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Space Time Regularized Zero Forcing in Downlink Code Division Multiple Access Systems with Complementary Codes

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Abstract

Complementary coded code-division multiple access (CC-CDMA) has been originated as one of the extremely robust multiuser access technique in designing high data rate systems with frequency diversity for futuristic wireless communication. The integration of multiple-input multiple-output (MIMO) systems with CC-CDMA offers space diversity gain in addition to the achievable frequency diversity in CC-CDMA systems. However, the performance of conventional chip level space–time receiver in MIMO CC-CDMA is deteriorated due to multiple access interference (MAI) and spatial interference under frequency selective fading channels. A zero-forcing receiver used for minimizing MAI provides unsatisfactory performance in interference limited environments due to amplification of noise and hence the use of regularized zero-forcing (RZF) receiver is proposed and investigated in this study to achieve a space–time interference cancellation (STIC) system. Simulation results are performed to reveal the significance of RZF-STIC in achieving performance gain than conventional equalization schemes, and at the same time enhancing frequency diversity and spatial diversity gain with less complexity at all system loads.

Keywords Regularized zero forcing · Multiple input multiple output · Code division multiple access · Complementary codes

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1 Introduction

The rapid development in internet and mobile communication systems has opened the need for improving the data rate, bandwidth and user capacity during downlink or uplink transmissions. Multicarrier code-division multiple access (MC-CDMA) was proposed in [1, 2], which was broadly investigated as a potential technology for next generation wireless systems. MC-CDMA allows wireless channel to be accessed by multiple users simultaneously by spreading each user's data signal in frequency domain. MC-CDMA combines the advantages of orthogonal frequency division multiplexing namely its robustness against multipath interference (MPI) and frequency diversity obtained using CDMA.

The error rate performance of MC-CDMA using Walsh codes deteriorates in frequency selective fading channels. The search for innovative spreading codes offering resistance towards MPI and MAI was done in [3]. CDMA systems using complementary codes (CC) was proposed in [4] and was studied for different fading environments in [5, 6]. CC-CDMA outperformed traditional CDMA systems in obtaining performance gain in downlink systems operating under frequency selective channels with severe MAI and MPI [7, 8].

Space–time (ST) coding techniques were introduced to achieve correlation between transmitted signals from several transmit antennas at different time periods and thereby exploiting the advantages of MIMO systems [9]. Alamouti studied ST block codes [10] to offer improved error rate performance using transmit diversity. A transmit diversity scheme based on ST spreading was proposed in [11] for CDMA systems to overcome MAI in MIMO systems. Different types of ST spreading techniques were introduced to achieve enhanced diversity gain in multiuser MIMO systems in [12–14]. Complementary coded ST systems were introduced to combine MIMO systems with CC-CDMA systems [15] to offer performance improvement in frequency selective fading channels. The use of MIMO CC-CDMA systems offering near interference free operation with both diversity and multiplexing capability in flat and frequency selective fading channels was investigated in [16].

CC-CDMA systems operating in frequency selective fading channels are affected by MAI and hence require additional interference cancellation schemes at the receiver to improve the error rate performance. In [17–19], single input single output (SISO) CDMA system was analyzed to show its superior performance with different equalization schemes under Rayleigh and Rician fading channels. In [20] STIC was analyzed at the receiver end in CC-CDMA systems using various equalization schemes under Rayleigh and Rician multipath fading channels. A chip level ST coding scheme was investigated in [21] to enhance the interference resilient feature of MIMO-CDMA using CC under multipath fading channels. STIC based detectors were proposed for spatially multiplexed SISO and MIMO systems for MC-CDMA systems in [22]. It was shown that proposed system was able to effectively decrease bit error rate (BER) providing improvement in diversity gain. However, the use of STIC techniques to improve the BER performance of MIMO CC-CDMA system under frequency selective fading channels has not been investigated in the recent literatures. Hence, in order to evaluate the system performance of MIMO CC-CDMA under frequency selective fading channels, we propose STIC to suppress MAI and improve the diversity gain.

In this paper, we provide a comprehensive study on the various issues related to MIMO CC-CDMA systems under downlink transmissions. The performance of the system is compared with detection techniques such as ZF, MMSE and RZF. The importance of efficient combining technique along with STIC in improving space diversity gain is analyzed for downlink communications. The influence of variation in number of receiver and transmitter antenna on the BER performance of MIMO CC-CDMA is also investigated through simulations. From our analysis and simulation results, it is observed that both MMSE and RZF based STIC constitute a favorable detection technique in providing higher user capacity and robust performance in frequency selective fading channels.

The rest of the paper is ordered as follows. The transmitter and receiver configuration of MIMO CC-CDMA with STIC is outlined in Sect. 2. Section 3 outlines the need for spatial interference suppression and Sect. 4 describes MAI suppression in MIMO CC-CDMA system. The simulation results are shown in Sect. 5 and finally Sect. 6 concludes the paper.

2 System Model

The block diagram of downlink MIMO CC-CDMA for user k is as shown in Fig. 1. At each transmitting antenna, the data symbol of kth user is spread with its corresponding signature sequence $C^{(k)}$, which indicates CCs assigned to user k. The CC assigned to a designated user consists of P element codes $C_p^{(k)}$, where $p \in \{1, 2, \dots, P\}$. A CC matrix assigned to transmit antenna n_T of user k is represented as

$$C_{P\times L_P}^{(k,n_T)} = \begin{bmatrix} C_1^{(k,n_T)} \\ C_2^{(k,n_T)} \\ \vdots \\ C_P^{(k,n_T)} \end{bmatrix} = \begin{bmatrix} C_{11}^{(k,n_T)} & C_{12}^{(k,n_T)} & \cdots & C_{1L_P}^{(k,n_T)} \\ C_{21}^{(k,n_T)} & C_{22}^{(k,n_T)} & \cdots & C_{2L_P}^{(k,n_T)} \\ \vdots & \vdots & & \vdots \\ C_{P1}^{(k,n_T)} & C_{P1}^{(k,n_T)} & \cdots & c_{PL_P}^{(k,n_T)} \end{bmatrix}, \tag{1}$$

where $C_{P\times L_P}^{(k,n_T)}$ represents the pth element code of length L_P assigned to the n_T th transmit antenna of user k. Each element code consists of L_P chips which contains symbols in the interval $\{+1, -1\}$.

In a MIMO CC-CDMA system P copies of same data from the source are spread separately using P element codes and are send by n_T th transmit antenna. The P copies of spread data of user k are transmitted using P different frequency channels and at the receiver, the transmitted symbol streams from different antennas of K users are extracted by correlating the received signal using the desired users CC. The complementary correlation between CC of any two antennas of different users are represented as

$$\rho\left(C_{P\times L_P}^{\left(k,n_{T_1}\right)}, C_{P\times L_P}^{\left(g,n_{T_2}\right)}; \tau\right) = \sum_{p=1}^{P} \sum_{l_p=1}^{L_P-\tau} C_{pl_P}^{\left(k,n_{T_1}\right)} C_{p(l_P+\tau)}^{\left(g,n_{T_2}\right)}, \tag{2}$$

where $k, g \in \{1, 2, \dots, K\}$, $\left(n_{T_1}, n_{T_2}\right) \in \left\{1, 2, \dots, N_T\right\}$ and $\tau \in \left\{0, 1, 2 \dots, L_P - 1\right\}$ represents the relative delay between the correlator at the receiver and the received signal. N_T denotes the total number of transmitting antennas for user k. The ideal correlation properties of any two CCs for shifts of even integer chips between different antennas is denoted as

$$\rho\left(C_{P\times L_P}^{\left(k,n_{T_1}\right)}, C_{P\times L_P}^{\left(g,n_{T_2}\right)}; 2\tau\right) = \begin{cases} PL_p, n_{T_1} = n_{T_2};\ k = g; \tau = 0 \\ 0, \qquad \textit{elsewhere} \end{cases} \tag{3}$$

where $n_{T_1}, n_{T_2} \in \left\{1, 2, \dots N_T\right\}$ and $\tau \in \left\{0, 1, 2 \dots, (L_P/2) - 1\right\}$.

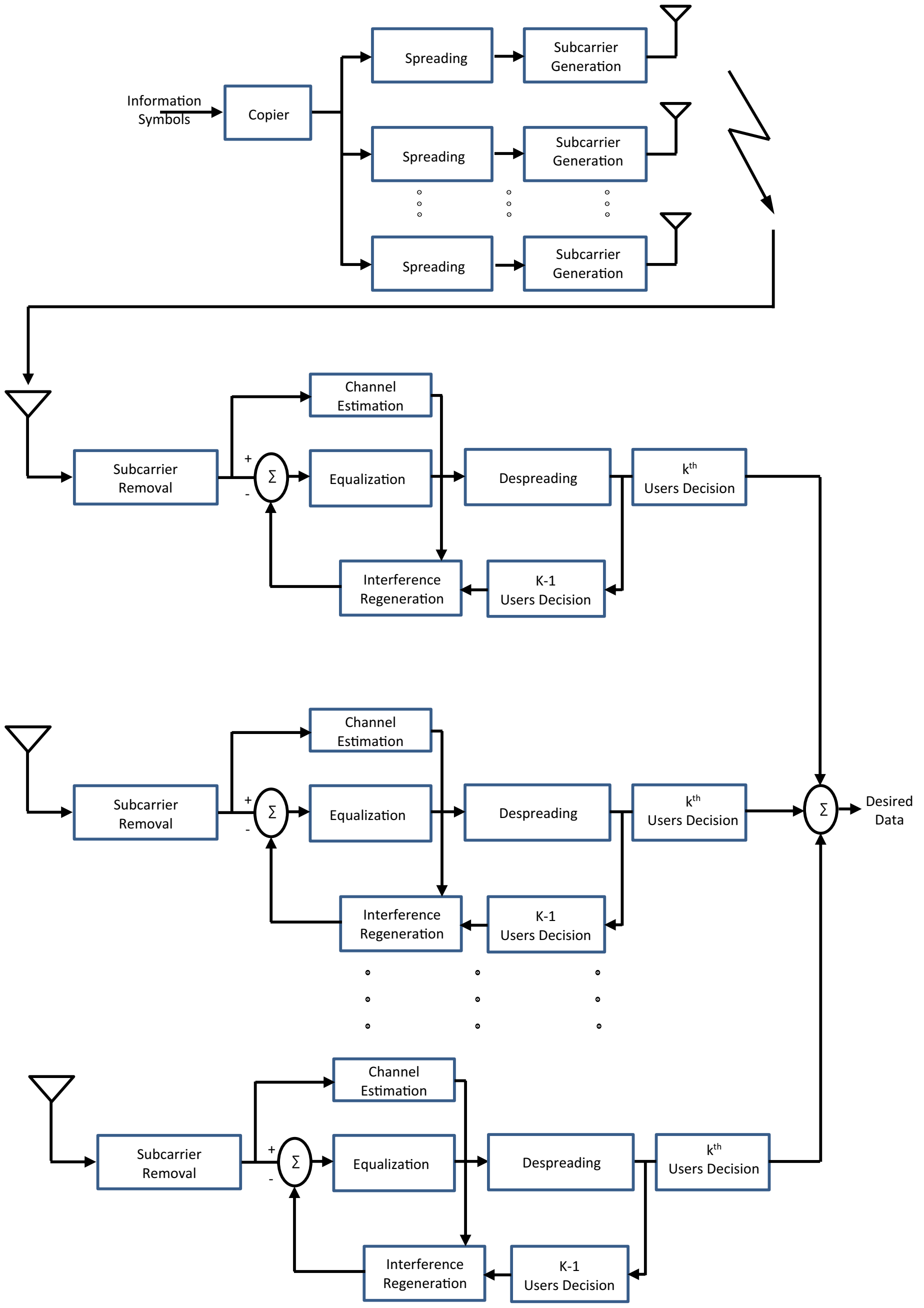

Fig. 1 Block diagram CC-CDMA systems with space time interference cancellation for user *k*

In downlink transmissions, the spread data for each user *k*, on n_T th antenna for *p*th subcarrier is expressed as

$$S_{k,p}^{(n_T)}(t) = \sum_{i=-\infty}^{\infty} \sqrt{P_k} b_k^{(n_T)} c_p^{(k,n_T)}(\mathrm{t}) \exp\left(j2\pi \frac{p}{T_b} t\right) q\left(t - iT_b\right), \tag{4}$$

where P_k is defined as the transmit power of user k denoted as $P_k = \begin{cases} \frac{E_b}{N_T P L_p T_c}, & 0 \le t \le T_b \\ 0 & elsewhere \end{cases}$. Here E_b is the bit energy and T_c represents the chip period. The bit interval $T_b = L_p T_c$. $q(t)$ represents rectangular pulse waveform defined as $q(t) = \begin{cases} \frac{1}{\sqrt{T_b}} & 0 \le t \le T_b \\ 0 & elsewhere \end{cases}$. $c_p^{(k,n_T)}(\mathrm{t})$ represents the CC assigned to n_T th transmit antenna of user k denoted as

$$c_p^{(k,n_T)}(\mathrm{t}) = \sum_{m=0}^{L_p} c_{p,m}^{(k,n_T)} w_{T_c}\left(t - mT_c\right), \tag{5}$$

where T_c is the chip period and $w_T(t)$ denotes the rectangular function with unit impulse response within the time period T_b.

The modulated data transmitted through n_T th antenna experiences frequency-selective Rayleigh fading, where the entire bandwidth of the system is assumed greater than the subcarrier bandwidth. Each subcarrier experiences frequency flat fading with bandwidth less than the coherence bandwidth of the channel. It is also presumed that the subcarrier corresponding to each user undergoes slow fading and hence the fading coefficients are assumed to be constant for the entire bit duration. The channel coefficients on each subcarrier undergo independent fading characteristics and hence resulting in subsequent reduction in code orthogonality among subcarriers. The resultant signal received at the n_R th receiving antenna of desired user g can be expressed as

$$r_g^{(n_R)}(t) = \sum_{n_T=1}^{N_T} \sum_{k=1}^{K} \sum_{p=1}^{P} h_{k,p}^{(n_T,n_R)} S_{k,p}^{(n_T)}(t) + n_{n_R}^{(p)}(t), \tag{6}$$

where $h_{k,p}^{(n_T,n_R)}$ denotes the complex channel coefficient from n_T th transmitting to n_R th receiving antenna of kth user. $n_{n_R}^{(p)}(t)$ is the noise term with zero mean and uncorrelated for each subcarrier p with variance $N_0/2$.

3 Spatial Interference Suppression in MIMO CC-CDMA System

The received signal at the n_Rth receiving antenna undergoes subcarrier removal and despread with the CC of desired user g for each transmit antenna. The despreaded data for subcarrier p of gth user for data send from transmit antenna n_{T_1}, where $n_{T_1} \in \left\{1, 2, \ldots N_T\right\}$ is denoted as

$$d_{g,p}^{\left(n_{T_1},n_R\right)} = \int_0^{T_b} r_g^{(n_R)}(t) c_p^{\left(g,n_{T_1}\right)}(\mathrm{t}) \exp\left(-j2\pi \frac{p}{T_b} t\right) dt. \tag{7}$$

Substituting Eq. (6) in Eq. (7), we get

$$d_{g,p}^{\left(n_{T_1},n_R\right)} = \sum_{n_T=1}^{N_T}\sum_{k=1}^{K} h_{k,p}^{\left(n_T,n_R\right)} \int\limits_0^{T_b} S_{k,p}^{\left(n_T\right)}(t)c_p^{\left(g,n_{T_1}\right)}(t)dt + \int\limits_0^{T_b} n_{n_R}^{(p)}(t)c_p^{\left(g,n_{T_1}\right)}(t)dt. \tag{8}$$

Substituting Eq. (4) in Eq. (8), and simplifying we get

$$\begin{aligned} d_{g,p}^{\left(n_{T_1},n_R\right)} = \sqrt{P_g}L_p h_{k,p}^{\left(n_{T_1},n_R\right)} b_g^{\left(n_{T_1}\right)} + \underbrace{\sum_{k\neq g}^{K}\sqrt{P_k}h_{k,p}^{\left(n_{T_1},n_R\right)} b_k^{\left(n_{T_1}\right)} \int\limits_0^{T_b} c_p^{\left(k,n_{T_1}\right)}(t)c_p^{\left(g,n_{T_1}\right)}(t)dt}_{MAI\ 1} \\ \underbrace{\sum_{n_T\neq n_{T_1}}^{N_T}\sum_{k\neq g}^{K}\sqrt{P_k}h_{k,p}^{\left(n_T,n_R\right)} b_k^{\left(n_T\right)} \int\limits_0^{T_b} c_p^{\left(k,n_T\right)} c_p^{\left(g,n_{T_1}\right)}(t)dt}_{MAI\ 2} + \int\limits_0^{T_b} n_{n_R}^{(p)}(t)c_p^{\left(g,n_{T_1}\right)}(t)dt. \end{aligned} \tag{9}$$

It is shown in Eq. (9) that the first term on the right hand side of the above equation corresponds to the transmitted chips from antenna n_{T_1} for the desired user g, where $n_{T_1} \in \left\{1, 2, \dots N_T\right\}$. The MAI arising from other user's data stream on antenna n_{T_1} and from all other transmitting antennas are expressed as MAI 1 and MAI 2 respectively. The fourth term represents the AWGN with mean zero and variance $N_o/2$. The presence of spatial interference and MAI on the data transmitted from multiple antennas reduces the frequency diversity gain offered by CC at the receiver of the desired user g. To suppress the spatial interference, equalization schemes such as ZF, MMSE filtering can be used to rebuild the energy of the signal scattered among different subcarriers.

The spatial interference resulting from the data transmitted from n_{T_1} th antenna can be suppressed by passing the received signal in (9) through a linear equalization filter. The interference suppressed signal for the pth subcarrier can be obtained from the equalization weights $W_p^{\left(n_T,n_R\right)}$ from n_T th transmit to n_R th receive antenna of the corresponding equalizing filter. With ZF equalizer the weights for the desired user g is denoted as

$$W_{g,p}^{\left(n_T,n_R\right)} = \frac{1}{h_{g,p}^{\left(n_T,n_R\right)}}. \tag{10}$$

The symbol estimates at the pth subcarrier of desired user g for the data transmitted from antenna n_{T_1} with ZF equalization can be expressed as

$$y_{g,p}^{\left(n_{T_1}\right)} = d_{g,p}^{\left(n_{T_1},n_R\right)} W_{g,p}^{\left(n_T,n_R\right)} \tag{11}$$

Substituting Eqs. (9) and (10) and using Eq. (2) in (11) we get

$$\begin{aligned} y_{g,p}^{\left(n_{T_1}\right)} &= \sqrt{P_g}L_p b_g^{\left(n_{T_1}\right)} + \sum_{k\neq g}^{K}\sqrt{P_k} b_k^{\left(n_{T_1}\right)} \rho_{k,g}^{\left(n_{T_1}\right)} \\ &+ \sum_{n_T\neq n_{T_1}}^{N_T}\sum_{k\neq g}^{K}\sqrt{P_k}h_{k,p}^{\left(n_T,n_R\right)} h_{k,p}^{\left(n_{T_1},n_R\right)} b_k^{\left(n_T\right)} \rho_{k,g}^{\left(n_T,n_{T_1}\right)} + n_p. \end{aligned} \tag{12}$$

The symbol decision statistics obtained for the data transmitted from antenna n_{T_1} is represented as

$$\begin{aligned} d_{g,p}^{\left(n_{T_1},n_R\right)} &= sgn\left(\sum_{p=1}^{P} y_{g,p}^{\left(n_{T_1}\right)}\right) \\ &= sgn\left(\sum_{p=1}^{P} \sqrt{P_g} L_p b_g^{\left(n_{T_1}\right)} + \sum_{p=1}^{P}\sum_{k\neq g}^{K} \sqrt{P_k} b_k^{\left(n_{T_1}\right)} \rho_{k,g}^{\left(n_{T_1}\right)}\right. \\ &\quad \left. + \sum_{p=1}^{P}\sum_{n_T\neq n_{T_1}}^{N_T}\sum_{k\neq g}^{K} \sqrt{P_k} h_{k,p}^{\left(n_T,n_R\right)} h_{k,p}^{\left(n_{T_1},n_R\right)} b_k^{\left(n_T\right)} \rho_{k,g}^{\left(n_T,n_{T_1}\right)} + \sum_{p=1}^{P} n_p\right). \end{aligned} \tag{13}$$

It is observed that similar to Eq. (9), the spatial interference suppressed signal consists of the estimate of desired user's data, MAI 1, MAI 2 and the noise respectively. Hence, in order to remove MAI 1 and MAI 2 from the estimated signal and to increase the achievable space diversity, suitable interference cancellation should be performed at the receiver.

4 MAI Suppression in MIMO CC-CDMA System

In downlink communications, the receivers at the MS are equipped with multiple receiving antennas and hence to remove MAI 1 and MAI 2 it is required to estimate the interfering users and suppress their effect on the received signal. The commonly used techniques in interference suppression involve calculation of MAI 1 and MAI 2 at the receiver using the knowledge of all interfering users spreading sequence [20]. The MAI estimated for the desired user g from other interfering users k, $k \neq g$, on a given subcarrier p, is obtained by respreading the estimated interfering users. If $z_{k,p}^{n_{T_1}}$ represents the symbol decision statistics obtained for each subcarrier p of kth interfering user, the MAI 1 estimate at n_R th receiver for data transmitted from antenna n_{T_1} is represented as

$$V_{k,p}^{\left(n_{T_1},n_R\right)} = z_{k,p}^{n_{T_1}} c_p^{\left(k,n_{T_1}\right)}. \tag{14}$$

The resultant MAI 1 estimate obtained for each interfering user is eliminated from the received signal at the pth subcarrier to obtain the interference suppressed signal at n_R th receiver antenna characterized by

$$I_{g,p}^{\left(n_{T_1},n_R\right)} = r_g^{\left(n_R\right)}(t) - \sum_{k\neq g}^{K} \sqrt{P_k} h_{k,p}^{\left(n_{T_1},n_R\right)} V_{k,p}^{\left(n_{T_1},n_R\right)}. \tag{15}$$

The interference estimation and cancellation for the data transmitted from other $N_T - 1$ transmit antennas are performed at the n_R th receiver by repeating the steps for interference regeneration stated above to remove MAI 2 from the received signal. The interference suppressed signal for N_T transmit antennas at receiver n_R is given by

$$\begin{aligned} I_{g,p}^{\left(n_{T_2},n_R\right)} &= I_{g,p}^{\left(n_{T_1},n_R\right)} - \sum_{k\neq g}^{K} \sqrt{P_k} h_{k,p}^{\left(n_{T_2},n_R\right)} V_{k,p}^{\left(n_{T_2},n_R\right)} \\ &\vdots \quad \vdots \quad \vdots \\ I_{g,p}^{\left(N_T,n_R\right)} &= I_{g,p}^{\left(N_T-1,n_R\right)} - \sum_{k\neq g}^{K} \sqrt{P_k} h_{k,p}^{\left(N_T-1,n_R\right)} V_{k,p}^{\left(N_T-1,n_R\right)}. \end{aligned} \tag{16}$$

The residual interference suppressed signal in (16) is equalized using suitable equalization weights to obtain a better estimate of the desired user's data. The interference estimation and cancellation derived using ZF solution doesn't take the effect of noise and MAI. This results in increasing noise during detection and ultimately reduces the detection performance. To overcome noise enhancement during interference cancellation, the interference suppression and regeneration at each n_R th receiver antenna can be obtained using MMSE equalization with weights given by

$$W_{k,p,MMSE}^{\left(n_{T_1},n_R\right)} = \frac{\left[h_{g,p}^{\left(n_{T_1},n_R\right)}\right]^*}{\left|h_{g,p}^{\left(n_{T_1},n_R\right)}\right|^2 + \sum_{n_T\neq n_{T_1}}^{N_T} \left|h_{g,p}^{\left(n_{T_1},n_R\right)}\right|^2 + \frac{PN_o}{KE_b}} \tag{17}$$

The MMSE solution in (17) is obtained by considering the effect of noise and MAI [21]. Nevertheless, it can be observed from (17) that MMSE requires the estimation of SNR and the interference term for equalization, which has to be estimated at the MS. This indicates that using MMSE receiver the complexity is more compared to ZF equalizer. Hence, the use of an efficient low complexity equalizer is required to overcome the problems associated with MMSE and ZF equalizer. In order to overcome the complexity problem, RZF based equalization can be a better solution to suppress the interference at the receiver in detecting the desired user's information. RZF equalization uses a regularization parameter instead of using the SNR and interference term as in MMSE scheme. The weighting coefficients for RZF scheme can be represented as

$$W_{k,p,RZF}^{\left(n_{T_1},n_R\right)} = \frac{\left[h_{g,p}^{\left(n_{T_1},n_R\right)}\right]^*}{\left|h_{g,p}^{\left(n_{T_1},n_R\right)}\right|^2 + \sum_{n_T\neq n_{T_1}}^{N_T} \left|h_{g,p}^{\left(n_{T_1},n_R\right)}\right|^2 + \alpha}, \tag{18}$$

where α is the regularization parameter. The main aim of using α in equalization is the need to avoid the problem of noise amplification in ZF and thus providing enhanced performance with lower complexity than the MMSE scheme in (17). The optimum value of α is chosen through simulations by varying the regularization parameter to increase the performance of the system.

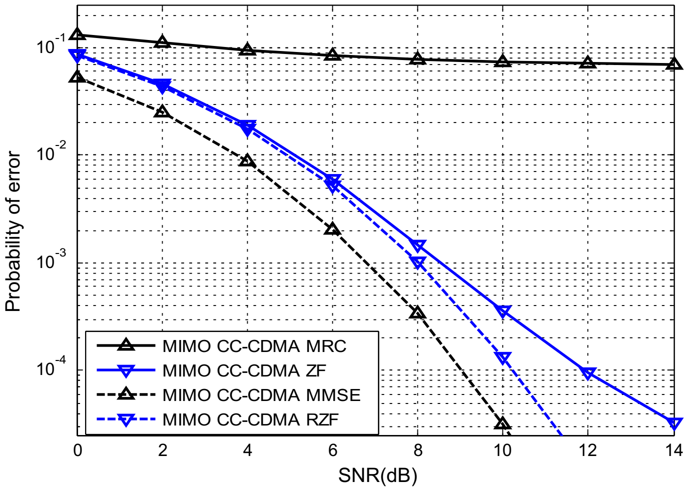

Fig. 2 Simulated BER performance of MIMO for different equalization schemes in CC-CDMA systems

The interference cancelled signal $I_{g,p}^{(N_T,n_R)}$ at n_R th receiving antenna can be equalized using Eqs. (17) or (18) and despread to yield an equalized signal for the desired user g as

$$\begin{aligned} d_g^{(n_R)} &= W_{g,p,RZF}^{\left(n_{T_1},n_R\right)} \int_0^{T_b} I_{g,p}^{\left(n_{T_1},n_R\right)} c_p^{\left(g,n_{T_1}\right)} dt \\ &= \sum_{p=1}^{P} \frac{L_p\sqrt{P_g}\left|h_{g,p}^{\left(n_{T_1},n_R\right)}\right|^2 b_g^{\left(n_{T_1}\right)}}{\left|h_{g,p}^{\left(n_{T_1},n_R\right)}\right|^2 + \sum_{n_T\neq n_{T_1}}^{N_T}\left|h_{g,p}^{\left(n_{T_1},n_R\right)}\right|^2 + \alpha} + \sum_{p=1}^{P}\sum_{k\neq g}^{K}\sqrt{P_k}\left(b_k^{\left(n_{T_1}\right)} - z_{k,p}^{\left(n_{T_1}\right)}\right)\rho_{k,g}^{\left(n_{T_1}\right)} \\ &\quad + \sum_{p=1}^{P}\sum_{n_T\neq n_{T_1}}^{N_T}\sum_{k\neq g}^{K}\sqrt{P_k}\left(b_k^{(n_T)} - z_{k,p}^{\left(n_{T_1}\right)}\right)\rho_{k,g}^{\left(n_T,n_{T_1}\right)} + \sum_{p=1}^{P} n_p, \end{aligned} \tag{19}$$

where n_p represents the noise term with RZF-STIC. Observing Eq. (19) it should be noted that, eventhough RZF-STIC plays an important role in improving performance gain a residual MAI exists during STIC. However, combining the interference cancelled data from N_R receiving antennas; a spatial diversity gain of order N_TN_R is achieved for the desired user g in addition to the P-fold subcarrier gain in CC-CDMA systems under frequency selective fading channels.

5 Simulation Results and Discussions

In this section, we perform numerous analysis for BER performance of the proposed RZF based STIC Systems in MIMO CC-CDMA, when conveying information under frequency selective Rayleigh fading channels. In our simulations, we choose the CC with element

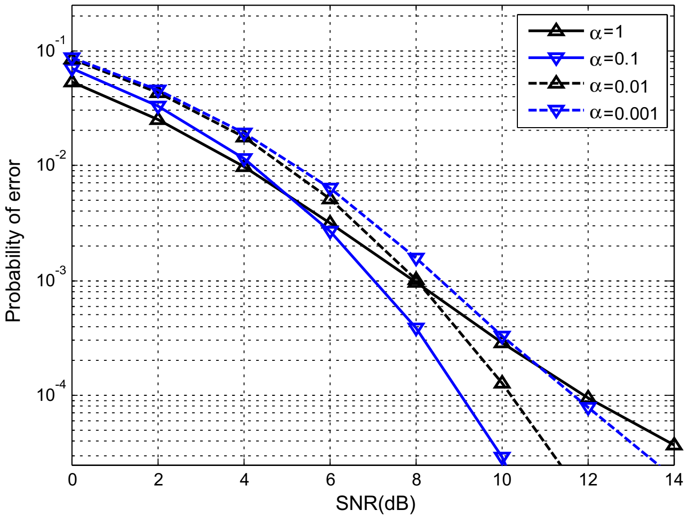

Fig. 3 Simulated BER performance of MIMO for different values of regularization parameter in CC-CDMA systems

code length $L_c = 1$ and block size 16 with processing gain (PG) 16. Hence the maximum number of users supported is considered as $K = 16$. We consider the number of subcarriers as 16 and the total transmit power is assumed same regardless of number of subcarriers in the system. Unless stated the number of transmitting and receiving antennas is assumed to be 2 in simulations.

In Fig. 2, the BER performance studies of different equalization schemes in MIMO CC-CDMA system in attaining improved performance than conventional maximal ratio combining (MRC) is performed without STIC. It can be noted that, in conventional MRC the error floor occurs under full load condition whereas ZF achieves improved performance due to compensation of channel coefficients at the receiver due to its inverse channel characteristics. MMSE achieves enhanced BER performance than other schemes at the cost of noise power and number of users accessing the system. The results illustrate that without any knowledge of noise power and users, RZF is capable of obtaining performance improvement compared to other equalization schemes. The value of regularization parameter used in simulation is $\alpha = 0.01$. It should be understood that a better choice of α further improves the BER performance of RZF. Figure 3 shows the variation in BER performance of MIMO CC-CDMA system with α for RZF. The main focus in this figure is to obtain the optimum value of α in providing additional diversity gain for RZF based system. It can be seen from the plot that he optimum value of α is 0.01, where RZF achieves a better BER performance than other values of α. Further, it can be seen that for $\alpha = 0.1$, MIMO CC-CDMA offers 3 dB gain at BER of 10^{-4} compared to $\alpha = 1$. Hence for remaining part of analysis we choose $\alpha = 0.1$.

The proposed MMSE and RZF based STIC is compared with non-interference cancellation schemes in Fig. 4. It is worth noting that the proposed RZF based STIC is capable of achieving improved performance compared to MMSE and RZF and close to MMSE-STIC at higher values of SNR under frequency selective fading channels. RZF-STIC achieves substantial performance gain compared to MMSE and RZF equalization techniques. This improvement is obtained without the knowledge of noise and number

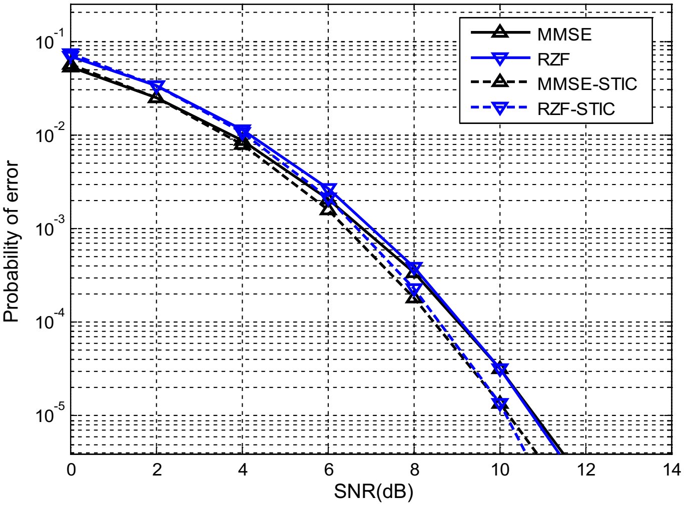

Fig. 4 Simulated BER performance of MIMO with space time interference cancellation in CC-CDMA systems

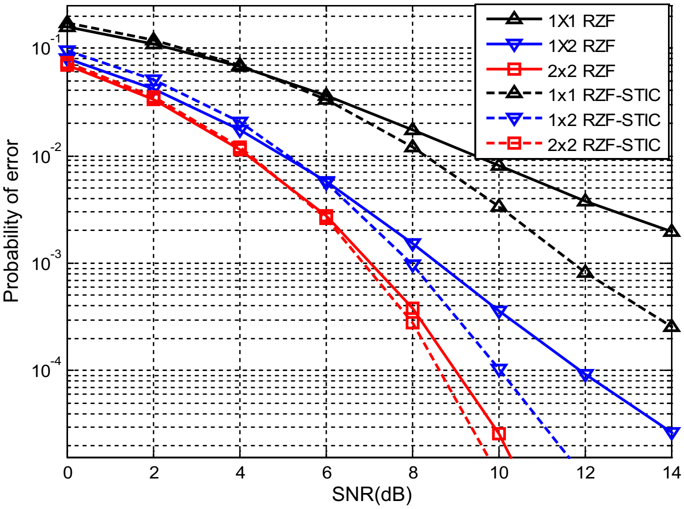

Fig. 5 BER performance comparison of SISO, SIMO and MIMO with different space time interference cancellation in CC-CDMA systems

of users as required in MMSE-STIC based systems, displaying the importance of RZF-STIC in MIMO CC-CDMA systems over other STIC techniques. In Fig. 5, we compare the performance of SISO (1 × 1), SIMO (1 × 2), and MIMO (2 × 2) systems for RZF equalization and RZF-STIC under synchronous MIMO environment. It can be observed that MIMO CC-CDMA system with STIC are effective in overcoming MAI and attaining remarkable gain compared to SISO and SIMO systems. With MIMO STIC-RZF

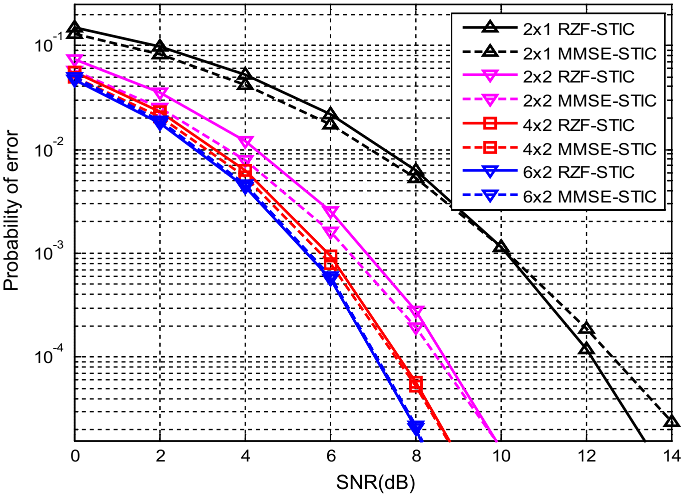

Fig. 6 BER performance comparison of STIC MIMO with variation in transmitting antennas in CC-CDMA systems

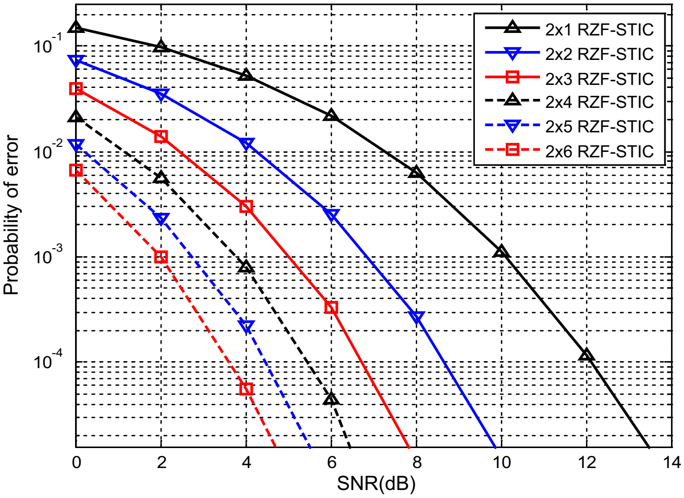

Fig. 7 BER performance comparison of STIC MIMO with variation in receiving antennas in CC-CDMA systems

equalization, the SNR gain at BER of 10^{-4} is around 6 dB, whereas the SIMO system provides a gain of 4 dB compared to SISO system.

In Fig. 6, we compare the performance of RZF-STIC and MMSE-STIC with variation in transmitting antennas. It can be noticed that MMSE-STIC has improved performance over RZF-STIC at lower SNR values, and at higher SNR values shows similar performance as RZF-STIC for cases (2 × 1), (2 × 2) and (4 × 2). However, it can be observed that with further increase in transmitting antennas the performance is same for both RZF-STIC and MMSE-STIC for all values of SNR. There exists an exact agreement between RZF-STIC and MMSE-STIC for SNR of 8 dB showing the supremacy of RZF-STIC in mitigating the effects of MAI under frequency selective fading channels without the knowledge of noise power and number of users.

In Fig. 7, the BER performance comparison of MIMO systems with variation in receiving antennas is analyzed. Here, it can be observed that as the number of receiving antennas increases the performance gain obtained increases two fold compared to the case in Fig. 6. For SNR of 6 dB and BER of 7×10^{-4}, RZF-STIC with 4 receiving antennas provides a SNR gain of 2 dB compared to the case of 4 transmitting antennas (Fig. 6). However, a 4 dB SNR gain is achieved with 6 receiving antennas compared to 6 transmitting antennas for RZF-STIC. This validates the superiority of RZF-STIC in MIMO CC-CDMA system over single receiver antenna system in suppressing MAI in downlink frequency selective fading channels and enhancing the spatial diversity gain with less computational complexity.

6 Conclusions

This paper addresses STIC in obtaining MAI free downlink MIMO CC-CDMA systems using various equalization techniques. STIC is proposed to eliminate space–time interference existing between CCs used to spread the user data among multiple antennas. The effect of RZF and number of multiple transmitting and receiving antennas in suppressing space–time interference and increasing the diversity gain was also discussed in this study. The comparison between different receivers revealed that RZF-STIC is capable of proving better performance than other conventional schemes. It was shown that the proposed RZF-STIC scheme is capable of avoiding noise amplification and the need for estimation of SNR compared to MMSE-STIC. It has also been demonstrated that the combination of regularization parameter with STIC acts as a suitable choice in MIMO CC-CDMA systems in suppressing MAI over frequency selective fading channels.

References

1. Yee, N., Linnartz, J. P., & Fettweis, G. (1993). Multicarrier CDMA in indoor wireless networks. *Proceedings of the IEEE PIMRC, 9,* 109–113.
2. Hara, S., & Prasad, R. (1999). Overview of multicarrier CDMA. *IEEE Communication Magazine, 35,* 126–133.
3. Chen, H. H., Chu, S. W., & Guzani, M. (2008). On the next generation CDMA technologies: The REAL approach for perfect orthogonal code generation. *IEEE Transactions on Vehicular Technology, 57,* 2822–2833.
4. Chen, H. H., Hank, D., Maganaz, M., & Guizani, M. (2007). Design of next generation CDMA using orthogonal complementary codes and ofset stacked spreading. *IEEE Wireless Communicaitons, 14,* 61–69.
5. Magaa, M. E., Rajatasereekul, T., Hank, D., & Chen, H. H. (2007). Design of MC-CDMA systems that uses complete complementary orthogonal spreading codes. *IEEE Transactions on Vehicular Technology, 56,* 2976–2989.
6. Li, J., Huang, A., Hank, D., Guizani, M., & Chen, H. H. (2008). Intergroup Complementary codes for interference-resistant CDMA wireless Communications. *IEEE Transactions on Wireless Comunications, 7,* 166–174.

7. Judson, D., & Albert Raj, A. (2016). Performance of multicarrier complementary-coded CDMA under frequency-selective Nakagami-m fading channels. *EURASIP Journal on Wireless Communications and Networking, 67,* 1–9.
8. Liu, X., Syu, H. M., Chen, H. H., Meng, W., & Wei, M. (2018). Complementary coded scrambling multiple access and its performance in downlink MIMO channels. *IEEE Transactions on Wireless Communications, 17,* 835–847.
9. Vucctic, B., & Yuan, J. (2003). *Space-time coding* (1st ed.). Hoboken, NJ: Wiley.
10. Alamouti, S. (1998). A simple transmit diversity technique for wireless communication. *IEEE Journal Selected Areas on Communications, 16,* 141–1458.
11. Hochwald, B., Marzetta, T., & Papadias, C. (2001). A transmitter diversity scheme for wideband CDMA system based on space-time spreading. *IEEE Journal Selected Areas on Communications, 19,* 48–60.
12. Petre, F., Leus, G., Deneire, L., Engels, M., Moonen, M., & Man, H. D. (2003). Space time block coding for single-carrier block transmission DS-CDMA downlink. *IEEE Journal Selected Areas on Communications, 21,* 350–361.
13. Shi, M., D'Amours, C., & Yongacoglu, A. (2010). Design of spreading permutations for MIMO-CDMA based on space-time block codes. *IEEE Communication Letters, 14,* 36–38.
14. Phasouliotis, A., & So, D. (2011). Layered space-time receiver for downlink multiple input multiple output multi-cattier code division multiple access systems. *IET Communications, 21,* 1907–1917.
15. Chen, H. H., Yeh, Y. C., Bi, Q., & Jamalipor, A. (2007). On the MIMO based open wireless architecture: Space time complementary coding. *IEEE Communication Magazine, 45,* 104–112.
16. Chen, H. H., Yeh, M., Guizani, Y., & Huang, Y. M. (2008). Space-time complementary coding MIMO with joint spatial diversity and multiplex capability. *IEEE Transactions Wireless Communications, 7,* 2950–2956.
17. Judson, D., & Bhaskar, V. (2018). Interference cancellation in CDMA systems employing complementary codes under Rician fading channels. *Wireless personal Communication, 101,* 897–914.
18. Meng, W. H., Sun, S. Y., & Chen, H. H. (2013). Multiuser interference cancellation in complementary coded CDMA with diversity gain. *IEEE Wireless Communication Letters, 2,* 303–306.
19. Davix, X. A., & Judson, D. (2019). Successive interference cancellation in asynchronous CC-CDMA systems under Rician fading channels. *Telecommunication Systems*. https://doi.org/10.1007/s11235-019-00562-y.
20. Judson, D., & Bhaskar, V. (2018). Error rate analysis of SIMO-CDMA with complementary codes under multipath fading channels. *Wireless Personal Communication, 98,* 1663–1677.
21. Han, S., Venkatesan, R., Chen, H. H., Meng, W., Li, C., & Yang, P. Y. (2014). A complete complementary coded MIMO system and its performance in multipath channels. *IEEE Wireless Communications Letters, 3,* 181–184.
22. Al-Fuhaidi, B. A., Hassan, H. E. A., & Salah, M. M. (2014). Interference cancellation with space diversity for downlink MC-CDMA system. *Wireless Personal Communication, 74,* 439–456.

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