

ACTIVE USER COOPERATION IN FADING MULTIPLE-ACCESS CHANNELS

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ABSTRACT

Consider a two-user fading cooperative multiple-access channel (CMAC), where each user, along with transmitting its own information to the destination, helps the other user by forwarding the latter's information. It is assumed that the transceivers (nodes) are capable of half-duplex communication and that full channel state information (CSI) is available at all the nodes. Cooperative transmission strategies based on a flow-theoretic approach are proposed. The proposed strategies include a sub-optimal but simple orthogonal relaying strategy for the CMAC (OR-CMAC), and a flow-optimized strategy for the CMAC (FO-CMAC). The proposed protocols are evaluated in terms of achievable rate regions and outage performances, for different scenarios. The boundaries of the achievable rate regions for the proposed strategies are characterized by convex optimization formulations, and FO-CMAC is shown to provide improved achievable rate regions as compared to the conventional multiple-access channel (MAC), and a previously proposed strategy based on the decode-and-forward (DF) approach. Although sub-optimal in terms of the achievable rate region, OR-CMAC is shown to provide outage performance close to FO-CMAC for the scenarios considered. Moreover, by comparing to a lower bound on the outage probability, both the proposed strategies are shown to achieve the optimal diversity order of two for the required rate region of interest.

I. INTRODUCTION

The growing emphasis on multi-user wireless communication systems and the ever-increasing demand for high data rates have heightened the importance of research in the area of user cooperation. Although wireless systems bring forth design challenges owing to multi-user interference and fading concerns, they also provide potential benefits, like the broadcast nature of the wireless medium and diversity advantages in multi-user systems. The MAC is one of the fundamental forms of multi-user communication systems. Conventionally, in a MAC, the users transmit directly to the destination, and the capacity region of such a system is well known. Recently, it

has been demonstrated [1], [2] that the rate region of the fading MAC can be increased by exploiting spatial diversity that is achieved by user cooperation in the form of forwarding each other's information to the destination, giving rise to the CMAC.

Although the capacity region for the CMAC is yet to be determined, there have been a number of different cooperative transmission strategies proposed in the literature. Two broad classes of works reported in this regard can be distinguished based on the transceiver capabilities of the wireless nodes, i.e. whether the nodes can support full-duplex communication or not.

In [1], the authors provide a system-level description of the CMAC wherein the nodes are capable of full-duplex communication. They present an achievable rate region based on block Markov encoding and backward decoding, and show the potential increase in the rate region as compared to the conventional MAC. It is assumed that the phase of the fading is known to the transmitters and this is exploited to perform coherent combining at the destination node to achieve beamforming gains. In [2], the CDMA implementation aspects of the scheme in [1] are considered, wherein the authors propose the use of different spreading codes to obtain different channels for simultaneous transmission and reception, without the use of complicated echo cancellation techniques. The power allocation problem for the CMAC with full-duplex nodes and full CSI available at all nodes has been addressed in [3] and [4]. In [3], the authors consider average power constraints and characterize the optimal power allocation policies that maximize the set of ergodic rates, achievable by block Markov encoding and backward decoding technique as in [1], by a dimensionality reduction approach, i.e. by noting that some of the power allocations are zero for every fading state. A more direct approach to solve the similar problem of optimal power allocation, with an almost closed-form solution, is presented in [4]. It has been established in [5] that windowed decoding is sufficient to achieve the same sum-rate as backward decoding for the block Markov

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superposition encoding scheme for the CMAC.

The optimal power and resource allocation problem for the CMAC with nodes capable of half-duplex communication is considered in [6], where it is assumed that full CSI is available at all the nodes, and the transmitters cooperate by relaying each other's information over orthogonal frequency bands or time slots. The solution to the problem is presented as a two-step convex optimization problem formulation: first, for a particular bandwidth (or time) sharing parameter value, the optimal power allocation is characterized by a convex optimization problem, and then, the optimal resource (bandwidth or time) sharing parameter is obtained as a solution to the quasi-concave problem of maximizing the rate of one user, given a target rate for the other. All the works mentioned above use the DF approach for the relaying of information to the destination.

In [7], the authors present a cooperative transmission scheme, based on the non-orthogonal amplify-and-forward (NAF) technique, that is proved to achieve the optimal diversity-multiplexing tradeoff of $N(1-r)$ for the N -user half-duplex CMAC, with symmetric data rate requirement and CSI available only at the receiving node of any link. According to the proposed strategy, time is divided into cooperation frames of length N cooperation symbols, and each user transmits only once during a cooperation frame. Every user is allotted unique transmission and reception symbol intervals, using a particular scheduling policy, and it transmits a linear combination of its own symbol and the signal observed during its most recent reception symbol interval, thereby creating an artificial inter-symbol interference (ISI) channel.

Similar in structure to the above NAF strategy, a cooperative transmission scheme for the two-user CMAC, based on superposition modulation and multiuser detection, has been proposed in [8]. This scheme uses a time division approach in which a user simultaneously transmits its own information and the other user's information by using the superposition coding (SPC) technique. This scheme is demonstrated to achieve a gain of about 1.5–2 dB over the traditional DF-based cooperative diversity scheme, and at the same level of system complexity of the latter. An extension of this idea to the general N -user CMAC is presented in [9], wherein the authors prove the optimality of the proposed scheme in achieving the optimal diversity-multiplexing tradeoff for the symmetric rate requirement scenario.

In this paper, we propose flow-theoretic cooperative transmission strategies for the two-user CMAC. First, we

present an orthogonal relaying strategy for the CMAC (OR-CMAC), wherein each user acts as a dedicated relay for the other in a time-division fashion. The flow-optimized relaying approach of [10], modified to incorporate coherent combining at the destination, is used for the constituent relay channels. This relaying strategy has been shown to achieve the optimal diversity order and provide better coding gains for the relay channel as compared to traditional DF relaying methods, by efficiently utilizing the CSI available at all nodes. Next, we propose the flow-optimized strategy for the CMAC (FO-CMAC) that decomposes the CMAC into two broadcast channels (BCs)¹ and a multiple access (MA) channel with common information. The boundaries of the achievable rate regions are characterized by means of convex optimization formulations. The performances of the proposed strategies improve as the amount of disparity between the direct channels increases. The outage performances of the proposed strategies indicate that although the much simpler OR-CMAC is sub-optimal in terms of the achievable rate region, it provides outage performance that is within 1 dB of that of FO-CMAC. Moreover, both the proposed strategies achieve the optimal diversity order of two for the required rate region of interest.

The rest of the paper is organized as follows. In Section II, the flow-theoretic strategies of OR-CMAC and FO-CMAC are presented, and the boundaries of the achievable rate regions are characterized using convex optimization formulations. This is followed by numerical results presenting the achievable average rate regions and outage performances for different scenarios in Section III. Finally, the paper is concluded in Section IV.

II. FLOW-THEORETIC TRANSMISSION STRATEGIES FOR THE CMAC

Consider a two-user CMAC where the two sources (S_1 and S_2) may actively cooperate to transmit information to a common destination (D). We use the phrase *active cooperation* to distinguish between the cooperation involved in transmission strategies in which one source may forward the other's information, and that in the conventional MAC, wherein a user cooperates by transmitting at a rate lower than the maximum single-user rate possible for the particular channel state and power expended. The quantification of this type of cooperative

¹The concept of "broadcast channel" should not be confused with that of "broadcast service". While the former is essentially unicast in nature, with a transmitted packet having different messages for different destinations, the latter refers to the case of the same information being transmitted to all the nodes in the system.

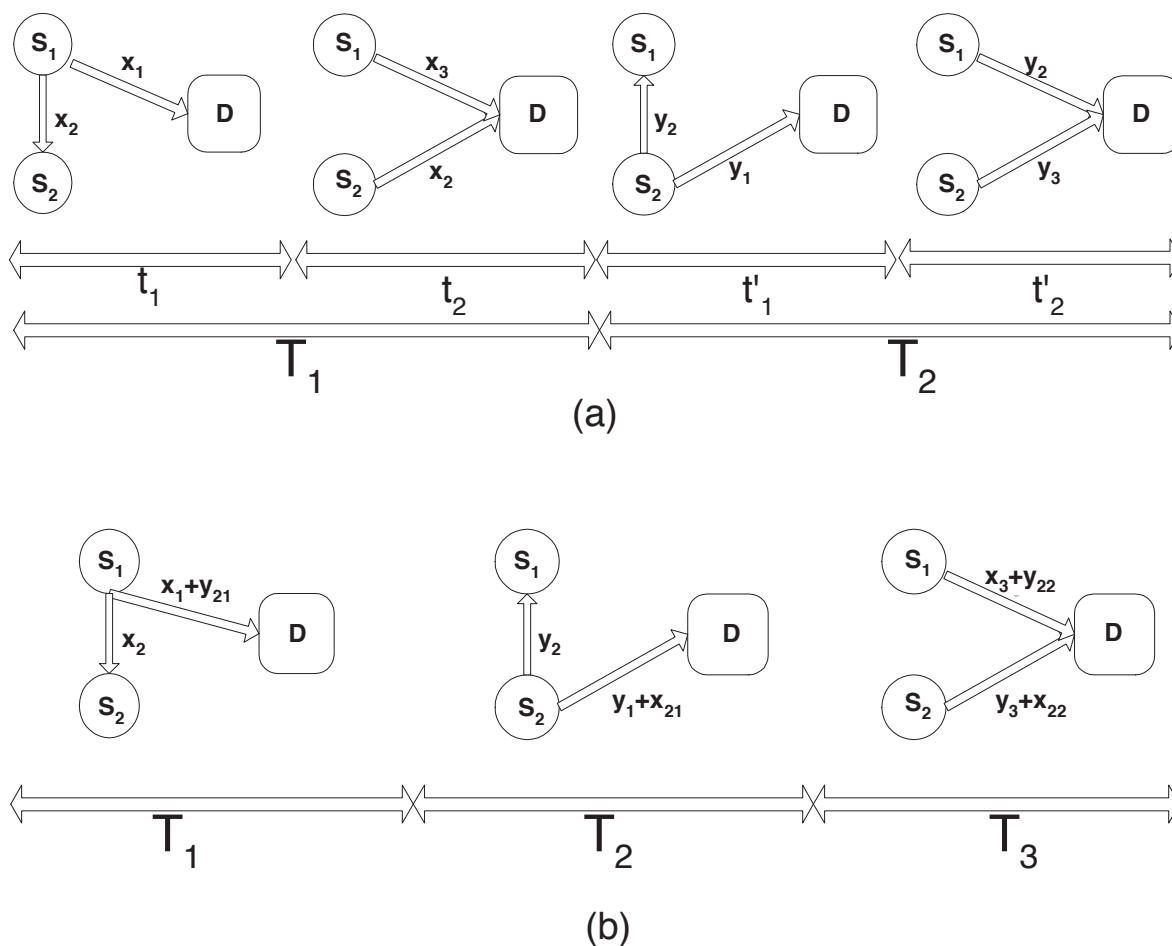


Fig. 1. Flow-theoretic transmission strategies for the CMAC: (a) OR-CMAC, (b) FO-CMAC.

behavior has been studied and reported in [11]. Thus, as a higher level of cooperative behavior, the users may relay the information of each other by utilizing the broadcast advantage of the wireless medium, giving rise to the CMAC model. We consider a discrete-time two-user fading MAC with unit bandwidth, in the presence of unit-variance Gaussian noise, with the fading state described by the power gain vector $\mathbf{Z} = (Z_{S_1 S_2} \ Z_{S_1 D} \ Z_{S_2 D})$. Note that, owing to the reciprocity of channels, we assume $Z_{S_1 S_2} = Z_{S_2 S_1}$.

The power gains for the wireless links are modeled as independent exponential random variables. We consider two types of fading models in this paper. In the first part of Section III, we consider the situation in which the channels are ergodic within a transmission block, for which we evaluate the transmission strategies using average rates as the performance metric. Then, we present the outage performance of the proposed strategies for the

model in which the fading is not fast enough and hence, the channels may not be ergodic during a transmission block. This system model can be easily generalized to the case where the bandwidth $W \neq 1$.

Let \bar{P}_i be the maximum transmission power available to the source S_i . In this paper, we consider short term power constraints only, and this precludes any potential advantage of power allocation. We assume that full CSI is available at all nodes in the system. Moreover, as a practical consideration, we assume that the nodes are not capable of transmitting and receiving information simultaneously over the same frequency, i.e. they are subjected to a half-duplex constraint. In the following subsections, we present two protocols based on flow-theoretic designs to develop cooperative transmission schemes for information transmission from the source nodes S_1 and S_2 to the destination node D .

A. Orthogonal Relaying Strategy for the CMAC (OR-CMAC)

In this subsection, we present a simple cooperative transmission strategy based on the conventional relaying approach. Time is divided into unit intervals. Owing to the half-duplex limitation of the sources, the two sources cannot relay each other's information at the same time. To address this, we divide each unit interval into time slots of lengths T_1 and T_2 . During the first time slot, S_2 solely assists S_1 , by acting as a dedicated relay for S_1 , to transmit the latter's information to D . The reverse happens during the second time slot. This is depicted in Figure 1.

Thus, we effectively have two relay channels over two orthogonal time slots. We use the flow-optimized transmission scheme of [10] for the three-node relay channel. According to the strategy presented therein, each time slot of length T_1 (resp. T_2) is further divided into two sub-slots of lengths t_1 and t_2 (resp. t'_1 and t'_2). Consider the first time slot of length T_1 . During the first sub-slot of length t_1 , S_1 sends two independent flows of information x_1 and x_2 to D and S_2 respectively using a BC, and in the second sub-slot of length t_2 , S_2 forwards x_2 to D and at the same time S_1 sends out another information flow x_3 to D . The two information flows, x_2 and x_3 , are received at D via multiple-access (MA).

To improve the achievable rates even further, we modify the second sub-slot, from a conventional MA slot, as described next. Since the flow x_2 , that S_2 forwards to D originated at S_1 , the latter is aware of it, and hence, we modify the second sub-slot from a conventional MAC to a MAC with common information [13], where x_2 forms the common information between S_1 and S_2 , x_3 is the independent information from S_1 , and S_2 does not have any independent information to transmit. For this relaying scheme, maximizing the overall transmission rate from S_1 to D can be formulated as the following optimization problem:

$$\max x_1 + x_2 + x_3 \quad (1)$$

over $t_1, t_2, x_1, x_2, x_3, P_1, \Upsilon_0$, subject to

non-negativity constraints: $x_1, x_2, x_3 \geq 0; t_1, t_2 \geq 0$;

total-time constraint: $t_1 + t_2 = T_1$;

capacity (power) constraints: $P_{BC} \leq \bar{P}_1$;

$x_3 \leq t_2 C(Z_{S_1 D} P_1); x_2 + x_3 \leq t_2 C(Z_{S_1 D} P_1 + \Upsilon_0)$;

$0 \leq P_1 \leq \bar{P}_1; \Upsilon_0 \leq Z_{S_1 D}(\bar{P}_1 - P_1) + Z_{S_2 D} \bar{P}_2 + 2\sqrt{Z_{S_1 D}(\bar{P}_1 - P_1)Z_{S_2 D} \bar{P}_2}$;

where $C(x) = \log(1+x)$ and P_{BC} , the minimum power required for the source to broadcast at rates x_1/t_1 and

x_2/t_1 to the destination and the relay, respectively, in the first sub-slot with $0 < t_1 \leq 1$, is given by (see [12, Lemma 3.1] for proof)

$$P_{BC} = \begin{cases} \frac{1}{Z_{S_1 D}}(e^{x_1/t_1} - 1) + \frac{1}{Z_{S_1 S_2}}e^{x_1/t_1}(e^{x_2/t_1} - 1) & \text{for } Z_{S_1 S_2} > Z_{S_1 D}, \\ \frac{1}{Z_{S_1 S_2}}(e^{x_2/t_1} - 1) + \frac{1}{Z_{S_1 D}}e^{x_2/t_1}(e^{x_1/t_1} - 1) & \text{for } Z_{S_1 S_2} \leq Z_{S_1 D}. \end{cases}$$

For $t_1 = 0$, $P_{BC} = 0$. P_1 is the power that S_1 allocates for the direct transmission of x_3 to D , and Υ_0 denotes the power corresponding to the common information flow (x_2), received at D .

It can be checked that the above maximization problem is a convex optimization problem, and standard numerical techniques can be used to obtain a solution. Let the solution of (1) be denoted by $X(\mathbf{Z}, T_1)$. Then it can be easily seen that $X(\mathbf{Z}, T_1) = T_1 X(\mathbf{Z}, 1)$. For the second time slot, an exactly similar optimization problem can be formulated as (1) with appropriate changes in the indices.

Therefore, for a particular fading state \mathbf{Z} , the regular points on the boundary of the achievable rate region can be obtained by maximizing a convex combination of the rates of the two sources, $X(\mathbf{Z}, T_1)$ and $Y(\mathbf{Z}, T_2)$, during the respective time slots. That is, for some $0 < \mu < 1$,

$$\max \mu X(\mathbf{Z}, T_1) + (1 - \mu)Y(\mathbf{Z}, T_2) \quad (2)$$

subject to $T_1, T_2 > 0; T_1 + T_2 = 1$. The extreme points of the boundary region, that correspond to maximizing only one source's rate, are given by $T_1 = 1, T_2 = 0$, etc. Unfortunately, this naive scheme of decomposing the CMAC into two orthogonal relay channels does not entail the best utilization of resources, and as we shall see in the following subsection, this can be improved upon by a more efficient flow-optimized transmission strategy.

B. Flow-optimized Strategy for the CMAC (FO-CMAC)

Instead of dividing the CMAC into two separate relay channels, we divide a unit interval into three time slots of lengths T_1, T_2, T_3 with no orthogonalization of the relaying actions. Now, the first two time slots are BC slots and the last one is an MA slot with common information, as shown in Figure 1. During the first time slot, S_1 transmits two independent flows: $x_1 + y_{21}$ and x_2 to D and S_2 respectively using a BC. Similarly, S_2 transmits two independent flows: $y_1 + x_{21}$ and y_2 to D and S_1 respectively using a BC in the second time slot. Finally, S_1 and S_2 send two flows, $x_3 + y_{22}$ and $y_3 + x_{22}$ respectively, to D using MA with common information. Here y_{21} and y_{22} are two parts of the information flow

$$P_{BC}^1 = \begin{cases} \frac{1}{Z_{S_1 D}} (e^{(x_1+y_{21})/T_1} - 1) + \frac{1}{Z_{S_1 S_2}} e^{(x_1+y_{21})/T_1} (e^{x_2/T_1} - 1) & \text{for } Z_{S_1 S_2} > Z_{S_1 D}, \\ \frac{1}{Z_{S_1 S_2}} (e^{x_2/T_1} - 1) + \frac{1}{Z_{S_1 D}} e^{x_2/T_1} (e^{(x_1+y_{21})/T_1} - 1) & \text{for } Z_{S_1 S_2} \leq Z_{S_1 D}. \end{cases} \quad (4)$$

For $T_1 = 0$, $P_{BC}^1 = 0$.

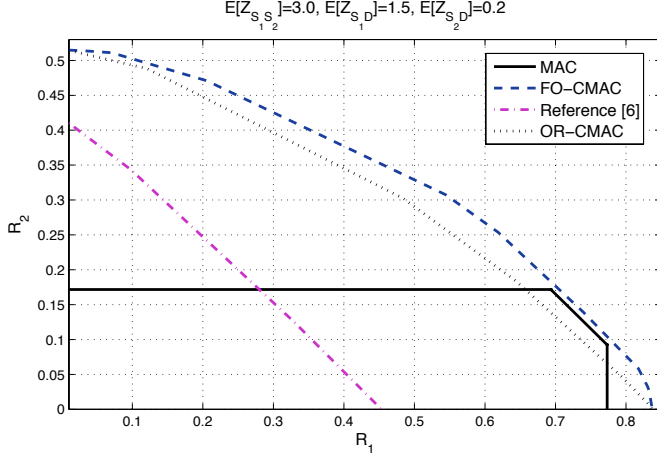


Fig. 2. Achievable rate regions - asymmetric situation.

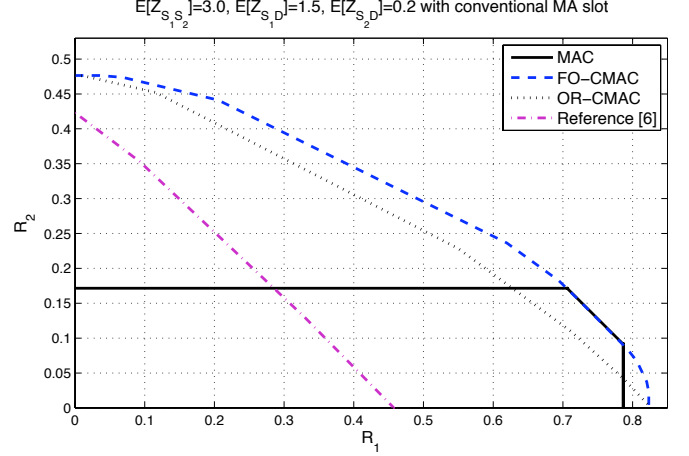


Fig. 3. Achievable rate regions - asymmetric situation with conventional MA slot (without common information).

y_2 that S_1 received from S_2 during the previous unit interval. Similarly, x_{21} and x_{22} constitute the amount of information that S_2 relays for S_1 . Thus, for this scheme, the flow constraints imply that $x_2 = x_{21} + x_{22}$, and $y_2 = y_{21} + y_{22}$. Also, for the last time slot, x_{22} and y_{22} are known to both the sources, and hence, they form the common information to be transmitted to D .

Hence, the total transmission rates from sources S_1 and S_2 are given by $X = x_1 + x_{21} + x_{22} + x_3$ and $Y = y_1 + y_{21} + y_{22} + y_3$ respectively. For this scheme, the boundary of the achievable rate region can be characterized as follows: the regular points on the boundary can be obtained by maximizing a convex combination of the rates X and Y , and the extreme points correspond to the CMAC degenerating into relay channels with one source solely acting as a relay for the other. For compactness, let the information flows corresponding to the two sources be represented by the vectors $\mathbf{x} = (x_1 \ x_{21} \ x_{22} \ x_3)$ and $\mathbf{y} = (y_1 \ y_{21} \ y_{22} \ y_3)$. The maximization problem that needs to be solved to obtain the regular points can be formally stated as given below:

$$\max \mu X + (1 - \mu)Y \text{ for } \mu \in (0, 1) \quad (3)$$

over $T_1, T_2, T_3, \mathbf{x}, \mathbf{y}, P_1, P_2, \Upsilon_0$, subject to

$$\begin{aligned} & \text{non-negativity constraints: } \mathbf{x}, \mathbf{y} \geq \mathbf{0}; \quad T_1, T_2, T_3 \geq 0; \\ & \text{total-time constraint: } T_1 + T_2 + T_3 = 1; \\ & \text{capacity (power) constraints: } P_{BC}^1 \leq \bar{P}_1; \quad P_{BC}^2 \leq \bar{P}_2; \\ & x_3 \leq T_3 C(Z_{S_1 D} P_1); \quad y_3 \leq T_3 C(Z_{S_2 D} P_2); \\ & x_{22} + x_3 + y_{22} + y_3 \leq T_3 C(Z_{S_1 D} P_1 + Z_{S_2 D} P_2 + \Upsilon_0); \\ & 0 \leq P_1 \leq \bar{P}_1; \quad 0 \leq P_2 \leq \bar{P}_2; \\ & \Upsilon_0 \leq Z_{S_1 D}(\bar{P}_1 - P_1) + Z_{S_2 D}(\bar{P}_2 - P_2) + \\ & \quad 2\sqrt{Z_{S_1 D}(\bar{P}_1 - P_1)Z_{S_2 D}(\bar{P}_2 - P_2)}. \end{aligned}$$

As in the previous subsection, P_{BC}^1 and P_{BC}^2 are the minimum powers required by S_1 and S_2 respectively for the two BC slots. P_{BC}^1 is defined as in (4) and P_{BC}^2 is defined similarly. Also, P_1 and P_2 are the powers allocated by S_1 and S_2 to transmit x_3 and y_3 respectively, and Υ_0 denotes the received power at D corresponding to the common information $x_{22} + y_{22}$.

Once again, it can be checked that the above maximization is a convex optimization problem that can be solved using standard numerical optimization methods. Thus, FO-CMAC addresses the half-duplex limitation of the nodes by dividing the CMAC into two BCs and one MAC with common information, and provides a more efficient utilization of system resources as compared to strategies using two separate relay channels.

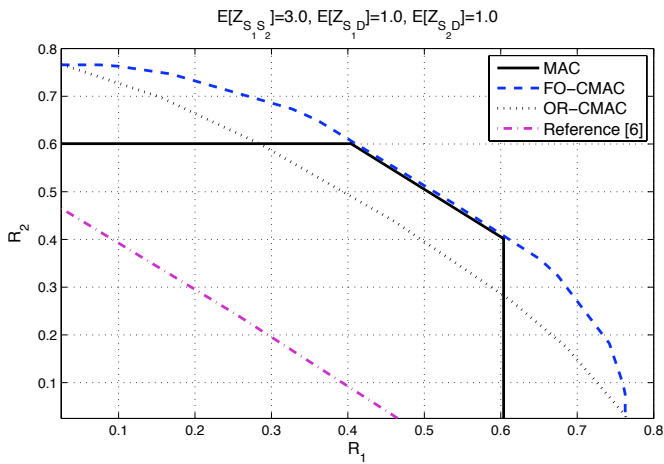


Fig. 4. Achievable rate regions - symmetric situation.

III. RESULTS

In this section, we present some numerical results to demonstrate the performance of the proposed strategies and compare them to the conventional MAC and the DF-based strategy proposed in [6]. Figures 2 through 4 show the achievable average rate regions for the various schemes for different scenarios. We consider different means of the fading gains as stated in the figures. The statistics of the fading gains for the channels Z_{S_1D} and Z_{S_2D} can be considerably different in practice owing to different path loss effects, and different amounts of shadowing and scattering that the two direct links experience. Thus, an asymmetric situation corresponds to the case when the direct link from one source to the destination is much worse than the other.

In Figure 2, the channel from S_2 to D is much worse compared to that from S_1 to D , and the large increase in the achievable rate region for the FO-CMAC rate region is evident. Moreover, we see that the much simpler OR-CMAC performs close to FO-CMAC for this scenario. On the other hand, the performance of the strategy of [6] is much poorer than the above two. Recall that, in this paper, we consider only short term power constraint, and thus we do not consider the power constraint over the entire unit interval as in [6]. This eliminates any potential gains from optimizing the power allocations for the different transmissions. So, for the present system model, the cooperative transmission strategy of [6] is clearly sub-optimal. Figure 3 is presented to highlight the increase in the achievable rate region resulting from the use of MA slots with common information (as in Figure 2) instead of the conventional MA slots. As can be seen from Figure 3, with the use of conventional MA slots,

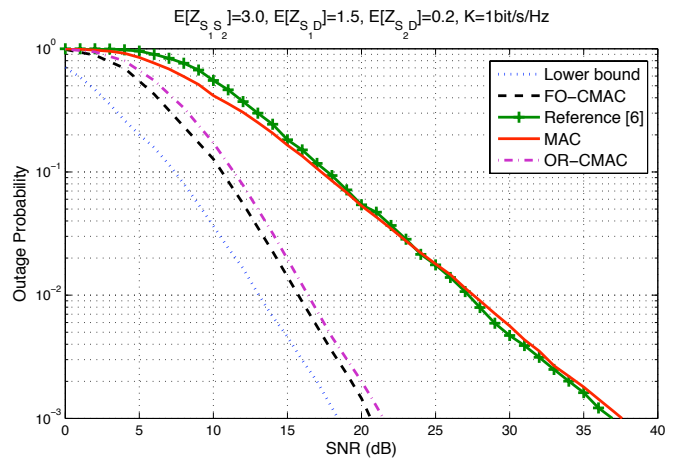


Fig. 5. Outage performance - asymmetric situation.

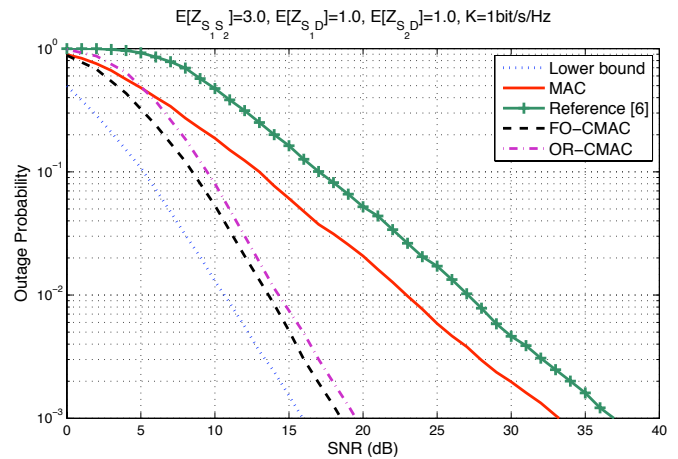


Fig. 6. Outage performance - symmetric situation.

the maximum sum-rate for the FO-CMAC coincides with that of the conventional MAC without active cooperation between the transmitters. The improvement in Figure 2 can be interpreted as the effect of the beamforming gain as in a two-transmitter one-receiver MISO system. Figure 4 presents the symmetric situation, when the two direct links are statistically identical. We see that in this case, the increase in the rate region is not as pronounced as in the previous situation. This can be attributed to the following reasons: the performance of a DF-based strategy for the CMAC depends heavily on the system asymmetry, and, the practical constraint of half-duplex communication leads to a sub-optimal utilization of the system resources as against its full-duplex counterpart.

We also evaluate the outage performances of the proposed strategies when the data rate requirement is symmetric at $K = 1$ bit/s/Hz for both users. The outage

event is defined similar to the definition in [14], i.e. it is the union of the events that either one or both of the users suffer an outage. The outage performances of the proposed strategies are compared to that of the conventional MAC, the strategy of [6], and a lower bound on the outage probability that is obtained by considering the case when the sources have a perfect noiseless channel between them. Figure 5 presents the outage performances for the asymmetric situation as in the average rates case, and Figure 6 presents the same for the symmetric situation. We see that the OR-CMAC suffers a loss of only 0.7 dB and 1.0 dB compared to FO-CMAC, at an outage probability of 10^{-3} , for the asymmetric and symmetric situations respectively. The performance of FO-CMAC is worse than the lower bound by about 2.2 dB and 2.5 dB at the same outage level, for the asymmetric and symmetric situations respectively. On the other hand, the performance of the DF strategy of [6] is significantly poorer, and even worse than the conventional MAC for the symmetric situation. Another important observation from the outage performance plots is that the slopes of the curves for FO-CMAC and OR-CMAC are identical to that for the lower bound curve. Since the latter is identical to the 2×1 MISO point-to-point system, it gives a diversity order of two. Hence, the above observation establishes the fact that both the proposed strategies achieve the optimal diversity order of two for the two-user CMAC for the required rate region of interest.

IV. CONCLUSIONS

In this paper, we propose flow-theoretic cooperative transmission strategies for the two-user fading CMAC, where the nodes are only capable of half-duplex communication and have access to full CSI. We propose two such strategies: a flow-optimized strategy for the CMAC (FO-CMAC), and a sub-optimal but simpler orthogonal relaying strategy for the CMAC (OR-CMAC). Both the proposed strategies are evaluated in terms of achievable rate regions and outage performances. Numerical results show that FO-CMAC yields the largest achievable rate region amongst the different schemes considered. Although OR-CMAC is clearly sub-optimal in terms of the achievable rate region, its outage performance is close (to within 1dB for the scenarios considered) to FO-CMAC, and both the proposed strategies achieve the optimal

diversity order of two for the required rate region of interest.

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