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Cooperative communication-aided multi-carrier code division multiple access downlink transmission with transmitter preprocessing: performance results

Prabagarane Nagaradjane[1], *Sriram Ravichandran*[2], *Nithin Srinivasan*[3], *Shruthi Ravichandran*[4], *Selvam Paranche Damodaran*[5]

[1]*Department of ECE, SSN Institutions, Chennai, India*
[2]*National Instruments, Bangalore, India*
[3]*Department of ECE,University of Southern California, CA, USA*
[4]*Department of ECE, Georgia Institute of Technology, Atlanta, USA*
[5]*Department of Mobile Communications, Telecom ParisTech, Eurecom, France*
E-mail: prabagaranen@ssn.edu.in

Abstract: In this correspondence, the authors study the performance of multi-user transmitter preprocessing (MUTP)-assisted cooperative downlink (DL) transmission for multi-carrier code division multiple access (MC-CDMA) system, where multi-user interference (MUI) and inter-relay interference (IRI) are the principal channel impairments. Relaying is facilitated with the aid of fixed infrastructure-based relays that perform additional signal processing like formulating the preprocessing matrix for mitigating MUI in addition to forwarding the information they receive from the base station (BS). Specifically, in this study, the authors analyse the performance of cooperative communication-aided DL MC-CDMA system by employing three cooperation strategies: (i) all users supported by a single relay with dominant MUI at the relay and mobile stations (MSs); (ii) each user supported by a single relay where, MUI and IRI are dominant at the relays and MSs, respectively, as well as weak IRI at the MSs; and (iii) all users supported by *L* relays where MUI is dominant at the relays, and MUI and IRI are dominant at the MSs. Our simulation study shows that MUTP-aided cooperative DL transmission results in better achievable bit error rate than the multi-user detection-aided system as the MUI at the relays and MUI and IRI at the MSs are perfectly eliminated.

1 Introduction

As content transfer has become increasingly popular, future generation mobile communications are envisaged to reliably purvey ubiquitous high data rate transmissions over large coverage areas. In this context, the Third Generation Partnership project Long-Term Evolution Advanced (3GPP-LTE-Advanced) task group has already started developing a new standard that will meet the coverage as well as throughput requirements of next-generation cellular networks [1–3]. Multiple-input–multiple-output (MIMO) systems can be invoked to meet the demand for higher data rates since on a given frequency–time resource, MIMO linearly increases the channel capacity without calling for any increase in average transmit power or bandwidth as it transmits multiple data streams on multiple spatial layers. Many of the existing and future wireless standards have already started utilising MIMO systems. In wireless communications, it is well known that the signal-to-noise ratio (SNR) at the destination mobile station (DMS) may vary rapidly because of multi-path fading thereby causing intricacies in achieving the promised data rates whenever the SNR drops below a required threshold [1–13]. This undesirable effect can be alleviated by invoking time, frequency or spatial diversity. Spatial diversity is typically realised by employing multiple antennas at the transmitter (transmit diversity) or at the receiver (receive diversity). However, in downlink (DL) communication, employing multiple antennas at the MS to reap the benefits offered by receive diversity is not practically feasible owing to size and energy constraints [4, 8, 9]. As a design choice, relay-aided cooperative communication systems can be exploited to overcome these constraints. Further, there exists a non-linear relationship between the path loss (PL) and propagation distance. This non-linear PL behaviour can be exploited to reduce the overall distance-dependent PL, as splitting the long-propagation path between the base station (BS) and the MSs with the aid of relays results in transmit power gain. This is because the combined PL of several relatively short paths will be less than the PL of the whole path [13].

Of late, cell edge performance of the cellular system is becoming increasingly important. With the aid of cooperative communications, the communication link quality, reliability and coverage can be improved. Coverage and cell edge users' throughput can be enhanced by the use of cooperative communications with fixed relays or user cooperation [1–3]. Also, relays can be deemed as additional transmit antennas that can be used to achieve transmit diversity. That is the reason why relaying and cooperative communications have enamored widespread attention as important research topics both in the academia and industry in the recent past [1–9]. Towards this, the IEEE 802.16j wireless standard working group has created different relaying scenarios. Relays specified in the IEEE 802.16j standard span from simple low-cost relays to complex and expensive relays [1–3]. Moreover, the 3GPP LTE-A also envisages employing relaying stations to meet throughput and coverage requirements [1]. Further, it is worth mentioning that the WINNER project for the most part concentrates on infrastructure-based relay networks [4].

Although cooperative communications emerged as a hot topic recently, its history dates back to the classical work of Meulen [6] and Cover and El-Gamal [7], which forms the foundation for most of the cooperative communication schemes reported in the literature. Primarily two types of relaying strategies namely amplify and forward (AF) and decode and forward (DF) have been widely studied [8]. Other strategies include selection relaying, coded cooperation, compress and forward, demodulate and forward etc. Among the aforementioned cooperation strategies, AF is a simple approach as the relays simply amplify the received signal from the BS and forward it to the MS. A multi-antenna relaying scheme that increases bandwidth efficiency has been reported in [10]. Hussain *et al.* [12] have provided the performance of selective cooperation with fixed gain relays in Nakagami-*m* channels. Beamforming (BF) that achieves both array and diversity gain for non-regenerative relay-aided networks with perfect channel state information (CSI) at the relays has been studied in [14]. Collaborative BF with the knowledge of perfect CSI for a dual-hop wireless relay network that jointly optimises complex relay weights to maximise the destination SNR is reported in [15]. A cooperative BF strategy for AF-based relay networks in frequency-selective channels with the design objective of maximising the SNR is discussed in [16]. In [17], MIMO relaying strategy with linear processing based on Tomlinson-Harashima preprocessing with adaptive modulation in fixed relay networks has been proposed and quantified in terms of achievable sum rate. Relay preprocessing based on minimum-mean-square error is proposed in [18]. Joint design of linear relay preprocessing and destination equaliser for dual-hop AF MIMO relay systems with channel uncertainties have been addressed in [19]. Single user performance of a direct-sequence code-division multiple-access (DS-CDMA) system with the aid of multiple relays has been investigated by Fang *et al.* [11]. Here, the authors have shown that the performance of DS-CDMA system greatly relies on the locations of the relays as well as on power allocation associated with the source MSs and relays.

Relay-aided cooperative communications implemented either via fixed relays with multiple antennas or with the aid of a number of MSs close to the desired MS chosen to act as relays provides relay diversity by circumventing the adverse effects of fading. However, in a multi-user environment, relay diversity can be achieved only if the signals arriving at the relays are free from multi-user interference (MUI) [13]. To quantify this, in [13], a relay assisted DS-CDMA DL transmission scheme using the transmit zero forcing or transmit minimum-mean-square error-based transmitter preprocessing that is independent of the CSI for suppressing the MUI has been proposed and investigated.

Despite the fact that technologies such as MIMO, orthogonal frequency division multiplexing, and sophisticated forward error correction codes augment the per-link throughput, they do not intrinsically mitigate the adverse effects of interference. Typically, in a relay-aided multi-carrier code division multiple access (MC-CDMA) DL transmission supporting multiple users, multi-user DL signals may interfere with each other contributing to MUI at the relays. As alluded to earlier, if this MUI is not suppressed, relay diversity may not be achieved. Hence, in this correspondence, we study the performance of fixed infrastructure-based relay-aided cooperative DL transmission for MC-CDMA system with the aid of multi-user transmitter preprocessing (MUTP) at the BS and relays to mitigate MUI and inter-relay interference (IRI) at the relays and MSs, respectively.

The key contributions of this correspondence are given in the list that follows:

1. The achievable bit error rate (BER) performance is presented when all the users are supported by a single relay for the case of dominant MUI at relay and MSs.
2. The attainable BER is demonstrated when each user is supported by one relay when MUI is dominant at the relays as well as IRI is dominant and weak at the MSs and,
3. The BER performance of the considered system is presented when all the users are supported by L relays with dominant MUI at the relays in addition to dominant MUI and IRI at the MSs.

The rest of the paper is structured as follows. Section 2 describes the system model. Section 3 discusses signal transmission from the relays and detection at the MS. Section 4 addresses the MUTP considered for our analysis. Section 5 elucidates the performance results, and in Section 6, conclusions are drawn.

Notations: Throughout the correspondence we follow the following notations: Bold uppercase letters, for instance, '$\boldsymbol{W}$' denote matrices, bold lower case letters like '$\boldsymbol{w}$' denote vectors and normal letters such as a denote scalars. The notation $\boldsymbol{W}^H$ denotes the Hermitian transpose of the matrix $\boldsymbol{W}$. $(.)^T$ denotes transpose of the argument, $\|.\|^2$ is the Euclidean norm of the argument and $E[.]$ gives the expectation of the argument. $[.]^+$ denotes the pseudo-inverse of the argument.

2 System model description

2.1 Transmitted signal representation and assumptions

Let us assume that the considered single-cell MC-CDMA system supports K DL users as shown in Fig. 1. Here, each of the K DL users' is supported by a single relay with one antenna. Hence, $K = L$ in this context (in dealing with the B channel, we first address system description for cooperation strategy 2 as other strategies can be easily derived from this strategy). The MSs and the BS are also assumed to be equipped with one antenna. In this treatise, we assume that the relays are capable of carrying out additional signal processing, that is, preprocessing on the signals received from the BS in addition to detection and forwarding. The channels B connecting the source BS to the relays are assumed to undergo Rayleigh fading, whereas the R

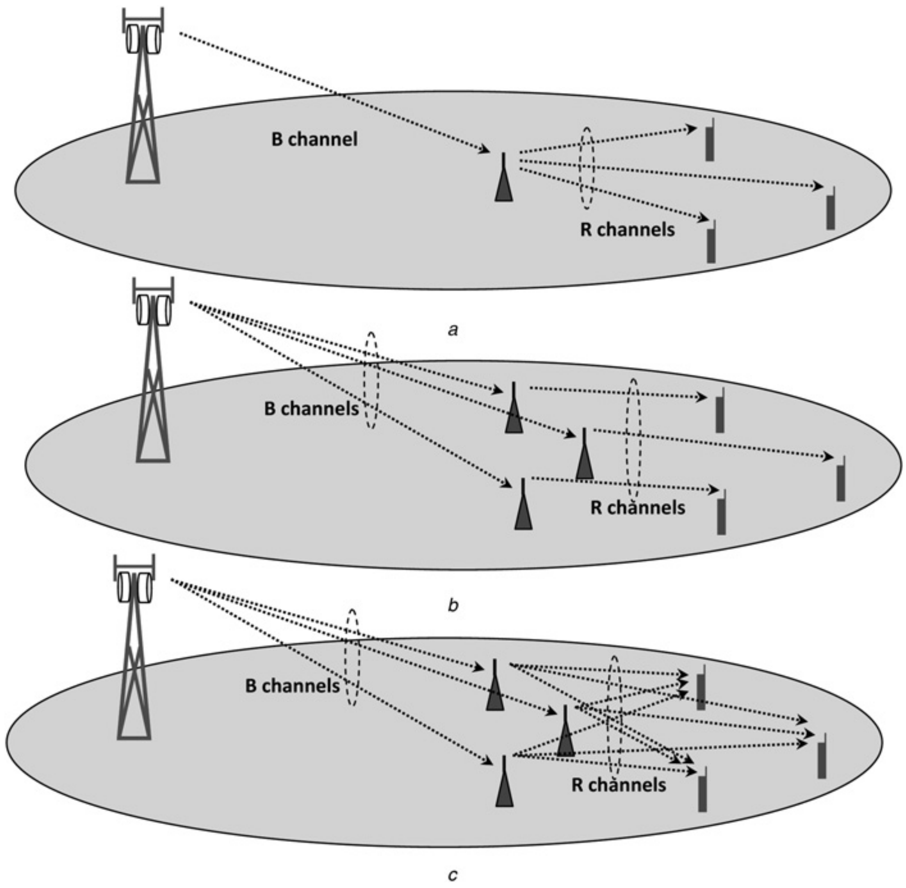

Fig. 1 *Illustration of various cooperation strategies*

a Cooperation strategy 1
b Cooperation strategy 2 case1
c Cooperation strategy 2 case 2 as well as cooperation strategy 3 (cases 1 and 2). The key difference is that in cooperation strategy 3 the relays forward multi-user signals to all the K MSs

channels connecting the relays to the MSs experience Nakagami-m fading. Although each of the MSs is supported by a single relay, as multi-user signals arrive at each of the relays from the BS, MUI at the relays will be dominant. Also, we assume that the distances between the source BS and the MSs are large enough that the contribution of the direct link to the received signal at the MSs is negligible. Let N_c denote the spreading length. It is assumed that $N_c \geq K$. Then, assuming binary phase shift keying (BPSK) modulation, the transmitted bit stream containing b bits denoted by

$$\boldsymbol{d}_k = \left[d_{k1}, d_{k2}, \ldots, d_{kb}\right]^T, \quad k = 1, 2, ..., K \tag{1}$$

will be transmitted to the kth user by the BS. Let

$$\boldsymbol{c}_k = \frac{1}{\sqrt{N_c}}\left[c_{k0}, c_{k1}, \ldots, c_{k(N_c-1)}\right]^T, \quad k = 1, 2, ..., K \tag{2}$$

represent the frequency domain spreading code assigned to the kth user. Further, the $(N_c b \times b)$ frequency domain (F-domain) spread matrix for the kth user is given by

$$\boldsymbol{C}_k = \text{diag}\left\{\boldsymbol{c}_k, \boldsymbol{c}_k, \boldsymbol{c}_k, \ldots, \boldsymbol{c}_k\right\} = \boldsymbol{I}_b \otimes \boldsymbol{c}_k, \quad k = 1, 2, ..., K \tag{3}$$

This $\boldsymbol{C}_k$ is invoked to effect the F-domain spreading of the kth user bit stream, which can be expressed as

$$\boldsymbol{x}_k = \boldsymbol{C}_k \boldsymbol{d}_k, \quad k = 1, 2, \ldots, K \tag{4}$$

In the context of K DL users the F-domain spread signal can be expressed as

$$\sum_{k=1}^{K} \boldsymbol{x}_k = \boldsymbol{x} \tag{5}$$

After transmitter preprocessing, multi-carrier modulation is carried out and the transmitted MC-CDMA signal over $N_c b$ subcarriers can be expressed as

$$\begin{aligned} \boldsymbol{s} &= \boldsymbol{FPx} \\ &= \boldsymbol{FPCd} \end{aligned} \tag{6}$$

where $\boldsymbol{P}$ and $\boldsymbol{s}$ correspond to the $(N_c b \times N_c b)$ preprocessing matrix and $N_c b$ length transmitted vector, respectively. In this context, $\boldsymbol{s}$ can be expressed as

$$\boldsymbol{s} = \left[s_1, s_2, \ldots, s_{N_c b}\right]^T \tag{7}$$

Further, in (6) $\boldsymbol{C} = [\boldsymbol{C}_1, \boldsymbol{C}_2, \ldots, \boldsymbol{C}_K]$ and $\boldsymbol{d} = \left[\boldsymbol{d}_1^T, \boldsymbol{d}_2^T, \ldots, \boldsymbol{d}_K^T\right]^T$. Furthermore, the $(N_c b \times N_c b)$ multi-carrier modulation matrix, $\boldsymbol{F}$, considered to carry out multi-carrier modulation is given by

$$\boldsymbol{F} = \operatorname{diag}\{\exp(j2\pi f_1 t),\ \exp(j2\pi f_2 t),\ \ldots,\ \exp(j2\pi f_{N_c b} t)\} \tag{8}$$

In CDMA-based systems, spreading and preprocessing can be implemented jointly [20]. Hence, (6) can be expressed as $\boldsymbol{s} = \boldsymbol{F}\bar{\boldsymbol{P}}\boldsymbol{d}$. Here, $\bar{\boldsymbol{P}}$ is a $(N_c b \times Kb)$ matrix that jointly implements preprocessing and spreading, that is, $\bar{\boldsymbol{P}} = \boldsymbol{PC}$.

2.2 Received signal representation at the relays

Assuming that each of the subcarriers experiences flat fading, the CSI vector connecting the BS and the lth relay supporting the kth user is given by

$$\boldsymbol{h}_k^l = \left[h_1^l, h_2^l, \ldots, h_{N_c b}^l\right] \qquad k = 1, 2, \ldots, K; \quad l = 1, 2, \ldots, L \tag{9}$$

In a frequency-selective channel, h_u^l can be modelled as [21]

$$h_u^l(t) = \sum_{\ell=1}^{\mathcal{L}} h_u^\ell \delta(t - \tau_\ell) \tag{10}$$

where $u = 1, 2, \ldots, N_c b$ and $\mathcal{L}$ denotes the number of paths. Then, the received signal at the lth relay corresponding to the kth user can be expressed as

$$y_l^k = \boldsymbol{h}_k^l \boldsymbol{s} + n \tag{11}$$

where n represents zero mean complex Gaussian noise. Here, we assume that the subcarriers are designed to be perfectly orthogonal to each other. Hence

$$f = \frac{1}{T_s}\int_0^{T_s} \exp(j2\pi f_u t)\exp(-j2\pi f_v t)\, dt = \begin{cases} 1, & \text{if } u = v \\ 0, & \text{if } u \neq v \end{cases} \tag{12}$$

Now, y_{lu}^k can be expressed as

$$y_{lu}^k = \frac{1}{T_s}\int_0^{T_s} y_l^k \exp(-j2\pi f_u t)\, dt \qquad \text{where} \quad u = 1, 2, \ldots, N_c b \tag{13}$$

By substituting y_l^k from (11) in (13), we have

$$y_{lu}^k = \tilde{\boldsymbol{h}}_u^l \bar{\boldsymbol{P}}\boldsymbol{d} + n_u, \quad k = 1, 2, \ldots, K; \ l = 1, 2, \ldots, L \tag{14}$$

where $\tilde{\boldsymbol{h}}_u^l$, $u = 1, 2, \ldots, N_c b$ is formulated by making all the elements of (9) zero, excluding h_u^l. Now, after multi-carrier demodulation, the observation vector at the lth relay can be expressed as

$$\boldsymbol{y}_l^k = \left[y_{l1}^k, y_{l2}^k, \ldots, y_{lN_c b}^k\right]^T, \qquad k = 1, 2, \ldots, K; \quad l = 1, 2, \ldots, L \tag{15}$$

Now, let us define

$$\boldsymbol{H}_l^k = \operatorname{diag}\left\{h_1^l, h_2^l, \ldots, h_{N_c b}^l\right\} \text{ and } \qquad \bar{\boldsymbol{n}}_l^k = \left[n_{l1}^k, n_{l2}^k, \ldots, n_{lN_c b}^k\right]^T \tag{16}$$

Hence, the observation vector at the lth relay in the context of kth user can also be expressed as

$$\boldsymbol{y}_l^k = \boldsymbol{H}_l^k \bar{\boldsymbol{P}}\boldsymbol{d} + \bar{\boldsymbol{n}}_l^k, \qquad k = 1, 2, \ldots, K; \ l = 1, 2, \ldots, L \tag{17}$$

Here, $\bar{\boldsymbol{n}}_l^k$ is the zero mean complex Gaussian vector with covariance matrix $E\left[\bar{\boldsymbol{n}}_l^k \bar{\boldsymbol{n}}_l^{kH}\right] = 2\sigma^2 \boldsymbol{I}_{N_c b}$.

The decision variable by invoking (17), for the kth user at the corresponding relay can be expressed as

$$\boldsymbol{r}_k = \boldsymbol{C}_k^T \boldsymbol{y}_l^k, \quad k = 1, 2, \ldots, K; \ l = 1, 2, \ldots, L \qquad = \boldsymbol{C}_k^T \boldsymbol{H}_l^k \bar{\boldsymbol{P}}\boldsymbol{d} + \tilde{\boldsymbol{n}}_k \tag{18}$$

where $\tilde{\boldsymbol{n}}_k = \boldsymbol{C}_k^T \bar{\boldsymbol{n}}_l^k$ denotes the zero mean complex Gaussian vector with covariance matrix $E\left[\tilde{\boldsymbol{n}}_k \tilde{\boldsymbol{n}}_k^H\right] = 2\sigma^2 \boldsymbol{I}_b$. In order to carry out MUTP, the decision variables of all the K users are grouped into a single Kb length vector $\boldsymbol{r}$ given by

$$\boldsymbol{r} = \left[\boldsymbol{r}_1^T, \boldsymbol{r}_2^T, \ldots, \boldsymbol{r}_K^T\right]^T \tag{19}$$

Hence, in the context of K users, the decision variable can also be expressed as

$$\boldsymbol{r} = \bar{\boldsymbol{C}}^T \boldsymbol{H}\bar{\boldsymbol{P}}\boldsymbol{d} + \ddot{\boldsymbol{n}} \tag{20}$$

where $\boldsymbol{d} = \left[\boldsymbol{d}_1^T, \boldsymbol{d}_2^T, \ldots, \boldsymbol{d}_K^T\right]^T$ denotes a $(Kb \times 1)$ symbol vector of all the K users, $\bar{\boldsymbol{C}} = \operatorname{diag}\{\boldsymbol{C}_1, \boldsymbol{C}_2, \ldots, \boldsymbol{C}_K\}$ is a $(KN_c b \times Kb)$ spread matrix, $\boldsymbol{H} = [(\boldsymbol{H}_1^1)^T, (\boldsymbol{H}_2^2)^T, \ldots, (\boldsymbol{H}_L^K)^T]^T$ is a $(KN_c b \times N_c b)$ component small scale fading matrix, $\bar{\boldsymbol{P}}$ is an $(N_c b \times Kb)$ component preprocessing matrix that includes the power normalisation coefficients and $\ddot{\boldsymbol{n}} = \left[\tilde{\boldsymbol{n}}_1^T, \tilde{\boldsymbol{n}}_2^T, \ldots, \tilde{\boldsymbol{n}}_K^T\right]^T$ is the zero mean complex Gaussian noise vector with covariance matrix $E\left[\ddot{\boldsymbol{n}}\ddot{\boldsymbol{n}}^H\right] = 2\sigma^2 \boldsymbol{I}_{Kb}$.

3 Signal transmission from the relays and detection at the mobile station

3.1 Cooperation strategy 1

In this cooperation strategy, as alluded to earlier, one relay supports all the K users' arbitrarily distributed in a single-cell DL system. Fig. 1*a* illustrates this strategy. As the DL preprocessing matrix completely eliminates the DL-MUI at the relay, the $(Kb \times 1)$ estimated vector $\hat{\boldsymbol{d}}$ of all the K DL users' at the relay after despreading can be conveniently expressed as

$$\hat{\boldsymbol{d}} = [\hat{\boldsymbol{d}}_1^T, \hat{\boldsymbol{d}}_2^T, \ldots, \hat{\boldsymbol{d}}_K^T]^T \tag{21}$$

The estimates of (21) are respread in order to formulate the transmit vector for the K DL users. Hence, in this context the F-domain spread signal can be readily

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expressed as

$$\sum_{k=1}^{K} \boldsymbol{C}_k \hat{\boldsymbol{d}}_k = \bar{\boldsymbol{x}} \tag{22}$$

After transmitter preprocessing, multi-carrier modulation is carried out and the transmitted MC-CDMA signal over $N_c b$ subcarriers can be expressed as

$$\begin{aligned} \bar{s} &= \bar{\boldsymbol{F}}\boldsymbol{P}\boldsymbol{C}\hat{\boldsymbol{d}} \\ &= \bar{\boldsymbol{F}}\bar{\boldsymbol{P}}\hat{\boldsymbol{d}} \end{aligned} \tag{23}$$

where $\bar{\boldsymbol{P}}$ and $\bar{s}$ correspond to the $(N_c b \times Kb)$ preprocessing matrix and the $N_c b$ length transmitted symbol vector, respectively. Assuming that the subcarriers experience independent fading, the received signal at the kth MS can be expressed as

$$\bar{y}_k = \boldsymbol{h}_k \bar{s} + \bar{n}_k, \quad k = 1, 2, \ldots, K \tag{24}$$

where $\boldsymbol{h}_k = [h_1, h_2, \ldots, h_{N_c b}]$ represents the channel vector connecting the relay and the kth MS and $\bar{n}_k$ denotes zero mean complex Gaussian noise. When the subcarriers are assumed to be perfectly orthogonal, the received signal $\bar{y}_{ku}$ after multi-carrier demodulation can be expressed as

$$\bar{y}_{ku} = \tilde{\boldsymbol{h}}_{ku}\bar{\boldsymbol{P}}\hat{\boldsymbol{d}} + \bar{n}_{ku} \tag{25}$$

where $\tilde{\boldsymbol{h}}_{ku}$, $u = 1, 2, \ldots, N_c b$ is devised by making all the elements of $\boldsymbol{h}_k$ zero, except h_u. Hence, after multi-carrier demodulation, the observation vector of the kth user can be expressed as

$$\bar{\boldsymbol{y}}_k = \left[\bar{y}_{k1}, \bar{y}_{k2}, \ldots, \bar{y}_{kN_c b}\right]^T, \quad k = 1, 2, \ldots, K \tag{26}$$

Defining $\bar{\boldsymbol{H}}_k = \mathrm{diag}\{h_{k1}, h_{k2}, \ldots, h_{kN_c b}\}$ and $\bar{\boldsymbol{n}}_k = [\bar{n}_{k1}, \bar{n}_{k2}, \ldots, \bar{n}_{kN_c b}]^{\mathrm{T}}$ the observation vector of the kth MS can also be expressed as

$$\bar{\boldsymbol{y}}_k = \bar{\boldsymbol{H}}_k \bar{\boldsymbol{P}}\hat{\boldsymbol{d}} + \bar{\boldsymbol{n}}_k, \quad k = 1, 2, \ldots, K \tag{27}$$

Here, $\bar{\boldsymbol{n}}_k$ is the zero mean complex Gaussian noise vector with covariance matrix $E[\bar{\boldsymbol{n}}_k \bar{\boldsymbol{n}}_k^H] = 2\sigma^2 \boldsymbol{I}_{N_c b}$. The decision variable by invoking (27) for the kth user can be expressed as

$$\begin{aligned} \bar{\boldsymbol{r}}_k &= \boldsymbol{C}_k^{\mathrm{T}} \bar{\boldsymbol{y}}_k \\ &= \boldsymbol{C}_k^T \bar{\boldsymbol{H}}_k \bar{\boldsymbol{P}}\hat{\boldsymbol{d}} + \tilde{\boldsymbol{n}}_k \end{aligned} \quad k = 1, 2, \ldots, K \tag{28}$$

where $\tilde{\boldsymbol{n}}_k = \boldsymbol{C}_k^T \bar{\boldsymbol{n}}_k$ denotes the zero mean complex Gaussian vector with covariance matrix $E[\bar{\boldsymbol{n}}_k \bar{\boldsymbol{n}}_k^H] = 2\sigma^2 \boldsymbol{I}_b$. Further, to carry out MUTP, the decision variables of all the K users are assembled into a single Kb length vector $\bar{\boldsymbol{r}}$ given by

$$\bar{\boldsymbol{r}} = [\bar{\boldsymbol{r}}_1^T, \bar{\boldsymbol{r}}_2^T, \ldots, \bar{\boldsymbol{r}}_K^T]^T \tag{29}$$

Hence, the decision variable in the case of K users' can also be expressed as

$$\bar{\boldsymbol{r}} = \widetilde{\boldsymbol{C}}^T \bar{\boldsymbol{H}}\bar{\boldsymbol{P}}\hat{\boldsymbol{d}} + \ddot{\boldsymbol{n}} \tag{30}$$

where $\widetilde{\boldsymbol{C}} = \mathrm{diag}\{\boldsymbol{C}_1, \boldsymbol{C}_2, \ldots, \boldsymbol{C}_K\}$ is a $(KN_c b \times Kb)$ spreading matrix, $\bar{\boldsymbol{H}} = [\bar{\boldsymbol{H}}_1^T, \bar{\boldsymbol{H}}_2^T, \ldots, \bar{\boldsymbol{H}}_K^T]^T$ is a $(KN_c b \times N_c b)$ component small scale fading matrix, $\bar{\boldsymbol{P}}$ is an $(N_c b \times Kb)$ component preprocessing matrix that includes the power normalisation coefficients and $\ddot{\boldsymbol{n}} = [\tilde{n}_1^T, \tilde{n}_2^T, \ldots, \tilde{n}_K^T]^T$ is the zero mean complex Gaussian noise vector with covariance matrix $E[\ddot{\boldsymbol{n}}\ddot{\boldsymbol{n}}^H] = 2\sigma^2 \boldsymbol{I}_{Kb}$.

3.2 Cooperation strategy 2

Fig. 1*b* shows strategy 2. In this cooperation strategy, initially we consider that the relays are spaced close enough so that IRI at the MSs is dominant. Further, it is assumed that each of the L relays supports one user so that the total number of relays employed equals total number of users, that is, $L = K$. As in the previous case, assuming that the preprocessing matrix completely eliminates the DL-MUI, after despreading and detection, the symbols that will be transmitted by the lth relay to the kth user can be expressed as

$$\begin{aligned} \hat{\boldsymbol{d}}_k^l &= \left[\hat{d}_{k1}^l, \hat{d}_{k2}^l, \ldots, \hat{d}_{kb}^l\right]^T, \\ & l = 1, 2, \ldots, L; \quad k = 1, 2, \ldots, K \end{aligned} \tag{31}$$

After spreading, and multi-carrier modulation, the received signal at the kth MS from the lth relay can be readily expressed as

$$\begin{aligned} \bar{y}_k^l &= \boldsymbol{h}_k^l \bar{\boldsymbol{F}}_k^l \ddot{\boldsymbol{P}}_k^l \hat{\boldsymbol{d}}_k^l + n_k \\ & l = 1, 2, \ldots, L; \quad k = 1, 2, \ldots, K \end{aligned} \tag{32}$$

where $\boldsymbol{h}_k^l$ is the channel vector connecting the lth relay corresponding to the kth user, $\bar{\boldsymbol{F}}_k^l$ represents multi-carrier modulation matrix employed by the lth relay to carry out multi-carrier modulation on the kth user's signal and $\ddot{\boldsymbol{P}}_k^l$ denotes the preprocessing matrix. Since we assumed L relays support K users, kth MS will experience IRI. Hence, in this context, the observation vector at the kth MS can be expressed as

$$\begin{aligned} \bar{y}_k &= \boldsymbol{h}_k^l \bar{\boldsymbol{F}}_k^l \ddot{\boldsymbol{P}}_k^l \hat{\boldsymbol{d}}_k^l + \underbrace{\sum_{i,j=1, i,j \neq l}^{L} \boldsymbol{h}_k^j \bar{\boldsymbol{F}}_i^j \ddot{\boldsymbol{P}}_i^j \hat{\boldsymbol{d}}_i^j}_{\mathrm{IRI}} + n_k \\ & l = 1, 2, \ldots, L; \quad k = 1, 2, \ldots, K \end{aligned} \tag{33}$$

After MC demodulation (assuming that the subcarriers employed by the lth relay are designed to be perfectly orthogonal with each other) the received signal on the uth subcarrier corresponding to the kth user from lth relay can be expressed as

$$\begin{aligned} y_{ku}^l &= \tilde{\boldsymbol{h}}_{ku}^l \ddot{\boldsymbol{P}}_k^l \hat{\boldsymbol{d}}_k^l + n_{ku} \\ & l = 1, 2, .., L; \ k = 1, 2, \ldots, K; \ u = 1, 2, \ldots, N_c b \end{aligned} \tag{34}$$

Now, without loss of generality, the observation vector at the kth MS because of the lth relay over $N_c b$ subcarriers can be given by

$$\bar{\boldsymbol{y}}_k = \bar{\boldsymbol{H}}_k^l \ddot{\boldsymbol{P}}_k^l \hat{\boldsymbol{d}}_k^l + \bar{\boldsymbol{n}}_k \quad l = 1, 2, \ldots, L; \ k = 1, 2, \ldots, K$$

where

$$\bar{\boldsymbol{H}}_k^l = \mathrm{diag}\left\{h_{k1}^l, h_{k2}^l, \ldots, h_{kN_cb}^l\right\} \quad \text{and } \bar{\boldsymbol{n}}_k = \left[\bar{n}_{k1}, \bar{n}_{k2}, \ldots, \bar{n}_{kN_cb}\right]^T \tag{35}$$

Finally, assuming that the preprocessing matrix completely eliminates $\bar{\boldsymbol{H}}_k^l$, after despreading with the aid of spreading sequence employed by the lth relay corresponding to the kth user, decision variable for b symbols in $\hat{\boldsymbol{d}}_k$ can be expressed as

$$\bar{\boldsymbol{r}}_k = \left(\boldsymbol{C}_k^l\right)^T \bar{\boldsymbol{y}}_k \quad l = 1, 2, \ldots, L; \quad k = 1, 2, \ldots, K \tag{36}$$

Consequently, after estimation, the estimates in the context of K users can be collected into a single vector of length Kb given by

$$\bar{\boldsymbol{d}} = \left[\bar{\boldsymbol{d}}_1^T, \bar{\boldsymbol{d}}_2^T, \ldots, \bar{\boldsymbol{d}}_K^T\right]^T \tag{37}$$

whereby definition, $\bar{\boldsymbol{d}}_k = \left[\bar{\hat{d}}_{k1}, \bar{\hat{d}}_{k2}, \ldots, \bar{\hat{d}}_{kb}\right]^T, k = 1, 2, \ldots, K.$

3.3 Cooperation strategy 3

As our next assumption, we assume that all the L relays forward the multi-user signals to all the K MSs. Fig. 1*c* elucidates strategy 3. In this context, the MSs will experience MUI and IRI. Now let $\hat{\boldsymbol{d}}^l = \left[(\hat{\boldsymbol{d}}_1^l)^T, (\hat{\boldsymbol{d}}_2^l)^T, \ldots, (\hat{\boldsymbol{d}}_K^l)^T\right]^T$ define the multi-user data transmitted by the lth relay to the kth MS. Then, after spreading and transmitter preprocessing, multi-carrier modulation is carried out and the transmitted MC-CDMA signal over N_cb subcarriers from the lth relay to kth MS can be expressed as

$$\bar{\boldsymbol{s}} = \bar{\boldsymbol{F}}^l \bar{\boldsymbol{P}} \hat{\boldsymbol{d}}^l \tag{38}$$

where $\bar{\boldsymbol{P}}$ and $\bar{\boldsymbol{s}}$ correspond to the $(N_cb \times Kb)$ preprocessing matrix and N_cb length transmitted vector, respectively. As earlier, $\boldsymbol{C}^l = \left[\boldsymbol{C}_1^l, \boldsymbol{C}_2^l, \ldots, \boldsymbol{C}_K^l\right]$ defines the spreading matrix employed by the lth relay to spread the K users' symbols. Here, we assume that each relay employs a unique spreading matrix to spread the K users' symbols that they forward to the destination MSs. In this context, the received vector at the kth MS can be expressed as

$$\bar{y}_k = \boldsymbol{h}_k^l \bar{\boldsymbol{F}}^l \bar{\boldsymbol{P}}^l \hat{\boldsymbol{d}}^l + n_k \quad l = 1, 2, \ldots, L; \ k = 1, 2, \ldots, K \tag{39}$$

After multi-carrier demodulation, the observation vector at the kth MS can be expressed as

$$\bar{\boldsymbol{y}}_k = \bar{\boldsymbol{H}}_k^l \bar{\boldsymbol{P}}^l \hat{\boldsymbol{d}}_k^l + \bar{\boldsymbol{n}}_k \quad l = 1, 2, \ldots, L; \ k = 1, 2, \ldots, K \tag{40}$$

The observation vector in the context of kth MS as a result of transmission from L relays can now be written as

$$\bar{\boldsymbol{y}}_k = \sum_{l=1}^{L} \bar{\boldsymbol{H}}_k^l \bar{\boldsymbol{P}}^l \hat{\boldsymbol{d}}^l + \bar{\boldsymbol{n}}_k \quad k = 1, 2, \ldots, K \tag{41}$$

As in the previous case, assuming that the preprocessing matrix completely eliminates $\bar{\boldsymbol{H}}_k^l$, and invoking the user-specific spreading sequence with respect to each relay, the decision variable of the kth user's transmitted symbols can be expressed as

$$\bar{\boldsymbol{r}}_k^l = \left(\boldsymbol{C}_k^l\right)^T \bar{\boldsymbol{y}}_k \quad l = 1, 2, \ldots, L; \quad k = 1, 2, \ldots, K \tag{42}$$

Explicitly, the decision variables of the kth MS's symbols forwarded by the L relays can be expressed as

$$\bar{\boldsymbol{r}}_k = \sum_{l=1}^{L} \left(\boldsymbol{C}_k^l\right)^T \bar{\boldsymbol{y}}_k \quad k = 1, 2, \ldots, K \tag{43}$$

From the above expression, it can be inferred that this cooperation strategy results in Lth order diversity.

4 Multi-user transmitter preprocessing

MUTP employed in our work is based on [20, 22]. Invoking (18) or (28) as germane (whether B channels or R channels are considered for formulating the preprocessing matrix. In our exposition we have considered the R channels for formulating the preprocessing matrix), the kth user's MS decision variable can be expressed as

$$\bar{\boldsymbol{r}}_k = \boldsymbol{C}_k^T \bar{\boldsymbol{H}}_k \bar{\boldsymbol{P}}_k \hat{\boldsymbol{d}}_k + \sum_{j=1, j\neq k}^{K} \boldsymbol{C}_k^T \bar{\boldsymbol{H}}_k \bar{\boldsymbol{P}}_j \hat{\boldsymbol{d}}_j + \tilde{\boldsymbol{n}}_k, \quad k = 1, 2, \ldots, K \tag{44}$$

The zero forcing MUTP is derived by satisfying the following conditions $\forall k \in \{1, 2, \ldots, K\}$:

$$\boldsymbol{C}_k^T \bar{\boldsymbol{H}}_k \bar{\boldsymbol{P}}_k > 0 \text{ and } \boldsymbol{C}_j^T \bar{\boldsymbol{H}}_j \bar{\boldsymbol{P}}_k = 0 \text{ for any } j \neq k \tag{45}$$

The preprocessing matrix $\bar{\boldsymbol{P}}_k$ corresponding to the kth user is a $(N_cb \times b)$ matrix designed to lie in the subspace determined by $\boldsymbol{C}_k^T \bar{\boldsymbol{H}}_k$ which is orthogonal to the $(K-1)b$ rank subspace constituted by all $\boldsymbol{C}_j^T \bar{\boldsymbol{H}}_j$, for $j = 1, 2, \ldots, K; j \neq k$. In other words, the preprocessing matrix is derived with the aid of the $[N_cb \times (K-1)b]$ CSI matrix associated with the interfering users. Now, without loss of generality, dropping the superscript l and denoting $\ddot{\boldsymbol{H}}_k$ as the CSI matrix for deriving the preprocessing matrix for the kth MS, $\ddot{\boldsymbol{H}}_k$ can be expressed as

$$\ddot{\boldsymbol{H}}_k = \left[\bar{\boldsymbol{H}}_1^H \boldsymbol{C}_1, \ldots, \bar{\boldsymbol{H}}_{k-1}^H \boldsymbol{C}_{k-1}, \bar{\boldsymbol{H}}_{k+1}^H \boldsymbol{C}_{k+1}, \ldots, \bar{\boldsymbol{H}}_K^H \boldsymbol{C}_K\right], \quad k = 1, 2, \ldots, K \tag{46}$$

Applying singular value decomposition (SVD) on (46), $\ddot{\boldsymbol{H}}_k$ can be expressed as

$$\ddot{\boldsymbol{H}}_k = \left[\ddot{\boldsymbol{U}}_{k,s} | \ddot{\boldsymbol{U}}_{k,n}\right] \begin{bmatrix} \boldsymbol{\Lambda}_{k,s}^{1/2} \\ \boldsymbol{0} \end{bmatrix} \ddot{\boldsymbol{V}}_k^H = \ddot{\boldsymbol{U}}_{k,s} \boldsymbol{\Lambda}_{k,s}^{1/2} \ddot{\boldsymbol{V}}_k^H, \quad k = 1, 2, \ldots, K \tag{47}$$

where $\ddot{\boldsymbol{U}}_k = \left[\ddot{\boldsymbol{U}}_{k,s} | \ddot{\boldsymbol{U}}_{k,n}\right]$ is an $(N_cb \times N_cb)$ component unitary matrix, $\ddot{\boldsymbol{V}}_k$ is a $[(K-1)b \times (K-1)b]$ component unitary matrix

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and $\boldsymbol{\Lambda}_{k,s}$ is a $[(K-1)b\times(K-1)b]$ component diagonal matrix constituting the eigen values of $\ddot{\boldsymbol{H}}_k\ddot{\boldsymbol{H}}_k^H$. $\ddot{\boldsymbol{U}}_{k,s}$ is a $[N_cb\times(K-1)b]$ matrix constituting the $(K-1)b$ columns of $\ddot{\boldsymbol{U}}_k$ that correspond to the non-zero eigen values of $\ddot{\boldsymbol{H}}_k\ddot{\boldsymbol{H}}_k^H$ and $\ddot{\boldsymbol{U}}_{k,n}$ is an $[N_cb\times(N_c-K+1)b]$ component matrix constituting the $(N_c-K+1)b$ columns of $\ddot{\boldsymbol{U}}_k$ that correspond to the null space of $\ddot{\boldsymbol{H}}_k\ddot{\boldsymbol{H}}_k^H$. The preprocessing matrix in the context of kth user derived with the aid of SVD for the DL MC-CDMA system can be expressed as [20, 22]

$$\bar{\boldsymbol{P}}_k=\psi_k\left(\ddot{\boldsymbol{U}}_{k,n}\ddot{\boldsymbol{U}}_{k,n}^H\right)\bar{\boldsymbol{H}}_k^H\boldsymbol{C}_K,\quad k=1,2,\ldots,K \tag{48}$$

where

$$\psi_k=\sqrt{\frac{b}{\mathrm{Trace}\left(\boldsymbol{C}_k^T\bar{\boldsymbol{H}}_k\ddot{\boldsymbol{U}}_{k,n}\ddot{\boldsymbol{U}}_{k,n}^H\bar{\boldsymbol{H}}_k^H\boldsymbol{C}_K\right)}},\quad k=1,2,\ldots,K$$

designates the power normalisation coefficient employed to maintain the transmission power unchanged even after preprocessing. Hence, for maintaining a constant transmission power the preprocessing matrix should satisfy the constraint

$$\mathrm{Trace}\left(\bar{\boldsymbol{P}}_k^H\bar{\boldsymbol{P}}_k\right)\le b \tag{49}$$

Finally, the overall preprocessing matrix $\bar{\boldsymbol{P}}$, realised based on $\bar{\boldsymbol{P}}_k$, that results in the zero forcing (ZF) solution can be expressed as

$$\bar{\boldsymbol{P}}=\left[\bar{\boldsymbol{P}}_1,\bar{\boldsymbol{P}}_2,\ldots,\bar{\boldsymbol{P}}_K\right] \tag{50}$$

where $\bar{\boldsymbol{P}}_k$ is defined according to (48). The above addressed preprocessing approach is applicable for implementation at the BS and at the relays for the cooperation strategies 1 and 3. In contrast, in cooperation strategy 2, each of the relays forwards only the corresponding user's symbol. Hence, simple transmit ZF can be invoked to implement transmitter preprocessing (TP) at the relays. Correspondingly the preprocessing matrix $\ddot{\boldsymbol{P}}_k^l$ is given by

$$\ddot{\boldsymbol{P}}_k^l=\left[\left(\boldsymbol{C}_k^l\right)^T\bar{\boldsymbol{H}}_k^l\right]^+\ddot{\psi}_k\quad k=1,2,\ldots,K;\quad l=1,2,\ldots,L \tag{51}$$

whereby definition, $\ddot{\psi}_k=\sqrt{\dfrac{b}{\mathrm{Trace}\left(\ddot{\boldsymbol{P}}_k^l\left(\ddot{\boldsymbol{P}}_k^l\right)^H\right)}}$

5 Performance results

In this section, we provide the simulation results to characterise the attainable BER performance of the relay aided DL MC-CDMA system employing transmitter preprocessing based on eigen approach. In our work, we assume that the cooperation strategy is typically based on the time-division principles. Explicitly, in this contribution, we assume that, each symbol duration is divided into two time slots. Within the first time slot, the BS will broadcast the multi-user signals to the L relays and within the second time slot, the L relays will forward the signals received from the BS to the K DMSs. Further, we assume that the distance between the BS and any of the MSs is too large that the contribution from the direct link to the received signal is not that very significant at the desired MS. Furthermore, for the sake of simplicity, in this paper, it is assumed that the total time taken by the signals to traverse through B and R channels to reach the DMS, almost equals the time taken by the signal that traverse through the direct (D) channel to reach the DMS if one such exists. The B and R channels are assumed to undergo frequency-selective Rayleigh fading with $\mathcal{L}=20$ time (T) domain resolvable paths and Nakagami-m fading, respectively. Explicitly, if the fast fading gains of the R channels can be expressed as $\left\{h_k^l=\alpha_k^l e^{j\theta_k^l},\quad l=1,\ldots,L;k=1,\ldots,K\right\}$, then the phases $\left\{\theta_k^l\right\}$ obey independent uniform distribution in $\{0,2\pi\}$ and $\left\{\alpha_k^l\right\}$ obey Nakagami-m distribution with the probability density function given by [13]

$$f_{\alpha_k^l}(y)=\frac{2m_l^{m_l}y^{2m_l-1}}{\Gamma(m_l)\Omega_l}\exp\left(-\frac{m_l}{\Omega_l}y^2\right),\qquad l=0,1,\ldots,L;\quad k=1,2,\ldots,K \tag{52}$$

where m_l represents the fading parameter of R channel and $\Omega_l=E\left[\left\{\alpha_k^l\right\}^2\right]$. In our simulations, we use the generalised Nakagami-m distribution given in (52) to model different fast-fading conditions experienced by the R channels. That is, the R channel may undergo moderate fading as compared to the B channel, since the distance between a MS and its corresponding relay will be shorter than that between the BS and the relays. Hence, to characterise less severe fading conditions, we model the channel with Nakagami-m fading coupled with relatively high value of m, that is, in our simulations m takes the value 2 for Nakagami fading. We also assume that the signals transmitted over DL channels experience PL which can be expressed as a function of Tx-Rx distance, that is $\mathrm{PL}(d)=\mathrm{PL}(d_0)\mathrm{dB}+10\eta\log(d/d_0)$. $\mathrm{PL}(d_0)\mathrm{dB}$ refers to the PL measured at a reference distance d_0 and η denotes the PL exponent. The typical value of η used in our simulations is 4 as this value is, at best, a mean value valid for the cellular environment. Further, it is assumed that the transmission power remains constant before and after TP, that is $E\left[\|\bar{\boldsymbol{P}}\boldsymbol{d}\|^2\right]\le Kb$ at the BS and $E\left[\|\bar{\boldsymbol{P}}\hat{\boldsymbol{d}}\|^2\right]\le Kb$ at each of the relays for cooperation strategies 1 and 3. Furthermore, for the cooperation strategy 2, it is assumed that $E\left[\|\ddot{\boldsymbol{P}}_k\hat{\boldsymbol{d}}_k\|^2\right]\le b$ for maintaining constant transmission power before and after preprocessing. The spreading length used in our simulation is $N_c=16$. The simulations are carried out for varying user load. The considered cooperative communication aided MC-CDMA system employs $N_cb=64$ subcarriers and $b=4$ bits are transmitted to each of the DL users. A carrier frequency offset of 222.22 Hz with subcarrier spacing of 15 KHz in accordance with 3GPP standard is also considered in our simulations. Fig. 2 shows the average BER against average SNR per bit performance for single relay assisted (*cooperation strategy* 1) MC-CDMA DL system supporting multiple users and employing transmitter preprocessing based on eigen approach that constructs an orthogonal subspace to the interfering subspace. The B channel is assumed to undergo Rayleigh fading with $\mathcal{L}=20$ T-domain resolvable paths and the R channel to experience Nakagami-m fading. From the figure it is observed that TP is capable of completely removing the

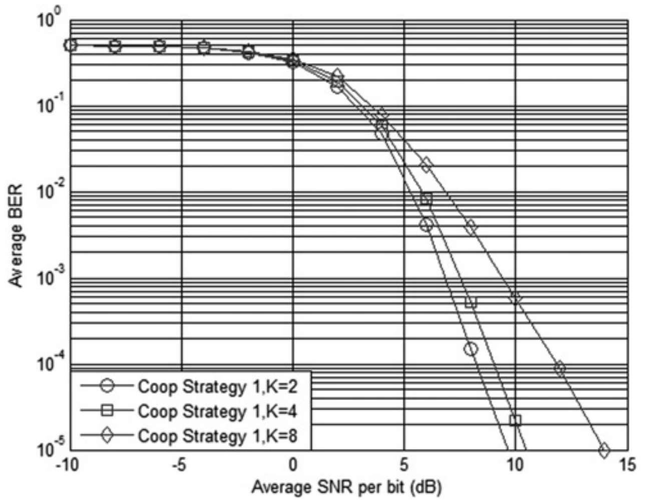

Fig. 2 *Average BER against SNR performance comparison of relay-aided MUTP-assisted DL MC-CDMA system supporting K = 2, 4 and 8 users with L = 1 under dominant MUI assumption at the relay and MSs. The B and R channels are assumed to undergo Rayleigh fading (frequency-selective with* $\mathcal{L} = 20$ *time* (T) *domain resolvable paths) and Nakagami-m fading with fading parameter m = 2, respectively. The simulations are based on the preprocessing matrix of (48) coupled with the power normalisation* ψ_k *with perfect CSI assumption. The spreading length used in our simulation is* $N_c = 16$

MUI at the relays and at the MSs. Nevertheless, when the number of DL users to be supported by the F-domain spread relay aided TP-assisted MC-CDMA increases; the attainable BER performance degrades significantly.

Fig. 3 shows the average BER against average SNR per bit performance for the relay assisted (*cooperation strategy*

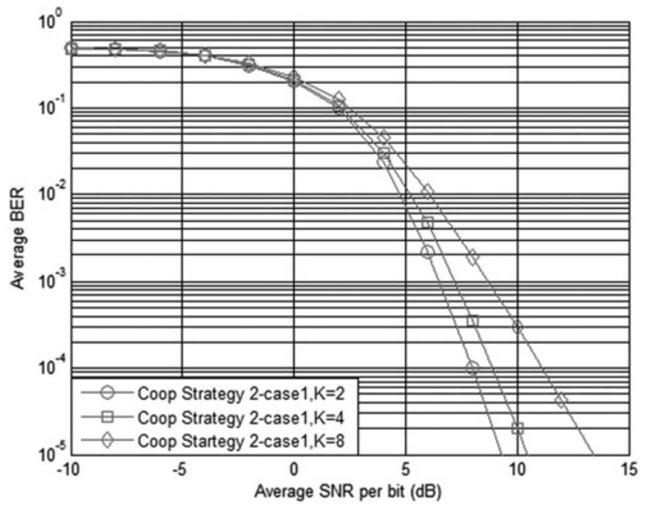

Fig. 3 *Average BER against SNR performance comparison of relay-aided MUTP assisted DL MC-CDMA system supporting K = 2, 4 and 8 users with L = 2, 4 and 8 under dominant MUI assumption at the relay and weak IRI assumption at the MSs. The B and R channels are assumed to undergo Rayleigh fading (frequency-selective with* $\mathcal{L} = 20$ *time* (T) *domain resolvable paths) and Nakagami-m fading with fading parameter m = 2, respectively. The simulations are based on the preprocessing matrices of (48) and (51) coupled with the power normalisation* ψ_k *and* $\ddot{\psi}_k$ *at the BS and relays, respectively, with perfect CSI assumption. The spreading length used in our simulation is* $N_c = 16$

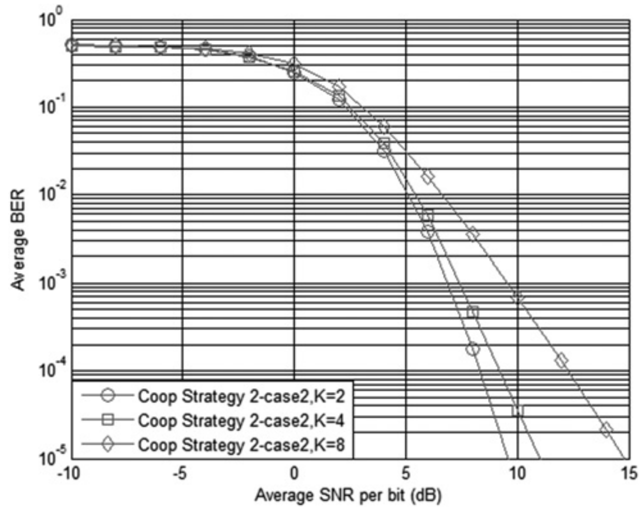

Fig. 4 *Average BER against SNR performance comparison of relay-aided MUTP assisted DL MC-CDMA system supporting K = 2, 4 and 8 users with L = 2, 4 and 8 under dominant MUI assumption at the relay and dominant IRI assumption at the MSs. The B and R channels are assumed to undergo Rayleigh fading (frequency-selective with* $\mathcal{L} = 20$ *time* (T) *domain resolvable paths) and Nakagami-m fading with fading parameter m = 2, respectively. The simulations are based on the preprocessing matrices of (48) and (51) coupled with the power normalisation* ψ_k *and* $\ddot{\psi}_k$ *at the BS and relays, respectively, with perfect CSI assumption. The spreading length used in our simulation is* $N_c = 16$

2-*case* 1) MC-CDMA DL system supporting multiple users and employing transmitter preprocessing based on (48) and (51) at the BS and relays, respectively. Here each of the DL users is supported by one relay. Further, it is assumed that

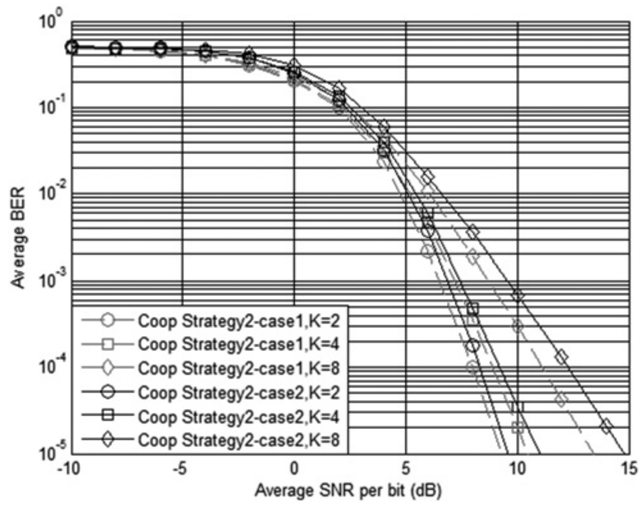

Fig. 5 *Average BER against SNR performance comparison of relay-aided MUTP assisted DL MC-CDMA system supporting K = 2, 4 and 8 users with L = 2, 4 and 8 under dominant and weak IRI assumptions at the MSs as well as dominant MUI assumption at the relays. The B and R channels are assumed to undergo Rayleigh fading (frequency-selective with* $\mathcal{L} = 20$ *time* (T) *domain resolvable paths) and Nakagami-m fading with fading parameter m = 2, respectively. The simulations are based on the preprocessing matrices of (48) and (51) coupled with the power normalisation* ψ_k *and* $\ddot{\psi}_k$ *at the BS and relays, respectively, with perfect CSI assumption. The spreading length used in our simulation is* $N_c = 16$

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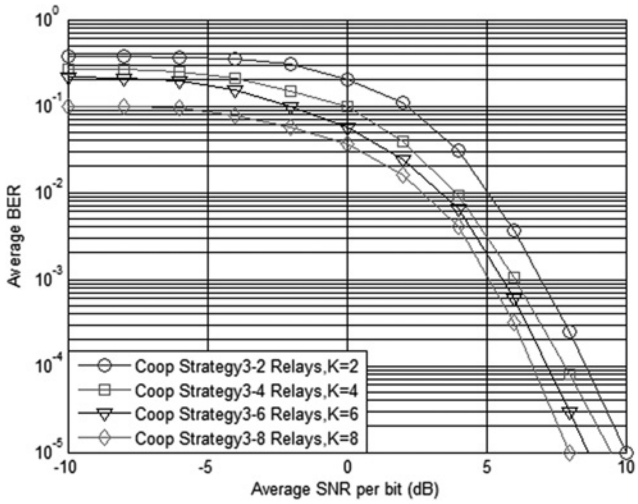

Fig. 6 *Average BER against SNR performance of relay-aided MUTP assisted DL MC-CDMA system supporting K = 2, 4, 6 and 8 users with L = 2, 4, 6 and 8 for dominant MUI at the relays and dominant MUI and IRI assumptions at the MSs. The B and R channels are assumed to undergo Rayleigh fading (frequency-selective with* $\mathcal{L} = 20$ *time* (T) *domain resolvable paths) and Nakagami-m fading with fading parameter m = 2, respectively. The simulations are based on the preprocessing matrix of (48) coupled with the power normalisation* ψ_k *with perfect CSI assumption. The spreading length used in our simulation is* $N_c = 16$

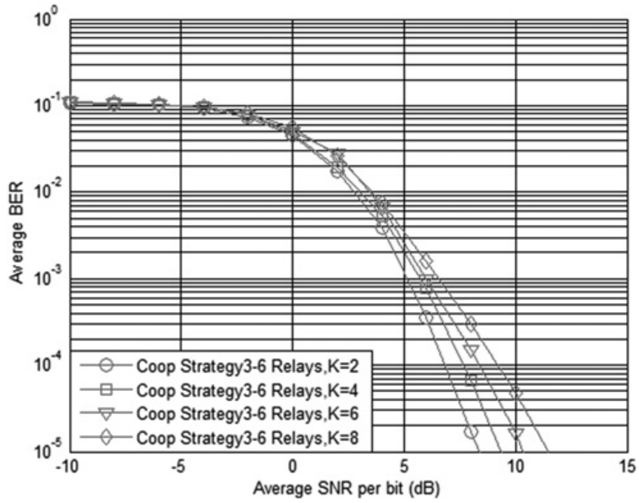

Fig. 7 *Average BER against SNR performance of relay-aided MUTP-assisted DL MC-CDMA system supporting K = 2, 4, 6 and 8 users with L = 6 for dominant MUI at the relays and dominant MUI and IRI assumptions at the MSs. The B and R channels are assumed to undergo Rayleigh fading (frequency-selective with* $\mathcal{L} = 20$ *time* (T) *domain resolvable paths) and Nakagami-m fading with fading parameter m = 2, respectively. The simulations are based on the preprocessing matrix of (48) coupled with the power normalisation* ψ_k *with perfect CSI assumption. The spreading length used in our simulation is* $N_c = 16$

the relays are spaced far apart from each other so that IRI at the MSs is inconsequential. The B and R channels are assumed to undergo Rayleigh fading having $\mathcal{L} = 20$ T-domain resolvable paths and Nakagami-*m* fading, respectively. From the figure, it is observed that the TP completely removes the MUI at the relays. However, the BER performance becomes poorer when the number of DL users supported by the F-domain spread TP-assisted system becomes higher. Furthermore, comparing Figs. 2 and 3, it can be readily concluded that the performance slightly improves when the F-domain spread relay aided TP-assisted DL MC-CDMA system employs individual relays to support each user.

In contrast to Fig. 3, in Fig. 4 (*cooperation strategy* 2-*case* 2), we demonstrate the achievable BER of the considered system when each of the relays supporting the *K* DL users is spaced close to each other so that IRI at the MSs is dominant. Comparing Figs. 3 and 4, we observe that the BER performance of the considered system degrades considerably because of IRI being dominant at the MSs. The same is being illustrated in Fig. 5. Fig. 6 demonstrates the performance of the system for varying user load and relays. Here all the relays (*co-operation strategy* 3-*case* 1) forward the multi-user data to all the *K* DL users and hence, relay diversity is achieved. Further, we assume dominant MUI at the relays and dominant MUI and IRI at the MSs. From the plot we observe that the BER performance significantly improves in the higher SNR regime, when the number of relays supporting a user increases, although the number of users to be supported increases. This clearly showcases the potential of transmitter preprocessing in removing the MUI in a relay diversity assisted system.

In Fig. 7, we elucidate the performance of the cooperative communication-aided MC-CDMA system employing fixed number of relays ($L = 6$) (*cooperation strategy* 3-*case* 2) to support the *K* DL users. As in the previous case, here also we have assumed dominant MUI at the relays and dominant MUI and IRI at the MSs. As demonstrated by the results, the performance of the system degrades when the number of users supported by the system increases. This performance loss is purely attributed by the loss of relay diversity and also because of the fact that MUI and IRI are dominant. In Fig. 8, we demonstrate the performance of the considered system when

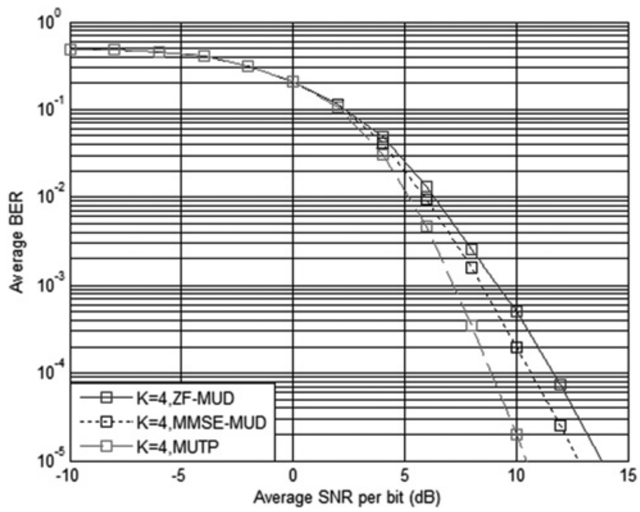

Fig. 8 *Average BER against SNR performance comparison of relay-aided MUTP and MUD assisted DL MC-CDMA system supporting K = 4 users with L = 1 for dominant MUI at the relays and at the MSs. The B and R channels are assumed to undergo Rayleigh fading (frequency-selective with* $\mathcal{L} = 20$ *time* (T) *domain resolvable paths) and Nakagami-m fading with fading parameter m = 2, respectively*

multi-user detection (MUD) and MUTP are invoked to mitigate MUI at the relays and at the MSs. The presented results are based on the cooperation strategy 2. From the simulation results we observe that MUTP-aided system results in better achievable BER in the higher SNR regime than MUD-aided system. This clearly demonstrates that MUTP is capable of completely removing the MUI thereby assisting in significantly enhancing the achievable error performance.

6 Conclusions

In this letter, we investigated the performance of F-domain spread relay aided MUTP-assisted DL MC-CDMA system in the presence of dominant MUI at the relays and dominant MUI, dominant and weak IRI at the MSs depending upon the cooperation strategy invoked. Our simulation study shows that MUTP completely eliminates the DL-MUI at the relays as well as MUI and IRI at the MSs. As the DL-MUI is completely eliminated at the relays, the signals that are forwarded from the relays to the users' are MUI free. Also, it is observed that among the three cooperation strategies, strategy 3 case 1 has resulted in significant performance improvement in terms of attainable BER when the number of relays that supports an MS augments amidst increase in number of users supported by the system. Further, our study reveals that the signal processing required at the relays and MSs is of low complexity when MUTP is invoked at the BS and relays to suppress MUI at the relays and MUI and IRI at the MSs, respectively. Furthermore, we may conclude that, to deal with the interference and to appreciably enhance the achievable BER performance, MUTP can be employed at both the BS and relays as a replacement for complex multi-user detectors. Throughout this contribution, we have made an idealistic assumption of perfect availability of CSI both at the BS and relays for realising the preprocessing matrix. Our future investigations will ponder the performance of the system under imperfect CSI as well as the performance when the required CSI is acquired via feedback channels contaminated by noise and fading which is the case in a typical frequency division duplex system. Also, our future research will focus on scenario where co-channel interference from the adjacent BSs and interference because of the relays in the neighbouring cells are the dominating channel impairments mainly in the transmitter signal-processing perspective.

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