QS-CDMA systems using concatenated ZCZ codes

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***Abstract*— The authors propose a novel use of zero correlation zone (ZCZ) codes to increase the performance of quasi-synchronous code division multiple access (CDMA) systems. In this new approach, each spread sequence associated to a active user is a concatenation of two or more ZCZ sequences. In the receiver, each of the component sequences is separately correlated in order to recover the original information. A comparison to the convencional receiver is fulfilled by analyzing the performance of both schemes in a multipath Rayleigh fading channel and similar system parameters.**

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

I. Introduction

In a CDMA uplink, the performance of the system, for a wireless fading channel, is degraded by multipath interference (MPI) and by multiuser interference (MAI). Besides, it is difficult to achieve perfect synchronization among signals transmitted from the users to the base station due to different signal propagation delays.

Despite of this, it is needed to nearly synchronize these multiple access sequences to within a few chips, in order to implement a uplink as a quasi-synchronous (QS) CDMA system. Once this nearly synchronization is performed, the interference can be mitigated, using a properly designed spreading codes that exhibit an interference-free window (IFW). Within this window, around the in-phase correlation position, the correlation sidelobes are zero and this window can be made large enough to contain the sum of multipath spread and multiple-access relative delay. Then, the performance of QS-CDMA systems can be improved by using this IFW sequences approach [1].

This paper is organized as follows. In section II the construction of ZCZ sequences is described. Section III presents the proposed system model. The performance of zero correlation zone sequences applied to a QS-CDMA system is analyzed in section IV and, finally, conclusions are drawn in Section V.

II. Introduction to Zero Correlation Zone Sequences

Lower bounds on the cross correlation and auto correlation of signals were established, by L.R. Welch, in 1974 [2]. According to these bounds, the side lobes of the correlation functions can not be zero everywhere. Moreover, the autocorrelations and the cross-correlations oppose each other, and small ISI leads to large MAI and vice-versa [3]. Then, perfect complex sequences whose auto-correlation and cross correlation side lobes are zero everywhere do not exist.

Many researches have been made based on binary sequences and a significant problem of the ZCZ codes is generating a sufficient number of sequences with useful IFW. The capacity of the QS-CDMA system using access codes with interference free window is dimension limited, that is, wider the IFW is, larger the dimension loss will be.

To cope with this limitation, one can make use of mutually orthogonal sequence sets. This procedure doubles the number of ZCZ sequences. However, a larger number of sequences does not assert the correlation proprieties among sequences of different sets for nonzero shifts.

Mutually orthogonal (MO) ZCZ sequence sets can be recursively constructed [4]. For a fixed IFW, it is possible to have mutually orthogonal sets such that each set has the maximum number of ZCZ sequences. The basis of mutually orthogonal ZCZ sequences sets is as follows [5], [6].

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

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

A sequence exhibit IFW properties, with width given by Z_{cz}, if it presents the following correlation characteristics [7]:

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

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) to maintaining an IFW of Z_{cz} chip interval.

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 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:

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

Start with pair of complementary sequences, Y_m and X_m, which is obtained recursively by:

$$\begin{aligned} [X_0, Y_0] &= [1, 1] \\ [X_m, Y_m] &= [X_{m-1} Y_{m-1}, (-X_{m-1}) Y_{m-1}]. \end{aligned} \tag{4}$$

$$F_1^{(0)} = \begin{bmatrix} -X_m & Y_m \\ -\overleftarrow{Y}_m & \overleftarrow{X}_m \end{bmatrix}_{2\times 2^{m+1}}, \tag{5}$$

where $\overleftarrow{Y}_m$ denotes the reverse of sequence Y_m and $-Y_m$ is the binary complement of Y_m.

Consider $F_2^{(0)}$ identical to $F_1^{(0)}$. For the nth iteration ($n \geq 1$), two mutually orthogonal sets of ZCZ sequences, $F_1^{(n)}$ and $F_2^{(n)}$, are obtained by a recursive procedure:

$$F_1^{(n)} = \begin{bmatrix} F_1^{(n-1)}F_1^{(n-1)} & F_1^{(n-1)}(-F_1^{(n-1)}) \\ F_1^{(n-1)}(-F_1^{(n-1)}) & F_1^{(n-1)}F_1^{(n-1)} \end{bmatrix}, \tag{6}$$

$$F_2^{(n)} = \begin{bmatrix} F_2^{(n-1)}F_2^{(n-1)} & (-F_2^{(n-1)})F_2^{(n-1)} \\ F_2^{(n-1)}(-F_2^{(n-1)}) & (-F_2^{(n-1)})(-F_2^{(n-1)}) \end{bmatrix}, \tag{7}$$

where $(-F_i^{(n-1)})$ is the matrix $F_i^{(n-1)}$ which entries are negated and $F_i^{(n-1)}F_i^{(n-1)}$ denotes the matrix whose ijth entry is the concatenation of the ijth entry of $F_i^{(n-1)}$ and the ijth entry of $F_i^{(n-1)}$ [8], [9].

Explicitly, we have $M = 2^{(n+1)}$, $N = 2^{(2n+m+1)}$ and $Z_{cz} = 2^{(m)}$. As an example, if $n = m = 1$, then the following sets can be generated:

$$F_1 = \begin{bmatrix} - - - - - + - + - - + + - + + - \\ - + - + - - - - - + + - - - + + \\ - - + + - + + - - - - - - + - + \\ - + + - - - + + - + - + - - - - \end{bmatrix}, \tag{8}$$

$$F_2 = \begin{bmatrix} - - - - - + - + + + - - + - - + \\ - + - + - - - - + - - + + + - - \\ - - + + - + + - + + + + + - + - \\ - + + - - - + + + - + - + + + + \end{bmatrix}. \tag{9}$$

Each row of the matrices, resulted from the nth iteration, represents a spreading sequence. This procedure doubles the number of ZCZ sequences.

III. System Model

A cellular QS-CDMA system with K active users, in the reverse link is considered. The signals are transmitted on a Rayleigh fading channel with L paths and binary phase-shift keying (BPSK) modulation is assumed. Fig. 1 illustrates the block diagram of the system model.

The received signal is the sum of antipodal modulated quasi-synchronous signature waveforms embedded in additive white gaussian noise (AWGN). Hence, the low pass received signal can be written as:

$$r(t) = \sum_{k=1}^{K}\sum_{l=1}^{L} A_k b_k \alpha_{k,l} e^{-j\phi_{k,l}} s_k(t - \tau_{k,l}) + n(t), \tag{10}$$

where:

- A_k is the amplitude of the kth signal.
- $b_k \ \epsilon \ \{+1, -1\}$ is the bit transmitted by the kth user.
- $\alpha_{k,l}$ is the fading coefficient, a Rayleigh random process.
- $\phi_{k,l}$, 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.

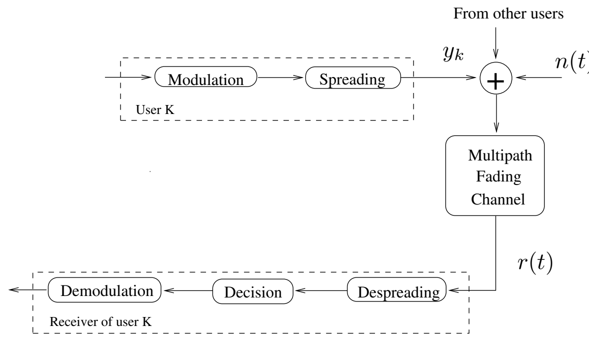


Fig. 1. Block diagram of the system model

- $\tau_{k,l}$ is the delay associated to the lth path between the kth user and the base station (BS).
- $n(t)$ is the additive white gaussian noise.

Instead of a spreading sequence, we propose to use two or more concatenated ZCZ sequences per user. This new sequence $s_k(t)$ has length equal to jN, where j represents the number of concatenated sequences. Thus, a transmitted bit is spread j times, in parallel, using different sequences (s_k^j) for the same user. This j spread information is then combined and transmitted as a one-code-per-user basis. The same process is made for all the users. The spreading scheme is depicted in Fig. 2.

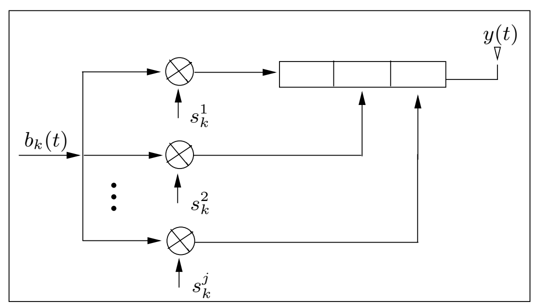
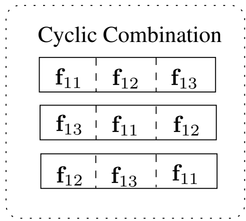


Fig. 2. Illustration of the spreading structure, for the user k.

The number of available ZCZ sequences is limited, and therefore, the number of concatenated sequences is also limited. Hence, we have to carefully choose the possible combination of the sequences to provide the best performance in order to take advantage of the zero correlation zone property

The adopted rule to concatenate the sequences is to apply all the possible combinations of the sequences at the same set F_i, thus the use of the the IFW is made. Next, the combinations among sequences from different sets are made (F_1 and F_2). Cyclic combinations must be avoided to limit high possible cross-correlations.



For instance, two MO sets are considered, $F_1 = [\mathbf{f}_{11}, \mathbf{f}_{12}, \ldots, \mathbf{f}_{1M}]$ and $F_2 = [\mathbf{f}_{21}, \mathbf{f}_{22}, \ldots, \mathbf{f}_{2M}]$, where $\mathbf{f}_{im}$ is the m-th sequence form the i-th set. Thus, a possible configuration of concatenated sequences for the scheme that uses a single set of ZCZ sequences is:

$$\begin{aligned} S_s = [&\mathbf{f}_{11}\mathbf{f}_{11}; \mathbf{f}_{12}\mathbf{f}_{12}; \mathbf{f}_{13}\mathbf{f}_{13}; \mathbf{f}_{14}\mathbf{f}_{14}; \\ &\mathbf{f}_{11}\mathbf{f}_{12}; \mathbf{f}_{11}\mathbf{f}_{13}; \mathbf{f}_{11}\mathbf{f}_{14}; \\ &\mathbf{f}_{12}\mathbf{f}_{13}; \mathbf{f}_{12}\mathbf{f}_{14}; \\ &\mathbf{f}_{13}\mathbf{f}_{14}]. \end{aligned} \tag{11}$$

If two sets of MO-ZCZ sequences are used to generate the concatenated sequences, a possible 20 sequences set is:

$$\begin{aligned} S_d = [&\mathbf{f}_{11}\mathbf{f}_{11}; \mathbf{f}_{12}\mathbf{f}_{12}; \mathbf{f}_{13}\mathbf{f}_{13}; \mathbf{f}_{14}\mathbf{f}_{14}; \\ &\mathbf{f}_{21}\mathbf{f}_{21}; \mathbf{f}_{22}\mathbf{f}_{22}; \mathbf{f}_{23}\mathbf{f}_{23}; \mathbf{f}_{24}\mathbf{f}_{24}; \\ &\mathbf{f}_{11}\mathbf{f}_{12}; \mathbf{f}_{13}\mathbf{f}_{14}; \mathbf{f}_{21}\mathbf{f}_{22}; \mathbf{f}_{23}\mathbf{f}_{24}; \\ &\mathbf{f}_{11}\mathbf{f}_{13}; \mathbf{f}_{12}\mathbf{f}_{14}; \mathbf{f}_{21}\mathbf{f}_{23}; \mathbf{f}_{22}\mathbf{f}_{24}; \\ &\mathbf{f}_{11}\mathbf{f}_{21}; \mathbf{f}_{12}\mathbf{f}_{22}; \mathbf{f}_{13}\mathbf{f}_{23}; \mathbf{f}_{14}\mathbf{f}_{24}]. \end{aligned} \tag{12}$$

After a rough synchronization procedure in the receiver, the concatenation process is reverted for each one of the users and for all the resolvable signals deriving from the multipath channel.

The peculiar idea is before reaching a decision on the transmitted bit, the received signal is matched to the pertinent sequence and, at each branch of the receiver, the correlation is evaluated and summed. Unless the sum of the correlation values is near maximum, the decision on the bit is not made. The outputs of the correlators are combined according to the maximal ratio combining scheme (MRC). Fig. 3 portrays the receiver structure.

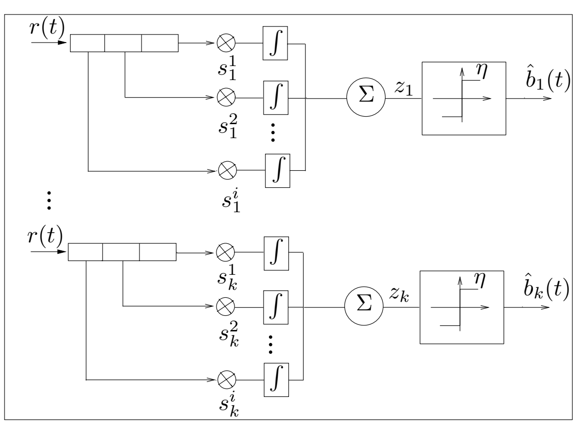


Fig. 3. Proposed receiver structure.

The parameter η predetermines the decision limiar of the receiver and his performance is conditioned to that value. We should search the limiar that reduce the bit-error rate. As η is close to unity (its maximum value) less is the asynchronism tolerance. Evidently, η could not be so low because the receiver could admit more interference than desirable, what would lead to a performance degradation.

The IFW allows an improvement in performance, and the proposed scheme performs better than those with single random sequences, with the same length of the concatenated sequences. This behavior can be observed in the next section.

IV. Performance of LS QS-CDMA

Performance results were obtained, in terms of average BER, by Monte Carlo simulation. The estimation of the channel weights is assumed to be perfect. The signal-to-noise ratio is set to 10 dB. The length N of the spreading sequences is 32 chips. The maximum delay difference τ is equal to $2T_c$ and there are $L = 3$ resolvable paths in the model.

Three schemes were simulated considering the same load and the same processing gain. The first scheme is a CDMA system with tradicional random spread sequences. This scheme presents highest bit-error rate because this sequences does not hold the zero periodic correlation zones. The second scheme uses a single orthogonal set of ZCZ sequences with $N = 16$ e $M = 4$. This M sequences are chosen peer-to-peer and concatenated, i.e. $j = 2$ and it results in 10 available sequences with processing gain equals to 32. This scheme provides better performance than the DS-CDMA. However, the load is limited by low number of sequences in the set. The last scheme utilizes concatenated ZCZ sequences deriving from two mutually orthogonal sets. The performance of such scheme is intermediate, but it can reach higher load.

Fig. 4 illustrates that as the load increases, the attainable performance of the QS-CDMA system, using the concatenated ZCZ sequences, decreases because the IFW can not stand the interference.

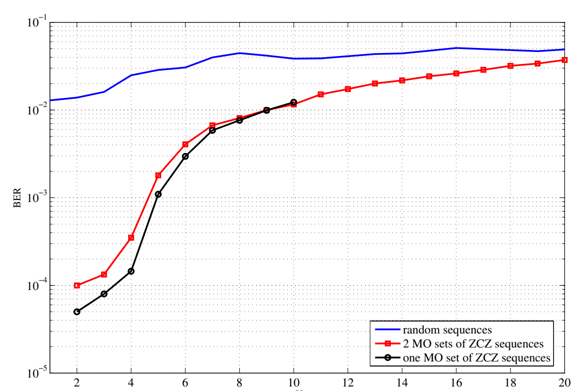


Fig. 4. Proposed receiver performance for three different schemes. Uplink, $N = 32$ and $\eta = 0.75$.

Notice that the order as the concatenated sequences are selected influences the overall performance. If the spread sequences are picked according to S_d, i.e., if the higher non periodic cross-correlations are avoid, the bit-error rate is reduced. The BER curves are plotted in Fig. 5, for a system using tradicional random sequences and for two systems using concatenated ZCZ sequences, from two MO sets. The system that presents the best performance was that whose sequences were taken as a predetermined order, by the sequence matrix S_d. If the concatenated sequences are allocated to the users in a random way, the system still performs better than that with tradicional random sequences, but this is not the preferable option.

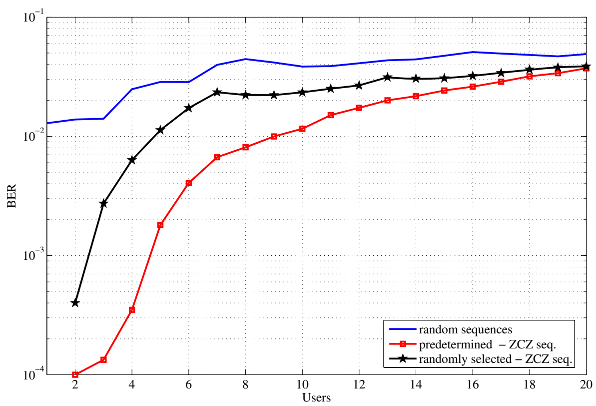


Fig. 5. System performance analysis for three different sequences selection. Uplink, $N = 32$ and $\eta = 0.75$.

Fig. 6 shows the influence of η on the system performance. For values of η near to the unity, the decision limiar is stern, and the evaluated correlation must be close to the maximum. For high load systems, the parameter η does not interfere in the result.

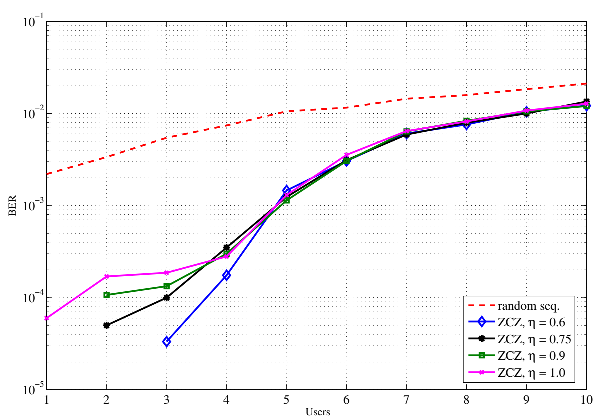


Fig. 6. Proposed receiver performance, parameterized by η. Uplink, $N = 32$.

V. Conclusion

This work employed a specific scheme of concatenated ZCZ spread sequences and a new receiver approach. Both principles brought improvements to the performance. Concatenated ZCZ sequences overcome the limitation in the number of sequences, and the variable decision limiar allowed a reduction at the bit error rate. And from the simulations, one can also conclude that the order in which the sequences are selected modifies the system performance.

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