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User Scheduling and Partner Selection for Multiplexing-based Distributed MIMO Uplink Transmission

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1. Introduction

During the last decade, multiple-input multiple-output (MIMO) systems, where both the transmitter and receiver are equipped with multiple antennas, have been verified to be a very promising technique to break the throughput bottleneck in future wireless communication networks. Based on countless results of analysis and field measurements that have been undertaken by many researchers around the world, it is indubitable that MIMO transceiver schemes can significantly improve the system performance. Some well-known standards for next-generation wireless broadband, including 3GPP Long Term Evolution (LTE) and IEEE 802.16 (WiMAX), adopt MIMO as a key feature of the physical layer. For instance, the standard of IEEE 802.16e supports three possible options of *advanced antenna systems* (AAS), namely transmit diversity (TD), beamforming (BF), and spatial multiplexing (SM). The extensions of these multi-antenna techniques are also envisaged in future standards such as IEEE 802.16m and LTE-A.

The potential benefits of MIMO systems are mainly attributed to the multiplexing/diversity gains provided by multiple antenna elements. With spatial multiplexing, multiple independent data streams are transmitted in a single time/frequency resource allocation, so spectral efficiency is thereby increased. In practice, it may be difficult, if not impossible, to equip multiple antenna elements at mobile stations (MS) due to their small physical sizes. In such cases, concurrent transmission of multiple data streams is not feasible, as the maximum number of data streams is limited by $m = \min(M_t, M_r)$, where M_t and M_r are the number of antennas at the transmitter and receiver, respectively. Furthermore, even if multiple antenna elements can be installed on a small mobile device, multiple closely-packed antennas may result in high spatial fading correlation, which theoretically leads to a reduced-rank channel and therefore degrades the performance of spatial multiplexing [Shiu et al., 2000].

In correspondence, the concept of *distributed MIMO communications* has emerged, which has received considerable attention from both academia and industry in recent years. By treating multiple distributed nodes as a single entity, each node can emulate a portion of a virtual antenna array, and the advantages of MIMO techniques can therefore be exploited with appropriate protocols. A common example of distributed MIMO is collaborative spatial multiplexing (CSM), which enhances system capacity by allowing multiple separate

users within a cell to send their uplink signals in the same time-frequency resource unit [Balachandran et al., 2009]. In this case, each user is virtually tantamount to a portion of the transmit antenna array of a point-to-point SM-based MIMO system. On the other hand, some other distributed MIMO topologies may involve the operations of data relaying; for instance, in cooperative relaying, each of the nodes may need to receive and then forward the messages on behalf of other users. The baseline configuration of a cooperative scheme encompasses three main roles, namely source (S), relay (R), and destination (D). Furthermore, the conventional half-duplex (all nodes are unable to transmit and receive simultaneously) cooperative transmission procedure is consisted of two phases. In the first phase (Phase 1), the relay obtains messages from the source. In the second phase (Phase 2), the relay forwards the data it has received during Phase 1 to the destination to complete the transmission.

This chapter considers user scheduling and partner selection problems for CSM and cooperative relaying spatial multiplexing (CRSM) respectively. For CSM-based uplink schemes, we assume it allows $N_u = 2$ users to transmit data simultaneously, so the base station (BS) needs to select two out of U users in each signalling interval. If the BS possesses the channel state information (CSI) of all users, it can perform *channel-dependent scheduling* by assessing certain quality metrics of the prevailing channel condition. Since CSM creates a virtual MIMO channel in the uplink, some intrinsic MIMO channel metrics may be employed for scheduling. One of the conventional scheduling algorithms is to choose the user pair with the highest capacity in order to maximize the system throughput [Wang et al., 2008]. This, however, may not be the best solution for CSM, because the resultant MIMO channel structure may not be *spatial multiplexing-preferred* in terms of the error performance even if it maximizes the channel capacity. Additionally, a scheduler that always selects the user pair with the highest capacity may not be able to give an acceptable fairness performance, especially in low mobility scenarios (such as indoor applications) where the channels of most users do not change rapidly.

Not many papers have appeared to examine scheduling strategies for CSM in spite of their importance. The authors of [Lee & Lee, 2008] have developed a scheduler for CSM based on antenna correlations at the BS. In this chapter, the problem is studied from a different perspective. We reasonably presume that the antenna spacings at the BS are large enough so the spatial correlation is negligible. An objective of this work is to scrutinize different scheduling modes and selection metrics for CSM, in terms of their search complexity, error performance, and fairness. Recently, we became aware that [Wang et al., 2008] has the similar goal. Nonetheless, [Wang et al., 2008] only considers *Semi Round Robin* user pairing mode (which will also be discussed subsequently in this chapter), while our study further examines some other user pairing modes of MIMO channel metric-dependent scheduling for CSM.

Most of the early developments in the context of cooperative relaying communications are aimed to provide higher spatial diversity gain [Laneman et al., 2004]. Due to the fact that the destination node in an uplink scenario (the base station) usually possesses multiple antennas, the extensions to cooperative spatial multiplexing have also appeared in the literature to achieve higher spectral efficiency [Kim & Cherukuri, 2005]. In CRSM, the source node first shares a portion of the data with the relay node in Phase 1, and then distinct data portions are jointly transmitted by the source and the relays to the destination in Phase 2. In general, the number of available spatial links in the MIMO channel is limited by the number

of antennas at transmitter. Analogously, it refers to the number of relays that cooperates with the source in CRSM. When the user population is dense, the number of potential relay candidates is likely to exceed the number of relays required for cooperation. Additionally, cooperation with too many relays may jeopardize the availability of system resources. Hence, a recruitment process is needed to select active relays from all potential candidates. Apparently, how the active relays are chosen would affect the overall system performance. The issues of relay selection have been studied extensively (for examples, [Norsratina & Hunter, 2007] and references therein) for cooperative diversity schemes, and the relevant research on CRSM is relatively sparse in existing literature.

From the discussions above, it is apparent that both user-scheduling for CSM and partner recruitment for CRSM need a MIMO channel-related selection metric. Thus, the main objective of this chapter is to develop a selection metric that can be applied to both CSM and CRSM. To be specific, the proposed metric is developed based on the condition number of the virtual MIMO channel, the magnitude of which could be employed to determine whether the MIMO channel is suitable for spatial multiplexing operation.

This chapter is organized as following. The channel model of a CSM system is elaborated in the next section. We review, as well as propose, several different user pairing modes and selection metrics in Section 3 and 4. Then, in Section 5, the proposed user selection criterion is further applied to design a partner recruitment algorithm for CRSM. The simulation-based investigation results are presented in Section 6, and a concise conclusion is drawn in Section 7.

2. System model for collaborative spatial multiplexing

This chapter firstly consider a CSM uplink transmission scenario, where $M_r \geq 2$ antennas are installed at the BS for reception, while each of the U users is equipped with $M_t = 1$ antenna. For sake of convenience, we postulate the number of users that intend to transmit with CSM, U , is always an even number. In each signalling interval, $N_u = 2$ out of U users are scheduled to transmit data simultaneously in the same time-frequency resource unit via CSM, as illustrated in Fig. 1. The channel vector of the u^{th} user can be written as:

$$\mathbf{h}_u = \begin{bmatrix} h_{1,u} \\ h_{2,u} \\ \vdots \\ h_{M_r,u} \end{bmatrix}, \quad (1)$$

where $h_{i,u}$ is the fading coefficient between the i^{th} antenna of the BS and the u^{th} user. All fading coefficients are modelled as complex Gaussian random variables with zero-mean (Rayleigh fading) and unit variance. We assume that the BS has acquired the full channel state information (CSI) of every user through pilot signals. As mentioned previously, it is reasonable to assume that the distances among antennas at the BS are sufficiently large, so all entries in the channel vector (1) are independent random variables. Note that the channel vectors of any two users are also independent as they are spatially dispersed. Thus, the overall channel for CSM formed by a pair of users is virtually equivalent to a $M_r \times 2$ MIMO system matrix with independent, identical distributed (i.i.d) entries:

$$\mathbf{H} = [\mathbf{h}_u \quad \mathbf{h}_v] = \begin{bmatrix} h_{1,u} & h_{1,v} \\ h_{2,u} & h_{2,v} \\ \vdots & \vdots \\ h_{M_r,u} & h_{M_r,v} \end{bmatrix}, \quad (2)$$

where u and v are user indices. Moreover, due to user mobility, each column of \mathbf{H} (the channel vector of each user) evolves with time in accordance with some time-correlation function $\rho(\tau)$. Hence,

$$\mathbf{h}(t + \tau) = \rho \mathbf{h}(t) + \sqrt{1 - \rho^2} \mathbf{a}, \quad (3)$$

where τ represents time displacement, and \mathbf{a} is a random Gaussian vector with identical dimension and statistics as \mathbf{h} . The value of ρ depends on τ and the Doppler frequency, f_D , of the associating user. The impacts of f_D on scheduling performance will be discussed in subsequent sections.

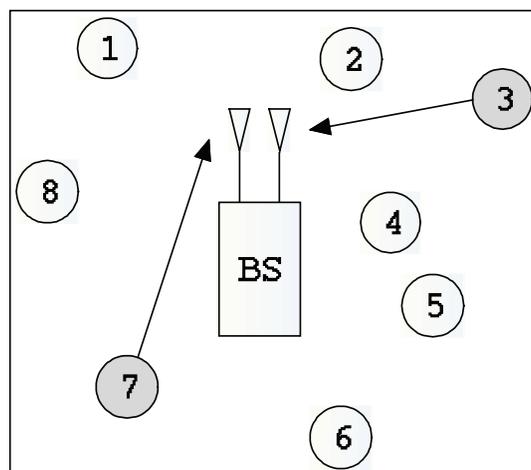


Fig. 1. The illustration of a collaborative spatial multiplexing (CSM) system with $M_t = 1$, $M_r = 2$ and $U = 8$. In this example, both user 3 and user 7 are scheduled for uplink transmission in the same resource unit, thereby creates a 2×2 virtual MIMO channel

3. User pairing modes for CSM

It is assumed that the BS schedules a pair of users in each of the signalling intervals for CSM transmission. Here we define three different modes of user pairing, namely *Pre-Defined Pairing*, *Instantaneous Pairing*, and *Semi Round Robin*. Each of them renders different search complexity. Note that the term *search complexity* (denoted as W) in this chapter is defined as the number of possible pairing choices that the BS has to examine before making the final decision. In other words, W represents the number of required iterations.

3.1 Mode 1: pre-defined pairing

In the initial stage of this mode, the BS arbitrarily divides all users into multiple pairs. That is, the BS first define a list of $U/2$ pairs in a random manner. Note that each user pair

forms a virtual MIMO channel, and is therefore associated with a certain MIMO channel metric. Then, in each of the subsequent signaling intervals, the BS chooses a pair from this pre-defined list based on the channel metric. When the number of users in the cell changes (the occurrence of handover), the BS initiates the pairing again to renew the candidate list. In fact, since the BS has full channel knowledge, the users could be paired base on their channel status (such as user channel orthogonality). However, the pair list may need to be updated more frequently due to channel variation in time, which potentially increases system complexity. Hence, we focus on random pre-defined pairing schemes in this chapter. In each of the signaling interval, the BS has to search over $U/2$ pair candidates and schedule one of these pairs for transmission. Thus, the search complexity of mode 1, W_1 , is

$$W_1 = \frac{U}{2} \quad (4)$$

Another advantage of using this mode is that each pair can be regarded as a single entity with two antennas. Thus, many well-known single-user scheduling strategies for conventional multiple access scenarios, such as proportional fair algorithms, can also be applied. Nonetheless, this is beyond the scope of this chapter.

3.2 Mode 2: instantaneous pairing

In this mode, exhaustive search is performed in every signaling interval to find the best user pair. Thus, the BS has to inspect the associated MIMO channel metrics of all possible user pairs. Intuitively, the system performance can be optimized with this pairing mode. The search complexity this pairing mode can be expressed as:

$$W_2 = \frac{U!}{(U-2)!2!} \quad (5)$$

3.3 Mode 3: semi round robin

When the user mobility levels are relatively low, the users with bad channels may be starved for a long time, and the overall fairness performance of the scheduler is therefore degraded. As there are two user vacancies for CSM scheduling, the BS may simply reserve the first vacancy for scheduling in a *round robin* manner. That is, the users occupy the first vacancy in a signaling interval by taking turns, without considering its channel status. The second vacancy, on the other hand, is given to one of the remaining users that can realize the most appropriate MIMO channel \mathbf{H} with the first reserved user. Thus, this mode attempts to strike a balance between scheduling fairness and system performance. Since a user is reserved, the BS only has to find one of the remaining candidates to pair up with the first user, the search complexity is therefore:

$$W_3 = U - 1 \quad (6)$$

By comparing these three modes, it is apparent that mode 2 should offer the optimum resultant system performance. However, mode 2 may be prohibited in practice due to its high computational complexity, especially when U is large. The search complexities for these three modes are compared as the functions of U in Fig. 2.

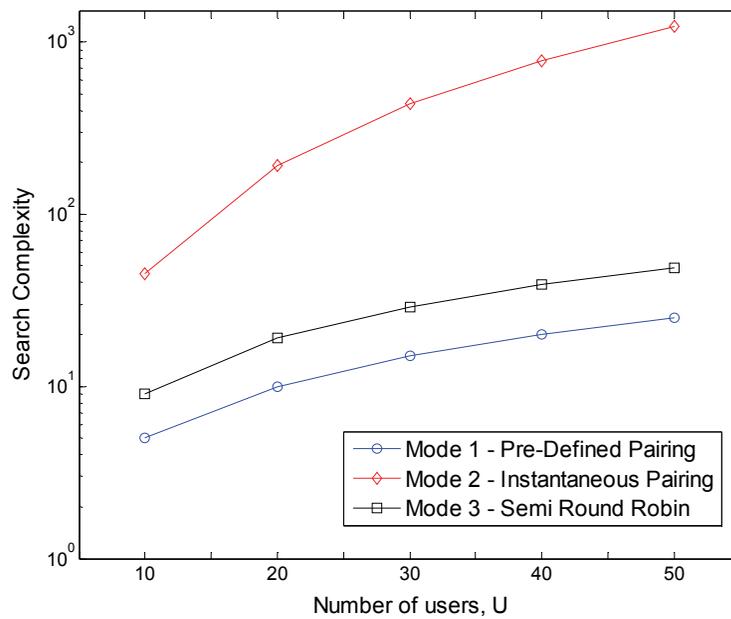


Fig. 2. Search complexities of three user pairing modes with different number of users in the system

4. Selection metrics

All pairing modes described in the preceding section schedule users in accordance to a certain MIMO channel metric. In this section, we elaborate some possible selection criteria that could be coupled with these pairing modes, including a newly proposed metric based on MIMO channel condition number.

4.1 Random Selection (RS)

This is the simplest selection method. The BS can choose the user pair without taking instantaneous channel condition into account. In pairing mode 1, the BS randomly selects a pair of users from the pre-defined list. In mode 2, on the other hand, two users are arbitrarily chosen and paired instantaneously. Finally, in pairing mode 3, the first scheduled user is scheduled in round robin fashion, while another user is randomly picked up by the BS.

4.2 Maximum Capacity (MC)

An intuitive way of scheduling is to select the pair of users that can realize the highest capacity. In CSM, a virtual MIMO channel is formed by cascading the channel vectors of two users. The BS can calculate the corresponding MIMO capacity by the following well-known formula:

$$C = \sum_{k=1}^2 \log_2(1 + P\lambda_k) \quad (7)$$

where P is signal to noise ratio (SNR) on each of the MIMO spatial links, and λ_k is the k^{th} eigenvalue of the channel correlation matrix $\mathbf{H}\mathbf{H}^\dagger$. Note that we denote eigenvalues in

descent order: $\lambda_1 > \lambda_2$. In each signaling interval, the BS finds the user pair that has the maximum channel capacity among all the available choices. That is, the pair index is chosen based on

$$j^* = \arg \max_j C_j, j = 1 \dots W, \quad (8)$$

where C_j is the MIMO channel capacity realized by the j^{th} choice among W options.

4.3 The proposed metric: Maximum Capacity with Spatial Multiplexing Preferred Channel (MC-SMPC)

In this chapter, we wish to propose a new selection metric that can improve the reception error rates. Although selecting the users based on the channel capacity can optimize the spectral efficiency, the resultant MIMO link may not be a spatial multiplexing-preferred channel, and the receiver is therefore more likely to decode the message erroneously. Additionally, the channel capacity is merely a theoretical bound and cannot be directly translated to the system throughput. In [Heath & Love, 2005], the authors have derived a method to determine whether a MIMO system with linear receiver is more suitable for multiplexing or diversity. In particular, it can be shown that a $M_r \times 2$ MIMO channel is spatial multiplexing-preferred if its condition number, $\kappa = \lambda_1 / \lambda_2$, satisfies the following criterion:

$$\kappa \leq \gamma = \frac{2^B - 1}{(2^{B/2} - 1)2}, \quad (9)$$

where B is the total number of bits that will be transmitted in one signaling interval. If both scheduled users in CSM send the data with identical modulation formats in the uplink transmission, B is simply the double of the bit number from the individual user. For examples, both users in the scheduled pair send their data with QPSK and 16-QAM when $B = 8$ and 4 respectively. Note that the condition number characterizes the spatial selectivity of a MIMO channel, and spatial multiplexing schemes are more appropriate for MIMO channels with spatial streams that are closer in magnitude. Thus, we may utilize the criterion of (9) to identify the user pairs that are capable to realize a spatial multiplexing-preferred MIMO channel. Then, among all these identified pairs, the BS chooses the pair with the highest capacity for scheduling. In short, we propose a novel metric:

$$\Phi_j = \max \left[0, C_j \left(\frac{\gamma - \kappa_j}{|\gamma - \kappa_j|} \right) \right], j = 1 \dots W \quad (10)$$

and the pair of user is scheduled by choosing the option index:

$$j^* = \arg \max_j \Phi_j, \quad (11)$$

If none of W options has a SM-preferred channel, i.e. all $\kappa_j > \gamma$ and hence all $\Phi_j = 0$, the BS simply choose the pair based on (8). This leads to an adaptive scheduling scheme which switches its selection metric between (11) and (8) depending on if all Φ_j are zero. Although

the mean channel capacity of this method may be lower than the one in Section 4.2, but it should provide better error performance, assuming that linear receiver is used at the BS.

Along with the advantages in error rates, using this novel metric may also improve the system fairness. In low mobility scenarios, the channels of the users do not change significantly over time. Hence, scheduling based on capacity may "starve" the users who have low quality channels for a long period of time. Nevertheless, the newly proposed selection metric takes the channel condition number into account, which reduces the chance of consecutively scheduling specific users. It can be explained by using the nature of condition number and capacity in terms of auto-correlation functions (ACF). As shown in Fig. 3, the ACF for $\kappa(t)$ decays faster than the one for $C(t)$, which means the variation of κ is more sensitive to channel fluctuations. Hence, in low mobility cases, scheduling based on the proposed metric can provide a better fairness performance, as the BS is less likely to schedule specific users for too long, due to the faster variation of the condition number.

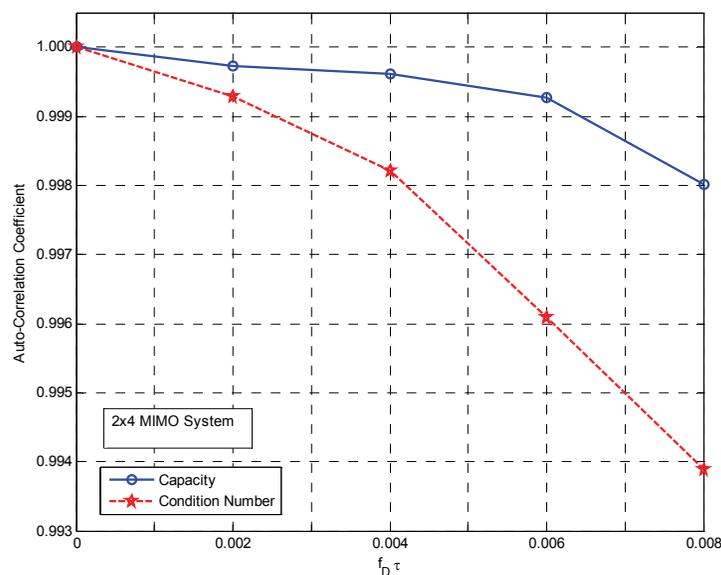


Fig. 3. Autocorrelation functions for MIMO channel capacity and condition number

5. Cooperative Relaying Spatial Multiplexing (CRSM)

In the last section, a novel metric for CSM user scheduling has been proposed. Here we further apply this metric to develop a relay recruitment algorithm for CRSM. In particular, the single-relay CRSM topology delineated in [Kim et al., 2007] is considered. At the beginning, the source node evenly splits the whole data stream, \mathbf{x} , into two segments (x_1 and x_2). Then, one of its N neighbouring nodes is chosen to play the role of relay. Phase 1 transmission is commenced once the active relay is chosen. During Phase 1, the source shares the data segment, x_2 , with the relay. In Phase 2, the relay forwards the data segment that it has received and decoded in Phase 1 (\hat{x}_2) to the destination, and the source also concurrently participates the transmission by sending x_1 to the destination. The topology of this CRSM scheme is illustrated in Fig. 4.

For CRSM schemes with decode-and-forward protocols, it is essential for the relay to correctly decode the messages from the source during Phase 1. Otherwise Phase 2 transmission would become pointless as the data forward by the relay is erroneous at the first place. This implies that the link strength between the source and the relay must be strong enough to ensure reliable transmission in Phase 1. Thus, it is more appropriate for CRSM to operate in a clustered system [Yuksel & Erkip, 2007], in which multiple closely-placed user nodes establish a cluster. In the cluster, inter-user links can be modelled as simple AWGN channels [Ng et al., 2007], and the information exchange between the source and the relays is certainly easier. In practice, a clustered system could be found in indoor applications, where the user nodes are relatively closer to each other. Also, since mobility levels of users in indoor wireless networks are generally low, cooperative schemes (many of which require quasi-static channels) are more feasible.

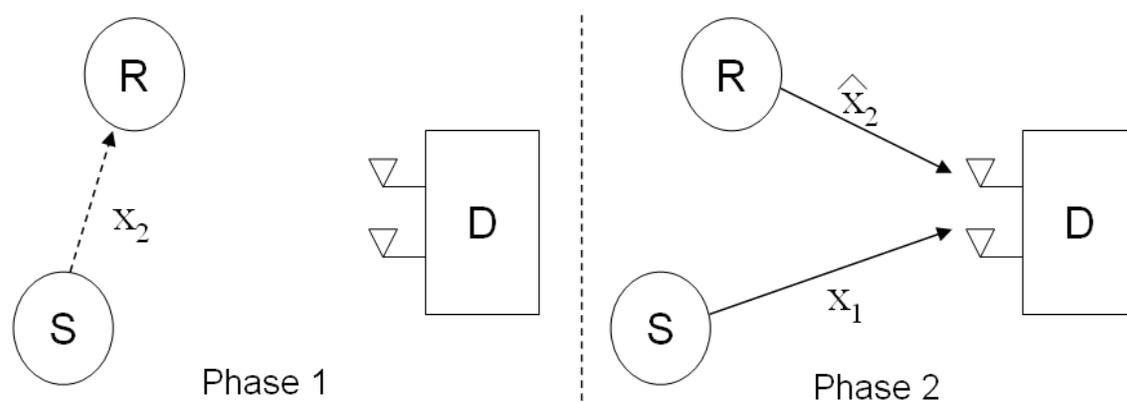


Fig. 4. The illustration of a decode-and-forward CRSM scheme: in Phase 1, the source node (S) shares a portion of data with the relay node (R). Both S and R concurrently send different portions of data in Phase 2 transmission

5.1 Channel model and assumptions

A single-cell, single-source uplink scenario is considered. The base station (destination) has $M_r > 1$ antennas, and each of the user nodes (including the source and all potential relays) is equipped with single antenna. The nodes are assumed to lie in either *AWGN Zone* or *Rayleigh Zone* of the source depending on their locations [Yuksel & Erkip, 2007]. The link from the source to a node is modelled as an AWGN channel with a scalar gain if the distance between these two terminals is smaller than the threshold q . Otherwise, a Rayleigh fading channel is used to model this inter-node link [Ng et al., 2007]. In this chapter, we assume that the source has established a cluster with some other user nodes in proximity based on certain protocols and techniques. It is further assumed that the user cluster and the destination are separated by a distance larger than q . Thus, while all intra-cluster links are AWGN, the link between the destination and every node in the cluster is modelled as a Rayleigh flat-fading channel. The model is depicted in Fig. 5, where we have termed the cluster as *S-R Cluster* since only the nodes within the cluster are considered as relay candidates R_C .

Virtually, during Phase 2, each of the user nodes (including the relay and the source itself) emulates a transmit antenna of a spatial multiplexing system. Hence, the effective virtual

MIMO channel matrix realized in Phase 2 is formed by cascading channel vectors of the source and relay:

$$\mathbf{H}_{eff} = [\mathbf{h}_S \quad \mathbf{h}_R] = \begin{bmatrix} h_{1,S} & h_{1,R} \\ h_{2,S} & h_{2,R} \\ \vdots & \vdots \\ h_{M_r,S} & h_{M_r,R} \end{bmatrix}, \quad (12)$$

where \mathbf{h}_S and \mathbf{h}_R represent the channel vector from the source and the relay to the destination (similar to (1)), respectively. Similarly, the entries of the fading channel vectors are modelled as a complex Gaussian with zero-mean and unit variance in this work. Furthermore, we assume that the source has full knowledge regarding the quality (such as channel state information and battery power) of the other nodes within the user cluster.

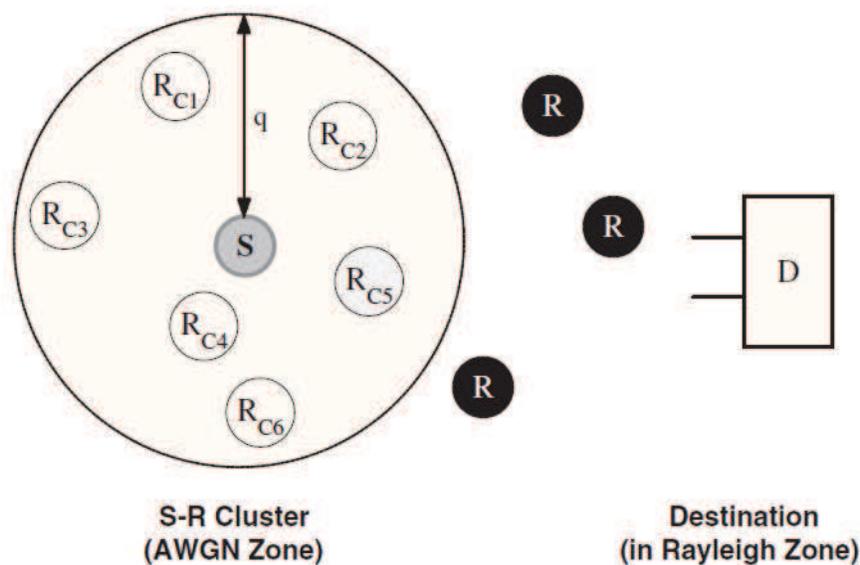


Fig. 5. A source establishes a cluster with some other user nodes that are within its AWGN Zone, and the destination is located in its Rayleigh Zone. The user nodes outside the cluster are not considered as candidates of relays

6. Relay recruitment algorithm for CRSM

6.1 Initial elimination

Once the source has obtained a list of N potential candidates in the cluster, it should first identify unqualified candidates and remove them from the list. As aforementioned, if errors occur in Phase 1 transmission, Phase 2 becomes pointless since the data forwards by the relay is erroneous in the first place. To make sure that the relays can decode the message correctly in Phase 1, the nodes that have weak intra-cluster links to the source should be discarded, as their link gains to the source are not strong enough to support reliable Phase 1 transmission. Additionally, the nodes that have insufficient battery power to participate the cooperation should notify the source and quit from the list. After withdrawing u nodes in this initial elimination, the number of remaining nodes on the candidate list is $Q = N - u$.

The next task is to find a suitable \mathbf{h}_R by selecting a relay out of the remaining Q candidates. In the special cases where $N=0$ (no other nodes are found in the cluster) or $N=u$ (all candidates in the cluster are unqualified), the source transmits the data to the destination directly without cooperation, and simple combining techniques (such as maximum ratio combining) can be leveraged at the receiver.

6.2 Decision metric

Intuitively, in order to maximize the system throughput, the relay could be chosen based on the maximum capacity criterion described in Section 4.2. However, as aforementioned, although the channel capacity can be optimized by choosing the relays based on the maximum value of (7), the characteristic of the resultant effective channel may not be appropriate for spatial multiplexing. To be specific, the error performance of a spatial multiplexing system is degraded if the channel matrix is *ill-conditioned*. As mentioned in Section 4.3, the condition number could be employed to judge if a MIMO channel is multiplexing-preferred. In particular, if the condition number is smaller than the threshold level given in (9), then the MIMO channel is more suitable for the operation of spatial multiplexing. Thus, the criterion proposed in Section 4.3 can be applied as the decision metric for relay selection of CRSM:

$$j^* = \arg \max_j \Phi_j, j = 1 \dots Q \quad (13)$$

where

$$\Phi_j = \max \left[0, C_j \left(\frac{\gamma - \kappa_j}{|\gamma - \kappa_j|} \right) \right], j = 1 \dots Q \quad (14)$$

The definitions of C , κ and γ are available in Section 4. In circumstances when the values of Φ_1, \dots, Φ_N are all zero (none of the relay candidates can realize a spatial multiplexing-preferred effective channel), the source computes the values of Φ_j for (13) again with a different formula:

$$\Phi_j = C_j, j = 1 \dots Q \quad (15)$$

This is simply tantamount to directly choosing a relay that maximizes the capacity.

6.3 Procedural summary

To recapitulate, the steps of the proposed recruitment algorithm is summarized as following:

1. Withdraw u unqualified candidates in the cluster from consideration. If $N=0$ or $N=u$ ($Q=0$), the source transmits the data to the destination directly without cooperation, and the algorithm terminates here. Otherwise, proceed to step 2.
2. Find the index of the relay $j^* = \arg \max_j \Phi_j$, where Φ_j is computed using (14). The algorithm finishes here if $\Phi_{j^*} > 0$. Otherwise, proceed to step 3.
3. If $\Phi_{j^*} = 0$, repeat step 2 with the computation of Φ_j using (15) in lieu of (14).

7. Simulation results

In order to illustrate the performance of the proposed selection metric in both CSM and CRSM schemes, several simulations have been carried out. In particular, the performance of the proposal is evaluated via observations on the resultant error rates. For all simulations, we assume a zero-forcing (ZF) MIMO detector is employed at the receiver (BS). Furthermore, in all cases, we assume that $B = 8$ or 4 bits are transmitted in one signaling interval, so each of the two nodes involved in cooperation sends 16-QAM (4 bits per node) or QPSK (2 bits per node) message in the multiplexing phase. We first examine the performance of CSM. By setting $U = 40$, vector symbol error rates (VSER) of CSM schemes with $B = 8$ and 4 under different pairing modes and selection metrics are shown in Fig. 6 and 7 respectively. Apparently, the proposed selection criterion (MC-SMPC) can achieve the best error performance regardless the pairing mode. As mentioned previously, the condition number-based metric also has the advantage of scheduling fairness as compared to maximum capacity, as the value of condition number changes more rapidly in time-varying channels. To show this, fairness performance of different pairing modes and selection metrics are shown in Fig. 8, and the fairness is measured by the Coefficient of Variance (CoV), which is defined as the ratio of standard deviation to mean number of times that each user is scheduled, so a lower CoV generally indicates better fairness. Remarkably, as shown in Fig. 8, user selections based on MC-SMPC are fairer than the ones based on MC in all three pairing modes, regardless the total number of users.

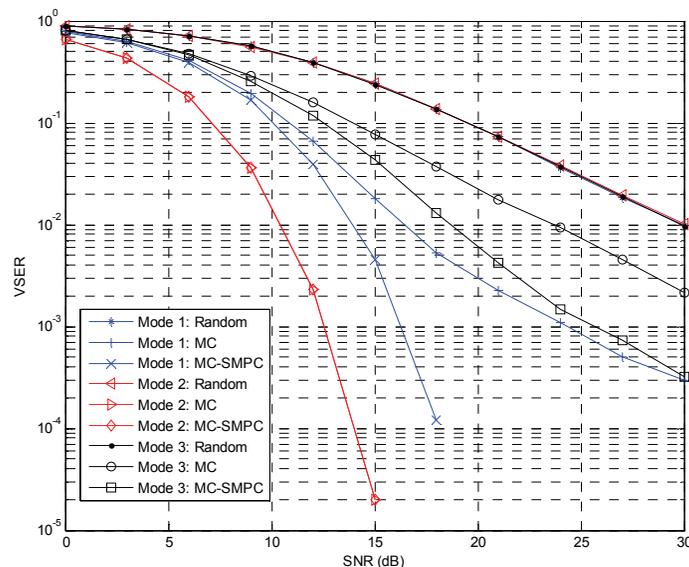


Fig. 6. The VSER performance of different scheduling strategies for CSM schemes with $B = 8$ and $U = 40$. Generally MC-SMPC gives better performance in most cases

Similarly, for CRSM, we compare VSER of three different relay selection criteria, including random selection, maximum capacity, and the proposed method based on condition number. In both Fig. 9 and 10, it is apparent that our proposed selection method can give the best error performance, since it first filters out the candidates that are not able to realize a spatial multiplexing-preferred MIMO channel. The gain of the proposed metric over the other selection criteria is more obvious in high SNR regime, Note that, due to *multi-candidate*

diversity, we expect the performance to improve with the number of relay candidates. As the number of candidates increases, it's more likely for the algorithm to find a more appropriate node to play the role of relay. As compared to the selection based on maximum capacity, the achievable capacity of the proposed method is only slightly lower. In order to inspect the loss in capacity, we further compared the average capacity of these relay selection metrics under different SNR in Fig. 11. Additionally, the cumulative distribution functions (CDFs) of the capacity are also compared in Fig. 12.

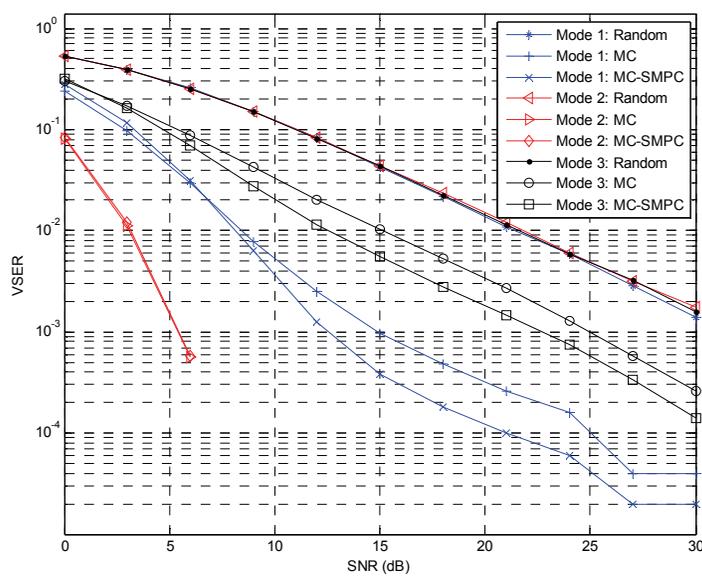


Fig. 7. The VSER performance of different scheduling strategies for CSM schemes with $B = 4$ and $U = 40$. Generally MC-SMPC gives better performance in most cases

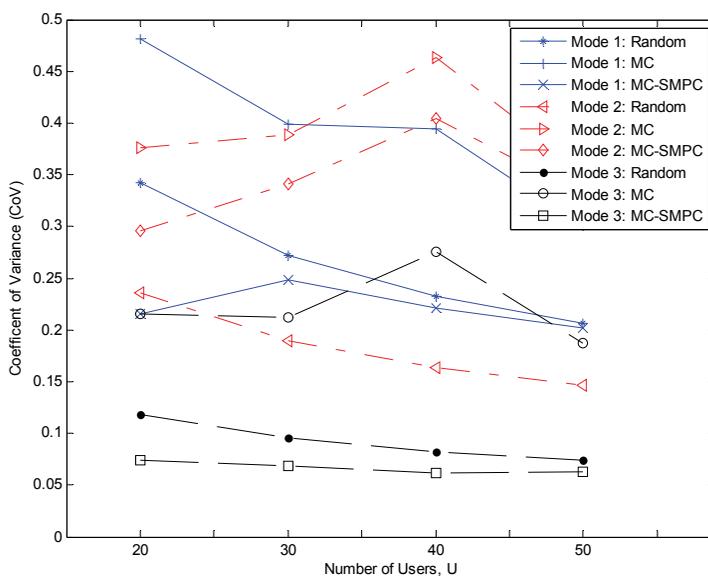


Fig. 8. The comparison of fairness of different user scheduling strategies for CSM schemes

8. Conclusions

This chapter mainly discussed two distributed MIMO uplink transmission schemes, including CSM and CRSM.

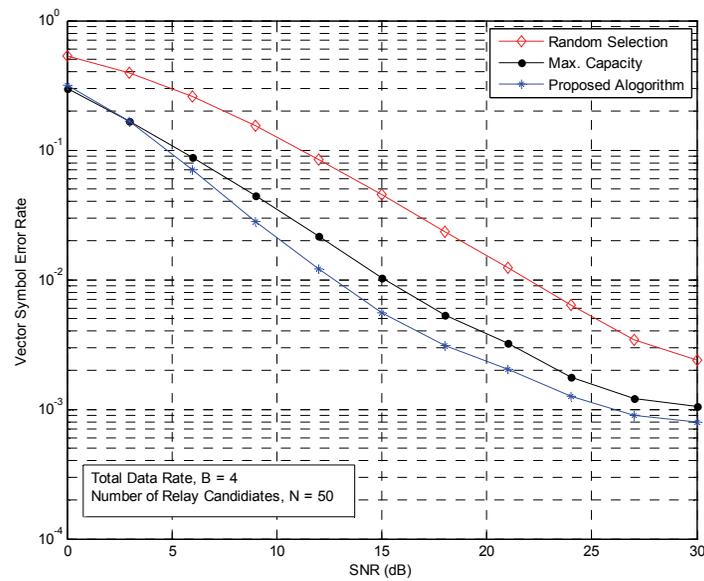


Fig. 9. The VSER performance of different relay selection strategies for CRSM schemes with $B = 4$ and $N = 50$

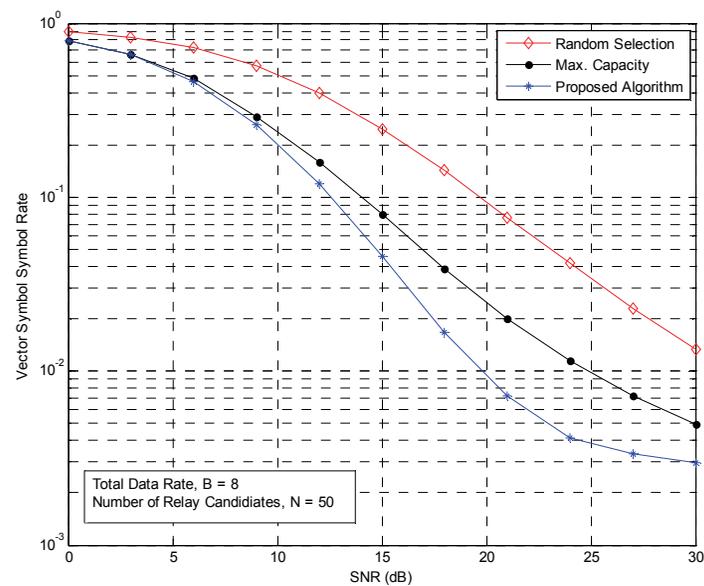


Fig. 10. The VSER performance of different relay selection strategies for CRSM schemes with $B = 8$ and $N = 50$

Both of these schemes allow multiple user nodes to form a virtual antenna array, thereby increases the system throughput via spatial multiplexing. In CSM, the BS is required to

schedule a pair of users to perform concurrent transmission. In CRSM, on the other hand, the source node needs to select a neighbour user as the relay to cooperate with. This chapter proposed a novel selection criterion based on MIMO channel condition number, which aims to provide a spatial multiplexing-preferred virtual MIMO channel for collaborative uplink transmission. In accordance to computer simulations, it is clear that the proposed selection criterion outperforms some other metrics in terms of the error performance, regardless it is being invoked for user scheduling in CSM or relay selection in CRSM.

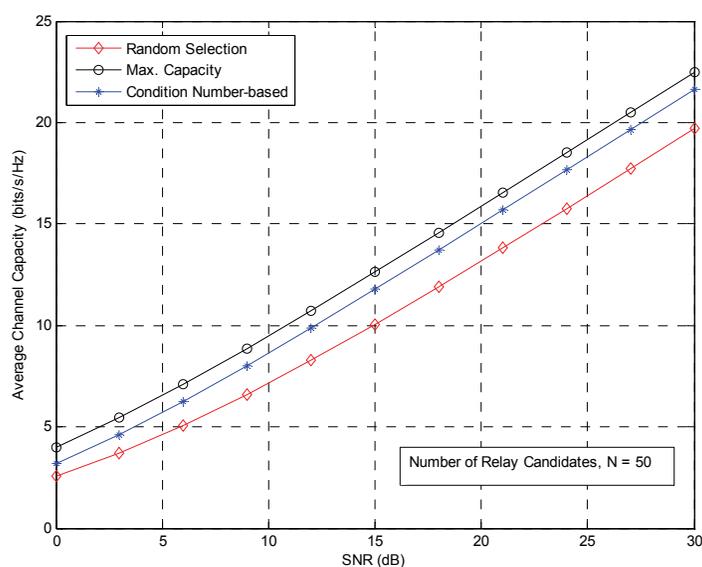


Fig. 11. The comparison of mean channel capacity for different relay selection algorithms with $N = 50$

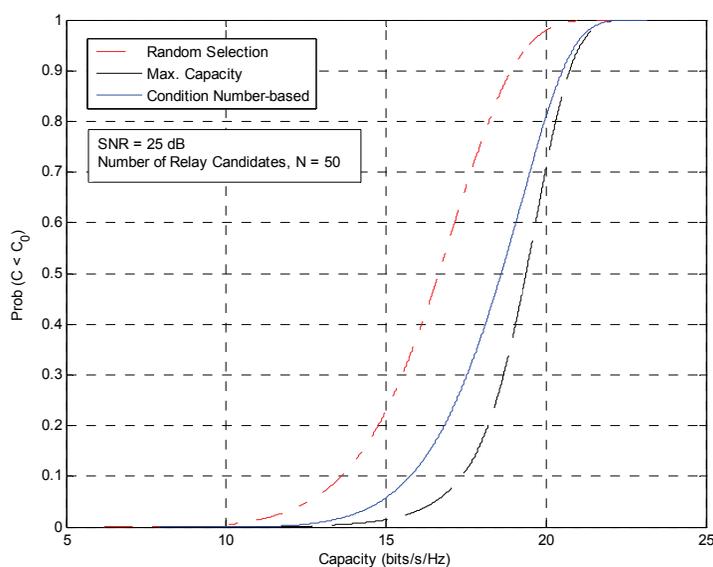
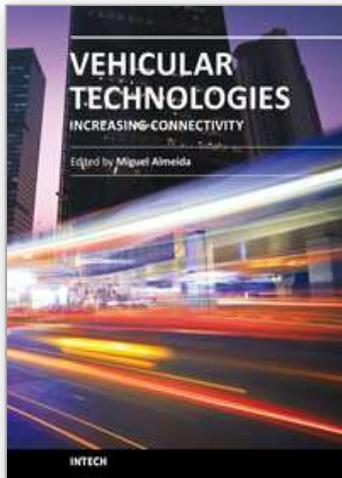


Fig. 12. The comparison of capacity cumulative density functions (cdf) for different relay selection algorithms with a SNR of 25dB and $N = 50$

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