Performance of Virtual Full-Duplex Relaying on Cooperative Multi-Path Relay Channels

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***Abstract*—We consider a cooperative multi-path relay channel (MPRC) where multiple half-duplex relays assist in the packet transmissions from a source to its destination. A *virtual full-duplex* (FD) relaying scheme is proposed that allows the source to transmit a new packet simultaneously with the selected best relay, with the rest of the relays attempting to decode this new packet. Thus a new source packet can be served in each time slot, as in FD relay systems. Taking into account the effect of inter-relay interference (IRI) that is caused by simultaneous relay and source transmissions, a Markov chain analytical model is used to characterize the decoding performance at the relays, based on which the overall outage probability of MPRC is obtained in closed-form expressions. The asymptotic performance analysis reveals that in low rate scenarios, a close-to-full diversity order is achieved by the proposed scheme while substantially improving the spectrum efficiency. In high rate scenarios, the decoding performance of relays is limited by IRI and the system outage performance experiences an error floor. Simulation results demonstrate the performance gains of the proposed scheme by comparisons with existing half-duplex and FD relay systems in the literature.**

***Index Terms*—Multi-path relay channels, half-duplex and full-duplex, opportunistic relaying, Markov chain, diversity.**

I. Introduction

In this paper, we consider a cooperative multi-path relay channel (MPRC) as shown in Fig. 1(a). With multiple intermediate relay terminals to assist the packet transmissions from the source to its corresponding destination, a packet can be potentially delivered through multiple independent paths. This brings cooperative diversity gains [2], [3] that can effectively combat the effects of wireless fading and significantly improve the communication reliability in future networks, e.g., long-term evolution (LTE) and 5G [4]–[6]. In order to exploit the inherent diversity gains of the cooperative MPRC, various relay selection schemes [7]–[9] have been proposed where a single or multiple best relays are selected to help forward the received source signal to the destination.

A MPRC with decode-and-forward (DF) relays was investigated in [10], where a single best relay was selected opportunistically using a distributed relay selection algorithm that requires only local channel knowledge. It was demonstrated that, in terms of the outage behavior, this opportunistic DF relaying is equivalent to the optimal DF protocol that employs all potential relays. A joint relay selection and cooperative beamforming method was proposed in [11], where the best two out of multiple intermediate relays were selected to forward the received signals through a common channel to the destination. Using two-bit quantized phase information of the channel gains from the two relays respectively to the destination, a full diversity order was achieved while bringing some performance gains. Relay selection schemes that aim at optimizing the outage performance of the MPRC with DF relays were investigated in [12] and [13], with and without a direct link between the source and destination, respectively. In [14], a DF-based cooperative multi-cast system was investigated. With an opportunistic relay selection, a lower bound of the outage probability and the diversity-multiplexing tradeoff were analyzed. In [15], the MPRC with amplify-and-forward (AF) and DF relays were investigated respectively with an interference-limited destination, i.e., there are multiple interferers located near the destination. Then a relay selection scheme was proposed to maximize the mutual information of the network. In [16], a successive relaying protocol was proposed in MPRC on relatively static channels. Within the duration that the channels remain unchanged, two relays are selected to assist the source transmissions alternatively, which enables the source to transmit a new packet in each time slot as in a two-path relay channel [22]. In addition, other relay selection schemes have also been proposed that aim at optimizing the energy efficiency or maximizing the lifetime of the MPRC with limited energy at the relays [19]–[21].

In the above works, with half-duplex (HD) relay terminals, a new source packet can be served only after the current packet is forwarded to the destination by the selected relay, which results in spectrum efficiency loss. In order to exploit the diversity gains of MPRC while improving its spectrum efficiency, multi-path relaying with relay selection has also been applied in bi-directional two-way relay systems [22], [23]. By exploiting the broadcast nature of wireless channels and with network coding performed at the intermediate relays,

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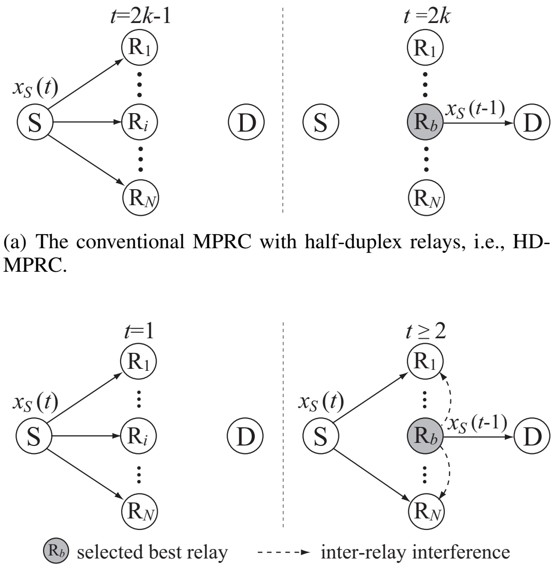


(a) The conventional MPRC with half-duplex relays, i.e., HD-MPRC.

(b) The proposed virtual full-duplex relaying scheme on MPRC, i.e., VFD-MPRC.

Fig. 1. Illustrations of the cooperative multi-path relay channels (MPRC).

it takes only three (or two) time slots for an information exchange between the two end users, thus improving the spectrum efficiency while reserving some diversity gains [24]–[26]. In addition, virtual full-duplex (FD) relaying schemes with buffer equipped at the relay were investigated in [27]–[32] to recover the spectrum efficiency loss caused by half-duplex relaying. With a joint design of buffer-aided relay selection and beamforming, the source and the selected relay simultaneously transmit their information to another relay and the destination, thus delivering a new packet to the destination in each time slot. On the other hand, in order to improve the performance of the conventional full-duplex relay system that is limited by the residual self-interference, a hybrid full-duplex/half-duplex relaying scheme was proposed in [33].

A close look at the MPRC shown in Fig. 1(a) indicates that both the source S and all relays except the selected relay stay idle every other time slot. A question arises naturally as to whether it is possible for S to also transmit during the relay transmission, as in [27]–[35]? With this observation in mind, we propose a virtual full-duplex relaying scheme on MPRC (VFD-MPRC) by exploiting half-duplex relays that are equipped with only a single antenna, as shown in Fig. 1(b). Among the relays that successfully decode the current source packet, a single best relay in terms of the relay-destination channel is selected to forward the decoded packet to the destination in the subsequent time slot. Concurrently, S transmits a new packet and all rest relays attempt to decode this packet. Then among these available relays that successfully decode the source packet, a single best relay is similarly selected, so on and so forth. If all intermediate relays are regarded as a single "super relay", then the considered MPRC becomes a full-duplex relay system through which a new source packet can be forwarded to the destination in each time slot. The contributions of this paper are summarized as follows.

- Taking into account the effect of inter-relay interference (IRI) that is caused by the simultaneous transmissions from the source and the selected relay, as shown in Fig. 1(b), we use a Markov analytical model [34], [35] to analyze the decoding performance at the relays, where successive interference cancellation (SIC) is performed to decode the desired source packet that is subject to IRI. On this basis, the overall end-to-end outage probability of VFD-MPRC is derived in closed-form expressions.
- The asymptotic performance of VFD-MPRC in the high SNR regime is analyzed. Our results demonstrate that in low rate scenarios, a close-to-full diversity order can be achieved by the proposed approach while significantly recovering the spectrum inefficiency in the conventional HD relay systems. In high rate scenarios, since the desired signal is subject to a comparable IRI, the performance of SIC is limited and the proposed VFD-MPRC experiences an error floor and thus no diversity gain is available.
- Simulation results demonstrate significant performance improvements achieved by the proposed VFD-MPRC over the conventional HD-MPRC in both low and modest SNR regimes, while HD-MPRC brings its advantage into play only in the high SNR regime where a full diversity order is achieved. Furthermore, by comparisons with existing full-duplex relay channels, a comparable performance can be achieved by the proposed approach while with only half-duplex relays.

Although a similar Markov analytical model to [1], [34], [35] is used in this paper, the proposed scheme can be applied to a general MPRC with non-symmetric relay channels, where the data source is able to transmit at an arbitrary target data rate. Furthermore, while [1], [34], [35] investigated the outage performance only, we attempt to also analyze the asymptotic performance of MPRC in the high SNR regime.

The rest of this paper is organized as follows. Section II describes the system model of the proposed VFD-MPRC. A Markov chain analytical model is introduced in Section III, based on which the end-to-end outage performance of VFD-MPRC is analyzed and closed-form expressions are derived in Section IV. Then the asymptotic system performance of VFD-MPRC is analyzed in Section V, where the diversity order and error floor are investigated. Simulation results and comparisons with existing work are presented in Section VI. Finally, Section VII concludes the paper.

II. System model and protocol description

As shown in Fig. 1(b), we consider a cooperative MPRC where a data source S communicates with its corresponding destination D with the assistance of N HD relays R_1, R_2, $\cdots$, R_N. Since there is a large distance between S and D, the direct link from S→D is so weak that can be neglected. We let $h_{s,i}$, $h_{i,d}$ and $h_{i,j}$ denote the channel coefficients from S→R_i, R_i→D and R_i→R_j respectively, where $i,j \in \mathcal{I} = \{1,2,\cdots,N\}$ and $i \neq j$. All terminals are assumed to operate in half-duplex mode and the channels remain static within a time slot but change independently from slot to slot following a circularly symmetric complex Gaussian distribution, i.e.,

$h_{u,v} \sim \mathcal{CN}(0, \delta_{u,v}^{-1})$ where $u \in \{s, \mathcal{I}\}$, $v \in \{\mathcal{I}, d\}$ and $u \neq v$. Then we have the corresponding channel power gain $\gamma_{u,v} = |h_{u,v}|^2 \sim \exp(\delta_{u,v})$ [36].

We define $x_S(t)$ as the packet originated at S in time slot t, which is transmitted with a pre-defined target data rate R_0 bits/slot/Hz. The transmission powers at S and R_i are defined as P_S and P_i respectively where $P_i = P_R \ \forall \ i \in \mathcal{I}$. The additive white Gaussian noise is defined as n_r where $r \in \{\mathcal{I}, d\}$, which is of zero mean and with unit variance.

In the considered VFD-MPRC, a data packet $x_S(t)$ is transmitted from S in each time slot t and all available relays attempt to decode this packet, as illustrated in Fig. 1(b). For ease of exposition, we define an index set $\mathcal{I}_d$ that contains all relays that successfully decode $x_S(t)$, where $\mathcal{I}_d \subseteq \mathcal{I}$. If $\mathcal{I}_d \neq \emptyset$, then a single best relay is selected from $\mathcal{I}_d$ to help forward $x_S(t)$ to the destination in the subsequent time slot $t+1$. Otherwise if $\mathcal{I}_d = \emptyset$, then $x_S(t)$ is discarded and an outage is declared. Without losing generality, we consider a data frame that consists of $L+1$ time slots. Detailed transmission process is discussed in the following.

1) In the initial time slot $t = 1$, S transmits a packet $x_S(1)$ and the corresponding received signal at R_i where $i \in \mathcal{I}$ is given as

$$y_i(1) = h_{s,i}\sqrt{P_S}x_S(1) + n_i(1). \tag{1}$$

All N relays attempts to decode this packet and the indices of the relays that correctly decode $x_S(1)$ are classified into $\mathcal{I}_d$. We assume that the channels are reciprocal. To facilitate relay selection, D sends back a clear-to-send (CTS) message at the end of each time slot. Upon receiving the CTS message, each relay R_i, $i \in \mathcal{I}_d$ runs a countdown timer, the initial value of which is inversely proportional to the estimated channel quality of the feedback channel from D. Then the best relay R_b in terms of the instantaneous relay-destination channel condition, i.e.,

$$b = \arg\max_{i \in \mathcal{I}_d}\{|h_{i,d}|^2\} = \arg\max_{i \in \mathcal{I}_d}\{\gamma_{i,d}\}, \tag{2}$$

is automatically selected in a distributed manner [10].

2) In the subsequent time slot $t = 2$, R_b proceeds to forward the decoded packet $x_S(1)$ and S transmits a new packet $x_S(2)$ simultaneously. Then the corresponding received signal at R_i where $i \in \mathcal{I} \setminus b$ and D is given as

$$\begin{aligned} y_i(2) &= h_{s,i}\sqrt{P_S}x_S(2) \\ &+ h_{b,i}\sqrt{P_R}x_S(1) + n_i(2), \qquad (3) \\ y_d(2) &= h_{b,d}\sqrt{P_R}x_S(1) + n_d(2). \qquad (4) \end{aligned}$$

If however $\mathcal{I}_d = \emptyset$, then $x_S(1)$ is discarded and an outage is declared. Then the corresponding received signal at R_i, for $i \in \mathcal{I}$, in slot $t = 2$ is given as

$$y_i(2) = h_{s,i}\sqrt{P_S}x_S(2) + n_i(2). \tag{5}$$

3) The above steps repeat that in time slot t, if $x_S(t)$ is successfully decoded by at least one relay, then a single best relay R_b is selected from $\mathcal{I}_d$ to forward $x_S(t)$ in the subsequent time slot $t+1$. Then the corresponding received signals at R_i where $i \in \mathcal{I} \setminus b$ and D are given as

$$\begin{aligned} y_i(t+1) &= h_{s,i}\sqrt{P_S}x_S(t+1) \\ &+ h_{b,i}\sqrt{P_R}x_S(t) + n_i(t+1), \qquad (6) \\ y_d(t+1) &= h_{b,d}\sqrt{P_R}x_S(t) + n_d(t+1), \qquad (7) \end{aligned}$$

respectively. All the remaining $N-1$ relays attempt to decode $x_S(t+1)$ that is subject to an IRI from $x_S(t)$ using successive interference cancellation (SIC) [37], and D attempts to recover $x_S(t)$ from $y_d(t+1)$. If however, none of the relays can decode $x_S(t)$, then $x_S(t)$ is simply discarded and an outage is declared. Thus the corresponding received signal at relay R_i where $i \in \mathcal{I}$ in time slot $t+1$ is given as

$$y_i(t+1) = h_{s,i}\sqrt{P_S}x_S(t+1) + n_i(t+1), \tag{8}$$

and all N relays attempt to decode $x_S(t+1)$ without IRI.

4) In the second last time slot $t = L$, similarly if $x_S(L)$ is successfully decoded by at least one relay, a single best relay R_b is selected to forward $x_S(L)$ in the last time slot $L+1$, whereas S holds its transmission until a new frame starts. Then the corresponding received signal at D is given as

$$y_d(L+1) = h_{b,d}\sqrt{P_R}x_S(L) + n_d(L+1). \tag{9}$$

If however, none of the relays can decode $x_S(L)$, then an outage is declared.

Remark 1: For the implementation of SIC at the intermediate relay R_i [37], only channel state information (CSI) of the two incoming channels S→R_i and R_b →R_i is required at the receiver side R_i. This can be obtained through typical channel estimation schemes by using training/pilot sequences [38], [39]. On the other hand, for the implementation of relay selection, assuming that the channels are reciprocal [10], the CSI of channel D→R_i is required at the receiver side R_i only. Compared to existing schemes, e.g. [17] that requires global CSI, our scheme requires only local CSI at the receiver side and can be implemented with relatively small overhead.

III. A Markov Chain Analytic Model

According to the decoding results at the relays, we define two states H_0 and H_1 at the end of each time slot t, where $t \in \{1, 2, \cdots, L\}$. H_1 denotes the state that $x_S(t)$ is successfully decoded by at least one relay, i.e., $\mathcal{I}_d \neq \emptyset$, and H_0 denotes the complementary state that $\mathcal{I}_d = \emptyset$. If the relays are known to be in state H_1 (or H_0) in a certain time slot, then the corresponding outage probability of the destination can be easily analyzed. However, for a data frame that consists of multiple time slots, without knowing the exact system state in each time slot, it is intractable to analyze the overall average outage probability of the destination using conventional methods.

From the protocol description in Section II, conditioned on state H_1 in time slot t, a best relay R_b is selected from $\mathcal{I}_d$ to forward the decoded packet $x_S(t)$ to D in the subsequent time slot $t+1$. This brings an IRI to the remaining $N-1$ relays that attempt to decode the new source packet $x_S(t+1)$ transmitted in time slot $t+1$. Conversely, conditioned on state H_0 in time slot t, $x_S(t)$ is simply discarded and all N relays attempt to decode the new packet $x_S(t+1)$ without IRI in time slot $t+1$. Thus, if the system is in state H_1 (or H_0) in time slot t, then the relays will (or will not) suffer from the IRI in time slot $t+1$, which leads to quite different decoding results of the new packet $x_S(t+1)$. That is to say, whether $x_S(t+1)$ can be decoded and forwarded to the destination depends on whether $x_S(t)$ has been decoded and forwarded. This results in a dependence of the state in time slot $t+1$ on the state in time slot t.

Since this one-slot memory coincides with the property of a Markov chain in which the probability distribution of the next state depends only on the current state and not on the sequence of events that preceded it, we use a two-state Markov chain to describe the state transitions between H_0 and H_1 in successive time slots. For ease of description, we define π_0 and π_1 as the steady-state probabilities of H_0 and H_1 respectively in the long term, and let P_{00}, P_{01}, P_{10} and P_{11} be the corresponding state-transition probabilities.

Then exploiting the properties of Markov chain [36], the stationary distribution of the system can be derived as

$$\begin{aligned} \boldsymbol{\pi}\boldsymbol{P} &= \boldsymbol{\pi}, &(10)\\ \pi_0+\pi_1 &= 1, &(11)\end{aligned}$$

where $\boldsymbol{\pi}=[\pi_0 \;\; \pi_1]$ denotes the steady-state probability vector and $\boldsymbol{P}=\begin{bmatrix} P_{00} & P_{01}\\ P_{10} & P_{11}\end{bmatrix}$ denotes the transition probability matrix. From (10) and (11), $\boldsymbol{\pi}$ can be obtained as

$$\boldsymbol{\pi}=\left[\begin{array}{cc}\frac{P_{10}}{P_{10}+P_{01}} & \frac{P_{01}}{P_{10}+P_{01}}\end{array}\right]. \tag{12}$$

Remark 2: From the above analysis, the steady-state probabilities π_1 and π_0 characterize the decoding performance at the relays. To be specific, out of L packets transmitted from S where L is a large finite value, $\pi_1 L$ packets are successfully decoded and relayed to the destination on average, whereas the remaining $\pi_0 L$ source packets fail to be decoded by the relays and are simply discarded. Thus π_0 characterizes the outage probability at the relays.

IV. Outage Performance Analysis

Based on the Markov chain analytical model described in Section III, in this section we first analyze the state-transition probabilities P_{00}, P_{01}, P_{10} and P_{11} respectively, through which the outage performance at the relays can be characterized. Then we proceed to analyze the outage performance at the destination, such that the end-to-end outage probability of the proposed VFD-MPRC can be obtained.

A. Outage Performance at the Relays

Without losing generality, we consider a time slot t and analyze the state transitions from time slot t to $t+1$. Then according to the decoding results of $x_S(t)$ at the relays in time slot t, i.e., H_0 and H_1, we have the following cases.

1) Conditioned on state H_0 in time slot t: No IRI exists in time slot $t+1$, in which all N relays attempt to decode the new source packet $x_S(t+1)$. From (8), with target rate R_0, the probability that $x_S(t+1)$ is successfully decoded by R_i where $i\in\mathcal{I}$ is given as

$$\begin{aligned} P_{01}^i &= \Pr\left\{\log_2\left(1+\gamma_{s,i}P_S\right)\geq R_0\right\}\\ &= \Pr\left\{\gamma_{s,i}\geq\frac{\gamma_0}{P_S}\right\}=e^{-\frac{\delta_{s,i}\gamma_0}{P_S}}, \end{aligned}\tag{13}$$

where $\gamma_0=2^{R_0}-1$. Since L data packets are transmitted from S to D during $L+1$ time slots, there is a pre-log factor of $\frac{L}{L+1}$. For simplicity of expressions, we consider a large but finite L such that $\frac{L}{L+1}\to 1$.

Thus conditioned on H_0, the corresponding state-transition probabilities P_{00} and P_{01} can be respectively obtained as

$$\begin{aligned} P_{00} &= \prod_{i\in\mathcal{I}}\left(1-P_{01}^i\right)=\prod_{i\in\mathcal{I}}\left(1-e^{-\frac{\delta_{s,i}\gamma_0}{P_S}}\right), &(14)\\ P_{01} &= 1-P_{00}. &(15)\end{aligned}$$

2) Conditioned on state H_1 in time slot t: IRI exists in time slot $t+1$, in which R_b forwards $x_S(t)$ to D and S transmits $x_S(t+1)$ to the rest $N-1$ relays simultaneously. From (6), SIC [37] is performed at each relay R_i, $i\in\mathcal{I}\setminus b$ to decode $x_S(t+1)$ that is subject to an IRI of $x_S(t)$.

If the received power level of $x_S(t+1)$ is higher than that of $x_S(t)$, then R_i attempts to decode the desired signal $x_S(t+1)$ directly and the IRI component of $x_S(t)$ is simply considered as noise. Then $x_S(t+1)$ can be successfully decoded if the following event

$$\begin{aligned} \mathcal{E}_{1,t+1}^i &= \left\{\log_2\left(1+\frac{\gamma_{s,i}P_S}{\gamma_{b,i}P_R+1}\right)\geq R_0\right\}\\ &= \left\{\gamma_{s,i}\geq\frac{P_R\gamma_0}{P_S}\gamma_{b,i}+\frac{\gamma_0}{P_S}\right\} \end{aligned}\tag{16}$$

occurs. On the contrary, if the received power level of $x_S(t)$ is higher than that of $x_S(t+1)$, considering the component of $x_S(t+1)$ as noise, $x_S(t)$ can be firstly decoded if

$$\begin{aligned} \mathcal{E}_{1,t}^i &= \left\{\log_2\left(1+\frac{\gamma_{b,i}P_R}{\gamma_{s,i}P_S+1}\right)\geq R_0\right\}\\ &= \left\{\gamma_{s,i}\leq\frac{P_R}{P_S\gamma_0}\gamma_{b,i}-\frac{1}{P_S}\right\} \end{aligned}\tag{17}$$

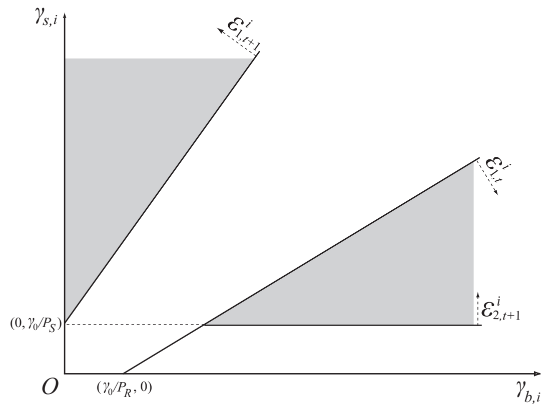
occurs. Then the IRI component of $x_S(t)$ can be perfectly reconstructed and removed from $y_i(t+1)$ and the desired signal $x_S(t+1)$ can be successively decoded if event

$$\mathcal{E}_{2,t+1}^i=\left\{\log_2\left(1+\gamma_{s,i}P_S\right)\geq R_0\right\}=\left\{\gamma_{s,i}\geq\frac{\gamma_0}{P_S}\right\} \tag{18}$$

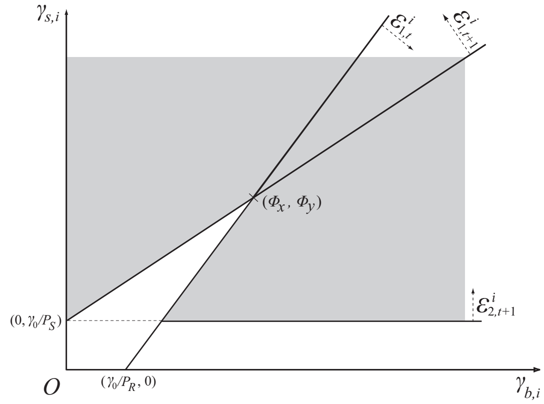
occurs. From (16)–(18), subject to the IRI of $x_S(t)$ from R_b, the probability that $x_S(t+1)$ is successfully decoded by R_i where $i\in\mathcal{I}\setminus b$ by using SIC is thus given as

$$P_{11}^i=\Pr\left\{\mathcal{E}_{1,t+1}^i\cup\left(\mathcal{E}_{1,t}^i\cap\mathcal{E}_{2,t+1}^i\right)\right\}. \tag{19}$$

In (16)–(18), each event is defined by a function of two independent random variables $\gamma_{b,i}$ and $\gamma_{s,i}$, whose joint probability density function (PDF) is $f(\gamma_{b,i},\gamma_{s,i})=$



(a) When $R_0 \geq 1$.



(b) When $R_0 < 1$.

Fig. 2. A graphical representation of the events that $x_S(t+1)$, which is subject to the IRI of $x_S(t)$, is successfully decoded by R_i using SIC.

$\delta_{b,i}\delta_{s,i}e^{-\delta_{b,i}\gamma_{b,i}-\delta_{s,i}\gamma_{s,i}}$. For a better illustration, we draw a 2-dimensional graph with respect to $\gamma_{b,i}$ and $\gamma_{s,i}$, in which the events defined in (16)–(18) are represented by their respective regions. As shown in Fig. 2, the events of successfully decoding $x_S(t+1)$ are represented by the shaded regions.

When $R_0 \geq 1$, as shown in Fig. 2(a), P^i_{11} can be derived by integrating over the shaded regions as

$$\begin{aligned}
&\overbrace{\int_0^\infty \int_{\frac{P_R\gamma_0}{P_S}\gamma_{b,i}+\frac{\gamma_0}{P_S}}^{\infty} f(\gamma_{b,i},\gamma_{s,i})d\gamma_{s,i}d\gamma_{b,i}}^{\Pr\left\{\mathcal{E}^i_{1,t+1}\right\}} \\
&+\overbrace{\int_{\frac{\gamma_0(\gamma_0+1)}{P_R}}^{\infty} \int_{\frac{\gamma_0}{P_S}}^{\frac{P_R}{P_S\gamma_0}\gamma_{b,i}-\frac{1}{P_S}} f(\gamma_{b,i},\gamma_{s,i})d\gamma_{s,i}d\gamma_{b,i}}^{\Pr\left\{\mathcal{E}^i_{1,t}\cap\mathcal{E}^i_{2,t+1}\right\}} \\
&=\frac{\delta_{b,i}P_S e^{-\frac{\delta_{s,i}\gamma_0}{P_S}}}{\delta_{b,i}P_S+\delta_{s,i}P_R\gamma_0}+\frac{\delta_{s,i}P_R e^{-\left[\frac{\delta_{b,i}\gamma_0(1+\gamma_0)}{P_R}+\frac{\delta_{s,i}\gamma_0}{P_S}\right]}}{\delta_{s,i}P_R+\delta_{b,i}P_S\gamma_0}. \quad (20)
\end{aligned}$$

Similarly, when $R_0 < 1$, P^i_{11} can be derived by integrating over the shaded regions in Fig. 2(b) as

$$\begin{aligned}
&\Pr\left\{\mathcal{E}^i_{1,t+1}\right\}+\Pr\left\{\mathcal{E}^i_{1,t}\cap\mathcal{E}^i_{2,t+1}\right\} \\
&\overbrace{-\int_{\phi_x}^{\infty}\int_{\frac{P_R\gamma_0}{P_S}\gamma_{b,i}+\frac{\gamma_0}{P_S}}^{\frac{P_R}{P_S\gamma_0}\gamma_{b,i}-\frac{1}{P_S}} f(\gamma_{b,i},\gamma_{s,i})d\gamma_{s,i}d\gamma_{b,i}}^{\Pr\left\{\mathcal{E}^i_{1,t+1}\cap\left(\mathcal{E}^i_{1,t}\cap\mathcal{E}^i_{2,t+1}\right)\right\}} \\
&=\frac{\delta_{b,i}P_S e^{-\frac{\delta_{s,i}\gamma_0}{P_S}}}{\delta_{b,i}P_S+\delta_{s,i}P_R\gamma_0}+\frac{\delta_{s,i}P_R e^{-\left[\frac{\delta_{b,i}\gamma_0(1+\gamma_0)}{P_R}+\frac{\delta_{s,i}\gamma_0}{P_S}\right]}}{\delta_{s,i}P_R+\delta_{b,i}P_S\gamma_0} \\
&-\left(\frac{\delta_{b,i}P_S}{\delta_{b,i}P_S+\delta_{s,i}P_R\gamma_0}-\frac{\delta_{b,i}P_S\gamma_0}{\delta_{b,i}P_S\gamma_0+\delta_{s,i}P_R}\right) \\
&\cdot e^{-\left[\frac{\delta_{s,i}\gamma_0}{P_S(1-\gamma_0)}+\frac{\delta_{b,i}\gamma_0}{P_R(1-\gamma_0)}\right]}, \quad (21)
\end{aligned}$$

where $(\phi_x, \phi_y) = \left(\frac{\gamma_0}{P_R(1-\gamma_0)}, \frac{\gamma_0}{P_S(1-\gamma_0)}\right)$ denotes the intersection point as shown in Fig. 2(b).

Thus conditioned on H_1 that a best relay R_b, $b \in \mathcal{I}$ is selected, the corresponding state-transition probabilities P_{10} and P_{11} can be respectively derived as

$$P_{10} = \sum_{j=1}^{N}\left[\Pr\{b=j\}\prod_{i\in\{\mathcal{I}\backslash j\}}\left(1-P^i_{11}\right)\right], \quad (22)$$

$$P_{11} = 1-P_{10}, \quad (23)$$

where $\Pr\{b=j\}$ denotes the probability that relay R_j, $j \in \mathcal{I}$ has successfully decoded the source packet $x_S(t)$ in slot t and is selected to forward $x_S(t)$ in slot $t+1$. For ease of analysis, we define $\mathcal{P}(\mathcal{I})$ as the power set of $\mathcal{I}$, which contains all subsets of $\mathcal{I}$ including $\mathcal{I}$ itself but excluding the empty set, and define $\mathcal{P}^j(\mathcal{I})$ as the set of all subsets of $\mathcal{I}$ that contains j. Then we have $\Pr\{b=j\}$ as (24), where (24a) denotes the probability that conditioned on state H_0 in slot $t-1$, all N relays attempted to decode $x_S(t)$ in time slot t, among which R_j is selected to forward $x_S(t)$ in slot $t+1$. (24b) denotes the probability that conditioned on state H_1 in slot $t-1$, a relay R_k was selected to forward $x_S(t-1)$ in slot t, meanwhile the rest $N-1$ relays attempted to decode $x_S(t)$, among which a relay R_j is selected to forward $x_S(t)$ in slot $t+1$.

B. Outage Performance at the Destination

We consider a steady-state time slot $t \in \{2, 3, \cdots, L\}$ in which the system is in either state H_0 or H_1. The corresponding outage performance at D is analyzed in the following.

1) Conditioned on State H_0: None of the relays decode the current source packet $x_S(t)$. Then $x_S(t)$ is discarded and an outage is declared, the corresponding outage probability at D is $P^0_{out} = 1$.

2) Conditioned on State H_1: At least one relay successfully decodes the source packet $x_S(t)$, from which a single best relay R_b is selected to forward $x_S(t)$ to D. Depending on whether the state H_1 in slot t was transferred from state H_0 or H_1 in slot $t-1$, we have the following cases.

- In the case of transferring from state H_0 in time slot $t-1$: none of the relays decoded the previous source packet $x_S(t-1)$ in time slot $t-1$, and thus all N relays attempt to decode the source packet $x_S(t)$ in the current time

$$\Pr\{b=j\} = \overbrace{\sum_{\mathcal{I}_d\subseteq\mathcal{P}^j(\mathcal{I})}\left[\pi_0\prod_{i\in\mathcal{I}_d}P_{01}^i\prod_{i\in\{\mathcal{I}\setminus\mathcal{I}_d\}}(1-P_{01}^i)\prod_{i\in\{\mathcal{I}_d\setminus j\}}\Pr\{\gamma_{j,d}\geq\gamma_{i,d}\}\right]}^{\text{conditioned on state } H_0 \text{ in slot } t-1} \tag{24a}$$

$$+ \overbrace{\sum_{k\in\mathcal{I},k\neq j}\Pr\{b=k\}\sum_{\mathcal{I}_d\subseteq\mathcal{P}^j(\mathcal{I}\setminus k)}\left[\prod_{i\in\mathcal{I}_d}P_{11}^i\prod_{i\in\{\mathcal{I}\setminus\{\mathcal{I}_d\cup k\}\}}(1-P_{11}^i)\prod_{i\in\{\mathcal{I}_d\setminus j\}}\Pr\{\gamma_{j,d}\geq\gamma_{i,d}\}\right]}^{\text{conditioned on state } H_1 \text{ in slot } t-1}. \tag{24b}$$

slot. Then we have the corresponding $\mathcal{I}_d \subseteq \mathcal{P}(\mathcal{I})$, among which a best relay R_b will be selected to forward $x_S(t)$ to D in the subsequent time slot $t+1$. The corresponding achievable rate of channel $\mathrm{R}_b \to$D is given as

$$R_{b,d} = \log_2\left(1+\max_{i\in\mathcal{I}_d}\{\gamma_{i,d}\}P_R\right). \tag{25}$$

From (25), the cumulative distribution function (CDF) of $R_{b,d}$ can be derived as

$$F_{R_{b,d}}(z) = \sum_{\mathcal{I}_d\subseteq\mathcal{P}(\mathcal{I})}\left[\pi_0\prod_{i\in\mathcal{I}_d}P_{01}^i \cdot \prod_{i\in\{\mathcal{I}\setminus\mathcal{I}_d\}}(1-P_{01}^i)\Pr\{R_{b,d}\leq z\}\right], \tag{26}$$

where

$$\Pr\{R_{b,d}\leq z\} = \Pr\left\{\max_{i\in\mathcal{I}_d}\{\gamma_{i,d}\}P_R\leq 2^z-1\right\} = \prod_{i\in\mathcal{I}_d}\left(1-e^{-\frac{\delta_{i,d}(2^z-1)}{P_R}}\right). \tag{27}$$

Thus transmitting at a target data rate R_0, the corresponding outage probability at D can be derived as

$$P_{out}^{01} = F_{R_{b,d}}(R_0). \tag{28}$$

- In the case of transferring from state H_1 in time slot $t-1$: a best relay R_k, $k\in\mathcal{I}$ was selected to forward the decoded source packet $x_S(t-1)$ and the rest $N-1$ relays attempt to decode the source packet $x_S(t)$ in the current time slot t. Then we have the corresponding $\mathcal{I}_d\subseteq\mathcal{P}(\mathcal{I}\setminus k)$, among which a best relay R_b will be selected to forward $x_S(t)$ to D in the subsequent time slot $t+1$. Then the corresponding CDF of the achievable rate $R_{b,d}$ can be derived as

$$F'_{R_{b,d}}(z) = \sum_{k\in\mathcal{I}}\Pr\{b=k\}\sum_{\mathcal{I}_d\subseteq\mathcal{P}(\mathcal{I}\setminus k)}\left[\prod_{i\in\mathcal{I}_d}P_{11}^i \cdot \prod_{i\in\{\mathcal{I}\setminus\{\mathcal{I}_d\cup k\}\}}(1-P_{11}^i)\prod_{i\in\mathcal{I}_d}\left(1-e^{-\frac{\delta_{i,d}(2^z-1)}{P_R}}\right)\right]. \tag{29}$$

Then with target data rate R_0, the corresponding outage probability at D is given as

$$P_{out}^{11} = F'_{R_{b,d}}(R_0). \tag{30}$$

C. End-to-end Outage Performance

Based on the above analysis, taking into account the possible states H_0 and H_1 in each time slot, the overall end-to-end outage probability of VFD-MPRC can be derived as

$$P_{out} = \overbrace{\pi_0 P_{out}^0}^{\text{conditioned on } H_0} + \overbrace{P_{out}^{01}+P_{out}^{11}}^{\text{conditioned on } H_1}. \tag{31}$$

D. MPRC with Symmetric Relay Channels

Since it is intractable to analytically derive $\Pr\{b=j\}$ from (24a) and (24b), we consider a scenario where the N relays are located close to each other [7], [17] and far away from the source and destination. Then it is reasonable to assume symmetric relay channels where $\delta_{s,i}^{-1}=\delta_{s,r}^{-1}$, $\delta_{i,d}^{-1}=\delta_{r,d}^{-1}$ and $\delta_{i,j}^{-1}=\delta_{r,r}^{-1}$, $\forall\ i,\ j\in\mathcal{I}$ and $i\neq j$. With this symmetric setup, each relay is selected with the same probability on average, i.e., $\Pr\{b=j\}=\frac{1}{N}\ \forall\ j\in\mathcal{I}$, thus we have from (22)

$$P_{10} = \prod_{i\in\{\mathcal{I}\setminus b\}}\left(1-P_{11}^i\right) = \left(1-P_{11}^i\right)^{N-1}. \tag{32}$$

From (14), P_{00} can be rewritten as

$$P_{00} = \prod_{i\in\mathcal{I}}\left(1-e^{-\frac{\delta_{s,i}\gamma_0}{P_S}}\right) = \left(1-e^{-\frac{\delta_{s,r}\gamma_0}{P_S}}\right)^N. \tag{33}$$

Substituting (32) and (33) into (12), we can thus analytically obtain π_0 and π_1.

Similarly, we have from (26)–(28)

$$P_{out}^{01} = \sum_{l=1}^{N}\binom{N}{l}\pi_0\left(P_{01}^i\right)^l\left(1-P_{01}^i\right)^{N-l}\left(1-e^{-\frac{\delta_{r,d}\gamma_0}{P_R}}\right)^l, \tag{34}$$

where $|\mathcal{I}_d|=l$ takes possible values from 1 up to N. From (29) and (30), similarly we have

$$P_{out}^{11} = \sum_{l=1}^{N-1}\binom{N-1}{l}\pi_1\left(P_{11}^i\right)^l\left(1-P_{11}^i\right)^{N-1-l} \cdot \left(1-e^{-\frac{\delta_{r,d}\gamma_0}{P_R}}\right)^l, \tag{35}$$

where $|\mathcal{I}_d|=l$ takes possible values from 1 up to $N-1$.

Substituting (34) and (35) into (31), we can thus analytically obtain P_{out}.

V. Asymptotic Performance Analysis

In the conventional HD-MPRC as shown in Fig. 1(a), the relays transmit and receive signals in orthogonal time slots.

When $P_S \to \infty$, all N intermediate relays can successfully decode the source packet with a probability approaching 1. Since the N source-relay-destination paths are independent with each other, a full diversity order of N can be achieved in the high SNR regime asymptotically [10]. However, in the considered VFD-MPRC as shown in Fig. 1(b), since the performance of the SIC decoding at the relays is limited by IRI whose strength scales with the relay transmission power, the achievable diversity order is not straightforward. Next, we investigate the asymptotic performance of VFD-MPRC in the high SNR regime, the important results are summarized in Theorem 1.

Theorem 1: In the high SNR regime where $P_S, P_R \to \infty$, without loss of generality, we let $\lim_{P_S,P_R\to\infty} \frac{P_S}{P_R} = \tau$ where τ is a finite constant. Then if the data source S transmits at a target data rate $R_0 \leq 1$, a diversity order of $N-1$ can be achieved by the proposed VFD-MPRC in the high SNR regime asymptotically. If however, S transmits at a target data rate $R_0 > 1$, then the proposed VFD-MPRC experiences an error floor in the high SNR regime where no diversity gain is available.

Proof: In order to evaluate the asymptotic performance of VFD-MPRC in the high SNR regime where $P_S, P_R \to \infty$ and $\lim_{P_S,P_R\to\infty} \frac{P_S}{P_R} = \tau$, next we analyze the asymptotic behavior for each of the components in (31).

Definition 1: For ease of analysis, we define an operator $\doteq$ such that for two functions $P_1(\mathrm{SNR})$ and $P_2(\mathrm{SNR})$, if $\lim_{\mathrm{SNR}\to\infty} \frac{\log P_1(\mathrm{SNR})}{\log P_2(\mathrm{SNR})} = 1$, then $P_1(\mathrm{SNR}) \doteq P_1(\mathrm{SNR})$.

Example 1: Following Definition 1, if there exists a probability P such that $-\lim_{\mathrm{SNR}\to\infty} \frac{\log P}{\log \mathrm{SNR}} = \alpha$, then we have $P \doteq \mathrm{SNR}^{-\alpha}$, which means that the probability P has an asymptotic decay rate of α with respect to SNR in the logarithmic scale, or in other words, a diversity order of α [40].

Example 2: Following Definition 1, we let $P_1(\mathrm{SNR}) = 1 - e^{-\frac{1}{\mathrm{SNR}}}$ and $P_2(\mathrm{SNR}) = \frac{1}{\mathrm{SNR}}$. Then from L'Hospital's Rule, we have [42]

$$1 - e^{-\frac{1}{\mathrm{SNR}}} \doteq \frac{1}{\mathrm{SNR}}. \tag{36}$$

A. When $R_0 < 1$

Substituting (21) into (32), we have

$$P_{10} = \left[\frac{\left(\delta_{s,i}\delta_{b,i}P_S P_R + \delta_{b,i}^2 P_S^2 \gamma_0\right)\left(1 - e^{-\frac{\delta_{s,i}\gamma_0}{P_S}}\right)}{\left(\delta_{b,i}P_S + \delta_{s,i}P_R\gamma_0\right)\left(\delta_{b,i}P_S\gamma_0 + \delta_{s,i}P_R\right)} + \frac{\left(\delta_{s,i}\delta_{b,i}P_S P_R + \delta_{s,i}^2 P_R^2 \gamma_0\right)\left(1 - e^{-\left(\frac{\delta_{b,i}\gamma_0(1+\gamma_0)}{P_R} + \frac{\delta_{s,i}\gamma_0}{P_S}\right)}\right)}{\left(\delta_{b,i}P_S + \delta_{s,i}P_R\gamma_0\right)\left(\delta_{b,i}P_S\gamma_0 + \delta_{s,i}P_R\right)} - \frac{\delta_{s,i}\delta_{b,i}P_S P_R(1-\gamma_0^2)\left(1 - e^{-\left[\frac{\delta_{s,i}\gamma_0}{P_S(1-\gamma_0)} + \frac{\delta_{b,i}\gamma_0}{P_R(1-\gamma_0)}\right]}\right)}{\left(\delta_{b,i}P_S + \delta_{s,i}P_R\gamma_0\right)\left(\delta_{b,i}P_S\gamma_0 + \delta_{s,i}P_R\right)} \right]^{N-1}. \tag{37}$$

Using the transformation in (36), we have

$$1 - e^{-\frac{\delta_{s,i}\gamma_0}{P_S}} \doteq \frac{\delta_{s,i}\gamma_0}{P_S} \doteq \frac{1}{P_R}, \tag{38}$$

$$1 - e^{-\left(\frac{\delta_{b,i}\gamma_0(1+\gamma_0)}{P_R} + \frac{\delta_{s,i}\gamma_0}{P_S}\right)} \doteq \frac{\delta_{b,i}\gamma_0(1+\gamma_0)}{P_R} + \frac{\delta_{s,i}\gamma_0}{P_S} \doteq \frac{1}{P_R}, \tag{39}$$

$$1 - e^{-\left[\frac{\delta_{s,i}\gamma_0}{P_S(1-\gamma_0)} + \frac{\delta_{b,i}\gamma_0}{P_R(1-\gamma_0)}\right]} \doteq \frac{\delta_{s,i}\gamma_0}{P_S(1-\gamma_0)} + \frac{\delta_{b,i}\gamma_0}{P_R(1-\gamma_0)} \doteq \frac{1}{P_R}, \tag{40}$$

respectively. Substituting (38)–(40) into (37), we have

$$P_{10} \doteq \left(\frac{1}{P_R}\right)^{N-1}. \tag{41}$$

From (33), similarly we have

$$P_{00} \doteq \left(\frac{\delta_{s,r}}{P_S}\right)^N \doteq \left(\frac{1}{P_R}\right)^N. \tag{42}$$

Since $\pi_0 = \frac{P_{10}}{P_{10}+P_{01}} = \frac{P_{10}}{1+(P_{10}-P_{00})}$ as given in (12), we have

$$\pi_0 \doteq P_{10} \doteq \left(\frac{1}{P_R}\right)^{N-1}. \tag{43}$$

On the other hand, we have from (13)

$$1 - P_{01}^i = 1 - e^{-\frac{\delta_{s,i}\gamma_0}{P_S}} \doteq \frac{\delta_{s,i}\gamma_0}{P_S} \doteq \frac{1}{P_R}. \tag{44}$$

Then substituting (44) into (34), we have

$$P_{out}^{01} = \sum_{l=1}^{N} \binom{N}{l} \pi_0 \left(P_{01}^i\right)^l \left(1 - P_{01}^i\right)^{N-l} \cdot \left(1 - e^{-\frac{\delta_{r,d}\left(2^{R_0}-1\right)}{P_R}}\right)^l \doteq \left(\frac{1}{P_R}\right)^{2N-1}. \tag{45}$$

From (35), similarly we have

$$P_{out}^{11} = \sum_{l=1}^{N-1} \binom{N-1}{l} \pi_1 \left(P_{11}^i\right)^l \left(1 - P_{11}^i\right)^{N-1-l} \cdot \left(1 - e^{-\frac{\delta_{r,d}\left(2^{R_0}-1\right)}{P_R}}\right)^l \doteq \left(\frac{1}{P_R}\right)^{N-1}. \tag{46}$$

Substituting (43), (45) and (46) into (31), we have

$$P_{out} = \pi_0 + P_{out}^{01} + P_{out}^{11} \doteq \left(\frac{1}{P_R}\right)^{N-1}. \tag{47}$$

Thus a diversity order of $N-1$ can be achieved for the proposed VFD-MPRC [40] when $R_0 < 1$ bit/slot/Hz.

$$\lim_{P_S,P_R\to\infty,\frac{P_S}{P_R}=\tau} P_{out}=\frac{\left[\tau\delta_{s,i}\delta_{b,i}\left(\gamma_0^2-1\right)\right]^{N-1}}{\left[\tau\delta_{s,i}\delta_{b,i}\left(\gamma_0^2-1\right)\right]^{N-1}+\left(\tau\delta_{b,i}+\delta_{s,i}\gamma_0\right)^{N-1}\left(\tau\delta_{b,i}\gamma_0+\delta_{s,i}\right)^{N-1}}. \tag{52}$$

$$\lim_{P_S,P_R\to\infty,\frac{P_S}{P_R}=\tau}\pi_0=\lim_{P_S,P_R\to\infty,\frac{P_S}{P_R}=\tau}\frac{P_{10}}{P_{10}+P_{01}}=\frac{\left[\tau\delta_{s,i}\delta_{b,i}\left(\gamma_0^2-1\right)\right]^{N-1}}{\left[\tau\delta_{s,i}\delta_{b,i}\left(\gamma_0^2-1\right)\right]^{N-1}+\left(\tau\delta_{b,i}+\delta_{s,i}\gamma_0\right)^{N-1}\left(\tau\delta_{b,i}\gamma_0+\delta_{s,i}\right)^{N-1}}. \tag{55}$$

B. When $R_0=1$

Substituting (20) into (32), we have

$$P_{10}=\left[\frac{\left(\delta_{s,i}\delta_{b,i}P_SP_R+\delta_{b,i}^2P_S^2\right)\left(1-e^{-\frac{\delta_{s,i}}{P_S}}\right)}{\left(\delta_{b,i}P_S+\delta_{s,i}P_R\right)^2}+\frac{\left(\delta_{s,i}\delta_{b,i}P_SP_R+\delta_{s,i}^2P_R^2\right)\left(1-e^{-\left(\frac{2\delta_{b,i}}{P_R}+\frac{\delta_{s,i}}{P_S}\right)}\right)}{\left(\delta_{b,i}P_S+\delta_{s,i}P_R\right)^2}\right]^{N-1}. \tag{48}$$

From (36), we have

$$1-e^{-\frac{\delta_{s,i}}{P_S}} \doteq \frac{\delta_{s,i}}{P_S}\doteq\frac{1}{P_R}, \tag{49}$$

$$1-e^{-\left(\frac{2\delta_{b,i}}{P_R}+\frac{\delta_{s,i}}{P_S}\right)} \doteq \frac{2\delta_{b,i}}{P_R}+\frac{\delta_{s,i}}{P_S}\doteq\frac{1}{P_R}, \tag{50}$$

respectively. Substituting (49) and (50) into (48), similarly we have

$$P_{10}\doteq\left(\frac{1}{P_R}\right)^{N-1}. \tag{51}$$

Then following the same steps as in (42)–(47), a diversity order of $N-1$ can be achieved by VFD-MPRC when $R_0=1$ bit/slot/Hz.

C. When $R_0>1$

Lemma 1: If the data source S transmits at a target data rate $R_0>1$, then the system of VFD-MPRC experiences an error floor as (52) in the high SNR regime and thus a zero-diversity order is achieved. A simple proof is given in the following.

Substituting (20) into (32), we have

$$\lim_{P_S,P_R\to\infty,\frac{P_S}{P_R}=\tau}P_{10}=\left(\frac{\tau\delta_{s,i}\delta_{b,i}\left(\gamma_0^2-1\right)}{\left(\tau\delta_{b,i}+\delta_{s,i}\gamma_0\right)\left(\tau\delta_{b,i}\gamma_0+\delta_{s,i}\right)}\right)^{N-1}, \tag{53}$$

which approaches to a non-zero value. On the other hand, from (14) and (15), we have

$$\lim_{P_S,P_R\to\infty,\frac{P_S}{P_R}=\tau}P_{01}=1-\lim_{P_S,P_R\to\infty,\frac{P_S}{P_R}=\tau}P_{00}=1. \tag{54}$$

Then from (12) we have (55), which again, approaches to a non-zero value. From (34) and (35), since

$$\lim_{P_R\to\infty}\left(1-e^{-\frac{\delta_{r,d}\left(2^{R_0}-1\right)}{P_R}}\right)^l=0, \tag{56}$$

we have

$$\lim_{P_S,P_R\to\infty,\frac{P_S}{P_R}=\tau}P_{out}^{01} = 0, \tag{57}$$

$$\lim_{P_S,P_R\to\infty,\frac{P_S}{P_R}=\tau}P_{out}^{11} = 0, \tag{58}$$

respectively. Then substituting (55), (57) and (58) into (31), we have

$$\lim_{P_S,P_R\to\infty,\frac{P_S}{P_R}=\tau}P_{out}=\lim_{P_S,P_R\to\infty,\frac{P_S}{P_R}=\tau}\pi_0. \tag{59}$$

Thus Lemma 1 is proved. ■

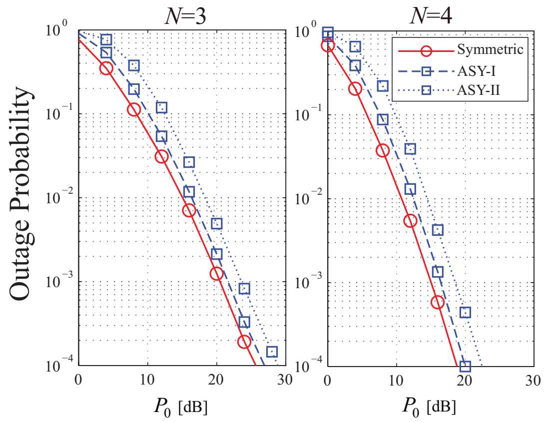
Remark 3: From the above analysis, when $R_0>1$, there exists a non-zero probability π_0 that none of the N relays can successfully decode the source packet in the high SNR regime. This is reasonable due to the existence of IRI. When $P_S,P_R\to\infty$ and $\lim_{P_S,P_R\to\infty}\frac{P_S}{P_R}=\tau$, the power ratio between the two interfering components received at a relay R_i, i.e. $\gamma_{s,i}P_S$ and $\gamma_{b,i}P_R$ as given in (16) and (17), is limited to a finite value. Then the performance of the SIC decoding at the relays is limited and there always exists a non-zero probability that a relay R_i, which is subject to IRI, fails to decode the source packet. In contrast, when $R_0\le1$, even subject to the IRI, the source packet can be successfully decoded by a relay R_i with a probability approaching 1 asymptotically, thus bringing diversity gains.

Lemma 2: From (55) and (59), it is observed that the error floor increases monotonically with $\lim_{P_S,P_R\to\infty,\frac{P_S}{P_R}=\tau}P_{10}$. Thus in order to lower the error floor, the probability

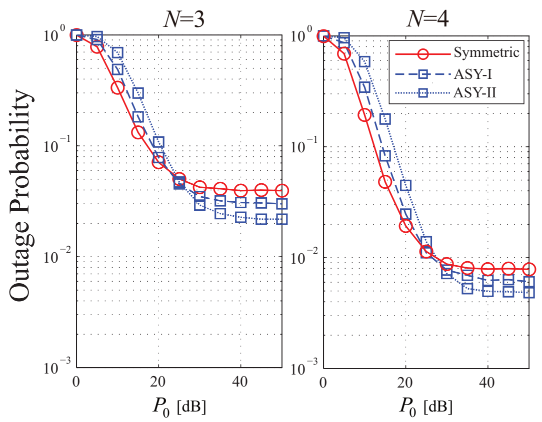
$$\begin{aligned}&\lim_{P_S,P_R\to\infty,\frac{P_S}{P_R}=\tau}P_{10}\\&=\left(\frac{\tau\delta_{s,i}\delta_{b,i}\left(\gamma_0^2-1\right)}{\left(\tau\delta_{b,i}+\delta_{s,i}\gamma_0\right)\left(\tau\delta_{b,i}\gamma_0+\delta_{s,i}\right)}\right)^{N-1}\\&=\left(\frac{\gamma_0^2-1}{\gamma_0^2+\left(\frac{\tau\delta_{b,i}}{\delta_{s,i}}+\frac{\delta_{s,i}}{\tau\delta_{b,i}}\right)\gamma_0+1}\right)^{N-1}\end{aligned} \tag{60}$$

should be kept as small as possible. Then from (60), the error floor can be abated as follows.

- Since $\frac{\gamma_0^2-1}{\gamma_0^2+\left(\frac{\tau\delta_{b,i}}{\delta_{s,i}}+\frac{\delta_{s,i}}{\tau\delta_{b,i}}\right)\gamma_0+1}<1$, $\lim_{P_S,P_R\to\infty,\frac{P_S}{P_R}=\tau}P_{10}$ can be reduced with a greater N. In other words, a lower error floor can be achieved with more available relays;
- Since $\tau\delta_{b,i},\delta_{s,i}>0$ and $\left(\frac{\tau\delta_{b,i}}{\delta_{s,i}}+\frac{\delta_{s,i}}{\tau\delta_{b,i}}\right)=2$ when $\tau\delta_{b,i}=\delta_{s,i}$, then in order to reduce $\lim_{P_S,P_R\to\infty,\frac{P_S}{P_R}=\tau}P_{10}$, the difference between $\tau\delta_{b,i}$ and



(a) When $R_0 = 1$ bit/slot/Hz.



(b) When $R_0 = 2$ bits/slot/Hz.

Fig. 3. Outage probabilities of VFD-MPRC under symmetric and asymmetric relay channels.

$\delta_{s,i}$ should be kept as big as possible, e.g., $\tau\delta_{b,i} \gg \delta_{s,i}$ or $\tau\delta_{b,i} \ll \delta_{s,i}$. In other words, a lower error floor can be achieved if the SIC decoding at the relays is facilitated;

- A lower error floor can be achieved with a smaller target data rate R_0.

VI. Simulation Results

In this section, we demonstrate the performance of the proposed VFD-MPRC. Firstly, we evaluate the performance of VFD-MPRC with symmetric and asymmetric relay channels. For the symmetric case, we assume that the relays are located close to each other at the middle of S and D, where $\delta_{s,i}^{-1} = \delta_{s,r}^{-1} = 0$ dB and $\delta_{i,d}^{-1} = \delta_{r,d}^{-1} = 0$ dB $\forall\ i \in \mathcal{I}$. For the asymmetric case, for ease of illustration, we consider a toy example where each relay R_i moves along the direct line between S and D subject to a constraint $\delta_{s,i}^{-1}$[dB]+$\delta_{i,d}^{-1}$[dB]= 0 dB $\forall\ i \in \mathcal{I}$. To isolate the effects of other parameters, we let $P_S = P_R = P_0$ and $\delta_{i,j}^{-1} = \delta_{r,r}^{-1} = 10$ dB $\forall\ i,\ j \in \mathcal{I},\ i \neq j$.

In Fig. 3, the outage performance of two asymmetric cases, denoted by ASY-I and ASY-II, are simulated and compared to that of the symmetric case. When there are $N = 3$ relays, we have $[\delta_{s,1}^{-1}, \delta_{s,2}^{-1}, \delta_{s,3}^{-1}] = [5, -2, -5]$ dB and $[\delta_{s,1}^{-1}, \delta_{s,2}^{-1}, \delta_{s,3}^{-1}] = [8, -4, -8]$ dB for ASY-I and ASY-II respectively. When there are $N = 4$ relays, we have $[\delta_{s,1}^{-1}, \delta_{s,2}^{-1}, \delta_{s,3}^{-1}, \delta_{s,4}^{-1}] = [5, 3, -3, -5]$ dB and $[\delta_{s,1}^{-1}, \delta_{s,2}^{-1}, \delta_{s,3}^{-1}, \delta_{s,4}^{-1}] = [8, 5, -5, -8]$ dB for ASY-I and ASY-II respectively. That is, ASY-II is more asymmetric compared to ASY-I.

In Fig. 3(a), the outage probabilities are demonstrated when $R_0 = 1$ bit/slot/Hz. It is observed that the same diversity order of $N-1$ is achieved by both symmetric and asymmetric cases. While the symmetric case achieves the best performance, a worse performance is achieved for more asymmetric relay channels. A possible reason is that for those relays with asymmetric relay channels, if it has a stronger source-relay link, then its corresponding relay-destination link is relatively weak. Conversely, if it has a stronger relay-destination link, then the corresponding source-relay link is relatively weak. Whereas for the symmetric case, no such limit exists.

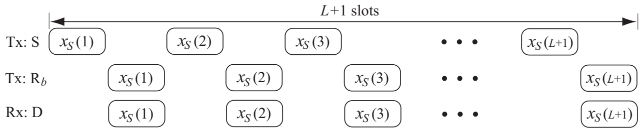
For better illustrations, the outage probabilities when $R_0 = 2$ bits/slot/Hz are also demonstrated in Fig. 3(b). In the low P_0 regime, it is observed that the symmetric case outperforms the asymmetric cases. This is reasonable as for those relays with asymmetric relay channels, a bottleneck exists either in the first hop or in the second hop. Whereas for the symmetric case where each relay has comparable source-relay and relay-destination links on average, there is a better chance that the source packet is successfully delivered to the destination. In the high P_0 regime, conversely, a better performance is achieved by the more asymmetric case. This is reasonable due to the employment of SIC decoding in dealing with the IRI. With asymmetric relay channels, potentially there exists a more significant power difference between the desired signal and the IRI received at the relays. This is able to facilitate the SIC decoding and result in a lower π_0, thus touching a lower error floor as given in (59).

A. Benchmark Cases

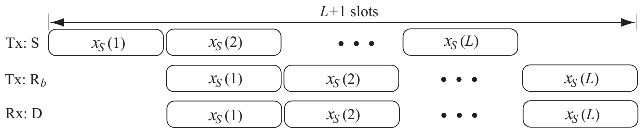
Next, we focus on the MPRC with symmetric relay channels and evaluate its performance in comparisons with the following two benchmark cases.

- HD-MPRC: a cooperative MPRC with N half-duplex relays, as shown in Fig. 1(a). For fair comparisons, the first half of a time slot is used for source transmission and the second half is used for relay transmission, as illustrated in Fig. 4(a);
- FD-MPRC: a cooperative MPRC with N full-duplex relays that are able to receive and transmit signals simultaneously with one slot processing delay. Similar to VFD-MPRC, an entire time slot is used for simultaneous source and relay transmissions, as illustrated in Fig. 4(b).

For the benchmark case of FD-MPRC, two antennas are deployed at each intermediate relay R_i, $i \in \mathcal{I}$ for simultaneous transmission and reception, respectively. Then there exists a self-loop interference (SI) channel $h_{i,i}$ from the transmit antenna to the receive antenna of R_i [41]. Although various SI cancellation schemes have been proposed, due to practical imperfection, there always exists a non-negligible component of residual SI. Besides this intrinsic residual SI, for FD-MPRC we use the same setup as that in the proposed VFD-MPRC. Specifically, a best relay R_b is selected to forward the

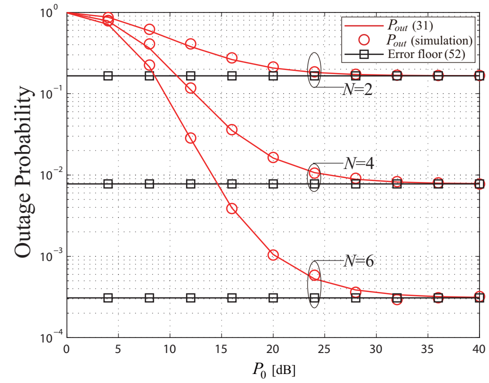


(a) HD-MPRC.

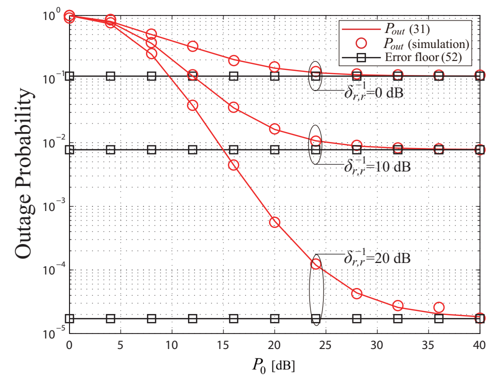


(b) VFD-MPRC.

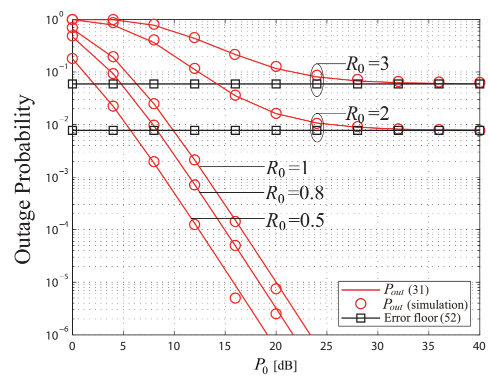
Fig. 4. Transmitted and received signals in a data frame that consists of $L + 1$ time slots.



(a) When $R_0 = 2$ bits/slot/Hz and $N = 2, 4, 6$ respectively.



(b) When $R_0 = 2$ bits/slot/Hz, $N = 4$ and $\delta_{r,r}^{-1} = 0$ dB, 10 dB, 20 dB respectively.



(c) When $N = 4$ and $R_0 = 0.5, 0.8, 1, 2, 3$ bits/slot/Hz respectively.

Fig. 5. Outage probability of VFD-MPRC and the corresponding error floor in the high P_0 regime.

previously received packet $x_S(t-1)$, meanwhile it attempts to decode the currently transmitted source packet $x_S(t)$ that is subject to the residual SI, and the rest $N-1$ relays attempt to decode $x_S(t)$ that is subject to an IRI from R_b. For comparison purposes, the following conditions for the residual SI are considered [42].

- FD-MPRC-I: the effective SI channel $h_{i,i}$ experiences flat fading that changes independently from slot to slot following a circularly symmetric complex Gaussian distribution $\mathcal{CN}(0, \delta_{SI}^{-1})\ \forall\ i \in \mathcal{I}$;
- FD-MPRC-II: there exists a residual SI component of constant power P_{SI} at relay $R_i\ \forall\ i \in \mathcal{I}$, irrespective of the SI channel condition and relay transmission power. This corresponds to an over-optimistic case.
- FD-MPRC-III: the SI component is perfectly cancelled at the full-duplex relays. This corresponds to an ideal case and the corresponding performance provides a performance upper bound.

Unless otherwise specified, in the following we let $\delta_{s,i}^{-1} = \delta_{s,r}^{-1} = 0$ dB, $\delta_{i,d}^{-1} = \delta_{r,d}^{-1} = 0$ dB and $\delta_{i,j}^{-1} = \delta_{r,r}^{-1} = 10$ dB respectively $\forall\ i,\ j \in \mathcal{I}$ and $i \neq j$. As illustrated in Fig. 5–Fig. 8, we use lines to denote the analytical results derived in this paper and use markers to denote the Monte Carlo simulation results.

B. Error Floor and Diversity Order of VFD-MPRC

Firstly, we evaluate the outage performance of the proposed VFD-MPRC. As illustrated in Fig. 5, with an increase in P_0, the outage performance of VFD-MPRC is improved. However, we cannot keep reducing the outage probability by increasing P_0, and an error floor is met in the high P_0 regime. This is consistent with Lemma 1 that due to the existence of IRI that scales with the relay transmission power, the received signal-to-interference-plus-noise ratio (SINR) at each relay is limited to a finite value when $P_S, P_R \to \infty$, as given in (16) and (17). This limits the SIC decoding and there always exists a non-zero probability that a source packet can be decoded by none of the relays.

From Fig. 5(a), with more relays available, a lower error floor can be reached. From Fig. 5(b), a lower error floor can be reached with stronger inter-relay channels through which the SIC decoding at the relays can be facilitated. Furthermore, with a lower target data rate, a lower error floor can be reached, as illustrated in Fig. 5(c). However, when $R_0 \leq 1$, no error floor exists any more and diversity gains can be achieved, as predicted in Theorem 1. This is reasonable as for low rate scenarios, even there exists IRI, the probability that a source packet is successfully decoded by a relay by using SIC approaches 1 asymptotically. In other words, the IRI and SIC decoding may bring a stringent bottleneck to high rate

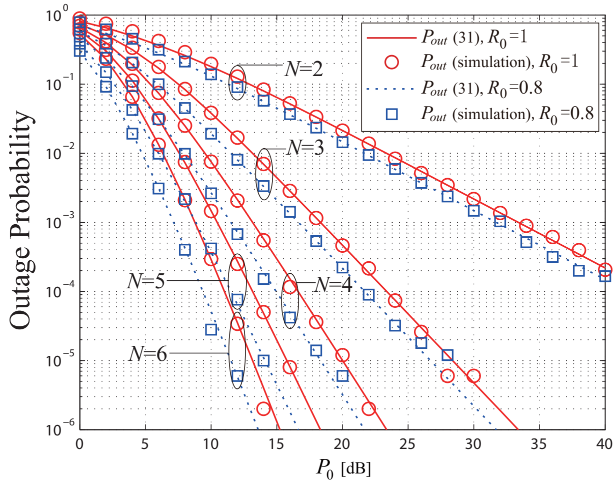
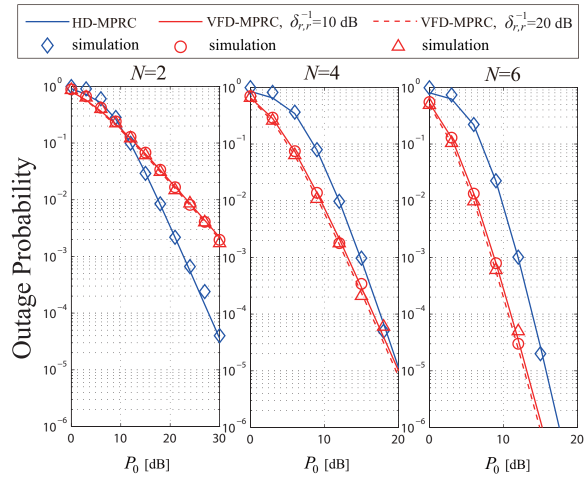
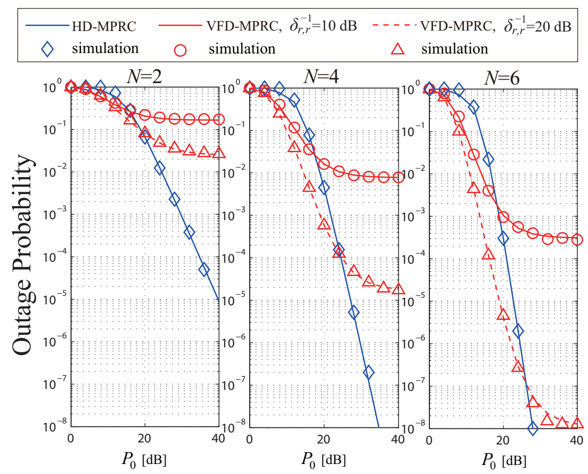


Fig. 6. Outage probability of the proposed VFD-MPRC when $R_0 = 0.8, 1$ bits/slot/Hz and $N = 2, 3, 4, 5, 6$ respectively.



(a) When $R_0 = 1$ bit/slot/Hz.



(b) When $R_0 = 2$ bits/slot/Hz.

Fig. 7. Outage probabilities of VFD-MPRC and HD-MPRC with a group of N intermediate relays.

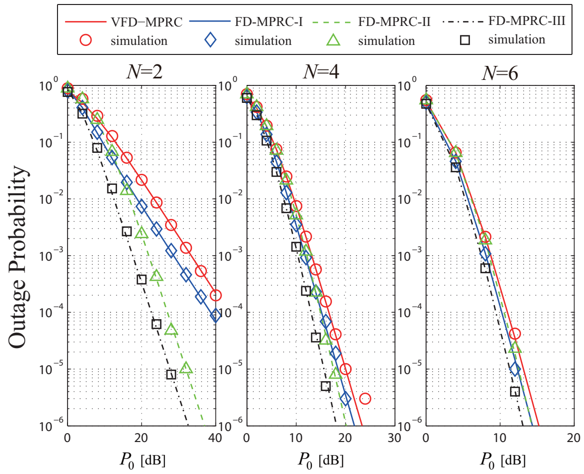
scenarios, e.g., $R_0 > 1$, whereas no such bottleneck exists for low rate scenarios, e.g., $R_0 \leq 1$. The above observations also validate Lemma 2 that although an error floor is inevitable for relatively high rate scenarios, the error floor can be debased by proper parameter designs thus achieving favorable system outage performance.

In order to better illustrate the diversity order of VFD-MPRC when $R_0 \leq 1$, the outage performance with different numbers of relays is demonstrated in Fig. 6 when $R_0 = 0.8, 1$ bits/slot/Hz respectively. It is observed that with more relays available, a higher diversity order can be achieved. To be specific, with N relays, a diversity order of $N-1$ can be achieved asymptotically in the high SNR regime. The reason why full diversity order cannot be achieved is that when the selected best relay R_b forwards the previously received source packet, only the remaining $N-1$ relays attempt to decode the current source packet. Since the source information can be delivered through at most $N-1$ independent paths, a diversity order of $N-1$ is achieved asymptotically [7]. On the other hand, with a lower target rate, i.e., $R_0 = 0.8$ bits/slot/Hz, it is observed that a better outage performance is achieved than the case where $R_0 = 1$ bit/slot/Hz while the same diversity order is achieved.

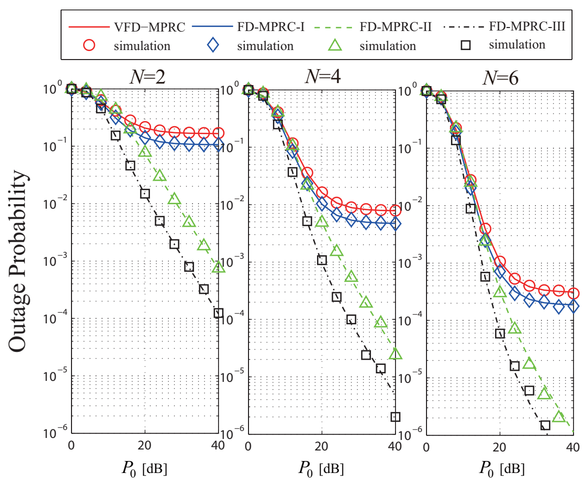
C. VFD-MPRC vs HD-MPRC

Next we compare the outage performance of the proposed VFD-MPRC to that of HD-MPRC in Fig. 7. As illustrated in Fig. 7(a), the outage probabilities are demonstrated when $R_0 = 1$ bit/slot/Hz. When there are $N = 2$ relays, it is observed that VFD-MPRC performs better when $P_0 \leq 10$ dB, whereas HD-MPRC performs better when $P_0 > 10$ dB. This is reasonable as a higher diversity order is achieved for HD-MPRC than VFD-MPRC, thus HD-MPRC performs better in the high P_0 regime where the diversity order dominates the outage performance. With more relays available, e.g., $N = 4, 6$, it is observed that significant performance improvements can be achieved by VFD-MPRC over HD-MPRC in both low and modest P_0 regimes. This is reasonable as although a lower diversity order is achieved by the proposed VFD-MPRC asymptotically, it achieves a pre-log factor approaching 1. Whereas there is a pre-log factor $\frac{1}{2}$ in the conventional HD-MPRC, thus it can bring its advantage into play only in the very high P_0 regime. Then the proposed VFD-MPRC is able to provide a higher achievable rate than that of the HD-MPRC, which results in a lower outage probability in both low and modest SNR regimes. On the other hand, it is observed that with stronger inter-relay channels, i.e., $\delta_{r,r}^{-1} = 20$ dB, since the SIC decoding at relays is facilitated, a slightly better outage performance is achieved for VFD-MPRC.

Fig. 7(b) displays the outage probabilities of VFD-MPRC and HD-MPRC when $R_0 = 2$ bits/slot/Hz. It is observed that while a full diversity order is achieved by HD-MPRC, no diversity gains are available in VFD-MPRC that always experiences an error floor with an increase in P_0. When $N = 2$, the proposed VFD-MPRC outperforms HD-MPRC when $P_0 < 18$ dB. With more relays available, i.e., $N = 4, 6$, performance gains can be achieved by the proposed VFD-MPRC over a wider range of P_0. This again, indicates that the



(a) When $R_0 = 1$ bit/slot/Hz.



(b) When $R_0 = 2$ bits/slot/Hz.

Fig. 8. Outage probabilities of VFD-MPRC and FD-MPRC with a group of N intermediate relays.

proposed VFD-MPREC is able to support a higher achievable rate, thus achieving performance improvements over HD-MPRC in both low and modest P_0 regimes. Whereas in the high P_0 regime, the diversity loss due to the IRI and SIC decoding at the relays severely limits the performance of VFD-MPRC. On the other hand, with stronger inter-relay channels, i.e., $\delta_{r,r}^{-1} = 20$ dB, it is observed that the SIC decoding at relays is facilitated thus significantly improving the outage performance of VFD-MPRC.

D. VFD-MPRC vs FD-MPRC

Next we compare the outage performance of the proposed VFD-MPRC to that of the FD-MPRC with a group of N full-duplex relays in Fig. 8. As illustrated in Fig. 8(a), the outage probabilities are demonstrated when $R_0 = 1$ bit/slot/Hz, and different conditions of the residual SI in FD-MPRC are considered. It is observed that comparable performances are achieved by the proposed VFD-MPRC and FD-MPRC. For FD-MPRC-I, we consider a fading SI channel between the well isolated transmit and receive antennas, e.g., $\delta_{SI}^{-1} = -10$ dB. Since the residual SI scales with the relay transmission power, it is observed that a same diversity order of $N-1$ is achieved by FD-MPRC-I as the proposed VFD-MPRC with an increase in P_0. For FD-MPRC-II where there is a residual SI component of fixed power $P_{SI} = 10$ dB irrespective of the relay transmission power, it is observed that a full diversity order of N is achieved asymptotically. This is reasonable as besides the rest $N-1$ relays, the selected best relay is able to forward the previous packet while decoding the currently transmitted source packet also. Whereas in the proposed VFD-MPRC, since the selected best relay cannot transmit and receive simultaneously, a diversity order of $N-1$ is achieved asymptotically. For the ideal case where the SI is perfectly cancelled, the best performance is achieved by FD-MPRC-III, which again, achieves a full diversity order of 2. With more relays available, e.g., $N = 4, 6$, it is observed that a reasonably good performance is achieved by the proposed VFD-MPRC compared to FD-MPRC.

For better illustrations, we also demonstrate the outage probabilities of the proposed VFD-MPRC and FD-MPRC when $R_0 = 2$ bits/slot/Hz in Fig. 8(b). Similarly, a comparable performance to FD-MPRC is achieved by VFD-MPRC. With a fading SI channel where $\delta_{SI}^{-1} = -10$ dB, the outage probability of FD-MPRC-I experiences an error floor and no diversity gains can be achieved. This is reasonable as for the selected best relay, the SI increases linearly with the relay transmission power. Whereas for the rest $N-1$ relays, the desired signal is subject to comparable IRI that limits the SIC decoding. With only a constant-power SI component where $P_{SI} = 10$ dB, it is observed that a diversity order of 1 is achieved by FD-MPRC-II. Again, the best performance is achieved by FD-MPRC-III where the SI is perfectly cancelled, and a diversity order of 1 is achieved. Whereas for the proposed VFD-MPRC, no diversity gains are available any more due to a bottleneck brought by SIC that is limited by the comparable IRI.

Remark 4: From the above comparisons and observations, a close-to-full diversity order can be exploited by the proposed VFD-MPRC in low rate scenarios where $R_0 \leq 1$, while significantly recovering the spectrum efficiency loss in HD-MPRC. On the other hand, in relatively high rate scenarios where $R_0 > 1$, although no diversity gains are available due to the IRI, performance improvements can be achieved by VFD-MPRC in both low and modest SNR regimes over the conventional HD-MPRC. Furthermore, with only half-duplex relays, a comparable performance can be achieved by the proposed VFD-MPRC to its full-duplex counterpart.

VII. Conclusions

In order to exploit the diversity gains while improving the spectrum efficiency of the conventional half-duplex relay systems, we proposed a virtual full-duplex relaying scheme on the cooperative MPRC with opportunistic relaying. By using a Markov analytical model, the system outage probability was analyzed and derived in closed-form expressions, without the need to consider whether the IRI exists in each time slot. The asymptotic system performance in the high SNR regime was also investigated, where both diversity order and error floor were analyzed and derived in closed-form expressions. By comparisons with existing half/full-duplex relay systems, our results demonstrate the advantages of the proposed approach in low rate scenarios, where a close-to-full diversity order is achieved while achieving a comparable spectrum efficiency to the full-duplex relay system. In high rate scenarios, the system is interference-limited as similar to a full-duplex relay system with self-loop interference channel. Even though, performance gains can be achieved over conventional half-duplex relay systems in low and/or modest SNR regimes.

An interesting extension of our work in future is that for those relays that successfully decode the source packet but are not selected, they can store the decoded data in buffer, which can be used for self-interference cancellation in the subsequent time slot. Intuitively, this is able to further mitigate the IRI thus enhancing the decoding performance of the relays.

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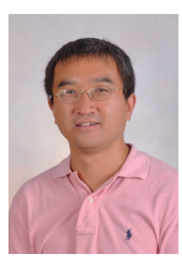

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