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Zero intersymbol interference multiuser system: a new architecture utilising *m*-sequence cyclic property

S. Lenty Stuwart[1] ✉, S. Tamil Selvi[2]

[1]Electronics and Communication Engineering, University College of Engineering Nagercoil, Anna University, Nagercoil, Kanyakumari 629004, Tamilnadu, India
[2]Electronics and Communication Engineering, National Engineering College, K.R. Nagar, Kovilpatti 628503, Tamilnadu, India
✉ E-mail: lenty_s@yahoo.com

Abstract: Code division multiple access (CDMA) based on spread spectrum technique has become one of the most important multiple access technologies in contemporary communication systems. The properties of spreading codes largely govern the performance of CDMA systems. Therefore, CDMA can insure interference free operation when code design methodology takes into account of major impairing factors such as intersymbol interference (ISI), asynchronous transmission and random signs in consecutive symbols. In this study, the authors propose a design scheme for CDMA signal reception with zero ISI in the multipath environment. Cyclic shift property of maximal length sequence (*m*-sequence) is utilised in the design to avoid ISI. The proposed scheme exploits inherent diversity present in the multipath channel and can be seen as antenna diversity. This scheme avoids the use of complex detectors and the performance is compared by simulations with conventional CDMA system using Walsh–Hadamard codes and *m*-sequence. The impact of the Rician factor on the end-to-end performance is also studied in detail and suitable receiver to be used has been suggested for different fading scenarios. Simulations results presented indicate that the proposed scheme provides superior performance over traditional systems.

1 Introduction

The simultaneous transmission of multiple data streams over the same channel can be achieved with different multiplexing schemes. Multiplexing schemes using code division have gained popularity and have become part of several wireless standards such as wideband code division multiple access/universal mobile telecommunications system (UMTS) and wireless local area network [1, 2]. Multiplexing schemes are often combined resulting in hybrid scheme systems like UMTS where code division multiple access (CDMA), time division multiple access and frequency division multiple access (FDMA) are used. The idea of the combination of spread spectrum and frequency hopping with sub-carrier modulation provided a room for alternative hybrid multiple access solutions such as orthogonal FDMA (OFDMA) and OFDMA with code division multiplexing (CDM) [3, 4]. Despite these schemes, the wireless channel suffers from attenuation due to destructive multipath components. The signals of paths with a propagation delay difference of more than the chip duration can be resolved in CDM based system operating in multipath environment [5]. However, in a multipath wireless environment, transmitted signal of a user is affected by interferences such as multiple access interference (MAI) due to the use of same spectrum by either several users or multiple data streams of same user, self-interference (SI) from the multipath components of the same user/data stream and also multipath interference (MPI) from other active users/data streams in the same channel. Therefore, intersymbol interference (ISI) enters into the receiver in the form of SI and MPI. Further, the use of large bandwidth in next generation wireless standards will make the ISI more severe. The spreading codes play key role in the performance of CDM based system. Specifically, the MAI enters from non-ideal cross correlation functions among all spreading codes and, SI and MPI are caused by non-trivial autocorrelation side-lobes of individual spreading code [6]. Hence, unsatisfactory properties of the spreading codes adopted by a system may face problems such as complex system implementation, low transmission rate and low capacity.

Spreading sequences have taken a long journey in communication era. Complementary codes were introduced to solve optical problems of multislit spectrometry which found applications in communication engineering [7]. Minimum distance codes were developed with the help of Walsh functions and Hadamard matrices [8]. Spread sequences with uniform low cross-correlation values originated form linear shift register sequences found extensive applications in spread spectrum communication [9]. Complex periodic sequences were developed as an alternative to binary sequences [10]. Structure of the Kronecker sequences introduced made it easy optimising the phases [11]. Bent sequences from non-linear binary signal sets were derived [12]. Correlation properties of dual-BCH codes and Kasami sequences were investigated for possible use in multi-access systems [13]. Complete complementary codes obtained from N-shift cross-orthogonal sequences found applications in synchronous multiuser spread spectrum systems [14]. As an alternative to PN sequences chaotic codes were developed based on chaos theory in which spreading sequences change from one to another [15]. Zero correlation zone codes were introduced to minimise MPI [16]. Novel code generation algorithm for orthogonal spreading codes maintaining minimum cross correlation was developed [17]. Recently 3-D complementary code is developed for MUI-free performance in MIMO systems [18].

The use of *m*-sequence in communication systems has been researchers' interest for several decades [19–27]. The detailed study on *m*-sequence as spreading code for CDMA communication is found in the literatures [28–30]. Though *m*-sequence possess very good autocorrelation property and moderate cross correlation property compared of Gold sequence and orthogonal codes, varying signs in the bit stream along with SI and MPI changes the autocorrelation property of a spreading code.

The use of Gold codes and orthogonal codes in recent CDMA standards has avoided the benefit of *m*-sequence [31]. Any attempt made to design a wireless communication system with well-known spreading code without considering the channel impairment such as SI and MPI cannot fulfil the design requirements. Thus, it is the time to use the code available with us in an appropriate way to get the benefit out of it. With this intention, a scheme is proposed in which the *m*-sequence is used as spreading code. The new design exploits the cyclic shift property of the spreading code to deal with the ISI.

The proposed scheme uses subcarriers for user separation and additionally uses CDM on data symbols belonging to the same user. One user maps L data symbols to one sub-system exclusive for transmission. Different users use different sub-systems. To increase the system robustness, a dynamic assignment of subcarriers in the form of frequency hopping for each user can be done. The user specific frequency mapping assigns each user independent subcarrier avoiding MAI from other active users. However, the system has to cope with the MAI caused by the superposition of L data streams from the same user, which is taken care with the use of *m*-sequence as spreading code.

The remainder of the paper is organised as follows. In Section 2, system model of the proposed scheme is presented. The system analysis is described in Section 3 with relevant examples. BER performance analysis using computer simulation experiments are carried out and presented in Section 4. Finally, results are summarised and concluded in Section 5.

2 System model

Let the vector $\boldsymbol{s}_l^k = [s_{l,1}^k, s_{l,2}^k, \ldots, s_{l,M}^k]^{\mathrm{T}}$ denote a frame of M antipodal modulated data symbols for lth data stream of user k, where $1 \le l \le L$ and $1 \le k \le K$. The matrix $\boldsymbol{C}^k = [\boldsymbol{c}^k(1), \boldsymbol{c}^k(2), \ldots, \boldsymbol{c}^k(N)]$ contains spreading code vectors of user k, where each normalised vector is *m*-sequence of length N. Let the vector $\boldsymbol{c}_l^k = \boldsymbol{c}^k(lP - P + 1) = [c_{l,1}^k, c_{l,2}^k, \ldots c_{l,N}^k]^{\mathrm{T}}$ is the spreading code vector for the lth data stream of user k.

For a multipath channel with P significant multipath components each having one chip delay with respect to first path, bth chip of lth data stream of user k after spreading is described as

$$\left.\begin{array}{ll} c_{l,b}^k = c_{l,b-pl+p}^k, & \text{for } 1 \le b \le N \text{ and } 1 \le p \le P \\ c_{l,v}^k = c_{l,N+v}^k, & \text{for } v = 0, -1, -2, \ldots -N-1 \end{array}\right\} \quad (1)$$

Fig. 1*a* shows the transmitter of the proposed system supporting K users, each user simultaneously transmitting L data streams, where $L = N/P$. The modulated spreading codes of L data streams of user k are synchronously added, resulting in the vector

$$\boldsymbol{d}^k = \boldsymbol{c}^k (\boldsymbol{s}^k)^{\mathrm{T}} \quad (2)$$

where $\boldsymbol{c}^k = [\boldsymbol{c}_1^k, \boldsymbol{c}_2^k, \ldots, \boldsymbol{c}_L^k]$ and $\boldsymbol{s}^k = [\boldsymbol{s}_1^k, \boldsymbol{s}_2^k, \ldots, \boldsymbol{s}_L^k]$. The receiver with coherent detection of the kth user signal is shown in Fig. 1*b*. The proposed scheme is typically applied for asynchronous uplink scenarios. In the sequel, transmission and detection of kth user signal will be analysed in detail and hence for simplicity the subscript k is omitted in further analysis.

Based on the channel length, symbol stream is block spread and then first chip sample of a symbol followed by second chip sample of next symbol is written and this procedure is continued for rest of the chip samples to construct a symbol frame. The detailed

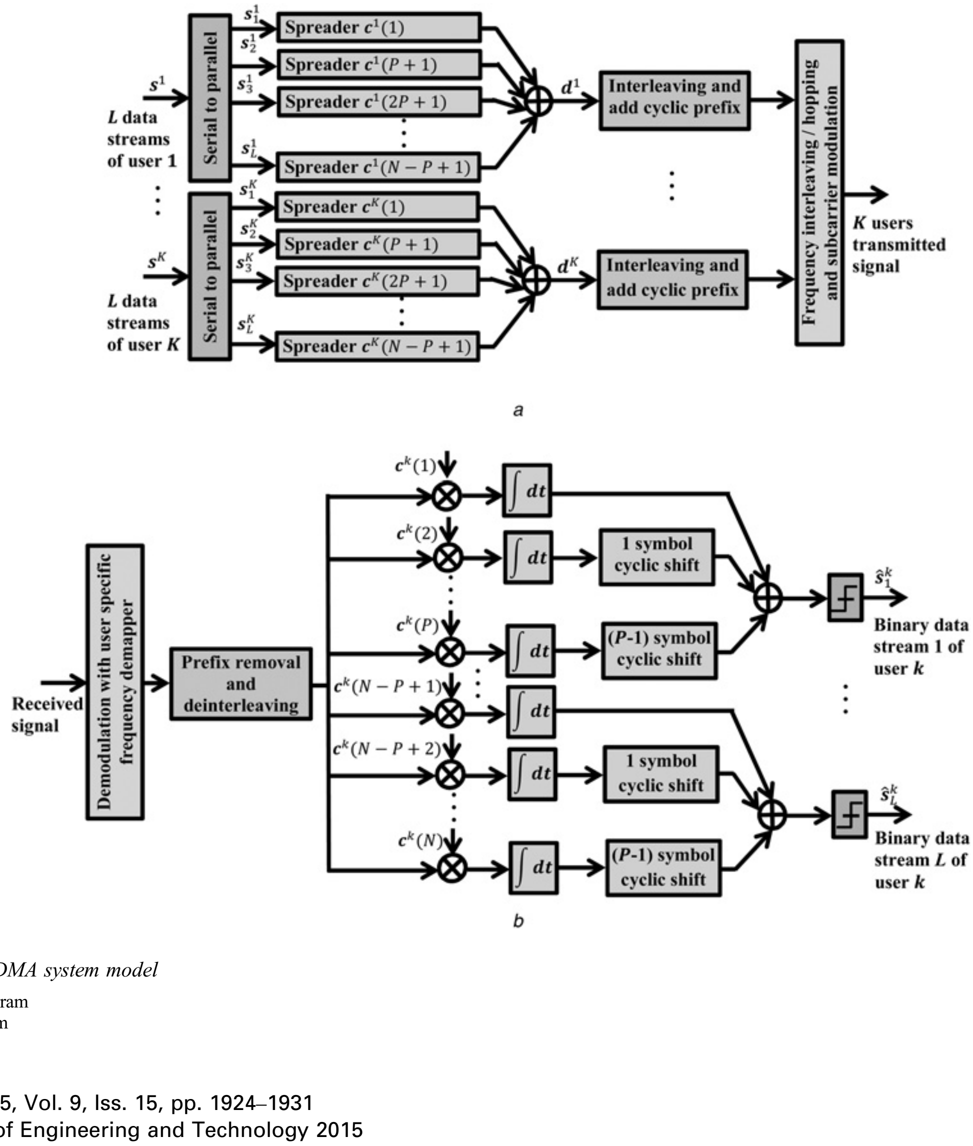

Fig. 1 *Proposed CDMA system model*

a Transmitter block diagram
b Receiver block diagram

procedure is as follows. The structure of symbol stream $\mathbf{s}_1$ after the spreading followed by interleaving is shown in Fig. 2*a*. The data stream and spreading code must satisfy the condition $M = N–1$. The *i*th column in spread data structure indicates the chip samples of *i*th modulated symbol in the stream. After spreading, chip samples in each column are arranged in reverse order and *i*-chip down-cyclic shift is introduced to the *i*th column, where $1 \le i \le M$.

Next, chip samples of each row are read as a block to construct a frame of N blocks. $N–1$ chip samples of M different symbols are present in each block as shown in Fig. 2*b*. $P–1$ chip samples are cyclic prefixed to the beginning of the frame for a multipath channel with channel impulse response length P.

The *m*th modulated data symbol of the *b*th block for the *l*th data stream after spreading and interleaving can be described as

$$d_{l,m}[b] = s_{l,m} c_{l,(m-b+1)} \tag{3}$$

where $s_{l,m}$ is the *m*th modulated symbol of the block for the *l*th data stream. $c_{l,(m-b+1)}$ is the *m*th chip of the *b*th block for the *l*th data stream and $1 \le b \le N$.

The modulated data symbol of *l*th stream can also be described as

$$s_{l,u} = s_{l,M+u}, \quad \text{for } u = 0, \ -1, \ -2, \ \ldots -M+1 \tag{4}$$

The proposed CDMA system adds a cyclic prefix of Q chips at the beginning of each frame. The resulting waveform is expressed as follows

$$\begin{aligned} x(t) = & \sum_{l=1}^{L} \sum_{m=1}^{Q} d_{l,(m+M-Q)}[N] \beta(t - (m-1)T_c) \\ & + \sum_{l=1}^{L} \sum_{b=1}^{N} \sum_{m=1}^{M} d_{l,m}[b] \beta(t - ((b-1)M + Q + m - 1)T_c) \end{aligned} \tag{5}$$

where, T_c is the chip duration. $\beta(t)$ is the rectangular function. The channel is assumed to be multipath delay-spread channel which is expressed as

$$p(t) = \sum_{p=1}^{P} \alpha_p \delta(t - \tau_p) \tag{6}$$

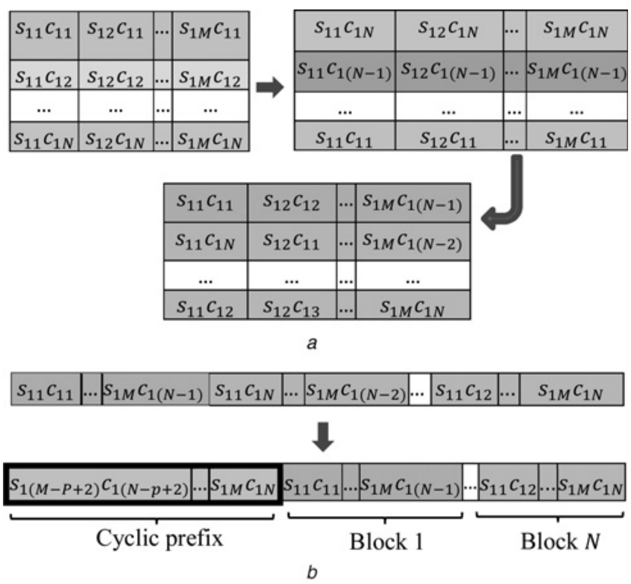

Fig. 2 *Transmitter data structure*

a Spreading and interleaving process
b Arranging as blocks and cyclic prefixing

where P is the number of paths, α_p is the normalised instantaneous complex path gain of the *p*th path, τ_p is the time delay of the *p*th path and $\delta(t)$ is the Dirac delta function.

After passing through the multipath channel, channel noise $n(t)$ modelled as additive white Gaussian noise (AWGN) is added to the signal resulting in the received signal of the form

$$r(t) = x(t) \otimes h(t) + n(t) \tag{7}$$

where $\otimes$ is the convolution operator, $h(t)$ is the combined impulse response of the transmit chip pulse shaping filter $p_t(t)$, frequency selective fading channel response $p(t)$ and the receive pulse shaping filter $p_r(t)$ which is expressed as

$$h(t) = p_t(t) \otimes p(t) + p_r(t) \tag{8}$$

The received signal is demodulated and matched filtering followed by chip-rate sampling is performed at the receiver. Cyclic prefix of Q chips at the beginning of the frame is discarded. The remaining M chip-spaced samples corresponding to the *b*th block of the frame can be described as follows

$$r_m[b] = \sum_{p=1}^{P} \sum_{l=1}^{L} s_{l,(m-p+1)} c_{l,(m-p-b+2)} h_p[b] + \varepsilon_m[b] \tag{9}$$

where $h_p = h(pT_c)$ and h_p is assumed to be zero for $p < 0$ and $p > P$. Besides, $h_p[b]$ denotes the *p*th path of the channel for the *b*th received block. Moreover, $\varepsilon_m[b]$ is the AWGN component at the *m*th sample of *b*th received block of the frame.

Deinterleaving is performed by replacing b with $m–b+1$ in (9), and the resultant expression can be rewritten as

$$y_m[b] = \sum_{p=1}^{P} \sum_{l=1}^{L} s_{l,(m-p+1)} c_{l,(b-p+1)} h_p[m-b+1] + \varepsilon_m[m-b+1] \tag{10}$$

where $y_m[b]$ is valid for $1 \le b \le N-1$. After deinterleaving, M data blocks are present in a data frame, each block has N chip samples of same modulated symbol of a data stream.

Let $s_{i,m}[j]$ is the data after despreading *m*th symbol of *i*th data stream from *j*th path, which can be described as

$$\begin{aligned} s_{i,m}[j] = & \sum_{b=1}^{N} y_m[b] c_{i,(b-j+1)} \\ = & \sum_{b=1}^{N} \sum_{p=1}^{P} \sum_{l=1}^{L} s_{l,(m-p+1)} c_{l,(b-p+1)} h_p[m-b+1] c_{i,(b-j+1)} \\ & + \sum_{b=1}^{N} \varepsilon_m[m-b+1] c_{i,(b-j+1)} \end{aligned} \tag{11}$$

Assuming the channel variation across the consecutive blocks of the frame negligible, $h_p[m-b+1]$ can be replaced with h_p. Hence (9) is rewritten as follows

$$s_{i,m}[j] = \sum_{b=1}^{N} \sum_{p=1}^{P} \sum_{l=1}^{L} s_{l,(m-p+1)} c_{l,(b-p+1)} h_p c_{i,(b-j+1)} + \varepsilon'_m \tag{12}$$

where $\varepsilon'_m = \sum_{b=1}^{N} \varepsilon_m[m-b+1] c_{i,(b-j+1)}$ represents AWGN component which has the variance σ_n^2 same as that of ε_m in (9).

Expanding (12) further can clearly indicate interference terms present in the estimated data as

$$s_{i,m}[j] = \sum_{p=1}^{P} s_{i,(m-p+1)} h_p \sum_{b=1}^{N} c_{i,(b-p+1)} c_{i,(b-j+1)} + \sum_{p=1}^{P} \sum_{\substack{l=1 \\ l \neq i}}^{L} s_{l,(m-p+1)} h_p \sum_{b=1}^{N} c_{l,(b-p+1)} c_{i,(b-j+1)} + \varepsilon'_m \tag{13}$$

Each term in (13) is represented in detail as follows

$$\begin{aligned} s_{i,m}[j] &= s_{i,(m-j+1)} h_j \sum_{b=1}^{N} c_{i,(b-j+1)} c_{i,(b-j+1)} \\ &+ \sum_{\substack{p=1 \\ p \neq j}}^{P} s_{i,(m-p+1)} h_p \sum_{b=1}^{N} c_{i,(b-p+1)} c_{i,(b-j+1)} \\ &+ \sum_{\substack{l=1 \\ l \neq j}}^{L} s_{l,(m-j+1)} h_j \sum_{b=1}^{N} c_{l,(b-j+1)} c_{i,(b-j+1)} \\ &+ \sum_{\substack{p=1 \\ p \neq j}}^{P} \sum_{\substack{l=1 \\ l \neq i}}^{L} s_{l,(m-p+1)} h_p \sum_{b=1}^{N} c_{l,(b-p+1)} c_{i,(b-j+1)} + \varepsilon'_m \end{aligned} \tag{14}$$

In (14), the first term represents the desired signal component, the second term belonging to the desired data stream is the interference owing to SI, the third and fourth terms are MAI due to other data streams and their MPI respectively. The last term is the noise component. It is clear that in the first term, $\sum_{b=1}^{G} c_{i,(b-j+1)}^2$ is the normalised autocorrelation of spreading code which is unity. Assuming that the correlation among the spreading codes present in the second, third and fourth terms is negligible, we can rewrite (14) as follows

$$s_{i,m}[j] = s_{i,(m-j+1)} h_j + \varepsilon'_m \tag{15}$$

It is clear from (15) that the SI, MPI and MAI are completely removed. In general, the correlation among the pseudo noise spreading codes is non-zero which leads to small performance degradation. However, this effect is insignificant compared with ISI that takes place in conventional systems.

In the case of rake receiver, each of the P signals due to the desired data stream i is combined as follows. A left cyclic shift of j for the jth correlator output is introduced by replacing $m = m + j - 1$ in (14), hence the mth symbol of data stream i is written from combiner output as

$$\begin{aligned} S_{i,m} &= \sum_{j=1}^{P} s_{i,m+j-1}[j] \\ &= s_{i,m} \sum_{j=1}^{P} h_j \sum_{b=1}^{N} c_{i,(b-j+1)} c_{i,(b-j+1)} \\ &+ \underbrace{\sum_{j=1}^{P} \sum_{\substack{p=1 \\ p \neq j}}^{P} s_{i,(m+j-p)} h_p \sum_{b=1}^{N} c_{i,(b-p+1)} c_{i,(b-j+1)}}_{\text{SI}} \\ &+ \underbrace{\sum_{\substack{l=1 \\ l \neq i}}^{L} s_{l,m} \sum_{j=1}^{P} h_j \sum_{b=1}^{N} c_{l,(b-j+1)} c_{i,(b-j+1)}}_{\text{MAI}} \\ & \underbrace{\sum_{j=1}^{P} \sum_{\substack{p=1 \\ p \neq j}}^{P} \sum_{\substack{l=1 \\ l \neq i}}^{L} s_{l,(m+j-p)} h_p \sum_{b=1}^{N} c_{l,(b-p+1)} c_{i,(b-j+1)}}_{\text{MPI}} + \sum_{j=1}^{P} \varepsilon'_{m+j-1} \end{aligned} \tag{16}$$

For negligible correlation among the spreading codes, (16) can be further simplified as

$$S_{i,m} = s_{i,m} \sum_{j=1}^{P} h_j + \sum_{j=1}^{P} \varepsilon'_{m+j-1} \tag{17}$$

Using (17), the desired mth estimated symbol of ith data stream $\boldsymbol{s}_i$ is described as

$$\begin{aligned} \hat{s}_{i,m} &= \operatorname{sgn}(\operatorname{Real}(S_{i,m})) \\ &= \operatorname{sgn}\left(s_{i,m} \operatorname{Real}\left\{ \sum_{j=1}^{P} h_j \right\} + \operatorname{Real}\left\{ \sum_{j=1}^{P} \varepsilon'_{m+j-1} \right\} \right) \end{aligned} \tag{18}$$

It is observed from (15), (17) and (18) that the simple combiner achieves high diversity gain in addition to ISI minimisation.

3 Proposed system analysis

The reasons for superior performance of the proposed scheme over conventional CDMA systems can be given with the help of analysing (14) and (15) followed by simple illustration of symbol detection steps at the receiver. Further, noise term is omitted for the brevity.

The value of correlator output $s_{i,m}[j]$ from (14) for various values of p and b is tabulated in Table 1. The parameters $M = 4$, $P = 4$, $N = 5$ and $L = 1$ are considered. It is assumed that $h_j = h_p = 1$. With unit normalised autocorrelation of spreading, the desired symbol metric for $j = p = 1$ is shown in the second row. Values for $j \neq p$ given in the next three rows are corresponding to the second term of (14).

From this it is perceived that the cross correlation value among the spreading codes decides the amount of SI and MPI added to the desired signal. Moreover, considering significant multipath components, careful selection of PN codes can make the MAI and MPI due to other data streams negligible.

From (15) the value of correlator output $s_{i,m}[j]$ for different values of i, m and j is shown in the Table 2. $M = 4$ and $P = 4$ are considered and assumed that $h_j = 1$.

It is observed from the Table 2 that the data stream detected from jth delayed path is j chip right cyclic shifted version of actual data stream transmitted. In multipath channel, the proposed scheme makes the replicas of the transmitted signal as constructive components and can be seen as antenna diversity in spatial domain.

Table 1 Computed values as given in (14)

$l, j, m, i = 1$	$b = 1$	$b = 2$	…	$b = 5$
$p = 1$	$s_{1,1}c_{1,1}c_{1,1}$	$s_{1,1}c_{1,2}c_{1,2}$	…	$s_{1,1}c_{1,5}c_{1,5}$
$p = 2$	$s_{1,0}c_{1,0}c_{1,1}$ $(s_{1,4}c_{1,5}c_{1,1})$	$s_{1,0}c_{1,1}c_{1,2}$ $(s_{1,4}c_{1,1}c_{1,2})$	…	$s_{1,0}c_{1,4}c_{1,5}$ $(s_{1,4}c_{1,4}c_{1,5})$
$p = 3$	$s_{1,-1}c_{1,-1}c_{1,1}$ $(s_{1,3}c_{1,4}c_{1,1})$	$s_{1,-1}c_{1,0}c_{1,2}$ $(s_{1,3}c_{1,5}c_{1,2})$	…	$s_{1,-1}c_{1,3}c_{1,5}$ $(s_{1,3}c_{1,3}c_{1,5})$
$p = 4$	$s_{1,-2}c_{1,-2}c_{1,1}$ $(s_{1,2}c_{1,3}c_{1,1})$	$s_{1,-2}c_{1,-1}c_{1,2}$ $(s_{1,2}c_{1,4}c_{1,2})$	…	$s_{1,-2}c_{1,2}c_{1,5}$ $(s_{1,2}c_{1,2}c_{1,5})$

Table 2 Computed values as given in (15)

$i=1$, $p=j$	$m=1$	$m=2$	$m=3$	$m=4$
$j=1$	$s_{1,1}$	$s_{1,2}$	$s_{1,3}$	$s_{1,4}$
$j=2$	$s_{1,0}=s_{1,4}$	$s_{1,1}$	$s_{1,2}$	$s_{1,3}$
$j=3$	$s_{1,-1}=s_{1,3}$	$s_{1,4}$	$s_{1,1}$	$s_{1,2}$
$j=4$	$s_{1,-2}=s_{1,2}$	$s_{1,3}$	$s_{1,4}$	$s_{1,1}$

Fig. 3 presents the flow chart representation of proposed scheme. Fig. 4 illustrates the transmission and reception of a data stream in a multipath channel. The structure of lth data stream $\boldsymbol{s}_l$ after spreading with the spreading code $\boldsymbol{c}_l$ is described as

$$\boldsymbol{d}^k = \boldsymbol{c}^k(\boldsymbol{s}^k)^{\mathrm{T}} = \begin{bmatrix} a_{11} & b_{11} & c_{11} & d_{11} \\ a_{12} & b_{12} & c_{12} & d_{12} \\ a_{13} & b_{13} & c_{13} & d_{13} \\ a_{14} & b_{14} & c_{14} & d_{14} \\ a_{15} & b_{15} & c_{15} & d_{15} \end{bmatrix} \quad (19)$$

where a_{lj} is the chip j of symbol a belonging to lth data stream, $M=4$, $N=5$ and $L=1$ and assumed that $h_p=1$. All the assumptions made here are only for illustrative purpose. The spread signal is interleaved and cyclic prefix is added followed by transmission using the suitable subcarrier. The received data frame denoted as U_{kj} is kth user data frame from jth path.

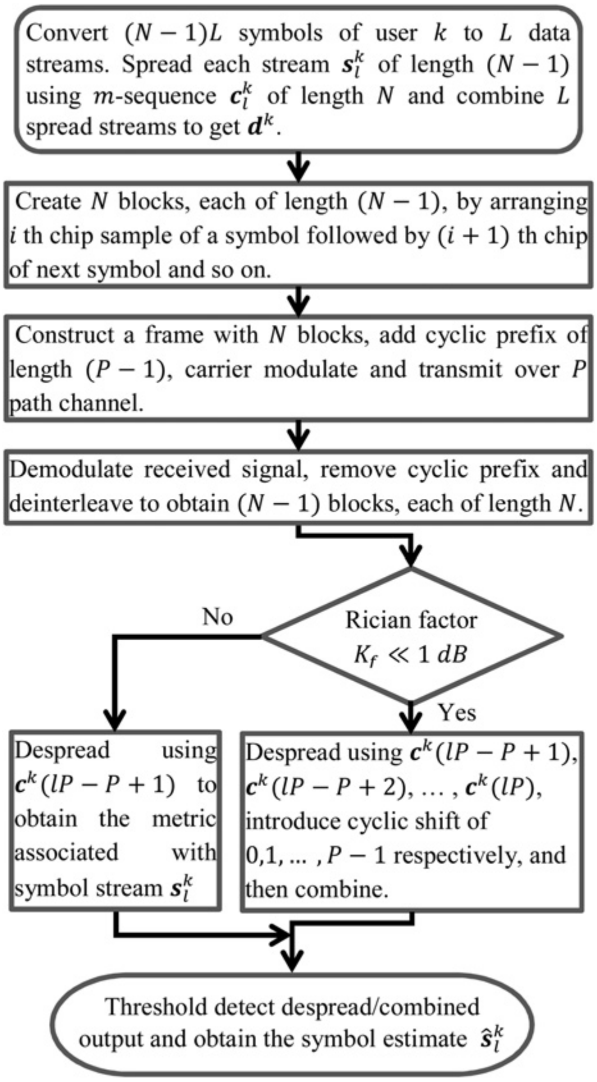

Fig. 3 *Flow chart of proposed scheme*

In multipath channel, after cyclic prefix removal and deinterleaving, each spread symbol of j chip delayed dataframe at the receiver appears as symbol spread with j chip right cyclic shifted version of the m-sequence used at the transmitter. Either a simple correlator with m-sequence corresponding to the desired data stream or rake structure with number of fingers equal to the number of multipath components, each finger with cyclic shifted version of the corresponding m-sequence, can be used to detect the symbols. In agreement with the mathematical model presented in the previous section, we note from Fig. 4 that the inherent diversity is exploited when retrieved symbols from all paths are combined after the appropriate left cyclic shift. Thus, due to cyclic shift property of the spreading code, multiple copies of the single transmitted data symbol are obtained at the receiver in the form of antenna diversity and can be combined by employing simple equal gain combiner (EGC). This avoids the use of complex receivers and signal processing needed in the existing CDMA systems to combat the effect of ISI. Hence the proposed scheme is a good candidate for the CDMA system operated in multipath environment.

4 Error analysis

CDMA system operating in a multipath fading environment is considered. BER as a function of channel noise, Rician factor and number of data streams L is considered to generate performance result. BPSK modulation without pulse shaping is considered. Simple correlation receiver and rake structure are used for different scenarios. Average scattered energy E_{scat} is computed and average energy in the LOS component is calculated as $E_{\mathrm{LOS}}=K_{\mathrm{f}}E_{\mathrm{scat}}$ so that the specified Rician factor K_{f} is satisfied. Frame of N–1 symbols is processed.

Several aspects of the simulation setup are idealised to isolate the fundamental performance characteristics of the systems. It is assumed that the average path gains are constant during a frame and vary from one frame to another. Negligible channel variation over a frame and independent between frames is assumed. Channel state information is not used at the receiver. 63 length m-sequence and 64 length Walsh–Hadamard code are used as spreading codes. Throughout the analysis, we would like to make comparison of the three CDMA systems: proposed scheme using m-sequence and conventional CDMA system based on Walsh–Hadamard code and m-sequence.

Fig. 5 examines the impact of multipath effect in terms of SI on the system performance. Number of multipath components is nearly equal to spreading factor. Although the multipath assumptions in the simulations may seem highly unrealistic, they give reference performance curves for comparison with known techniques. For $K_{\mathrm{f}}=1$ dB the proposed scheme makes single user 63 path signals to appear as data in each path spread with different spreading code as illustrated in Fig. 4 which leads to performance improvement compared with other systems. Poor autocorrelation property of orthogonal codes degrades the performance compared with other two systems.

In all three cases, weak LOS component for $K_{\mathrm{f}}=-20$ dB degrades the performance compared with that of $K_{\mathrm{f}}=1$ dB. The small Rician factor destroys the autocorrelation property of m-sequence and orthogonal codes which leads to irreducible error in conventional CDMA system. However the proposed scheme gives superior performance due to the average energy of LOS component is comparable with average energy of each scattered component.

Fig. 6 demonstrates the performance of proposed scheme against the MAI for $K_{\mathrm{f}}=1$ dB. In the first case, the desired user transmits 31 different data streams over two path channel which introduces MAI. Each data stream is distinguished by its specific PN code. The multipath amplitude profile for two path channel is [1 0.8913]. The MAI due to the transmission of multiple data streams and interference such as SI and MPI due to multipath fading depend only on the correlation of spreading codes which leads to proposed scheme with superior performance. In contrast, in conventional CDMA systems, the multipath components destroy the correlation

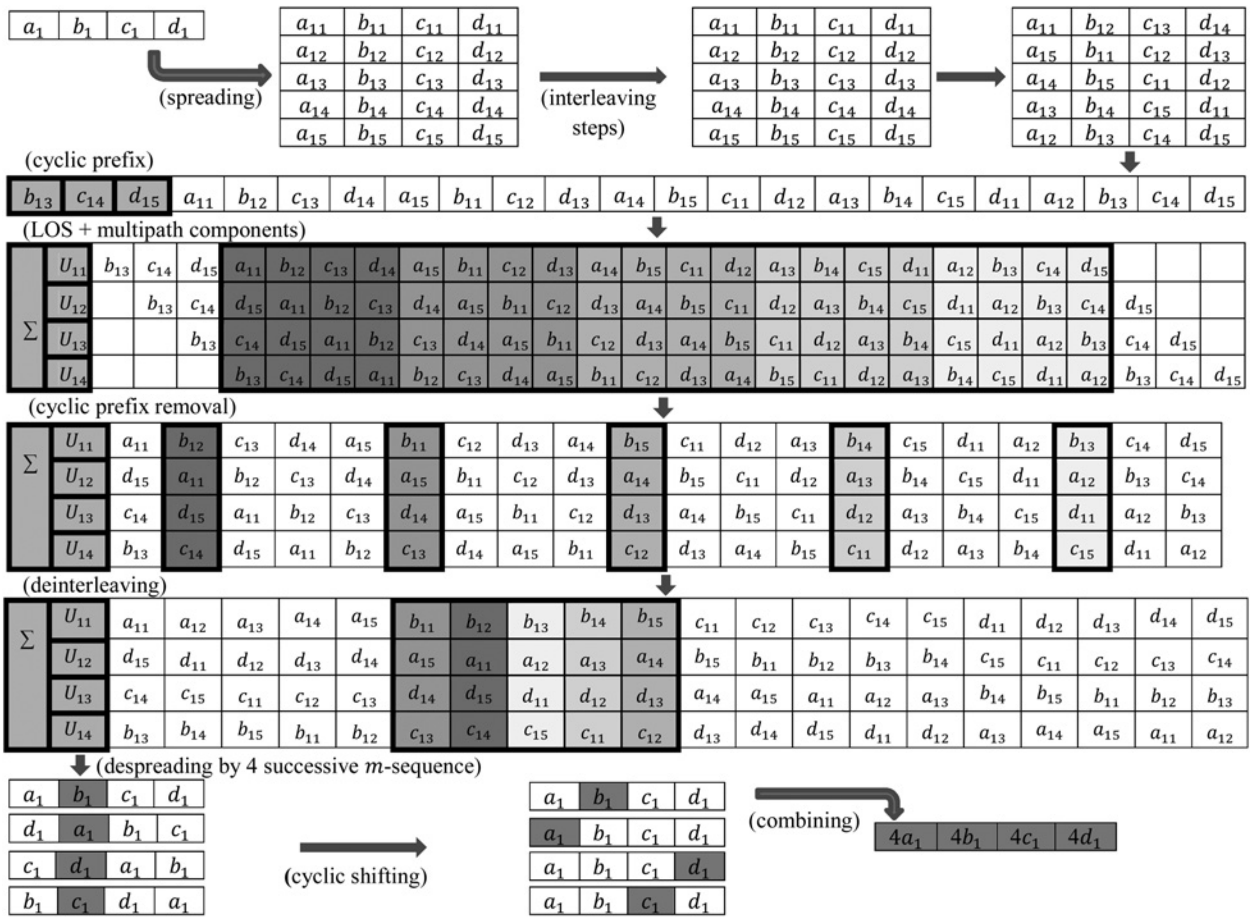

Fig. 4 *Steps in detecting transmitted symbols*

properties of orthogonal codes and *m*-sequence, which makes the performance significantly worse than the previous one.

In the second case, three data streams are transmitted over 21 path channel. We can see that, at low SNR, performance of conventional CDMA system with *m*-sequence is not better than that of its orthogonal codes counterpart, then it starts improving at high SNR due to decrease in noise level. Clearly, the performance of the proposed scheme is much better than other systems. We can see

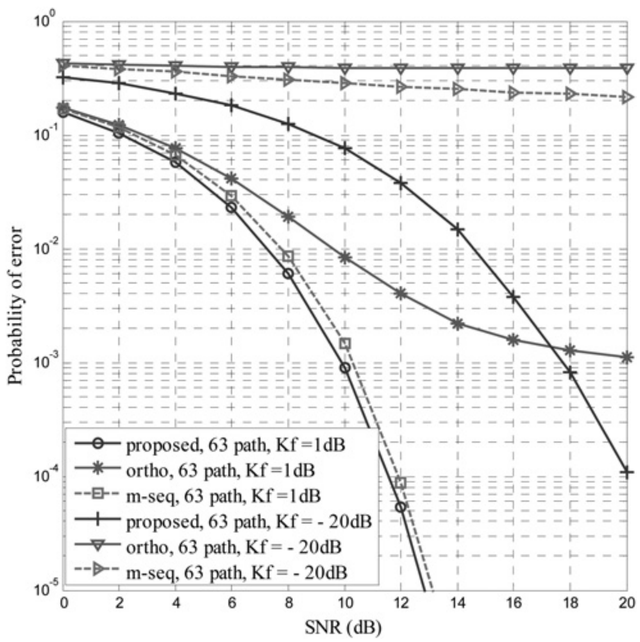

Fig. 5 *Performance of proposed system and conventional CDMA system with m-sequences and orthogonal codes for L = 1*

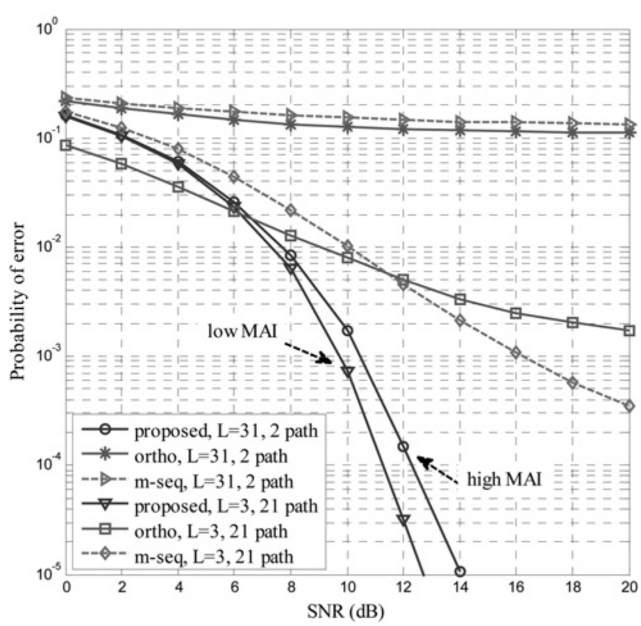

Fig. 6 *Performance of the different CDMA systems for L = 3, L = 31 and* K_f *= 1 dB*

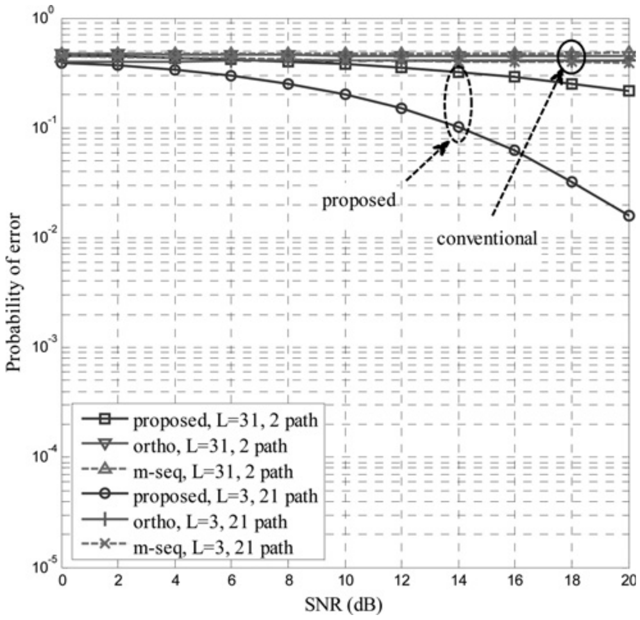

Fig. 7 *Performance of the three CDMA systems for L = 3, L = 31 and* $K_f = -20$ dB

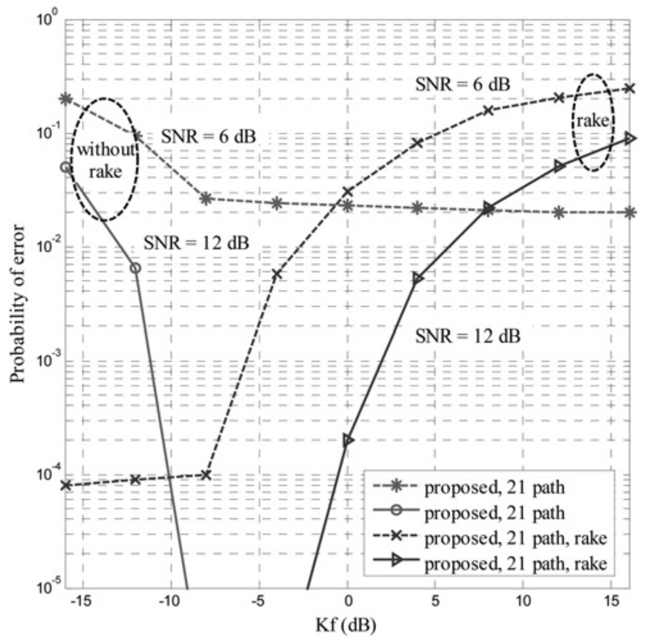

Fig. 9 *Performance comparison of the proposed system as a function of Rician factor with simple correlator and rake structure at the receiver for L = 3*

only a small loss in performance due to high MAI in the previous case.

In Fig. 7 we examine the performance of proposed system in severe multipath fading channel. Rician factor is set to $K_f = -20$ dB while the other parameters remain the same as those given in previous analysis. The multipath amplitude profile for 2 path channel is [0.1 1]. The negligible power in LOS component affects all the systems. A great impairment can be seen for the conventional CDMA system based on orthogonal codes and *m*-sequence. The proposed scheme, though affected by a performance degradation compared with Fig. 6, maintains acceptable behaviour. Although, the proposed scheme performs better than the other two systems, the performance difference is not large when system with large K_f is compared. It is noted that the use of simple correlator is inadequate at the receiver for multipath channel satisfying very small Rician factor.

Fig. 8 investigates all the systems with rake structure employed at the receiver for $K_f = -20$ dB. The conventional CDMA system based on orthogonal codes and *m*-sequence suffers greatly due to insignificant LOS component. A superior performance of the proposed scheme over other two systems for 2 path delay is still evident. When compared with 2 path system, the 21 path system gives remarkable performance due to multipath diversity gain.

In Fig. 9 we present the comparison between the performances of proposed scheme for simple correlator and rake receiver. BER of 21 path channel is presented for SNR = 6 dB and SNR = 12 dB. The study describes the range of K_f values for which rake structure can be employed at the receiver to achieve optimum performance. The scattered components are strong and significant compared with

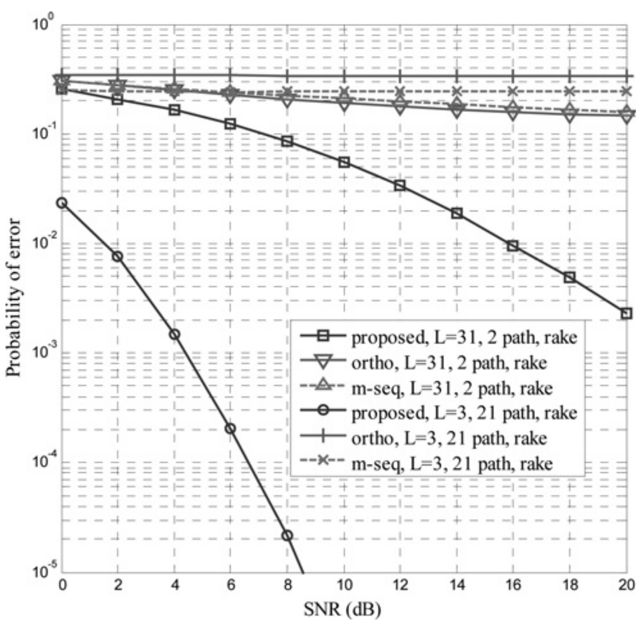

Fig. 8 *Performance of the three CDMA systems using rake structure at the receiver for L = 3, L = 31 and* $K_f = -20$ *dB*

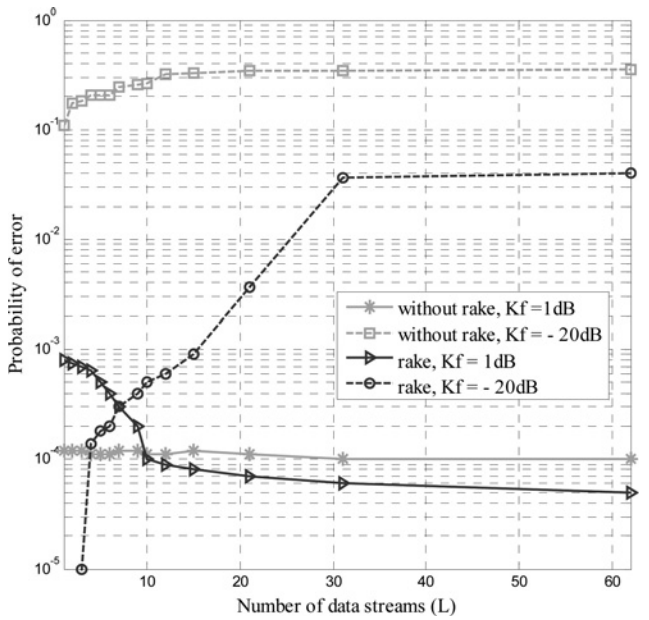

Fig. 10 *Performance comparison of the proposed system as a function of L with simple correlator and rake structure at the receiver for* $K_f = 1$ dB, $K_f = -20$ dB *and SNR = 12 dB*

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LOS component for small Rician factor. Hence, the performance of rake receiver is excellent and the use of the other receiver is completely impractical in such a situation. However, large value of v deteriorates the rake performance. The negligible power in the scattered components reduces the number of significant multipath components and the rake fingers handling weak path signals lead to performance degradation. On the contrary, the simple correlator outperforms rake receiver.

Fig. 10 shows the performance of proposed scheme for different number of data streams L. For small L, multipath component at $K_f = 1$ dB are insignificant and the rake performance is not good. However, it starts to improve for large L due to the rise of significant multipath components. Conversely, no difference in performance can be seen between small and large L for simple correlator due to strong LOS component. Rake receiver performance at $K_f = -20$ dB is very good at small L as a result of diversity contributed by significant multipath components. Alternately, when L increases from 1 to 63, the number of multipath components are greatly reduced and, consequently the proposed system incurs performance loss. The result indicates that rake and simple correlator are suitable for small and large Rician factors respectively.

5 Conclusion

This paper introduced a new scheme for zero ISI CDMA system. CDM on data symbols belonging to same user exploited the advantages given by the combination of spread spectrum technique and cyclic property of *m*-sequence. The possible use of simple correlator and rake structure with EGC at the receiver was studied. The use of rake structure improved the performance of the proposed system in multipath channel satisfying very small Rician factor. Furthermore, for the channel satisfying large Rician factor, simple correlator used in the proposed system outperformed conventional CDMA systems operating with well-known spreading codes. The proposed scheme achieved antenna diversity and is giving a great hope as a promising candidate for the multipath channel.

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