Virtual Full-Duplex Buffer-Aided Relaying – Relay Selection and Beamforming

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***Abstract*—In this paper, we study virtual full-duplex (FD) buffer-aided relaying to recover the multiplexing loss of half-duplex (HD) relaying in a network with multiple buffer-aided relays, each of which has multiple antennas, through opportunistic relay selection and beamforming. The main idea of virtual FD buffer-aided relaying is that a source and a relay simultaneously transmit their own information to another relay and a destination, respectively. In this network, inter-relay interference (IRI) is a crucial problem which has to be resolved like self-interference in the FD relaying. In contrast to previous work that neglected the IRI, we propose two buffer-aided relay selection and beamforming schemes taking the IRI into consideration. Numerical results show that our proposed relay selection scheme with zero-forcing beamforming (ZFB)-based IRI cancellation approaches the average end-to-end capacity of IRI-free upper bound as the numbers of relays and antennas increase.**

I. Introduction

Since cooperative relaying can improve both spectral efficiency and spatial diversity, it is a promising core technology for next-generation wireless communication networks. So far, many studies have considered half-duplex (HD) relaying based on two-phase operation where a source transmits data to relays in the first phase and the relays forward it to a destination in the second phase [1]. However, this HD relaying causes *multiplexing loss* expressed as $\frac{1}{2}$ pre-log factor. To overcome the multiplexing loss, Jain *et al.* have recently proposed a practical full-duplex (FD) relaying scheme based on signal inversion and digital cancellation to resolve strong self-interference [2]. Although this work showed feasibility of FD relaying using WiFi devices, it is still premature for cellular communications, which require additional cancellation gains.

In order to mitigate the multiplexing loss in HD relaying, *successive relaying* protocols have been proposed in a two-relay network [3] and multiple-relay networks [4], [5]. In these protocols, two relays take turn on acting as receivers and transmitters successively and a source and a transmitting relay transmit their own codewords simultaneously. Here, the source transmits a new codeword and the relay transmits a previously received codeword. The successive relaying asymptotically achieves the spectral efficiency of the FD relaying. In [3], [4], successive interference cancellation (SIC) or joint decoding (JD) has been employed for *inter-relay interference* (IRI) cancellation. However, SIC requires strong interference scenarios and JD requires high computational complexity. Instead of the SIC for IRI, an interference subtraction scheme using a decoding set of relays has been proposed in [5]. Even if this scheme avoids the strong interference requirement, it uses a fixed low-rate transmission in order to increase the size of the decoding set.

On the other hands, *buffer-aided relaying* has been proposed in a three-node network [6]–[8]. The key idea is an opportunistic relaying mode selection (buffering or forwarding) according to channel conditions. The HD buffer-aided relaying can achieve up to two-fold spectral efficiency, compared to HD relaying without buffer. By extending to multiple-relay networks, several *opportunistic relaying* schemes, which exploit the best HD buffer-aided relay, have been proposed [9]–[11]. Ikhlef *et al.* [9] have proposed the $\max-\max$ relay selection (MMRS) scheme, which selects the best $\{\mathcal{S}-\mathcal{R}\}$ and $\{\mathcal{R}-\mathcal{D}\}$ relays with the maximum channel gains. However, the MMRS scheme does not fully take advantage of the benefits of buffer-aided relaying since it maintains the two-phase operation. Therefore, Krikidis *et al.* [10] have proposed the $\max-\mathrm{link}$ relay selection scheme, which selects the best relaying mode as well as the maximum channel gain.

Most recently, Ikhlef *et al.* [11] have proposed the space full-duplex $\max-\max$ relay selection (SFD-MMRS) scheme, which mimics the FD relaying by utilizing the best receiving and transmitting relays operating simultaneously. In this scheme, they did not consider IRI by assuming fixed-relays with highly directional antennas. However, this assumption does not always hold and it is hard to be practically realized as the number of relays increases. With consideration of IRI, Nomikos *et al.* [12] have proposed a buffer-aided successive opportunistic relay selection scheme employing the SIC at the receiving relay. Even if it partially overcame the strong interference requirement of SIC through power allocation at the source and relays, the main objective was to minimize the total energy expenditure under fixed rate transmission.

In this paper, our main goal is to approach the average end-to-end capacity of ideal virtual FD relaying even in the presence of IRI. To this end, we propose transmission schemes based on maximizing the weighted sum of instantaneous rates to achieve the average end-to-end capacity. We present two relay selection schemes without and with IRI cancellation. For the IRI cancellation, we adopt multiple antennas at relays and design linear beamformers at the receiving and transmitting relays, respectively. To focus on maximizing the average end-to-end capacity, we employ adaptive rate transmission at the source and relays, and consider delay-tolerant applications.

The rest of this paper is organized as follows. In Section II, the system model is presented. The instantaneous rates and average end-to-end capacity of a buffer-aided relaying network are described in Section III. Buffer-aided relay selection schemes considering the IRI are proposed in Section IV. In Section V, numerical results are presented. Finally, conclusive remarks are drawn in Section VI.

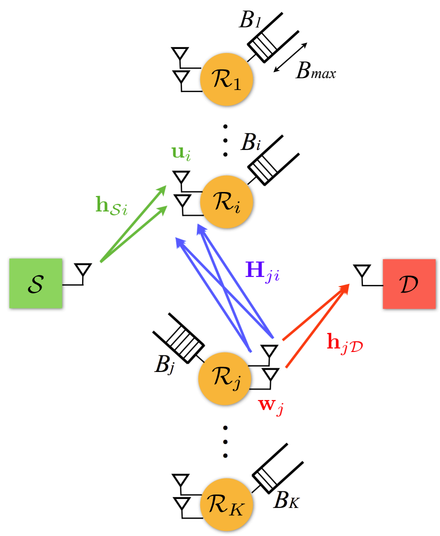

Fig. 1. System Model: a single source, a single destination, and multiple relays with buffer and multiple antennas (e.g., $M = 2$).

II. System Model

In this paper, we consider a source, $\mathcal{S}$, and a destination, $\mathcal{D}$, which have a single antenna, and K buffer-aided relays with M antennas each (e.g., in Fig. 1, $M = 2$). Denote the set of HD buffer-aided decode-and-forward (DF) relays by $\mathcal{K} = \{1, \ldots, K\}$. We assume that there is no direct path between the source and destination as is common in the literature [5]–[12]. This system model can be regarded as an example of relay-assisted device-to-device (D2D) communications where the source and destination are low-cost devices with some limitations such as a single antenna. The source is supposed to always have data traffic to transmit. In addition, let $\mathbf{h}_{\mathcal{S}i}$, $\mathbf{h}_{j\mathcal{D}}$, and $\mathbf{H}_{ji}$, $i, j \in \mathcal{K}$ denote the channel coefficient vectors and matrix of $\{\mathcal{S}-\mathcal{R}\}$, $\{\mathcal{R}-\mathcal{D}\}$, and $\{\mathcal{R}-\mathcal{R}\}$ links, respectively. If we denote elements of $\mathbf{h}_{\mathcal{S}i}$, $\mathbf{h}_{j\mathcal{D}}$, and $\mathbf{H}_{ji}$ as $h^m_{\mathcal{S}i}$, $h^m_{j\mathcal{D}}$, and h^{ml}_{ji}, $i, j \in \mathcal{K}$, $m, l \in \{1, \ldots, M\}$, they are circular symmetric complex Gaussian random variables with zero mean and variances $\sigma^2_{\mathcal{SR}}$, $\sigma^2_{\mathcal{RD}}$, and $\sigma^2_{\mathcal{RR}}$, respectively, i.e., $h^m_{\mathcal{S}i} \sim \mathcal{CN}(0, \sigma^2_{\mathcal{SR}})$, $h^m_{j\mathcal{D}} \sim \mathcal{CN}(0, \sigma^2_{\mathcal{RD}})$, and $h^{ml}_{ji} \sim \mathcal{CN}(0, \sigma^2_{\mathcal{RR}})$. Here, $\mathbf{H}_{ii} = 0$ due to no self-interference of the HD relaying.

In order to mimic FD relaying, $\{\mathcal{S}-\mathcal{R}\}$ and $\{\mathcal{R}-\mathcal{D}\}$ transmissions are performed simultaneously by using the best pair of receiving and transmitting relays as in [11], [12]. For a given selected relay pair (i, j), the received signal vector at the receiving relay i is expressed as:

$$\begin{aligned} \mathbf{y}_i &= \mathbf{h}_{\mathcal{S}i} x_{\mathcal{S}} + \mathbf{H}_{ji}\mathbf{x}_j + \mathbf{n}_i \\ &= \mathbf{h}_{\mathcal{S}i} x_{\mathcal{S}} + \mathbf{H}_{ji}\mathbf{w}_j x_j + \mathbf{n}_i, \end{aligned} \tag{1}$$

where $\mathbf{h}_{\mathcal{S}i} = [h^1_{\mathcal{S}i}, \ldots, h^M_{\mathcal{S}i}]^T$ denotes the channel vector from the source to the i-th relay where $(\cdot)^T$ denotes the transpose operation, $\mathbf{H}_{ji} \in \mathbb{C}^{M\times M}$ denotes the inter-relay channel matrix from the j-th relay to the i-th relay, $x_{\mathcal{S}}$ denotes the transmitted data symbol from the source, and $\mathbf{x}_j = \mathbf{w}_j x_j$ denotes the transmitted data symbol vector from the j-th relay where $\mathbf{w}_j = [w^1_j, \ldots, w^M_j]^T$ and x_j represent the transmit beamforming vector of the j-th relay and the desired data symbol of the j-th relay, respectively. Here, $\mathbb{E}\left[|x_{\mathcal{S}}|^2\right] \le P_{\mathcal{S}}$ and $\mathbb{E}\left[|x_j|^2\right] \le P_{\mathcal{R}}$ where $P_{\mathcal{S}}$ and $P_{\mathcal{R}}$ denote the transmitting powers of the source and the relay, respectively, and $\|\mathbf{w}_j\| = 1$ for $i, j \in \mathcal{K}$ where $\|\cdot\|$ denotes the 2-norm operation. $\mathbf{n}_i$ denotes the additive white Gaussian noise (AWGN) vector with zero mean and covariance $\sigma^2_n \mathbf{I}_M$ where $\mathbf{I}_M$ denotes the $M\times M$ identity matrix, i.e., $\mathbf{n}_i \sim \mathcal{CN}(0, \sigma^2_n \mathbf{I}_M)$. For the transmitting relay j, a received signal at the destination is expressed as:

$$\begin{aligned} y_d &= {\mathbf{h}_{j\mathcal{D}}}^H \mathbf{x}_j + n_{\mathcal{D}} \\ &= {\mathbf{h}_{j\mathcal{D}}}^H \mathbf{w}_j x_j + n_{\mathcal{D}}, \end{aligned} \tag{2}$$

where $(\cdot)^H$ denotes the complex conjugate and transpose operation, $\mathbf{h}_{j\mathcal{D}} = [h^1_{j\mathcal{D}}, \ldots, h^M_{j\mathcal{D}}]^T$ denotes the channel vector from the j-th relay to the destination, and $n_{\mathcal{D}}$ denotes the AWGN with zero mean and variance σ^2_n, i.e., $n_{\mathcal{D}} \sim \mathcal{CN}(0, \sigma^2_n)$.

III. Instantaneous Rates and Average End-to-End Capacity of a Buffer-Aided Relaying Network

If we employ a receive beamforming vector at the i-th receiving relay as $\mathbf{u}_i = [u^1_i, \ldots, u^M_i]^T$, the received signal after the decoding is given by

$$r_i = {\mathbf{u}_i}^H \mathbf{y}_i = {\mathbf{u}_i}^H \mathbf{h}_{\mathcal{S}i} x_{\mathcal{S}} + {\mathbf{u}_i}^H \mathbf{H}_{ji}\mathbf{w}_j x_j + \tilde{n}_i, \tag{3}$$

where $\tilde{n}_i = {\mathbf{u}_i}^H \mathbf{n}_i \sim \mathcal{CN}(0, \sigma^2_n)$ since $\|\mathbf{u}_i\| = 1$ and $\mathbf{u}_i$ is independent of $\mathbf{n}_i$. From Eqns. (3) and (2), instantaneous received SINR/SNR for both $\{\mathcal{S}-i\}$ and $\{j-\mathcal{D}\}$ links at time slot t are expressed, respectively, as:

$$\gamma_{\mathcal{S}i}(t) = \frac{\rho_{\mathcal{S}} |{\mathbf{u}_i}^H \mathbf{h}_{\mathcal{S}i}|^2}{1 + \rho_{\mathcal{R}} |{\mathbf{u}_i}^H \mathbf{H}_{ji}\mathbf{w}_j|^2}, \tag{4}$$

and

$$\gamma_{j\mathcal{D}}(t) = \rho_{\mathcal{R}} |{\mathbf{h}_{j\mathcal{D}}}^H \mathbf{w}_j|^2, \tag{5}$$

where $\rho_{\mathcal{S}} = P_{\mathcal{S}}/\sigma^2_n$, and $\rho_{\mathcal{R}} = P_{\mathcal{R}}/\sigma^2_n$. Let $B_i(t)$ denote the number of bits in the buffer of the i-th relay at the end of time slot t. If we assume an information-theoretic capacity achieving channel coding scheme, with consideration of buffer status at the receiving relay i, instantaneous rate of the $\{\mathcal{S}-i\}$ link is given by

$$C_{\mathcal{S}i}(t) = \min\left\{\log_2\left(1 + \gamma_{\mathcal{S}i}(t)\right), B_{max} - B_i(t-1)\right\}, \tag{6}$$

where $\min\{\cdot,\cdot\}$ denotes the minimum value of arguments, B_{max} denotes the maximum buffer length in bits, and the number of bits in the buffer of the i-th relay is updated by

$$B_i(t) = B_i(t-1) + C_{\mathcal{S}i}(t).$$

For the transmitting relay j, the instantaneous rate of link $\{j-\mathcal{D}\}$ in time slot t is obtained by

$$C_{j\mathcal{D}}(t) = \min\left\{\log_2\left(1 + \gamma_{j\mathcal{D}}(t)\right), B_j(t-1)\right\}, \tag{7}$$

where the number of bits in the buffer of the j-th relay is updated by

$$B_j(t) = B_j(t-1) - C_{j\mathcal{D}}(t).$$

Assuming stationarity of the buffers, the average end-to-end capacity of a buffer-aided relay network is almost surely given by a minimum of average $\{\mathcal{S}-\mathcal{R}\}$ and $\{\mathcal{R}-\mathcal{D}\}$ link capacities [6], [11], i.e.,

$$\bar{C} = \min\left\{\mathbb{E}[\tilde{C}_{\mathcal{SR}}(t)], \mathbb{E}[\tilde{C}_{\mathcal{RD}}(t)]\right\}, \tag{8}$$

where $\mathbb{E}[\cdot]$ denotes the expectation operation, $\tilde{C}_{\mathcal{SR}}(t)$ and $\tilde{C}_{\mathcal{RD}}(t)$ denote the effective instantaneous rates of the $\{\mathcal{S}-\mathcal{R}\}$ link and the $\{\mathcal{R}-\mathcal{D}\}$ link in time slot t, respectively, where relays for both links are dynamically selected at each transmission instance according to relay selection schemes. Then, the effective instantaneous rate of link k is given by

$$\tilde{C}_k(t) = \log_2(1+\tilde{\gamma}_k(t)), \tag{9}$$

where $k \in \{\mathcal{SR}, \mathcal{RD}\}$ and $\tilde{\gamma}_k(t)$ denotes the effective SNR of link k after relay pair selection with optimal beamforming and they are obtained by

$$(\tilde{\gamma}_{\mathcal{SR}}(t), \tilde{\gamma}_{\mathcal{RD}}(t)) = \underset{(\gamma_{\mathcal{S}i}(t),\gamma_{j\mathcal{D}}(t)):\mathbf{u}_i,\mathbf{w}_j, i\neq j, \forall i,j\in\mathcal{K}}{\arg\max} \bar{C}. \tag{10}$$

IV. Buffer-Aided Relay Selection Schemes in the Presence Inter-Relay Interference

Our main objective is to maximize the average end-to-end capacity given in Eq. (8) through relay pair selection and beamforming design. Since a relay selection and beamforming are based on instantaneous rate for each link, we need to find an equivalent objective function based on the instantaneous rate which maximizes the average end-to-end capacity. A minimum of instantaneous rates, which is the main objective function of traditional HD relay selection schemes, provides a lower bound of the average end-to-end capacity [6]. Here, we propose alternative approach based on a Lagrange relaxation.

In a virtual FD buffer-aided relaying network, the average end-to-end capacity maximization is formulated as follows:

$$\begin{aligned} \max_{\mathbf{u}_i,\mathbf{w}_j, i\neq j, \forall i,j\in\mathcal{K}} \quad & \min\left\{\mathbb{E}[\tilde{C}_{\mathcal{SR}}(t)], \mathbb{E}[\tilde{C}_{\mathcal{RD}}(t)]\right\} \\ \text{s. t.} \quad & \text{power constraints.} \end{aligned} \tag{11}$$

This optimization problem can be reformulated into

$$\begin{aligned} \max_{\mathbf{u}_i,\mathbf{w}_j, i\neq j, \forall i,j\in\mathcal{K}} \quad & z \\ \text{s. t.} \quad & \mathbb{E}[\tilde{C}_{\mathcal{SR}}(t)] \geq z, & \text{(12a)} \\ & \mathbb{E}[\tilde{C}_{\mathcal{RD}}(t)] \geq z, & \text{(12b)} \\ & \text{power constraints.} & \text{(12c)} \end{aligned}$$

Introducing Lagrange multipliers for first two constraints (12a)–(12b), we obtain the partial Lagrangian

$$\begin{aligned} \max_{\mathbf{u}_i,\mathbf{w}_j, i\neq j, \forall i,j\in\mathcal{K}} \quad & z + \lambda_{\mathcal{SR}}\left(\mathbb{E}[\tilde{C}_{\mathcal{SR}}(t)] - z\right) \\ & + \lambda_{\mathcal{RD}}\left(\mathbb{E}[\tilde{C}_{\mathcal{RD}}(t)] - z\right) \\ \text{s. t.} \quad & \text{power constraints.} \end{aligned} \tag{13}$$

Assuming instantaneous power constraints, the optimization over the transmit covariance matrix is equivalent to

$$\begin{aligned} & \max \mathbb{E}[\lambda_{\mathcal{SR}}\tilde{C}_{\mathcal{SR}}(t) + \lambda_{\mathcal{RD}}\tilde{C}_{\mathcal{RD}}(t)] \\ \Leftrightarrow \quad & \max \lambda_{\mathcal{SR}}\tilde{C}_{\mathcal{SR}}(t) + \lambda_{\mathcal{RD}}\tilde{C}_{\mathcal{RD}}(t). \end{aligned} \tag{14}$$

Rescaling (14) by $1/(\lambda_{\mathcal{SR}}+\lambda_{\mathcal{RD}})$ and introducing a parameter $\alpha = \lambda_{\mathcal{SR}}/(\lambda_{\mathcal{SR}}+\lambda_{\mathcal{RD}})$, we arrive at

$$\max_{\mathbf{u}_i,\mathbf{w}_j, i\neq j, \forall i,j\in\mathcal{K}} \alpha\tilde{C}_{\mathcal{SR}}(t) + (1-\alpha)\tilde{C}_{\mathcal{RD}}(t). \tag{15}$$

Hence, assuming the maximum transmission powers at the source and relays, the optimal relay selection and beamforming scheme is to find the best relay pair $(i^\star, j^\star)$ for the receive beamformer $\mathbf{u}_i$ and the transmit beamformer $\mathbf{w}_j$, i.e.,

$$\begin{aligned} \max_{\mathbf{u}_i,\mathbf{w}_j, i\neq j, \forall i,j\in\mathcal{K}} \quad & \alpha C_{\mathcal{S}i}(t) + (1-\alpha)C_{j\mathcal{D}}(t) \\ \text{s. t.} \quad & \|\mathbf{u}_i\| \leq 1, \|\mathbf{w}_j\| \leq 1. \end{aligned} \tag{16}$$

where $C_{\mathcal{S}i}(t)$ and $C_{j\mathcal{D}}(t)$ are given in Eq. (6) and Eq. (7), respectively. However, to find the optimal beamforming vectors for every given relay pair is non-convex and we therefore propose low-complexity suboptimal alternative relay selection schemes in the rest of this section.

A. *Proposed SINR-based Relay Selection Scheme with IRI-free Beamforming*

Obviously, if there is no IRI, a maximal ratio combining (MRC) at the receiving relay and a maximal ratio transmit (MRT) beamforming at the transmitting relay are optimal. Although these IRI-free beamformers are not optimal in the presence of IRI, we propose to use them and utilize an SINR measure for the $\{\mathcal{S}-\mathcal{R}\}$ link in the relay selection.

For a (i,j) relay pair, a receive beamforming vector for the MRC is designed by $\mathbf{u}_i = \frac{\mathbf{h}_{\mathcal{S}i}}{\|\mathbf{h}_{\mathcal{S}i}\|}$ and a transmit beamforming vector for the MRT is obtained by $\mathbf{w}_j = \frac{\mathbf{h}_{j\mathcal{D}}}{\|\mathbf{h}_{j\mathcal{D}}\|}$. Then, the received signal at the i-th relay is

$$\begin{aligned} r_i &= {\mathbf{u}_i}^H\mathbf{y}_i = {\mathbf{u}_i}^H\mathbf{h}_{\mathcal{S}i}x_{\mathcal{S}} + {\mathbf{u}_i}^H\mathbf{H}_{ji}\mathbf{w}_j x_j + {\mathbf{u}_i}^H\mathbf{n}_i \\ &= \|\mathbf{h}_{\mathcal{S}i}\|x_{\mathcal{S}} + \frac{{\mathbf{h}_{\mathcal{S}i}}^H\mathbf{H}_{ji}\mathbf{h}_{j\mathcal{D}}}{\|\mathbf{h}_{\mathcal{S}i}\|\cdot\|\mathbf{h}_{j\mathcal{D}}\|}x_j + \tilde{n}_i, \end{aligned} \tag{17}$$

where $\tilde{n}_i \sim \mathcal{CN}(0, \sigma_n^2)$. Moreover, the received signal at the destination is given by

$$\begin{aligned} y_d &= {\mathbf{h}_{j\mathcal{D}}}^H\mathbf{w}_j x_j + n_{\mathcal{D}}, \\ &= \|\mathbf{h}_{j\mathcal{D}}\|x_j + n_{\mathcal{D}}. \end{aligned} \tag{18}$$

Therefore, the instantaneous SINR and SNR of both the $\{\mathcal{S}-i\}$ and $\{j-\mathcal{D}\}$ links are given, respectively, by

$$\gamma_{\mathcal{S}i}(t) = \frac{\|\mathbf{h}_{\mathcal{S}i}\|^2\rho_{\mathcal{S}}}{1 + \frac{|{\mathbf{h}_{\mathcal{S}i}}^H\mathbf{H}_{ji}\mathbf{h}_{j\mathcal{D}}|^2}{\|\mathbf{h}_{\mathcal{S}i}\|^2\|\mathbf{h}_{j\mathcal{D}}\|^2}\rho_{\mathcal{R}}}, \tag{19}$$

and

$$\gamma_{j\mathcal{D}}(t) = \rho_{\mathcal{R}}\|\mathbf{h}_{j\mathcal{D}}\|^2. \tag{20}$$

Finally, the best relay pair is determined by

$$(i^\star, j^\star) = \underset{(i,j):i\neq j,\forall i,j\in\mathcal{K}}{\arg\max} \alpha C_{\mathcal{S}i}(t) + (1-\alpha)C_{j\mathcal{D}}(t),$$

where $C_{\mathcal{S}i}(t) = \min\{\log_2(1+\gamma_{\mathcal{S}i}(t)), B_{max} - B_i(t-1)\}$ and $C_{j\mathcal{D}}(t) = \min\{\log_2(1+\gamma_{j\mathcal{D}}(t)), B_j(t-1)\}$.

B. *Proposed Relay Selection Scheme with Zero-Forcing Beamforming (ZFB)-based IRI Cancellation*

In this subsection, we propose to optimize a transmit beamformer based on zero-forcing (ZF) at the receiving relay. First of all, we use $\mathbf{u}_i = \frac{\mathbf{h}_{\mathcal{S}i}}{\|\mathbf{h}_{\mathcal{S}i}\|}$ for the receiving relay i and then we maximize the effective channel power gain of the

$\{\mathcal{R} - \mathcal{D}\}$ link under a ZF condition. Therefore, for a relay pair (i, j), the following optimization problem is formulated:

$$\begin{aligned} \max \quad & |\mathbf{w}_j{}^H \mathbf{h}_{j\mathcal{D}}|^2 \\ \text{s. t.} \quad & \mathbf{u}_i{}^H \mathbf{H}_{ji} \mathbf{w}_j = 0, \\ & \|\mathbf{w}_j\| = 1. \end{aligned} \tag{21}$$

Let $\mathbf{V}_{ji} \in \mathbb{C}^{M \times (M-1)}$ be a matrix of which columns span the null-space of $\mathbf{H}_{ji}{}^H \mathbf{u}_i$. Then, any beamforming vector $\mathbf{w}_j$ fulfilling the first constraint in (21) can be written as $\mathbf{w}_j = \mathbf{V}_{ji}\boldsymbol{\beta}$, where $\boldsymbol{\beta} \in C^{(M-1)\times 1}$. Hence, the optimization problem is reformulated by

$$\begin{aligned} \max_{\boldsymbol{\beta}} \quad & |\boldsymbol{\beta}^H \mathbf{V}_{ji}{}^H \mathbf{h}_{j\mathcal{D}}|^2, \\ \text{s. t.} \quad & \|\mathbf{V}_{ji}\boldsymbol{\beta}\| = 1. \end{aligned} \tag{22}$$

Finally, the optimization problem is rewritten by

$$\begin{aligned} \max_{\boldsymbol{\beta}} \quad & \frac{\boldsymbol{\beta}^H \mathbf{V}_{ji}{}^H \mathbf{h}_{j\mathcal{D}} \mathbf{h}_{j\mathcal{D}}{}^H \mathbf{V}_{ji} \boldsymbol{\beta}}{\boldsymbol{\beta}^H \mathbf{V}_{ji}{}^H \mathbf{V}_{ji} \boldsymbol{\beta}}, \\ \text{s. t.} \quad & \|\mathbf{V}_{ji}\boldsymbol{\beta}\| = 1. \end{aligned} \tag{23}$$

The solution of this problem is $\boldsymbol{\beta}^\star = b(\mathbf{V}_{ji}{}^H \mathbf{V}_{ji})^{-1} \mathbf{V}_{ji}{}^H \mathbf{h}_{j\mathcal{D}}$, resulting in $\mathbf{w}_j{}^\star = b\mathbf{V}_{ji}(\mathbf{V}_{ji}^H \mathbf{V}_{ji})^{-1} \mathbf{V}_{ji}{}^H \mathbf{h}_{j\mathcal{D}} = b\mathbf{q}_j{}^\star$, where the scalar b is chosen so that $\|\mathbf{w}_j{}^\star\| = 1$, i.e. $\mathbf{w}_j{}^\star = \frac{\mathbf{q}_j{}^\star}{\|\mathbf{q}_j{}^\star\|}$.

$$\begin{aligned} \mathbf{q}_j{}^\star &= \mathbf{V}_{ji}(\mathbf{V}_{ji}{}^H \mathbf{V}_{ji})^{-1} \mathbf{V}_{ji}{}^H \mathbf{h}_{j\mathcal{D}} \\ &= \left(\mathbf{I}_{M-1} - \frac{\mathbf{H}_{ji}{}^H \mathbf{u}_i \mathbf{u}_i{}^H \mathbf{H}_{ji}}{\mathbf{u}_i{}^H \mathbf{H}_{ji} \mathbf{H}_{ji}{}^H \mathbf{u}_i} \right) \mathbf{h}_{j\mathcal{D}} \\ &= \mathbf{h}_{j\mathcal{D}} - c\mathbf{H}_{ji}{}^H \mathbf{h}_{\mathcal{S}i}, \end{aligned} \tag{24}$$

where the scalar $c = \frac{\mathbf{h}_{\mathcal{S}i}{}^H \mathbf{H}_{ji} \mathbf{h}_{j\mathcal{D}}}{\|\mathbf{h}_{\mathcal{S}i}{}^H \mathbf{H}_{ji}\|^2}$ since $\mathbf{u}_i = \frac{\mathbf{h}_{\mathcal{S}i}}{\|\mathbf{h}_{\mathcal{S}i}\|}$. This optimum solution implies a projection of $\mathbf{h}_{j\mathcal{D}}$ onto the null-space $\mathbf{V}_{ji}$.

According to this scheme, the received signal at the receiving relay i is obtained by

$$\begin{aligned} r_i = \mathbf{u}_i{}^H \mathbf{y}_i &= \mathbf{u}_i{}^H \mathbf{h}_{\mathcal{S}i} x_{\mathcal{S}} + \mathbf{u}_i{}^H \mathbf{H}_{ji} \mathbf{w}_j x_j + \mathbf{u}_i{}^H \mathbf{n}_i \\ &= \|\mathbf{h}_{\mathcal{S}i}\| x_{\mathcal{S}} + \tilde{n}_i, \end{aligned} \tag{25}$$

where $\tilde{n}_i \sim \mathcal{CN}(0, \sigma_n^2)$ and third equality comes from $\mathbf{u}_i{}^H \mathbf{H}_{ji} \mathbf{w}_j = 0$. For the transmitting relay j, the received signal at the destination is given by

$$\begin{aligned} y_d = \mathbf{h}_{j\mathcal{D}}^H \mathbf{w}_j{}^\star x_j + n_{\mathcal{D}} &= \mathbf{h}_{j\mathcal{D}}^H \frac{\mathbf{q}_j{}^\star}{\|\mathbf{q}_j{}^\star\|} x_j + n_{\mathcal{D}} \\ &= \frac{\|\mathbf{h}_{j\mathcal{D}}\|^2 - \tilde{c}}{\|\mathbf{h}_{j\mathcal{D}} - c\mathbf{H}_{ji}{}^H \mathbf{h}_{\mathcal{S}i}\|} x_j + n_{\mathcal{D}}, \end{aligned} \tag{26}$$

where the scalar value $\tilde{c} = \frac{|\mathbf{h}_{\mathcal{S}i}{}^H \mathbf{H}_{ji} \mathbf{h}_{j\mathcal{D}}|^2}{\|\mathbf{h}_{\mathcal{S}i}{}^H \mathbf{H}_{ji}\|^2}$. Therefore, the instantaneous SNRs for the $\{\mathcal{S} - i\}$ and $\{j - \mathcal{D}\}$ links are expressed, respectively, as:

$$\gamma_{\mathcal{S}i}(t) = \rho_{\mathcal{S}} \|\mathbf{h}_{\mathcal{S}i}\|^2, \tag{27}$$

and

$$\gamma_{j\mathcal{D}}(t) = \frac{\rho_{\mathcal{R}} \left| \|\mathbf{h}_{j\mathcal{D}}\|^2 - \tilde{c} \right|^2}{\|\mathbf{h}_{j\mathcal{D}} - c\mathbf{H}_{ji}{}^H \mathbf{h}_{\mathcal{S}i}\|^2}. \tag{28}$$

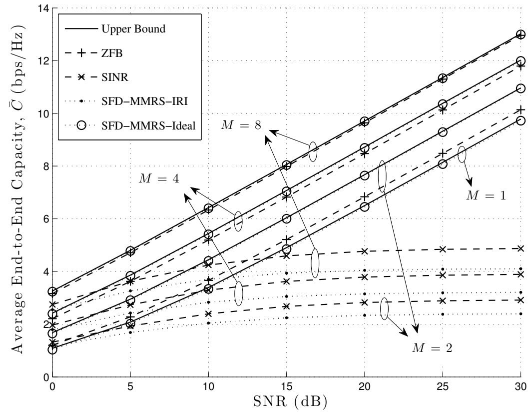

Fig. 2. Average end-to-end capacity vs. SNR ($K = 2$, $M = 1, 2, 4, 8$, and $B_{max} = \infty$)

The best relay pair is determined by

$$(i^\star, j^\star) = \underset{(i,j):\mathbf{u}_i, \mathbf{w}_j, i \neq j, \forall i,j \in \mathcal{K}}{\arg\max} \alpha C_{\mathcal{S}i}(t) + (1 - \alpha) C_{j\mathcal{D}}(t),$$

where $C_{\mathcal{S}i}(t) = \min\{\log_2(1 + \gamma_{\mathcal{S}i}(t)), B_{max} - B_i(t-1)\}$ and $C_{j\mathcal{D}}(t) = \min\{\log_2(1 + \gamma_{j\mathcal{D}}(t)), B_j(t-1)\}$.

V. Numerical Results

In this section, we evaluate the performance of the proposed relay selection schemes through Monte-Carlo simulations, compared to the conventional SFD-MMRS scheme representing state-of-the-art in the literature. Since the SFD-MMRS scheme assumes a single antenna at relays and no IRI, we extend it to that with multiple antennas at relays and assume that the receiving relay suffers IRI. For a multiple-antenna extension, we suppose that it uses the IRI-free beamformers which are the MRC at the receiving relay and the MRT at the transmitting relay. As upper bound of the average end-to-end capacity, we consider the optimal relay pair selection and beamforming based on the maximum weighted sum-rate in Eq. (16) by assuming no IRI. The optimal weight factor $\alpha^\star$ is numerically found through a line search for each scheme and each setup, and it is given as a lookup table in advance. We assume identical and independently distributed (i.i.d.) Rayleigh block fading with $\sigma_{\mathcal{SR}}^2 = \sigma_{\mathcal{RD}}^2 = \sigma_{\mathcal{RR}}^2 = 1$ for channel realizations and $P_{\mathcal{S}} = P_{\mathcal{R}}$.

Fig. 2 shows the average end-to-end capacity for varying SNRs and number of antennas when $K = 2$ and $B_{max} = \infty$. The ideal SFD-MMRS scheme with no IRI assumption almost achieves the IRI-free upper bound. However, if we impose IRI, its performance is significantly degraded with increasing SNR, i.e., in the interference-limited regime. Although the proposed SINR-based scheme improves the average end-to-end capacity, its contribution is not significant when $K = 2$. The proposed ZFB-based scheme always outperforms the other schemes thanks to additional power gains. Moreover, the proposed ZFB-based scheme almost approaches the IRI-free upper bound as the number of antennas increases since it has a larger dimensional null-space with increasing number of antennas. Note that the proposed ZFB-based scheme outperforms the IRI-free upper bound with a single antenna by using one additional antenna at relays in the presence of IRI.

Fig. 3 shows the average end-to-end capacity for various numbers of relays when $M = 4$ and $B_{max} = \infty$. All the

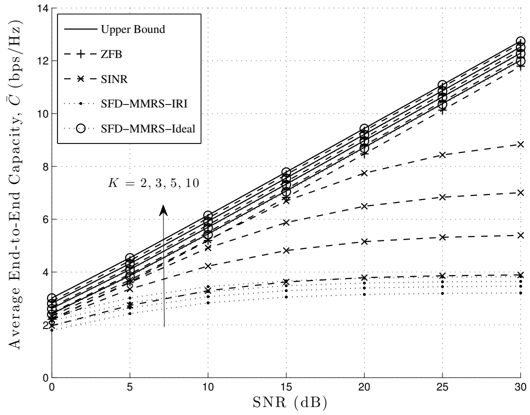

Fig. 3. Average end-to-end capacity vs. SNR ($K = 2, 3, 5, 10$, $M = 4$, and $B_{max} = \infty$)

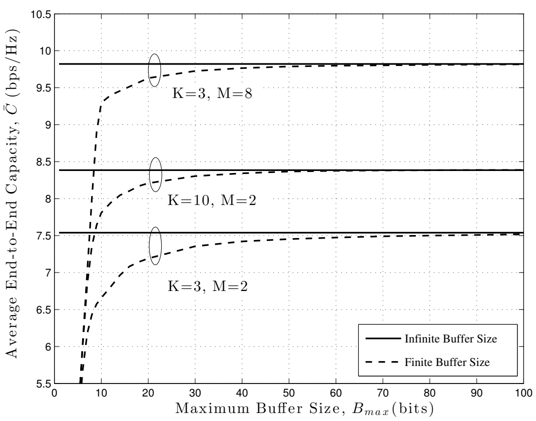

Fig. 4. Effect of maximum buffer size in the proposed ZFB-based scheme ($K = 3, 10$, $M = 2, 8$, and SNR = 20 dB)

schemes achieve the improved average end-to-end capacity thanks to a multi-relay diversity gain as the number of relays increases. Differently from the previous results, the proposed SINR-based scheme obtains significant gains with increasing number of relays. Thus, it has relatively good performance in low/medium SNR regions even if its performance is still less than that of the proposed ZFB-based scheme. In contrast, the SFD-MMRS scheme with IRI has just marginal improvements, while the proposed ZFB-based scheme almost achieves the IRI-free upper bound as the number of relays increases.

Fig. 4 shows the average end-to-end capacity of the proposed ZFB-based relay selection scheme for varying the maximum buffer size when $\text{SNR} = 20$ dB. The proposed ZFB-based scheme rapidly converges to the performance with infinite buffer size as the maximum buffer size increases. In all three considered scenarios, a buffer size of $B_{\max} \geq 50$ is sufficient to obtain almost the same performance as with infinite buffers. Hence, the maximum buffer size is not a significant factor that degrades the average end-to-end capacity if it is set to an appropriately large value. Comparing the case of $(K = 3, M = 2)$ with the case of $(K = 10, M = 2)$, smaller maximum buffer size is required for larger number of relays. Similarly, the required maximum buffer size decreases as the number of antennas increases from a comparison between the cases of $(K = 3, M = 2)$ and $(K = 3, M = 8)$.

VI. Conclusion

In this paper, we proposed virtual FD buffer-aided relay selection and beamforming schemes considering IRI in a buffer-aided relay network with multiple relays. More specifically, we proposed an SINR-based relay selection scheme with IRI-free beamforming and a relay selection scheme with ZFB-based IRI cancellation. Numerical results show that the conventional SFD-MMRS scheme with IRI significantly degrades regardless of the numbers of relays and antennas. In contrast, the SINR-based scheme is useful in the low SNR region while the ZFB-based scheme always outperforms the other schemes and asymptotically approaches the IRI-free upper bound as the numbers of relays and antennas increase. Finally, the effect of maximum buffer size is not significant if it is set to an appropriately large value.

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