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Hybrid Buffer-Aided Relay Selection Based on Half-Duplex and Virtual Full-Duplex Transmission

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Abstract—In this paper, we propose novel buffer-aided relaying selection in a two-hop cooperative network, which is capable of exploiting virtual full-duplex (VFD) and half-duplex transmissions in a hybrid manner. The proposed scheme consists of five relay selection modes, i.e., two unicast modes, a broadcast mode, a cooperative beamforming mode, and a VFD mode. The broadcast mode allows multiple relay nodes to seamlessly share a common packet, which allows us to solve the inter-relay interference problem imposed on the VFD mode. Our numerical results demonstrate that the proposed scheme achieves a high throughput performance and a lower outage probability over the conventional schemes while maintaining an acceptable average delay profile.

Index Terms—Buffer, cooperative network, half-duplex, Markov chain, outage probability, relay selection, virtual full-duplex.

I. INTRODUCTION

The classic relay-assisted cooperative communications [1–3] were designed for exploiting the spatial diversity gain, hence increasing the capacity and coverage. In order to further increase the achievable diversity gain of the conventional cooperative protocol, the buffer-aided relaying selection was proposed [4–6], which leads to flexible transmission based on the quality of channel state information (CSI). In a two-hop buffer-aided cooperative network, the max-max relay selection (MMRS) scheme was proposed [7], where source-to-relay (SR) link and relay-to-destination (RD) links were selected alternately in each time slot. The MMRS scheme can achieve a lower average end-to-end delay than the conventional schemes that do not rely on data buffers of relay nodes. In [8], the max-link (ML) scheme was proposed, where a single strongest link out of all available links was selected for transmission in each time slot, and a higher diversity order than the MMRS scheme counterpart is achieved. To avoid the detrimental states of buffer overflow and empty buffer at the relay nodes, the buffer-state-based (BSB) relay selection [9] was proposed as an extension of the ML scheme. Moreover, the generalized MMRS (G-MMRS) and generalized max-link (G-ML) schemes were proposed [10], which exploits the broadcast nature of wireless channels. More specifically, multiple SR links are simultaneously activated to allow relay nodes to share a packet. This increases the degree of freedom, which provide a better performance in term of an outage probability

and an average end-to-end packet delay than the conventional MMRS, ML, and BSB counterparts. Furthermore, in [11] and [12], the cooperative beamforming and non-orthogonal multiple access (NOMA) techniques were incorporated into the G-ML protocol, where the average delay and the average throughput are further reduced, respectively.

In full-duplex (FD) transmission [13], a wireless terminal is allowed to transmit and receive simultaneously in the same frequency band and achieves a doubled throughput compared to traditional half-duplex (HD) transmission. While the FD transceiver suffers from strong self-interference, several techniques to mitigate self-interference were proposed [14–16]. Also, cooperative communication with an FD relay node was proposed [17]. However, sufficient self-interference cancellation with the practical terminal cost is still an open issue. To combat this limitation, the concept of FD transmission is incorporated into buffer-aided relay selection with HD relay nodes, which is referred to as virtual full-duplex (VFD) [18–20]. In the VFD scheme, a single relay node receives a packet from a source node, while another relay node transmits a packet to a destination node, hence enabling the FD transmission in a virtual manner without suffering from self-interference. However, in [18–20], the detrimental effects of inter-relay interference (IRI) were ignored for the sake of simplicity. Furthermore, in [21, 22], the effects of IRI in the VFD scheme were taken into consideration, where IRI is canceled with the aid of multiple antenna processing at the relay nodes. More recently, Nomikos *et al.* combined the concepts of FD and NOMA in the context of buffer-aided opportunistic relay selection [23, 24], which is capable of improving the sum-rate performance of the network.

Against this background, the novel contributions of this paper are as follows. We propose a novel buffer-aided relaying selection scheme that relies on hybrid exploitation of VFD and HD transmission in order to increase an average throughput over the network. The proposed scheme consists of five transmission modes, i.e., (1) a unicast mode for SR transmission, (2) a unicast mode for RD transmission, (3) a broadcasting mode for SR transmission, (4) a cooperative beamforming mode for RD transmission, and (5) a VFD mode for SR and RD transmissions, which correspond to Figs. 2(a)–2(e), respectively. Depending on the buffer states and the CSI,

Fig. 1. System model of the proposed scheme, which consists of a single source node, a single destination node, and two relay nodes with the buffer size of L .

the best mode is selected in each time slot. Specifically, since the VFD mode allows us to have a doubled rate compared to the other modes, the VFD mode is activated with a high priority. Unlike other studies, since our broadcast mode allows the relay nodes to share a packet, it is possible to carry out cancel the effects of IRI imposed at the receiving relay node with the aid of successive interference cancellation (SIC).

II. SYSTEM MODEL

Fig. 1 depicts a two-hop relay network, considered in this paper, which consists of a single source node, multiple K relays nodes, and a single destination node. Each relay node has a buffer of finite size L . The number of packets stored at k th relay node $k \in \{1, \dots, K\}$ is denoted as ψ_k ($0 \leq \psi_k \leq L$). In the network, each node is equipped with a single antenna element, operating in the HD and decode-and-forward (DF) principles. Furthermore, we assume that there is no direct link between the source and destination nodes. The channel coefficient of the i th SR, the relay-to-relay (RR) between the i th and the j th relay nodes, and the j th RD links are denoted as h_{SR_i} , $h_{RR_{ji}}$ and h_{RD_j} , respectively. All the $2K$ links are the independent and identically distributed (IID) frequency-flat Rayleigh fading channel. The transmission rate is fixed to r_0 bps/Hz at each node. After the destination node successfully decodes a packet, an acknowledge (ACK) packet is sent from the destination node to all the relay nodes with low-rate feedback links. Then, the packet stored in the buffers is deleted from the buffer of each associated relay node.

Similar to [1, 2], we assume that CSI and buffer state information (BSI) are collected at a central coordinator. In our protocol, the transmission is classified into five modes, i.e., (1) a unicast mode for SR transmission, (2) a unicast mode for RD transmission, (3) a broadcasting mode for SR transmission, (4) a cooperative beamforming mode for RD transmission, and (5) a VFD mode for SR and RD transmissions, which correspond

to Figs. 2(a)–2(e), respectively. The central coordinator is in charge of selecting one of the five modes based on the collected CSI and BSI.

A. Unicast Mode for SR Transmission

Fig. 2(a) shows the unicast mode for SR transmission, where a single out of the SR links is activated, and a single packet is stored at the buffer of the selected relay node. The channel capacity of i th SR link is given by

$$C_{\text{Uni}}^{\text{SR}}(i) = \frac{1}{2} \log_2(1 + |h_{SR_i}|^2 \gamma_{\text{SR}}), \quad (1)$$

where γ_{SR} denotes the average signal-to-noise ratio (SNR) for the SR links. If $C_{\text{Uni}}^{\text{SR}_i} > r_0$ and if the buffer of the i th relay node is not full, the associated unicast from the source node to the i th relay node is successful.

B. Unicast Mode for RD Transmission

Fig. 2(b) shows the unicast mode for RD transmission, where a single RD link is activated, similar to the unicast mode for SR transmission of Section II-A. The channel capacity of the j th RD link is given by

$$C_{\text{Uni}}^{\text{RD}}(j) = \frac{1}{2} \log_2(1 + |h_{RD_j}|^2 \gamma_{\text{RD}}), \quad (2)$$

where γ_{RD} is the average SNR of the RD links. If $C_{\text{Uni}}^{\text{RD}_j} > r_0$ and if the buffer of the j th relay node is not empty, the corresponding unicast from the j th relay node to the destination node is successful.

C. Broadcast Mode for SR Transmission

Fig. 2(c) shows the broadcast mode for the SR transmission, where the multiple SR links are activated simultaneously, which is available without imposing any additional time slot owing to the broadcast nature of wireless channels. A source packet is transmitted from the source node to the relay nodes associated with the activated SR links, and the packet is stored in the buffers of the associated relay nodes.

Let us define the index set of the activated SR nodes as $\mathcal{T}$. Then, the broadcast mode is successful, when all the buffers of the relay nodes corresponding to the activated SR links are not full, and the capacity of the activated SR links are higher than r_0 , i.e.,

$$C_{\text{Uni}}^{\text{SR}}(i) \geq r_0 \text{ for } i \in \mathcal{T}, \quad (3)$$

Note that this broadcast mode plays an important role in the proposed scheme since the packet sharing among the relay nodes allows us to seamlessly carry out SIC in the cooperative beamforming and VFD modes, which is achieved without relying on the use of multiple antenna elements at the relay nodes.

D. Cooperative Beamforming Mode for RD Transmission

Fig. 2(d) shows the cooperative beamforming mode for RD transmission, where a packet shared among the subset of the relay nodes is simultaneously transmitted from the selected relay nodes to the destination node in a coherent

Fig. 2. Five transmission modes of the proposed scheme; (a) unicast mode for SR transmission, (b) unicast mode for RD transmission, (c) broadcast mode for SR transmission, (d) cooperative beamforming mode for RD transmission, and (e) VFD mode for SR and RD transmission.

manner. The transmission weight at the j th relay node is set to $w_j = g_j^* / \|\mathbf{g}_c\|$, where we have $\mathbf{g}_c = [g_1, g_2, \dots, g_K]^T$. The weights corresponding to the selected relay nodes are the same as the corresponding RD links, i.e., $g_j = h_{RD_j}$, while those of the unselected relay nodes are set to zeros.

The capacity of all RD links for the cooperative beamforming mode is given by

$$C_{\text{Beam}}^{\text{RD}}(\mathbf{g}_c) = \frac{1}{2} \log_2(1 + \|\mathbf{g}_c\|^2 \gamma_{\text{RD}}). \quad (4)$$

E. VFD Mode for SR and RD Transmission

All the above four modes of Sections II-A–II-D operate in the HD principle, where either transmission or reception is done at the relay nodes in each time slot. By contrast, Fig. 2(e) shows the VFD mode, where a single receiving relay node receives a packet from the source node, while another single transmitting relay node transmits a packet in the buffer to the destination node simultaneously. Let us assume that the i th and the j th relay nodes as the receiving and transmitting relay nodes. Then, the signals received at the receiving relay node and the destination node are given by

$$y_S(i) = h_{SR_i} x_S + h_{RR_{ji}} x_j + n_i \quad (5)$$

$$y_D(j) = h_{RR_{ji}} x_j + n_D, \quad (6)$$

where x_S and x_j denote packets transmitted from the source node and the j th relay node, respectively. Also, n_i and n_D are the associated AWGNs. $h_{RR_{ji}} \in \mathbb{C}$ is the channel coefficient between the i th and the j th relay nodes.

Under the assumption that the second term of (5) is eliminated at the receiving relay node, the channel capacities

corresponding to (5) and (6) are given, respectively, by

$$C_{\text{VFD}}^{\text{SR}}(i) = \frac{1}{2} \log_2(1 + |h_{SR_i}|^2 \gamma_{SR_i}) \quad (7)$$

$$C_{\text{VFD}}^{\text{RD}}(j) = \frac{1}{2} \log_2(1 + |h_{RD_j}|^2 \gamma_{RD_j}). \quad (8)$$

In order to activate the VFD mode, the both receiving and transmitting relay nodes have to have a common packet in their buffers, which is used for eliminating IRI at the receiving relay node with the aid of SIC. Hence, we have the relationship of $C_{\text{VFD}}^{\text{SR}}(i) = C_{\text{Uni}}^{\text{SR}}(i)$. The VFD mode is not in outage, when the both capacities of $C_{\text{VFD}}^{\text{SR}}(i)$ and $C_{\text{VFD}}^{\text{RD}}(j)$ are higher than the target fixed rate r_0 , i.e.,

$$\min\{C_{\text{VFD}}^{\text{SR}}(i), C_{\text{VFD}}^{\text{RD}}(j)\} \geq r_0. \quad (9)$$

In the VFD mode, two parallel SR and RD links are activated, and the total transmission rate is doubled compared to the other four modes. Hence, in our protocol, the VFD mode is activated as many times as possible, as shown in the following section.

III. PROPOSED RELAY SELECTION ALGORITHM

The proposed relay selection algorithm is designed for operating in the VFD transmission as often as possible in order to increase an average throughput over the network. In order to activate the VFD mode, the following constraints have to be satisfied;

- (C1) The receiving and the transmitting relay nodes (i, j) are different, i.e., $i \neq j$.
- (C2) The receiving and the transmitting relay nodes have a common packet in the buffers.
- (C3) The SR and RD links associated with the receiving and transmitting relay nodes are not in outage, i.e., the inequality (9) is satisfied.

If these three constraints are not satisfied, instead of the VFD mode, one out of the other four HD modes is activated based on the priorities of the available SR and RD links. When all the constraints (C1)–(C3) are satisfied, the VFD mode is activated. Here, let us define $\Theta_{i,j}$ as a set of the SR and RD link pairs that satisfy (C1)–(C3).

A. Case of $\Theta_{i,j} \neq \emptyset$

Let us consider the case where the VFD mode is activated, i.e., $\Theta_{i,j} \neq \emptyset$. Here, an SR and RD link pair for the VFD transmission is selected according to

$$(\hat{i}, \hat{j}) = \arg \max_{i,j \in \Theta_{i,j}} \{\min(\mathcal{C}_{\text{VFD}}^{\text{SR}}(i), \mathcal{C}_{\text{VFD}}^{\text{RD}}(j))\}, \quad (10)$$

where $\hat{i}$ and $\hat{j}$ are the indices of the selected receiving and transmitting relay nodes, respectively.

B. Cases of $\Theta_{i,j} = \emptyset$

By contrast, when either of the constraints (C1)–(C3) is not satisfied, one out of the four HD modes is selected based on the priorities of the available SR and RD links corresponding to BSI. Here, let us introduce the target number of packets stored in the buffer of the k th relay node as ζ_k . Furthermore, the difference from the target number of packets is calculated by

$$\Delta_k = \Psi_k - \zeta_k, \quad k \in \{1, \dots, L\}. \quad (11)$$

This gives us the priority to each available SR and RD links as follows:

- The priority of the i th SR link is counted as a high priority, if $\Delta_k < 0$, where $i = k$.
- The priority of the j th RD link is counted as a high priority, if $\Delta_k \geq 0$, where $j = k$.

Moreover, let us define the number of the SR and RD links with a high priority as $q^{(i)}$ and $q^{(j)}$, respectively. Based on $q^{(i)}$ and $q^{(j)}$, we can select one out of four modes as follows.

1) $q^{(i)} > q^{(j)}$: When $q^{(i)} > q^{(j)}$, one out of the two SR modes, i.e., the unicast and broadcast modes, is activated. More specifically, the broadcast mode is activated if multiple SR links are not in outage and if the buffers of the associated relay nodes are not full. Otherwise, the unicast mode is activated by selecting a single strongest SR link.

2) $q^{(i)} < q^{(j)}$: When $q^{(i)} < q^{(j)}$, one out of the two RD modes, i.e., the unicast and the cooperative beamforming modes, is selected. More specifically, If multiple RD links are not in outage and if the buffers of the associated relay nodes are not empty, the cooperative beamforming mode for RD transmission is activated. Otherwise, the unicast mode for RD transmission is activated by selecting a single strongest RD link.

3) $q^{(i)} = q^{(j)}$: When $q^{(i)} = q^{(j)}$, either of SR transmission mode (the unicast or the broadcast modes) or RD transmission mode (the unicast or the cooperative beamforming mode) is selected. If the strongest link is the SR one, one out of the two SR modes is activated according to 1). Similarly, if the

Fig. 3. Outage probabilities of the proposed, MMRS, G-MMRS, ML and G-ML schemes, where we considered the system parameters of $(K, L) = (3, 3)$ and the target number of packets $\zeta_k = 2$.

strongest link is the RD one, one out of the two RD modes is activated according to 2).

IV. SIMULATION RESULTS

In this section, we provide our performance results to characterize the proposed scheme in terms of the outage probability, the average delay, and the average throughput. The performance is compared with the existing benchmark schemes, i.e., the MMRS, ML, G-MMRS, and G-ML schemes. We assumed that the transmission rate of each node is fixed to $r_0 = 1$ bps/Hz. Furthermore, in each Monte Carlo simulation, the initial buffer state of each relay node is set to empty, and a sufficiently high number of packets are transmitted from the source node to the destination node. Also, we considered the systematic channel scenario of $\gamma_t = \gamma_{\text{SR}} = \gamma_{\text{RD}}$.

Fig. 3 shows the outage probability of the proposed scheme and the four benchmarks, where we have the system parameters of $(K, L) = (3, 3)$ and the target number of packets was set to $\zeta_k = 2$. As shown in Fig. 3, the proposed scheme achieved the lowest outage probability of the five schemes, owing to the adaptive selection of multiple modes based on BSI, unlike the four benchmarks.

In Fig. 4, we investigated the effect of the target size ζ_k on the outage probability of the proposed scheme, where we considered the system parameters of $(K, L) = (2, 6)$ and $(3, 6)$. The target number of packets was given by $\zeta_k = 1, 3, 5$, and the SNR was varied from $\gamma_t = 5$ dB to 13 dB. As shown in Fig. 4, in each K scenario, the proposed scheme with the target value of $\zeta_k = 3$ achieved the best performance. This may be because both the detrimental effects of empty and full buffer states can be avoided.

Furthermore, Fig. 5 shows the average delay of the proposed scheme with the target number of packets $\zeta_k = 1$, which is compared with the four benchmark schemes. The system

Fig. 4. Outage probabilities of the proposed scheme, where we considered the system parameters of $(K, L) = (2, 6)$ and $(3, 6)$, while the target number of packets ζ_k was given by $\zeta_k = 1, 3$, and 5 .

Fig. 5. Average delay comparisons between the proposed, ML, G-ML, MMRS, and G-MMRS schemes, where we considered the system parameters of $(K, L) = (3, 3)$.

parameters were given by $(K, L) = (3, 3)$, and the SNR was varied from $\gamma_t = 0$ dB to 20 dB. Observe in Fig. 5 that the proposed scheme outperformed the four benchmark schemes in the low SNR region of approximately $\gamma_t \leq 12$ dB. Upon increasing the SNR, the delay of the proposed scheme converged to a specific value, which was the same as those of the G-ML and the G-MMSE schemes.

To provide further insight, in Fig. 6, we investigated the effects of the target number of packets ζ_k on the average delay of the proposed scheme, where the target number of packets was given by $\zeta_k = 1, 2$, and 3 , while maintaining the SNR was fixed to $\gamma_t = 5$ dB. More specifically, in Fig. 6(a), the buffer size L was varied with the fixed number of relay nodes

(a)

(b)

Fig. 6. Average delay of the proposed scheme, where we considered the target number of packets $\zeta_k = 1, 2, 3$. (a) $K = 3$ and (b) $L = 6$.

$K = 3$, while in Fig. 6(b), the number of relay nodes K was varied with the fixed buffer size $L = 6$. Observe in Figs. 6(a) and 6(b) that the proposed scheme with the target $\zeta_k = 1$ achieved the lowest average delay. This is because the total packets stored in the buffers were maintained to be low with $\zeta_k = 1$.

Finally, the achievable average throughput was investigated. Fig. 7 shows the average throughput of the proposed scheme, compared with the ML, G-ML, MMRS, and G-MMRS benchmark schemes, where we considered the system parameters of $(K, L) = (6, 6)$, and the target number of packets was fixed to $\zeta_k = 1$. As shown in Fig. 7, the proposed scheme outperforms the four benchmark schemes in the entire SNR range, owing to the explicit benefits of the presence of the VFD mode in the proposed scheme.

Fig. 7. Average throughput of the proposed scheme, compared with the ML, G-ML, MMRS and G-MMRS benchmarks, where we considered the system parameters of $(K, L) = (6, 6)$.

V. CONCLUSIONS

In this paper, we proposed the novel buffer-aided relay selection scheme that is capable of adaptively selecting the four HD and a single VFD transmission modes based on CSI and BSI. More specially, in the VFD mode, the detrimental effects of IRI are eliminated with the aid of SIC, which is enabled owing to a common packet shared by multiple relay nodes. The simulation results demonstrated that the proposed scheme provides higher average throughput than the four benchmark HD schemes. Also, the proposed scheme achieved a lower outage probability with an acceptable average end-to-end packet delay than the benchmark schemes.

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