Buffer-Aided Relaying Improves Throughput of Full-Duplex Relay Networks With Fixed-Rate Transmissions

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***Abstract*— The concept of buffer-aided relaying has recently emerged as a viable solution for improving the performance of wireless networks with half-duplex relays. In this letter, we show that buffer-aided relaying is also beneficial to wireless networks with ideal full-duplex (FD) relays. To this end, we investigate the two-hop FD relay network, which is comprised of a source, an FD relay equipped with a buffer, and a destination where a direct source–destination link does not exist. For this network, we assume that the source and the relay select their transmission rates from discrete sets of available transmission rates, and propose a corresponding buffer-aided relaying scheme, which maximizes the throughput. Our numerical results show that the proposed buffer-aided relaying scheme provides the significant throughput gains compared with conventional FD relaying schemes, which do not employ buffers at the relays.**

***Index Terms*— Buffer-aided relaying, full-duplex, throughput.**

I. Introduction

RECENTLY, full-duplex (FD) communication was shown to be feasible in practice, which has led to an enormous interest in FD communication, see [1], [2], and references therein. In FD communication, an FD node can receive and transmit simultaneously and in the same frequency band. As a result, an FD node transmits and receives in twice the time/frequency resources compared to a half-duplex (HD) node, which can only transmit and receive in orthogonal time or frequency resource blocks. As a result, the FD mode achieves significant performance gains compared to the HD mode. On the other hand, FD communication is impaired by self-interference (SI), which can degrade its performance. However, latest advances in hardware design have shown that the SI of an FD node can be suppressed by about 120 dB, see [2]. Hence, for some scenarios, even current SI suppression technology can make the SI negligible, resulting in ideal FD communication. As a result, in this letter, we study ideal FD communication without SI.

According to the latest technological predictions from the industry, e.g. see [3], the first immediate application of FD communication would be in FD relaying. In particular, the idea is to support current HD base stations by deploying FD relays which will relay information from the base stations to users that are at a significant distance from the base stations. The system model resulting from such a scenario is the two-hop FD relay network, which is comprised of a source, an FD relay, and a destination, where a direct source-destination link does not exist due to the assumed large distance between the source and the destination. On the other hand, in current and future wireless standards [4], the transmitting nodes select their transmission rates from discrete and finite sets of available transmission rates. Motivated by this, in this letter, we investigate the two-hop FD relay network for the practical case where in each time slot the source and the relay select their transmission rates from predefined and finite sets of available transmission rates. For this network, we propose an optimal buffer-aided relaying scheme which maximizes the achievable throughput. We note that an optimal buffer-aided relaying scheme which maximizes the throughput of the two-hop HD relay network with discrete transmission rate was investigated in [5].

Buffer-aided relaying is a relatively novel relaying concept, which was originally proposed for HD relay networks, see [6]–[8]. The underlaying idea is HD relays to use buffers in order to relax their stringent reception-transmission constraints. In particular, in contrast to conventional HD relaying, where reception and transmission at HD relays has a predetermined schedule which is independent of the qualities of the receiving and transmitting channels, in buffer-aided relaying, the HD relays adaptively select to either receive or transmit in a given time slot based on the qualities of the receiving and transmitting channels. Thereby, buffer-aided relaying always utilizes for transmission the stronger channels and, as a result, reduces the negative effects of fading. In this letter, we show that buffer-aided relaying is a more general concept since it can also be applied to FD relay networks. In particular, we show that instead of restricting the FD relays to always simultaneously receive and transmit in each time slot as in conventional FD relaying, *in buffer-aided FD relaying, the FD relays should select adaptively to either receive, transmit, or simultaneously receive and transmit in a given time slot based on the qualities of the receiving and transmitting channels*. Thereby, by using buffer-aided relaying we relax the stringent reception-transmission constraints for FD relays as well. We note that the reception-transmission constraints of FD relays can be relaxed only by the employment of buffers. To the best of our knowledge, there are only few works which explore the benefits of buffer-aided relaying for FD relay networks [9]–[11]. In particular, in [9] and [10], buffer-aided relaying was shown to improve the effective capacity (i.e., the constant supportable arrival rate at the source). Whereas, in [11], the authors show that buffers improve the rates given a more tight constraint on the codeword lengths.

II. System Model

We consider a two-hop FD relay network comprised of a source (S), an ideal FD relay (R) with a buffer of unlimited size, and a destination (D), where a direct S-D link does not exist. The transmission time is assumed to be

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divided into slots of equal lengths, where the number of time slots, denoted by N, satisfies $N \to \infty$. We assume that the S-R and R-D links are complex-valued unit-variance additive white Gaussian noise (AWGN) channels impaired by slow fading. Thereby, the fading is assumed to remain constant during one time slot and changes from one time slot to the next. In time slot i, let $\gamma_{SR}(i)$ and $\gamma_{RD}(i)$ denote the squares of the channel coefficient amplitudes of the S-R and R-D channels, respectively. Assuming constant powers at the source and the relay during all time slots, denoted by P_S and P_R, respectively, we can represent the channel capacities of the S-R and R-D links in time slot i as $C_{SR}(i) = \log_2\big(1 + P_S\gamma_{SR}(i)\big)$ and $C_{RD}(i) = \log_2\big(1 + P_R\gamma_{RD}(i)\big)$, respectively. In addition, we assume that the source and the relay transmit codewords which span one time slot and are encoded using capacity achieving codes. Moreover, we assume that the non-zero data rates of the codewords at the source and the relay are selected from a predetermined finite sets of date rates, denoted by $\mathcal{S} = \{S_1, S_2, \dots, S_K\}$ and $\mathcal{R} = \{R_1, R_2, \dots, R_L\}$, respectively, where K and L denote the total number of non-zero data rates available at the source and the relay, respectively.

III. Throughput Maximization

In this section, we provide the optimal buffer-aided relaying scheme which maximizes the throughput of the considered two-hop FD relay network with discrete transmission rates.

A. Problem Formulation

To model the rate selection at the source and the relay, we introduce rate selection variables $a_k(i)$ and $b_l(i)$ defined as

$$a_k(i) = \begin{cases} 1, & \text{if source uses rate } S_k \text{ in time slot } i \\ 0, & \text{otherwise,} \end{cases} \tag{1}$$

$$b_l(i) = \begin{cases} 1, & \text{if relay uses rate } R_l \text{ in time slot } i \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

Hence, if $a_k(i) = 1$, then, in time slot i, the source selects to transmit to the relay a codeword with rate S_k. Similarly, if $b_l(i) = 1$, then, in time slot i, the relay selects to transmit to the destination a codeword with rate R_l. Otherwise, if $a_k(i) = 0$ and $b_l(i) = 0$, rates S_k and R_l are not selected for transmission at the source and the relay in time slot i, respectively. Since a single data rate can be selected at the source and the relay in each time slot, the following has to hold

$$\sum_{k=1}^{K} a_k(i) \in \{0,1\} \text{ and } \sum_{l=1}^{L} b_l(i) \in \{0,1\}, \quad \forall i, \tag{3}$$

where if the sums on the left and right hand sides of (3) assume the value zero, it means that the source and relay are silent in time slot i, respectively. On the other hand, since the available transmission rates at the source and the relay are discrete, outages can occur. An outage occurs if the data rate of the transmitted codeword is larger than the capacity of the underlaying channel. To model the outages on the S-R and R-D links, we introduce the binary variables $O_{SR_k}(i)$ and $O_{RD_l}(i)$, respectively, defined as

$$O_{SR_k}(i) = \begin{cases} 1, & S_k \le C_{SR}(i) \\ 0, & \text{otherwise,} \end{cases};$$
$$O_{RD_l}(i) = \begin{cases} 1, & R_l \le C_{RD}(i) \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

Hence, in time slot i, outages on the S-R and R-D links will not occur if source and relay transmit codewords with rates S_k and R_l, and $S_k \le C_{SR}(i)$ and $R_l \le C_{RD}(i)$ hold, respectively. Otherwise, if $S_k > C_{SR}(i)$ and $R_l > C_{RD}(i)$ hold, outages will occur on the S-R and R-D channels in time slot i, respectively.

Let $Q(i)$ denote the number of bits normalized by the number of symbols of a codeword in the buffer of the relay in the beginning of time slot i (i.e., at the end of time slot $i-1$). For the proposed buffer-aided scheme, we assume that if rate R_l is selected at the relay in time slot i, and there is not sufficient amount of (normalized) information in the buffer of the relay in the beginning of time slot i, then the relay is silent. To model these silences at the relay due to insufficient information in the buffer, we introduce a binary variable $q_l(i)$, for $l = 1, \dots, L$, defined as

$$q_l(i) = \begin{cases} 1, & Q(i) \ge R_l \\ 0, & \text{otherwise.} \end{cases} \tag{5}$$

Using the above notations, the input-output relation for the buffer of the relay in the beginning of time slot $i+1$ is obtained as

$$\begin{aligned} Q(i+1) = Q(i) &+ \sum_{k=1}^{K} O_{SR_k}(i) a_k(i) S_k \\ &- \sum_{l=1}^{L} O_{RD_l}(i) q_l(i) b_l(i) R_l. \end{aligned} \tag{6}$$

On the other hand, the average number of bits/symbol that are received successfully at the relay and the destination, denoted by τ_{SR} and τ_{RD}, respectively, are obtained as

$$\tau_{SR} = \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} \sum_{k=1}^{K} O_{SR_k}(i) a_k(i) S_k \tag{7}$$

$$\tau_{RD} = \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} \sum_{l=1}^{L} O_{RD_l}(i) q_l(i) b_l(i) R_l. \tag{8}$$

Note that (8) is also the system throughput. Hence, our task is to maximize (8) by optimal selection of the rates at the source and the relay during all $N \to \infty$ time slots, i.e., by optimal selection of the variables $a_k(i)$ and $b_l(i)$, $\forall k, l, i$. Note that $a_k(i)$ and $b_l(i)$, $\forall k, l, i$ are the only variables with degrees of freedom in the considered system model, i.e., the variables $Q(i)$, and $q_l(i)$, $\forall k, l, i$, are completely dependent on $a_k(i)$ and $b_l(i)$, $\forall k, l, i$. To maximize (8) given the system constraints, we devise the following optimization problem

$$\begin{aligned} &\max_{a_k(i), b_l(i)} \ \tau_{RD} = \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} \sum_{l=1}^{L} O_{RD_l}(i) q_l(i) b_l(i) R_l \\ &\text{s.t. } a_k(i) \in \{0,1\};\ b_l(i) \in \{0,1\};\ (3);\ (5);\ \text{and } (6). \end{aligned} \tag{9}$$

Note that the maximization problem in (9) is non-concave and therefore very difficult to solve analytically, in general. However, the following lemma from [7, Th. 2] will provide us with the necessary tools for solving the maximization problem in (9).

Lemma 1: The throughput of the considered system is maximized when $a_k(i), b_l(i), \forall k, l, i$ are chosen such that

$$\lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} \sum_{k=1}^{K} O_{SR_k}(i) a_k(i) S_k = \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} \sum_{l=1}^{L} O_{RD_l}(i) b_l(i) R_l \quad (10)$$

holds. On the other hand, when (10) holds, the following also holds

$$\lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} \sum_{l=1}^{L} q_l(i) b_l(i) = \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} \sum_{l=1}^{L} b_l(i), \quad (11)$$

i.e., the number of time slots when $b_l(i) = 1$ and $q_l(i) = 0$ is negligible compared to the number of time slots when $b_l(i) = 1$ and $q_l(i) = 1$ as $N \to \infty$. Hence, when (10) holds, there is almost always sufficient amount of information in the buffer of the relay. Consequently, when (10) holds, the throughput in (8) can be written equivalently as

$$\tau_{RD} = \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} \sum_{l=1}^{L} O_{RD_l}(i) b_l(i) R_l \upsilon. \quad (12)$$

Proof: For proof, see the proof of [7, Th. 2]. ■

Now, if we add the constraint in (10) to the optimization problem in (9), we will obtain a new optimization problem, given by

$$\max_{a_k(i), b_l(i)} \tau_{RD} = \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} \sum_{l=1}^{L} O_{RD_l}(i) q_l(i) b_l(i) R_l$$
$$\text{s.t. } a_k(i) \in \{0, 1\};\, b_l(i) \in \{0, 1\};\, (3);\, (5);\, (6);\, \text{and}\, (10). \quad (13)$$

In the optimization problem in (13), since (10) holds, the objective function (i.e., the throughput) in (13) can be written equivalently as (12), according to Lemma 1. As a result, constraints (5) and (6) in the optimization problem in (13) become unnecessary and can be removed. Thereby, we obtain the following equivalent optimization problem

$$\max_{a_k(i), b_l(i), \forall k,l,i} \tau_{RD} = \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} \sum_{l=1}^{L} O_{RD_l}(i) b_l(i) R_l$$
$$\text{s.t. } a_k(i) \in \{0, 1\};\, b_l(i) \in \{0, 1\};\, (3);\, \text{and}\, (10). \quad (14)$$

Fortunately, (14) can be solved analytically and thereby the optimal values of $a_k(i), b_l(i), \forall k, l, i$ can be obtained in closed-form. In other words, we can obtain the optimal buffer-aided relaying scheme which maximizes the throughput of the considered two-hop FD relay network in an analytical form. This is shown in the following.

B. Optimal Protocol for Throughput Maximization

Before we state the solution of (14), we first introduce some auxiliary notations. In time slot i, we compute the products $O_{SR_k}(i) S_k$, $\forall k$, and collect these products in a set $\mathcal{A}(i)$. Moreover, in time slot i, we compute the products $O_{RD_l}(i) R_l$, $\forall l$, and collect these products in a set $\mathcal{B}(i)$. Hence, sets $\mathcal{A}(i)$ and $\mathcal{B}(i)$ are given by

$$\mathcal{A}(i) = \left\{O_{SR_1}(i) S_1, O_{SR_2}(i) S_2, \ldots, O_{SR_K}(i) S_K\right\}, \quad (15)$$
$$\mathcal{B}(i) = \left\{O_{RD_1}(i) R_1, O_{RD_2}(i) R_2, \ldots, O_{RD_L}(i) R_L\right\}. \quad (16)$$

Using sets $\mathcal{A}(i)$ and $\mathcal{B}(i)$, we define $S_{\max}(i)$ and $R_{\max}(i)$ as

$$S_{\max}(i) = \max\{\mathcal{A}(i)\} \text{ and } R_{\max}(i) = \max\{\mathcal{B}(i)\}. \quad (17)$$

We refer to $S_{\max}(i)$ and $R_{\max}(i)$ as the *maximal feasible rates* on the S-R and R-D links in time slot i, respectively, since for any rates in $\mathcal{S}$ and $\mathcal{R}$ higher than $S_{\max}(i)$ and $R_{\max}(i)$ outages occur on the S-R and R-D links, respectively. In addition, let $C(i) \in \{0, 1\}$ denote the outcome of a coin flip in time slot i with probability $P_C = \Pr\{C(i) = 1\}$. We are now ready to provide the solution of (14).

Theorem 1: For the considered two-hop FD relay network, the optimal values of the rate selection variables $a_k(i)$ and $b_l(i)$, $\forall k, l, i$, which maximize the throughput are given as follows.

Case 1: If $E\{S_{\max}(i)\} \le E\{R_{\max}(i)\}$, where $E\{\cdot\}$ denotes expectation, the optimal rate selection variables are given by

$$a_k(i) = \begin{cases} 0, & \text{if } S_k \neq S_{\max}(i) \\ 1, & \text{if } S_k = S_{\max}(i) \end{cases} \quad (18)$$

$$b_l(i) = \begin{cases} 0, & \text{if } R_l \neq R_{\max}(i) \\ 1, & \text{if } R_l = R_{\max}(i). \end{cases} \quad (19)$$

Case 2: If $E\{S_{\max}(i)\} > E\{R_{\max}(i)\}$, the optimal rate selection variables are given by

$$a_k(i) = \begin{cases} 0, & \text{if } S_k \neq S_{\max}(i) \\ & \quad \text{or } \big(S_k = S_{\max}(i) \text{ and } C(i) = 0\big) \\ 1, & \text{if } S_k = S_{\max}(i) \text{ and } C(i) = 1, \end{cases} \quad (20)$$

$$b_l(i) = \begin{cases} 0, & \text{if } R_l \neq R_{\max}(i) \\ 1, & \text{if } R_l = R_{\max}(i), \end{cases} \quad (21)$$

where $P_C = E\{R_{\max}(i)\}/E\{S_{\max}(i)\}$. Using the optimal rate selection variables defined above, the maximum throughput is given by

$$\tau_{RD} = \min\left\{\lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} S_{\max}(i)\, ,\, \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} R_{\max}(i)\right\} = \min\big\{E\{S_{\max}(i)\}, E\{R_{\max}(i)\}\big\}. \quad (22)$$

Proof: We only show a sketch of the proof since the proof is relatively straightforward. First, from (14) we obtain a new optimization problem by relaxing the constraints $a_k(i) \in \{0, 1\}$ and $b_l(i) \in \{0, 1\}$ to $0 \le a_k(i) \le 1$ and $0 \le b_l(i) \le 1$, respectively, and relaxing constraint (3) to $0 \le \sum_{k=1}^{K} a_k(i) \le 1$ and $0 \le \sum_{l=1}^{L} b_l(i) \le 1$. The resulting new optimization problem is concave and therefore can be relatively easily solved using the Lagrange method. Solving the corresponding Lagrangian of this optimization problem reveals that the optimal $a_k(i)$ and $b_l(i)$, $\forall k, l, i$, are always at the boundaries 0 and 1. As a result, the solution of this optimization problem is also the solution of the optimization problem in (14). On the other hand, (10) in (14), denoted by μ, given by $0 < \mu \le 1$ and $\mu = 0$, respectively. Moreover, the probability P_C is obtained such that constraint (10) in (14) holds. ■

Theorem 1 has the following interpretation. In time slot i, source and relay select the highest rates which do not cause outages on the S-R and R-D links, respectively. However, when Case 2 holds, although in some time slots the source has a chance to transmit since the S-R link is not in outage, the source remains silent with probability $1 - P_C$ in order to make the buffer at the relay to be rate-stable, i.e., not to cause buffer over-flow.

C. Practical Considerations

In order for the proposed buffer-aided relaying scheme to be implemented in practice, certain amount of channel state information (CSI) and feedback is required. In particular, the relay and the destination need CSI of the S-R and R-D links for coherent detection, respectively. In addition, using the acquired CSI, the relay and the destination can compute the highest feasible rates which do not cause outages on the S-R and R-D links, respectively, i.e., compute $S_{\max}(i)$ and $R_{\max}(i)$, respectively. Next, the relay and the destination feedback the corresponding $S_{\max}(i)$ and $R_{\max}(i)$ to the source and the relay using $\log_2(K)$ and $\log_2(L)$ bits of information, respectively. Using this feedback information, the source and the relay can select the corresponding transmission rates. On the other hand, if either source or relay do not receive feedback information, they should be silent in the corresponding time slot, respectively. Note that, for the proposed protocol, the source and the relay do not transmit with rates which cause outages since source and relay are silent when outages can occur. Hence, using the proposed protocol, resending information is not needed.

On the other hand, if conventional relaying where buffers are not used is implemented on the considered network, the relay and the destination would also need CSI of the S-R and R-D links for coherent detection, respectively. In addition, when a codeword is not decoded correctly at the destination, feedback is also required to inform the source and the relay of the unsuccessful detection in order for the undecoded information to be resend.

Hence, as can be seen from the discussion above, the conventional relaying scheme has a similar signaling overhead as the proposed buffer-aided relaying scheme. On the other hand, we also note that the proposed buffer-aided relaying scheme achieves a better delay than the conventional relaying scheme. This is due to the fact that, using the proposed buffer-aided relaying scheme, the destination receives information in time slots i for which $q(i)R_{\max}(i) > 0$ hold, which is more frequent than in conventional relaying where the destination will receive information in a time slot i if the S-R and R-D links are not in outages in time slots $i-1$ and i, respectively.

IV. Numerical Results

For the numerical example in this section, we assume independent identically distributed Rayleigh fading on the S-R and R-D links. In addition, for simplicity, we assume that $\mathcal{S} = \mathcal{R}$, $S_k = R_l$ for $k = l$, and $S_k = R_k = kR$, where $k = 1, 2, \dots, K$. All numerical results presented in this section are obtained by simulations.

In Fig. 1, we illustrate the maximum throughput achieved with the proposed buffer-aided relaying scheme for $K = 1, 2, 4, 16$ available transmission rates, where KR is kept fixed to $KR = 1$ bit/symb, i.e., $R = 1/K$. Thereby, two throughputs are shown. One assuming unlimited buffer size, $Q_{\max} \to \infty$, and the other assuming limited buffer size of $Q_{\max} = 20R_K$. As can be seen from Fig. 1, although the proposed buffer-aided relaying scheme was derived for $Q_{\max} \to \infty$, it works almost without any throughput loss for $Q_{\max} = 20R_K$ as well. As benchmark, we also show the throughputs achieved with conventional FD relaying where the source is also assumed to receive feedback from the relay informing the source about the maximal feasible rate in each time slot. Note that, since in conventional FD relaying a buffer is not used at the relay, in time slot i, the FD relay can only transmit with rate with which the source transmitted in the previous, i.e, $(i-1)$-th time slot. In addition, for completeness, we also show as benchmark the throughput achieved for a HD relay using the scheme in [5].

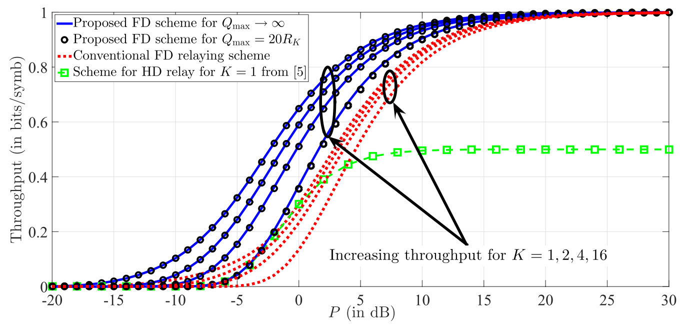

Fig. 1. Throughputs achieved with the proposed buffer-aided relaying scheme and with conventional FD relaying for different numbers of available transmission rates K as a function of the transmit SNR $P = P_S = P_R$.

Fig. 1 shows that the proposed buffer-aided scheme indeed achieves significant performance gains compared to conventional FD relaying. For example, there is 3 dB, 4 dB, and 5 dB power gains for $K = 1$, $K = 2$, and $K = 4$, respectively.

Now, since buffer-aided relaying improves the throughput of the simplest FD relay network with fixed-rate transmissions, we conjecture that buffer-aided relaying also improves the throughput of more complex FD relay networks with fixed-rate transmissions.

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