CAO-SIR: Channel Aware Ordered Successive Relaying

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***Abstract*—Cooperative communication suffers from multiplexing loss and low spectral efficiency due to the half duplex constraint of relays. To improve the multiplexing gain, successive relaying, which allows concurrent transmission of the source and relays, has been proposed. However, the severe inter-relay interference becomes a key challenge. In this paper, we propose a channel aware successive relaying protocol, also referred to as CAO-SIR, which is capable of thoroughly mitigating inter-relay interference by carefully adapting relays' transmission order and rate. In particular, a relay having a poorer link to the source is scheduled first to forward a message, the data rate of which is adapted to the link quality of the source-relay and relay-destination channels. By this means, each relay may decode the messages intended for the preceding relays, and then cancel these relays' interference in a low complexity which is equal to that of Decision Feedback Equalizer (DFE). To further optimize and analyze CAO-SIR, we present its equivalent parallel relay channel model, based upon which the adaptive relay selection and power allocation schemes are proposed. By employing M half duplex relays, CAO-SIR is capable of achieving an diversity-multiplexing tradeoff (DMT) given by $d(r) = \max\left\{(M+1)\left(1-\frac{M+2}{M+1}r\right), (1-r)\right\}$, where $d(r)$ and r denote the diversity and multiplexing gains, respectively. Its DMT asymptotically approaches the DMT upper bound achieved by $(M+1)\times 1$ MISO systems or M full duplex relays, when M is large.**

***Index Terms*—Successive relaying, interference cancellation, relay ordering, rate adaptation, relay selection, power allocation, water filling, opportunistic communications, diversity-multiplexing tradeoff.**

I. Introduction

Cooperative communications have been receiving much attention recently because they hold the promise of achieving huge diversity gains over the harsh wireless link, without paying a price of adding more antennas at transceivers, or occupying additional frequency/temporal resources. The fundamental idea behind cooperative communications relies on the fact that the signals transmitted by a source to its destination are also received by other neighbor nodes in a wireless environment. These nodes can then act as relays to process and retransmit the signals which they receive in a distributed manner, thereby creating a virtual multiple antenna system through the use of the relays' antennas.

User cooperation was firstly proposed by Sendonaris *et al.* for CDMA wireless cellular networks [1], [2]. Laneman *et al.* studied the diversity order and DMT of various cooperative diversity schemes including fixed relaying, selection relaying, and incremental relaying from an information theoretic perspective [3], [4]. It was shown that amplify-and-forward (AF) and selective decode-and-forward (DF) protocols achieve the maximal diversity gain, which is equal to the number of nodes participating in cooperative transmission. Based upon network path selection, a simple cooperative diversity protocol without the need for relay signal synchronization or space-time coding was proposed in [5]. The above works mainly focused on two-timeslot relaying protocols, where relays listen to the source in the first timeslot and forward its message in the second timeslot. Such two-timeslot scheduling is proposed to meet the half duplex constraint, i.e. a node cannot transmit and receive simultaneously in the same frequency band. As a result, these relaying protocols will suffer from a significant multiplexing loss. In particular, their multiplexing gains are upper bounded by 1/2.

To recover this multiplexing loss, AF and DF based successive relaying was proposed in pioneering works [6] and [7]. Its core idea relies on the concurrent transmissions of the source and its relays. More specifically, the source transmits to one relay, while another relay transmits to the destination simultaneously. In this protocol, it takes less than two timeslots to send one message in average. As a result, its multiplexing gain is greater than 1/2, while the half duplex constraint is also satisfied. However, it was also noticed that successive relaying may create severe inter-relay interference. It may suffer from poor reliability unless the inter-relay interference is effectively mitigated. The interference cancellation method for AF based successive relaying was extensively studied in [6], [8], and [9]. Yang and Belfiore formulated an equivalent MIMO channel, based on which a joint decoding scheme for MIMO receivers was adopted to mitigate the inter-relay interference [6]. In [8], Wicaksana *et al.* proposed a self-interference cancellation method based on an equivalent MIMO model. More recently, a two-path AF successive relaying method for frequency-selective block fading channels was further investigated by Baek and Seo in [9].

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For DF based successive relaying, inter-relay interference will result in severe decoding error and error propagation. Therefore, interference cancellation becomes a more critical issue. In [7], the decoding method for Gaussian Interference Channel (GIC) with strong interference was adopted in DF based successive relaying. The work in [10] investigated the interference mitigation method, where two symbols transmitted by the source and relay are jointly decoded. A hybrid receiver that carries out both successive cancellation and joint decoding was designed for DF based successive relaying in [11]. For multi-relay scenario, [12] studied the cluster successive relaying, where interference alignment is adopted to avoid interference among relay clusters. Other interference suppression methods such as beamforming and dirty paper coding were also applied into DF based successive relaying in [13] and [14], respectively. Relay scheduling or selection was adopted to further improve the throughput of successive relaying in recent work [15] and [16]. With a focus on the two-path DF successive relaying, recent work [17] and [18] further optimized the interference mitigation schemes at relays. In particular, a robust low complexity interference cancellation based on received signal sample only was presented in [17]. A novel hybrid demodulate and forward method, where relays carry out straightforward and differential demodulation schemes jointly, were proposed in [18]. Most recently, successive relaying is designed and optimized for practical CDMA systems in [19], [20].

It is worth noting that jointly decoding for either AF or DF based succussive relaying results in high computational and hardware complexity at the receivers. Relay selection may avoid adopting jointly decoding in DF based successive relaying [21], but it induces multiplexing loss, because some relays are not qualified to participate in the cooperation. As a result, how to achieve the optimal throughput and DMT in low complexity becomes a challenging issue for successive relaying. In this paper, we propose a simple DF based successive relaying method, namely, Channel Aware Ordered SuccessIve Relaying protocol, also referred to as CAO-SIR. Without jointly decoding, it allows all the selected relays to participate in relaying and thoroughly mitigate the inter-relay interference in low complexity, simply by exploiting two novel mechanisms, namely, relay ordering and message rate adaptation. This is in contrast to conventional successive relaying, where the relays may transmit in arbitrary order and the messages forwarded by different relays have the equal data rate.

The fundamental idea of CAO-SIR relies on our previous work on Network Interference CancEllation, also referred to as NICE [22]. In particular, if the channel gain from a source to an interfered node is greater than that from the source to its relay, the interfered node is capable of decoding the source's message encoded at an appropriate data rate. Then the interfered node may utilize the priori knowledge on the source's message to thoroughly cancel the relay's interference, when the message is forwarded by the relay. Based upon NICE, a novel joint relay ordering and rate adaptation scheme is proposed for CAO-SIR. In particular, relays will forward the source's messages successively in the reverse order of their source-to-relay (SR) channel gains. In other words, the poorer a relay's SR link is, the earlier it transmits. Once the transmission order of each relay is determined, the source further adapt the data rate of the message forwarded by each relay for the relay's SR and relay-to-destination (RD) link quality. The proposed rate adaptation scheme assures that each relay reliably decodes the source's signal and obtains priori knowledge on the messages to be forwarded in proceed timeslots. In this context, we present a rate adaptation aided successive cancellation for both relays and destinations, which is capable of canceling the inter-relay interference thoroughly. In practice, the implementation complexity of the proposed cancellation method is equal to that of Decision Feedback Equalizer (DFE). After the rate adaptation aided interference cancellation, each relay forwards a packet from the source to the destination as if there is no interference at all. This observation motivates us to formulate an equivalent parallel relay channel model, based on which CAO-SIR is further optimized and analyzed. More specifically, we optimize the power allocation and relay selection in CAO-SIR. A double water-filling policy and a one-dimensional search algorithm are presented for power allocation and relay selection respectively, to maximize the throughput and outage probability of CAO-SIR at arbitrary Signal-to-Noise Ratio (SNR). By borrowing the idea of DMT analysis for OFDM systems [23], [24], we show that CAO-SIR achieves a DMT of $d(r) = \max\left\{(M+1)\left(1-\frac{M+2}{M+1}r\right), (1-r)\right\}$, where M is the number of relays. When M is large, its DMT asymptotically approaches the DMT upper bound achieved by $(M+1)\times 1$ MISO systems or M full duplex relays.

The rest of this paper is organized as follows. Section II presents the system model. A basic CAO-SIR is presented along with its interference cancellation scheme in Section III. Section IV optimizes CAO-SIR through relay selection and power allocation. Performance analysis is carried out in Section V. Section VI presents the numerical results. Finally, conclusions and future works are given in Section VII.

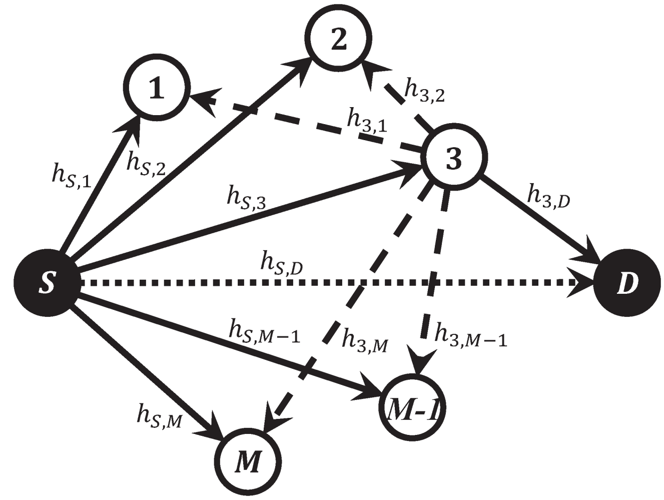

Fig. 1. System model.

II. System Model

Consider a cooperative communication system, where a source node S transmits to its destination node D with the help of M potential relays, as shown in Fig. 1. Let us denote

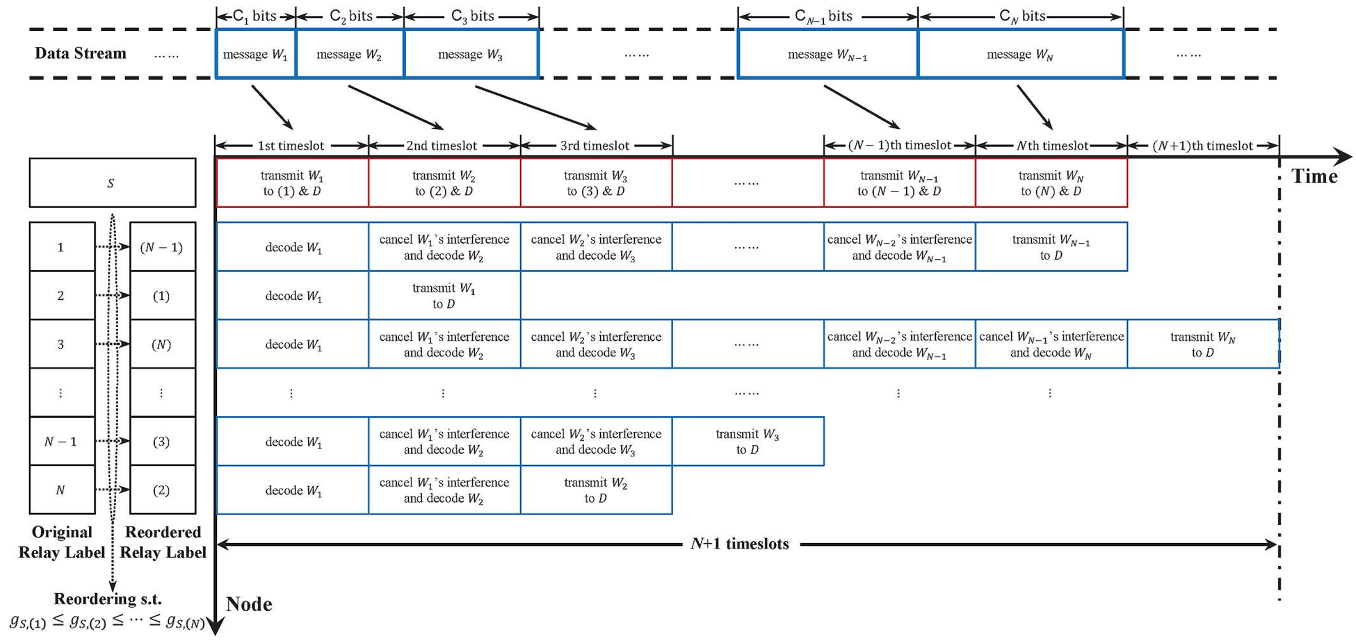

Fig. 2. CAO-SIR protocol: Relay ordering, scheduling, bit loading, and rate adaptation.

the set of potential relays that may help the transmission of S to be $\{1, 2, \ldots, M\}$. The channel coefficient and channel gain of the link between nodes a and b, where $a \in \{S, 1, \cdots, M\}$ and $b \in \{1, \cdots, M, D\}$ are denoted by $h_{a,b}$ and $g_{a,b} = |h_{a,b}|^2$, respectively. Quasi-static or slow fading channels are assumed. The channels remain fixed in each successive relaying period, within which the selected relays forward the source's messages one after another. Furthermore, pilot based channel estimation and Channel State Information (CSI) feedback are adopted. More specifically, the source and relays send pilots at the beginning of each successive relaying period. Then the source-relay, relay-relay, and relay-destination channel coefficients can be estimated. In particular, D has the CSI of the source-destination and relay-destination channels. A relay has the CSI of links spanning from S and other relays to itself. Finally, the the source-relay, source-destination and relay-destination channel gains are reported to the source via a signaling channel.

Throughout this paper, half duplex constraint is assumed. In particular, a relay node cannot transmit and receive simultaneously. In this context, time-slotted scheduling is assumed. The signal transmitted by node a in the kth timeslot is denoted by $X_a[k]$. Node b, which does not transmit in the kth timeslot, will receive a signal obtained by

$$Y_b[k] = \sum_{a \in \mathfrak{A}[k]} h_{a,b} X_a[k] + Z_b[k], \tag{1}$$

where $\mathfrak{A}[k]$ and $Z_b[k]$ denote the set of nodes which transmit in the kth timeslot and the Additive White Gaussian Noise (AWGN) at node b's receiver, respectively. $Z_b[k]$ is subject to normal distribution with zero mean and a variance of σ^2, i.e., $Z_b[k] \sim \mathcal{CN}(0, \sigma^2)$. The transmission power of node a is denoted by $P_a = E\{|X_a[k]|^2\}$. The transmitter side SNR is denoted by $\gamma_a = \frac{P_a}{\sigma^2}$. Given the above system model, we shall present a set of relaying protocols that can maximize the degrees of freedom. In each degree of freedom, an individual symbol can be transmitted without causing any interference to other symbols. As a result, a carefully designed relaying protocol that maximizes the degrees of freedom may efficiently recover the multiplexing loss due to the half-duplex constraint of relays in practice.

III. Basic CAO-SIR

In this section, we shall present basic CAO-SIR with a fixed relay set and equal power allocation. First, a scheduling scheme for CAO-SIR is proposed along with its baseband model. Second, we present a rate adaptive bit loading method, based on which a successive cancellation method is proposed to cancel the inter-relay interference thoroughly.

Assume that S employs N relays, namely, $\{1, 2, \ldots, N\}$ without loss of any generality.[1] Each node has the same transmission power P, i.e., $P = E\{|X_a[k]|^2\}$ for all $a \in \{S, 1, \cdots, N\}$. In CAO-SIR, N relays are firstly re-ordered according to their link qualities to S. The orders of relays are computed centrally by the source node. Let us rewrite the relay set $\{1, 2, \cdots, N\}$ to be $\{(1), (2), \cdots, (N)\}$, which satisfies the reverse order of channel gains given by

$$g_{S,(1)} \leq g_{S,(2)} \leq \cdots \leq g_{S,(N)}. \tag{2}$$

In other words, (n) denotes the relay which has the nth smallest channel gain to S.

[1]In contrast to M, which denotes the total number of potential relays that can be employed, N stands for the number of relays employed in the basic CAO-SIR. In this section, which focuses on the physical layer design and scheduling of the basic CAO-SIR, how to optimize the relay selection has not been considered yet. As a result, N can be any integer satisfying $1 \leq N \leq M$. Furthermore, S randomly select N relays out of the M potential relays.

Algorithm 1 Rate Adaptation assisted Successive Interference Cancellation for Relay (n)

Decode message W_1 from $Y_{(n)}[1]$
For $k = 2 : n$
Construct $X_{(k-1)}[k]$ by re-encoding W_{k-1}
Cancel the interference from relay $(k-1)$ by
$Y_{(n)}[k] - h_{(k-1),(n)}X_{(k-1)}[k] = h_{S,(n)}X_S[k] + Z_{(n)}[k]$
Estimate $X_S[k]$ so as to obtain W_k
End

The scheduling strategy of basic CAO-SIR occupies $N+1$ timeslots, as shown in Fig. 2. In the 1st timeslot, only S broadcasts its 1st symbol $X_S[1]$. In the kth timeslot, $k = 2, \ldots, N$, Stransmits its kth symbol $X_S[k]$, while relay $(k-1)$ transmits its symbol $X_{(k-1)}[k]$ concurrently. In the last timeslot, only relay (N) sends its symbol $X_{(N)}[N+1]$. The above scheduling method yields the following equivalent baseband model. In particular, the received signals at relays are presented by

$$Y_{(n)}[1] = h_{S,(n)}X_S[1] + Z_{(n)}[1], \tag{3}$$

$$Y_{(n)}[k] = h_{S,(n)}X_S[k] + h_{(k-1),(n)}X_{(k-1)}[k] + Z_{(n)}[k],\ N \neq k-1. \tag{4}$$

The received signals at the destination D are presented by

$$Y_D[k] = h_{S,D}X_S[k] + h_{(k-1),D}X_{(k-1)}[k] + Z_D[k],\ k \geq 1, \tag{5}$$

$$Y_D[N+1] = h_{(N),D}X_{(N)}[N+1] + Z_D[N+1]. \tag{6}$$

Next, we propose a channel-aware rate adaptation and bit loading method for CAO-SIR. Let us define the equivalent channel gain of relay (n) as

$$g_{(n)} := \min\left\{g_{S,(n)}, g_{(n),D}\right\},$$

and the transmitter side SNR as $\gamma := \frac{P}{\sigma^2}$, respectively. The number of bits of the nth message of the source, denoted by W_n, is determined by

$$\mathsf{C}_n = \log\left(1 + g_{(n)}\gamma\right). \tag{7}$$

In this context, the transmitter of S loads C_n bits on its symbol $X_S[n]$. Since W_n is forwarded by relay (n), C_n bits are loaded on relay (n)'s symbol $X_{(n)}[n+1]$. From an information theoretic perspective, S may realize the above rate adaptation by using different codebooks in different timeslots. In practice, such rate adaptation can be realized by Adaptive Modulation and Coding (AMC), which adjusts the constellation size and channel coding rate jointly so as to meet the target transmission rate determined by Eq. (7).

Algorithm 2 Reverse Successive Decoding for D

Decode message W_N from $Y_D[N+1]$
For $k = N : -1 : 2$
Construct $X_S[k]$ by re-encoding W_k
Cancel the interference from S by
$Y_D[k] - h_{S,D}X_S[k] = h_{(k-1),D}X_{(k-1)}[k] + Z_D[k]$
Estimate $X_{(k-1)}[k]$ so as to obtain W_{k-1}
End

Having established the bit loading method, we turn our attention to interference cancellation for relays and the destination. Algorithm 1 presents a rate adaptation assisted successive interference cancellation method for relay (n) in detail.

Next, we shall show that the relay ordering and rate adaptation mechanism in CAO-SIR can avoid error propagation in successive interference cancellation and guarantee reliably decoding in Algorithm 1. From Eq. (2) and the definition of $g_{(n)}$, we have the inequality $g_{S,(n)} \geq g_{S,(i)} \geq g_{(i)}$, which yields that

$$\mathsf{C}_i \leq \log\left(1 + g_{S,(n)}\gamma\right), \tag{8}$$

for any $i = 1, \ldots, n$. By inserting $i = 1$ into Eq. (8), we have

$$\mathsf{C}_1 \leq \log\left(1 + g_{S,(n)}\gamma\right). \tag{9}$$

It shows that the channel gain from S to relay (n) is sufficiently large that relay (n) is capable of reliably decoding $X_S[1]$ and obtaining priori knowledge on the message W_1 to be forwarded by relay (1). Based on the priori knowledge, relay (n) can forecast and then cancel the interference from relay (1) by re-encoding W_1 into $X_{(1)}[2]$. Now suppose that relay (n) is capable of reliably decoding W_i for $i = 2, \ldots, n-1$ sent by S in the ith timeslot. Under this assumption, this relay may re-encode W_i into $X_{(i)}[i+1]$. Using this prior knowledge, relay (n) can thoroughly mitigate relay (i)'s interference as

$$Y_{(n)}[i+1] - h_{(i),(n)}X_{(i)}[i+1] = h_{S,(n)}X_S[i+1] + Z_{(n)}[i+1]. \tag{10}$$

The right side of Eq. (10) implies an AWGN channel without any inter-relay interference. From Eq. (10), it may be concluded that relay (n) is capable of reliably decoding $X_S[i+1]$ encoded at a bit rate of C_{i+1}. Using the mathematical induction method, we assert that relay (n) may reliably decode W_n when it adopts the rate adaptation assisted successive cancellation in algorithm 1. To cancel the inter-relay interference by using Eq. (10), a relay only needs the perfect local CSI on the links from other relays to itself. Since each relay will broadcast a pilot, a relay may easily estimate the required CSI locally without any CSI feedback.

Note that the concurrent transmission of S and relay $(n), n = 1, \ldots, N-1$, also induces mutual interference at the receiver of D, as shown in Eq. (5). A reverse successive decoding method is proposed for D in Algorithm 2. Similarly, we shall

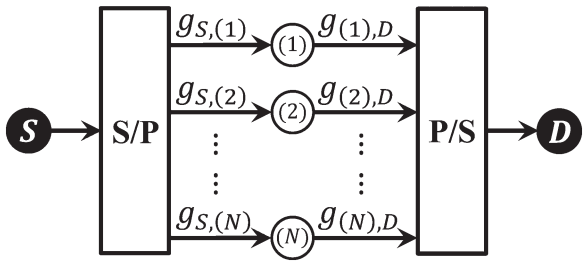

Fig. 3. Equivalent parallel relay model.

show that Algorithm 2 may reliably decode all the messages $W_n, n = 1, \ldots, N$, for D, also through the mathematical induction method. From Algorithm 2, D start with decoding the Nth message W_N from its received $Y_D[N+1]$, where there is no interference, as shown in Eq. (6). Since $g_{(N)} \leq g_{(N),D}$, it follows that

$$\mathsf{C}_N \leq \log\left(1 + g_{(N),D}\gamma\right), \tag{11}$$

which shows that the channel gain from relay (N) to D is sufficiently high that D can reliably decode W_N from $Y_D[N+1]$. Now suppose that D is capable of reliably decoding W_i forwarded by relay (i). In this scenario, D may reconstruct $X_S[i]$ by re-encoding W_i. Using this prior knowledge, D is capable of thoroughly mitigating S's interference in Eq. (5) as

$$Y_D[i] - h_{S,D}X_S[i] = h_{(i-1),D}X_{(i-1)}[i] + Z_D[i]. \tag{12}$$

Similarly, the right side of Eq. (12) implies an AWGN channel without any interference from the source. Since $g_{i-1} \leq g_{(i-1),D}$, we see that

$$\mathsf{C}_{i-1} \leq \log\left(1 + g_{(i-1),D}\gamma\right). \tag{13}$$

It shows that D may reliably decoding message W_i consisting of C_{i-1} bits. Using the mathematical induction method, we assert that D may reliably decode W_n for $n = 1, \ldots, N$.

Having proposed basic CAO-SIR, we shall turn our attention to its reliable transmission rate. As shown above, the proposed relay ordering, rate adaptation, and interference cancellation methods assure that all the messages W_i, each consisting of C_i bits for $i = 1, \ldots, N$ are reliably transmitted within $N+1$ timeslots. Clearly, the basic CAO-SIR is capable of achieving a reliable transmission rate presented by

$$\bar{\mathsf{C}} = \frac{1}{N+1}\sum_{i=1}^{N}\mathsf{C}_i. \tag{14}$$

Finally, recalling Eqs. (10) and (12), one may note that the proposed inference cancellation creates an equivalent parallel relay model without direct $S-D$ links, as shown in Fig. 3, where N relays, each two occupying orthogonal channels, will forward S's messages to D. Each orthogonal channel has a degree of freedom of $\frac{1}{N+1}$, because $N+1$ timeslots is consumed in each transmission of CAO-SIR. Furthermore, it is not difficult to see that the equivalent channel model still holds if we change the number of relays and/or their transmission power. As a result, we may further optimize relay selection and power allocation based on this model in the next section.

IV. Relay Selection and Power Allocation for CAO-SIR

In this section, relay selection and power allocation are presented to further increase the achievable rate of CAO-SIR based on the equivalent parallel relay model.

A. Relay Selection

CAO-SIR with relay selection, also referred to as CAO-SIR-R, is proposed in this part. Recall that the N relays are randomly selected in the basic CAO-SIR. S may may employ relays with poor channel conditions and minor contribution to the sum rate. As shown in Eq. (14), the achievable rate $\bar{\mathsf{C}}$ is obtained by multiplying the sum rate $\sum_{i=1}^{N}\mathsf{C}_i$ and $\frac{1}{N+1}$. If a relay with low C_i is employed, the sum rate is slightly increased, but $\frac{1}{N+1}$ may be significantly decreased. As a result, relay selection is desired to remove relays that have minor contribution to the sum rate. To achieve this goal, S will first collect the CSI of the source-relay and relay-destination channels by enabling pilot based channel estimation and CSI feedback via a signaling channel. Then S may use its collected CSI to calculate each relay's message rate, or equivalently, its contribution to the sum rate, based on which a low complexity relay selection scheme is presented below.

Note that exhaustive search may result in a high complexity of $O(M!)$ because selecting K relays out of M potential relays will result in $\binom{M}{K}$ possible combinations. Fortunately, the complexity of relay selection can be significantly reduced by relay re-ordering. The core idea relies on the fact that relay (i) having higher C_i is always preferred. As a result, let us re-order the M potential relays according to their message rate C_i. Specifically, let us rewrite the relay set $\{(1), (2), \cdots, (M)\}$ to be $\{\widetilde{(1)}, \widetilde{(2)}, \cdots, \widetilde{(M)}\}$, which satisfies

$$\mathsf{C}_{\widetilde{(1)}} \geq \mathsf{C}_{\widetilde{(2)}} \geq \cdots \geq \mathsf{C}_{\widetilde{(M)}}, \tag{15}$$

or equivalently $g_{\widetilde{(1)}} \geq g_{\widetilde{(2)}} \geq \cdots \geq g_{\widetilde{(M)}}$.[2]

In this context, the best K relays out of the entire potential relay set $\{1, \cdots, M\}$ are relays $\{\widetilde{(1)}, \widetilde{(2)}, \cdots, \widetilde{(K)}\}$.[3] As a result, the relay selection algorithm only needs to determine the optimal number of relays K^* as,

$$K^* = \arg\max_{K\in\{1,\cdots,M\}} \frac{1}{K+1}\sum_{i=1}^{K}\mathsf{C}_{\widetilde{(i)}}. \tag{16}$$

[2]A careful reader may notice that if the relays are originally ordered based on $g_{(n)}$, the notations here can be simplified because there is no need to re-order the relays again. However, $g_{(n)}$ based relay ordering is inapplicable in the next subsection, where power allocation is adopted. It is easily found a counterexample. In this relay ordering policy, there may exist a relay scheduled in the first timeslot, relay (1), having very large $g_{S,(1)}$ but very small $g_{(1),D}$. If the power allocated to relay (1) is high, it will forward a message with large data rate, which, unfortunately, cannot be decoded by other relays.

[3]In contrast to N, which denotes the number of randomly selected relays, K represents the number of the best relays that can be selected by CAO-SIR-R. More specifically, they are the top K relays in terms of the message rate that can be contributed to the sum rate. Furthermore, K cannot be any integer satisfying $1 \leq N \leq M$. Instead, it should be carefully optimized to maximize the sum rate. Therefore, a new notation, K, is introduced to distinguish it from other notations on the number of relays.

Clearly, the complexity of the proposed relay selection is $O(N)$. To give more insights, let us present a remark on the optimal number of relays. From a statistical perspective, the optimum number of relays is increased with the average receiver side SNR, namely, the product of the transmitter side SNR and the average channel gain. In the low SNR regime, only the best relay is employed to maximize the receiver side SNR. When the average receiver side SNR increases, the degree of freedom becomes the bottleneck that limits the throughput. As a result, more relays should be employed to increase the degree of freedom, or equivalently, the number of parallel relay channels shown in Fig. 3. Furthermore, CAO-SIR-R always outperforms the CAO-SIR protocol with the fixed number of best relays. Thanks to the relay number optimization, Eq. (16), CAO-SIR-R is the throughput-optimum policy among all the CAO-SIR protocols employing K best relays, where K is a fixed integer satisfying $K \in \{1, 2, \ldots, M\}$.

A careful reader will notice that S may also transmit to D directly without any help of relays, thereby achieving a reliable transmission rate of

$$\mathsf{C}_d = \log\left(1 + g_{S,D}\gamma\right). \tag{17}$$

In this scenario, CAO-SIR-R will employ the best K^* relays, if $\frac{1}{K^*+1}\sum_{i=1}^{K^*} \mathsf{C}_{\widetilde{(i)}} \geq \mathsf{C}_d$. Otherwise, S transmits to D directly. Clearly, the achievable rate of CAO-SIR-R can be given by

$$\bar{\mathsf{C}}_R^* = \max\left\{\mathsf{C}_d, \frac{1}{K^*+1}\sum_{i=1}^{K^*} \mathsf{C}_{\widetilde{(i)}}\right\}. \tag{18}$$

In the high SNR regime, the degree of freedom is maximized by direct transmission. Then the optimum relay number is zero.

B. Power Allocation

In this part, we turn our attention to CAO-SIR with power allocation, also referred to as CAO-SIR-P. Given a total power constraint, we shall allocate power among different relays and/or difference timeslots of the source node. Assume that N relays, $\{(1), (2), \cdots, (N)\}$, are employed. Let us denote the power allocated to relay (i) to be $P_{R,i}$, i.e., $P_{R,i} = E\{|X_{(i)}[i+1]|^2\}$, and the power allocated to S in the ith timeslot to be $P_{S,i}$, i.e., $P_{S,i} = E\{|X_S[i]|^2\}$. By taking power allocation into account, we shall present a modified rate adaptation scheme. In particular, the data rate of message W_i is determined by

$$\mathsf{C}_i(P_{S,i}, P_{R,i}) = \log\left(1 + \frac{\min\left\{g_{S,(i)}P_{S,i}, g_{(i),D}P_{R,i}\right\}}{\sigma^2}\right). \tag{19}$$

In this scenario, it is not difficult to verify that relay (i) can reliably decode $W_n, n \leq i$, having $\mathsf{C}_n(P_{S,n}, P_{R,n})$ bits by using Algorithm 1, while the destination node can reliably decode all of the messages W_i by using Algorithm 2. As a result, totally $\frac{1}{N+1}\sum_{i=1}^{N} \mathsf{C}_i(P_{S,i}, P_{R,i})$ bits are reliably transmitted from S to D in $N+1$ timeslots.

For a fair comparison, we present total power constrains for both the relay set and S, which are given by $\sum_{i=1}^{N} P_{R,i} \leq NP$ and $\sum_{i=1}^{N} P_{S,i} \leq NP$, respectively. To maximize the sum rate under the total power constraint, we formulate the power allocation problem as:

$$\max \quad \frac{1}{N+1}\sum_{i=1}^{N}\log\left(1 + \frac{\min\left\{g_{S,(i)}P_{S,i}, g_{(i),D}P_{R,i}\right\}}{\sigma^2}\right)$$
$$s.t. \quad \begin{cases} \sum_{i=1}^{N} P_{S,i} \leq NP \\ \sum_{i=1}^{N} P_{R,i} \leq NP \\ P_{S,i} \geq 0 \\ P_{i,D} \geq 0. \end{cases} \tag{20}$$

Next, we shall present a double water filling policy to obtain the optimal solution to problem (20). Let λ and μ denote the solutions to $\sum_{i=1}^{N}\left(\lambda - \frac{\sigma^2}{g_{S,(i)}}\right)^+ = NP$ and $\sum_{i=1}^{N}\left(\mu - \frac{\sigma^2}{g_{(i),D}}\right)^+ = NP$, respectively. Let $\alpha_i := \frac{g_{S,(i)}}{g_{(i),D}}$. In this context, Theorem 1 presents the optimal double water filling policy.

Theorem 1: The optimal power allocation is presented by

$$P_{S,i}^* = \left(\lambda - \frac{\sigma^2}{g_{S,(i)}}\right)^+, \tag{21}$$

$$P_{R,i}^* = \alpha_i\left(\lambda - \frac{\sigma^2}{g_{S,(i)}}\right)^+, \tag{22}$$

if $\sum_{i=1}^{N}\alpha_i\left(\lambda - \frac{\sigma^2}{g_{S,(i)}}\right)^+ \leq NP$. Otherwise,

$$P_{S,i}^* = \alpha_i^{-1}\left(\mu - \frac{\sigma^2}{g_{(i),D}}\right)^+, \tag{23}$$

$$P_{R,i}^* = \left(\mu - \frac{\sigma^2}{g_{(i),D}}\right)^+. \tag{24}$$

Proof: Our proof relies on an intuitive observation that the optimal power allocation must satisfy $g_{S,(i)}P_{S,i}^* = g_{(i),D}P_{R,i}^*$. Otherwise, there must be some power wasted. As a result, the optimization problem (20) can be simplified to be

$$\max \quad \frac{1}{N+1}\sum_{i=1}^{N}\log\left(1 + \frac{g_{S,(i)}P_{S,i}}{\sigma^2}\right)$$
$$s.t. \quad \begin{cases} \sum_{i=1}^{N} P_{S,i} \leq NP \\ \sum_{i=1}^{N} \alpha_i P_{S,i} \leq NP \\ P_{S,i} \geq 0. \end{cases} \tag{25}$$

It is not difficult to verify that problem (25) is a convex optimization problem. As a result, the optimal solution in Theorem 2 can be obtained by Lagrangian Multiplier method along with complementary slackness condition. ■

Remark 1: Theorem 1 presents a "Double Water Filling" policy. To give more insights, we present the following straightforward explanation of its core idea. The policy first supposes that the total power for relays is sufficiently high that each relay has enough power to transmit its message to D reliably. Under this assumption, the second constraint of problem (20) or (25) is relaxed. Then we focuses on the maximization of the sum rate, or equivalently the power efficiency of the first hop. In this case, the optimal power allocation for the first hop, $P^*_{S,i}$, is obtained by conventional water filling policy Eq. (21). To forward W_i reliably, the minimal transmission power of relay (i) is given by $P^*_{R,i} = \alpha_i P^*_{S,i}$. Now, let us test whether the total power constraint NP is truly high enough to afford the total power required by all of the relays. If $\sum_{i=1}^{N} \alpha_i P^*_{S,i} \le NP$, the original assumption holds and the above solution is optimal. Otherwise, we may come to the conclusion that the the second hop of the equivalent channel model is the bottleneck. In other words, the power efficiency of the second hop should be maximized. To achieve this goal, we shall release the first constraint of problem (20) and obtain the optimal power allocation for relays, $P^*_{R,i}$, by using water filling policy at the second hop. In this case, $P^*_{S,i} = \alpha_i^{-1} P^*_{R,i}$ due to the relaxation of the first constraint.

Next, we turn our attention to a simpler special case, where power allocation is carried out only for different timeslots of S, while each relay transmits in a fixed power P. Intuitively, the optimal power allocation must satisfy $P^*_{S,i} \le \alpha_i^{-1} P$. Otherwise, the source's power allocated to ith timeslot will be wasted. Based on this observation, we may formulate the following optimization problem.

$$\begin{aligned} \max \quad & \frac{1}{N+1} \sum_{i=1}^{N} \log\left(1 + \frac{g_{S,(i)} P_{S,i}}{\sigma^2}\right) \\ s.t. \quad & \begin{cases} \sum_{i=1}^{N} P_{S,i} \le NP \\ P_{S,i} \le \alpha_i^{-1} P \\ P_{S,i} \le 0. \end{cases} \end{aligned} \tag{26}$$

From our previous work [25], the optimal power allocation in this scenario can be obtained by

$$P^*_{S,i} = min\left\{\frac{P}{\alpha_i}, \left(\lambda - \frac{\lambda^2}{g_{S,(i)}}\right)^+\right\}, \tag{27}$$

which is also referred to as "Water Filling in Cellar" policy [25]. In a similar scenario, where power is allocated among different relays, while S transmits in a fixed power P in different timeslots, the optimal power allocation can be also obtained by "Water Filling in Cellar" policy for relays.

C. Joint Relay Selection and Power Allocation

In this part, we propose a low complexity joint relay selection and power allocation method for CAO-SIR, also referred to as CAO-SIR-RP. The core idea is to remove the relay having the least contribution to the sum rate in each iteration. Because either the relay having the worst channel to S or the relay having the worst channel to D may have the least contribution, the two relays are candidates to be removed. To identify which one should be removed, we shall compare the optimal sum rate after removing each one of the two candidate relays. In particular, we first remove one of the candidates from the relay set. Then double water filling policy is adopted to allocate the total power over the relay set. For normalization, the total power is the product of the number of relays and the average power P. Based on the optimal power allocation, the maximal sum rate after removing this relay can be obtained. Similarly, we may calculate the maximal sum rate after deleting the other candidate. By comparing the two sum rates, we know which one of them has the least contribution and should be removed. A detailed CAO-SIR-RP is presented in Algorithm 3 as follows.

Algorithm 3 CAO-SIR-RP: Joint Relay Selection and Power Allocation for CAO-SIR

Initialize $\mathcal{R} = \{(1), (2), \ldots, (M)\}$ and $\mathcal{R}^* \leftarrow \mathcal{R}$
Calculate $P^*_{S,i}$ by double water filling over $\mathcal{R}$
$\bar{\mathsf{C}}^*_{RP} = \frac{1}{|\mathcal{R}|+1} \sum_{i\in\mathcal{R}} \log\left(1 + \frac{g_{S,(i)} P^*_{S,i}}{\sigma^2}\right)$
while $|\mathcal{R}| \ge 2$
  $(i_1) = \arg\min_{(i_1)\in\mathcal{R}} g_{S,(i_1)}$, $(i_2) = \arg\min_{(i_2)\in\mathcal{R}} g_{(i_2),D}$
  for $m = 1:2$
    $\mathcal{R}_m = \mathcal{R} - \{(i_m)\}$
    Allocate $|\mathcal{R}_m|P$ over $\mathcal{R}_m$ by double water filling
    $\bar{\mathsf{C}}^*_m = \frac{1}{|\mathcal{R}_m|+1} \sum_{i\in\mathcal{R}_m} \log\left(1 + \frac{g_{S,(i)} P^*_{S,i}}{\sigma^2}\right)$
  end
  $i = \arg\max_m \bar{\mathsf{C}}^*_m$
  $\mathcal{R} \leftarrow \mathcal{R}_i$
  if $\bar{\mathsf{C}}^*_i > \bar{\mathsf{C}}^*_{RP}$
    $\bar{\mathsf{C}}^*_{RP} \leftarrow \bar{\mathsf{C}}^*_i$, $\mathcal{R}^* \leftarrow \mathcal{R}_i$
  end
end
$\mathsf{C}_d = \log\left(1 + \frac{g_{S,D} P^*_{S,D}}{\sigma^2}\right)$
if $\mathsf{C}_d \ge \bar{\mathsf{C}}^*$
  $\bar{\mathsf{C}}^*_{RP} \leftarrow \mathsf{C}_d$, $\mathcal{R}^* = \emptyset$
end

From Algorithm 3, it is seen that CAO-SIR-RP has a complexity of $O(M)$. In contrast, the complexity of exhaustive search is $O(2^M)$. The proposed method reduces the computational complexity significantly.

V. Performance Analysis

In this section, the performance of various CAO-SIR protocols is analyzed. We are interested in the average throughput and the diversity-multiplexing tradeoff in fading channels. Throughout this section, the channel spanning from node a to node b are assumed to be independent distributed Rayleigh fading channel. In this context, the the probability density function (*p.d.f.*) of the power gain $g_{a,b}$ is presented by $f_{g_{a,b}}(x) = \frac{1}{\bar{g}_{a,b}} \exp(-\frac{x}{\bar{g}_{a,b}})$, where $\bar{g}_{a,b} = \mathbb{E} g_{a,b} = \mathbb{E}|h_{a,b}|^2$ denote the average power gain between nodes a and b.

A. Average Throughput

In this part, we focus on the average throughput of basic CAO-SIR, as well as, its high and low SNR approximations for CAO-SIR with relay selection and/or power allocation. Consider the basic CAO-SIR employing relays $\{1, 2, \ldots, N\}$. From Eq. (14), one can easily see that its average throughput is given by $\mathbb{E}\{\bar{\mathsf{C}}\} = \frac{1}{N+1}\sum_{i=1}^{N}\mathbb{E}\{\log(1+g_{(i)}\gamma)\}$. Since $g_{(i)} = \min\{g_{S,(i)}, g_{(i),D}\}$ and $g_{S,(i)}$ is the ith order statistic of $g_{S,i}$, it is not a trivial work to obtain the *p.d.f.* of $g_{(i)}$. Fortunately, the summation of multiple variables remains fixed if we simply change their order. By noticing this, we have

$$\mathbb{E}\{\bar{\mathsf{C}}\} = \frac{1}{N+1}\sum_{i=1}^{N}\mathbb{E}\left\{\log(1+g_i\gamma)\right\}, \tag{28}$$

where $g_i = \min\{g_{S,i}, g_{i,D}\}$ denotes the equivalent channel gain of relay i. From the theory of order statistics[4] [26], the *p.d.f.* of g_i can be given by

$$f_{g_i}(x) = \frac{1}{\bar{g}_i}\exp\left(-\frac{x}{\bar{g}_i}\right), \tag{29}$$

where

$$\bar{g}_i = \mathbb{E}g_i = \frac{\bar{g}_{S,i}\bar{g}_{i,D}}{\bar{g}_{S,i}+\bar{g}_{i,D}}. \tag{30}$$

To give more insights, let us consider the independent and identically distributed (*i.i.d.*) fading case, where $\bar{g}_{a,b} = 1$ for and node pair (a, b). From Eqs. (29) and (30), the *p.d.f.* of g_i can be given by $f_{g_i}(x) = 2\exp(-2x)$. As a result, we have

$$\mathbb{E}\{\bar{\mathsf{C}}\} = \frac{2N}{N+1}\int_0^\infty \log(1+x\gamma)\exp(-2x)dx. \tag{31}$$

Next, let us turn our attention to CAO-SIR with relay selection and/or power allocation. Unfortunately, it is not a trivial to derive the close-form expressions of the average throughputs of these enhanced protocols in arbitrary SNR, because neither of these protocols has a close-form solution to the relay selection and/or power allocation. Instead, they adopt low complexity numerical search methods determine how to select relays and/or allocate power. As a result, we are interested in the asymptotic results of their average throughput in the high and low SNR regimes. Fortunately, there exist close-form solutions to the asymptotic average throughputs in these cases.

Consider the high SNR regime first. Due to its bandwidth limited nature, the optimal average throughput is achieved by utilizing the maximum degree of freedom. As a result, the optimal relay selection will not employ any relay. When S transmits to D directly, the maximal average throughput given by $\mathbb{E}\{\bar{\mathsf{C}}\} \approx \log\gamma + \mathbb{E}\{\log g_{S,D}\}$ is achieved.

In the low SNR regime, the optimal strategy is to utilize the best sub-channel due to the power limited nature. In CAO-SIR-RP, double water filling policy will allocate all the power to the best relay with the largest equivalent channel gain $\max\limits_{i=1,2,\ldots,M} g_i$. Then, other relays having zero power allocation and no contribution to the sum rate will be removed from the relay set. In other words, CAO-SIR-RP will be reduced to the opportunistic transmission through the best relay. In this case, the low SNR approximate throughput is obtained by $\gamma\frac{\log e}{2}\max g_i$. Also note that direct transmission from S to D achieves a low SNR approximate throughput given by $\gamma\log e g_{S,D}$. As a result, the average throughput of CAO-SIR-RP in the low SNR regime is obtained by

$$\begin{aligned}\mathbb{E}\left\{\bar{\mathsf{C}}^*_{RP}\right\} &= \gamma\log e\mathbb{E}\max\left\{\frac{g_i}{2}, g_{S,D}\right\} \\ &= \gamma\log e\int_0^\infty x \\ &\quad\times d\left(1-\exp\frac{-x}{\bar{g}_{S,D}}\right)\prod_{i=1}^{M}\left(1-\exp\frac{-2x}{\bar{g}_i}\right).\end{aligned} \tag{32}$$

By assuming *i.i.d.* Rayleigh fading with $\bar{g}_{a,b} = 1$, we may further simplify the above equation to be

$$\mathbb{E}\left\{\bar{\mathsf{C}}^*_{RP}\right\} = \gamma\log e\left[1-\sum_{i=1}^{M}\frac{(-1)^i\binom{M}{i}}{2i(2i+1)}\right]. \tag{33}$$

B. Diversity Multiplexing Tradeoff

In this part, we investigate the diversity-multiplexing tradeoff, which jointly characterizes the reliability and efficiency of CAO-SIR. Let the multiplexing gain be denoted by r, and the diversity gain, as a function of r, be denoted by $d(r)$. More specifically, the diversity gain is defined as

$$d(r) = -\lim_{\gamma\to\infty}\frac{\log p_o(r,\gamma)}{\log\gamma}, \tag{34}$$

where $p_o(r, \gamma)$ denotes the outage probability given the transmitter side SNR γ and the target rate $r\log\gamma$.

Let us consider the basic CAO-SIR first. From (14), it can be seen that the outage probability of this protocol is presented by

$$p_o(r,\gamma) = \Pr\left\{\frac{1}{N+1}\sum_{i=1}^{N}\log\left(1+g_{(i)}\gamma\right) \le r\log\gamma\right\}.$$

Since it is not easy to derive the *p.d.f.* of $g_{(i)}$, we rewrite the outage probability as

$$p_o(r,\gamma) = \Pr\left\{\frac{1}{N+1}\sum_{i=1}^{N}\log(1+g_i\gamma) \le r\log\gamma\right\}, \tag{35}$$

by noticing that re-ordering of multiple variables will not change their summation. Based on Eq. (35), the optimal DMT of basic CAO-SIR is presented as follows.

Theorem 2: Given a multiplexing gain r, the diversity gain of basic CAO-SIR is presented by

$$d(r) = N\left(1-\frac{N+1}{N}r\right). \tag{36}$$

[4] $\Pr\{g_i \le x\} = 1-\Pr\{g_{S,i} > x\}\Pr\{g_{i,D} > x\} = 1-\exp\left[-x\left(\frac{1}{\bar{g}_{S,i}}+\frac{1}{\bar{g}_{i,D}}\right)\right]$

Proof: Our proof will be divided two steps. First, we will show that Eq. (36) holds under the assumption of *i.i.d.* Rayleigh channels. Based on the conclusion of the first step, we may present the upper and lower bounds of the outage probability for a more general case with independent non-identical distributed (*i.ni.d.*) Rayleigh channels. Then these bounds are adopted to show that Eq. (36) also holds *i.ni.d.* Rayleigh channels.

In the *i.i.d.* case, we have $\bar{g}_{a,b} = \bar{g}$ for any node pair (a, b). From Eqs. (29) and (30), the *p.d.f.* of g_i is presented by

$$f_{g_i}(x) = \frac{2}{\bar{g}} \exp\left(-\frac{2x}{\bar{g}}\right), \tag{37}$$

Since Eq. (35) can be rewritten as

$$p_o\left(\frac{Nr}{N+1}, \gamma\right) = \Pr\left\{\sum_{i=1}^{N} \log(1 + g_i\gamma) \leq Nr \log \gamma\right\},$$

the DMT analysis of basic CAO-SIR is quite similar to that of parallel Rayleigh fading channels in [23] and [24]. From [23] and [24], we have

$$\lim_{\gamma\to\infty} \frac{\log \Pr\left\{\sum_{i=1}^{N} \log(1 + g_i\gamma) \leq Nr \log \gamma\right\}}{-\log \gamma} = N(1 - r).$$

It follows that

$$d(r) = -\lim_{\gamma\to\infty} \frac{\log p_o\left(\frac{N+1}{N}\left(\frac{N}{N+1}r\right), \gamma\right)}{\log \gamma} \tag{38}$$

$$= N\left(1 - \frac{N+1}{N}r\right), \tag{39}$$

which completes the proof under the assumption of *i.i.d.* Rayleigh channels.

Next, we proceed to show that Eq. (36) holds for *i.ni.d.* Rayleigh Channels. In this case, g_i is an exponentially distributed random variable, the *p.d.f.* of which is presented by Eqs. (29) and (30). To derive the optimal DMT in this case, let $g_i^{\max}, i = 1, \ldots, N$, be *i.i.d.* random variables generated from the exponential distribution with a *p.d.f.* given by

$$f_{g_i}^{\max}(x) = \frac{1}{\bar{g}^{\max}} \exp\left(-\frac{x}{\bar{g}^{\max}}\right), \tag{40}$$

where $\bar{g}_{\max} = \max_{i\in\{1,\ldots,N\}} \bar{g}_i$. Also let $g_i^{\min}, i = 1, \ldots, N$, be *i.i.d.* random variables generated from the exponential distribution with a *p.d.f.* given by

$$f_{g_i}^{\min}(x) = \frac{1}{\bar{g}^{\min}} \exp\left(-\frac{x}{\bar{g}^{\min}}\right), \tag{41}$$

where $\bar{g}_{\min} = \min_{i\in\{1,\ldots,N\}} \bar{g}_i$.

In this context, we may bound the outage probability for *i.ni.d.* Rayleigh channels by that for *i.i.d.* Rayleigh channels. In particular, we have

$$p_o^{\min}(r, \gamma) \leq p_o(r, \gamma) \leq p_o^{\max}(r, \gamma), \tag{42}$$

where the upper and lower bounds are presented by

$$p_o^{\max}(r, \gamma) = \Pr\left\{\frac{1}{N+1}\sum_{i=1}^{N} \log\left(1 + g_i^{\max}\gamma\right) \leq r \log \gamma\right\},$$

$$p_o^{\min}(r, \gamma) = \Pr\left\{\frac{1}{N+1}\sum_{i=1}^{N} \log\left(1 + g_i^{\min}\gamma\right) \leq r \log \gamma\right\}.$$

From Eqs. (38) and (39), we have

$$-\lim_{\gamma\to\infty} \frac{\log p_o^{\max}(r, \gamma)}{\log \gamma} = N\left(1 - \frac{N+1}{N}r\right), \tag{43}$$

$$-\lim_{\gamma\to\infty} \frac{\log p_o^{\min}(r, \gamma)}{\log \gamma} = N\left(1 - \frac{N+1}{N}r\right). \tag{44}$$

By substituting Eq. (42) into Eqs. (43) and (44), it follows that

$$N\left(1 - \frac{N+1}{N}r\right) \leq \lim_{\gamma\to\infty} \frac{\log p_o(r, \gamma)}{-\log \gamma} \leq N\left(1 - \frac{N+1}{N}r\right).$$

Consequently, Eq. (36) holds for *i.ni.d.* Rayleigh channels. ■

It is worth noting that Eq. (36) in Theorem 2 may also characterize the DMT of CAO-SIR-P employing N relays, because power allocation will not change the DMT defined in the high SNR regime. As shown in Theorem 2, the maximal diversity gain of basic CAO-SIR and CAO-SIR-P is $d^{\max} = N$, while their maximal multiplexing gain is $r^{\max} = \frac{N}{N+1}$. Since their DMT curve is a straight line connecting DMT pairs, $(N, 0)$ and $\left(0, \frac{N}{N+1}\right)$. Clearly, all of the M potential relays should be employed to optimize the DMT of basic CAO-SIR and CAO-SIR-P.

Finally, let us investigate the optimal DMT of CAO-SIR-RP and CAO-SIR-R based on Theorem 2. As the DMT analysis focuses on the high SNR regime, equal power allocation is near the optimal. Hence, CAO-SIR-RP and CAO-SIR-R achieves the same DMT, as shown in the following Theorem.

Theorem 3: Given a multiplexing gain r, the diversity gain of CAO-SIR-RP and CAO-SIR-R is presented by

$$d(r) = \max\left\{(M+1)\left(1 - \frac{M+2}{M+1}r\right), (1 - r)\right\}, \tag{45}$$

or equivalently

$$d(r) = \begin{cases} (M+1)\left(1 - \frac{M+2}{M+1}r\right) & r \leq \frac{M}{M+1} \\ 1 - r & r > \frac{M}{M+1}. \end{cases} \tag{46}$$

Proof: Our proof starts with the observation that note that

$$(M+1)\left(1 - \frac{M+2}{M+1}r\right) = 1 - r, \tag{47}$$

when $r = \frac{M}{M+1}$. Hence, it is easily seen that Eqs. (45) and (46) are equivalent. Then we focus on the proof of Eq. (46).

Due to the bandwidth limited nature in the high SNR regime, CAO-SIR-RP and CAO-SIR-R will either employ all the M potential relays, or implement direct transmission to maximize the degree of freedom. As shown in Theorem 2, the maximal multiplexing gain is bounded by $\frac{M}{M+1}$, when relays are employed. Accordingly, when $r > \frac{M}{M+1}$, CAO-SIR-RP/CAO-SIR-R has to be reduced to direct transmission, because there

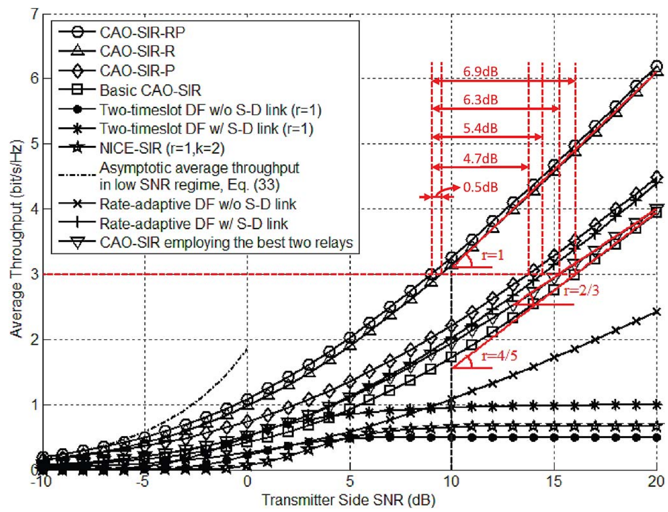

Fig. 4. The Average Throughput in *i.i.d.* Case. The proposed CAO-SIR protocols are compared with two-timeslot relaying [4] and conventional successive relaying, namely, NICE-SIR [21].

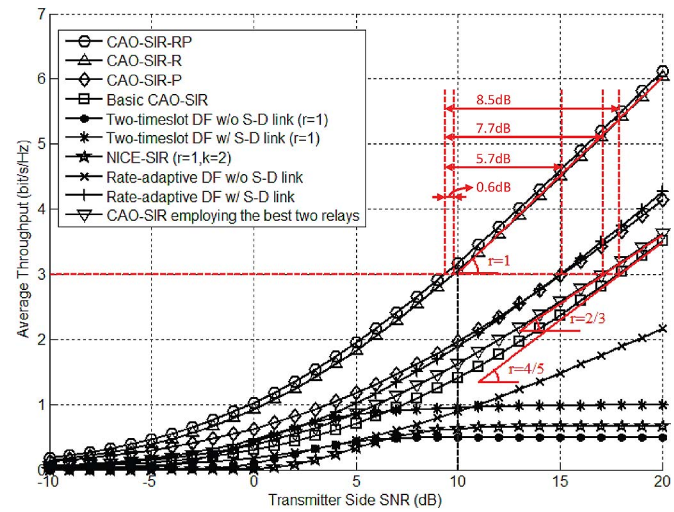

Fig. 5. The Average Throughput in *i.ni.d.* Case. The proposed CAO-SIR protocols are compared with two-timeslot relaying [4] and conventional successive relaying, namely, NICE-SIR [21].

is no half duplex relaying method which can attain such a high multiplexing gain. In this case, the DMT of CAO-SIR-RP/CAO-SIR-R is equal to that of direct transmission. From [23], we have

$$d(r) = -\lim_{\gamma\to\infty} \frac{\log p_o^D(r,\gamma)}{\log\gamma} = 1 - r, \tag{48}$$

where $p_o^D(r,\gamma) = \Pr\{\log(1 + g_{S,D}\gamma) \le r\log\gamma\}$ denotes the outage probability of direct transmission.

Next, let us turn our attention to the scenario where $r \le \frac{M}{M+1}$. In this case, outage occurs if and only if the target rate is greater than both the capacity of the direct transmission and that of the basic CAO-SIR employing M relays. As a result, the outage probability is determined by

$$p_o(r,\gamma) = p_o^R(r,\gamma)p_o^D(r,\gamma), \tag{49}$$

where $p_o^R(r,\gamma) = \Pr\left\{\frac{1}{M+1}\sum_{i=1}^{M}\log(1 + g_i\gamma) \le r\log\gamma\right\}$ stands for the outage probability of basic CAO-SIR employing M relays.

From Eq. (34), we have

$$d(r) = -\lim_{\gamma\to\infty} \frac{\log p_o^R(r,\gamma)}{\log\gamma} - \lim_{\gamma\to\infty} \frac{\log p_o^D(r,\gamma)}{\log\gamma}. \tag{50}$$

By inserting $N = M$ into Eq. (39), it follows that

$$-\lim_{\gamma\to\infty} \frac{\log p_o^R(r,\gamma)}{\log\gamma} = M\left(1 - \frac{M+1}{M}r\right). \tag{51}$$

Substituting Eqs. (48) and (51) into Eq. (50), we have

$$d(r) = (M+1)\left(1 - \frac{M+2}{M+1}r\right), \tag{52}$$

when $r \le \frac{M}{M+1}$. Combining Eqs. (48) and (52), we have Eq. (46) and thus complete the proof. ■

One may notice that equal power allocation is adopted in the above proof. In this case, CAO-SIR-RP is reduced to CAO-SIR-R. In other words, the optimal DMT of CAO-SIR-RP is also given by Eq. (46). Thanks to the use of direct link from S to D, CAO-SIR-RP and CAO-SIR-R may achieve the maximal diversity gain of $M + 1$ and the maximal multiplexing gain of 1. Finally, it is worth noting that the DMT outer bound for M potential relays is presented by $d(r) = (M + 1)(1 - r)$, which can be achieved by employing M full duplex relays to create an equivalent $(M + 1) \times 1$ MISO channel. In the scenario where only half duplex relays are available, both CAO-SIR-R and CAO-SIR-RP may achieve a near optimal DMT for large M.

VI. Numerical Results

In this section, numerical results are presented to validate the theoretical analysis and demonstrate the potential of CAO-SIR. Assume that there are four potential relays. Both *i.i.d.* and *i.ni.d.* Rayleigh fading channels will be considered. For the *i.i.d.* case, we assume that $\bar{g}_{a,b} = 1$ for any node pair (a, b). For the *i.ni.d.* case, we assume $\bar{g}_{a,b} = d_{a,b}^{-2}$ where $d_{a,b}$ stands for the distance between nodes a and b, due to the path-loss model [27]. To determine $d_{a,b}$, we assume the following network topology. The coordinates of S and D are given by (0,0) and (1,0) respectively. Four relays are located in coordinates (0,1), (0,−1), (1,1), and (1,−1). To give more insights, CAO-SIR protocols are compared with conventional two-timeslot DF relaying protocols with fixed target rate [3]–[5], conventional successive relaying [7], [11], [21], e.g., NICE-SIR [21], and rate-adaptive two-timeslot DF relaying where the transmission rate is optimized to maximize its average throughput at arbitrary SNR. For conventional successive relaying, we assume that two out of four relays are chosen to forward messages successively and that direct link can be utilized.

A. Average Throughput

The average throughput versus transmitter side SNR curves for *i.i.d.* and *i.ni.d.* cases are presented in Figs. 4 and 5 respectively. In particular, the basic CAO-SIR and CAO-SIR protocols with relay selection and/or power allocation are investigated. We assume that all of the four potential relays are employed in basic CAO-SIR and CAO-SIR-P protocols. For conventional relaying protocols with fixed target rate, we set $\mathsf{r} = 1$.

For basic CAO-SIR, its theoretical average throughput can be obtained at arbitrary SNR from Eqs. (28) and (31). Since the average throughput obtained by Eqs. (28) and (31) matches well with the simulation results, the theoretical analysis can be validated. For CAO-SIR with relay selection and/or power allocation, let us verify asymptotic theoretical analysis in the low and high SNR regimes. In the low SNR regime, the asymptotic average throughput obtained by Eqs. (32) and (33) matches well with simulation results. In the high SNR regime, we are interested in the slope of the throughput versus SNR curves. In particular, the slope of CAO-SIR-RP and CAO-SIR-R is one, because CAO-SIR-RP and CAO-SIR-R will be reduced to direct transmission with high probability in the degree of freedom limited high SNR regime. The slope of basic CAO-SIR and CAO-SIR-P which employs four relays is 4/5. As a result, we may conclude that the asymptotic theoretical analysis results in the low and high SNR regimes are validated.

For arbitrary SNR, CAO-SIR-RP always achieves the optimal average throughput, thanks to its joint optimization of relay selection and power allocation. More specifically, let us focus on the required SNR when CAO-SIR protocols achieve an average throughput of 3 bit/s/Hz. In the *i.i.d.* case, the SNR gains of CAO-SIR-RP over CAO-SIR-R, CAO-SIR-P, and basic CAO-SIR are 0.5 dB, 4.7 dB, and 6.9 dB, respectively. In the *i.ni.d.* scenario, the SNR gains of CAO-SIR-RP over CAO-SIR-R, CAO-SIR-P, and basic CAO-SIR are 0.6 dB, 5.7 dB, and 8.5 dB, respectively. A careful reader may notice that CAO-SIR-RP only achieves a marginal SNR gain over CAO-SIR-R. To give more insights, this observation is explained as follows. In the low SNR regime, both CAO-SIR-RP and CAO-SIR-R reduce to the opportunistic communication over the best channel in Fig. 3 in order to maximize the power efficiency. In other words, both of them will only employ the best relay with high probability. In the high SNR regime, both CAO-SIR-RP and CAO-SIR-R will employ all potential relays to create as many as possible parallel channels in Fig. 3, thereby maximizing the degree of freedom. In this case, power allocation may bring marginal gain to CAO-SIR-RP because power efficiency is less important due to the bandwidth limited nature. Then let us turn our attention to the arbitrary SNR scenario. Note that the embedded channel selection avoids choosing the poor channels, while the probability that a channel has a very large gain is extremely low under the Rayleigh fading assumption. Since the channel gains of the selected parallel channels are not significantly different, power allocation cannot bring a significant throughput gain for CAO-SIR-RP.

In Figs. 4 and 5, the average throughput versus transmitter side SNR curves of a relay selection aided CAO-SIR protocol, which always employs the best two relays in arbitrary SNR, are also presented. The slope of these throughput curves are 2/3, because S always transmits two messages in three timeslots. From the comparison between CAO-SIR employing the two best relays and CAO-SIR-R, one may see that it is near optimal to always employ the two best relays. However, the throughput gap between this two-relay CAO-SIR and CAO-SIR-R is enlarged with the increase of SNR. This is simply due to the fact that the optimum number of relays is increased with the transmitter side SNR from a statistical perspective, as discussed in Section IV-A. The theoretical analysis on the optimum number is also validated by the numerical results. Furthermore, even the basic CAO-SIR protocol employing four relays can outperform the CAO-SIR protocol employing the two best relays when the transmitter side SNR is sufficiently high, because the slope of the throughput curve of the basic CAO-SIR is greater than that of the two-relay CAO-SIR.

Next, let us turn our attention to the comparison between CAO-SIR protocols and conventional relaying protocols in the *i.i.d.* and *i.ni.d.* cases. It is worth noting that it might be unfair to compare CAO-SIR with conventional relaying protocols having fixed target rate, because the average throughput for the fixed rate relaying saturates in the high SNR regime, as shown in Figs. 4 and 5. More specifically, let us focus on a transmitter side SNR of 10 dB. Given a fixed target rate $\mathsf{r} = 1$, the asymptotic average throughputs of fixed-rate two-timeslot DF relaying with and without direct $S - D$ link, as well as, conventional NICE-SIR, in the high SNR regime are 1 bit/s/Hz, 1/2 bit/s/Hz, and 4/5 bit/s/Hz, respectively. Although this upper bound in the high SNR regime can be increased with the target rate, one should also notice that a higher target rate will result in a lower average throughput in the low SNR regime. In contrast, since the proposed CAO-SIR is capable of adapting its transmission rate to the channel gains, is may always achieve the optimal average throughput for arbitrary SNR. In the *i.i.d.* scenario, even the basic CAO-SIR achieves a huge throughput gain of 180%, 350%, and 260% over fixed-rate two-timeslot DF relaying with and without direct $S - D$ link, as well as, NICE-SIR, respectively. In the *i.ni.d.* scenario, The throughput gain of the basic CAO-SIR over fixed-rate two-timeslot DF relaying with and without direct $S - D$ link, as well as, NICE-SIR are 150%, 280%, and 220%, respectively.

For a fairer comparison, the average throughput versus transmitter side SNR curves of rate-adaptive two-timeslot DF relaying with and without direct $S - D$ link are also presented in Figs. 4 and 5. In particular, the transmission rate of rate-adaptive two-timeslot DF relaying is optimized in order to maximize its average throughput. As a result, its average throughput versus transmitter side SNR curve is an upper envelope of the throughput curves of the fixed-rate two-timeslot DF relaying. Thanks to the transmission rate adaptation, the average throughput of the conventional two-timeslot DF relaying is significantly increased and hence does not saturate in the high SNR region. However, the proposed CAO-SIR protocols still outperform the rate-adaptive two-timeslot DF relaying, as shown in Figs. 4 and 5. More specifically, let us focus on the required SNR when the interested relaying protocols achieve an average throughput of 3 bit/s/Hz. In the *i.i.d.* case, the SNR gains of CAO-SIR-RP over rate-adaptive two-timeslot DF relaying with and without direct $S - D$ link are 5.4 dB and 14.7 dB, respectively. In the *i.ni.d.* case, the SNR gains of CAO-SIR-RP over rate-adaptive two-timeslot DF relaying with and without direct $S - D$ link are 5.7 dB and 16.2 dB, respectively.

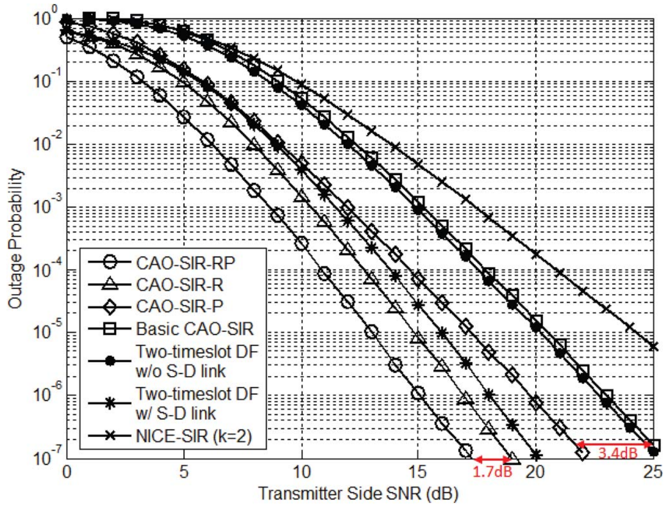

Fig. 6. The Outage Probability in *i.i.d.* Case. The target rate and the multiplexing gain are set to be $\mathsf{r} = 1$ and $r = 0$, respectively.

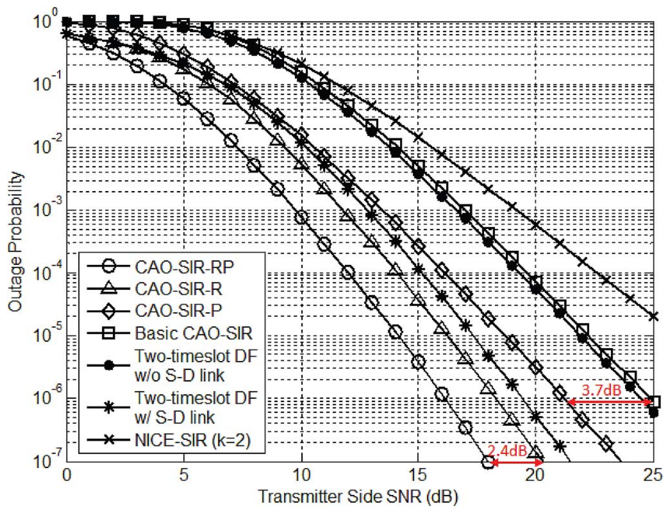

Fig. 7. The Outage Probability in *i.ni.d.* Case. The target rate and the multiplexing gain are set to be $\mathsf{r} = 1$ and $r = 0$, respectively.

B. Outage Probability

In this subsection, we shall turn our attention to the outage probability, as well as, the diversity and multiplexing gains. More specifically, given a multiplexing gain, the diversity gain can be can be estimated from the slope of the outage probability versus transmitter side SNR curve. In this subsection, we are interested in the outage probability for two target rates, $\mathsf{r} = 1$ and $\mathsf{r} = 0.3 \log \gamma$. In this context, the outage probability curves may show diversity gains for multiplexing gains $r = 0$ and $r = 0.3$.[5]

[5]In this subsection, we shall not present the numerical results for the rate-adaptive two-timeslot DF relaying protocols because they achieve the same outage probability as the conventional two-timeslot DF relaying protocols. Note that the outage probability is defined as the probability that the achievable rate is less than a certain target rate. However, neither can rate adaptation increase the achievable rate of conventional two-timeslot DF relaying, nor recover its 50% multiplexing loss due to the inherent half-duplex constraint. As a result, it does not bring any gain to the conventional two-timeslot DF relaying, when outage probability or DMT is chosen as a performance metric.

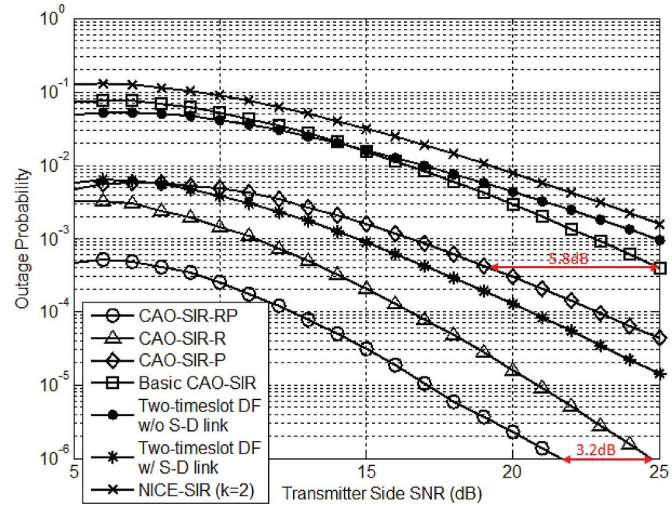

Fig. 8. The Outage Probability in *i.i.d.* Case. The multiplexing gain are set to be $r = 0.3$. Thus, the target rate is determined by $\mathsf{r} = 0.3 \log \gamma$.

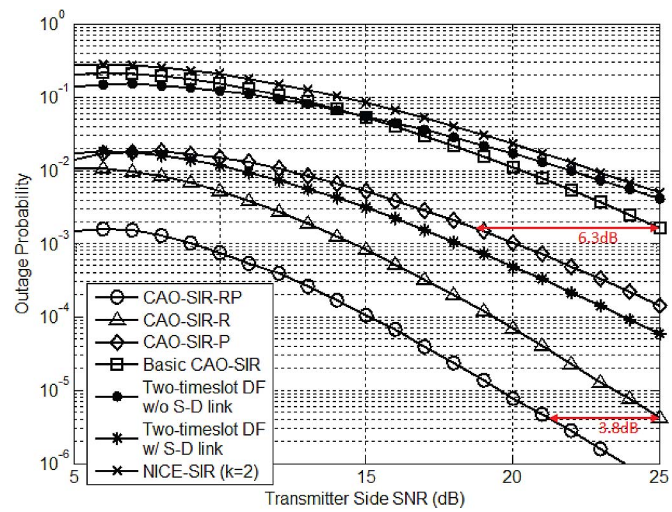

Fig. 9. The Outage Probability in *i.ni.d.* Case. The multiplexing gain are set to be $r = 0.3$. Thus, the target rate is determined by $\mathsf{r} = 0.3 \log \gamma$.

First, let us set the target rate to be $\mathsf{r} = 1$. Figs. 6 and 7 present the outage probability versus transmitter side SNR curves for the *i.i.d.* and *i.ni.d.* cases respectively. From the slope of outage probability curves, it can be seen that the diversity gain of CAO-SIR-RP and CAO-SIR-R is 5, while that of basic CAO-SIR and CAO-SIR-P is 4. Because CAO-SIR-RP and CAO-SIR-R make use of the direct link, they achieve higher diversity gain than basic CAO-SIR and CAO-SIR-P. As a result, the DMT formulas given by Eqs. (36) and (46) are validated for $r = 0$. Thanks to the power allocation, CAO-SIR-RP has a SNR gain of 1.7 dB over CAO-SIR-R, while CAO-SIR-P has a SNR gain of 3.4 dB over basic CAO-SIR in the *i.i.d.* scenario. Such SNR gains are even higher in the *i.ni.d.* case. By comparing the outage probabilities of basic CAO-SIR in Figs. 6 and 7, we may also validate Eq. (42), where the outage probability of *i.ni.d.* case is bounded by that of *i.i.d.* case. Both CAO-SIR and conventional relaying protocols has a significant diversity gain over the direct transmission. More specifically, two-timeslot

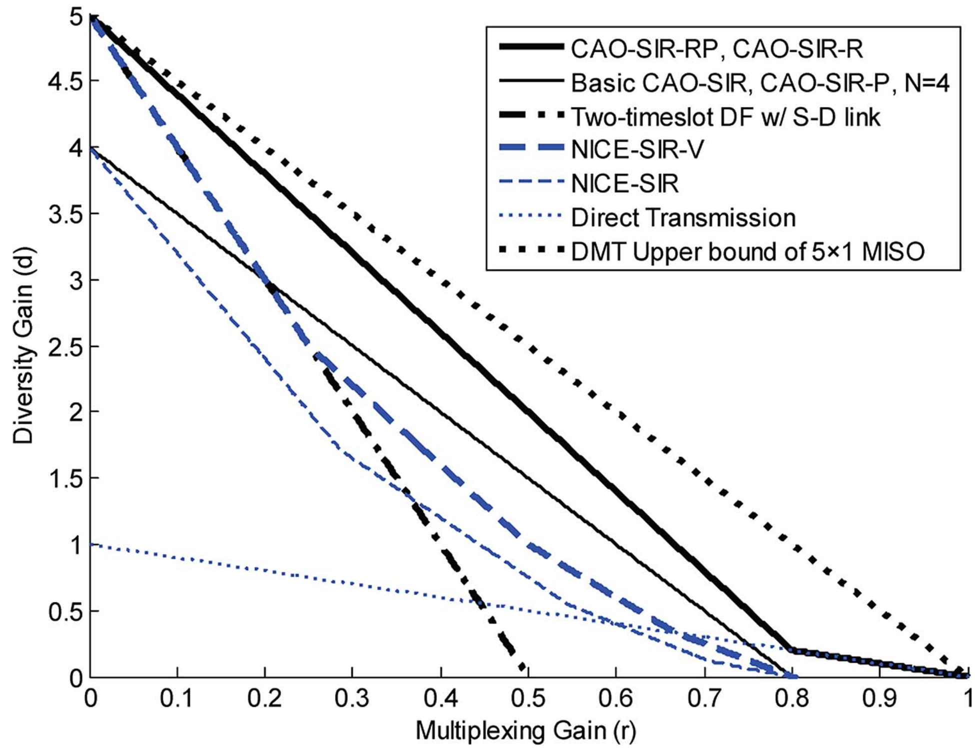

Fig. 10. The Diversity Multiplexing Tradeoff. The proposed CAO-SIR protocols are compared with direct transmission, two-timeslot relaying [4], and conventional successive relaying, namely, NICE-SIR [21].

DF relaying also performs well, when $r = 0$. Specifically, without utilizing the direct link, it achieves a full diversity gain of 4. The diversity gain of conventional successive relaying is also 4, which matches with the theoretical analysis in [11], [21].

Next, let us set the multiplexing gain to be $r = 0.3$ and therefore the target rate to be $\mathrm{r} = 0.3 \log \gamma$. The outage probability versus transmitter side SNR curves are presented in Figs. 8 and 9, respectively. Similarly, we estimate the diversity gains of various relaying protocols from the slope of outage probability curves. In both *i.i.d.* and *i.ni.d.* cases, the diversity gain of CAO-SIR-RP and CAO-SIR-R is 3.2, while that of CAO-SIR and CAO-SIR-P is 2.5. Again, the simulation results verified the DMT analysis presented by Eqs. (36) and (46) for $r = 0.3$. Due to the use of power allocation, CAO-SIR-RP has a SNR gain of 3.2 dB over CAO-SIR-R, while CAO-SIR-P has a SNR gain of 5.7 dB over basic CAO-SIR in the *i.i.d.* case. Similar to the observation on Figs. 6 and 7 where $r = 0$, such SNR gains are even higher in the *i.ni.d.* scenario. In contrast to the observation on Figs. 4 and 5, A careful reader may notice that CAO-SIR-RP achieves a significant SNR gain over CAO-SIR-R when the outage probability is chosen as a performance metric in Figs. 6–9. This is mainly because the outage tends to occur when there exists some poor sub-channels in deep fading. In this case, fortunately, power allocation is extremely useful and may significantly increase the sum rate, thereby effectively reducing the outage probability that the sum rate is smaller than a target rate. Furthermore, from the comparison of the outage probabilities of basic CAO-SIR in Figs. 8 and 9, we may draw a conclusion that Eq. (42) can be validated even when the target rate is not fixed.

It is interesting to compare the diversity gains of various relaying protocols for $r > 0$, where spectral efficiency plays a more important role. Specifically, it is observed from Figs. 8 and 9 that the diversity gains of two-timeslot DF relaying and conventional successive relaying are 1.6 and 2.2, respectively. Clearly, successive relaying achieves higher diversity gain than two-timeslot DF relaying. This is because two-timeslot DF relaying has to pay more diversity gain loss as a price to achieve a certain multiplexing gain due to its poor spectral efficiency. In contrast, successive relaying takes more advantage of its high spectral efficiency when high multiplexing gain is required. From [11] and [21], 2.2 is the maximal diversity gain that can be achieved by fixed target rate successive relaying with direct link for $r = 0.3$, even if the number of selected relays is optimized according to r. However, even the basic CAO-SIR without using the direct link may achieve higher diversity gain than the optimal fixed target rate successive relaying with direct link. As a result, we may draw a conclusion that rate adaption in CAO-SIR may improve its DMT significantly.

C. Diversity Multiplexing Tradeoff

Having validated the diversity given by Eqs. (36) and (46) for sampling multiplexing gain $r = 0$ and $r = 0.3$, we next turn our attention to the comparison of DMT curves, which characterize the diversity gain for arbitrary multiplexing gain $r \in [0, 1]$. In Fig. 10, we draw the DMT curve of CAO-SIR-RP and CAO-SIR-R based on Eq. (46), and that of the basic CAO-SIR and CAO-SIR-P based on Eq. (36). For the basic CAO-SIR and CAO-SIR-P, all the four potential relays are employed so as to optimize the DMT. The optimal DMT curves of two-timeslot DF relaying, fixed rate successive relaying, as well as, direct transmission, are also presented in the same figure. For the fixed rate successive relaying, the number of selected relays is adapted to r in order to maximize $d(r)$, as shown in [11] and [21].

From Fig. 10, it can be observed that CAO-SIR-RP and CAO-SIR-R are the optimal among all the interested relaying protocols. Their DMT curve is the outer envelop of two straight lines, one connecting two DMT pairs, $(M+1, 0)$ and $\left(0, \frac{M+1}{M+2}\right)$, and the other connecting two DMT pairs, (1, 0) and (0, 1). The two lines are joint at $\left(\frac{M}{M+1}, \frac{1}{M+1}\right)$. Since the basic CAO-SIR and CAO-SIR-P do not exploit the direct link, they suffer from a slight diversity and multiplexing gain loss compared to CAO-SIR-RP and CAO-SIR-R. In particular, their DMT curve is a straight line connecting two DMT pairs $(M, 0)$ and $\left(0, \frac{M}{M+1}\right)$. When M is large, the gap between the two DMT curves will be negligible. In Fig. 10, we also present a DMT outer bound characterize by $d(r) = (M+1)(1-r)$. Such a outer bound can be achieved by cooperative communications employing M full duplex relays, or equivalently, an $(M+1)\times 1$ MISO transmission. When M is large, the gap becomes negligible. In other words, CAO-SIR, which only employs half duplex relays, may asymptotically achieve the DMT outer bound as if the same number of full duplex relays are utilized. From Fig. 10, the gap between the DMT curves of CAO-SIR and its outer bound is very small even when $M = 4$. As a result, the DMT of CAO-SIR with reasonable M may well approximate its outer bound. In practice, a slow fading channel easily remains fixed during a successive relaying period lasting for $(M+1)$ timeslots if M is not very large. Hence, CAO-SIR can be adopted to achieve a near-optimal DMT in slow fading channels.

To give more insights, we compare CAO-SIR with existing relaying protocols. Two-timeslot DF relaying achieves full diversity when $r = 0$. Unfortunately, its diversity gain decreases dramatically with the increase of the multiplexing gain r. When $r = \frac{1}{2}$, its diversity gain drops to zero, despite of the number of relays. This is simply due to its poor spectral efficiency induced by the multiplexing loss. In contrast, direct transmission achieves high spectral efficiency but suffers from poor diversity gain, because it only utilizes the $S-D$ link. Conventional successive relaying may achieve either significant diversity gain of $M+1$ or high multiplexing gain of $\frac{M}{M+1}$, by optimizing the number of selected relays according to r, as shown in [11] and [21]. However, its DMT curve is not a straight line but a convex curve connecting two DMT pairs, $(M+1, 0)$ and $\left(0, \frac{M+1}{M+2}\right)$. Let us also note that $d(r) \le (M+1)\left(1 - \frac{M+2}{M+1}r\right)$ characterizes the lower bound of the DMT of CAO-SIR-RP/CAO-SIR-R. Since the lower bound is a straight line connecting the two end points of DMT curve of conventional successive relaying, we may conclude that there must be a gap between the DMT curves of CAO-SIR and conventional successive relaying. Due to the convexity of DMT curve of the fixed rate successive relaying, the gap is large when r is neither too large or too small. For $M = 4$ in our simulation, CAO-SIR-RP/CAO-SIR-R has a significant diversity gain of 1 over conventional successive relaying when $\frac{1}{4} \le r \le \frac{1}{2}$. For large M, CAO-SIR-RP/CAO-SIR-R may achieve at most $\frac{\sqrt{4M+9}-3}{2}$ diversity gain over conventional successive relaying. Hence, we arrive at the conclusion that the joint channel aware relay ordering and rate adaptation mechanism greatly improves the efficiency and reliability of successive relaying.

VII. Conclusion and Future Works

In this paper, a simple but spectral efficient cooperative communication method referred to as CAO-SIR was proposed and analyzed. In contrast to conventional successive relaying, where the transmission order and the forwarded message rate of various relays are both fixed, CAO-SIR carefully adapts both the relays' transmission order and data rates to the relays' link qualities. Relying on the idea of NICE, the joint channel aware relay ordering and rate adaptation mechanism assures that both the relays and the destination are capable of thoroughly mitigating the inter-relay interference induced by successive relaying. With the help of M relays, CAO-SIR may reliably transmit M messages to the destination in $M+1$ timeslots, thereby achieving high spectral efficiency. By formulating an equivalent model of parallel relay channels, we proposed low complexity algorithms including rate-ordering based search, double water filling, and water filling in cellar in order to further optimize the relay selection and power allocation of CAO-SIR. Noticing the similarity of the equivalent channel model of CAO-SIR and the parallel channel model like OFDM, we derive the upper and lower bounds of the outage probability of CAO-SIR and therefore derived its optimal DMT, which is presented by $d(r) = \max\left\{(M+1)\left(1 - \frac{M+2}{M+1}r\right), (1-r)\right\}$ given M potential relays. Given a large number of half-duplex relays, CAO-SIR may asymptotically achieve its DMT upper bound as if a $(M+1)\times 1$ MISO channel or M full duplex relays are employed. Since the complexity of CAO-SIR is equal to that of DFE, it has much lower complexity compared to the jointly decoding based successive relaying. Interesting future theoretical topics include CAO-SIR for AF or non-generative relays nodes, as well as, relay nodes equipped with multiple antennas. There are also several important future works in order for implementing CAO-SIR in practice. First, distributed relay selection and ordering methods are desired to reduce the protocol overhead of CAO-SIR. Second, when practical AMC is adopted to realize rate adaptation, decoding error along with error propagation in successive interference cancellation should be taken into account. Finally, more attentions can be paid to CAO-SIR for arbitrary time-varying channels, where opportunistic scheduling and rateless coding may be potentially helpful.

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