A Low-Delay Hybrid Half/Full-Duplex Link Selection Scheme for Cooperative Relaying Networks

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***Abstract*—In this paper, we propose a hybrid half-duplex (HD)/full-duplex (FD) link selection scheme for cooperative buffer-aided (BA) relaying networks with small buffers. FD BA relaying offers high spectral efficiency but it does not change the buffer states, while HD relaying offers the ability to change the buffer states, which can be exploited to minimize the outage probability and the average delay by controlling the queue length of the relays. Unlike the existing hybrid BA relaying schemes and opportunistic relying schemes, the proposed scheme considers the average buffering delay and uses probabilistic relay selection (RS) instead of using a fixed RS policy. It probabilistically prioritizes the selection of one of the FD and HD modes over the other. Markov chain (MC) theory is used to model the considered system and derive the throughput, average delay and outage probability as functions of the prioritizing probabilities. Based on the buffer and average channel states, the prioritizing probabilities are determined such that the overall average delay is minimized using the accelerated proximal gradient method. As compared to the existing HD, opportunistic, and hybrid BA relaying schemes, simulation results show that the proposed scheme offers higher throughput and lower average delay.**

***Index Terms*—Cooperative relay networks, buffer-aided, full-duplex, throughput, average delay.**

I. INTRODUCTION

RECENTLY, cooperative buffer-aided (BA) relaying has attracted a lot of attention due to its ability to improve the performance of wireless relay networks. Since relays are equipped with buffers, the relay selected for reception can store the received packet in its buffer and is not required to retransmit the packet immediately in the next time slot. Hence, in each time slot, among all the available source-to-relay (SR) and relay-to-destination (RD) links, the best one is selected based on a specific metric, which consequently contributes to performance improvement. In the selection process, a relay is considered to have an available link to the source if its buffer is not full, whereas a link to the destination is considered available if the corresponding relay's buffer is not empty. The flexibility offered by the buffering capability of the relays has been exploited to enhance the communication reliability, coverage, power consumption and/or throughput of cooperative networks [1].

The potential improvements from the exploitation of the buffering capability of the relays, however, come at the price of having a higher packet delay [1], which is a significant problem since low transmission delay is required by most modern wireless systems to provide persistent services. Therefore, the state-of-the-art half-duplex based (HD-based) BA link selection schemes, such as those discussed in [2]–[7], consider the buffer state information (BSI) in their selection policies in order to minimize the average packet delay as well as to avoid empty and full states where relays with empty (full) buffers cannot be selected for transmission (reception). Recently, the utilization of additional randomness to the link selection policy, instead of using a fixed policy, proved to be useful. More specifically, in [8], the probability of prioritizing the selection of the RD links over the SR links is controlled such that the average delay can be minimized. Also, the authors in [9] tackled a more complicated scenario in which the buffer state is considered. Some of the aforementioned schemes, e.g., [2], [3], [7], [9], offer comparable performance to the selection bound of HD BA relaying. However, these schemes remain subject to the spectral loss of HD relaying, where reception from the source and transmission to the destination require orthogonal channels in time or frequency.

To recover the spectral loss of HD relaying, either full-duplex (FD) relaying or opportunistic relaying where two different relays are selected for transmission and reception, is adopted. In-band FD communications, where nodes are able to transmit and receive simultaneously over the same band, can achieve high spectral efficiency as opposed to HD communications. Recently, the impressive improvement in self-interference cancellation (SIC) techniques (e.g., in the order of $70-110$ dB) has attracted a lot of attention to in-band FD communication as a promising technology for future wireless systems [10].

Despite its lower spectral efficiency as compared to FD BA relaying, HD BA relaying still offers higher reliability (i.e., lower outage probability). This is because in the latter, an outage event will not occur if one of the available SR or RD links is not in outage; while in the former, the selected relay must be capable of transmission and reception simultaneously.

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Furthermore, the ability of HD BA relaying to change the buffer states can be exploited to ensure short queues at the relays, which in turn decreases the average buffering delay. In addition, empty and full buffer states can be avoided in HD BA relaying via selecting the corresponding relay for reception and transmission, respectively, which decreases the outage probability and increases the throughput.

Based on the above, several hybrid HD/FD BA relaying schemes have been proposed in the literature to enjoy the benefits of both modes [1], [11]–[13]. However, in all hybrid HD/FD BA relaying schemes that assume finite buffer sizes (or even in opportunistic relaying schemes that mimic FD BA relaying such as in [14]–[16]), minimizing the average buffering delay has not been considered. In these schemes, the high reliability of HD BA relaying is exploited, while the ability to change the buffer states, i.e., shortening the queues to minimize the average delay, is neglected. More specifically, HD relaying is only used if the FD or opportunistic modes cannot be used in order to avoid an outage event. While FD relaying does not change the buffer states, the use of opportunistic or HD relaying in the hybrid HD/FD schemes may lead to lengthy queues, which increases the average buffering delay.

The goal of this paper is thus to garner the full potential of both HD and FD modes, viz., exploiting the high spectral efficiency of FD communications and in the same time the ability of HD BA relaying to shorten the queues to achieve higher throughput with low average buffering delay. Towards that end and inspired by the recent results of the probabilistic schemes in [8] and [9], we propose a probabilistic hybrid HD/FD link selection scheme for cooperative BA relaying networks. Hereafter, we refer to this scheme as the probabilistic hybrid relay selection (PHRS) scheme. Based on the buffer states and average channel states, the proposed PHRS scheme uses prioritizing probabilities to control the selection of the FD mode over each potential relay selection (RS) for transmission or reception in the HD mode.

In order to model and analyse the considered network, Markov chain (MC) theory is used where each state of the MC represents the number of packets in the buffers of the relays. Based on the CSI, BSI and prioritizing probabilities, the analysis is derived assuming independent and non-identically distributed (i.n.i.d.) fading channels and any arbitrary number of relays and buffer sizes. First, the probabilities of all potential events (i.e., outage, selecting a relay for FD transmission and selecting a relay for transmission or reception in HD mode) are determined. Then, based on these probabilities, the state transition matrix and the stationary distribution of the MC are determined. Closed-form expressions of the outage probability, throughput and average packet delay as functions of the prioritizing probabilities are finally derived.

Due to the complicated expression of the delay and the large number of possible buffer states, it is difficult to find the optimal values for all the prioritizing probabilities at low complexity. Alternatively, we defined these probabilities as functions of weights that depend on the buffer states and an auxiliary variable. The auxiliary variable that minimizes the overall average delay is found using either the accelerated proximal gradient method for non-convex programming in [17], or grid search. In addition, high signal-to-noise-ratio (SNR) performance, in terms of the operation mode, queues lengths, average buffering delay and diversity order are discussed. Simulation results are also presented to assess the performance of the proposed scheme.

To conclude, the main contributions of this paper are:

- Proposing the first probabilistic hybrid HD/FD BA scheme to garner the full potential of both modes.
- Unlike existing hybrid BA schemes, the proposed heuristic scheme considers and aims to reduce the overall average buffer delay. By virtue of the aforementioned attributes, it offers higher throughput with low average delay.

The rest of the paper is organized as follows: the next section surveys the related works in the literature, Section III presents the system model under consideration along with other assumptions, the proposed PHRS scheme is then introduced in Section IV. The system is then modelled and analysed using MC theory in Section V. Simulation results and discussions are then presented in Section VI before the paper is finally concluded in Section VII.

II. Related Work

Due to the great potential of BA relaying, its usages in different networks, e.g., delay-tolerant networks, device-to-device (D2D) Communications, vehicle-to-vehicle (V2V) Communications, non-orthogonal multiple access (NOMA) relay-assisted networks [18] and Internet of Things (IoT), have been investigated. The use of BA relaying in different types of wireless networks is well covered by the surveys in [1] and [19]. In this section, we provide a brief review of the most related BA relay selection schemes.

In [20], the max-link scheme that exploits the flexibility offered by the relays' buffering capability to achieve a diversity order of twice the number of relays is proposed. In each time slot, the available link that offers the strongest channel among all available SR and RD links is selected. In [2], the buffer-state-based (BSB) scheme that considers the BSI, to keep the states of the buffers away from empty and full states, is proposed. To minimize the average delay, it uses the queue length of one as a targeted queue length, where relays with empty buffers and relays that buffer more than one packet are given the highest priority to adjust their queues by the selection for reception and transmission, respectively. In [7], a link selection scheme that maintains the buffer states by keeping the buffers in half-full state as much as possible is proposed. As compared to the BSB scheme, it offers lower outage probability, but the improvement came at the price of higher delay. Moreover, the authors in [3] proposed a priority-based link selection scheme that gives the highest priority to relays with empty buffers, then to relays with full buffers. Otherwise, it works as the max-link in [20].

Recently, the authors of [8] shed light on the potential improvement of the utilization of additional randomness to the selection policy. In particular, their scheme selects the SR and RD links that have the strongest channels among all available

SR and RD links, respectively. Then, it probabilistically selects one of them based on the used random variable that will be adjusted to minimize the average delay. In [9], a probabilistic buffer-state-based scheme is proposed. In particular, it selects the SR and RD links that have the minimum and maximum number of buffered packets, respectively. Likewise, it probabilistically selects one of them, where the auxiliary random variable is controlled to minimize the average delay. Some of the aforementioned schemes, e.g., [2], [3], [7], [9], offer comparable performance to their selection bound in which neither of the buffers is empty nor full, and accordingly all SR and RD links are always available for selection. However, these schemes remain limited by the spectral loss of HD relaying.

To recover the spectral loss of HD relaying, FD relaying could be mimicked using HD relaying. In [14], two different relays are selected for reception and transmission simultaneously. However, inter-relay interference (IRI) is neglected, and buffers are assumed to have infinite size. Similarly, the authors in [15] proposed an opportunistic relaying scheme that selects two different relays for reception and transmission but taking into consideration the IRI. In particular, the feasibility of IRI cancellation is checked for each pair of relays and the pair that offers the minimum power consumption is selected. If all pairs do not satisfy the feasibility check, the max-link scheme in [20] is used instead. Also, in [16], a simple network consisting of a source, two HD relays that are equipped with buffers of infinite size and a destination is considered. This scheme selects between four transmission modes such that the average throughput of the system is maximized.

As mentioned earlier, in-band FD communication offers high spectral efficiency; while HD communication offers higher reliability and the ability to change the buffer states. Hybrid HD/FD BA relaying schemes can enjoy the benefits of both modes. In [12], a simple network consisting of a source, an FD BA relay and destination is considered, where ideal assumptions of perfect SIC and infinite buffer size are used. In each time slot, the transmission mode (HD or FD) of the relay and the transmission rate of each link are selected from a set of discrete rates such that the average system throughput is maximized. Similar to [12], the authors of [13] considered a single relay network with infinite buffer size, but the SI has been taken into account. Depending on the channel conditions, the relay selects between HD and FD transmission modes to maximize the system throughput.

The authors of [15] have extended their work in [1] and [11] considering instantaneous and statistical CSI, respectively. More specifically, two relays are selected for reception and transmission; however, the same relay can be selected for both reception and transmission. In this case, the transmission mode is referred to as FD instead of opportunistic relaying. Similar to [15], among all potential relay pairs that satisfy the IRI cancellation feasibility check, the pair that offers the minimum power expenditure is selected. If none of the pairs satisfy the IRI cancellation feasibility check, the HD-based max-link scheme in [20] is used. In both of the hybrid schemes in [1] and [11], link selection depends on the CSI, while the average buffering delay is neglected in their selection policies. Since in this work, we assume that the instantaneous CSI is available, we will consider the hybrid scheme in [1] as a benchmark scheme for fair comparison.

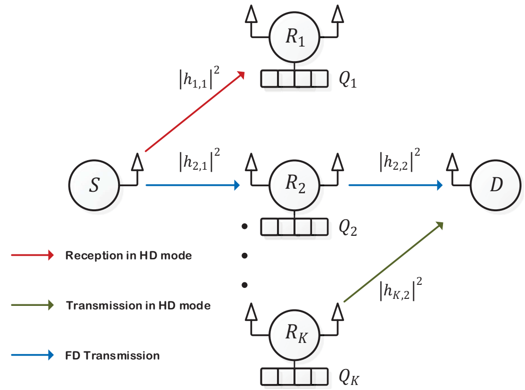

Fig. 1. A schematic of the system model.

In the aforementioned hybrid HD/FD BA relaying or opportunistic schemes that exploit HD BA relaying to mimic FD BA relaying that assume finite buffer size, the average buffering delay is neglected as in [1], [11] and [15]. In all of these schemes, the ability of HD BA relaying to shorten the queues of the relay buffers in order to minimize the delay has not been exploited. In this work, the high spectral efficiency of FD communications and the ability of HD BA relaying to shorten queues lengths are exploited in order to achieve high throughput with low average packet delay as will be clarified in the sequel.

III. SYSTEM MODEL

A. Network Model

We consider a cooperative relay network consisting of one source node S, one destination node D, and K relays, $R_1, R_2, \ldots, R_K$, that are using the decode and forward (DF) technique for relaying. We assume that no direct link exists between the source and destination nodes and that communication can only be established through relays. Each of the source and destination nodes are equipped with a single antenna; while each relay R_k is equipped with two antennas, and accordingly is capable of FD communications. Also, each relay R_k is equipped with a data buffer Q_k of size L elements each of which can be used to store a packet. We also assume that the source node S is saturated with data (i.e., always has data to transmit). Time is split into equal slots, where in each slot, one of the relays is selected to work in FD or HD mode. Fixed transmission rate r_0 bits per channel use (BPCU) is used, which requires the adaptation of the modulation type and coding in order to maintain the target rate r_0. The extension to discrete transmission rates is not difficult as considered in [21]. In each time slot, one of the relays is selected to work in either HD or FD mode. This system model can be regarded as a relay-assisted D2D communications, which is widely used and intensively studied in the literature [22]. Finally, we note that packets received at the destination node may arrive in a different order from the one in which they were transmitted from the source node and the order at the source can be recovered by adding order information to the preamble of each packet [7].

Although the system model considers a single-source scenario, the extension to a multi-source system can be achieved by allocating orthogonal channels to each of them. In addition, since modern communication systems have high-capacity requirements, the selection of a single relay may not be enough to fulfill the high-capacity requirements. To overcome this problem, multiple relays can be selected based on the proposed PHRS scheme. However, communicating with different relays on orthogonal channels (since narrow band frequency non-selective fading is considered as will be discussed in Section III-B) may entail a more complex synchronization algorithm. Also, relay selection, mode selection and channel assignment must be jointly done. More specifically, we have to find which relay nodes will be selected to serve the source node, their operation modes (HD or FD mode), and which channels will be assigned to each of the SR and RD links. Despite these challenges, the scenario of multiple relay selection has been reported before in the literature such as in [23] and [24]. Lastly, the assumption of fixed transmission rate limits the utilization of the proposed PHRS scheme in modern communication systems that entail high spectral efficiency. As a future research opportunity and to cover a wider range of applications, a Lyapunov-based relay selection scheme can be investigated. Lyapunov framework has the ability to use arbitrary arriving traffic, channels (i.e., possibly unknown distribution) and mobility patterns [25]. In particular, the multi-hop queueing networks section of the Lyapunov framework [26, Chapter 5.3] can be exploited, where the transmission rate of a given node is the arrival rate of the next node.

B. Channel Model

All links are subject to fading and additive white Gaussian noise (AWGN). We assume frequency non-selective Rayleigh block fading, which means fading coefficients remain constant during one time slot and vary independently from one time slot to another according to a circularly symmetric complex Gaussian random distribution with zero mean and variances of $\sigma^2_{i,j}, i \in \mathcal{K}, j \in \{1,2\}$ where $\mathcal{K} = \{1,2,\dots,K\}$. Let $l_{i,j}$ denote the links, where $l_{i,1}$ denotes the link between the source and relay R_i and $l_{i,2}$ denotes the link between relay R_i and the destination. Furthermore, we use $h_{i,1}$ and $h_{i,2}$ to represent the fading coefficients of the links $l_{i,1}$ and $l_{i,2}$, respectively. For Rayleigh fading, the channel power gain $|h_{i,j}|^2$ is exponentially distributed with parameter $\sigma^{-2}_{i,j}$, i.e., $|h_{i,j}|^2 \sim \text{Exp}(\sigma^{-2}_{i,j})$ [27]. Transmission power of the link $l_{i,j}$ is denoted by $P^t_{i,j}$, where $P^t_{i,1}$ ($P^t_{i,2}$) is the power used by the source (relay R_i) to communicate with relay R_i (the destination) through the link $l_{i,1}$ ($l_{i,2}$). We also assume that the AWGN is with zero mean and variance σ^2_n. Fig. 1 shows a schematic model of the considered network.

In each time slot, one of the relays is selected to work in either HD mode or FD mode. If the relay R_i is selected for reception in HD mode, the SNR of the link $l_{i,1}$ is equal to

$$\gamma^{\text{HD}}_{i,1} = \frac{P^t_{i,1}\,|h_{i,1}|^2}{\sigma^2_n}. \tag{1}$$

Likewise, if the relay R_i is selected for transmission in HD mode, the SNR of the link $l_{i,2}$ is given by

$$\gamma_{i,2} = \frac{P^t_{i,2}\,|h_{i,2}|^2}{\sigma^2_n}. \tag{2}$$

An outage event occurs if the SNR of the selected link is less than a predefined threshold γ_o, which depends on several factors such as the required data rate, modulation type and error-correction scheme [11], [28].

On the other hand, if the relay R_i is selected for FD transmission, the signal-to-interference-plus-noise-ratio (SINR) of the link $l_{i,1}$ is equal to

$$\gamma^{\text{FD}}_{i,1} = \frac{P^t_{i,1}\,|h_{i,1}|^2}{\beta P^t_{i,2}\,|h_{i,\text{SI}}|^2 + \sigma^2_n}, \tag{3}$$

where $|h_{i,\text{SI}}|^2$ is the channel power gain of the SI of the relay R_i, which is also assumed exponentially distributed with parameter $\lambda_{k,\text{SI}}$. The fact that the SI cannot be removed perfectly is captured using the factor β that represents the residual SI, where $0 \le \beta \le 1$. Since we assumed that no direct link exists between the source node and destination node, the source transmission does not cause interference to the destination and the SNR of the link $l_{i,2}$ is given by (2).

C. CSI Acquisition

We assume that the source and destination nodes successively broadcast reference signals to all relays at the beginning of each time slot. Accordingly, each relay R_i can perfectly estimate its channel gains $|h_{i,1}|^2$ and $|h_{i,2}|^2$ of the links $l_{i,1}$ and $l_{i,2}$, respectively. Also, relay nodes are capable of implementing combined analog and digital SIC techniques that offers SIC in the order of $70 - 110$ dB when combined together [10]. Based on the BSI, the SIC ability and the estimated $|h_{i,1}|^2$ and $|h_{i,2}|^2$, each relay can determine the viability of FD and HD communications (i.e., transmission or reception only). The determined communication viability will then be transferred, error-free, to the central controller, which we assume to be one of the relay nodes. Similar assumptions have been made in [2]–[7]. The central node then decides which link is selected and informs the transmitting node or nodes based on whether HD or FD communication is selected. The receiving node can detect the received signal, while other nodes remain silent.

IV. Proposed Hybrid Link Selection Scheme

In this section, we propose a hybrid HD/FD link selection scheme that aims to provide higher throughput than the existing BA relaying schemes and at the same time lower average delay. To achieve that, it exploits the high spectral efficiency of FD relaying and the ability of HD relaying to control the lengths of the relay buffers. In each time slot, based on the CSI and BSI information, the proposed hybrid scheme selects one of the relays to work in either HD or FD mode. The proposed scheme consists of two stages. First, among all SR and RD links that are capable of successful transmission, it selects a candidate link for HD mode based on a certain criterion as will be described next. Then, taking into account the average delay and system throughput, it selects between the candidate link for HD mode and the FD mode.

A. Proposed Half-Duplex Link Selection Policy

In this subsection, we introduce the link selection policy that selects a candidate link for HD mode. For simplicity, most of the existing hybrid BA schemes, e.g., the schemes in [1] and [11], are using the max-link scheme [20] for HD relaying although it has high outage probability and high average delay. In this work, the BSB selection policy in [2, Table II] is adopted due to its improved performance, in terms of outage probability, average delay and computational complexity. The first and second cases of the BSB policy are set to avoid full and empty buffer states, respectively. In the proposed hybrid scheme, relays with full buffers can be selected for FD transmission. Hence, we modify the BSB selection policy slightly by merging the first and third cases while moving the second case up to have the highest priority. This change does not lead to significant improvement in the performance, but it reduces the analysis complexity a little bit. The proposed scheme thus selects the candidate for HD relaying according to the following selection policy in *successive priority order*:

a) *Case A:* Among all relays that have empty buffers and are capable of receiving successfully from the source node, select one of them randomly according to the uniform distribution. A relay R_i satisfies this condition if the link $l_{i,1}$ is not in outage (i.e., $\gamma_{i,1}^{\text{HD}} \geq \gamma_o$) and its buffer is empty (i.e., $\Phi(Q_i) = 0$, where $\Phi(Q_i)$ denotes the number of stored packets in the buffer Q_i).
b) *Case B:* Among all relays that store more than one packet in their buffers (i.e., $\Phi(Q_i) > 1$) and are capable of transmitting successfully to the destination node (i.e., $\gamma_{i,2} \geq \gamma_o$), select the relay $R_{I_{max}}$ that has the maximum number of packets in its buffer. If the maximum number of packets is owned by more than one relay, select one of them in a uniformly random manner.
c) *Case C:* Among all relays that have non-empty and non-full buffers concurrently ($0 < \Phi(Q_i) < L$) and are capable of receiving successfully from the source node (i.e., $\gamma_{i,1}^{\text{HD}} \geq \gamma_o$), select the relay $R_{I_{min}}$ that has the minimum number of packets in its buffer. If the minimum number of packets is possessed by more than one relay, select one of them in a uniformly random manner.
d) *Case D:* Among all relays that store one packet only in their buffers and are capable of transmitting successfully to the destination node (i.e., $\Phi(Q_i) = 1$ and $\gamma_{i,2} \geq \gamma_o$), select one of them in a uniformly random manner.
e) *Case E:* Lastly, if none of the aforementioned selection conditions are satisfied, all nodes remain silent, i.e., an outage event occurs.

In the above scheme, cases A and B that have the highest two priorities are set to avoid empty and full buffer states in order to exploit the full spatial diversity, which in turn minimizes the outage probability and increases the throughput. From the delay perspective, beside increasing the throughput, these two cases move the system into the state in which each relay stores one packet only in its buffer as will be discussed in Section V-D1. Since the average delay is equal to the ratio between the average queue length to the throughput, the adopted HD relaying policy leads to low average delay. Hereafter, we will refer to the queue length of one packet as the targeted queue length. Lastly, case C represents link selections that increase the queue length more than the targeted queue length, while case D leads to an empty buffer state. Accordingly, the lowest priorities have been assigned to the cases C and D.

B. Proposed Probabilistic Hybrid Relaying Selection Scheme

In this section, we present the proposed PHRS scheme that selects between the FD mode and the selected candidate link for HD mode in Section IV-A. Before discussing the proposed PHRS scheme, two special cases of the proposed scheme are introduced first in order to show the impact of prioritizing one of the FD and HD modes over the other.

Obviously, FD relaying offers high spectral efficiency, while the first two cases of the proposed HD selection policy in Section IV-A represent the advantages of the HD mode over the FD mode; in particular, the ability to avoid empty and full buffer states (i.e., ensuring the full spatial diversity) and shortening the queues at the relays. Indeed, if FD mode is not available, HD mode will be selected. FD mode is available for selection if there is a relay R_i that has a non-empty buffer ($\Phi(Q_i) > 0$) and both of the links $l_{i,1}$ and $l_{i,2}$ are not in outage (i.e., $\gamma_{i,1}^{\text{FD}} \geq \gamma_o$, and $\gamma_{i,2} \geq \gamma_o$). However, mode selection is a real challenge when the advantages of both modes are available, and hence one mode must be prioritized over the other. We use the prioritizing probability $P^{\text{FD,HD}}$, where $P^{\text{FD,HD}} = 1$ ($P^{\text{FD,HD}} = 0$) if the FD mode (HD mode) is prioritized. Next, in order to demonstrate and assess the impact of the prioritizing probability $P^{\text{FD,HD}}$, we will present two special cases of the proposed PHRS scheme first before introducing the proposed scheme itself.

1) Special case one: In this special case of the proposed scheme, FD mode is always prioritized over HD mode by setting $P^{\text{FD,HD}} = 1$. Hence, only if the FD mode is not available, it moves to the HD mode and selects a link as described in Section IV-A. In this special case, the high spectral efficiency of FD mode will be exploited at the price of the possibility of having lengthy queues at the relays.

2) Special case two: Here, if the selected candidate for the HD mode is case A or case B, the HD mode is prioritized over the FD mode by setting $P^{\text{FD,HD}} = 0$. Otherwise, the FD mode will be prioritized since case C and case D of the HD mode have no advantages over the FD mode as mentioned earlier. Accordingly, case A and case B of the proposed HD mode in Section IV-A have the highest priority followed by the FD mode, case C and case D of the HD mode, respectively. In this special case, we can ensure that the queues at the relays do not exceed the targeted queue length at the price of an occasional missing of the high spectral efficiency of FD communication.

TABLE I
FULL-/HALF-DUPLEX MODE SELECTION OF THE PROPOSED SPECIAL CASES IN ALL POTENTIAL SCENARIOS

HD candidate	Special case one	Special case two
Case A (Rx: $\Phi(Q_{I_{min}}) = 0$)	$P^{\text{FD,HD}} = 1$	$P^{\text{FD,HD}} = 0$
Case B (Tx: $\Phi(Q_{I_{max}}) > 1$)	$P^{\text{FD,HD}} = 1$	$P^{\text{FD,HD}} = 0$
Case C (Rx: $\Phi(Q_{I_{min}}) > 0$)	$P^{\text{FD,HD}} = 1$	$P^{\text{FD,HD}} = 1$
Case D (Tx: $\Phi(Q_{I_{max}}) = 1$)	$P^{\text{FD,HD}} = 1$	$P^{\text{FD,HD}} = 1$

As compared to special case one, special case two offers lower average delay but at the price of a drop in the throughput as will be shown in Section VI. Table I shows the FD/HD mode selection when both modes are available for selection. The first column represents all potential scenarios of the selected candidate for HD relaying according to the policy described in Section IV-A, i.e., cases A-D. In the last two rows, the FD mode is always selected since the HD mode has no advantages over the FD mode as mentioned earlier. In the remaining cases, both of the FD and HD modes have advantages and the mode selection depends on our decision of the priority $P^{\text{FD,HD}}$ in each of the special cases.

3) Proposed PHRS scheme: Instead of choosing between exploiting the high spectral efficiency of FD mode and ensuring short queue lengths at the relays by the HD mode, we aim to exploit the merits of both modes. We use the probability $P^{\text{FD,HD}} \in [0, 1]$ instead of $P^{\text{FD,HD}} \in \{0, 1\}$ as in the special cases presented earlier and all the existing hybrid BA schemes in the literature. Our goal is to study the impact of prioritizing the FD mode by a certain probability, i.e., the probability $P^{\text{FD,HD}} \in [0, 1]$, and find the best value for $P^{\text{FD,HD}}$. For example, if $P^{\text{FD,HD}} = 0.6$, the FD mode will be prioritized for selection in 60% of the time slots in which both modes are available, while the HD candidate is selected in the remaining 40%. The priority assigned to the FD mode over the selection of a relay with two packets for transmission in HD mode is not necessarily equal to that assigned over the selection of a relay with more than two packets or the selection of the relay with empty buffer for reception. Accordingly, we will use prioritizing probabilities associated with the buffer states, i.e., $P_q^{\text{FD,Rx}}$ and $P_q^{\text{FD,Tx}}$ where $q = \Phi(Q_i)$. Note that finding the optimal $P_q^{\text{FD,Rx}}$ and $P_q^{\text{FD,Tx}}$ is a very difficult task since there are L valid buffer states for each of relay transmission and reception as will be discussed in Section V. Alternatively, inspired by the probabilistic scheme in [9], we define these prioritizing probabilities as functions of weights and an auxiliary variable α. The probability of prioritizing the FD mode over the selection of a relay R_i with q buffered packets, $q = \Phi(Q_i)$, for reception in HD mode is defined as

$$P_q^{\text{FD,Rx}} = \frac{1}{1 + \alpha w_{\text{Rx},q}}, \tag{4}$$

where $\alpha \in \mathbb{R}_+$ to ensure that $P_q^{\text{FD,Rx}} \in [0, 1]$. The notation $\mathbb{R}_+$ denotes to the set of non-negative real numbers. The weights $w_{\text{Rx},q} \geq 0$ are used to enforce the impact of the buffer states on the mode selection as illustrated in Table I. In particular, reception in HD mode has advantages over FD mode only if the relay R_i has an empty buffer, and thus we set $w_{\text{Rx},0} > 0$ and $w_{\text{Rx},q} = 0$ for $q \in \{1, 2, \ldots, L-1\}$. Likewise, the probability of prioritizing the FD mode over the selection of a relay R_i with q buffered packets for transmission in HD mode is given by

$$P_q^{\text{FD,Tx}} = \frac{1}{1 + \alpha w_{\text{Tx},q}}. \tag{5}$$

We set $w_{\text{Tx},1} = 0$ to always prioritize the FD mode over the selection of the relay with a single packet for transmission in HD mode, which leads to an empty state as presented in the last row of Table I. Also, the need for selecting the relay for transmission in HD mode over the FD mode to shorten the queue is increased as the number of buffer packets increases. Accordingly, for $q \in \{2, 3, \ldots, L\}$, we set $w_{\text{Tx},q} > 0$ in ascending order with q. In the next section, we will determine α that minimizes the overall average delay, where small (large) α leads to more utilization of the FD mode (HD mode).

V. ANALYSIS OF THE PROPOSED PHRS SCHEME

In this section, we study the performance of the proposed PHRS scheme using MC theory. To model the system, each state of the MC represents the number of packets in the buffers of the relays. Therefore, there are $N = (L + 1)^K$ possible combinations that represent the total number of possible states of the MC. The j-th state of the MC can be defined as $s_j \triangleq (\Phi(Q_1, j), \Phi(Q_2, j), \ldots, \Phi(Q_K, j))$, where $\Phi(Q_k, j)$ denotes the number of stored packets in the buffer Q_k in state s_j. To analyse system performance based on MC theory, the state transition matrix and the stationary distribution of the MC need to be determined based on the proposed PHRS selection policy presented in Section IV-B3. The performance is analysed in terms of outage probability, average buffering delay, throughput and diversity order. Also, queue length, operation mode (i.e., HD/FD) and average buffering delay at high SNR are discussed as follows.

A. State Transition Matrix

In this section, the state transition matrix, denoted by $\boldsymbol{A}$ hereafter, that contains the probabilities of transitions between the states of the MC is determined. The element $\boldsymbol{A}_{i,j}$ represents the probability of the transition from state s_j to state s_i. Clearly, transitions between states may occur due to the selection of one of the relays for transmission or reception in HD mode. On the other hand, all buffer states remain unchanged (i.e., the system remains in the current state of the MC) in outage events and FD mode where the selected relay both transmits and receives one packet.

Based on the proposed selection policy in Section IV-B3, probabilities of all potential events will be found. To achieve that, we define the sets B_q to save the indices of the SR links based on the number of buffered packets in the relays, i.e., the index of the SR link $l_{m,1}$ is saved in the set B_q if $q = \Phi(Q_m, j)$. Since a relay with a full buffer cannot be selected for reception in the HD mode, we only have the sets $B_0, B_1, \ldots, B_{L-1}$. Likewise, the sets G_q are used to save the indices of the RD links based on the number of buffered packets in the relays, i.e., the index of the RD link $l_{m,2}$ is saved in the set G_q if $q = \Phi(Q_m, j)$. Since a relay with an empty buffer cannot be selected for transmission, only the sets $G_1, G_2, \ldots, G_L$ will be used. Also, we define the sets F_q, where $q \in \{1, 2, \ldots, L\}$, to save the indices of the eligible relays for FD transmission based on the number of buffered packets, i.e., $m \in F_q$ if $q = \Phi(Q_m, j)$. Lastly, we define the set F as $F = F_1 \bigcup F_2 \bigcup \ldots F_L \bigcup$.

1) Outage Event: In state s_j, an outage event P_j^{out} occurs if all the available SR and RD links are in outage, viz.,

$$P_j^{\text{out}} = \prod_{n=1}^{L} \overline{P_{G_n}} \prod_{n=0}^{L-1} \overline{P_{B_n}}, \tag{6}$$

where $\overline{P_{B_n}}$ is the probability that all SR links that belong to B_n are in outage, which can be calculated as

$$\overline{P_{B_n}} = \begin{cases} 1, & \text{if } |B_n| = 0 \\ \prod_{m=1}^{|B_n|} P^o_{B_n(m)}, & \text{otherwise} \end{cases}, \tag{7}$$

where $|\cdot|$ denotes the cardinality of the set. Similarly, $\overline{P_{G_n}}$ is the probability that all RD links that belong to G_n are in outage, given by

$$\overline{P_{G_n}} = \begin{cases} 1, & \text{if } |G_n| = 0 \\ \prod_{m=1}^{|G_n|} P^o_{G_n(m)}, & \text{otherwise} \end{cases}. \tag{8}$$

In both (7) and (8), $B_n(m)$ and $G_n(m)$ denote the index of the m-th element of the corresponding set. Also, $P^o_{l_{i,j}} = \Pr\left(|h_{i,j}|^2 < \gamma_o \sigma_n / P^t_{i,j}\right)$ is the probability that the link $l_{i,j}$ is in outage in HD mode. Since $|h_{i,j}|^2$ is exponentially distributed, the probability that the link $l_{i,j}$ is in outage is equal to

$$P^o_{l_{i,j}} = 1 - \exp\left(-\frac{\gamma_o \sigma_n^2}{P^t_{i,j} \sigma_{i,j}^2}\right). \tag{9}$$

Indeed, if a relay cannot be selected for transmission or reception in HD mode, it cannot be selected for FD communications either. Thus, the outage in (6) is computed based on the outage of HD mode only.

2) Relay reception in HD mode: Based on the proposed selection policy in Section IV-B3, a given SR or RD link $l_{i,j}$ is selected if two conditions are met. First, all the links with higher priority of selection according to the HD selection policy in Section IV-A are in outage. Second, either none of the relays are eligible for FD transmission or the HD mode have been given the priority of selection over the FD mode. Links that belong to the same set B_q or G_q have the same priority of selection. It is not necessary that all the links of the considered set are not in outage simultaneously. Thus, to determine the probability of selecting the link $l_{i,j}$, the probability of occurrence of all possible subsets of the holding set (B_q or G_q) that contain $l_{i,j}$ must be found [2]. Here, the subset represents the case in which out of all the links of the holding set (B_q or G_q) only the members of the subset are not in outage concurrently. For an SR link $l_{i,1}$ that belongs to B_q, there are $2^{|B_q|-1}$ subsets of B_q each of which contains $l_{i,1}$. These subsets are denoted by $C^1_{i,1}, C^2_{i,1} \ldots, C^{2^{|B_q|-1}}_{i,1}$. Similarly, for an RD link $l_{i,2}$ that belongs to G_q, there are $2^{|G_q|-1}$ subsets of G_q each of which contains $l_{i,2}$. These subsets are denoted by $D^1_{i,2}, D^2_{i,2} \ldots, D^{2^{|G_q|-1}}_{i,2}$. Among all the links of the subset that are not in outage, the proposed PHRS scheme selects one of them uniformly.

It is worth mentioning here that the methodology of the computation of the state transition matrix in i.n.i.d. fading channels that was provided in [2] is a very useful starting point in our analysis. However, the state transition matrix in [2] is computed for a simple network that consists of two relays only with buffer size equals two and the state transition matrix for any buffer size and number of relays is not found. In particular, the term $\Pr(s_n \to s_m | \Psi^s_n)$ in [2, Eq. (6)], which depends on the link selection policy that differs from one link selection scheme to another, is not found. Although our proposed scheme has a more complicated selection policy due to the consideration of FD mode and prioritizing probabilities, the state transition matrix of the proposed scheme for any buffer size and number of relays is determined in this section.

Now, the probability of selecting the relay R_k for reception as the HD relaying candidate, i.e., selecting the link $l_{k,1}$ that belongs to the set B_q where $q = \Phi(Q_k, j)$, is equal to the sum of the probabilities of selecting the link $l_{k,1}$ in all possible subsets of B_q that contain the link $l_{k,1}$ ($C^a_{k,1} \subseteq B_q$ and $l_{k,1} \in C^a_{k,1}$). Hence, one can write

$$P^{j,\text{HD}}_{l_{k,1}} = \sum_{a=1}^{2^{|B_q|-1}} \frac{1}{\left|C^a_{k,1}\right|} \Pr(C^a_{k,1}) x_{q,a}, \tag{10}$$

where $\Pr(C^a_{k,1})$ is the probability of occurrence of the subset $C^a_{k,1}$, which is equal to

$$\Pr(C^a_{k,1}) = \prod_{l_{m,1} \in C^a_{k,1}} (1 - P^o_{l_{m,1}}) \prod_{l_{m,1} \in B_q \setminus C^a_{k,1}} P^o_{l_{m,1}}, \tag{11}$$

and $x_{q,a}$ is equal to

$$x_{q,a} = \begin{cases} 0, & \text{if } q = L \\ 1, & \text{if } q = 0 \\ \prod_{n=0}^{q-1} \overline{P_{B_n}} \prod_{n=2}^{L} \overline{P_{G_n}}, & \text{if } 1 \le q < L \end{cases}. \tag{12}$$

The probability of actually selecting the relay candidate R_k for reception in the HD mode is equal to

$$P^{j,\text{Hybrid}}_{l_{k,1}} = P^{j,\text{HD}}_{l_{k,1}} \left[1 - (1 - z) P^{\text{FD,Rx}}_q\right], \tag{13}$$

where $P^{\text{FD,Rx}}_q$ is given by (4) and z is equal to

$$z = \begin{cases} 1, & \text{if } q > 1 \\ \prod_{m=1}^{L} \overline{F_m}, & \text{if } q = 0 \\ \prod_{\forall l_{m,1} \in C^a_{k,1}} P^o_{l_{m,2}}, & \text{if } q = 1 \end{cases}, \tag{14}$$

and $\overline{F_m}$ is the probability that all relays that belong to F_m, i.e., relays with m buffered packets, are not capable of FD transmission, which is given by

$$\overline{F_m} = \begin{cases} 1, & \text{if } |F_m| = 0 \\ \prod_{b=1}^{|F_m|} P^o_{b,\text{FD}}, & \text{if } q = 0 \end{cases}, \tag{15}$$

where $P^{o}_{b,\text{FD}}$ is probability that the relay R_b is not capable of FD communications, which occurs if the SINR of the SR link $\gamma^{\text{FD}}_{b,1}$ or the SNR of the RD link $\gamma_{b,2}$ is less than the threshold γ_o. The probability of $\gamma^{\text{FD}}_{b,1} < \gamma_o$ is given by [11]

$$P^{o,\text{FD}}_{l_{b,1}} = 1 - \frac{P^t_{b,1}\sigma^2_{b,1}}{P^t_{b,1}\sigma^2_{b,1} + \beta P^t_{b,2}\gamma_o\sigma^2_{b,\text{SI}}}\exp\left(-\frac{\gamma_o\sigma^2_n}{P^t_{b,1}\sigma^2_{b,1}}\right), \tag{16}$$

where $|h_{b,1}|^2 \sim \text{Exp}(\sigma^{-2}_{b,1})$ and $|h_{b,\text{SI}}|^2 \sim \text{Exp}(\sigma^{-2}_{b,\text{SI}})$. Since the direct link does not exist, there is no interference from the source to the destination nodes, and the probability that the RD link $l_{b,2}$ is in outage (i.e., $\gamma_{i,2} < \gamma_o$) can be found using (9). Therefore, the probability that the relay R_b is not capable of FD communications is equal to

$$P^{o}_{b,\text{FD}} = 1 - (1 - P^{o,\text{FD}}_{l_{b,1}}) \times (1 - P^{o}_{l_{b,2}}). \tag{17}$$

The aforementioned probabilities in (10)-(14) are straightforwardly derived from the proposed PHRS scheme. For more clarity, the probability of selecting the relay R_k for reception has four possible cases. First, $P^{j,\text{HD}}_{l_{k,1}} = P^{j,\text{Hybrid}}_{l_{k,1}} = 0$ if the relay R_k has a full buffer. Second, since the proposed HD scheme in Section IV-A gives the highest priority to relays with empty buffers (i.e., case A), one of these relays could be selected uniformly as the HD relaying candidate regardless of the status of links in other sets (i.e., $x_{0,a} = 1$). Then, this candidate will be selected if the FD mode is not available or the HD mode has been prioritized over the FD mode, which can be written as in (13), i.e., one minus the probability that the FD mode exists and has been prioritized. Third, relays that buffer more than one packet (i.e., $q > 1$) will not be selected as HD relaying candidates unless the following occurs: all relays with more than one packet cannot transmit successfully to the destination node (i.e., these RD links are in outage) and all relays with fewer buffered packets cannot be selected for reception. Concurrently, these two conditions ensure that none of the relays are capable of FD transmission, and accordingly no more terms are needed to ensure the outage of the FD mode that always has the priority over this HD case as given in (14). Lastly, if the relay buffer has one packet (i.e., $q = 1$), the two conditions of the previous case must be met. These two conditions ensure that all relays are not capable of FD transmission except those belonging to the set F_1. Since all relays with SR links belonging to the set $C^a_{k,1}$ are capable of reception, we need to ensure that the RD links of these relays are in outage as shown in (14); otherwise, one of them will be selected in the FD mode that always has the priority over this HD case.

3) Relay transmission in HD mode: Similar to what is mentioned in the previous subsection, the probability of selecting the relay R_k for transmission as HD relaying candidate, i.e., selecting the link $l_{k,2}$ that belongs to the set G_q where $q = \Phi(Q_k, j)$, is equal to

$$P^{j,\text{HD}}_{l_{k,2}} = \sum_{a=1}^{2^{|G_q|-1}} \frac{1}{\left|D^a_{k,2}\right|}\text{Pr}(D^a_{k,2})y_q, \tag{18}$$

where $\text{Pr}(D^a_{k,2})$ is the probability of occurrence of the subset $D^a_{k,2}$ given by

$$\text{Pr}(D^a_{k,2}) = \prod_{l_{m,2}\in D^a_{k,2}} (1 - P^o_{l_{m,2}}) \prod_{l_{m,2}\in G_q \setminus D^a_{k,2}} P^o_{l_{m,2}}. \tag{19}$$

and y_q is equal to

$$y_q = \begin{cases} 0, & \text{if } q = 0 \\ \overline{P_{B_0}}, & \text{if } q = L \\ \overline{P_{B_0}} \prod_{n=q+1}^{L} \overline{P_{G_n}}, & \text{if } 2 \le q \le L \\ \prod_{n=0}^{L-1} \overline{P_{B_n}} \prod_{n=2}^{L} \overline{P_{G_n}}, & \text{if } q = 1 \end{cases}. \tag{20}$$

The probability of actually selecting the relay candidate R_k for transmission in the HD mode is equal to

$$P^{j,\text{Hybrid}}_{l_{k,2}} = P^{j,\text{HD}}_{l_{k,2}}\left[1 - (1-u)\,P^{\text{FD,Tx}}_q\right], \tag{21}$$

where $P^{\text{FD,Tx}}_q$ is given by (5) and u is equal to

$$u = \begin{cases} 1, & \text{if } q = 1 \\ \prod_{\forall l_{m,2}\in D^a_{k,2}} P^{o,\text{FD}}_{l_{m,1}} \prod_{m=1}^{q-1} \overline{F_m}, & \text{if } q > 1 \end{cases}, \tag{22}$$

where $P^{o,\text{FD}}_{l_{m,1}}$ is given by (16). Again, according to the proposed PHRS scheme, the probability of selecting the relay R_k for transmission has three possible cases. First, $P^{j,\text{HD}}_{l_{k,2}} = P^{j,\text{Hybrid}}_{l_{k,2}} = 0$ if the relay R_k has an empty buffer. Second, relays with more than one packet in their buffers will not be selected for transmission as an HD candidate unless all relays with more packets in their buffers cannot be selected for transmission. Also, the FD mode must be not available or the HD mode has been prioritized over the FD mode as given in (21). Note that the first condition ensures that all relays with more buffered packets are not capable for FD transmission, but the ability of other relays with less than or equal number of packets of FD transmission must be considered as shown in (22). Second, relays that store one packet only will not be selected as an HD candidate unless all relays with more packets in their buffers cannot be selected for transmission and all relays cannot receive successfully from the source node. These conditions ensure that none of the relays are capable of FD transmission, and hence no more terms are needed to ensure the outage of the FD mode as given in (22).

4) Relay transmission in FD mode: FD transmission does not change the buffer states. Thus, if the priority of selection is assigned to the FD mode over the available HD links, one of the eligible relays for FD transmission is selected uniformly as follows

$$P^{j}_{k,\text{FD}} = \sum_{a=1}^{2^{|F|-1}} \frac{1}{|V^a_k|}\text{Pr}(V^a_k)\Big\{1 - \Big[\sum_{m=1}^{K} P^{j,\text{HD}}_{l_{m,1}}\Big(1 - P^{\text{FD,Rx}}_q\Big) + \sum_{m=1}^{K} P^{j,\text{HD}}_{l_{m,2}}\Big(1 - P^{\text{FD,Tx}}_q\Big)\Big]\Big\}, \tag{23}$$

where $q = \Phi(Q_k, j)$, the set F saves the indices of the eligible relays for FD transmission as mentioned earlier and $V^a_k \subseteq F$

and $k \in V_k^a$ is one of the $2^{|F|-1}$ subsets of F that contain the index of the relay R_k. The probability of occurrence of V_k^a is equal to

$$\Pr(V_k^a) = \prod_{k \in V_k^a} (1 - P_{k,\text{FD}}^o) \prod_{k \in F \setminus V_k^a} P_{k,\text{FD}}^o, \tag{24}$$

where $P_{k,\text{FD}}^o$ is the probability that the relay R_k is not capable of FD communications, which is given by (17). It is worth recalling that the priorities $P_q^{\text{FD,Rx}}$ and $P_q^{\text{FD,Tx}}$ are equal to one if the HD mode has no advantages over the FD mode; otherwise, they belong to the period [0,1] as mentioned in Section IV-B3.

So far, we presented the probabilities of the four possible events, namely, relay reception in HD mode, relay transmission in HD mode, FD transmission and the outage event. Now we are ready to present the computation of the state transition matrix $\boldsymbol{A}$ based on these probabilities. In an outage event or if a relay is selected for FD transmission, all buffer states remain unchanged, which means the system remains in the current state of the MC. Hence, the probability $\boldsymbol{A}_{j,j}$ is equal to the sum of the probabilities of the outage event in state s_j that is given by (6) and the probability that one of the relays is selected for FD transmission given in (23). In state s_j, if a relay R_k is selected for either reception or transmission in HD mode, the number of packets in the buffer Q_k will be either increased or decreased by one, respectively. Thus, the system moves to a connected state s_i that has the same buffer states as state s_j except for the selected relay R_k. Therefore, the two states s_j and s_i are connected if $s_i - s_j \in \Theta$, where $\Theta \triangleq \pm\{I_{1,\bullet}, I_{2,\bullet}, \ldots, I_{K,\bullet}\}$ and $I_{k,\bullet}$ is the k-th row of the identity matrix I. Based on which element of Θ is equal to $s_i - s_j$, the index of the affected relay R_k from the transition can be found. In state s_j, a transition to a connected state s_i in which the number of packets in the affected relay buffer Q_k is larger (smaller) by one occurs with probability $P_{l_{k,1}}^{j,\text{Hybrid}}$ ($P_{l_{k,2}}^{j,\text{Hybrid}}$), where the probabilities $P_{l_{k,1}}^{j,\text{Hybrid}}$ and $P_{l_{k,2}}^{j,\text{Hybrid}}$ are given by (13) and (21), respectively. In summary, the entries of $\boldsymbol{A}$ are given by

$$\boldsymbol{A}_{i,j} = \begin{cases} P_j^{\text{out}} + \sum_{k=1}^{K} P_{k,\text{FD}}^j, & \text{if } i = j \\ P_{l_{k,1}}^{j,\text{Hybrid}}, & \text{if } s_i - s_j \in \Theta \\ & \text{and } \Phi(Q_k, i) > \Phi(Q_k, j) \\ P_{l_{k,2}}^{j,\text{Hybrid}}, & \text{if } s_i - s_j \in \Theta \\ & \text{and } \Phi(Q_k, i) < \Phi(Q_k, j) \\ 0, & \text{otherwise}, \end{cases} . \tag{25}$$

Clearly, due to the structure of the problem, one can reach any state from any state in the MC through successive selection of relays for transmission or reception in HD mode, where the number of buffered packets will be decremented or incremented by one, respectively. Therefore, the states of the MC represent one communication class and the MC is irreducible [29]. Also, since the outage probability of any state P_j^{out} is greater than zero, there exists $M \in \mathbb{N}$ such that the probability of being at state s_j after M and $M+1$ transitions, is greater than zero. Hence, the MC of the proposed PHRS scheme is aperiodic [20], [29]. Since the MC is irreducible and aperiodic, there exists a unique stationary distribution that is equal to [29]

$$\pi = \boldsymbol{A}\pi, \tag{26}$$

where $\pi = (\pi_1, \pi_2, \cdots, \pi_N)^T$, $(\cdot)^T$ denotes the transpose of the matrix and $\sum_{j=1}^{N} \pi_j = 1$.

B. System Performance

Unlike the HD-based BA schemes that use fixed rate for transmission such as [2] and [7], the performance of the proposed PHRS scheme cannot be assessed merely by the outage probability, where the performance depends on whether FD mode or HD mode has been selected during non-outage slots. Accordingly, delay and throughput are the main metrics used to assess the performance of the proposed PHRS scheme. However, the outage probability remains very useful as it reflects the exploitation of the spatial diversity. Also, since a fixed transmission rate is assumed, minimizing the outage probability directly increases the system throughput.

1) Outage probability: As mentioned earlier, in state s_j, an outage event occurs with probability P_j^{out} given by (6). Clearly, this outage probability depends on the number and indices of the links available for selection, which may indeed differ from one state to another. Hence, the overall outage probability of the system is equal to

$$P^{\text{out}} = \sum_{j=1}^{N} \pi_j P_j^{\text{out}}, \tag{27}$$

2) System throughput: The system throughput in terms of bits per channel use (BPCU) can be computed from the probabilities of selecting relays with non-empty buffers for transmission to the destination node in both the HD and FD modes. The system throughput is thus given by

$$\tau = r_0 \sum_{j=1}^{N} \left(\pi_j \sum_{k=1}^{K} P_{l_{k,2}}^{j,\text{Hybrid}} + P_{k,\text{FD}}^j \right), \tag{28}$$

where r_o is the packet size in bits.

3) Transmission delay: From Little's law, the average buffering delay (in time slots) can be defined as the ratio between the average queue length to the throughput [5]. The overall transmission delay consists of the sum of the buffering delay at the source node and at the relays. First, the average buffering delay at the source node is given by [2]

$$d_s = \frac{\mathbb{E}[r_0 \Phi(Q_s)]}{\tau_s} = \frac{r_0 (1 - \sum_{j=1}^{N} \pi_j \sum_{k=1}^{K} P_{l_{k,1}}^{j,\text{Hybrid}} + P_{k,\text{FD}}^j)}{r_0 \sum_{j=1}^{N} \pi_j \sum_{k=1}^{K} P_{l_{k,1}}^{j,\text{Hybrid}} + P_{k,\text{FD}}^j}, \tag{29}$$

where $\mathbb{E}[\cdot]$ denotes the expected value, $\mathbb{E}[r_0 \Phi(Q_s)]$ is the average queue length in bits and τ_s is the throughput of the source node in bits per slot, where τ_s is equal to the probability of selecting the source node for transmission to one of the relays in HD or FD mode multiplied by the packet size [2].

Second, the average buffering delay at the k-th relay is given by [5]

$$d_k = \frac{\mathbb{E}[r_0 \Phi(Q_k)]}{\tau_k} = \frac{r_0 \sum\limits_{j=1}^{N} \pi_j \Phi(Q_k, j)}{r_0 \sum\limits_{j=1}^{N} (P_{l_{k,2}}^{j,\text{Hybrid}} + P_{k,\text{FD}}^{j})}, \quad (30)$$

where $\mathbb{E}[r_0 \Phi(Q_k)]$ is the average queue length of the k-th relay buffer and τ_k is the average throughput of the k-th relay.

Although the proposed scheme gives the relay nodes equal priority of selections based on the BSI as stated in Section IV, the consideration of the i.n.i.d. fading may lead to different probability of selections of these relays for transmission and reception. Accordingly, the average delay may differ from a relay node to another. Similar to [2], to assess the buffering delay at the relays, we deal with the buffers of all relays as one equivalent buffer to determine the average buffering delay at the relays. In other words, we will deal with all the relays as one equivalent relay in terms of the average queue length and the average throughput. Therefore, the average buffering delay at the relays is given by [2]

$$d_R = \frac{\sum\limits_{j=1}^{N} r_0 \sum\limits_{k=1}^{K} \pi_j \Phi(Q_k, j)}{\tau}. \quad (31)$$

The overall buffering delay is equal to the sum of the buffering delays at the source node d_s and the relay nodes d_R that are given by (29) and (31), respectively.

C. Delay Minimization

To this point, the state transition matrix $\boldsymbol{A}$, the stationary distribution π, the outage probability, the average buffering delay and the system throughput have been found. All these parameters depend on the priorities $P_q^{\text{FD,Rx}}$ and $P_q^{\text{FD,Tx}}$, which in turn are functions of the auxiliary variable α as given in (4) and (5), respectively. Accordingly, the performance of the proposed PHRS scheme depends on the computation of α. Between maximizing the throughput and minimizing the delay, we chose to minimize the overall average delay, i.e., $d_R + d_s$, since delay is the main concern about using BA relaying in modern communication systems in addition to the fact that minimizing d_R necessitates having high throughput as given in (31). Hence, the auxiliary variable α is determined by

$$\min_{\alpha,\ s.t.\ \alpha \geq 0} \quad d_R + d_s. \quad (32)$$

This objective function is neither decreasing nor increasing monotonically with α. Accordingly, unlike the probabilistic scheme in [9], we cannot exploit the delay bound to search for α^* in a specific range. Alternatively, two methods can be used. First, we propose to use the accelerated proximal gradient method for non-convex programming in [17]. In this method, the solution is within $O(\frac{1}{k^2})$ from the optimal value, where k is the number of iterations. Straightforward implementation of this method is presented in [17, Algorithm 2]. Second, since the objective function is not extremely sensitive to α, a grid search can be used to find α that leads to the minimum average delay. Grid search offers lower computational complexity. We note that α must be searched in a set that is formed carefully such that it contains adequately diverse values as used in Section VI. As can be seen in (4) and (5), small α means more FD mode selection (i.e., spectral efficiency), while large α leads to more HD mode selection and the exploitation of its advantages.

To make the implementation of the proposed PHRS scheme straightforward, Algorithm 1 is presented. The function rand in Line 18 returns a random number in $(0, 1)$ according to the uniform distribution. In addition, special case one, presented in Section IV-B1, can be obtained by setting priority $= 1$ in Lines 17 and 25, while special case two can be implemented by setting priority $= 0$ in Lines 17 and 25. Note that the objective function $d_R + d_s$ depends on the average channel states of the links $\sigma_{i,j}^2$ (i.e., not the instantaneous $|h_{i,j}|^2$), and accordingly the computation of α may not be needed in every slot as stated in Line 1. The remaining steps of Algorithm 1, such as selecting the relay that stores the maximum or minimum number of packets, are of order $O(K)$ [7], i.e., the worst-case complexity of Algorithm 1 grows linearly with respect to the number of relays K.

D. Performance at High SNR

1) Buffer states and operation mode: At high SNR (i.e., $P_{i,j}^t \rightarrow \infty$), the outage probability of an available SR or RD link $l_{i,j}$, given by (9), is equal to zero. Accordingly, the proposed PHRS scheme takes the system to the state in which each relay buffers one packet only, which is our targeted queue length as mentioned in Section IV-A. More specifically, for case A and case B of the proposed HD link selection policy in Section IV-A (i.e., HD reception for relays with empty buffers and HD transmission for relays that buffer more than one packet), the priority of selections over the FD mode equal to $(1 - P_q^{\text{FD,Rx}})$ and $(1 - P_q^{\text{FD,Tx}})$, respectively. On the other hand, for case C and case D of the proposed HD link selection policy (i.e, HD reception of relays with non-empty buffers and HD transmission of relays that buffer one packet), the priority of selections are equal to zero, i.e., $(1 - P_q^{\text{FD,Rx}}) = (1 - P_q^{\text{FD,Tx}}) = 0$ as mentioned in Section IV-B. Accordingly, based on the values of $P_q^{\text{FD,Rx}}$ and $P_q^{\text{FD,Tx}}$, after finite number of time slots, the proposed PHRS scheme ensures that all relays possess one packet in their buffers regardless of the initial buffer states. At this point, all relays are eligible for FD transmission and the FD mode has the priority of selection over all the HD links, where all the priorities $P_1^{\text{FD,Rx}} = P_1^{\text{FD,Tx}} = 1$. Since FD transmission does not change the buffer states, in all the upcoming time slots, the proposed PHRS scheme will select one of the relays uniformly for FD transmission.

2) Average delay: Since the proposed PHRS scheme always works in FD mode at high SNR, the system throughput τ is equal to r_0 BPCU where every time slot a packet of the size r_0 bits will be delivered to the destination node. Hence, the average buffering delay at the source node is equal to zero as given in (29). Also, there is one packet in the buffer of each relay, and accordingly the average buffering delay at the relays d_R, given in (31), is equal to $r_0 K / r_0 = K$ time slots.

Algorithm 1 Proposed PHRS Algorithm

Inputs: K, L, $P^t_{i,j}$, γ_o, β, r_0 and $\sigma^2_{i,j}$ for all $i, j \in \mathcal{K}$.
At the initialization and whenever one of the variances $\sigma^2_{i,j}$ has changed, update α by solving (32) using [17, Algorithm 2], or using grid search.
Select a candidate link for HD mode:
Among all capable relays of successful reception, select the relay $R_{I_{min}}$ as described in Section IV-A. Set the flag Rx_HD $= 1$ if an eligible relay is found; otherwise, Rx_HD $= 0$.
Select the relay $R_{I_{max}}$ as described in Section IV-A. Set the flag Tx_HD $= 1$ if an eligible relay is found.
Among all capable relays of FD transmission according to (17), select one of them uniformly, which will be referred to as $R_{I_{\text{FD}}}$. Set the flag FD_ability $= 1$ if an eligible relay is found.
Full-/Half-duplex mode selection:
if FD_ability $= 0$ **then** % Only HD mode is available
    if Rx_HD $= 1$ AND $Q_{I_{min}} = 0$ **then**
        Select the relay $R_{I_{min}}$ for reception in HD mode.
    else if Tx_HD $= 1$ AND $Q_{I_{max}} > 1$ **then**
        Select the relay $R_{I_{max}}$ for HD transmission.
    else if Rx_HD $= 1$ **then**
        Select the relay $R_{I_{min}}$ for reception in HD mode.
    else if Tx_HD $= 1$ **then**
        Select the relay $R_{I_{max}}$ for HD transmission.
    end if
else % FD mode is available
    if Rx_HD $= 1$ AND $Q_{I_{min}} = 0$ **then**
        priority $= 1/(1 + \alpha w_{\text{Rx},0})$.
        tmp $=$ rand().
        if tmp $>$ priority **then**
            Select $R_{I_{min}}$ for reception in HD mode.
        else
            Select $R_{I_{\text{FD}}}$ for FD transmission.
        end if
    else if Tx_HD $= 1$ AND $Q_{I_{max}} > 1$ **then**
        priority $= 1/(1 + \alpha w_{\text{Tx},Q_{I_{max}}})$.
        tmp $=$ rand().
        if tmp $>$ priority **then**
            Select $R_{I_{max}}$ for transmission in HD mode.
        else
            Select $R_{I_{\text{FD}}}$ for FD transmission.
        end if
    else
        Select the relay $R_{I_{\text{FD}}}$ for FD transmission.
    end if
end if

3) Diversity order: As mentioned already, at high SNR, the system stays at the state in which all relays can be selected for either transmission or reception. An outage thus occurs if all the SR and RD links of the K relays are in outage. Accordingly, the proposed PHRS scheme exploits the full spatial diversity, i.e., $2K$. Mathematically, the diversity order, which is the gain in spatial diversity, used to enhance the communication reliability, is given by [15]

$$\begin{aligned} d^o &= -\lim_{P\to\infty} \frac{\log P^{\text{out}}_{*}(P)}{\log P} \\ &= -\lim_{P\to\infty} \frac{\log\left[\prod_{k=1}^{K} P^o_{l_{k,1}} \prod_{k=1}^{K} P^o_{l_{k,2}}\right]}{\log P} \\ &= -\lim_{P\to\infty} \frac{\sum_{k=1}^{K} \log\left(P^o_{l_{k,1}}\right) + \log\left(P^o_{l_{k,2}}\right)}{\log P}, \end{aligned} \tag{33}$$

where $P^{\text{out}}_{*}(P)$ is the overall outage probability at high SNR. For simplicity of presentation, since $P^t_{i,j} \to \infty$ for all nodes, we used P to denote the transmission powers of all nodes in the reminder of this section. At high SNR, using the approximation $1 - e^{-x} \approx x$ as $x \to 0$ in (9), each element of the summation in (33) can be expressed as

$$\begin{aligned} d^o &= -\lim_{P\to\infty} \left\{ \frac{\log\left(-\frac{\gamma_o \sigma_n^2}{P\sigma_{k,1}^2}\right) + \log\left(-\frac{\gamma_o \sigma_n^2}{P\sigma_{k,2}^2}\right)}{\log P} \right\} \\ &= -\lim_{P\to\infty} \left\{ \frac{\log\left(-\sigma_{k,1}^{-2}\gamma_o\sigma_n^2\right) - \log(P)}{\log P} \right. \\ &\quad \left. + \frac{\log\left(-\sigma_{k,2}^{-2}\gamma_o\sigma_n^2\right) - \log(P)}{\log P} \right\} = 2. \end{aligned} \tag{34}$$

Each of the K elements in the summation in (33) can be treated similarly, and accordingly the diversity order is equal to $2K$.

VI. Analytical and Simulation Results

In this section, the performance of the proposed PHRS scheme is assessed via analytical and simulation results. The performance, in terms of throughput, average delay and outage probability, is compared with that of the hybrid scheme in [1] and the HD scheme in [3]. As mentioned in Section V-B, the average buffering delay and throughput are the main metrics that will be used to assess the performance of the proposed PHRS scheme. However, the outage probability remains very useful as it shows the exploitation of the spatial diversity that can be found from the slopes of the outage probability curves. Also, since a fixed transmission rate is considered, minimizing the outage probability directly increases the system throughput. For simplicity of the presentation, in all simulations presented in this section, we used a fixed transmission power P for all nodes and the modelling of the i.n.i.d. fading is realized by assigning different variances for the links. For the hybrid scheme in [1], P is set at the maximum allowed transmission power of the nodes, which is used to check the feasibility of the pairs of IRI cancellation. Also, in the computation of the prioritizing probabilities in (4) and (5), the weights are set to $w_{\text{Rx},q} = \{1, 0, \cdots, 0\}$, where $q \in \{0, 1, 2, \cdots, L-1\}$ and $w_{\text{Tx},q} = \{0, 2, 3, \cdots, L\}$, where $q \in \{1, 2, \cdots, L\}$ as discussed in Section IV-B. Lastly, the SIC is equal to 90 dB ($\beta = -90$ dB) unless mentioned otherwise.

First, simulations with $K = 2$ relays, buffer size $L = 3$ and $\gamma_o = 3$ were performed and the variances $\sigma^2_{1,1} = 0.18, \sigma^2_{1,2} =$

TABLE II
STATIONARY DISTRIBUTION FOR DIFFERENT SNRS (P); $K = 2$, $L = 3$ AND $\gamma_o = 3$

	The stationary distribution π			
Buffer state	$P = 0$ dB	$P = 10$ dB	$P = 20$ dB	$P = 30$ dB
$s_0 \triangleq (0, 0)$	0.0372	0.0025	4.9×10^{-5}	3.7×10^{-9}
s_{empty}	0.99	0.487	0.0087	6.1×10^{-5}
s_{full}	0.911	0.2275	4.25×10^{-4}	1.15×10^{-8}
$s_{\text{ones}} \triangleq (1, 1)$	8.9×10^{-9}	0.2255	0.9667	0.9998

$0.9734, \sigma^2_{2,1} = 0.81, \sigma^2_{2,2} = 0.49$ are used to model the i.n.i.d. fading. To show that the proposed PHRS scheme keeps the system away from empty and full buffer states and moves the system toward the state in which all relays buffer one packet only, the steady state distributions of some cases are presented in Table II. In particular, the state in which all buffers are empty, the state in which all relays store one packet, the group of states in which at least one buffer is empty and the group of states in which at least one buffer is full are depicted in the table and are denoted by s_0, s_{ones}, s_{empty} and s_{full}, respectively. Each of the groups s_{empty} and s_{full} consists of seven states. Based on MC modelling in Section V, they are defined as $s_0 \triangleq 00$, $s_{\text{ones}} \triangleq 11$, $s_{\text{empty}} \triangleq \{00, 01, 10, 02, 20, 03, 30\}$ and $s_{\text{full}} \triangleq \{03, 30, 13, 31, 23, 32, 33\}$. Clearly, at high SNR, the steady state distribution of s_{ones} approaches one. At this state, all relays are eligible for FD transmission, and the proposed scheme selects one of them uniformly for FD transmission.

Figs. 2, 3 and 4 show the throughput, outage probability and average delay, respectively, of the considered schemes. It is clear from the figures that the theoretical and simulation results of the proposed PHRS scheme are in perfect match, which reveals the accuracy of our analysis. The theoretical results of the outage probability, throughput, average delay at the source and average delay at the relays are given by (27), (28), (29) and (31), respectively

Since the throughput of the HD scheme in [3] is limited by the spectral loss of HD relaying, the proposed hybrid scheme and the hybrid scheme in [1] both offer higher throughput as shown in Fig. 2. By virtue of its ability to keep the buffer states away from empty and full states, the proposed PHRS scheme offers lower outage probability than the hybrid scheme in [1] as shown in Fig. 3. Since a fixed transmission rate is considered, minimizing the outage probability directly increases the system throughput. Therefore, the proposed PHRS scheme offers higher throughput than the hybrid scheme in [1]. As discussed in Section IV-A and confirmed in Table II, case A and case B of the proposed HD relaying policy ensure that the system moves towards the state in which each relay stores one packet only. This results in a lower average delay as illustrated in Fig. 4. Also, in agreement with our discussion in Section V-D, at high SNR, the proposed scheme offers an average delay equals K time slots as clearly depicted in the figure.

As discussed in Section IV, by always setting the priorities $P_q^{\text{FD,Rx}}$ and $P_q^{\text{FD,Tx}}$ to one or zero, we obtain the special cases one and two of the proposed PHRS scheme, respectively. In special case one, we can achieve a higher throughput at the expense of having a higher average delay as can be seen in Figs. 2 and 4. This is because FD communications offers high spectral efficiency but it does not change the buffer states, which may lead to long queues at the relays and high average delay as given in (30). On the other hand, in special

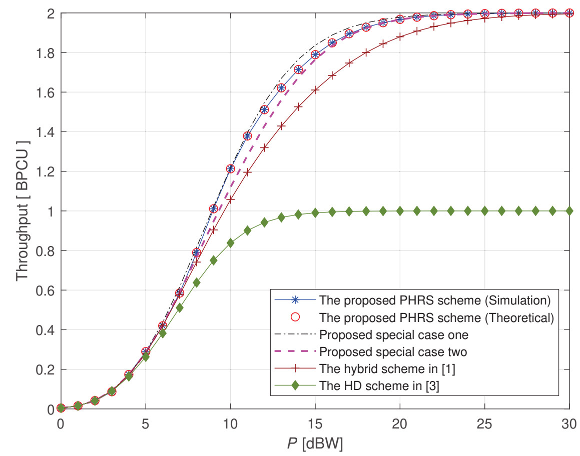

Fig. 2. A comparison between the proposed scheme and the considered benchmark schemes in terms of system throughput in BPCU.

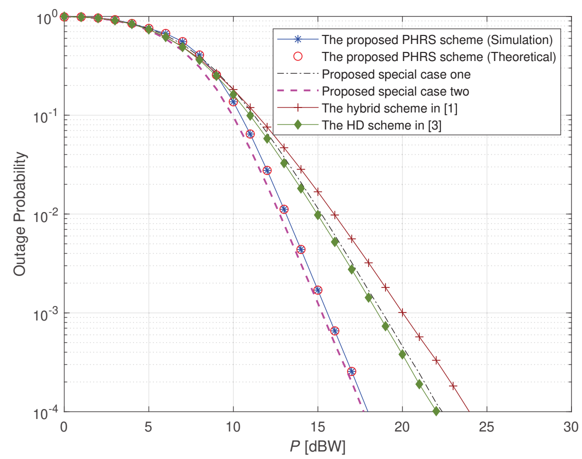

Fig. 3. The performance in terms of outage probability versus P in dBW.

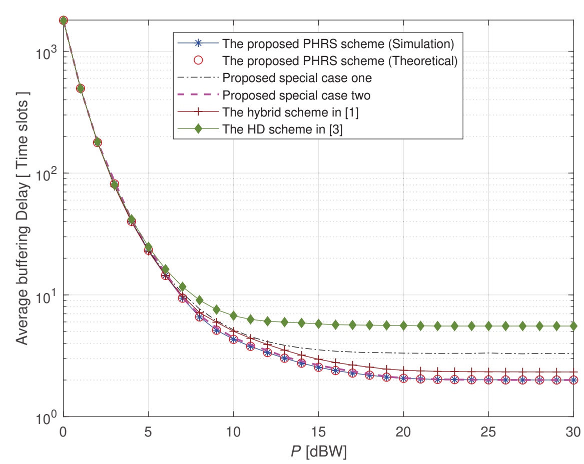

Fig. 4. A comparison between the proposed scheme and the considered benchmark schemes in terms of average buffering delay in time slots.

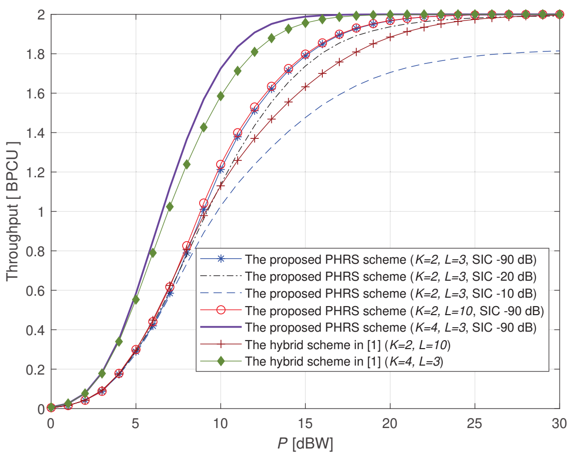

Fig. 5. The impact of the number of relays and buffer size on the performance in terms of system throughput.

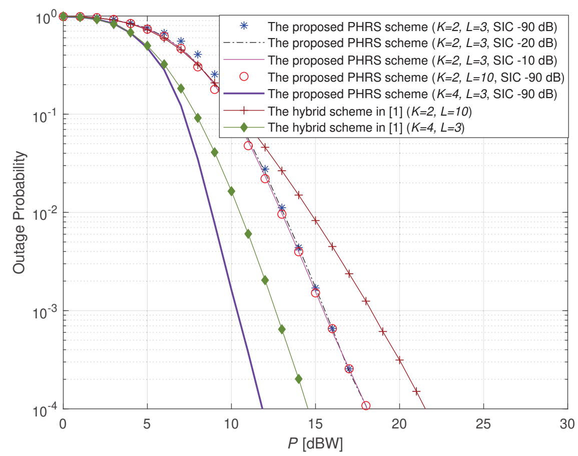

Fig. 6. The impact of the number of relays and buffer size on the performance in terms of outage probability.

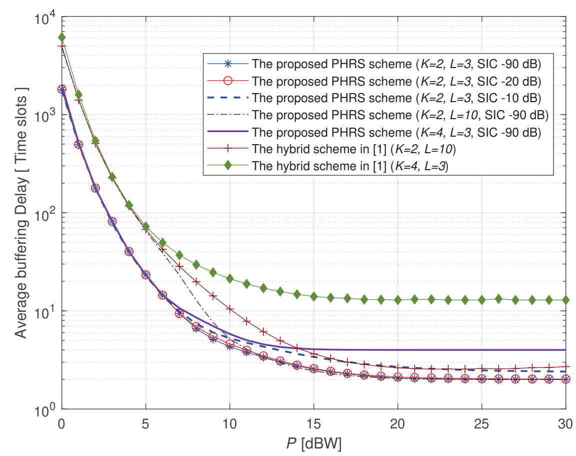

Fig. 7. The impact of the number of relays and buffer size on the performance in terms of average buffering delay.

case two, by giving the priority of selection to cases A and B of the proposed HD relaying in Section IV-A over FD mode, we ensure that the system moves towards the state in which each relay stores one packet, and accordingly short queues at the relays. While the proposed PHRS scheme offers a balanced performance between throughput and delay, the proposed special case one represents a better solution for delay insensitive applications.

Figs. 5, 6 and 7 show the impact of the number of relays on the performance in terms of throughput, outage probability and average delay, respectively. Clearly, using more relays results in a greater spatial diversity, i.e., more SR and RD links will be available for selection. Since an outage event occurs only if all the available links for selection are in outage as given in (6), the outage probability decreases as the number of relays increases, which in turn increases the throughput as illustrated in Figs. 5 and 6. This improvement comes at the price of a higher average delay as shown in Fig. 7, where the selection will be shared by more relays (i.e., more buffering time). Again, in agreement with our discussion of Fig. 4 and in Section V-D, at high SNR, the proposed PHRS scheme offers an average delay equals $K = 4$ time slots. As compared to the hybrid scheme in [1], the proposed scheme offers higher throughput and lower average delay as evident from the figures.

In addition to the above, the figures show the impact of the buffer size on the performance. Using larger buffer sizes minimizes the outage probability by minimizing the probability of empty and full states of the relay buffers, which in turn increases the system throughput as illustrated in Figs. 5 and 6. However, the impact of that is small and limited to low SNR as shown in Fig. 5, [2, Fig. 4] and [7, Fig. 8]. Furthermore, the improvement comes at the price of a higher average delay as depicted in Fig. 7. At high SNR, the proposed scheme offers an average delay equals K time slots regardless of the buffer size.

Also, Figs. 5 and 7 show the impact of the SIC on performance of proposed PHRS scheme. As the SIC increases (i.e., β decreases) the capability of the relays to use FD transmission increases as given in (17), which in turn increases the system throughput. When the SIC decreases ($\beta = -20$ or -10 dB), the proposed scheme increases the utilization of the HD mode over FD mode, which degrades the throughput as shown in Fig. 5. Also, in agreement with (31), the average delay increases as the throughput decreases as shown in Fig. 7. Fortunately, as mentioned in Section I, the impressive improvement in SIC techniques (e.g., in the order of $70 - 110$ dB reported in [10]) makes the use of the proposed PHRS scheme justifiable.

Lastly, the impact of the auxiliary variable α on the performance of the proposed PHRS scheme is shown in Fig. 8. To assess the impact of α, we considered diverse ranges of α. In particular, we considered the ranges [0,1], [1.1,9.1] and [11,861] with steps of size 0.05, 1 and 50, respectively. As mentioned in Section V-D1, at high SNR, the FD mode is always prioritized over the HD mode. Hence, the prioritizing probabilities, given by (4) and (5), are approaching one as seen in Fig. 8 (i.e., $\alpha \approx 0$). As the SNR decreases, the availability of the FD mode decreases due to the high outage probability of the links (9). Accordingly, the demand for the HD mode increases in order to enjoy the full spatial diversity, by avoiding empty and full buffer states, and to ensure short queue lengths

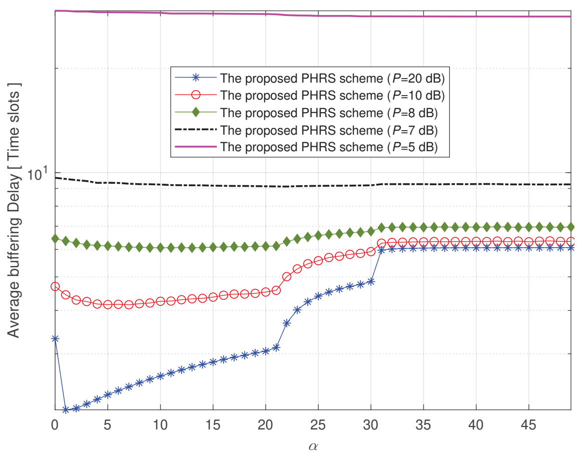

Fig. 8. The impact of the auxiliary variable α on the performance of the proposed PHRS scheme.

as discussed in Section IV-A. As shown in Fig. 8, as the SNR decreases, the value of α that leads to the minimum average delay increases. In other words, the prioritization of the HD mode over the FD mode increases.

VII. Conclusion

We proposed a probabilistic hybrid HD/FD relay selection (PHRS) scheme for cooperative relaying networks with small buffers. It exploits the high spectral efficiency of FD communications and the ability of HD BA relaying to control the queue length of the relay buffers in order to achieve high throughput and minimize the average delay. Unlike the existing hybrid BA schemes that adopt fixed selection policy, the proposed scheme uses prioritizing probabilities for mode selection. Using MC theory, the system is modelled and the system throughput, overall average delay and outage probability are derived as functions of the prioritizing probabilities. Due to the complexity of the average delay expression, it is difficult to find the optimal values for all the prioritizing probabilities. Alternatively, the prioritizing probabilities are obtained using either the accelerated proximal gradient method for non-convex programming or grid search. It has been shown that the proposed probabilistic scheme can achieve the full diversity and offers low average delay that approaches the number of relays at high SNR independent of the buffer size. Compared to existing HD and hybrid schemes, the proposed PHRS scheme offers higher throughput and lower average delay.

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