Relay Pair Selection Using Phase-Alignment in Buffer-Aided Successive Opportunistic Relaying

Themistoklis Charalambous, Su Min Kim, Nikolaos Nomikos, Mats Bengtsson, and Mikael Johansson

***Abstract*—In this paper, we consider a cooperative network consisting of a buffer-aided multi-antenna source, multiple single-antenna half-duplex buffer-aided relays and a single-antenna destination. Such a setup could represent a cellular downlink scenario, in which the source can be a more powerful wireless device with a buffer and multiple antennas, while a set of intermediate less powerful devices are used as relays to reach the destination. For this setup we assume that the channel state information is only available at the receiving side (CSIR), being either a relay or the destination, with the ability to provide limited feedback to the transmitting side. The main target is to recover the multiplexing loss of the network by facilitating successive transmissions by having the source to transmit its information to a relay, while another relay simultaneously transmits its information to the destination. Successive transmissions, however, cause inter-relay interference (IRI). In order to mitigate the IRI, we propose a relay pair selection policy that employs a phase alignment technique. The performance of the proposed relay pair selection policy is evaluated and compared with other state-of-the-art relaying schemes in terms of outage and throughput. The numerical results demonstrate that the proposed scheme can provide considerable performance improvements.**

I. INTRODUCTION

In multi-relay networks, simultaneous transmissions by the relays are in general difficult to handle; towards this end, opportunistic relay selection has been suggested in [1] to improve the resource utilization and to reduce the hardware complexity. Stemming from the relay selection concept, various improved selection techniques have been proposed in previous studies (see, *e.g.*, [2]–[4]). Traditional half-duplex (HD) relaying schemes partition the packet transmission slot into two phases, where the transmission on the source-relay $\{S{\rightarrow}R\}$ link happens in the first phase, and the transmission on the relay-destination $\{R{\rightarrow}D\}$ link occurs in the second phase. However, this relaying scheme limits the maximum achievable multiplexing gain to 0.5, which also results in a loss in spectral efficiency.

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In order to overcome such multiplexing and bandwidth limitations, several techniques have been proposed in the literature; see, *e.g.*, [5]. Among them, the successive relaying scheme in [6] incorporates multiple relay nodes and allows concurrent transmissions between source-relay and relay-destination to mimic an ideal full-duplex (FD) transmission. However, this scheme targets scenarios with a long distance between the relays and thus inter-relay interference is not considered. An extension of this work is discussed in [7], where the authors assume that inter-relay interference (IRI) is strong (in co-located or clustered relays) and can always be decoded at the affected nodes; this decoded IRI is exploited in a superposition coding scheme that significantly improves the diversity-multiplexing tradeoff performance of the system.

In earlier work, in which relays were assumed to lack data buffers, relay selection was mainly based on the $\max-\min$ criterion and its variations (see, for example, [1]–[4]). Here, the relay that receives the source signal is also the one that forwards the signal to the destination. With the adoption of buffer-aided relays, this coupling is broken allowing increased degrees of freedom. Buffering at the relay nodes has been shown to be a promising solution for cooperative networks and motivates the investigation of new protocols and transmission schemes (see [8] for an overview). Ikhlef *et al.* [9] proposed a novel criterion based on $\max-\max$ relay selection (MMRS), in which the relay with the best source-relay $\{S{\rightarrow}R\}$ link is selected for reception and the relay with the best relay-destination $\{R{\rightarrow}D\}$ link is selected for transmission on separate slots. In [10], at each slot the best link is selected among *all* available $\{S{\rightarrow}R\}$ and $\{R{\rightarrow}D\}$ links, as a part of the proposed $\max-\mathrm{link}$ policy, thus offering an additional degree of freedom to the network.

In order to recover the HD multiplexing loss, [11] suggests to combine MMRS with successive transmissions (called SFD-MMRS). As the proposed topology aims to mimic FD relaying, different relays are selected in the same time slot; however, relays are considered isolated and the effect of IRI is ignored. Kim and Bengtsson [12], [13] proposed buffer-aided relay selection and beamforming schemes taking the IRI into consideration; they consider a model where the source and destination are low-cost devices with a single antenna and the base stations comprise more powerful relays with buffers and multiple antennas. Numerical results show that their approach outperforms SFD-MMRS when interference is taken into consideration, and when the number of relays and antennas increases they approach the performance of the interference-free SFD-MMRS, herein called the *ideal* SFD-MMRS.

In many cases (*e.g.*, wireless sensors), the relay nodes are hardware-limited to be HD, while the source can be a more powerful wireless device with multiple antennas. Although this observation is not always true (*e.g.*, in D2D communications [12], [13]), it is a reasonable and common practical scenario. In this work, we relax the assumption of having knowledge of the full CSI. Instead, we allow for CSIR knowledge with limited feedback, *i.e.*, each receiving node has CSI of the channel it receives data from and it can provide some information to the transmitting node. More specifically, each (receiving) relay feeds back to the source a phase value via a reliable communication link. This approach is closely related to phase feedback schemes proposed and standardized for MISO transmission (see, *e.g.*, [14]–[17]). Under these conditions, we propose a relay pair selection scheme that performs partial phase alignment of signals, based on CSIR knowledge with limited feedback. The main target is to take advantage of the multi-antenna source in order to mitigate IRI. The numerical results demonstrate that the use of a multi-antenna source can provide considerable performance improvements.

II. System model

We consider a cooperative network consisting of a buffer-aided source S with multiple antennas, a set $\mathcal{K} \triangleq \{1, 2, \ldots, K\}$ of K HD decode-and-forward (DF) relays with buffers, and a single destination D. Fig. 1 illustrates a simple example with a buffer-aided two-antenna source S, two buffer-aided single-antenna HD DF relays, and a single-antenna destination D. To simplify the analysis, we examine the case where connectivity between the source and the destination is established only via the relays and ignore the direct $\{S \rightarrow D\}$ link (as in, *e.g.*, [9]–[13]). The number of data elements in the buffer of relay R_k is denoted by Q_k, $k = 1, \ldots, K$, and its capacity by $Q_{\max}$. In this work, we assume a fixed rate transmission policy, in which the packets are transmitted at a fixed rate of C_0 bits per channel use (BPCU), and the data of each transmission occupies 1 slot in the buffer.

First, we provide the signals received at relay R and destination D. At the destination, at any arbitrary time-slot n the following signal is received:

$$y_D[n] = h_{TD} x[p] + \eta_D[n] \; , \tag{1}$$

where $x[p]$ is the signal received and stored in a previous time-slot p in the buffer of the now transmitting relay T, h_{TD} denotes the channel coefficient from the transmitting relay T to the destination D, and $\eta_D[n]$ denotes the AWGN at the destination in the n-th time slot, *i.e.*, $\eta_D[n] \sim \mathcal{CN}(0, \sigma_D^2)$. It must be noted that $x[p]$ was not necessarily received in the previous time-slot (*i.e.*, $p \leq n-1$). At the same time, the reception of the source's signal by relay R is interfered from the transmission of T which forwards a previous signal $x[p]$ to the destination. Hence, R receives

$$y_R[n] = \sum_{i \in \mathcal{A}} h_{S_i R} w_i[n] x_{S_i}[n] + h_{TR} x[p] + \eta_R[n], \tag{2}$$

where $\mathcal{A}$ denotes the index set of transmit antennas at the source, *i.e.*, $\mathcal{A} = \{1, 2, \ldots, \nu\}$, $h_{S_i R}$ denotes the channel

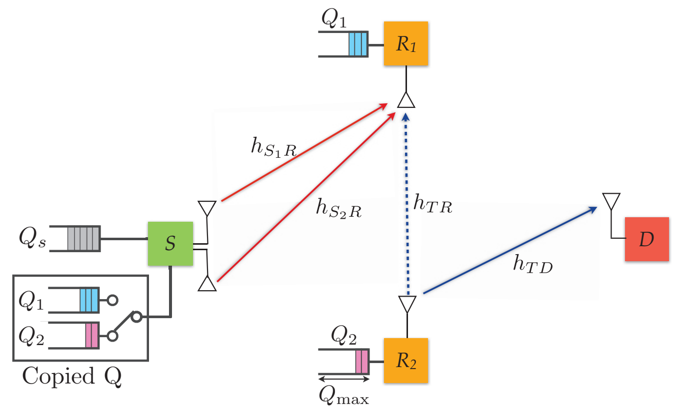

Fig. 1. A simple example of a cooperative network consisting of a buffer-aided source S with two antennas (S_1 and S_2), two HD relays (the receiving relay is denoted by R and the transmitting relay by T) and a destination D; in this example, $R_1 \equiv R$ and $R_2 \equiv T$. The buffers at S consist basically of replicas of the data queues of the relays; the source has new packets in the source buffer Q_S and replicas of the successfully transmitted packets to the relays in a set of copied buffers.

coefficient from the i-th transmit antenna at the source to the receiving relay R, h_{TR} denotes the channel coefficient from the transmitting relay T to the receiving relay R, $x_{S_i}[n]$ denotes the transmitted signal from the i-th transmit antenna at the source in the n-th time slot, $x_T[n]$ denotes the transmitted signal from the transmitting relay in the n-th time slot, $w_i[n]$ denotes the "beamforming" weights at the source, and $\eta_R[n]$ denotes the AWGN at the receiving relay in the n-th time slot, *i.e.*, $\eta_R[n] \sim \mathcal{CN}(0, \sigma^2)$.

The source S is assumed to be saturated (infinite backlog) and hence, it has always data to transmit. The buffering memory at the source is organized into K queues, which basically contain replicas of the data queues of the relays, in order to exploit it for IRI mitigation or cancellation.

The operation is assumed to be divided into time slots. In each time slot, the source and a relay simultaneously transmit their own data to mimic FD relaying (cf. [11]–[13], [18], [19]). The transmission powers of the source and the transmitting relay are denoted by P_S and P_T, respectively. For notational simplicity, we assume throughout this paper that all devices use a common fixed transmit power level (*i.e.*, $P_S = P_T = P$, $\forall T \in \mathcal{K}$), unless otherwise specified. We also assume the signals to be normalized so that $E|x_i[n]|^2 = P$. Moreover, we assume that the receivers send short-length error-free acknowledgment/negative-acknowledgment (ACK/NACK) messages over a separate control channel.

We assume narrowband Rayleigh block fading channels. Each channel coefficient is constant during one time slot and varies independently between time slots. For each time slot, the channel coefficient h_{ij} for link $\{i \rightarrow j\}$ follows a circular symmetric complex Gaussian distribution with zero mean and variance σ_{ij}^2, *i.e.*, $h_{ij} \sim \mathcal{CN}(0, \sigma_{ij}^2)$. Thus, the channel power gain $g_{ij} \triangleq |h_{ij}|^2$ follows an exponential distribution, *i.e.*, $g_{ij} \sim \text{Exp}(\sigma_{ij}^{-2})$. In addition, we assume additive white Gaussian noise (AWGN) at each receiver with variance σ^2.

III. Buffer-Aided Relay Selection Based on Buffer-Aided Phase Alignment

We aim at recovering the multiplexing loss of the network by having the source and a relay to align phases of channel gains, such that IRI is reduced. The phase value can be quantized into the desired number of bits using uniform quantization. The source signal can use such phase value in one of two possible ways: (a) to mitigate the interfering signal, so that the overall interference is reduced or even eliminated; (b) to amplify the interfering signal, so that it can be decoded and removed from the rest of the received signals. The relay pair selection is performed by choosing the pair that achieves the maximum end-to-end SINR.

A. Buffer-Aided Phase Alignment (BA-PA)

For overhead reduction on CSI estimation at the receiver, we consider to use just two of the antennas: (i) one for transmitting a new packet to a relay and (ii) the other to mitigate the IRI using a packet stored in the copied queue. The existence of more than two antennas, however, can increase the diversity gain by choosing a subset of antennas based on CSI. Given that not all available antennas are included, the overhead for CSI estimation is reduced. Assuming two antennas used, the received signal at R in (2) is given by

$$\begin{aligned} y_R[n] =& h_{S_1R}w_1[n]x_{S_1}[n] + h_{S_2R}w_2[n]x_{S_2}[n] \\ &+ h_{TR}x[p] + \eta_R[n], \end{aligned} \tag{3}$$

where we set $w_1[n] = 1/\sqrt{2}$ and $w_2[n] = e^{j\phi}/\sqrt{2}$. In each time slot, the signal from the second antenna of the source $x_{S_2}[n]$ is used in one of the following two ways:

(a) to minimize the interference caused by the transmitting relay; this is done by transmitting $x[p]$ with a shifted phase such that the interfering signal and the signal from the second antenna is in anti-phase. The optimal phase for this is given by

$$\phi^\star = \arg\min_{\phi} \left| \frac{h_{S_2R}}{\sqrt{2}} e^{j\phi} + h_{TR} \right|^2, \tag{4}$$

(b) to maximize the interference caused by the transmitting relay in order to make the signal strong enough to be decoded first, and hence, eliminate it. The optimal phase for this is given by

$$\phi^\dagger = \arg\max_{\phi} \left| \frac{h_{S_2R}}{\sqrt{2}} e^{j\phi} + h_{TR} \right|^2. \tag{5}$$

Proposition 1. *The phase $\phi^\star$ such that the interfering signal at the receiving relay R from the transmitted signal $x[p]$ of the transmitting relay T is minimized is given by*

$$e^{j\phi^\star} = -\frac{h^H_{S_2R}h_{TR}}{|h^H_{S_2R}h_{TR}|}. \tag{6}$$

Similarly, the phase $\phi^\dagger$ such that the interfering signal at the receiving relay R from the transmitted signal $x[p]$ of the transmitting relay T is maximized is given by

$$e^{j\phi^\dagger} = \frac{h^H_{S_2R}h_{TR}}{|h^H_{S_2R}h_{TR}|}. \tag{7}$$

Proof. By the triangle inequality,

$$\left| \frac{h_{S_2R}}{\sqrt{2}} e^{j\phi} + h_{TR} \right| \geq \left| \left| \frac{h_{S_2R}}{\sqrt{2}} \right| - |h_{TR}| \right|. \tag{8}$$

The optimization problem

$$\min_{\phi} \left| \frac{h_{S_2R}}{\sqrt{2}} e^{j\phi} + h_{TR} \right|^2 \tag{9}$$

is minimized when inequality (8) holds with equality; this occurs when h_{S_2R} is in phase with $-h_{TR}$. Let $\phi^\star$ the optimal angle ϕ for optimization (9). Since $\left|e^{j\phi}\right| = 1$, then the minimization yields $e^{j\phi^\star} = -\frac{h^H_{S_2R}h_{TR}}{|h^H_{S_2R}h_{TR}|}$.

Similarly, by the triangle equality,

$$\left| \frac{h_{S_2R}}{\sqrt{2}} e^{j\phi} + h_{TR} \right| \leq \left| \frac{h_{S_2R}}{\sqrt{2}} \right| + |h_{TR}|. \tag{10}$$

The optimization problem

$$\max_{\phi} \left| \frac{h_{S_2R}}{\sqrt{2}} e^{j\phi} + h_{TR} \right|^2 \tag{11}$$

is maximized when inequality (10) holds with equality; this occurs when h_{S_2R} is in phase with h_{TR}. Let $\phi^\dagger$ the optimal angle ϕ for optimization (11). Since $\left|e^{j\phi}\right| = 1$, the maximization yields $e^{j\phi^\dagger} = \frac{h^H_{S_2R}h_{TR}}{|h^H_{S_2R}h_{TR}|}$. $\square$

Proposition 1 gives the expressions for phase alignment for each of the two approaches considered. By appropriately choosing the phase shift ϕ of the signal from one of antennas at the source, the source can minimize or maximize the interfering signal in order to mitigate it or eliminate it completely. Note that the optimal value of ϕ (either $\phi^\star$ or $\phi^\dagger$) can be quantized into the desired number of bits using uniform quantization and hence, only a single value (*e.g.*, 1-byte suffices to provide a good approximation) is required to be fed back from a relay to the source.

B. Fixed Rate Relay Pair Selection Policy

Since only CSIR is available, the transmitters employ fixed rate transmission. In such a case, the main objective is to minimize the outage probability. Independently of nodal distribution and traffic pattern, a transmission from the transmitter to its corresponding receiver is successful (error-free) if the SINR at the receiver is above or equal to a certain threshold, called the *capture ratio* γ_0. Therefore, at the receiving relay R for a successful reception when the relay T is transmitting at the same time, we require that

$$\Gamma^S_R \triangleq \frac{|h_{S_1R}|^2 P/2}{\left| \frac{h_{S_2R}}{\sqrt{2}} e^{j\phi} + h_{TR} \right|^2 P + \sigma^2} \geq \gamma_0, \tag{12}$$

and at the destination, we require that

$$\Gamma^T_D \triangleq \frac{|h_{TD}|^2 P}{\sigma^2} \geq \gamma_0. \tag{13}$$

An outage event occurs at the relay R and destination D when $\Gamma^S_R < \gamma_0$ and $\Gamma^T_D < \gamma_0$, respectively. The outage probability is denoted by $\mathbb{P}(\Gamma^k_i < \gamma_0)$, where i represents the receiving node and k the transmitting node. Each relay i is able to estimate the SINR for each transmitting relay k, denoted by Γ_i^k, $k \neq i$ (the full pilot protocol needed to the channel estimation is out of the scope of this work). We assume that this information can be communicated to the destination. In addition, the destination node can compute its own SNR due to each of the transmitting relays, denoted by Γ_D^k, $k \in \{1, \dots, K\}$. Finally, we assume that the destination node has buffer state information[1] and selects the relays for transmission and reception, based on some performance criterion, *e.g.*, with the maximum end-to-end SINR (as it is defined in [11]), through an error-free feedback channel. Note that by having the destination to take the decision, no global CSI is required at any node.

As we have seen in Proposition 1, the source can minimize the interfering signal or maximize it in order to eliminate it by appropriately choosing the phase shift ϕ of the signal from one of antennas at the source. It can be easily deduced that at low IRI, it is beneficial to try to remove the interfering signal, whereas at high IRI, it is beneficial to amplify the interfering signal and thus, eliminate it completely by decoding it first. The receiving relay is able to compute which option gives the highest SINR in each case, since it has knowledge of the channel states and hence, it can decide which phase to feed back to the source at each time slot.

The procedure of the proposed algorithm is as follows: By examining *one-by-one* the possible relay pairs, first we calculate the power of the signal received at D which is $P_D = |h_{TD}|^2 P + \sigma^2$ for an arbitrary relay T with non-empty buffer. The buffer of the receiving relay R must be non-full and differ from the transmitting relay. For each candidate relay i for reception, a *feasibility check* for interference cancellation (IC) is performed, *i.e.*,

$$\Gamma_i^k = \frac{\left|h_{R_k R_i}\right|^2 P}{|h_{S_1 R_i} + h_{S_2 R_i} e^{j\phi}|^2 P/2 + \sigma^2} \geq \gamma_0.$$

If IC is feasible, the candidate relay is examined whether SNR at the receiving relay after IC is above the *capture ratio* γ_0 or not, *i.e.*, once interference is removed (12) becomes

$$\Gamma_R^S \triangleq \frac{|h_{S_1 R}|^2 P/2}{\sigma^2} \geq \gamma_0.$$

If IC is infeasible, interference mitigation (IM) is considered. Hence, it is examined whether SINR at the receiving relay after IM is above the *capture ratio* or not. If the relay denoted by R can provide an SNR/SINR above the capture ratio after IC/IM, it is considered as a candidate receiving relay.

For the selected relay pair (R^*, T^*), the queue lengths are updated at the end of time slot as

$$Q_{R^*}(t) = \min\{Q_{R^*}(t-1) + C_0, Q_{\max}\}, \quad (14a)$$
$$Q_{T^*}(t) = \max\{Q_{T^*}(t-1) - C_0, 0\}, \quad (14b)$$

Note that since we assume fixed rate transmission, the queue length is equivalently modeled as the number of packets in the queue.

[1]The destination can know the status of the relay buffers by monitoring the ACK/NACK signaling and the identity of the transmitting/receiving relay.

IV. Numerical Results

In the simulations, we assume that the clustered relay configuration ensures i.i.d. Rayleigh block fading with average channel qualities $\sigma_{SR}^2 = \sigma_{RR}^2 = \sigma_{RD}^2 = 0$ dB for all the $\{S \rightarrow R\}$, $\{R \rightarrow R\}$, and $\{R \rightarrow D\}$ links, respectively.

Fig. 2 shows the outage probability[2] with various SNR values for the transmission rate $C_0 = 1$ BPCU, three relays ($K = 3$), and infinite length of buffer ($Q_{\max} \rightarrow \infty$). The proposed BA-PARS scheme achieves similar performance to the BA-SOR scheme at low SNR, but it is not degraded at high SNR thanks to a hybrid mode of IC and IM. In addition, assuming a powerful source node such as base station, we depict the case of double power at the source for the proposed BA-PARS scheme, which shows that the proposed BA-PARS scheme can achieve the outage performance of the ideal SFD-MMRS scheme. Hence, if extra power at the source is available, the proposed BA-PARS scheme can provide the best outage performance.

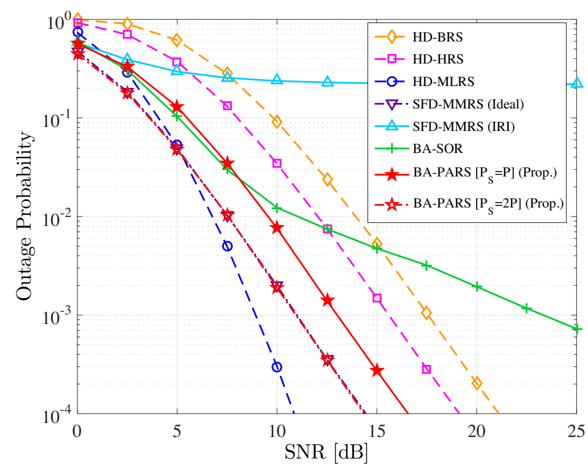

Fig. 2. Outage probability for $C_0 = 1$ BPCU, $K = 3$, and $Q_{\max} \rightarrow \infty$. For the proposed BA-PARS scheme, we additionally consider double power at the source (denoted by '[2P]') to show the case of a powerful source node.

Fig. 3 shows the outage probability of the proposed BA-PARS scheme for varying the maximum buffer size when $C_0 = 1$ BPCU and $K = 3$. As in [11], [18], we assume that half of buffer elements are occupied at initial phase (in order to reach the steady-state queue lengths quicker). As the maximum buffer size $Q_{\max}$ increases, the outage performance is improved and converges to the case of having buffers of infinite length. The convergence occurs at lower buffer sizes at high SNR than at low SNR, since buffer full/empty events contribute more in outage events at high SNR due to sufficiently good received signal strengths (*i.e.*, outage events due to bad channel conditions occur rarely and outage events happen due to buffer full/empty events).

Fig. 4 shows the average end-to-end achievable rate with three different transmission data rates ($C_0 = 1.5$ and $C_0 = 2.5$ BPCU) when $K = 3$ and $Q_{\max} = 10$. The conventional HD schemes achieve half the data rate due to the HD limitation

[2]While an outage is defined in [11] when a minimum of channel gains of both $\{S \rightarrow R\}$ and $\{R \rightarrow D\}$ links is less than the capture ratio γ_0, we define the outage probability as a portion of successfully transmitted packets among the total number of transmitted packets since the previous definition is not rigorous for the case of concurrent transmissions with IRI.

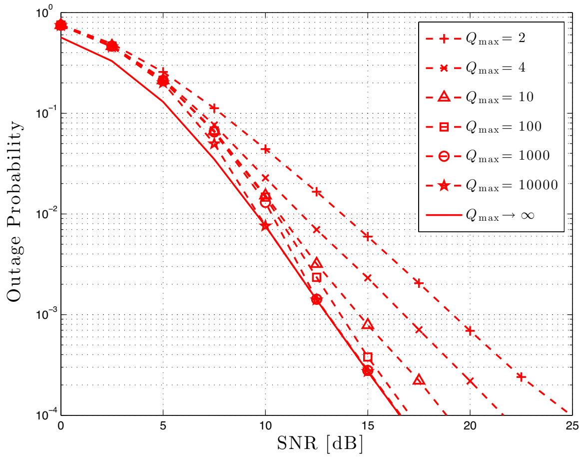

Fig. 3. Outage probability of the proposed BA-PARS scheme for varying the maximum buffer size $Q_{\max}$ when $C_0 = 1$ BPCU and $K = 3$. The convergence occurs at lower buffer sizes at high SNR than at low SNR.

although the HD-MLRS scheme achieves a full diversity in outage performance. The BA-SOR scheme approaches the full data rate with $C_0 = 1.5$ BPCU at high SNR but significantly degrades with higher data rates. In contrast, the proposed BA-PARS scheme can achieve the full data rates for all the cases such that it guarantees the required data rate if a proper data rate is chosen according to SNR, even if it has some gaps compared to the ideal SFD-MMRS scheme since the source power is split for IC/IM. Similarly to the outage performance, if double power at the source is available, the proposed BA-PARS scheme can approach the achievable rate of the ideal SFD-MMRS scheme without suffering from IRI.

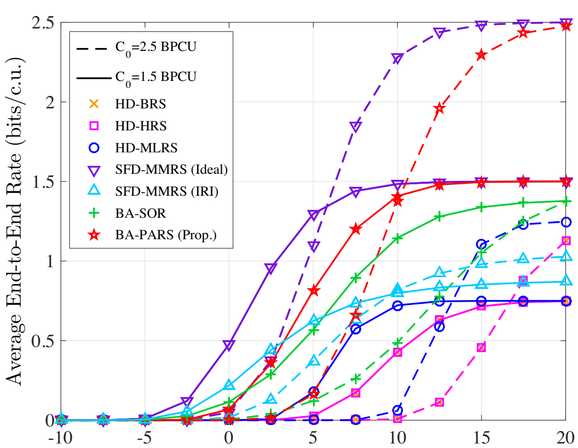

Fig. 4. Average end-to-end rate with three different fixed data rates ($C_0 = 1.5$ and $C_0 = 2.5$ BPCU) when $K = 3$ and $Q_{\max} = 10$.

V. Conclusions and Future Directions

In this work, we present a relay pair selection policy that employs a buffer-aided multi-antenna source, a cluster of HD buffer-aided relays and a destination. Assuming CSI at receiver only, a phase alignment technique is applied by the source in order to mitigate/cancel IRI. Then, a relay pair is selected, such that the maximum end-to-end SINR is achieved. The benefits of this network deployment are demonstrated via a numerical evaluation, where the improved performance is observed with respect to the outage probability and average end-to-end rate.

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