Abstract—Because of the high system capacity and excellent capability against narrowband interference (NBI), Direct Sequence-Code Division Multiple Access (DS-CDMA) is widely used in Geosynchronous Earth Orbit satellite systems. However, due to the existence of the uncertain non-cooperative external interference, traditional colored noise suppression methods cannot achieve high performance in DS-CDMA systems. In this paper, based on spectrum shaping, combining with the feature analysis of the external interference, an eigen-based spreading sequences design framework for CDMA satellite systems is proposed. In this proposal, by the uniform orthogonal transformation (UOT), the eigen-based spreading sequences can combat not only the multiple access interference (MAI) but also the external interference and support multiple users’ performance fairness. Furthermore, the design physical significance is analyzed. By simulations, it’s verified that both MAI and the external interference can be eliminated by the proposed eigen-based spreading sequences and the fairness of different users can be efficiently guaranteed.

Keywords—Direct Sequence - Code Division Multiple Access; external co-frequency interference; eigen-based spreading sequences; uniform orthogonal transformation

I. INTRODUCTION

Due to the wide coverage of satellite communication systems, e.g., Geosynchronous Earth Orbit satellite systems, the satellite transponder is inevitably impaired by the external co-frequency interference from some non-cooperative terrestrial communication systems or even from some other non-cooperative satellite communication systems. The external interference is always uncertain and uncontrollable, leading to the decrease of spectral efficiency and power efficiency, which is quite essential for satellite communication systems. Especially, in Direct Sequence-Code Division Multiple Access (DS-CDMA) satellite systems, the existence of not only the external interference but also the multiple access interference (MAI) makes the interference suppression even more complicated and intractable.

For MAI in CDMA satellite systems, the studies in non-Gaussian channels, e.g., early studies in [1]-[3] and the robust optimal and near-optimal multiuser detection recently in [4]-[6], mainly addressed the impulsive noise with larger tail probabilities and thus cannot be directly used for combating the non-impulsive external interference which may well be communication signals. For the non-cooperative external interference, the interference suppression approaches based on spectrum shaping are widely adopted. In [7], a new approach based on spectrum shaping of the spreading sequences waveforms in ultra wideband (UWB) systems was developed. However, it’s for the narrow band interference (NBI) with fixed and known frequency and also the MAI cannot be minimized as the sequences truncation.

Inspired by the spectrum shaping, designing spreading sequences according to the colored noise environment in CDMA systems was investigated in [8] and [9]. In [8], the sum capacity are used to optimize the optimal receiver and the signal-to-interference ratio to optimize the linear minimum mean square error (LMMSE) receiver respectively. However, only the qualitative description was derived. In [9], the signal to noise power ratio (SNR) was maximized by designing the de-spreading sequences, but pseudo random noise (PN) sequences were still used for the spreading, which cannot obtain sufficient processing gain against the external interference. In [10], environmentally-shaped colored spreading sequences were designed for Direct Sequence Spread Spectrum (DSSS) systems. However, the design method was derived quite briefly without detailed derivation and only the single user case was investigated. If the colored spreading sequences are directly extended to CDMA systems, there will be the performance gap between different users especially when the user number is large, which is not acceptable for multiuser satellite systems.

In this paper, an eigen-based spreading sequences design framework is detailedly derived for multiuser satellite systems in which a uniform orthogonal transformation (UOT) module is designed for fairness among different users. Finally, the physical significance of the eigen-based spreading sequences design is analyzed. By simulations, it’s verified that the spreading sequences can be robust against both the MAI and the external interference and also the performance gap can be efficiently decreased. Moreover, the environment of satellite communication systems is complicated but quite stable, and the spreading sequences allocation can be completed in the earth station. Therefore, the proposed framework becomes

An Eigen-based Spreading Sequences Design Framework for CDMA Satellite Systems

Na Gu, Linling Kuang, Xiang Chen, Zuyao Ni, Jianhua Lu
1Department of Electronic Engineering, Tsinghua University
2Tsinghua Space Center, Tsinghua University
3Shenzhen Key Laboratory of Wireless Broadband Communication and Signal Processing, Tsinghua University
4Research Institute of Information Technology, Tsinghua University

Beijing 100084, China
E-mail: gun08@mails.tsinghua.edu.cn, {kll, chenxiang, nzy, lhh_dee}@tsinghua.edu.cn

978-1-4799-4482-8/14/$31.00 ©2014 IEEE
more feasible for the CDMA satellite system with complicated interference.

The remainder of this paper is organized as follows. In Section II, a system model and an optimization problem is established for CDMA satellite systems with the external interference. In Section III, an eigen-based spreading sequences design framework for CDMA satellite systems is detailedly derived. In Section IV, the physical significance analysis of the design framework is stated. In Section V, the performance and integrality of the proposed framework is evaluated through numerical simulation. Finally, conclusions are given in Section VI.

II. SYSTEM MODEL AND INTERFERENCE ANALYSIS

For a Direct Sequence-Code Division Multiple Access (DS-CDMA) system, let the vector \( x_{k,m} = [x_{1,k,m}^T \ x_{2,k,m}^T \ \cdots \ x_{M,k,m}^T] \) denotes the chip sequence of the user \( k \) during the \( m \) th symbol interval, which can be expressed as \( x_{k,m} = b_{k,m}^T s_k \), where \( b_{k,m} \) denotes the \( m \) th binary phase shift keying (BPSK) modulated information bit sent by the user \( k \), and \( s_k \) denotes the spreading sequence of the user \( k \), which is restricted to have unity inner product, \( s_k^H s_k = \|s_k\|^2 = 1 \). In the satellite communication system considered, the transmitted signals will be impaired by propagation loss, additive white Gaussian noise (AWGN), and other interference signals received by the satellite transponder, which can be considered as additive colored interference (ACI). So the received CDMA signal for the \( m \) th symbol interval can be expressed in vector form as

\[
y_m = \sum_{k=1}^{K} A_k x_{k,m} + n_m + v_m \tag{1}
\]

where \( A_k \) is the channel attenuation factor due to the propagation loss of the user \( k \), \( n_m \) is the Gaussian noise for the \( m \) th symbol interval with zero mean and the variance \( \sigma_n^2 \), and \( v_m \) is the external interference received by the satellite transponder or ACI for the \( m \) th symbol interval.

In the receiver, the signal for the \( m \) th symbol interval of the user \( j \) is derived by the corresponding matched filter.

\[
y_{j,m} = s_j^H \left( \sum_{k=1}^{K} A_k x_{k,m} + n_m + v_m \right) = A_j b_{j,m} s_j^H s_j + \sum_{k \neq j} A_k b_{j,k,m} s_j^H s_k + s_j^H n_m + s_j^H v_m \tag{2}
\]

The first item in (2) is the contribution of the desired information, and the second item is the contribution caused by non-zero cross-correlation between different users’ spreading sequences, which is also called MAI. The other two items in (2) are the contribution of AWGN and the external interference or ACI respectively. Generally, the receiver performance requires maximizing the signal-to-interference-plus-noise ratio (SINR), which is the power in the first item in (2) relative to the sum of the powers in the other three items.

The system is assumed to be chip-level synchronous. With (2), the SINR after matched filter can be expressed as

\[
\text{SINR} = \frac{A_j^2 P_n |s_j^H s_j|}{\sum_{k \neq j} A_k^2 |s_j^H s_k| + \sigma_n^2 |s_j^H s_j| + s_j^H R s_j} \tag{3}
\]

where \( P_n \) is the power per information bit of the user \( k \), \( \sigma_n^2 \) is the variance of the AWGN, and \( R \) is the covariance matrix of the external interference or ACI. For the spreading sequences, \( s_j^H s_k = \|s_k\|^2 = 1 \) is assumed to be established, thus when an AWGN power is given, maximizing the SINR can be turned into maximizing the SIR expressed as

\[
\text{SIR} = \frac{A_j^2 P_n |s_j^H s_j|}{\sum_{k \neq j} A_k^2 |s_j^H s_k| + s_j^H R s_j}. \tag{4}
\]

In CDMA systems, the spreading sequences are normally designed to have low autocorrelation sidelobes and almost zero cross-correlation values, which is good for the suppression of the MAI. In order to eliminate MAI as well as the external interference, an optimization problem can be modeled as follows.

\[
\begin{align*}
\min_{s_j} & \quad s_j^H R s_j \\
\text{subject to} & \quad s_j^H s_j = 1 \\
& \quad s_j^H s_k = 0 \quad \text{when } k \neq j
\end{align*} \tag{5}
\]

The main purpose of the optimization problem is to minimize the power contribution from the external interference or ACI given the AWGN power, and also to ensure good orthogonality of the spreading sequences.

III. THE EIGEN-BASED SPREADING SEQUENCES DESIGN FRAMEWORK FOR CDMA SATELLITE SYSTEMS

A. The optimality conditions

For simplification, the optimization problem (5) can be simplified as follows.

\[
\begin{align*}
\min_{s_j} & \quad s_j^H R s_j \\
\text{subject to} & \quad s_j^H s_j = 1 \\
& \quad s_j^H s_k = 0 \quad \text{when } k \neq j
\end{align*} \tag{6}
\]

Construct the cost function by Lagrangian method,

\[
J = s_j^H R s_j + \lambda_j (1 - s_j^H s_j) + \mu_j s_j^H s_k \tag{7}
\]

let \( \frac{\partial J}{\partial s_j} = 0, \forall k \neq j \), with (7), we obtain

\[
\begin{align*}
\frac{\partial}{\partial s_j} \left[ s_j^H R s_j + \lambda_j (1 - s_j^H s_j) + \mu_j s_j^H s_k \right] &= \begin{cases} R_j - \lambda_j s_j + \mu_j s_k = 0 & (\forall k \neq j) \end{cases} \tag{8}
\end{align*}
\]
Further with (8),
\[
\mu_j = 0 , \quad \mathbf{R}_{s_j} = \lambda_j \mathbf{s}_j , \quad (j = 1, 2, \ldots, K) \tag{9}
\]

We assume the covariance matrix \( \mathbf{R} \) is known, when the spreading sequence \( \mathbf{s}_j \) is selected from the eigenvectors of the matrix \( \mathbf{R} \), the objective function \( \mathbf{s}_j^H \mathbf{R} \mathbf{s}_j \) approaches a minimum. However, the value of the minimum is related to the chosen eigenvectors. In order to maximizing the SIR in (4), the value of \( \mathbf{s}_j^H \mathbf{R} \mathbf{s}_j \) should be as small as possible. Thus further analysis need to be discussed about the matrix \( \mathbf{R} \).

\[B. \quad \text{Further discussion about the minimum}\]

The external interference signal is sampled at the earth station acquiring the samples \( \{i_1, i_2, \ldots, i_{MN-1}\} \), where \( M \) is an arbitrary value, \( N \) is the expected length of the spreading sequences. Usually, \( M > N > K \) is assumed to be established, where \( K \) is the number of users. Form a column vector with every \( N \) samples.

\[
\mathbf{i}_1 = [i_{1,1} \ i_{1,2} \ \cdots \ i_{1,N-1}]^T
\]
\[
\mathbf{i}_2 = [i_{2,1} \ i_{2,2} \ \cdots \ i_{2,N-1}]^T
\]
\[
\mathbf{i}_j = [i_{j,1} \ i_{j,2} \ \cdots \ i_{j,N-1}]^T
\]
\[
\mathbf{i}_m = [i_{m,1} \ i_{m,2} \ \cdots \ i_{m,N-1}]^T
\]  \quad (10)

\[
\text{Compute the covariance matrix } \mathbf{R} \text{ of } \mathbf{i} \in \mathbb{R}^{N \times M}, \text{as follows,}
\]
\[
\mathbf{R} = \mathbb{E} \left\{ (\mathbf{i}_n - E[\mathbf{i}_n])(\mathbf{i}_s - E[\mathbf{i}_s])^T \right\}
\]  \quad (11)

where \( m,n \) are the column indexes of the matrix \( \mathbf{i} \in \mathbb{R}^{N \times M} \) and \( m,n = 1,2,\ldots,M \). The covariance matrix can be expressed as

\[
\mathbf{R} = \begin{bmatrix}
\sum_i \mathbb{E}(i_n - \mathbb{E}(i_n))(i_s - \mathbb{E}(i_s)) & \sum_i \mathbb{E}(i_n - \mathbb{E}(i_n))(i_s - \mathbb{E}(i_s)) & \ldots & \sum_i \mathbb{E}(i_n - \mathbb{E}(i_n))(i_s - \mathbb{E}(i_s)) \\
\sum_i \mathbb{E}(i_n - \mathbb{E}(i_n))(i_s - \mathbb{E}(i_s)) & \sum_i \mathbb{E}(i_n - \mathbb{E}(i_n))(i_s - \mathbb{E}(i_s)) & \ldots & \sum_i \mathbb{E}(i_n - \mathbb{E}(i_n))(i_s - \mathbb{E}(i_s)) \\
\vdots & \vdots & \ddots & \vdots \\
\sum_i \mathbb{E}(i_n - \mathbb{E}(i_n))(i_s - \mathbb{E}(i_s)) & \sum_i \mathbb{E}(i_n - \mathbb{E}(i_n))(i_s - \mathbb{E}(i_s)) & \ldots & \sum_i \mathbb{E}(i_n - \mathbb{E}(i_n))(i_s - \mathbb{E}(i_s)) \\
\end{bmatrix}
\]  \quad (12)

The diagonal element \( \sum_{i} \mathbb{E}(i_n - \mathbb{E}(i_n))(i_s - \mathbb{E}(i_s)) \) \((n = 1,2,\ldots,N)\)

\( \mathbf{R} \) denotes the energy of the samples in the \( n \)th column. So the trace of the matrix is the total energy of all the interference signal samples shown as follows.

\[
\text{tr}(\mathbf{R}) = \sum_i \mathbb{E}(i_n - \mathbb{E}(i_n))^2 + \sum_i \mathbb{E}(i_s - \mathbb{E}(i_s))^2 + \ldots
\]
\[
\ldots + \sum_i \mathbb{E}(i_{M-n} - \mathbb{E}(i_{M-n}))^2
\]  \quad (13)

Perform an eigen-decomposition on the covariance matrix \( \mathbf{R} \).

\[
\mathbf{R} = \mathbf{U} \mathbf{\Lambda} \mathbf{U}^H
\]
\[
= \begin{bmatrix}
u_1 & u_2 & \cdots & u_N
\end{bmatrix}
\]
\[
\begin{bmatrix}
\lambda_1 & 0 & 0 & 0 \\
0 & \lambda_2 & 0 & 0 \\
0 & 0 & \ddots & 0 \\
0 & 0 & 0 & \lambda_N
\end{bmatrix}
\]  \quad (14)

As discussed in the previous subsection, the condition that the optimization problem approaches the minimum is the spreading sequence \( \mathbf{s}_j \) should be selected from the eigenvectors \( \mathbf{u}_t \) \((t = 1,2,\ldots,N)\), therefore the value of \( \mathbf{s}_j^H \mathbf{R} \mathbf{s}_j \) is computed as

\[
\mathbf{s}_j^H \mathbf{R} \mathbf{s}_j = \mathbf{u}_t^H \mathbf{R} \mathbf{u}_t
\]
\[
= \begin{bmatrix}
u_1 & u_2 & \cdots & u_N
\end{bmatrix}
\begin{bmatrix}
\lambda_1 & 0 & 0 & 0 \\
0 & \lambda_2 & 0 & 0 \\
0 & 0 & \ddots & 0 \\
0 & 0 & 0 & \lambda_N
\end{bmatrix}
\begin{bmatrix}
u_1 \\
u_2 \\
\vdots \\
u_N
\end{bmatrix}
\]  \quad (15)

When the spreading sequence \( \mathbf{s}_j \) is generated by choosing and quantifying the number of users \( K \) eigenvectors corresponding to the smaller non-zero eigenvalues, the minimum of the optimization problem is smaller, so that the SIR is much larger for all users. Meanwhile, due to the orthogonality between the eigenvectors, MAI can be efficiently suppressed. For the special case of single user, the eigenvector corresponding to the smallest eigenvalue is directly quantified to get the spreading sequence, which is in accordance with the method in [10].

\[C. \quad \text{The eigen-based spreading sequences design framework for CDMA satellite systems}\]

Based on the theory of the eigen subspace, one eigen subspace \( \zeta \) is spanned by the eigenvectors \( \{\mathbf{u}_1, \mathbf{u}_2, \ldots, \mathbf{u}_N\} \) corresponding to the \( N-K \) larger eigenvalues, and the residual eigenvectors \( \{\mathbf{u}_{N-K+1}, \mathbf{u}_{N-K+2}, \ldots, \mathbf{u}_N\} \) corresponding to the other \( K \) smaller eigenvalues constitute the eigen subspace \( \psi \), which is orthogonal to \( \zeta \). These \( K \) eigenvectors are a set of complete orthonormal basis for the subspace \( \psi \), which can be denoted as \( \{\hat{\mathbf{u}}_1, \hat{\mathbf{u}}_2, \ldots, \hat{\mathbf{u}}_K\} = \{\mathbf{u}_{N-K+1}, \mathbf{u}_{N-K+2}, \ldots, \mathbf{u}_N\} \).

As discussed in the previous subsection, the eigen-based spreading sequences for multiuser CDMA systems can be acquired by directly quantifying the basis. However, with (15), as the eigenvalues \( \{\lambda_{N-K+1}, \lambda_{N-K+2}, \ldots, \lambda_N\} \) are different, the SIR of each user computed by (4) is different, which leads to the performance gap between different users. This is not acceptable for a multiuser satellite system, in
The larger eigenvalues are used in the first order to average the performance of all users, the value of \( s_i^R R_s = (u_i')^H R u_i' \) can be expressed as follows:

\[
\begin{align*}
\frac{1}{K} & \sum_{i=1}^{K} t_{k,i} u_i = \sum_{i=1}^{K} t_{k,i} u_{N-K+i} = (I_{K, K} - \sum_{i=1}^{K} t_{k,i} u_i u_i^H)
\end{align*}
\]

where \( t_{k,i} \) is the element at the \( k \)th row and \( i \)th column of the matrix \( T \).

If we design the spreading sequences based on the new vectors, then (15) can be approximated as follows.

\[
\begin{align*}
\lambda_l & \geq \lambda_2 \geq \cdots \geq \lambda_K \\
\sum_{i=1}^{K} t_{k,i} u_i u_i^H & = \sum_{i=1}^{K} t_{k,i} u_{N-K+i} u_{N-K+i}^H \\
& = \sum_{i=1}^{K} t_{k,i}^2 \lambda_{N-K+i} u_{N-K+i} u_{N-K+i}^H \\
& = \sum_{i=1}^{K} t_{k,i}^2 \lambda_{N-K+i} (k = 1, 2, \ldots, K)
\end{align*}
\]

The minimum of the optimization problem described as (5) is the weighted average of the \( K \) smaller eigenvalues. In order to average the performance of all the users, the value of \( s_i^R R_s \) should be as equal as possible for different value of \( k \), which means that \( t_{k,i} \) should be as similar as possible according to (18). And also the matrix \( T \) should be an orthogonal matrix for the elimination of MAI. The matrix which satisfies the conditions is called uniform orthogonal transformation (UOT) matrix in this paper.

In order to satisfy the conditions, the matrix \( T \) is proposed to be selected as follows:

- For \( K = 4k \), a Hadamard matrix of degree \( K \) can be selected as the matrix \( T \);
- For \( K \neq 4k \), Monte Carlo method is employed. From a sufficient number of random matrices, (e.g., \( >10^3 \)), which are orthogonalized by Gram-Schmidt algorithm, the matrix with the minimal variance about the elements’ absolute values is selected.

Above all, an eigen-based spreading sequences design framework for CDMA satellite systems is detailedly derived. The functional block diagram of this processing framework is shown as follows. The generated multiple-level spreading sequences are called eigen-based spreading sequences in this paper. The method in [10] can be seen as a special case of this proposed design framework for single user.

![Diagram](image)

**Fig. 1.** The block diagram of the eigen-based spreading sequences design framework for multiuser systems

### IV. THE PHYSICAL SIGNIFICANCE ANALYSIS

For a random signal, which is impossible to be represented as a deterministic function of time, the power spectral density (PSD) is usually used to describe the characteristic in frequency domain. According to Wiener-Khinchin theorem, the PSD and the autocorrelation function of a signal should be a Fourier transform pair. Therefore, the subspace analysis and eigen spectrum of the covariance matrix can reflect the power distribution in the frequency domain.

With (12) and (13), according to the definition and properties of matrix trace, the total energy of all the interference signal samples can be expressed as

\[
tr(R) = \sum_{m} \{i_{n,m} - E\{i_{n,m}\}\}^2 + \sum_{m} \{i_{n,m} - E\{i_{n,m}\}\} + \cdots + \sum_{m} \{i_{n,m} - E\{i_{n,m}\}\}^2
\]

As \( \lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_K \) is established, if there are \( P \) larger eigenvalues, (19) can be approximated as follows.

\[
\sum_{m} \{i_{n,m} - E\{i_{n,m}\}\}^2 + \sum_{m} \{i_{n,m} - E\{i_{n,m}\}\} + \cdots + \sum_{m} \{i_{n,m} - E\{i_{n,m}\}\}^2
\]

Comparing (19) and (20), we can conclude that the cumulative energy of these \( P \) larger eigenvalues approximately equals to the total energy of the interference signal. According to principal component analysis and the theory of the eigen subspace, these \( P \) larger eigenvalues are referred to as the principal eigenvalues, and the eigenvectors corresponding to them are referred to as the principle components of the interference signal that portray higher PSD in the frequency domain, spanning the eigen principal...
subspace. And the other $N-P$ eigenvectors corresponding to the smaller eigenvalues portray lower PSD, which is always referred to as the minor components spanning the eigen minor subspace.

As it is stated in Section III that the spreading sequence $s_j$ should be generated according to the minor components, the PSD corresponding to which is lower in the frequency domain. For example, according to the practical satellite systems, several communication signals are received to be the external interference by a certain satellite transponder. The PSD of the interference and the eigen-based spread signal is shown in Fig. 2. It’s indicated that the power of the spread signal will be mainly concentrated on the frequency domain where the PSD of the interference signal is lower, so that the CDMA system is robust against the interference or the ACI, which means the increase of spectral efficiency. Moreover, MAI can also be eliminated by the orthogonality of the generated sequences.

V. NUMERICAL RESULTS

In this section, we evaluate the performance of the proposed eigen-based spreading sequences in CDMA satellite systems. We use the bit error rate (BER) to measure each user’s performance. Take a certain satellite transponder as an example, several communication signals are received to be the external interference, and the spreading factor is 32, the number of users is 8 and the length of spreading sequences is 32. The performance of the system is investigated at NIR = $-10\ dB$ while the AWGN power level is held constant such that SNR is constant.

Firstly, the average performance of the CDMA system with the proposed eigen-based spreading sequences is compared with that of gold sequences. As shown in Fig. 3, it’s indicated that with gold sequences, an unacceptable performance is yield. While with the proposed eigen-based spreading sequences, a higher performance can be achieved, which means the increase of the spectral efficiency and power efficiency. So it’s concluded that not only the external interference but also MAI can be efficiently suppressed with the proposed eigen-based spreading sequences.

Then the effect of the UOT module is investigated. In Fig. 4, the dashed curves show three typical users’ performance with the eigen-based sequences acquired without UOT including the best and the worst users. It can be seen that the performance of these users is not average. The performance of the worst user is almost 6dB lower than that of the best user, which is not acceptable for the multiuser satellite system. Thus the UOT shown in Fig. 1 should be operated. As we assume the number of users is 8, so the transformation matrix can be selected as a Hadamard matrix of degree 8. The solid curves in Fig. 4 show the performance of the typical users with the eigen-based spreading sequences after UOT including the best user, the worst user and also the average of all the users. It’s indicated that the performance of each user is efficiently averaged through UOT. Furthermore, Fig. 5 shows the average
performance of the eigen-based spreading sequences with and without UOT respectively. In the same simulation case as Fig. 4, when the SINR is under -24dB, the average performance of both kinds of sequences is close to each other. And when the SINR is higher than -24dB in this special simulation case, the average performance of the proposed eigen-based spreading sequences with UOT shown by the solid curve is higher than that of the sequences without UOT shown by the dashed curve. Similar simulation results can also be obtained when the number of users is $K \neq 4k$ and the UOT matrix is selected by the Monte Carlo method. So it’s concluded that UOT is indispensable for the proposed framework, which can guarantee the fairness of all the users.

VI. CONCLUSION

In order to combat the external interference inevitably received by satellite communication systems, in this paper, an eigen-based spreading sequences design framework for CDMA satellite systems is detailedly derived and analyzed by the theory of eigen subspace combining with the physical significance of signal processing and matrix analysis. Especially, a UOT module is included in the proposed design framework to overcome the performance gap between different users which is not acceptable in practical multiuser systems. By simulations, it’s verified that the CDMA satellite system can efficiently eliminate both the MAI and the external interference when the proposed eigen-based sequences are used comparing with that of gold sequences. Moreover, the performance of different users is effectively averaged, verifying the integrality of the proposed framework.

ACKNOWLEDGMENT

This work was supported by the National Basic Research Program of China under Grant No. 2013CB329001 and the National Nature Science Foundation of China under grant numbers 91338101, 91338108, 61021001 and Co-innovation Laboratory of Aerospace Broadband Network Technology.

REFERENCES