Relay Power Control for In-Band Full-Duplex Decode-and-Forward Relay Networks Over Static and Time-Varying Channels

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***Abstract*—This article considers a one-way full-duplex decode-and-forward relay network consisting of a source, a relay, and a destination. Due to the self-interference (SI) channel estimation error at the relay, SI cannot be completely canceled. In the presence of the residual SI, there is a tradeoff between the achievable rate of the relay–destination link in a given time slot and that of the source–relay link in the next time slot depending on the relay transmit power in that time slot. As the relay transmit power increases, the achievable rate from the relay to destination increases, whereas the achievable rate from the source to the relay in the next time slot decreases. Motivated by this observation, relay power control schemes for maximizing achievable rates over static and time-varying channels are proposed in this article. Next, a closed-form expression for the relay transmit power in each time slot is derived. Numerical results show that the proposed relay power control schemes outperform the conventional maximum power transmission scheme in terms of achievable rates.**

***Index Terms*—Achievable rate, decode-and-forward, full-duplex (FD), one-way relay, power control.**

I. Introduction

FULL-duplex (FD) transmission is envisaged as a key enabling technology for the next-generation wireless systems to improve spectral efficiency [1]–[5] because FD systems can transmit and receive simultaneously on the same frequency band. *In-band FD* technology allows a wireless terminal to transmit and receive simultaneously in the same frequency band, thus increasing the throughput of wireless communication networks. Specifically, FD relay systems have recently been studied in [6]–[15]. The beamforming design schemes were proposed in [6] and [7], and the simultaneous wireless information and power transfer systems were studied in [8]–[11]. Also, the power allocation and control schemes for FD relay systems in the presence of the residual *self-interference* (SI) were investigated in [12]–[15]. FD systems come with SI, which degrades the system performance, if not treated. In particular, SI cannot be wholly canceled in an FD relay due to the SI channel estimation error at the relay and the limited dynamic range of the analog-to-digital converters [1]–[3]. For this reason, exploring techniques for mitigating SI performance degradation is essential.

Buffer-aided relay networks have been studied in [16]–[18]. Razlighi and Zlatanov [16] proposed buffer-aided relaying schemes with adaptive reception/transmission for the two-hop FD relay channel with SI when the source and the relay both perform continuous-rate transmission with adaptive-power allocation, continuous-rate transmission with fixed-power allocation, and discrete-rate transmission, respectively. In [17], source and relay power allocation for the buffer-aided FD relaying networks was studied, assuming constant data rate arrivals at the source buffer. Zlatanov *et al.* [18] studied the capacity of the Gaussian two-hop FD relay channel with linear residual SI considering the worst-case linear residual SI model. Also, the authors presented that the capacity is achieved by a zero-mean Gaussian input distribution at the source whose variance depends on the amplitude of the transmit symbols at the relay.

The FD system and low-latency communication are key technologies of fifth-generation (5G) wireless communication. In view of this trend, this article considers the FD relay-assisted transmissions for low-latency communication. The achievable data rate of buffer-aided relay networks can be greater than that of buffer-free relay networks; however, buffer-aided relay networks are considered mainly in delay-tolerant networks and require memory. For those reasons, this article considers buffer-free FD relay networks.

In one-way FD decode-and-forward relay networks, the signal from the source is transmitted to the relay in a time slot, and the decoded signal at the relay is transmitted to the destination in the next time slot. Therefore, the achievable rate from the source to the destination in a given time slot is determined by the minimum value of the achievable rate from the source to the relay in the previous time slot and the achievable rate from the relay to the destination in that time slot.

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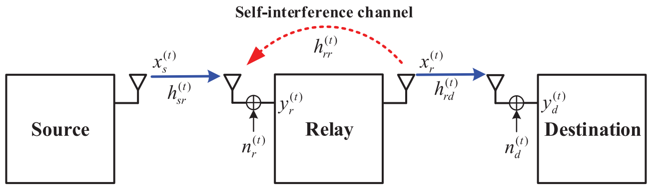


Fig. 1. One-way FD decode-and-forward relay networks in time slot t.

For these reasons, as the relay transmit power in a time slot increases, the achievable rate from the relay to the destination in the corresponding time slot increases, whereas the achievable rate from the source to the relay in the next time slot decreases due to the residual SI at the relay. This implies that there exists a tradeoff between the achievable rate from the relay to the destination in a time slot and the achievable rate from the source to the relay in the next time slot depending on the relay transmit power in that time slot. Motivated by this observation, this article studies the relay power control scheme for maximizing the achievable rate in each time slot.

Dun *et al.* [12] proposed power allocation schemes for the base station (BS) and relay in the FD amplify-and-forward relay-aided device-to-device communication. The optimal power allocation for two-way FD amplify-and-forward relay networks was studied in [13]. The power control schemes for the FD relay networks were proposed in [14] and [15]. Li *et al.* [14] proposed the relay power control scheme for two-way FD amplify-and-forward relay networks in each time slot over static channels. The FD decode-and-forward relay-enhanced cellular networks consisting of an FD BS, two FD relays, and two half-duplex user equipments (UEs) are studied in [15]. This study proposed a power control scheme for the BS, relays, and UEs that maximize the achievable end-to-end spectral efficiency of the uplink and downlink UEs in a certain time slot. To the best of our knowledge, the relay power control schemes in each time slot for one-way FD decode-and-forward relay networks over static and time-varying channels have not been proposed in the literature.

The remainder of this article is organized as follows. Section II describes the system model. Sections III and VI provide the proposed relay power control schemes over static and time-varying channels, respectively. Section V shows the numerical results for the proposed relay power control schemes. Finally, Section VI concludes this article.

Notations: The operator $\mathbb{E}[\cdot]$ indicates the expectation. Notations $|a|$ denotes the absolute value of a for any scalar. Notations $\max(\cdot)$ and $\min(\cdot)$ denote the largest value of the arguments and the smallest value of the arguments, respectively.

II. System Model

Consider a one-way FD *decode-and-forward* relay network consisting of one source node s, one relay node r, and one destination node d, as shown in Fig. 1. Since the relay is assumed to operate in the FD mode, there is the SI channel. The *channel state information* (CSI) of SI is assumed to be imperfect due to channel estimation errors.

In time slot 0, the source transmits its signal $x_s^{(0)}$ to the relay. The received signal at the relay is written as

$$y_r^{(0)} = h_{sr}^{(0)} x_s^{(0)} + n_r^{(0)} \tag{1}$$

where $h_{sr}^{(0)}$ is the channel coefficient between the source and relay in time slot 0. Also, $n_r^{(0)}$ is the additive white Gaussian noise (AWGN) at the relay in time slot 0 whose mean is zero and variance is $\sigma_{n,r}^2$.

In time slot 1, the relay forwards the decoded signal to the destination and the source transmits its next signal to the relay at the same time. In this manner, the source transmits its signal to the relay and the relay transmits the decoded signal to the destination in each time slot. In time slot $t-1$, the source transmits the signal $x_s^{(t-1)}$ using maximum transmit power p_s, i.e., $\mathbb{E}[|x_s^{(t-1)}|^2] = p_s$. Also, the relay transmits the signal $x_r^{(t-1)}$ using transmit power $p_r^{(t-1)}$ with $\mathbb{E}[|x_r^{(t-1)}|^2] = p_r^{(t-1)} (0 < p_r^{(t-1)} \le p_r^{\max})$. The estimated received signal at the relay after subtracting SI in time slot $t-1$ is written as

$$\begin{aligned}\hat{y}_r^{(t-1)} &= y_r^{(t-1)} - \hat{h}_{rr}^{(t-1)} x_r^{(t-1)} \\ &= h_{sr}^{(t-1)} x_s^{(t-1)} + h_{rr}^{(t-1)} x_r^{(t-1)} + n_r^{(t-1)} - \hat{h}_{rr}^{(t-1)} x_r^{(t-1)} \\ &= h_{sr}^{(t-1)} x_s^{(t-1)} + \Delta_{rr}^{(t-1)} x_r^{(t-1)} + n_r^{(t-1)}\end{aligned} \tag{2}$$

where $h_{rr}^{(t-1)}$, $\hat{h}_{rr}^{(t-1)}$, and $\Delta_{rr}^{(t-1)}$ are the true SI channel coefficient, the estimated SI channel coefficient, and the SI channel estimation error in time slot $t-1$, respectively. The mean and the variance of the SI channel estimation error are zero and σ_e^2, respectively. Also, $h_{sr}^{(t-1)}$ is the channel coefficient between the source and the relay in time slot $t-1$. In addition, $n_r^{(t-1)}$ is the AWGN at the relay in time slot $t-1$, and it has zero mean whose variance is $\sigma_{n,r}^2$.

The received signal at the destination in time slot t is written as

$$y_d^{(t)} = h_{rd}^{(t)} x_r^{(t)} + n_d^{(t)} \tag{3}$$

where $h_{rd}^{(t)}$ is the channel coefficient between the relay and the destination in time slot t. In addition, $n_d^{(t)}$ is the AWGN at the destination in time slot t, and it has zero mean whose variance is $\sigma_{n,d}^2$.

The achievable rate from the source to relay in time slot $t-1$ is given by

$$\begin{aligned}R_{sr}^{(0)} &= \log_2\left(1 + \frac{p_s^{(0)} |h_{sr}^{(0)}|^2}{\sigma_{n,r}^2}\right) \\ R_{sr}^{(t-1)} &= \log_2\left(1 + \frac{p_s^{(t-1)} |h_{sr}^{(t-1)}|^2}{\sigma_{n,r}^2 + \sigma_e^2 p_r^{(t-1)}}\right) \quad \text{for } t \ge 2.\end{aligned} \tag{4}$$

Note that the relay is not affected by the residual SI in time slot 0 because the source only transmits the signal to the relay. The achievable rate from the relay to destination in time slot t is given by

$$R_{rd}^{(t)} = \log_2\left(1 + \frac{p_r^{(t)} |h_{rd}^{(t)}|^2}{\sigma_{n,d}^2}\right) \quad \text{for } t \ge 1. \tag{5}$$

In FD decode-and-forward relay networks, the achievable rate from the source to the destination in time slot t is determined by the minimum value of $R_{sr}^{(t-1)}$ and $R_{rd}^{(t)}$ [15], [19]. Therefore, $R^{(t)}$ is given by

$$R^{(t)} = \min(R_{sr}^{(t-1)}, R_{rd}^{(t)}) \quad \text{for } t \geq 1. \tag{6}$$

It follows from (4) and (5) that as $p_r^{(t)}$ increases, $R_{rd}^{(t)}$ increases; however, $R_{sr}^{(t)}$ decreases due to the residual SI.

III. Proposed Relay Power Control Scheme Over Static Channels

This section introduces a relay power control scheme provided that CSI in each time slot is fixed. Therefore, the relay knows the CSI in all time slots. We consider the minimum achievable rate among the achievable rate in each time slot for guaranteeing the quality of service. When one frame consists of T time slots and the relay transmits the decoded signal to the destination until time slot T, the optimization problem for maximizing the minimum achievable rate can be written as

$$(\mathbf{P1.1}) \quad \underset{p_r^{(1)},\ldots,p_r^{(T)}}{\text{maximize}} \quad \min\{R^{(1)}, \ldots, R^{(T)}\} \tag{7a}$$

$$\text{subject to} \quad 0 < p_r^{(1)}, \ldots, p_r^{(T)} \leq p_r^{\max} \tag{7b}$$

where T is the number of time slots in one frame. In problem $(\mathbf{P1.1})$, the minimum achievable rate can be obtained by Lemma 1.

Lemma 1: The minimum achievable rate $\min\{R^{(1)}, \ldots, R^{(T)}\}$ is equivalent to

$$\min\left(\frac{p_s|h_{sr}|^2}{\sigma_{n,r}^2 + \sigma_e^2 p_{\max}}, \frac{p_{\min}|h_{rd}|^2}{\sigma_{n,d}^2}\right) \tag{8}$$

where $p_{\max} = \max(p_r^{(1)}, \ldots, p_r^{(T-1)})$ and $p_{\min} = \min(p_r^{(1)}, \ldots, p_r^{(T-1)})$.

Proof: The logarithm is an increasing function and $\min\{\min(c_1, c_2), \ldots, \min(c_{2T-1}, c_{2T})\}$ is equivalent to $\min(c_1, c_2, \ldots, c_{2T-1}, c_{2T})$. Therefore, $\min\{R^{(1)}, \ldots, R^{(T)}\}$ can be simply rewritten as

$$R_{\min} = \min\left\{\frac{p_s|h_{sr}|^2}{\sigma_{n,r}^2}, \frac{p_s|h_{sr}|^2}{\sigma_{n,r}^2 + \sigma_e^2 p_r^{(1)}}, \ldots, \frac{p_s|h_{sr}|^2}{\sigma_{n,r}^2 + \sigma_e^2 p_r^{(T-1)}}, \right.$$
$$\left. \times \frac{p_r^{(1)}|h_{rd}|^2}{\sigma_{n,d}^2}, \ldots, \frac{p_r^{(T-1)}|h_{rd}|^2}{\sigma_{n,d}^2}, \frac{p_r^{(T)}|h_{rd}|^2}{\sigma_{n,d}^2}\right\} \tag{9}$$

where $p_s^{(0)} = \cdots = p_s^{(T-1)} = p_s$, $|h_{sr}^{(0)}|^2 = \cdots = |h_{sr}^{(T-1)}|^2 = |h_{sr}|^2$, and $|h_{rd}^{(1)}|^2 = \cdots = |h_{rd}^{(T)}|^2 = |h_{rd}|^2$ by assumption. Since the source transmits until time slot $T-1$ and the relay transmits until time slot T, $p_r^{(T)}$ is set to $p_r^{\max}$. Due to $p_r^{(T)} = p_r^{\max}$, $\frac{p_r^{(T)}|h_{rd}|^2}{\sigma_{n,d}^2}$ is greater than or equal to $\frac{p_r^{(t)}|h_{rd}|^2}{\sigma_{n,d}^2}$ for $1 \leq t \leq T-1$. In addition, $\frac{p_s|h_{sr}|^2}{\sigma_{n,r}^2}$ is greater than $\frac{p_s|h_{sr}|^2}{\sigma_{n,r}^2+\sigma_e^2 p_r^{(t)}}$ for $1 \leq t \leq T-1$ unless σ_e^2 is zero, i.e., when there is no residual SI. Therefore, $R_{\min}$ can be written as

$$R_{\min} = \min(a_1, a_2) \tag{10}$$

where a_1 and a_2 are given by

$$a_1 = \min\left(\frac{p_s|h_{sr}|^2}{\sigma_{n,r}^2 + \sigma_e^2 p_r^{(1)}}, \ldots, \frac{p_s|h_{sr}|^2}{\sigma_{n,r}^2 + \sigma_e^2 p_r^{(T-1)}}\right)$$
$$a_2 = \min\left(\frac{p_r^{(1)}|h_{rd}|^2}{\sigma_{n,d}^2}, \ldots, \frac{p_r^{(T-1)}|h_{rd}|^2}{\sigma_{n,d}^2}\right). \tag{11}$$

In (11), a_1 and a_2 can be rewritten as $f_1(p_{\max})$ and $f_2(p_{\min})$, respectively

$$f_1(p_{\max}) = \frac{p_s|h_{sr}|^2}{\sigma_{n,r}^2 + \sigma_e^2 p_{\max}}$$
$$f_2(p_{\min}) = \frac{p_{\min}|h_{rd}|^2}{\sigma_{n,d}^2} \tag{12}$$

where $p_{\max} = \max(p_r^{(1)}, \ldots, p_r^{(T-1)})$ and $p_{\min} = \min(p_r^{(1)}, \ldots, p_r^{(T-1)})$. ■

By Lemma 1, the problem $(\mathbf{P1.1})$ can be rewritten as

$$(\mathbf{P1.2}) \ \underset{p_{\max}, p_{\min}}{\text{maximize}} \ R_{\min}(p_{\max}, p_{\min})$$
$$= \min\{f_1(p_{\max}), f_2(p_{\min})\}$$
$$\text{subject to} \ 0 < p_{\max}, p_{\min} \leq p_r^{\max}. \tag{13}$$

Lemma 2: The minimum achievable rate $R_{\min}(p_{\max}, p_{\min}) = \min\{f_1(p_{\max}), f_2(p_{\min})\}$ is maximized when $p_{\max} = p_{\min}$.

Proof: By definition, $p_{\max}$ is greater than or equal to $p_{\min}$. Let $p_{\max}^\star$ and $p_{\min}^\star$ be the optimal solution for $p_{\max}$ and $p_{\min}$ that maximizes $\min\{f_1(p_{\max}), f_2(p_{\min})\}$. First of all, we consider $p_{\max} > p_{\min}$. Suppose $p_{\max}^\star > p_{\min}^\star$. We can divide the problem into three cases depending on the relation between $f_1(p_{\max}^\star)$ and $f_2(p_{\min}^\star)$.

1) *Case* $f_1(p_{\max}^\star) < f_2(p_{\min}^\star)$*:* In this case, $R_{\min}(p_{\max}^\star, p_{\min}^\star) = f_1(p_{\max}^\star)$. We consider the case in which $p_{\max}^\star$ is decreased by ϵ, where ϵ is a small positive value such that satisfy $f_1(p_{\max}^\star - \epsilon) < f_2(p_{\min}^\star)$. When $p_{\max}^\star$ is decreased by ϵ, $R_{\min}(p_{\max}^\star - \epsilon, p_{\min}^\star) > R_{\min}(p_{\max}^\star, p_{\min}^\star)$ because of $f_1(p_{\max}^\star - \epsilon) > f_1(p_{\max}^\star)$. In other words, there exists $p_{\max}$ and $p_{\min}$ that satisfy $R_{\min}(p_{\max}, p_{\min}) > R_{\min}(p_{\max}^\star, p_{\min}^\star)$. Therefore, this case is a contradiction to the supposition that $p_{\max}^\star$ and $p_{\min}^\star$ are optimal.
2) *Case* $f_1(p_{\max}^\star) > f_2(p_{\min}^\star)$*:* In this case, $R_{\min}(p_{\max}^\star, p_{\min}^\star) = f_2(p_{\min}^\star)$. We consider the case in which $p_{\min}^\star$ is increased by ϵ, where ϵ is a very small positive value such that satisfy $f_1(p_{\max}^\star) > f_2(p_{\min}^\star + \epsilon)$. When $p_{\min}^\star$ is increased by ϵ, $R_{\min}(p_{\max}^\star, p_{\min}^\star + \epsilon) > R_{\min}(p_{\max}^\star, p_{\min}^\star)$ because of $f_2(p_{\min}^\star + \epsilon) > f_2(p_{\min}^\star)$. In other words, there exists $p_{\max}$ and $p_{\min}$ that satisfy $R_{\min}(p_{\max}, p_{\min}) > R_{\min}(p_{\max}^\star, p_{\min}^\star)$. Therefore, this case is a contradiction to the supposition that $p_{\max}^\star$ and $p_{\min}^\star$ are optimal.
3) *Case* $f_1(p_{\max}^\star) = f_2(p_{\min}^\star)$*:* We consider this case because we have identified two cases. In this case, $R_{\min}(p_{\max}^\star, p_{\min}^\star) = f_1(p_{\max}^\star) = f_2(p_{\min}^\star)$. We consider

the case in which $p_{\max}^\star$ is decreased by ϵ_1 and $p_{\min}^\star$ is increased by ϵ_2, where ϵ_1 and ϵ_2 are very small positive values such that satisfy $f_1(p_{\max}^\star - \epsilon_1) = f_2(p_{\min}^\star + \epsilon_2)$. When $p_{\max}^\star$ is decreased by ϵ_1 and $p_{\min}^\star$ is increased by ϵ_2, $R_{\min}(p_{\max}^\star - \epsilon_1, p_{\min}^\star + \epsilon_2) > R_{\min}(p_{\max}^\star, p_{\min}^\star)$ because of $f_1(p_{\max}^\star - \epsilon_1) = f_2(p_{\min}^\star + \epsilon_2) > f_1(p_{\max}^\star) = f_2(p_{\min}^\star)$. In other words, there exists $p_{\max}$ and $p_{\min}$ that satisfy $R_{\min}(p_{\max}, p_{\min}) > R_{\min}(p_{\max}^\star, p_{\min}^\star)$. Therefore, this case is a contradiction to the supposition that $p_{\max}^\star$ and $p_{\min}^\star$ are optimal.

To sum up, $p_{\max}^\star$ should not be greater than $p_{\min}^\star$. Therefore, there exists the optimal $p_{\max}^\star$ and $p_{\min}^\star$ for maximizing $R_{\min}(p_{\max}, p_{\min})$ when $p_{\max}^\star = p_{\min}^\star$. ■

By Lemma 2, we consider the case that $p_{\max}^\star$ and $p_{\min}^\star$ are the same. For $p_{\max}^\star$ and $p_{\min}^\star$ to be equal, the relay transmit power in each time slot should be the same because $p_{\max}^\star$ and $p_{\min}^\star$ are the maximum and minimum values of the relay transmit power value in each time slot, respectively. We define p_r as $p_{\max}^\star = p_{\min}^\star$ and problem $(\mathbf{P1.2})$ can be rewritten as

$$(\mathbf{P1.3}) \quad p_r^* = \arg\max_{p_r} \ \min\{f_1(p_r), f_2(p_r)\} \tag{14a}$$

$$\text{subject to } \ 0 < p_r \le p_r^{\max} \tag{14b}$$

where $f_1(p_r)$ and $f_2(p_r)$ are given by

$$f_1(p_r) = \frac{p_s|h_{sr}|^2}{\sigma_{n,r}^2 + \sigma_e^2 p_r}$$

$$f_2(p_r) = \frac{p_r|h_{rd}|^2}{\sigma_{n,d}^2}. \tag{15}$$

Theorem 1: The optimal relay transmit power $p_r^{*(t)}$ for maximizing the minimum achievable rate $\min\{f_1(p_r), f_2(p_r)\}$ is $\min(\alpha, p_r^{\max})$ for $1 \le t \le T-1$ and $p_r^{\max}$ for $t = T$, where

$$\alpha = \sqrt{\left(\frac{\sigma_{n,r}^2}{2\sigma_e^2}\right)^2 + \frac{\sigma_{n,d}^2 p_s|h_{sr}|^2}{\sigma_e^2|h_{rd}|^2}} - \frac{\sigma_{n,r}^2}{2\sigma_e^2}. \tag{16}$$

Proof: It is noted that $f_1(p_r)$ is a strictly decreasing function and $f_2(p_r)$ is a strictly increasing function with respect to p_r. In addition, $f_1(0)$ is greater than $f_2(0)$. Therefore, $f_1(p_r)$ and $f_2(p_r)$ meet at one point if we ignore the constraint, which is defined as α. By solving $f_1(p_r) = f_2(p_r)$ using the quadratic formula, α can be obtained.

Two cases are considered depending on the relation between α and $p_r^{\max}$. Fig. 2 shows possible cases. We determine p_r for maximizing $\min\{f_1(p_r), f_2(p_r)\}$.

1) *Case I* $(0 < \alpha \le p_r^{\max})$*:* As shown in Fig. 2(a), $\min\{f_1(p_r), f_2(p_r)\}$ can be written as

$$\min\{f_1(p_r), f_2(p_r)\} = \begin{cases} f_2(p_r), & \text{for } 0 < p_r \le \alpha \\ f_1(p_r), & \text{for } \alpha \le p_r \le p_r^{\max}. \end{cases} \tag{17}$$

According to (17), $\min\{f_1(p_r), f_2(p_r)\}$ is strictly increasing on $(0, \alpha]$ and strictly decreasing on $[\alpha, p_r^{\max}]$. Therefore, p_r for maximizing $\min\{f_1(p_r), f_2(p_r)\}$ is α.

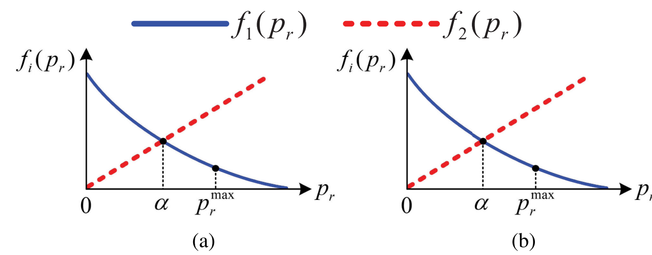


Fig. 2. Possible cases depending on the relation between α and $p_r^{\max}$. (a) $0 < \alpha \le p_r^{\max}$. (b) $0 < p_r^{\max} \le \alpha$.

2) *Case II* $(0 < p_r^{\max} \le \alpha)$*:* As shown in Fig. 2(b), $\min\{f_1(p_r), f_2(p_r)\}$ can be written as

$$\min\{f_1(p_r), f_2(p_r)\} = f_2(p_r) \ \text{ for } \ 0 < p_r \le p_r^{\max} \tag{18}$$

According to (18), $\min\{f_1(p_r), f_2(p_r)\}$ is strictly increasing on $(0, p_r^{\max}]$. Therefore, p_r for maximizing $\min\{f_1(p_r), f_2(p_r)\}$ is $p_r^{\max}$. From the two cases, the optimal p_r^* is given by

$$p_r^* = \begin{cases} \alpha, & \text{for } \ 0 < \alpha \le p_r^{\max} \\ p_r^{\max}, & \text{for } \ 0 < p_r^{\max} \le \alpha. \end{cases} \tag{19}$$

As mentioned, the optimal $p_r^{*(t)}$ is $p_r^{\max}$. Therefore, the optimal relay transmit power in each time slot is given by

$$p_r^{*(t)} = \begin{cases} \min(\alpha, p_r^{\max}), & \text{for } \ 1 \le t \le T-1 \\ p_r^{\max}, & \text{for } \ t = T. \end{cases} \tag{20}$$

■

IV. Proposed Relay Power Control Scheme Over Time-Varying Channels

This section considers a different scenario in which the CSI in each time slot is variant. In time slot t, the relay knows the CSI in time slot t. Due to the causality, it is impossible to consider the achievable rate after the $(t+1)$th time slot in time slot t over time-varying channels. Therefore, we formulate the problem for finding $p_r^{(t)}$ that maximizes the weighted sum rate of $R^{(t)} = \min(R_{sr}^{(t-1)}, R_{rd}^{(t)})$ and $R_{sr}^{(t)}$ in each time slot. The optimization problem that maximizes $R^{(t)}(p_r^{(t)}) + \lambda R_{sr}^{(t)}(p_r^{(t)})$ for $\lambda \ge 0$ can be written as

$$(\mathbf{P2}) \quad \underset{p_r^{(t)}}{\text{maximize}} \ R^{(t)}(p_r^{(t)}) + \lambda R_{sr}^{(t)}(p_r^{(t)}) \tag{21a}$$

$$\text{subject to } 0 < p_r^{(t)} \le p_r^{\max}. \tag{21b}$$

It is difficult to solve the problem $(\mathbf{P2})$ because it is nonconvex problem. As mentioned, $R^{(t+1)}$ is determined by $R_{rd}^{(t+1)}$ as well as $R_{sr}^{(t)}$. Since $R_{rd}^{(t+1)}$ cannot be considered in the tth time slot, we maximize $R^{(t)}(p_r^{(t)})$ and then $R_{sr}^{(t)}(p_r^{(t)})$ by setting λ to very close to zero. When λ is very close to zero, the problem $(\mathbf{P2})$ can be changed to the problem for maximizing $R_{sr}^{(t)}(p_r^{(t)})$ among $p_r^{(t)}$ values that maximize $R^{(t)}(p_r^{(t)})$. The reformulated problem can be written as

$$(\mathbf{P3}) \quad \underset{p_r^{(t)}}{\text{maximize}}\ R_{sr}^{(t)}(p_r^{(t)}) \tag{22a}$$

$$\text{subject to } p_r^{(t)} \in \{\bar{p}_r^{(t)} | \bar{p}_r^{(t)} = \underset{0<p_r^{(t)}\le p_r^{\max}}{\arg\max}\ R^{(t)}(p_r^{(t)})\} \tag{22b}$$

The set $\mathcal{A}^{(t)} \triangleq \{\bar{p}_r^{(t)} | \bar{p}_r^{(t)} = \arg\max_{0<p_r^{(t)}\le p_r^{\max}} R^{(t)}(p_r^{(t)})\}$ is the set of $p_r^{(t)}$ that maximizes $R^{(t)}(p_r^{(t)})$ subject to the constraint $0 < p_r^{(t)} \le p_r^{\max}$. Also, $R^{(t)}(p_r^{(t)})$ is given by

$$R^{(t)}(p_r^{(t)}) = \min\{\log_2(1+c_{sr}^{(t-1)}), \log_2(1+f_{rd}^{(t)}(p_r^{(t)}))\} \tag{23}$$

where $c_{sr}^{(t-1)}$ and $f_{rd}^{(t)}(p_r^{(t)})$ are given by

$$c_{sr}^{(0)} = \frac{p_s^{(0)}|h_{sr}^{(0)}|^2}{\sigma_{n,r}^2}$$

$$c_{sr}^{(t-1)} = \frac{p_s^{(t-1)}|h_{sr}^{(t-1)}|^2}{\sigma_{n,r}^2 + \sigma_e^2 p_r^{(t-1)}}, \quad \text{for } t \ge 2$$

$$f_{rd}^{(t)}(p_r^{(t)}) = \frac{p_r^{(t)}|h_{rd}^{(t)}|^2}{\sigma_{n,d}^2}, \quad \text{for } t \ge 1. \tag{24}$$

First, we find the set $\mathcal{A}^{(t)}$. The optimization problem for obtaining the set $\mathcal{A}^{(t)}$ can be written as

$$(\mathbf{P4.1}) \quad p_r^{*(t)} = \underset{p_r^{(t)}}{\arg\max}\ R^{(t)}(p_r^{(t)}) \tag{25a}$$

$$\text{subject to } 0 < p_r^{(t)} \le p_r^{\max}. \tag{25b}$$

Since logarithm is a monotonically increasing function, the problem $(\mathbf{P4.1})$ can be rewritten as

$$(\mathbf{P4.2}) \quad \underset{p_r^{(t)}}{\text{maximize}}\ \min\{c_{sr}^{(t-1)}, f_{rd}^{(t)}(p_r^{(t)})\} \tag{26a}$$

$$\text{subject to} \quad 0 < p_r^{(t)} \le p_r^{\max}. \tag{26b}$$

From (24), we can know that $c_{sr}^{(t-1)}$ is constant and $f_{rd}^{(t)}(p_r^{(t)})$ increases as $p_r^{(t)}$ increases. Let $\beta^{(t)}$ denote $p_r^{(t)}$ for satisfying $c_{sr}^{(t-1)} = f_{rd}^{(t)}(p_r^{(t)})$, and it is given by

$$\beta^{(0)} = \frac{p_s^{(0)}\sigma_{n,d}^2|h_{sr}^{(0)}|^2}{\sigma_{n,r}^2|h_{rd}^{(1)}|^2}$$

$$\beta^{(t-1)} = \frac{p_s^{(t-1)}\sigma_{n,d}^2|h_{sr}^{(t-1)}|^2}{(\sigma_{n,r}^2+\sigma_e^2 p_r^{(t-1)})|h_{rd}^{(t)}|^2}, \quad \text{for } t \ge 2. \tag{27}$$

The two cases are considered depending on the relation between $\beta^{(t)}$ and $p_r^{\max}$. Fig. 3 shows possible cases in the tth time slot. We determine $p_r^{(t)}$ for maximizing $R^{(t)}$.

1) *Case I* $(0 < \beta^{(t)} \le p_r^{\max})$*:* This case considers $0 < \beta^{(t)} \le p_r^{\max}$. As shown in Fig. 3(a), $R^{(t)}$ can be written as

$$R^{(t)} = \begin{cases} f_{rd}^{(t)}(p_r^{(t)}), & \text{for } 0 < p_r^{(t)} \le \beta^{(t)} \\ c_{sr}^{(t-1)}, & \text{for } \beta^{(t)} \le p_r^{(t)} \le p_r^{\max}. \end{cases} \tag{28}$$

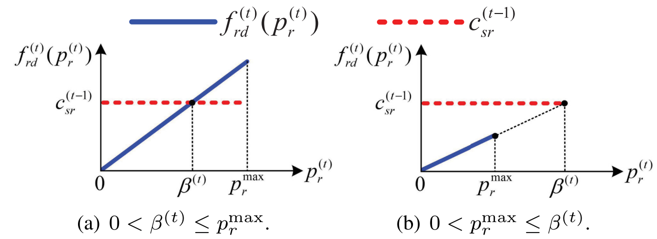


Fig. 3. Possible cases depending on the relation between $\beta^{(t)}$ and $p_r^{\max}$ in time slot t. (a) $0 < \beta^{(t)} \le p_r^{\max}$. (b) $0 < p_r^{\max} \le \beta^{(t)}$.

$R^{(t)}$ is a strictly increasing function with respect to $p_r^{(t)}$ on $(0, \beta^{(t)}]$ and constant on $[\beta^{(t)}, p_r^{\max}]$. Therefore, $p_r^{(t)}$ for maximizing $R^{(t)}$ in the tth time slot is $[\beta^{(t)}, p_r^{\max}]$.

2) *Case II* $(0 < p_r^{\max} \le \beta^{(t)})$*:* This case considers $0 < p_r^{\max} \le \beta^{(t)}$. As shown in Fig. 3(b), $R^{(t)}$ can be written as

$$R^{(t)} = f_{rd}^{(t)}(p_r^{(t)}), \quad \text{for } 0 < p_r^{(t)} \le p_r^{\max}. \tag{29}$$

$R^{(t)}$ is a strictly increasing function with respect to $p_r^{(t)}$ on $(0, p_r^{\max}]$. Therefore, $p_r^{(t)}$ for maximizing $R^{(t)}$ is $p_r^{\max}$.

From the two cases, $\bar{p}_r^{(t)}$ is given by

$$\bar{p}_r^{(t)} = \begin{cases} [\beta^{(t)}, p_r^{\max}], & \text{for } 0 < \beta^{(t)} \le p_r^{\max} \\ p_r^{\max}, & \text{for } 0 < p_r^{\max} \le \beta^{(t)}. \end{cases} \tag{30}$$

Hence, the set $\mathcal{A}^{(t)}$ is $\{\bar{p}_r^{(t)} | \min(\beta^{(t)}, p_r^{\max}) \le p_r^{(t)} \le p_r^{\max}\}$.

In problem $(\mathbf{P3})$, since $R_{sr}^{(t)}$ decreases as $p_r^{(t)}$ increases, $p_r^{*(t)}$ for maximizing $R_{sr}^{(t)}$ should be the smallest of the set $\mathcal{A}^{(t)}$. Therefore, $p_r^{*(t)}$ is given by

$$p_r^{*(t)} = \begin{cases} \beta^{(t)}, & \text{for } 0 < \beta^{(t)} \le p_r^{\max} \\ p_r^{\max}, & \text{for } 0 < p_r^{\max} \le \beta^{(t)}. \end{cases} \tag{31}$$

V. Numerical Results

In this section, we numerically investigate the performances of the proposed relay power control schemes over static and time-varying channels. We compare the proposed relay power control schemes with the maximum power transmission scheme. In the maximum power transmission scheme, the relay transmits the decoded signal using the maximum transmit power in each time slot. It is assumed that the transmit power in each time slot at the source is the same, i.e., $p_s^{(1)} = p_s^{(2)} = \cdots = p_s$. Also, we assume that the noise variance at each node is the same, i.e., $\sigma_{n,d}^2 = \sigma_{n,r}^2 = \sigma_n^2$. The signal-to-noise ratio (SNR) and interference-to-noise ratio (INR) are defined as p_s/σ_n^2 and σ_e^2/σ_n^2, respectively.

Fig. 4 plots the performance for the proposed power control scheme over static channels when $|h_{sr}^{(t)}|^2 = |h_{rd}^{(t+1)}|^2 = 1$ for $t \ge 0$. Fig. 4(a) shows the minimum achievable rate versus SNR for different INRs when $p_s = 27$ dBm and $p_r^{\max} = 27$ dBm. It is seen that the minimum achievable rate of the proposed power control scheme is greater than that of the maximum power transmission scheme. The ideal FD system refers to the

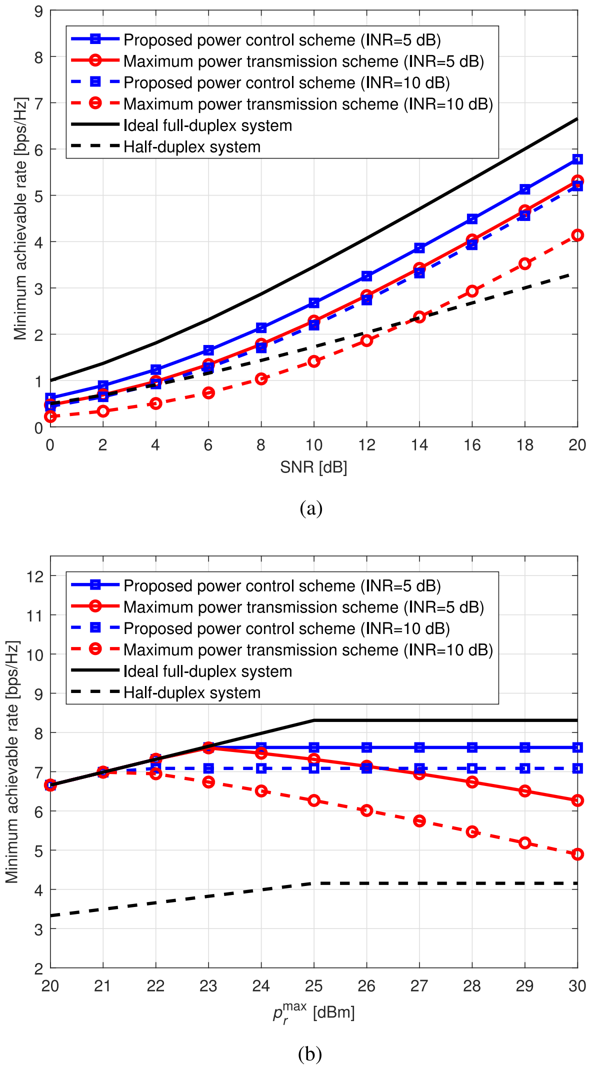


Fig. 4. Performance for the proposed power control and maximum power transmission schemes over static channels. (a) Minimum achievable rate versus SNR for different INRs. (b) Minimum achievable rate versus maximum transmit power at the relay for different INRs.

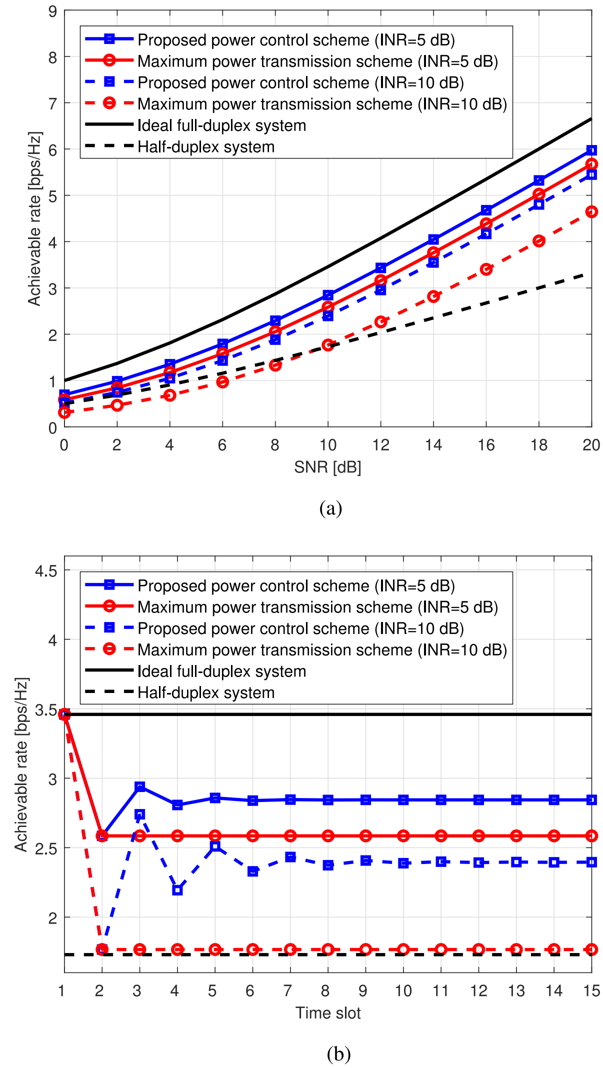
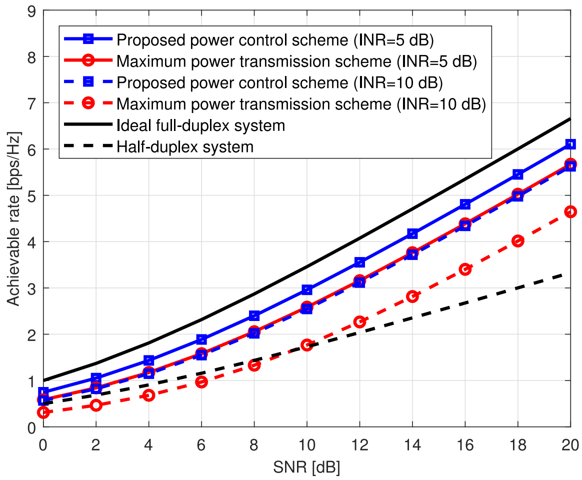


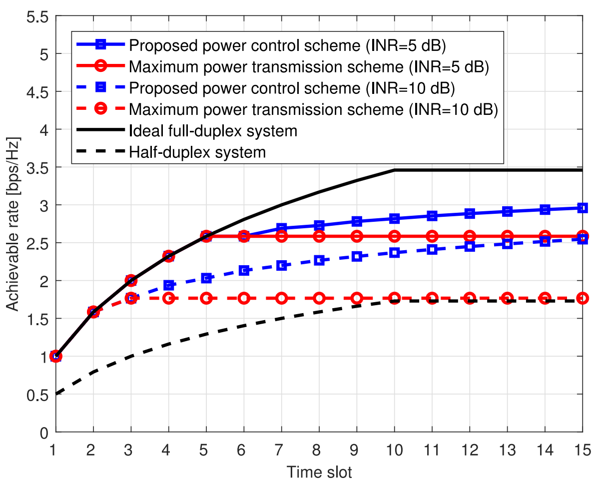
Fig. 5. Performance for the proposed power control and maximum power transmission schemes over time-varying channels. (a) Achievable rate versus SNR for different INRs in time slot 15. (b) Achievable rate versus time slot for different INRs.

proposed scheme when INR $= 0$, i.e., there is no residual SI. Therefore, the minimum achievable rate of the ideal FD system is superior to those of the other schemes. Fig. 4(b) shows the minimum achievable rate versus $p_r^{\max}$ for different INRs when SNR $= 25$ dB and $p_s = 25$ dBm. The minimum achievable rate of the proposed power control scheme is greater than that of the maximum power transmission scheme. It can be verified that when INR $= 5$ dB, the optimal $p_r^{*(t)}$ is $p_r^{\max}$ for $20 \leq p_r^{\max} \leq 23$ dBm and the optimal $p_r^{*(t)}$ is α for $23 \leq p_r^{\max} \leq 30$ dBm. Therefore, the minimum achievable rate of the proposed power control scheme and that of the maximum power transmission scheme are the same for $20 \leq p_r^{\max} \leq 23$ dBm. In addition, the minimum achievable rate of the maximum power transmission scheme increases for $20 \leq p_r^{\max} \leq 23$ dBm and decreases for $23 \leq p_r^{\max} \leq 30$ dBm. Similarly, when INR $= 10$ dB, the minimum achievable rate of the maximum power transmission scheme increases for $20 \leq p_r^{\max} \leq 21$ dBm and decreases for $21 \leq p_r^{\max} \leq 30$ dBm.

Fig. 5 plots the achievable rates for the proposed power control scheme over time-varying channels when $p_s = 25$ dBm, $p_r^{\max} = 25$ dBm, $|h_{sr}^{(t)}|^2 = 1$, and $|h_{rd}^{(t+1)}|^2 = 1$ for $t \geq 0$. Fig. 5(a) shows the achievable rate versus SNR for different INRs up to the 15th time slot. The achievable rate of the proposed power control scheme is greater than that of the maximum power transmission scheme regardless of SNR and INR values. Fig. 5(b) shows the achievable rate versus time slot for different INRs when SNR $= 10$ dB. It can be seen that the achievable rate of the proposed power control scheme is greater than that of the maximum power transmission scheme in each time slot. It can also be seen that the achievable rate of the proposed power control scheme changes from a time slot to another. This is because relay transmit power in each time slot is updated by its transmit power in the previous time slots in order to maximize the achievable rate. Therefore, the influence of the relay transmit power in the



(a)



(b)

Fig. 6. Performance of the proposed power control and maximum power transmission schemes over time-varying channels when channel gains are changed. (a) Achievable rate versus SNR for different INRs in time slot 15. (b) Achievable rate versus time slot for different INRs.

latest time slot on the achievable rate decreases as the number of time slots increases. Hence, the achievable rate becomes constant as the number of time slots goes to infinity. Since only the source transmits a signal in time slot 0, the achievable rate in time slot 1 is not affected by residual SI. Therefore, the achievable rate of all schemes is the same in time slot 1.

Fig. 6 plots the achievable rates for the proposed power control scheme over time-varying channels when $p_s = 25$ dBm, $p_r^{\max} = 25$ dBm, $|h_{sr}^{(t)}|^2 = 1$, and $|h_{rd}^{(t+1)}|^2 = 0.1(t+1)$ for $t \geq 0$. Fig. 6(a) shows the achievable rate versus SNR for different INRs up to the 15th time slot. Even if the channel gain changes, it is observed that the achievable rate of the proposed power control scheme is greater than that of the maximum power transmission scheme. Fig. 6(b) shows the achievable rate versus time slot for different INRs when SNR $= 10$ dB. In addition, a general trend seen in all achievable rate plots in Figs. 4–6 is that the minimum achievable rate increases as the SNR increases or the INR decreases.

VI. Conclusion

In this article, we proposed two power control schemes at the relay for one-way FD decode-and-forward relay networks over static and time-varying channels. The relay transmit power in each time slot was updated by the transmit power in the previous time slots. Even if the channel gain, channel estimation error variance, and noise variance are invariant, the transmit power at the relay should be different in each time slot to maximize the achievable rate. Since the proposed power control scheme has a closed-form solution, its complexity is very low.

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