A CODE SELECTION CRITERION FOR A DS-CDMA SYSTEM USING DESPREADING SEQUENCES WEIGHTED BY STEPPING CHIP WAVEFORMS

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ABSTRACT

We propose a simple and accurate criterion which enables the determination of the spreading sequences in a given set achieves better bit error rate (BER) performances than others for a DS-CDMA system using despreading sequences weighted by stepping chip waveforms.

I. INTRODUCTION

Direct Sequence Code Division Multiple Access (DS-CDMA) is an emerging medium sharing methodology that promises capacity increases for future wireless and personal communication systems. A typical DS-CDMA scenario involves many users who simultaneously access and utilize a radio channel [1].

In a DS/CDMA system with perfect power control, the major limitation in performance, and hence capacity, is due to multipath fading and Multiple Access Interference (MAI). With the objective of MAI rejection, an optimum multiuser receiver was proposed in [2]. However, it is extremely complex. Based on a noise whitening approach, a simple structure called the integral equation receiver was proposed in [3]. The integral equation receiver employs a despreading function, which is the solution of a Fredholm integral equation of the second kind and consists of $2N^2$ exponential terms with N(2N+1), where N is the processing gain. Based on the property that the despreading function given in [3] emphasizes the transitions in the received signal of the reference user for MAI rejection, it is proposed to weight the despreading sequence by stepping chip weighting waveforms [4]. This leads to easy tuning of the despreading function in practice to achieve the best performance.

II. SYSTEM DESCRIPTION

Suppose there are *K* DS-CDMA users accessing the channel. User *k* transmits a data sequence $b_k(t)$ and employs a spreading sequence $a_k(t)$ to spread each data bit. The spreading and data signals for the *k*th user are given by

$$a_{k}(t) = \sum_{j=-\infty}^{\infty} a_{j}^{(k)} P_{T_{c}}(t - jT_{c}), \quad b_{k}(t) = \sum_{j=-\infty}^{\infty} b_{j}^{(k)} P_{T_{b}}(t - jT_{b})$$
(1)

where T_c and T_b are the chip and data duration's, respectively, and $P_x(y)=1$, for 0 < y < x, and $P_x(y)=0$ otherwise. It is assumed that there are N chips of a spreading spreading sequence in the interval of each data bit T_b and the spreading sequence has period equal to N. The transmitted signal for the kth user is

$$S_k(t) = \sqrt{2Pb_k(t)a_k(t)\cos(\omega_c t + \theta_k)}$$
(2)

where the transmitted power *P* and the carrier frequency ω_c are common to all users. Thus, the received signal r(t) at the base station can be represented as

$$r(t) = \sqrt{2P} \sum_{k=1}^{K} b_k (t - \tau_k) a_k (t - \tau_k) \cos(\omega_c t + \phi_k) + n(t)$$
(3)

where *K* denotes the number of active users. The random time delays and phases along the communication links between the *K* transmitters and the receiver are denoted by τ_k and $\phi_k (= \theta_k - \omega_c \tau_k)$ for $1 \le k \le K$, respectively. The ambient channel noise n(t) is modeled as an additive white Gaussian noise (*AWGN*) process with two-side spectral density $N_0 / 2$. The random variables τ_k and ϕ_k are independent of one another and uniformly distributed in $[0, T_b]$ and $[0, 2\pi]$, respectively.

III. SYSTEM PERFORMANCE

The weighted despreading sequence for the *k*th receiver is given by

$$\hat{a}_{k}(t) = \sum_{j=-\infty}^{\infty} a_{j}^{(k)} w_{j}^{(k)} \left(t - jT_{c} \left| \left\{ c_{j}^{(k)}, c_{j+1}^{(k)} \right\} \right\} P_{T_{c}}(t - jT_{c}) \right.$$
(4)

where $c_j^{(k)} = a_{j-1}^{(k)} a_j^{(k)}$ and $w_j^{(k)} \left(t | \left\{ c_j^{(k)}, c_{j+1}^{(k)} \right\} \right)$, for $0 \le t \le T_c$, is the *j*th chip weighting waveform for the *k*th receiver, conditioned on the status of three consecutive chips $\left\{ a_{j-1}^{(k)}, a_j^{(k)}, a_{j+1}^{(k)} \right\}$. Each $c_j^{(k)}$ is a random variable which indicates whether or not the next element of the *k*th spreading signal is the same as the preceding element. $\left(c_j^{(k)} = -1 if \ a_{j-1}^{(k)} \ne a_j^{(k)} \ and \ c_j^{(k)} = 1 \ if \ a_{j-1}^{(k)} = a_j^{(k)} \right)$. The *j*th chip conditional weighting waveform for the *k*th receiver is defined as

$$w_{j}^{(k)}(t|\{c_{j}^{(k)}, c_{j+1}^{(k)}\}) = \begin{cases} m_{1}(t) & \text{if } c_{j}^{(k)} = +1 \text{ and } c_{j+1}^{(k)} = +1 \\ m_{2}(t) & \text{if } c_{j}^{(k)} = -1 \text{ and } c_{j+1}^{(k)} = -1 \\ m_{3}(t) & \text{if } c_{j}^{(k)} = -1 \text{ and } c_{j+1}^{(k)} = +1 \\ m_{4}(t) & \text{if } c_{j}^{(k)} = +1 \text{ and } c_{j+1}^{(k)} = -1 \end{cases}$$
(5)

where $m_p(t)$ for $p \in [1, 2, 3, 4]$ are the chip weighting waveforms. The elements of the chip weighting waveforms vector $\{m_1(t), m_2(t), m_3(t), m_4(t)\}$ given by the following:

$$m_{1}(t) = L(\varepsilon)P_{T_{c}}(t)$$

$$m_{2}(t) = P_{T_{c}}(t) - [1 - L(\varepsilon)]P_{T_{c}-2T_{\Delta}}(t - T_{\Delta})$$

$$m_{3}(t) = P_{T_{\Delta}}(t) + L(\varepsilon)P_{T_{c}-T_{\Delta}}(t - T_{\Delta})$$

$$m_{4}(t) = L(\varepsilon)P_{T_{c}-T_{\Delta}}(t) + P_{T_{c}}(t) - P_{T_{c}-T_{\Delta}}(t)$$
(6)

where $T_{\Delta} \in (0, T_c / 2]$, $\varepsilon = T_c / T_{\Delta} \in [2, \infty)$ is a parameter of the stepping chip weighting waveforms. The $L(\varepsilon) \in$ [0,1] is a monotonically decreasing function of ε and for ease of implementation, it is defined as $L(\varepsilon)=[C(\varepsilon/2-1)+1]^{-1}$, where the constant *C* is chosen equal to 10 [4]. Assuming that user *i* is the reference user ($\tau_i = 0$ and $\phi_i = \theta_i - \omega_c \tau_i = 0$) based on the definitions in [4], the conditional *SINR_i*, conditioned on $\{c_i^{(i)}\}$, is given by

$$SINR_{i} = \left\{ \frac{\varepsilon \left[2\chi + (\varepsilon - 2\chi)L^{2}(\varepsilon) \right]}{2\kappa_{b} \left[2\chi + (\varepsilon - 2\chi)L(\varepsilon) \right]^{2}} + \frac{(K - 1)\Xi(\Gamma^{\left\{c_{j}^{(i)}\right\}}, \varepsilon)}{2\varepsilon N \left[2\chi + (\varepsilon - 2\chi)L(\varepsilon) \right]^{2}} \right\}^{-1}$$

$$(7)$$

where $E_b = PT_b$, $\kappa_b = E_b / N_0$, $\chi = \hat{N}_i / N \cdot \hat{N}_i$, is a random variable which represents the number of times of occurrence that $c_j^{(i)} = -1$ for all $j \in [0, N-1]$. $\Xi(\Gamma^{\left\{c_j^{(i)}\right\}}, \varepsilon)$ in the equation (7) is given by

$$\begin{split} \Xi \left(\Gamma^{\{c_{j}^{(i)}\}}, \varepsilon \right) &= \frac{1}{N} \left\{ \Gamma^{(i)}_{\{-1,-1,-1\}} \left[\frac{(\varepsilon - 2)^{2}(4 + \varepsilon)L^{2}(\varepsilon)}{3} + \frac{8}{3} \right] \\ &+ 16 \left(\frac{\varepsilon}{4} - \frac{1}{2} \right) L(\varepsilon) + \left(\Gamma^{(i)}_{\{-1,-1,1\}} + \Gamma^{(i)}_{\{1,-1,-1\}} \right) \left[\frac{5}{3} + \left(3\varepsilon - \frac{16}{3} \right) L(\varepsilon) \right] \\ &+ \left(\frac{\varepsilon^{2}}{3} - 3\varepsilon + \frac{11}{3} \right) L^{2}(\varepsilon) + \left(\Gamma^{(i)}_{\{-1,1,1\}} + \Gamma^{(i)}_{\{1,1,-1\}} \right) \left[\frac{1}{3} + \left(\varepsilon - \frac{2}{3} \right) L(\varepsilon) \right] \\ &+ \left(\varepsilon^{3} - \varepsilon + \frac{1}{3} \right) L^{2}(\varepsilon) + \Gamma^{(i)}_{\{-1,1,-1\}} \left[\frac{2}{3} + 2 \left(\varepsilon - \frac{2}{3} \right) L(\varepsilon) \right] \\ &+ \left(\varepsilon^{3} - 2\varepsilon + \frac{2}{3} \right) L^{2}(\varepsilon) + \Gamma^{(i)}_{\{1,-1,1\}} \left[\frac{2}{3} + \left(2\varepsilon - \frac{8}{3} \right) L(\varepsilon) \right] \\ &+ \left(\frac{\varepsilon^{2}}{3} - 2\varepsilon + 2 \right) L^{2}(\varepsilon) + \varepsilon^{3} L^{2}(\varepsilon) \Gamma^{(i)}_{\{1,1,1\}} \right] \end{split}$$

where $\Gamma_{\{\nu_1,\nu_2,\nu_3\}}^{(i)}$ is the number of times of occurrence that $\{c_{j-1}^{(i)}, c_j^{(i)}, c_{j+1}^{(i)}\} = \{v_1, v_2, v_3\}$ for all *j* in the *i*th user's spreading sequence and each $v_n, n \in [1, 2, 3]$, takes values +1 or -1 with equal probabilities.

IV. EFFECT OF THE REFERENCE CODE ON RECEIVER PERFORMANCE

In this section, we present numerical results on the BER performance of the *ith* user's receiver in a DS-CDMA system when different spreading sequences are employed as references. We have chosen 25 Gold codes from a set of length N=63 for using as reference [5]. The probability of error P_e for the data symbol $b_{\lambda}^{(i)}$ in all the BER curves is defined as $P_e = Q(\sqrt{\max[SINR_i]})$ where,

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} \exp(-t^{2}/2) dt$$
 (9)

where $max[SINR_i]$ is the maximum value of $SINR_i$. Note that the parameter ε , should be tuned with respect to each signal to noise ratio (SNR) so as to maximize the $SINR_i$ [6]. Table 1 shows the calculated elements of the set $\{\Gamma_{\{v_1,v_2,v_3\}}^{(i)}\}$, for each spreading code. Figure 1 shows the BER performances of the ith user's receiver when the codes (fourth, ninth and twentieth) which have different \hat{N}_i occurrences are used as reference, respectively. We can see from this figure that especially in relative high κ_b (> 15 dB), the BER's are mostly caused by the MAI, also in low $\kappa_{\rm h}$ (< 5 dB), where the BER's mostly caused by the AWGN, the minimum BER will be achieved by using the codes which have the highest \hat{N}_i occurrences. But as it will be seen from Table 1, it must be observed that in the set of codes there are a great number of codes whose \hat{N}_i occurences are equal and the elements of their



Figure 1. Performance comparison of the receiver using various spreading codes have different number of \hat{N} when N=63 and K=25.

 $\{\Gamma_{\{v_1,v_2,v_3\}}^{(i)}\}\$ are not completely the same as each other. Figure 2 shows the BER performances attained at the *ith* user's receiver for the situation where the codes (fifth, sixth and seventh) having the characteristics mentioned above used as reference codes. From this figure it is obvious that although the \hat{N}_i occurrences of these codes are equal, the achieved BER performances for the *ith* user are not the same when the MAI is significant.



Figure 2. Performance comparison of the receiver employs different spreading codes have equal number of \hat{N} when *N*=63 and *K*=25.

V. NUMERICAL ANALYSIS

Eqn. (8) can be rearranged as given below

$$\Xi\left(\Gamma^{\{\varepsilon_{j}^{(i)}\}},\varepsilon\right) = \frac{1}{N} \left[A(\varepsilon) \Gamma^{(i)}_{\{-1,-1,-1\}} + B(\varepsilon) \right. \\ \left(\Gamma^{(i)}_{\{-1,-1,1\}} + \Gamma^{(i)}_{\{1,-1,-1\}}\right) + C(\varepsilon) \left(\Gamma^{(i)}_{\{-1,1,1\}} + \Gamma^{(i)}_{\{1,1,-1\}}\right) \\ \left. + D(\varepsilon) \Gamma^{(i)}_{\{-1,1,-1\}} + E(\varepsilon) \Gamma^{(i)}_{\{1,-1,1\}} + F(\varepsilon) \Gamma^{(i)}_{\{1,1,1\}}\right]$$
(10)

where $A(\varepsilon)$, $B(\varepsilon)$, $C(\varepsilon)$, $D(\varepsilon)$, $E(\varepsilon)$ and $F(\varepsilon)$ are the expressions in front of the elements of the set $\Gamma_{\{v_1, v_2, v_3\}}^{(i)}$, respectively. Hence a simple criterion which will evaluate the BER performances of the *i*th user's receiver can be constructed, we assumed the codes (fifth, sixth and seventh) are selected as reference and the achieved performances which are shown in Figure 2 and which are obtained by using these codes are taken into consideration.

Table 1. The calculated elements of the set $\{\Gamma_{\{v_1, v_2, v_3\}}^{(i)}\},\$

 $(i \in [1, 25])$

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c o d e s	Γ(-1,-1,-1)	Γ(-1,-1,1) + Γ(1,-1,-1)	Γ _(-1,1,1) + Γ _(1,1,-1)	Γ(-1,1,-1)	Γ(1,-1,1)	Γ(1,1,1)	Ñ
1	2	12	20	6	10	13	24
2	4	8	24	4	12	11	24
3	8	8	16	4	8	19	24
4	6	12	20	2	6	17	24
5	2	20	12	14	10	5	32
6	8	16	16	8	8	7	32
7	10	20	12	6	2	13	32
8	6	20	12	10	6	9	32
9	8	16	16	8	8	7	32
10	6	20	12	10	6	9	32
11	14	12	12	6	6	13	32
12	10	12	20	6	10	5	32
13	4	16	16	12	12	3	32
14	2	12	12	14	14	5	32
15	8	16	8	12	8	11	32
16	6	12	20	10	14	1	32
17	10	12	12	10	10	9	32
18	4	24	16	8	4	7	32
19	12	16	16	4	4	11	32
20	16	16	8	12	8	3	40
21	18	20	12	6	2	5	40
22	12	24	8	12	4	3	40
23	14	20	12	10	6	1	40
24	20	16	16	4	4	3	40
25	16	16	8	12	8	3	40

These codes have been arbitrarily chosen from a group of codes whose  $\hat{N}_i$  occurrences are equal and the elements of  $\{\Gamma_{\{v_1,v_2,v_3\}}^{(i)}\}$  are different (a few elements may be the same). For simplicity, let

$$\Xi^{(5)} = \Xi \left( \Gamma^{\left\{ \epsilon_{j}^{(5)} \right\}}, \varepsilon \right) \qquad \Xi^{(6)} = \Xi \left( \Gamma^{\left\{ \epsilon_{j}^{(6)} \right\}}, \varepsilon \right)$$
$$\Xi^{(7)} = \Xi \left( \Gamma^{\left\{ \epsilon_{j}^{(7)} \right\}}, \varepsilon \right) \qquad (11)$$

Figure 3 shows the  $\Xi^{(5)}/\Xi^{(6)}, \Xi^{(6)}/\Xi^{(7)}$  and  $\Xi^{(5)}/\Xi^{(7)}$  variations for the situation where the three codes mentioned are used as reference. If the receiver is accepted to have been tuned to the same  $\varepsilon$  value for these three codes, it is clear that the best receiver performance will be achieved by using the reference code which will make the smallest  $\Xi^{(i)}$  contribution, and the lowest performance will be achieved by using the code which

will make the highest contribution to the  $SINR_i$  expression given by eqn. (7). From this fact, the performance situation shown in Figure 2 for these three codes can be achieved with the  $\varepsilon$  values which will satisfy the following condition

$$\Xi^{(5)} \langle \Xi^{(6)} \langle \Xi^{(7)}$$
 (12)

As seen from Figure 3, because of  $(\Xi^{(5)}/\Xi^{(7)}) > (\Xi^{(5)}/\Xi^{(6)})$ (mean that  $\Xi^{(7)} < \Xi^{(6)}$ ) for the values of  $\varepsilon$  which are selected from the interval before the crossing point ( $\varepsilon \approx 2.4$ ) the condition given by eqn. (12) can not be met.



**Figure 3.** The  $\Xi^{(i)}/\Xi^{(j)}$ ,  $i \in [5, 6]$ ,  $j \in [6, 7]$ , variations against the parameter  $\varepsilon$  for the fifth, sixth and seventh codes.

As shown in Figure 4, when the value of the  $\boldsymbol{\epsilon}$  is chosen from an interval where

$$\frac{d}{d\varepsilon} \left( \Xi^{(7)} - \Xi^{(6)} \right) = 0 \text{ and } \frac{d}{d\varepsilon} \left( \Xi^{(7)} - \Xi^{(5)} \right) \cong 0 \quad (13)$$

the difference between the  $\Xi^{(7)}$  and  $\Xi^{(6)}$  will be maximum and the difference between  $\Xi^{(7)}$  and  $\Xi^{(5)}$  will be sufficiently great. Also, the values of  $\Xi^{(6)}$  will be greater than the values of  $\Xi^{(5)}$  in this interval. So the condition given by (12) will be easily satisfied.



**Figure 4.**  $(\Xi^{(7)} - \Xi^{(5)})$ ,  $(\Xi^{(6)} - \Xi^{(5)})$  and  $(\Xi^{(7)} - \Xi^{(6)})$  against the parameter  $\varepsilon$ .

## VI. PROPOSED CRITERION

The criterion which enables the determination of the spreading sequences in a given code set achieves better BER performances (or lower bit error rates) than others when employed as references for a DS-CDMA system is given by

$$\Psi^{(i)}\left(\Gamma^{(i)}_{\{\nu_{1},\nu_{2},\nu_{3}\}}\right) = a \Gamma^{(i)}_{\{-1,-1,-1\}} + b \left(\Gamma^{(i)}_{\{-1,-1,1\}} + \Gamma^{(i)}_{\{1,-1,-1\}}\right) + c \left(\Gamma^{(i)}_{\{-1,1,1\}} + \Gamma^{(i)}_{\{1,1,-1\}}\right) + d \Gamma^{(i)}_{\{-1,1,-1\}} + c \Gamma^{(i)}_{\{1,-1,1\}} + f \Gamma^{(i)}_{\{1,1,1\}}$$
(14)

where;  $\boldsymbol{a} = A(\boldsymbol{\varepsilon}=\varepsilon_c), \boldsymbol{b} = B(\boldsymbol{\varepsilon}=\varepsilon_c), \boldsymbol{c} = C(\boldsymbol{\varepsilon}=\varepsilon_c), \boldsymbol{d} = D(\boldsymbol{\varepsilon}=\varepsilon_c), \boldsymbol{e} = E(\boldsymbol{\varepsilon}=\varepsilon_c), \boldsymbol{f} = F(\boldsymbol{\varepsilon}=\varepsilon_c)$  and  $\varepsilon_c$  is a specific value of  $\varepsilon$ . The process of determining the coefficient values of the elements of {  $\Gamma_{\{v_1,v_2,v_3\}}^{(i)}$ } is important for obtaining accurate evaluations by using the proposed criterion. For the reasons described above, the  $\varepsilon_c$  value is chosen from the interval where the conditions given by eqn.(12) and (13) are satisfied. By using a specific value of the  $\varepsilon$ ,  $\varepsilon_c=11$ , we have

$$\mathbf{a} = A(\varepsilon_c) = 3.64$$
,  $\mathbf{b} = B(\varepsilon_c) = 2.27$   $\mathbf{c} = C(\varepsilon_c) = 1.18$   
 $\mathbf{d} = D(\varepsilon_c) = 1.73$   $\mathbf{e} = E(\varepsilon_c) = 1.28$   $\mathbf{f} = F(\varepsilon_c) = 0.63$ 

So, the resulting selection criterion can be written as

$$\Psi^{(i)} \left( \Gamma^{(i)}_{\{\nu_{1},\nu_{2},\nu_{3}\}} \right) = 3.64 \Gamma^{(i)}_{\{-1,-1,-1\}} + 2.27 \left( \Gamma^{(i)}_{\{-1,-1,1\}} + \Gamma^{(i)}_{\{1,-1,-1\}} \right) + 1.18 \left( \Gamma^{(i)}_{\{-1,1,1\}} + \Gamma^{(i)}_{\{1,1,-1\}} \right) + 1.73 \Gamma^{(i)}_{\{-1,1,-1\}} + 1.28 \Gamma^{(i)}_{\{1,-1,1\}} + 0.63 \Gamma^{(i)}_{\{1,1,1\}}$$
(15)

## VII. SELECTION PROCEDURE AND NUMERICAL RESULTS

If the number of active users is less than the total number of codes in a given code set, the selection process should be realized by the steps given below based on the results of the proposed criterion:

*i*-) First, begin with the codes group which have the largest value of  $\hat{N}_i$ . If the number of the active users is less than the number of codes in this group, select the spreading codes which have *lowest*  $\Psi$  values.

*ii*-) If there are any users still waiting for assignment, follow the same procedure for the next group which has a  $\hat{N}_i$  value closest to previous until there are no user waiting for assignment.

Table 2 shows the calculated values of the criterion and the performance evaluations related to these results for two different values of  $\varepsilon$ . It is clear that the criterion using any value of  $\varepsilon_c$  which are selected before the

Code Groups	C O D E S	Exact (P _e ) (×10 ⁻⁶ )	Performance Status According to P _e	Ψ (εc=2.1)	Performance Evaluations According to $\Psi$ ( $\epsilon$ =2.1 )	Ψ (ε _c =11)	Performance Evaluations According to $\Psi$ ( $\epsilon_c=11$ )
1	1	35		224		89	
, <b>I</b>	2	36	1>2>4>3	227	1=4 >2=3	90	1>2>4>3
N = 24	3	47		227		95	
	4	45		224	(Faulty)	94	(Correct)
	5	5.6	5>13>14=16> 18>8=10>6=9= 15>12=17>7> 19>11	210		107	
	6	7.4		212		113	
	7	9.0		209		117	
	8	7.2		209		112	
	9	7.4		212	18>7=8=10>5>6 =9=15=19>13> 11>12=17> 14=16 (Faulty)	113	5>12>14-16>
	10	7.2		209		112	3>13>14=10>
2	11	9.5		214		119	16>6-10>0-9-
$\hat{N} = 32$	12	7.6		215		114	10>11
.,	13	5.8		213		108	19>11
	14	6.0		216		109	(Correct)
	15	7.4		212		113	(Correct)
	16	6.0		216		109	
	17	7.6		215		114	
	18	6.9		206		111	
	19	9.2		212		118	
	20	1.6	22>23>20=25>	203		137	
3	21	1.8		200	22>21=23>24>20	141	22>23>20=25>
^	22	1.4		197	=25	135	21>24
N = 40	23	1.5	21>24	200		136	
	24	1.9		202	(Faulty)	142	(Correct)
	25	1.6		203		137	

**Table 2.** Testing the accuracy of the proposed criterion for various  $\varepsilon_c$  values with different spreading code groups ( $\kappa_b = E_b/N_0 = 20 \text{ dB}$  and K=25)

crossing point,  $\varepsilon_c \in [2, 2.4]$ , will produce results which will cause the evaluations faulty as shown in Table 3. The criterion using coefficient values calculated according to the values of  $\varepsilon_c$  which are selected from an interval having properties given by eqn. (12) and (13) will enable the evaluations to be done correctly.

## VIII. CONCLUSION

The effects of the spreading codes on the receiver performance are determined before the code assignment process provides the flexibility of the selection of the codes with a high performance when the number of the users is less than the total number of the codes in a given code set. In this paper, we have presented a simple and efficient criterion which enables the determination of the optimal spreading sequences in a given code set achieves better BER performances than others when used as references for a DS-CDMA system using despreading sequences weighted by stepping chip waveforms.

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