Quasi-synchronous CDMA system using spreading sequences with zero-correlation zone

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***Abstract*— Current code-division multiple access (CDMA) systems are interference limited and suffer from both inter-symbol and multiple-access interference in time dispersive channel. The choice of the spreading sequences predetermines some properties of the system. Therefore, considerable efforts have been invested in designing zero-correlation zone sequences that exhibit the so-called interference-free window, where the autocorrelation and cross-correlation of the codes remain equal to zero. This research has drawn on the features of this sequences to improve the CDMA system performance.**

***Index Terms*— zero-correlation zone, spreading sequences, interference-free window**

I. INTRODUCTION

In typical CDMA systems, as the frequency selectivity of the propagation channel increases, the orthogonality of signature spread-sequences tends to diminish because of the increasing inter-cell interference. The inter-symbol interference (ISI) and multiple-access interference (MAI) are the result of random time offsets amongst the signals, that make unfeasible the code waveforms to be completely orthogonal. Tradicional spreading sequences [10], such as m-sequences, Kasami codes, Gold codes and Walsh codes, employed as channelisation codes, exhibit non-zero off-peak autocorrelations and cross-correlations, which limits the achievable performance, in asynchronous or in quasi-synchronous scenarios. Consequently, to suppress both ISI and MAI, the sidelobes of the correlations should be as small as possible. According to the Welch bound, the side lobes of the correlation functions can not be zero everywhere. Moreover, it is known that the autocorrelations and the cross-correlations oppose each other, so that smaller ISI leads to larger MAI and vice-versa.

It is possible to devise a novel multiple access scheme, known as large area synchronous CDMA (LAS-CDMA), which based on two families of spreading codes, large area (LA) and loosely synchronous (LS) codes. LA codes form a family of ternary codes having ± 1 or 0 elements. The pulse intervals are carefully designed, in order to assert a unitary maximum correlation magnitude. LA codes are mainly used to reduce adjacent cell interference. The specific family of spreading codes, namely Loosely Synchronized (LS) codes, exhibits zero correlation values, when a relative code offset is in the interference free window (IFW), also known as zero-correlation zone (ZCZ). Therefore, LS codes are more robust to multipath propagations channels and it may mitigate the effects of ISI and MAI. Hence, we focus our the attention to this promising sequences.

This paper is organized as follows. In section 2 the construction of ZCZ sequences is described. Section 3 presents the system model. The performance of ZCZ sequences applied to a CDMA system is analyzed in section 4 and, finally, conclusions are drawn in Section 5.

II. CONSTRUCTION OF ZCZ SEQUENCES

Methods to construct sets of orthogonal sequences are abundant [1]-[4]. Unfortunately, the use of such sets in CDMA systems requires a perfect synchronization of received spreading sequences, which is difficult to maintain in a multipath channel. Moreover, systematic methods of constructing sequences with favorable aperiodic correlation properties that would effectively combat the ISI and the MAI in an asynchronous CDMA system are not known. In LAS-CDMA, a coarse synchronization of received signal is established to optimize the aperiodic correlations of the sequences in a small window (IFW) around the zero shift.

In both methods, iterative construction by employing complementary Golay pair [4] [6] and ZCZ sequences based on perfect sequences and unitary matrices, the number of sequences with zero-correlation zone decreases with the IFW length. Unfortunately, the theoretical bounds shows that it is hard to obtain a large number of LS sequences while maintaining the size of orthogonal zone. In order to provide larger number of spreading sequences, a solution is to construct several LS codes sets, each one with the same correlation properties, but having minimum crosscorrelation between any pair from different LS code sets.

In [2], mutually orthogonal ZCZ sequence sets are recursively constructed. For a fixed IFW, it is possible to have mutually orthogonal sets such that each set has the maximum number of ZCZ sequences. Let us introduce the basis of mutually orthogonal ZCZ sequences sets.

Let $\mathbf{c_k}$ denote the spreading code with chip time duration T_c corresponding to user k, and code length equal to N, i.e.

$$\mathbf{c}_k = [c^{(1)}, c^{(2)}, ..., c^{(N)}]. \tag{1}$$

LS spreading code exhibit a IFW, with width given by Z_{cz}, if it presents the following correlation characteristics:

$$\phi_{j,k} = \sum_{i=0}^{N-1} c_j^{(i)} c_k^{(i+\tau)} = \begin{cases} N, & \text{for } \tau = 0,\ j = k \\ 0, & \text{for } \tau = 0,\ j \neq k \\ 0, & \text{for } 0 < |\tau| \leq Z_{cz}. \end{cases} \tag{2}$$

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where the superscript addition $i+\tau$ is performed *modulo* N.

The aperiodic correlation $\phi_{j,k}$ of two sequences $\mathbf{c_j}$ and $\mathbf{c_k}$ has to satisfy (2) for the sake of maintaining an IFW of Z_{cz} chip intervals.

A set of sequences $\{c_i\}_{i=1}^{M}$, each one with length N, and IFW of Z_{cz} is denoted as ZCZ-(N, M, Z_{cz}), where $Z_{cz} = \min\{Z_{acz}, Z_{ccz}\}$, Z_{acz} and Z_{ccz} denote, respectively, the zero periodic autocorrelation and zero cross-correlation zones, which are defined as [4]:

$$\begin{aligned} Z_{acz} &= \max\{T \mid \phi_{c^j c^j}(\tau) = 0, \forall j, \tau \neq 0, |\tau| \leq T\} \\ Z_{ccz} &= \max\{T \mid \phi_{c^j c^k}(\tau) = 0, \forall j \neq k, |\tau| \leq T\}. \end{aligned}$$

Two distinct sets of ZCZ sequences $\{c1_i\}_{i=1}^{M}$ and $\{c2_i\}_{i=1}^{M}$ are mutually orthogonal, if:

$$\phi_{c1_k c2_j}(0) = 0 \quad \forall j, k. \tag{3}$$

A. Construction of spreading sequences sets

We start with pair of complementary sequences mates, defined as [4] [1]:

$$F_1^{(0)} = \begin{bmatrix} F_{11}^{(0)} & F_{12}^{(0)} \\ F_{21}^{(0)} & -F_{22}^{(0)} \end{bmatrix} = \begin{bmatrix} -X_m & Y_m \\ -\overleftarrow{Y}_m & \overleftarrow{X}_m \end{bmatrix}_{2\times 2^{m+1}}, \tag{4}$$

where $\overleftarrow{Y}_m$ denotes the reverse of sequence Y_m and $-Y_m$ is the binary complement of Y_m. The two sequences Y_m and X_m are obtained recursively by:

$$\begin{aligned} [X_0, Y_0] &= [1, 1] \\ [X_m, Y_m] &= [X_{m-1}Y_{m-1}, (-X_{m-1})Y_{m-1}]. \end{aligned} \tag{5}$$

Consider $F_2^{(0)}$ identical to $F_1^{(0)}$. For the nth iteration ($n \geq 1$), $F_1^{(n)}$ and $F_2^{(n)}$ are obtained by a recursive procedure. First, $F^{(n-1)}$ was split into two matrices, as shown below:

$$F_i^{(n-1)} = \left[\begin{array}{c|c} A & B \end{array}\right] = \left[\begin{array}{c|c} \mathbf{a}_1 & \mathbf{b}_1 \\ \mathbf{a}_2 & \mathbf{b}_2 \\ \vdots & \vdots \\ \mathbf{a}_M & \mathbf{b}_M \end{array}\right]. \tag{6}$$

For the nth iteration ($n \geq 1$):

$$F_1^{(n)} = \begin{bmatrix} \mathbf{a}_1\mathbf{a}_1\mathbf{b}_1\mathbf{b}_1 & \mathbf{a}_1(-\mathbf{a}_1)\mathbf{b}_1(-\mathbf{b}_1) \\ \mathbf{a}_2\mathbf{a}_2\mathbf{b}_2\mathbf{b}_2 & \mathbf{a}_2(-\mathbf{a}_2)\mathbf{b}_2(-\mathbf{b}_2) \\ \vdots & \vdots \\ \mathbf{a}_M\mathbf{a}_M\mathbf{b}_M\mathbf{b}_M & \mathbf{a}_M(-\mathbf{a}_M)\mathbf{b}_M(-\mathbf{b}_M) \\ & \\ \mathbf{a}_1(-\mathbf{a}_1)\mathbf{b}_1(-\mathbf{b}_1) & \mathbf{a}_1\mathbf{a}_1\mathbf{b}_1\mathbf{b}_1 \\ \mathbf{a}_2(-\mathbf{a}_2)\mathbf{b}_2(-\mathbf{b}_2) & \mathbf{a}_2\mathbf{a}_2\mathbf{b}_2\mathbf{b}_2 \\ \vdots & \vdots \\ \mathbf{a}_M(-\mathbf{a}_M)\mathbf{b}_M(-\mathbf{b}_M) & \mathbf{a}_M\mathbf{a}_M\mathbf{b}_M\mathbf{b}_M \end{bmatrix}. \tag{7}$$

$$F_2^{(n)} = \begin{bmatrix} (-\mathrm{a}_1) - \mathbf{a}_1(-\mathbf{b}_1)(-\mathbf{b}_1) & (-\mathbf{a}_1)\mathbf{a}_1(-\mathbf{b}_1)\mathbf{b}_1 \\ (-\mathbf{a}_2) - \mathbf{a}_2(-\mathbf{b}_2)(-\mathbf{b}_2) & (-\mathbf{a}_2)\mathbf{a}_2(-\mathbf{b}_2)\mathbf{b}_2 \\ \vdots & \vdots \\ (-\mathbf{a}_M)(-\mathbf{a}_M)(-\mathbf{b}_M)(-\mathbf{b}_M) & (-\mathbf{a}_M)\mathbf{a}_M(-\mathbf{b}_M)\mathbf{b}_M \\ & \\ \mathbf{a}_1(-\mathbf{a}_1)\mathbf{b}_1(-\mathbf{b}_1) & \mathbf{a}_1\mathbf{a}_1\mathbf{b}_1\mathbf{b}_1 \\ \mathbf{a}_2(-\mathbf{a}_2)\mathbf{b}_2(-\mathbf{b}_2) & \mathbf{a}_2\mathbf{a}_2\mathbf{b}_2\mathbf{b}_2 \\ \vdots & \vdots \\ \mathbf{a}_M(-\mathbf{a}_M)\mathbf{b}_M(-\mathbf{b}_M) & \mathbf{a}_M\mathbf{a}_M\mathbf{b}_M\mathbf{b}_M \end{bmatrix}, \tag{8}$$

where $-\mathbf{a}_1$ is the vector $\mathbf{a}_1$ which entries are negated. Note that this recursive operation is similar to the Kronecker product, but it is not the same. Each row of the matrix $F_i^{(n)}$, resulted from the nth iteration, is a spreading sequence.

The aim of this paper is to ally the method of construction of mutually orthogonal sets [2] with the construction of generalized sequences [1] to form this prior sets $F^{(0)}$.

Once the complementary pair is obtained, we can construct the matrix $F^{(0)}$, according to Eq. (4). The matrix $F^n(N, M, Z_{cz})$ of the codes can be constructed according to Eq. (7) and (8). Explicitly, we have $M = 2^{(n+1)}$, $N = 2^{(2*n+m+1)}$ and $Z_{cz} = 2^{(m)}$. As an example, if $n = m = 1$, then we can generate the following sets:

$$F_1 = \begin{bmatrix} ----- + - + + + -- + -- + \\ - + - + ---- + -- + + + -- \\ + + -- + -- + ----- + - + \\ + -- + + + --- + - + ---- \end{bmatrix}, \tag{9}$$

$$F_2 = \begin{bmatrix} + + + + + - + --- + + - + + - \\ + - + - + + + + - + + --- + + \\ + + -- + -- + ----- + - + \\ + -- + + + --- + - + ---- \end{bmatrix}. \tag{10}$$

Figures 1 and 2 portray, respectively, the autocorrelation magnitude of a LS sequence and the cross-correlation magnitude of LS sequence pair in the same set.

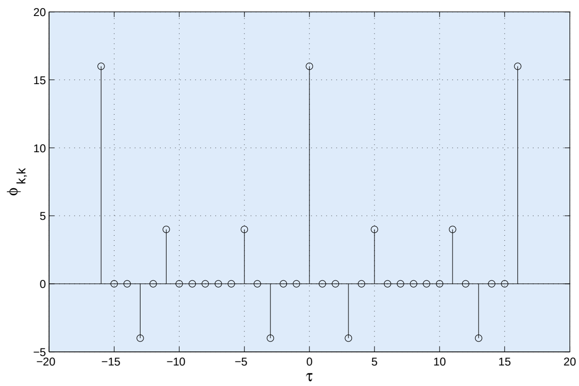

Fig. 1. LS code aperiodic autocorrelation

One can hardly obtain more LS sequences while maintaining the orthogonal zone, since the current LS family is already nearly optimal.

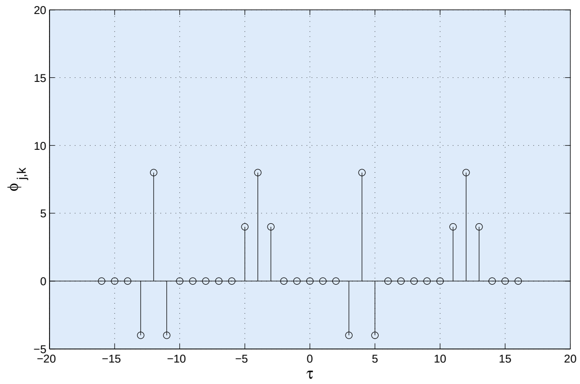

Fig. 2. LS code aperiodic cross-correlation

III. System model

A quasi-synchronous CDMA system with K users, in the reverse link is considered. The signals are transmitted on a Rayleigh fading channel with L paths. A LS spreading sequence per user and BPSK (binary phase-shift keying) modulation are assumed. The received signal is the sum of antipodal modulated quasi-synchronous signature waveforms embedded in additive white gaussian noise. Hence, the received signal can be expressed as:

$$r(t) = \sum_{k=1}^{K} \sum_{l=1}^{L} A_k b_k \alpha_{k,l} e^{-j\phi_{k,l}} s_k(t - \tau_{k,l}) + n(t), \quad (11)$$

where:

- A_k is the amplitude of the kth users signal.
- $b_k \;\epsilon\; \{+1, -1\}$ is the bit transmitted by the kth user.
- $\alpha_{k,l}$ is the fading coefficient, a random process with Rayleigh distribution and $\phi_{k,l}$, uniformly distributed, is the channel phase for the user k at the lth path.
- $s_k(t)$ is the signature waveform assigned to the kth user.
- $\tau_{k,l}$ is the delay associated to the lth path between the kth user and the BS (base station).
- $n(t)$ is the white gaussian noise.

The received signal is, then, introduced in a bank of matched filters, where each code waveform is regenerated and correlated with the received signal in a separate detector branch. The outputs of the correlators are combined by a RAKE detector, using the maximal ratio combining scheme (MRC). The estimation of the parameters of the channel are assumed perfect.

IV. Simulation Results

In this section the achievable performance of an LS-QS-CDMA system is obtained by Monte Carlo simulation. The signal-noise ratio (SNR) considered is 5 dB and each user transmits 10^5 bits, which guarantees a reliable estimation of the bit error probability (BER).

Fig. 3 portrays the performance, over different values of fading, of the random spreading sequences (RS), which length are $N = 16$, and the LS codes, with $m = 1$ e $n = 1$. All users are assumed to communicate in a quasi-synchronous manner, where the maximum delay difference τ is assumed to be $2T_c$.

We can observe from Fig. 3 that when the $(M+1)$th user is activated there is a degradation in performance of LS-coded-based system because the sequence associated to this user belongs to the second group and the zero-correlation characteristics are not maintained for all shifts among all sequences of the two groups. Even so, the LS-coded-based system exhibits better bit error rate than random spreading sequences, regardless of the value of L.

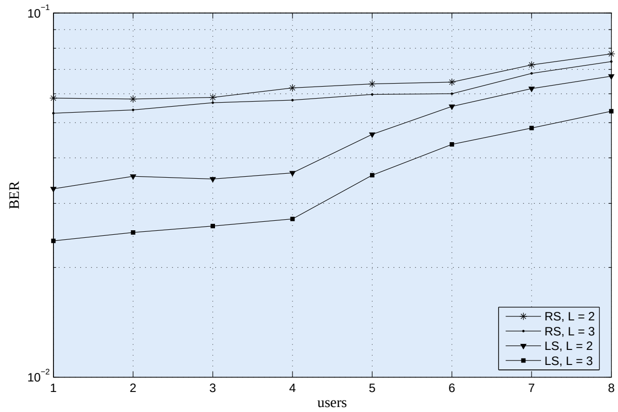

Fig. 3. Random codes and LS codes performance

As long as the relative delays, due to the inaccurate access synchronization and multipath propagation, do not exceed the IFW, the orthogonality between the signals is still maintained.

Observe from Fig. 4 that when the channel is more dispersive, the LS-QS-CDMA system performance significantly degrades. The reason for this performance degradation is that many of the paths will be located outside the IFW when τ is high, and the correlations of the LS codes outside the IFW is higher than those of the random codes.

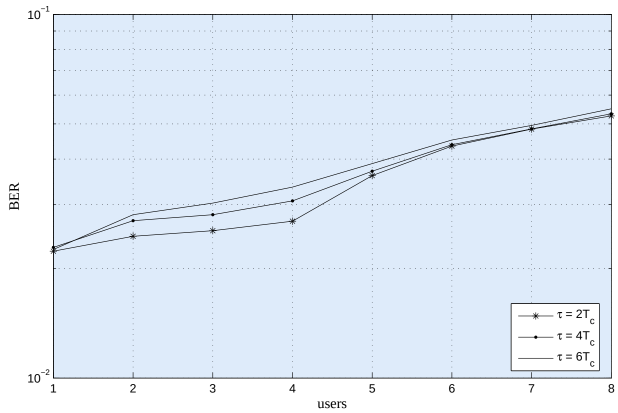

Fig. 4. Random codes and LS codes performance

In the system design, it is not always possible to let the IFW cover all the multipath spread. Assuming that there is a percentage (ϵ) [9] of multipath signal power outside the IFW, the ISI and MAI will be reduced to a low level, because (1-ϵ)

of the multipath components will fall in the IFW and thus will be absorbed.

There is a trade-off between the size of the IFW and the number of LS codes to improve the system performance and capacity.

V. CONCLUSIONS

ZCZ codes as spread sequences allow to the next wireless systems generations more tolerance to the multipath problem. The "near far effect" can be reduced significantly and the spectral efficiency of the system can be also enhanced. To make effective use of the ZCZ codes, the system should be designed in order to limit the delay time to a threshold.

LS spreading codes can be considered a breakthrough for LAS-CDMA. Therefore, LAS-CDMA can be a promising candidate for 4G wireless systems in the context of broadband services and applications.

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