

On a method to improve correlation properties of orthogonal polyphase spreading sequences

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Abstract — In this paper, we propose a simple but efficient method for improving correlation properties of polyphase spreading sequences for asynchronous direct sequence code division multiple access (DS CDMA) applications. The proposed method can be used to reduce the mean square value of aperiodic crosscorrelation or the mean square value of aperiodic autocorrelation, the maximum value of aperiodic crosscorrelation functions, merit factor or other properties of the sequence set. The important feature of the method is that while it modifies correlation properties of the sequence set, it preserves sequence orthogonality for perfect synchronization, if this is the property of the original sequence set.

Keywords — spread spectrum communication, orthogonal sequences, wireless communication, wireless LAN, correlation.

1. Introduction

Walsh-Hadamard bipolar spreading sequences are generally used for channel separation in direct sequence code division multiple access systems, e.g. [1]. They are easy to generate, and orthogonal [2] in the case of perfect synchronization. However, the crosscorrelation between two Walsh-Hadamard sequences can rise considerably in magnitude if there is a non-zero delay shift between them [3]. Unfortunately, this is very often the case for up-link (mobile to base station) transmission, due to the differences in the corresponding propagation delays. As a result, significant multi-access interference (MAI) [4] occurs which needs to be combated either by complicated multi-user detection algorithms [5], or reduction in bandwidth utilization.

Another possible solution to this problem can be use of orthogonal complex valued polyphase spreading sequences, like those proposed in [6], which for some values of their parameters can exhibit a reasonable compromise between autocorrelation and crosscorrelation functions. However, in most cases the choice of the parameters is not simple. In addition, improving one of the characteristics is usually associated with significant degradation of the others [7].

In the paper, we propose a method to optimize correlation properties of polyphase sequences which allows to use standard optimization techniques, like the Nelder-Mead simplex search [8] being implemented in several mathematical software packages, e.g. MATLAB. By using a standard optimization technique, one can choose the penalty function in a way, which takes to account all the important correlation characteristics. The numerical example shows application

of the method to optimize properties of the orthogonal sequence set of the length 31 from the family of sequences proposed in [6]. The results show that significant changes in sequence characteristics can be achieved. Another example illustrates application of the method to change the characteristics of the orthogonal bipolar sequences, i.e. Walsh-Hadamard sequences of length 32.

The paper is organized as follows. In Section 2, we introduce the method used later to optimize correlation characteristics of the spreading sequences. Section 3 introduces optimization criteria, which can be used for DS CDMA applications. The numerical example of optimization applied to orthogonal polyphase sequences is given in Section 4. Section 5 deals with application of the proposed modification method in case of bipolar sequences, i.e. Walsh-Hadamard sequences, and Section 6 concludes the paper.

2. Modification method

Sets of spreading sequences used for DS CDMA applications can be represented by $M \times N$ matrices \mathbf{S}_{MN} , where M is the number of sequences in the set and N is the sequence length. The sequences are referred to as orthogonal sequences if, and only if the matrix \mathbf{S}_{MN} is orthogonal, i.e.

$$\mathbf{S}_{MN}\mathbf{S}_{MN}^H = k\mathbf{I}_M, \quad (1)$$

where k is a constant, \mathbf{S}_{MN}^H is the Hermitian transposition of matrix \mathbf{S}_{MN} , (i.e. transposition and taking complex conjugate of the elements of matrix \mathbf{S}_{MN}), and \mathbf{I}_M is an $M \times M$ unity matrix.

There are a few families of orthogonal spreading sequences proposed in literature, e.g. [2, 6, 9, 10, 11]. Out of them, the most commonly applied are Walsh-Hadamard sequences. Some of the proposed sequence families are designed in a parametric way, which allows for some manipulation of parameters to change the desired correlation characteristics. However, those changes are usually of a limited magnitude, and very often while improving the crosscorrelation functions, a significant worsening of the autocorrelation functions is experienced, e.g. [7].

Here, we propose to modify correlation properties of the set of orthogonal spreading sequences by multiplying the matrix \mathbf{S}_{MN} by another orthogonal $N \times N$ matrix \mathbf{D}_N . Hence,

the new set of spreading sequences is represented by a matrix \mathbf{W}_{MN}

$$\mathbf{W}_{MN} = \mathbf{S}_{MN} \mathbf{D}_N \quad (2)$$

that, of course, is also orthogonal. Hence, the matrix \mathbf{D}_N satisfies the condition:

$$\mathbf{D}_N \mathbf{D}_N^H = c \mathbf{I}_N, \quad (3)$$

where c is a real constant. In addition, if $c = 1$, then the sequences represented by the matrix \mathbf{W}_{MN} are not only orthogonal, but possess the same normalization as the original sequences represented by the matrix \mathbf{S}_{MN} . However, other correlation properties of the sequences defined by \mathbf{W}_{MN} can be significantly different to those of the original sequences.

To this point, it is not clear how to choose the matrix \mathbf{D}_N to achieve the desired properties of the sequences defined by the \mathbf{W}_{MN} . A simple class of orthogonal matrices are diagonal matrices with their elements $d_{m,n}$ fulfilling the condition:

$$|d_{m,n}| = \begin{cases} 0 & \text{for } m \neq n \\ c & \text{for } m = n \end{cases}; \quad m, n = 1, \dots, N. \quad (4)$$

To achieve the same signal power as in the case of spreading by means of the original sequences defined by \mathbf{S}_{MN} , the elements of \mathbf{D}_N , being in general complex numbers, must be of the form:

$$d_{m,n} = \begin{cases} 0 & \text{for } m \neq n \\ \exp(j\phi_m) & \text{for } m = n \end{cases}; \quad m, n = 1, \dots, N, \quad (5)$$

where the phase coefficients ϕ_m ; $m = 1, 2, \dots, N$, are real numbers taking their values from the interval $[0, 2\pi)$, and $j^2 = -1$. The values of ϕ_m ; $m = 1, 2, \dots, N$, can be chosen to improve the correlation and/or spectral properties, e.g. reduce out-of-phase autocorrelation or value of peaks in aperiodic crosscorrelation functions.

3. Optimization criteria

In order to compare different sets of spreading sequences, we need a quantitative measure for the judgment. Therefore, we introduce here some useful criteria, which can be considered for such a purpose. They are based on correlation functions of the set of sequences, since both the level of multiaccess interference and synchronization amenability depend on the crosscorrelations between the sequences and the autocorrelation functions of the sequences, respectively. There are, however, several specific correlation functions that can be used to characterize a given set of spreading sequences [4, 7, 12].

One of the first detailed investigations of the asynchronous DS CDMA system performance was published in 1969 by Anderson and Wintz [13]. They obtained a bound on the signal-to-noise ratio at the output of the correlation receiver for a CDMA system with hard-limiter in the channel. They also clearly demonstrated in their paper the need for

considering the aperiodic crosscorrelation properties of the spreading sequences. Since that time, many additional results have been obtained (e.g. [4] and [14]), which helped to clarify the role of aperiodic correlation in asynchronous DS CDMA systems.

For general polyphase sequences and $\{s_n^{(i)}\}$ and $\{s_n^{(k)}\}$; $n = 1, 2, \dots, N$, of length N , the discrete aperiodic correlation function is defined as [12]:

$$c_{i,k}(\tau) = \begin{cases} \frac{1}{N} \sum_{n=0}^{N-1-\tau} s_n^{(i)} [s_{n+\tau}^{(k)}]^*, & 0 \leq \tau \leq N-1 \\ \frac{1}{N} \sum_{n=0}^{N-1+\tau} s_{n-\tau}^{(i)} [s_n^{(k)}]^*, & 1-N \leq \tau < 0 \\ 0, & |\tau| \geq N \end{cases} \quad (6)$$

where $[\bullet]^*$ denotes a complex conjugate operation. When $\{s_n^{(i)}\} = \{s_n^{(k)}\}$, Eq. (6) defines the discrete aperiodic autocorrelation function.

Another important parameter used to assess the synchronization amenability of the spreading sequence $\{s_n^{(i)}\}$ is a merit factor, or a figure of merit [15], which specifies the ratio of the energy of autocorrelation function mainlobes to the energy of the autocorrelation function sidelobes in the form:

$$F = \frac{c_i(0)}{2 \sum_{\tau=1}^{N-1} |c_i(\tau)|^2}. \quad (7)$$

In DS CDMA systems, we want to have the maximum values of aperiodic crosscorrelation functions and the maximum values of out-of-phase aperiodic autocorrelation functions as small as possible, while the merit factor as great as possible for all of the sequences used.

The bit error rate (BER) in a multiple access environment depends on the modulation technique used, demodulation algorithm, and the signal-to-noise power ratio (SNR) available at the receiver. Pursley [4] showed that in case of a BPSK asynchronous DS CDMA system, it is possible to express the average SNR at the receiver output of a correlator receiver of the i th user as a function of the average interference parameter (AIP) for the other K users of the system, and the power of white Gaussian noise present in the channel. The SNR for i th user, denoted as SNR_i , can be expressed in the form:

$$\text{SNR}_i = \left(\frac{N_0}{2E_b} + \frac{1}{6N^3} \sum_{\substack{k=1 \\ k \neq i}}^K \rho_{k,i} \right)^{-0.5}, \quad (8)$$

where E_b is the bit energy, N_0 is the one-sided Gaussian noise power spectral density, and $\rho_{k,i}$ is the AIP, defined for a pair of sequences as

$$\rho_{k,i} = 2\mu_{k,i}(0) + \text{Re}\{\mu_{k,i}(1)\}. \quad (9)$$

The crosscorrelation parameters $\mu_{k,i}(\tau)$ are defined by:

$$\mu_{k,i} = N^2 \sum_{n=1-N}^{N-1} c_{k,i}(n) [c_{k,i}(n+\tau)]^*. \quad (10)$$

However, following the derivation in [16], $\rho_{k,i}$ for polyphase sequences may be well approximated as:

$$\rho_{k,i} \approx 2N^2 \sum_{n=1-N}^{N-1} |c_{k,i}(n)|^2. \quad (11)$$

In order to evaluate the performance of a whole set of M spreading sequences, the average mean-square value of crosscorrelation for all sequences in the set, denoted by R_{CC} , was introduced by Oppermann and Vucetic [7] as a measure of the set crosscorrelation performance:

$$R_{CC} = \frac{1}{M(M-1)} \sum_{i=1}^M \sum_{\substack{k=1 \\ k \neq i}}^M \sum_{\tau=1-N}^{N-1} |c_{i,k}(\tau)|^2. \quad (12)$$

A similar measure, denoted by R_{AC} was introduced in [7] for comparing the autocorrelation performance:

$$R_{AC} = \frac{1}{M} \sum_{i=1}^M \sum_{\substack{\tau=1-N \\ \tau \neq 0}}^{N-1} |c_{i,i}(\tau)|^2. \quad (13)$$

The measure defined by (13) allows for comparison of the autocorrelation properties of the set of spreading sequences on the same basis as the crosscorrelation properties. It can be used instead of the figures of merit, which have to be calculated for the individual sequences.

For DS CDMA applications we want both parameters R_{CC} and R_{AC} to be as low as possible [7]. Because these parameters characterize the whole sets of spreading sequences, it is convenient to use them as the optimization criteria in design of new sequence sets. Therefore, we will use them for optimizing the values of the phase coefficients ϕ_m ; $m = 1, 2, \dots, N$, in the considered numerical examples. We will also look into the maximum value of aperiodic crosscorrelation functions since this parameter is very important when the worst-case scenario is considered. Optimization criteria, not based on the correlation characteristics, can be envisaged as well.

4. Optimization of orthogonal polyphase sequences

Oppermann and Vucetic introduced in [7] a new family of polyphase spreading sequences. The elements $u_n^{(k)}$ of these sequences $\{u_n^{(k)}\}$ are given by:

$$u_n^{(k)} = (-1)^{kn} \exp \left[\frac{j\pi(n^m k^p + k^s)}{N} \right], \quad 1 \leq n \leq N, \quad (14)$$

where k can take integer values being relatively prime to N such that $1 \leq k < N$, and the parameters m , p , s can take any real values. They showed there that – depending on the choice of the parameters m , p , and s – the sequences could have a wide range of the correlation properties. However, no clear method for selecting the appropriate values of the parameters depending on the desired correlation characteristics was given in [7]. Later in [6], Oppermann showed

that the sequences defined by (14) were orthogonal if $p = 1$ and m is a positive nonzero integer.

In this section, we apply the developed method to improve the properties of the spreading sequence set belonging to the family defined by (14), with $N = 31$, $p = 1$, and $m = 1$. Since N is a prime number, k can take any nonzero integer value lower than 31, i.e. $k = 1, 2, \dots, 30$, and the maximum number of sequences in the set is 30. To select the appropriate value for s , we plotted in Fig. 1 the values of R_{CC} , R_{AC} and the value of the maximum peak in all aperiodic crosscorrelation functions C_{\max} as the functions of s . From the plots we choose $s = 2.5$, for which $R_{CC} = 0.9803$, $R_{AC} = 0.5713$, and $C_{\max} = 0.4546$.

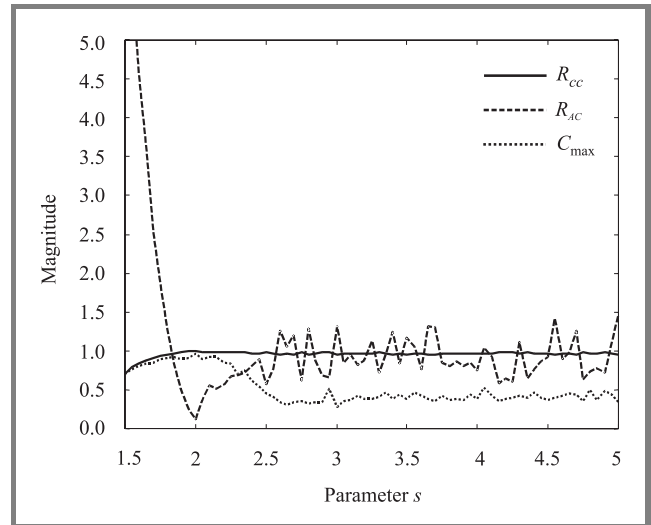


Fig. 1. Plots of the values of R_{CC} , R_{AC} , and C_{\max} as functions of the parameter s for the sequences $\{u_n^{(k)}\}$, with $N = 31$, $p = 1$, $m = 1$, and $k = 1, 2, \dots, 30$.

To illustrate the modification method, we first applied it to reduce the value of R_{CC} for this set of sequences. The process was performed using the standard “*fmin*” function of MATLAB [8] with the optimized function being $R_{CC}(\Phi)$, where

$$\Phi = [\phi_m; m = 1, 2, \dots, 31] \quad (15)$$

and the phase coefficients ϕ_m ; $m = 1, 2, \dots, 31$, being used to define the elements of the modification matrix \mathbf{D}_N (see Eq. (5)).

The function $R_{CC}(\Phi)$ is very irregular and may have several local minima. Therefore, depending on the starting point, different local minima can be reached. To illustrate this, we selected randomly 6 vectors $\Phi_1, \Phi_2, \dots, \Phi_6$, and run “*fmin*” for each of them chosen as a starting point. The results of the obtained values of R_{CC} , R_{AC} and C_{\max} are given in Table 1.

Next we repeat the procedure, this time finding the sequences to reduce the value of R_{AC} , and finally to achieve reduction in the value of C_{\max} . The results of R_{CC} , R_{AC} and C_{\max} are given in Tables 2 and 3, respectively.

Table 1

Values of R_{CC} , R_{AC} and C_{max} obtained for the sequences optimized to achieve minimum R_{CC}

Coefficients	R_{CC}	R_{AC}	C_{max}
$\Phi_{1,opt}$	0.3262	18.1835	0.3262
$\Phi_{2,opt}$	0.3199	18.9537	0.3199
$\Phi_{3,opt}$	0.3774	17.6342	0.3334
$\Phi_{4,opt}$	0.3583	18.3313	0.3233
$\Phi_{5,opt}$	0.3990	17.8249	0.3561
$\Phi_{6,opt}$	0.4314	16.8953	0.3872

Comparison of the results listed in Tables 1, 2, and 3, indicates that the best compromise amongst the values of R_{CC} , R_{AC} and C_{max} were obtained while searching for the lowest value of C_{max} . The values of the phase coefficients leading to the values listed in Table 3 are presented in Table 4.

Table 2

Values of R_{CC} , R_{AC} and C_{max} obtained for the sequences optimized to achieve minimum R_{AC}

Coefficients	R_{CC}	R_{AC}	C_{max}
$\Phi_{1,opt}$	0.9965	0.1006	0.5310
$\Phi_{2,opt}$	0.9974	0.0749	0.3795
$\Phi_{3,opt}$	0.9969	0.0910	0.3774
$\Phi_{4,opt}$	0.9963	0.1081	0.3583
$\Phi_{5,opt}$	0.9974	0.0762	0.3990
$\Phi_{6,opt}$	0.9972	0.0824	0.4314

Table 3

Values of R_{CC} , R_{AC} and C_{max} obtained for the sequences optimized to achieve minimum C_{max}

Coefficients	R_{CC}	R_{AC}	C_{max}
$\Phi_{1,opt}$	0.9743	0.7475	0.2817
$\Phi_{2,opt}$	0.9592	1.1846	0.2871
$\Phi_{3,opt}$	0.9763	0.6872	0.2855
$\Phi_{4,opt}$	0.9748	0.7323	0.2933
$\Phi_{5,opt}$	0.9720	0.8141	0.2781
$\Phi_{6,opt}$	0.9692	0.8940	0.2730

To show that the modified sequences are still orthogonal, in Fig. 2, we plotted the function $C_{max}(\tau)$ for the sequences $\{w_n^{(k)}\}$ obtained from the original sequences $\{u_n^{(k)}\}$ by modifying them using the vector $\Phi_{6,opt}$ from Table 4. For the comparison, we plotted there also the function $C_{max}(\tau)$ for the original sequences $\{u_n^{(k)}\}$ using a dashed line. It is clearly visible that both sets of sequences are orthogonal, and the values of $C_{max}(\tau)$ are significantly lower for the new sequence set than for the original one around

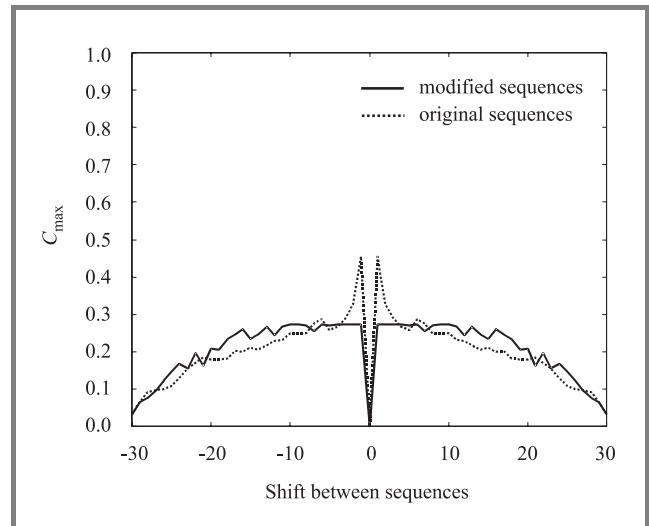


Fig. 2. Plots of the maximum peaks in the crosscorrelation functions versus the relative shift between the sequences, $C_{max}(\tau)$.

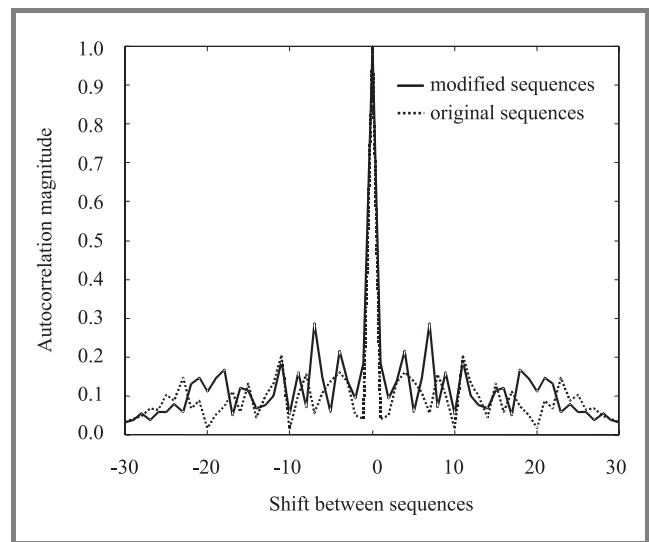


Fig. 3. Plots of the maximum magnitudes of the autocorrelation functions, $A_{max}(\tau)$.

zero, which corresponds to the point of perfect synchronization.

To compare the synchronization amenability of the original sequences $\{u_n^{(k)}\}$ and these new sequences $\{w_n^{(k)}\}$, we plotted the maximum magnitudes of the autocorrelation functions $A_{max}(\tau)$

$$A_{max}(\tau) = \max_i c_{i,i}(\tau), \quad i = 1, 2, \dots, 31 \quad (16)$$

for both sets of sequences in Fig. 3. It is possible to notice that the maxima in the off-peak autocorrelation are slightly higher for the set of sequences $\{w_n^{(k)}\}$ than for the set of sequences $\{u_n^{(k)}\}$. However, in both cases the peak at zero shift, corresponding to the perfect synchronization, is very significant.

Table 4

Values of the phase coefficients for which the results listed in Table 3 were obtained

Coefficients	$\Phi_{1,opt}$	$\Phi_{2,opt}$	$\Phi_{3,opt}$	$\Phi_{4,opt}$	$\Phi_{5,opt}$	$\Phi_{6,opt}$
Φ_1	0.3925	5.2150	4.6452	4.0811	3.9235	1.4734
Φ_2	0.5345	4.2788	4.6753	5.3314	1.5435	2.0594
Φ_3	3.7864	4.4254	5.8496	5.0765	4.7242	2.8292
Φ_4	1.1751	1.8707	2.5273	3.7142	2.8908	0.1822
Φ_5	5.0800	1.0640	3.8517	3.0107	5.5125	3.9440
Φ_6	1.0535	1.0444	5.4272	0.7436	2.8254	2.1154
Φ_7	1.1270	1.1725	1.1420	4.0309	5.9926	3.3442
Φ_8	0.4683	2.7861	5.0271	2.0431	0.4931	3.6686
Φ_9	3.0181	5.1669	3.8160	0.8948	3.1154	0.9194
Φ_{10}	2.5626	3.1003	4.0349	3.4789	2.1240	4.5375
Φ_{11}	2.0366	0.5176	1.3245	4.4366	5.5740	5.7438
Φ_{12}	1.8242	2.6811	3.1068	4.3561	2.1648	3.7034
Φ_{13}	2.0952	2.6034	0.3976	5.8205	3.1619	0.1789
Φ_{14}	3.5153	2.5592	2.1515	5.7127	0.3111	5.0597
Φ_{15}	0.7190	2.1976	3.8016	0.4326	2.2879	3.6221
Φ_{16}	0.2276	6.1675	2.3824	2.4168	3.4585	4.7125
Φ_{17}	2.5854	0.0353	4.5556	3.9018	2.6660	0.5854
Φ_{18}	4.3384	1.8769	4.5526	1.6916	3.7406	2.7495
Φ_{19}	0.8591	0.3220	2.8490	3.7723	3.8776	2.3331
Φ_{20}	1.5947	4.3013	2.7105	0.2738	0.6973	1.3127
Φ_{21}	1.0851	4.4499	3.9996	3.5643	5.4335	5.3541
Φ_{22}	4.1919	5.2382	4.8776	5.4238	5.6328	4.9300
Φ_{23}	1.6175	2.6795	2.0416	0.2190	5.3110	3.1792
Φ_{24}	4.3589	2.5970	2.7735	5.0224	4.1288	5.7822
Φ_{25}	0.5043	1.3012	3.7371	4.9092	4.1911	0.9306
Φ_{26}	4.0159	4.2658	3.8720	3.0306	1.0407	5.7265
Φ_{27}	5.2438	4.7754	3.6737	3.7614	1.8494	4.9512
Φ_{28}	0.0640	2.6637	2.5367	5.2247	4.2399	2.6627
Φ_{29}	0.9041	0.0558	4.4353	0.6034	3.6006	3.9809
Φ_{30}	4.8797	2.6827	3.3236	4.9620	0.3715	6.0747
Φ_{31}	2.7785	5.3831	1.1931	5.8136	0.5456	3.9853

5. Application to bipolar sequences

From the implementation point of view, the most important class of spreading sequences are bipolar or biphasic sequences, where the ϕ_m ; $m = 1, 2, \dots, N$, can take only two values 0 and π . This results in the elements on the diagonal of \mathbf{D}_N being equal to either “+1” or “-1”. Even for this bipolar case, we can achieve significantly different properties of the sequences defined by the \mathbf{W}_N than those of the original bipolar sequences of the same length. As an example, let us compare some properties of Walsh-Hadamard sequences, with the properties of the sequence set defined by the bipolar matrix \mathbf{W}_{32} , with the diagonal of the \mathbf{D}_{32} represented for the simplicity by a sequence of “+” and “-” corresponding to “+1” and “-1”, respectively:

$$\{++++-----++--+-+---+---+---+\}. \tag{17}$$

For the unmodified set of 32 Walsh-Hadamard sequences of length $N = 32$, the maximum in the aperiodic crosscorrelation function C_{\max} reaches 0.9688, and the mean square out-of-phase aperiodic autocorrelation R_{AC} is equal to 6.5938. That high value of R_{AC} indicates the possibility of significant difficulties in the sequence acquisition process, and the high value of C_{\max} means that for some time shifts the interference between the different DS CDMA channels can be unacceptably high. On the other hand, for the set of sequences defined by the matrix \mathbf{W}_{32} considered here, we have $C_{\max} = 0.4375$, and $R_{AC} = 0.8438$. This means lower peaks in the instantaneous bit-error-rate due to the MAI and a significant improvement in the sequence acquisition process.

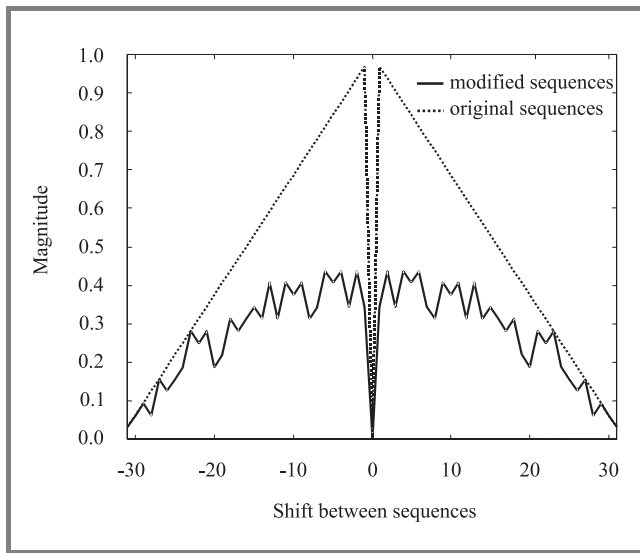


Fig. 4. Plots of the maximum value of the aperiodic crosscorrelation ACC_{\max} for all possible pairs of the sequences versus the relative shift between them.

In Figure 4, we present the plot of the upper limits for the aperiodic crosscorrelation functions for the set of

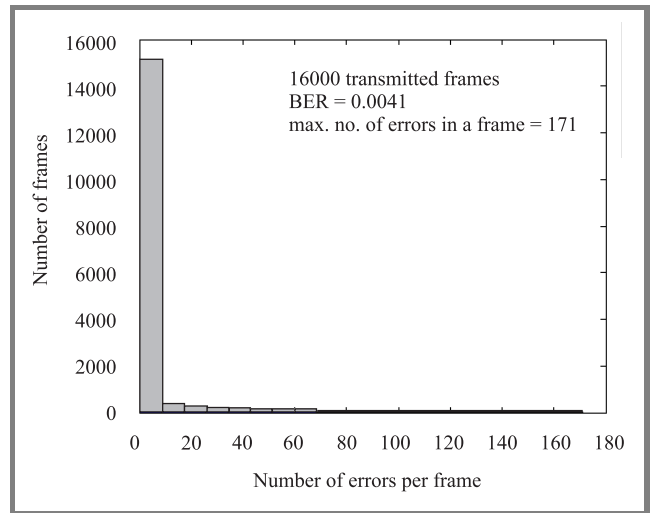


Fig. 5. Histogram of a number of errors in a transmitted frame for the DS CDMA system utilizing Walsh-Hadamard spreading sequences.

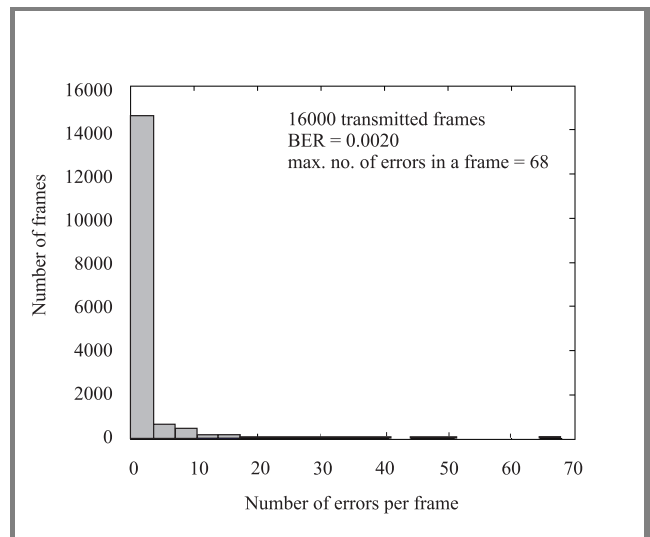


Fig. 6. Histogram of a number of errors in a transmitted frame for the DS CDMA system utilizing spreading sequences defined by the matrix \mathbf{W}_{32} .

Walsh-Hadamard sequences and the set of sequences defined by our matrix \mathbf{W}_{32} . The presented plots illustrate the improvement that can be achieved by our modification. This, of course, translates directly on the level of BER caused by MAI, which has been confirmed by simulations involving transmission of 500 frames of 524-bites over 32-channel asynchronous DS CDMA systems. One of those systems utilized 32-chip original Walsh-Hadamard sequences and another one employed 32-chip modified sequences defined by the matrix \mathbf{W}_{32} . In both cases, the number of simultaneously active users was equal to 8. From the simulations, we achieved an average BER over all 32 channels equal to 0.0041 for the original Walsh-Hadamard sequences, and 0.0020 for the modified se-

quences, respectively. In addition to the reduction in BER, the maximum number of errors in any frame is much lower for the system utilizing the modified sequences, i.e. equal to 68 compared to 171 for the system utilizing the unmodified sequences. This is illustrated in Figs. 5 and 6 showing the histograms of the number of errors per received frame for the system utilizing the original Walsh-Hadamard sequences and the modified sequences, respectively.

6. Conclusions

In the paper, we presented a simple method to modify orthogonal spreading sequences to improve their correlation properties for asynchronous applications, while maintaining their orthogonality for perfect synchronization. The method leads, in general, to complex polyphase sequences but can also be used to obtain real bipolar sequences. In the case of polyphase sequences, the phase coefficients can be chosen to achieve the required correlation/spectral properties of the whole set of sequences. The presented numerical example illustrates how different correlation characteristics can be successfully modified or even optimized for the set of polyphase orthogonal sequences. Of course, different search criteria can be used depending on the particular application. Another presented example shows that for practical applications, where bipolar sequences are preferred, the method can also yield a significant improvement in the properties of the sequence set over those of pure Walsh-Hadamard sequences. Simulation results indicated that the asynchronous DS CDMA system utilizing our sequences has lower BER and significantly smaller number of errors per frame than that can be achieved when the system utilizes unmodified Walsh-Hadamard sequences.

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