_s \tau)$ given by the Clark model [6] where $J_0(.)$ is a zero-order first type Bessel function, $f_d$ is the Doppler frequency, and $T_s$ is the data symbol period. The results in Fig. 5 are for a product $f_d.T_s = 10^{-5}$ and those in Fig. 6 are for $f_d.T_s = 10^{-3}$.. Note that the performance curves of the CS-CDMA receiver operating with MMSE and with the MMSE Simplified equalizers are very close (practically coincident in the orthogonal code case) which indicates that the MAI is negligible in this system. A slight loss of performance occurs when the product $f_d.T_s$ increases, however the performance of the CS-CDMA maintains a remarkable superiority over that of the DS-CDMA system.

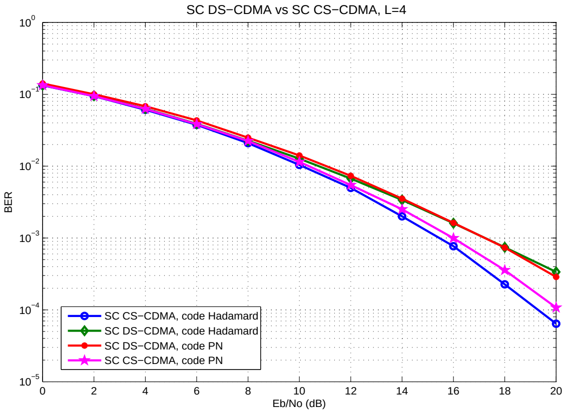

Fig. 4. BER versus $E_b/N_0$ for SC CS-CDMA and SC DS-CDMA systems operating with $K = 16$, (Hadamard code: T=32, PN code T=31), *down-link*.

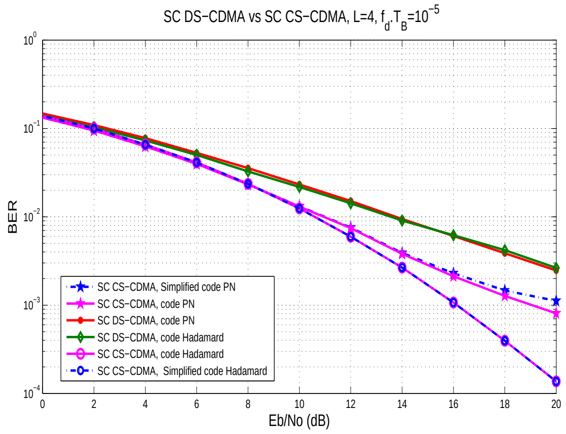

Fig. 5. BER versus $E_b/N_0$ for SC CS-CDMA vs SC DS-CDMA operating with $K = 16$ active users in both system and $f_d.T_s = 10^{-5}$, *up-link*

The curves in Figure 7 and Figure 8 shows bit error rate curves versus $E_b/N_0$ for the two systems, obtained in *down-link* channel with $K = 16$ active users in the system. The channel associated to each active user is modeled by the time-varying channel described above with $f_d.T_s = 10^{-5}$ and $f_d.T_s = 10^{-3}$ respectively. The results show that for both values of Doppler the SC DS-CDMA system has a significantly lower performance when compared to the SC CS-CDMA system in the case of orthogonal codes. Once again MAI is virtually non-existent in the SC CS-CDMA system. The difference in

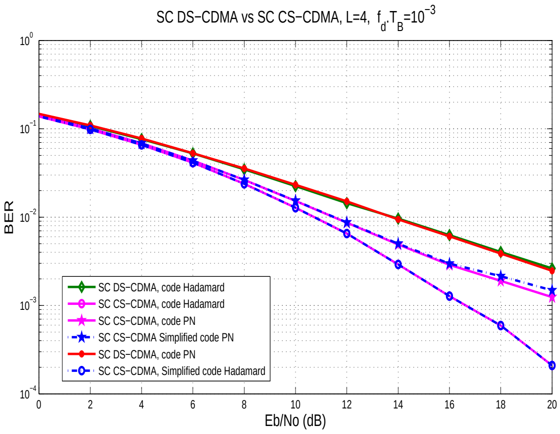

Fig. 6. BER versus $E_b/N_0$ for SC CS-CDMA vs SC DS-CDMA operating with $K = 16$ active users in both system and $f_d.T_s = 10^{-3}$, *up-link*

performaces decreases when the channel variations become faster.

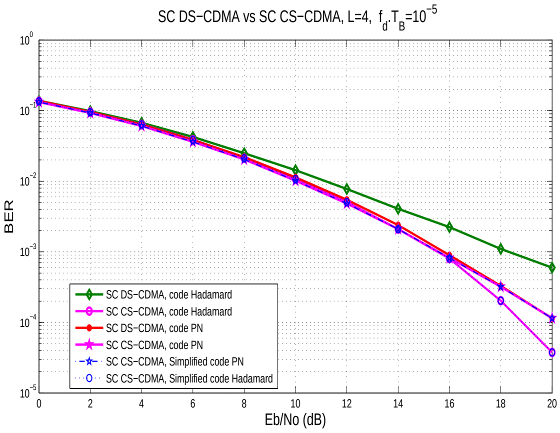

Fig. 7. BER versus $E_b/N_0$ for SC CS-CDMA vs SC DS-CDMA operating with $K = 16$ active users in both system and $f_d.T_s = 10^{-5}$, *down-link*

## VI. CONCLUSIONS

In this article a detailed analysis of the CS-CDMA scheme and a comparative performace study with the tradicional DS-CDMA in more general conditions was presented. The *up-link* performance results revealed the superiority of the SC CS-CDMA over the traditional SC DS-CDMA system in all scenarios considered. In the *down-link* scenario the SC DS-CDMA system has shown an evident superiority over the SC CS-CDMA system for orthogonal codes and a comparable performance for non-orthogonal codes. It is to be emphasized the ability of SC CS-CDMA system to eliminate, or nearly eliminate, the MAI in both *up-link* and *down-link* scenarious. This allows the MMSE Simplified equalizer to be used without a noticiable loss of performance. This is even more significant in the *down-link*, since to implement the full MMSE equalizer, the receiver needs to know which users are being served by the BS and their respective spreading codes, while the Simplified MMSE requires only the channel matrix and the code of the user whose signal is being detected. The performance results presented for *up-link* and *down-link* revealed the superiority of the SC CS-CDMA system, indicating that the use of this system is truly advantageous when compared to the traditional SC DS-CDMA system.

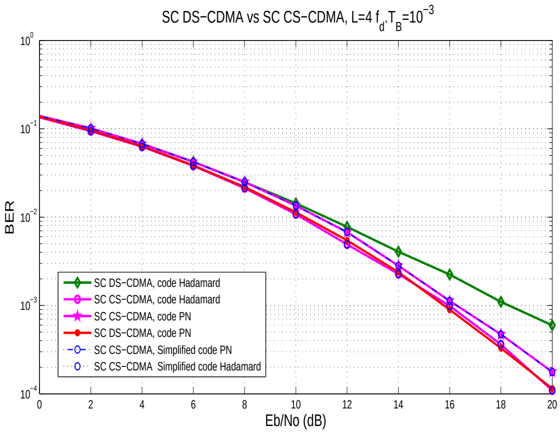

Fig. 8. BER versus $E_b/N_0$ for SC CS-CDMA vs SC DS-CDMA operating with ($K = 16$) active users in both system and $f_d.T_B = 10^{-3}$, *down-link*

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