Spectral-Efficient Bidirectional Decode-and-Forward Relaying for Full-Duplex Communication

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Abstract—As a benefit of sophisticated interference cancelation techniques, full-duplex (FD) transceiver design may become feasible, even possibly on the aggressive time-scale of fifth-generation (5G) wireless communication systems. Hence, we further develop the recent bidirectional relaying [i.e., the two-way half-duplex (HD) relaying] aided cooperative network to its more radical counterpart, which entirely consists of FD entities for the sake of adapting to emerging FD communication scenarios. In more detail, the proposed bidirectional relaying-aided FD network operates in a decode-and-forward (DF) style and exploits the advanced network coding (NC) concept. We analyze its achievable error-free data rate, where the effects of both the self-interference (SI) and of the geographic location of the relay node (RN) are evaluated. Furthermore, the potential variations of the networking scenario are also taken into account. Based on this theoretical analysis, the optimum rate allocation scheme maximizing the system’s error-free data rate is found. Our results demonstrate that a significant spectral efficiency gain is achieved by the proposed system.

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I. INTRODUCTION

A set of cooperating mobiles may be viewed as a distributed multiple-input–multiple-output (MIMO) system relying on the spatially distributed single antennas of the cooperating mobiles, where the correlation of the antenna elements imposed by their insufficient separation experienced in conventional MIMO systems is efficiently avoided [1]. Furthermore, the detrimental path-loss effects may also be significantly mitigated by incorporating relay nodes (RNs) along the source-to-destination link, which results in an increased radio coverage area. However, despite these benefits, cooperation techniques impose their own problems as well. In the early stage of the node-cooperation research, constrained by the fact that practical transceivers cannot transmit and receive at the same time, the classic relaying regimes [2]–[4] had to rely on a pair of orthogonal channels for the reception and transmission at the RN. This implies that the conventional relaying regimes typically 42 impose a factor-two throughput loss compared to their direct-transmission-based counterparts.

For the sake of recovering the throughput loss imposed 44 by half-duplex (HD) relaying, sophisticated relaying protocols 46 may be used [5]–[7]. For the particular scenario of two nodes exchanging messages with the aid of an RN, HD-based two-way relaying was devised in [5] and [8], which is capable of 49 efficiently compressing the four distinct transmission phases required by conventional relaying regimes into three or even just two phases. Another conceptually straightforward solution 52 conceived for avoiding the HD-relaying-induced throughput 53 loss is that of replacing the HD relay (HDR) by a full-duplex 54 relay (FDR). In this spirit, the early discussion of a practical 55 FDR system was raised in [9]. The critical problem incurred in FDR is that a high-power interfering signal will be fed back 57 to the RN’s input from the RN’s output, which results in the 58 so-called “self-interference” (SI). Hence, abundant studies of 59 the FDR concept focused on canceling or suppressing the SI, e.g., as shown in [10] and [11]. Along with the development of SI cancelation techniques, the theoretical analysis of the achievable performance of FDR systems was also carried out 63 in [12]–[14], where the impact of SI was taken into account. 64 Furthermore, the research of FDR systems was extended to 65 multihop scenarios [15], [16].

However, if we extend our horizon a little further, the full-duplex (FD) transceiver design has substantial benefits beyond 68 the scope of FDR systems. Recently, researchers at Stanford University made substantial progress in building FD radios 70 [17], [18], although they still relied on utilizing multiple antennas. As a radical improvement of their early works, the first complete WiFi single-antenna aided FD link was reported 73 a little later in [19], which is capable of reducing the SI noise floor by providing as much as 110 dB of linear cancellation, 80 dB of nonlinear cancellation, and 60 dB of analog cancelation. Based on these achievements in FD transceiver design, it is reasonable to expect that practical in-band FD systems may become a commercial reality in time for replacing the emerging fifth-generation (5G) wireless networks [20].
Given the aforementioned advances, the time has come for incorporating the FD technique into each and every component of a cooperative network. In this spirit, the early attempt of adapting the spectral-efficient two-way relaying protocol to an FD communication scenario had been reported by Cheng et al. [21] and by Cui et al. [22], where amplify-and-forward (AF) relaying and the associated analog network coding (NC) concept were invoked at the RN. Then, Zheng [23] further extended their networking prototype to a multihop architecture.

Against this background, our novel contributions are as follows:

- We conceive a network topology, where a pair of FD users exchange their information with the aid of an FD RN. Correspondingly, we propose the bidirectional decode-and-forward (DF) relaying concept for the sake of retaining the high spectral efficiency of FD communication, while reducing the path-loss effect. Based on DF relaying, a beneficial digital NC is conceived for the RN.
- We analyze the maximum achievable error-free data rate (MAEFDR) of the proposed bidirectional DF-relaying-aided FD network (BD-DF-FDN), where the effects of both the SI and of the geographic location of the RN are evaluated.
- The potential unbalance between the receive duration and the transmit duration of the RN is also taken into account in our analysis. Moreover, the MAEFDR of the proposed system is maximized by our optimum transmission rate allocation approach.

The remainder of this paper is organized as follows: The network topology of our bidirectional DF relaying regime and a range of important assumptions are introduced in Section II. Consequently, the convex region of our system is characterized in Section III. Then, we commence the analysis of MAEFDR of the proposed BD-DF-FDN in Section IV, where the impact of the SI and that of the geographic RN location, as well as that of the variations of the network framework, are taken into account. Based on our optimum transmission rate allocation scheme, the simulation results characterizing the MAEFDR are provided in Section V. Finally, we conclude this paper in Section VI.

II. SYSTEM MODEL

Here, we conceive the aforementioned bidirectional DF-relaying-aided FD network, which is referred to as “BD-DF-FDN,” where two FD users, namely, “User 1” and “User 2,” exchange their information with the aid of an FD DF-TW (FD-DF-TW) RN. Observe in Fig. 1 that User 1 and User 2 broadcast their kth information frames $I_1[k]$ and $I_2[k]$ at the 129 rates of $R_1$ and $R_2$, respectively. Correspondingly, the RN receives these signals and attempts to detect both $I_1[k]$ and $I_2[k]$ and then employs the advanced NC concept in [24]–[27] for creating another information frame $I_3[k]$, which accommodates both the information carried by $I_1[k]$ and that carried by $I_2[k]$. In more detail, let $|I[k]|$ represent the number of information bits carried by $I[k]$. Then, without loss of generality, we may assume that $|I_2[k]| \geq |I_1[k]|$. Hence, after detecting $I_1[k]$ and 136 $I_2[k]$, the RN pads the frame $I_1[k]$ with zero bits for generating 137 $I_1^p[k]$, which satisfies $|I_1^p[k]| = |I_2[k]|$. Resultantly, the information frame $I_3[k]$ is created by the XOR operation at the RN as 139 follows:

\[ I_3[k] = I_1^p[k] \oplus I_2[k]. \]  

The entire process described earlier may be referred to as the 141 uplink (UL) of BD-DF-FDN.

As a substantial advantage of FD transceivers, along with 143 the aforementioned UL transmission of BD-DF-FDN, the RN 144 is capable of simultaneously forwarding the information frame 145 $I_3[k - \tau]$ in the same frequency band to both User 1 and to 146 User 2, which was generated by the RN \( \tau \) time slots ago. 147 Meanwhile, User 1 attempts to detect $I_3[k - \tau]$, namely, the 148 frame that was originally transmitted by User 2 and carried 149 by $I_3[k - \tau]$, which is achieved by implementing the XOR 150 operation of $I_1^p[k - \tau] \oplus I_3[k - \tau]$. A similar detection process 151 is implemented by User 2. These operations constitute the 152 downlink (DL) of the BD-DF-FDN in Fig. 1.

As shown at the top of the antennas of User 1 and of User 2 154 as well as of the RN in Fig. 1, the high-power transmitted signal 155 of these transceivers will be fed back to their receiver’s input, 156 which results in the SI problem. Hence, instead of directly 157 forwarding $I_3[k]$, the RN forwards a previously generated in- 158 formation frame $I_3[k - \tau]$ in the DL of BD-DF-FDN, for the 159 sake of guaranteeing that the output of the RN always remains 160 uncorrelated with its simultaneous input, which is a precondi- 161 tion of achieving high-quality SI cancelation, as detailed in [11] 162 and 13. The number of information bits transmitted by the 163 RN has to be equal to that input into it. Hence, $I_1[k - \tau]$ and 164 $I_2[k]$ have the same number of information bits. 2 Moreover, 165 it is assumed that User 1, User 2, and the RN may have the 166 same SI suppression capability, owing to employing the same 167 FD transceiver technique.

Definition 2.1: The time required by User 1 and 2 for trans- 169 mitting $I_1[k]$ and $I_2[k]$ to the RN via the UL of the BD-DF-FDN 170

1Without loss of generality, we explicitly take the case of $|I_2[k]| \geq |I_1[k]|$ as an example. Apparently, the detailed NC operations associated with another case of $|I_2[k]| < |I_1[k]|$ should obey similar principles.

2This implies that if $I_1[k - \tau] = I_1^p[k - \tau] \oplus I_2[k - \tau]$, then we may assume that $I_3[k - \tau] = I_4[k - \tau] = I_1^p[k - \tau]$, and $|I_2[k - \tau]| = |I_2[k]|$. 

Fig. 1. Fundamental network topology of BD-DF-FDN: two FD users, namely, “User 1” and “User 2”, exchange their information with the aid of an FD-DF-TW relaying-based RN.
in Fig. 1 is regarded as the UL period. Simultaneously, the
time required by the RN for broadcasting $k_3[k]$ to both User 1 and
2 via the DL of the BD-DF-FDN is regarded as the DL period. Finally, the time required for completing a pair of UL and DL periods is regarded as a complete BD-DF-FDN period. Naturally, the BD-DF-FDN period is equal to max [UL period, DL period].

The path-loss reduction gain (PLRG) achieved by the reduced transmission distance experienced in cooperative systems is introduced next. As detailed in [28], the average PLRGs of the User-1-to-RN link and of the User-2-to-RN link are given by $G_1 = (D/D_1)^\alpha$ and $G_2 = (D/D_2)^\alpha$, respectively, where $D, D_1, D_2$ are the distances from User 1 to User 2, from User 1 to the RN, and from User 2 to the RN, respectively. Throughout this paper, the path-loss exponent is fixed to $\alpha = 4$, for representing a typical urban area. In practice, the direct link between User 1 and User 2 of our system may become weak, while simultaneously being interfered by the strong and weak, while simultaneously being interfered by the strong

In more detail, considering the UL in Fig. 1, if the RN $h_3$ for the User-1-to-RN link and of the User-2-to-RN link, respectively, while $S_1, S_2, S_3$ represent the symbols transmitted by User 1, User 2, and the RN, respectively. Finally, $n_3$ is the additive white Gaussian noise (AWGN) imposed on the RN, which obeys $n_3 \sim CN(0, \sigma^2$).

Based on these assumptions, the signal received at the RN within the transmission of a specific information frame is given by $y_3 = h_1 \sqrt{G_1} S_1 + h_2 \sqrt{G_2} S_2 + h_3 S_3 + n_3$, where $h_1$ and $h_2$ are the fading coefficients of the User-1-to-RN link and of the User-2-to-RN link, respectively, while $S_1, S_2, S_3$ represent the symbols transmitted by User 1, User 2, and the RN, respectively. Finally, $n_3$ is the additive white Gaussian noise (AWGN)

$y_3 = h_1 \sqrt{G_1} S_1 + h_2 \sqrt{G_2} S_2 + h_3 S_3 + n_3$. \hspace{1cm} (2)

**III. CONVEX REGION OF $(R_1 + R_2)$**

Based on the system model built in Section II, particularly on the physical concepts introduced in Section II, we now define

\begin{align*}
C\left(\frac{\gamma_1}{\gamma_2 + \gamma_3 + 1}\right) &= \frac{|h_1|^2 G_1 P_1}{\gamma_1} \\
&= \frac{|h_2|^2 G_2 P_2 + |h_3|^2 P_3 + \sigma^2}{\gamma_2 + \gamma_3 + 1}. \hspace{1cm} (4)
\end{align*}

In this case, the associated capacity of the User-1-to-RN link may be formulated as $4 C\left(\gamma_1/(\gamma_2 + \gamma_3 + 1)\right)$, which is also the lower bound of $R_1$, namely, $R_1^{\text{lower}}$, when simultaneously satisfying the flawless decodability of information frames received at the RN, while simultaneously attaining the maximum sum rate of $(R_1 + R_2)$.

$3$This implies that the higher one between $\gamma_1$ and $\gamma_2$ is always represented by the label "\gamma_2."

$4$It is exploited herein that $C(x) = \log_2 (1 + x)$. 

Without loss of generality, we may assume that $\gamma_2 \geq \gamma_1$. Since the RN in Fig. 1 relies on the DF protocol, we have to carefully avoid the error propagation problem. Hence, the transmission rates $R_1$ and $R_2$ have to be specifically chosen to ensure that the information frames $I_1[k]$ and $I_2[k]$ can be perfectly decoded at the RN. According to the multiple-access channel capacity theorem in [29], these rate pairs $(R_1, R_2)$ have to lie within the convex region shown in Fig. 2. Furthermore, the rate pairs $(R_1, R_2)$ distributed along the segment $AB$ will result in the maximum sum rate of $(R_1 + R_2)$.

In more detail, considering the UL in Fig. 1, if the RN first decodes the information frame $I_1[k]$, it may regard the information frame $I_2[k]$ as a contamination. Hence, according to (2), the overall signal-to-inference-plus-noise power ratio (SINR) of the User-1-to-RN link is given by

$$\text{SINR}_{1 \rightarrow 3} = \frac{|h_1|^2 G_1 P_1}{|h_2|^2 G_2 P_2 + |h_3|^2 P_3 + \sigma^2} = \frac{\gamma_1}{\gamma_2 + \gamma_3 + 1}. \hspace{1cm} (4)$$
Then, the RN proceeds to decode the information frame $I_2[k]$. Since the information frame $I_1[k]$ has been perfectly decoded, the RN is capable of perfectly eliminating the interference component $h_1 \sqrt{G_1 S_1}$ from (2).\(^5\) Resultantly, the SINR of the User-2-to-RN link is given by

$$\text{SINR}_{2 \rightarrow \text{RN}} = \frac{|h_2|^2 G_2 P_2}{|h_3|^2 P_3 + \sigma^2} = \frac{\gamma_2}{\gamma_3 + 1}$$

which yields the upper bound of $R_2$, namely, $R_{2}^{\text{upper}}$. Hence, we obtain a specific rate pair of $(R_1 + R_2)$ as follows:

$$\begin{align*}
R_1^{\text{lower}} &= C \left( \frac{\gamma_1}{\gamma_1 + \gamma_3 + 1} \right) \\
R_1^{\text{upper}} &= C \left( \frac{\gamma_1}{\gamma_1 + \gamma_3 + 1} \right) \\
R_2^{\text{lower}} &= C \left( \frac{\gamma_2}{\gamma_2 + \gamma_3 + 1} \right) \\
R_2^{\text{upper}} &= C \left( \frac{\gamma_2}{\gamma_2 + \gamma_3 + 1} \right)
\end{align*}$$

This is represented as the point $A(R_1^{\text{upper}}, R_2^{\text{lower}})$ in Fig. 2. Alternatively, the RN may first decode $I_2[k]$ and then proceed to decode $I_1[k]$. Correspondingly, this case results in the lower bound of $R_2$ and the upper bound of $R_1$, which may be formulated as Case B as follows:

$$\begin{align*}
R_1^{\text{upper}} &= C \left( \frac{\gamma_1}{\gamma_1 + \gamma_3 + 1} \right) \\
R_2^{\text{lower}} &= C \left( \frac{\gamma_2}{\gamma_2 + \gamma_3 + 1} \right)
\end{align*}$$

Theorem 3.1: To simultaneously satisfy both the decodability of the information frames received at the RN and the attainability of the maximum sum rate of the BD-DF-FDN shown in Fig. 1, the rate pairs $[R_1(\lambda), R_2(\lambda)]$ have to obey

$$\begin{align*}
R_1(\lambda) &= \lambda \left[ C \left( \frac{\gamma_1}{\gamma_1 + \gamma_3 + 1} \right) - C \left( \frac{\gamma_1}{\gamma_1 + \gamma_3 + 1} \right) \right] \\
&\quad + C \left( \frac{\gamma_1}{\gamma_1 + \gamma_3 + 1} \right), \quad 0 \leq \lambda \leq 1 \\
R_2(\lambda) &= \lambda \left[ C \left( \frac{\gamma_2}{\gamma_2 + \gamma_3 + 1} \right) - C \left( \frac{\gamma_2}{\gamma_2 + \gamma_3 + 1} \right) \right] \\
&\quad + C \left( \frac{\gamma_2}{\gamma_2 + \gamma_3 + 1} \right), \quad 0 \leq \lambda \leq 1
\end{align*}$$

where $R_1(\lambda)$ or $R_2(\lambda)$ is the transmit rate of User 1 or User 2 during the UL period, respectively. $\lambda$ is the time-sharing parameter, which determines the time that User $i$ transmits in its upper bound rate $R_i^{\text{upper}}$ and in its lower bound rate $R_i^{\text{lower}}$. The rate pairs of $[R_1(\lambda), R_2(\lambda)]$ stipulated by (7) constitute the segment $\overline{AB}$ in Fig. 2.

\(^5\)In this paper, we assume that perfect channel-state information (CSI) is always available at the receivers. Moreover, since all the nodes of BD-DF-FDN work in FD style and the related channels are assumed to be reciprocal, this assumption will also result in CSI becoming available at the transmitters.

\(^6\)Alternatively, $N$ is also the time required for transmitting $|I_2[k]|$ information bits at the rate of $R_2(\lambda)$.  

IV. Maximum Achievable Error-Free Data Rate

Based on the fundamental architecture of BD-DF-FDN, as demonstrated in Fig. 1 in Section II, we will categorize the BD-DF-FDN into several distinct scenarios. In different subcases, its MAEFD for will be characterized by different formulas. During the entire derivation process, the rate pair $(R_1(\lambda), R_2(\lambda))$ will obey the convex region stipulated in Section III. Particularly, the monotonicity determined by (7) will be referred to everywhere.

A. Case I: $\gamma_2 \geq \gamma_1 + (1/(\gamma_3 + 1))\gamma_1^2$

In this case, we have the relationship of $C(\gamma_2/(\gamma_1 + \gamma_3 + 1)) \geq C(\gamma_1/(\gamma_3 + 1))$. According to (7), $R_2(\lambda)$ is a monotonically decreasing function of the rate-allocation parameter $\lambda$, while $R_1(\lambda)$ is a monotonically increasing function of $\lambda$, and $R_2(1) = C(\gamma_2/(\gamma_1 + \gamma_3 + 1))$, $R_1(1) = C(\gamma_1/(\gamma_3 + 1))$. Hence, we can readily arrive at

$$R_2(\lambda) \geq C \left( \frac{\gamma_2}{\gamma_1 + \gamma_3 + 1} \right) \geq C \left( \frac{\gamma_1}{\gamma_3 + 1} \right) \geq R_1(\lambda).$$

Therefore, the capacity of the RN-to-User-1 link is $C(\gamma_1/(\gamma_3 + 1))$. Similarly, it can be shown that the capacity of the RN-to-User-2 link is $C(\gamma_2/(\gamma_3 + 1))$.

To satisfy that $I_2[k]$ and $I_1[k]$ are decodable by User 1 and 2, respectively, $I_1[k]$ has to be transmitted at the lower rate being tsoever the capacity of the RN-to-User-1 link and that of the RN to-User-2 link. Since we have $C(\gamma_2/(\gamma_3 + 1)) \geq C(\gamma_1/(\gamma_3 + 3101))$, $I_1[k]$ is first transmitted at the rate of $C(\gamma_1/(\gamma_3 + 1))$. As stated in Section II, the amount of information transmitted via $\overline{ACE}$ is identical to that transmitted via $\overline{ACE}$ transmitted via the RN-to-User-1 link during the DL period. Hence, it can be anticipated that the UL transmission session 316 shown in Fig. 1 will terminate earlier than the DL session. As 317 sequentially, the framework of the BD-DF-FDN shown in Fig. 1 is actually transformed into that shown in Fig. 3, where the time 318 following the termination of the UL period up to the completion 320 of the DL transmission is referred to as the "Residual-Period."  

As illustrated in Fig. 3, transmitting $I_1[k]$ and $I_2[k]$ to the RN is completed during the UL period at the rates of $R_1(\lambda)$ and $R_2(\lambda)$, respectively, which implies that we may have $|I_1[k]| = N R_1(\lambda)$, $|I_2[k]| = N R_2(\lambda)$, where $N$ is the time required for 325 transmitting $|I_1[k]|$ number of information bits at the rate of $R_1(\lambda)$.  

Alternatively, $N$ is also the time required for transmitting $|I_2[k]|$ information bits at the rate of $R_2(\lambda)$.  

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As stated before, during the DL period, the RN will first broadcast $I_3[k]$ at the lower rate between the capacity of the RN-to-User-1 link and that of the RN-to-User-2 link, until the specific one from the set of $I_1[k]$ and $I_2[k]$, which carries less information bits, has been completely transmitted/received. In this case, according to (8), we have $R_2(\lambda) \geq R_1(\lambda)$, which leads to $|I_2[k]| \geq |I_1[k]|$. Hence, the transmission of the information bits of $I_1[k]$ via the RN-to-User-2 link will terminate first during the DL period. Accordingly, the length of the residual period shown in Fig. 3 is determined by the transmission of the information bits of $I_2[k]$ via the RN-to-User-1 link.

During the UL period, the RN broadcasts $I_1[k]$ at the rate of $C(\gamma_1/(\gamma_3 + 1))$. Hence, during the residual period, there are $|I_2[k]| - N \cdot C(\gamma_1/(\gamma_3 + 1))$ information bits of $I_2[k]$, which still have to be transmitted via the RN-to-User-1 link. Meanwhile, since the transmission via the UL has been terminated, we would no longer incur any SI during the residual period. Consequently, the capacity of the RN-to-User-1 link is increased to $C(\gamma_1)$. Hence, the length of the residual period should be $(|I_2[k]| - N \cdot C(\gamma_1/(\gamma_3 + 1))/C(\gamma_1))$.

**Definition 4.1:** We divide the number of decodable information bits exchanged between User 1 and User 2 with the aid of our BD-DF-FDN by the associated time to define the overall achievable error-free data rate.

Hence, the achievable error-free data rate of BD-DF-FDN for Case 1 is given by

$$R_{BD-DF-FDN, \ Case \ 1}(\lambda) = \frac{|I_1[k]| + |I_2[k]|}{\text{BD-DF-FDN period}} = \frac{NR_1(\lambda) + NR_2(\lambda)}{N + \frac{|I_2[k]| - N \cdot C(\gamma_1/(\gamma_3 + 1))}{C(\gamma_1)}} = \frac{C\left(\frac{\gamma_1 + \gamma_2}{\gamma_1 + \gamma_3 + 1}\right) C(\gamma_1)}{C(\gamma_1) - C\left(\frac{\gamma_1}{\gamma_1 + \gamma_3 + 1}\right) + R_2(\lambda)}.$$  

(10)

According to (10), $R_{BD-DF-FDN, \ Case \ 1}(\lambda)$ is a monotonically decreasing function of $R_2(\lambda)$. Hence, we may assign to User 2 its minimum transmission rate of $R_2(1) = C(\gamma_2/(\gamma_1 + \gamma_3 + 1))$ during the UL period of BD-DF-FDN. Given this optimum rate allocation scheme, the MAEFDR of Case 1 of BD-DF-FDN may be expressed as

$$R_{BD-DF-FDN}^{\text{max}}(\lambda) = \frac{C\left(\frac{\gamma_1 + \gamma_2}{\gamma_1 + \gamma_3 + 1}\right) C(\gamma_1)}{C(\gamma_1) + C\left(\frac{\gamma_2}{\gamma_1 + \gamma_3 + 1}\right) - C\left(\frac{\gamma_1}{\gamma_1 + \gamma_3 + 1}\right)}$$

$$\text{if } \gamma_2 \geq \gamma_1 + \left(\frac{1}{\gamma_3 + 1}\right) \gamma_1^2.$$  

(11)

**B. Case 2:** $\gamma_1 + (1/(\gamma_3 + 1)) \gamma_1^2 > \gamma_2 \geq \gamma_1$

In this case, it is possible to arrive at

$$\begin{align*}
R_2(\lambda_1) &= C\left(\frac{\gamma_2}{\gamma_1 + \gamma_3 + 1}\right) \\
R_2(\lambda_0) &= R_1(\lambda_0)
\end{align*}$$

(12)

where the specific values of the associated rate-allocation parameters are given by

$$\begin{align*}
\lambda_1 &= \frac{C\left(\frac{\gamma_1}{\gamma_1 + \gamma_3 + 1}\right) - C\left(\frac{\gamma_2}{\gamma_1 + \gamma_3 + 1}\right)}{C\left(\frac{\gamma_2}{\gamma_1 + \gamma_3 + 1}\right) + C\left(\gamma_2/(\gamma_1 + \gamma_3 + 1)\right) - C\left(\frac{\gamma_1}{\gamma_1 + \gamma_3 + 1}\right)} \\
\lambda_0 &= \frac{C\left(\frac{\gamma_2}{\gamma_1 + \gamma_3 + 1}\right) + C\left(\gamma_2/(\gamma_1 + \gamma_3 + 1)\right) - C\left(\frac{\gamma_1}{\gamma_1 + \gamma_3 + 1}\right)}{C\left(\frac{\gamma_2}{\gamma_1 + \gamma_3 + 1}\right) + C\left(\gamma_2/(\gamma_1 + \gamma_3 + 1)\right) - C\left(\frac{\gamma_1}{\gamma_1 + \gamma_3 + 1}\right)}.
\end{align*}$$

(13)

Based on (13) as well as on the condition of $\gamma_1 + (1/(\gamma_3 + 1)) \gamma_1^2 > \gamma_2 \geq \gamma_1$, it can be shown that

$$0 \leq \lambda_1 < \lambda_0 < 1.$$  

(14)

Hence, as our next step, we further divide “Case 2” into several subclasses according to the range of $\lambda$.

1) **Case 2.1:** Where $\lambda \in [0, \lambda_1]$: According to (7), $R_2(\lambda)$ is a monotonically decreasing function of $\lambda$. Since $\lambda \leq \lambda_1$, we have $R_2(\lambda) \geq R_2(\lambda_1)$. Then, $R_1(\lambda)$ is a monotonically increasing function of $\lambda$. Since $\lambda > \lambda$, we reach $R_1(\lambda) > R_1(\lambda_1)$. According to (12), we have $R_2(\lambda_1) = C(\gamma_1/(\gamma_3 + 1)) = R_1(1)$. Finally, we arrive at $R_2(\lambda) \geq C(\gamma_1/(\gamma_3 + 1)) > R_1(\lambda)$, which is almost the same as the relationship given in (8). This implies that the achievable error-free data rate for Case 2.1 of BD-DF-FDN may be characterized by the same formula as that 376 given in (10). The only difference is that, in Case 1, the minimum transmission rate, which can be assigned to User 2, is $C(\gamma_2/(\gamma_1 + \gamma_3 + 1))$. By contrast, in Case 2.1, this becomes $C(\gamma_1/(\gamma_3 + 1))$, owing to the rate-allocation strategy specified according to $\lambda \in [0, \lambda_1]$. Resultantly, after substituting the new
According to (16) and (17), we get $|I_2[k]| \geq |I_1[k]|$. Hence, following the principles detailed in Section IV-A, in Case 2.2, 400 the length of the DL period is determined by the 401 transmission of the information bits of $I_2[k]$ via the RN-to-User-1 link, since 402 $I_2[k]$ carries more information bits than $I_1[k]$. Furthermore, 403 before either the UL or the DL completes its transmission, the 404 transmission of the information bits of $I_2[k]$ via the RN-to- 405 User-1 link is carried out at the same rate of $C(\gamma_1/(\gamma_3+1))$. 406 Meanwhile, the transmission of the information bits of $I_2[k]$ via 407 the User-2 to RN link, which determines the transmit duration 408 of the UL, is carried out at the rate of $R_2(\lambda)$. Hence, accord- 409 ing to (17), we get $C(\gamma_1/(\gamma_3+1)) > R_2(\lambda)$, which implies 410 that, in Case 2.2, the DL transmission will terminate earlier 411 than the UL transmission. Consequently, the framework of the 412 BD-DF-FDN shown in Fig. 1 is actually transformed into that 413 shown in Fig. 4 for Case 2.2. In this scenario, the definition of 414 the “Residual-Period” has been changed to the time duration 415 following the termination of the DL period and spanning to the 416 end of the UL transmission.

Observe in Fig. 4 that, according to the aforementioned 418 analysis, the length of the entire DL period is determined by 419 the transmission of the information bits of $I_2[k]$ via the RN-to- 420 User-1 link at the fixed rate of $C(\gamma_1/(\gamma_3+1))$, which is given 421 by $T = |I_2[k]|/C(\gamma_1/(\gamma_3+1)) = N R_2(\lambda)/C(\gamma_1/(\gamma_3+1))$. 422 where $N$ is still defined as the time required for transmit- 423 ting $|I_2[k]|$ number of information bits at the rate of $R_2(\lambda)$. 424 Resultantly, the number of residual information bits of $I_1[k]$ 425 and $I_2[k]$, which pertain to the UL transmission and will be 426 transmitted during the ensuing residual period, are given by 427 $|I_1[k]| - TR_1(\lambda)$ and $|I_2[k]| - TR_2(\lambda)$, respectively.

Observe during the residual period in Fig. 4 that, when the 429 transmissions via the DL are terminated, the detrimental SI 430 naturally disappears, which simplifies the architecture of our 431 BD-DF-FDN to the first step of conventional two-way relaying, 432 as shown for example in [8, Fig. 1(b)]. Therefore, the opti- 433 mum transmission rate proposed in [8], which was detailed in 434 [8, (25–28)], becomes applicable to the residual period in Fig. 4. 435 Consequently, during the residual period in Fig. 4, according to 436 [8, (25–28)], Theorem 3.1 is modified to

$$
\begin{aligned}
R'_1(\lambda') &= N' \left( C(\gamma_1) - C\left(\frac{\gamma_1}{\gamma_3+1}\right) \right) \\
&\quad + C\left(\frac{\gamma_1}{\gamma_3+1}\right), \quad 0 \leq \lambda' \leq 1 \\
R'_2(\lambda') &= N' \left( C\left(\frac{\gamma_1}{\gamma_3+1}\right) - C(\gamma_2) \right) \\
&\quad + C(\gamma_2), \quad 0 \leq \lambda' \leq 1
\end{aligned}
$$

(18)

where the rate pairs $[R'_1(\lambda'), R'_2(\lambda')]$ are capable of maximizing the 438 sum rate of the UL during the residual period in Fig. 4, 439 which hence will be utilized for updating the transmission rates 440 of User 1 and 2 during this period.

Additionally, the transmissions of the residual information 442 bits of $I_1[k]$ and $I_2[k]$ at the rates of $R'_1(\lambda')$ and $R'_2(\lambda')$, respec- 443 tively, should be completed simultaneously, which implies that 444 we have to find a rate pair of $[R'_1(\lambda'), R'_2(\lambda')]$, which satisfies 445

$$
\frac{|I_1[k]| - TR_1(\lambda)}{R'_1(\lambda')} = \frac{|I_2[k]| - TR_2(\lambda)}{R'_2(\lambda')},$$

(19)
The condition stipulated by (19) may be identically trans-
formed to
\[ \frac{R_2(\gamma)}{R_1(\gamma)} = \frac{R'_2(\gamma)}{R'_1(\gamma)}. \] (20)

Then, it can be shown that, under the condition of \( \gamma_1 + (1/\gamma_2) \geq \gamma_3 \geq \gamma_4 \), we always have \( R_2(\gamma)/R_1(\gamma) \in [1, 2] \), where \( C(\gamma_1/(\gamma_2 + 1)/C(\gamma_2/(\gamma_1 + \gamma_4 + 1))) \) is always a solution of
\[ C(\gamma_1/(\gamma_2 + 1)/C(\gamma_2/(\gamma_1 + \gamma_4 + 1)) \) and [1, 2]. Hence, if we allocate the number of information bits represented by (16), which inherently satisfies
\[ C(\gamma_1/(\gamma_2 + 1)/C(\gamma_2/(\gamma_1 + \gamma_4 + 1))) \] the residual period, we arrive at the MAEFDR of Case 2.3 that we have
\[ \frac{C(\gamma_1/\gamma_3 + 1)}{R_1(\gamma)} > R_2(\gamma). \] (24)

According to (23) and (24), it can be shown that \(|I_1[k]| > |I_2[k]|\).

Since we have \(|I_1[k]| > |I_2[k]|\), after broadcasting \(I_3[k]\) at the 483
rate of \(C(\gamma_1/(\gamma_3 + 1))\) for a time duration of \(T_1\), the RN has to continue transmitting the information bits of \(I_3[k]\) via the RN-to-User-1 link. Hence, we only have to consider the decodability of the transmission via the RN-to-490
User-2 link. Correspondingly, from now on, the RN will broadcast \(I_3[k]\) at a higher rate of \(C(\gamma_2/(\gamma_3 + 1))\). The time required for completing the transmission of the residual information bits of \(I_1[k]\) at the rate of \(C(\gamma_1/(\gamma_3 + 1))\) is given by
\[ T_2 = \frac{|I_1[k]| - T_1 C(\gamma_1/\gamma_3 + 1)}{C(\gamma_2/\gamma_3 + 1)}. \] (26)

Meanwhile, during the UL session, User 2 transmits the 495
information bits of \(I_2[k]\) at the fixed rate of \(R_2(\lambda)\), unless 496
the DL transmission has been completed. As mentioned earlier 497
in Section IV-A, the associated time required by User 2 for 498
completing this transmission is represented by \(N\). Then, it can be shown that \(T_1 + T_2 < N\), which implies that, in Case 2.3, 500
the DL transmission will be terminated earlier than the UL 501
transmission. Hence, the practical framework of Case 2.3 is 502
similar to that illustrated in Fig. 4, with the slight difference 503
that, in Case 2.3, the DL period relies on two steps. In the first 504
step, the RN broadcasts \(I_3[k]\) at the rate of \(C(\gamma_1/(\gamma_3 + 1))\) for 505
a time of \(T_1\), where the transmission of the information bits of 506
\(I_2[k]\) is completed. Then, in the next step, the RN broadcasts 507
\(I_3[k]\) at the rate of \(C(\gamma_2/(\gamma_3 + 1))\) for a time of \(T_2\), during 508
which the entire DL transmission is completed.

Hence, similar to the scenario depicted for the residual period 510
in Fig. 4, during the residual period of Case 2.3, User 1 and 511
User 2 also have to update their UL transmission rates to the rate 512
pair of \([R'_1(\lambda), R'_2(\lambda)]\), as stipulated in (18). Therefore, similar 513
to the additional condition discussed in Section IV-B2 and 514
stipulated by (19) and (20), we also have to find the specific rate 515
pair of \([R'_1(\lambda), R'_2(\lambda)]\), which is capable of simultaneously 516
satisfying (18) and \(R_2(\lambda)/R_1(\lambda) \) is \(R'_2(\lambda)/R'_1(\lambda)\). In this case, 517
we have \(R_1(\lambda)/R_2(\lambda) \in (1, (C(\gamma_1/(\gamma_3 + 1))/C(\gamma_2/(\gamma_1 + \gamma_4 + 1))) \) and \(R'_2(\lambda)/R'_1(\lambda) \in ([C(\gamma_1/(\gamma_3 + 1))/C(\gamma_2)], (C(\gamma_1)/C(\gamma_2/(\gamma_1 + \gamma_3 + 1))))\). Then, it can be shown that \((1, (C(\gamma_1/(\gamma_3 + 1)/C(\gamma_2/(\gamma_3 + 1)])/C(\gamma_2/(\gamma_1 + \gamma_3 + 1)))\) and \([C(\gamma_2/(\gamma_1 + \gamma_3 + 1))/C(\gamma_2)], (C(\gamma_2)/C(\gamma_2/(\gamma_1 + \gamma_3 + 1)))\). Hence, an appropriate rate pair of \([R'_1(\lambda), R'_2(\lambda)]\).
Based on the holistic analysis provided in Section IV, the overall achievable error-free data rate of Case 2.3 is given by

$$R_{BD-DF-FDN, Case 2.3}(\lambda) = \frac{|I_1(k)| + |I_2(k)|}{T_1 + T_2 + \{1_{i=1}^k |I_3(k)| - (\gamma_1 + \gamma_2)\rho(k)\lambda + T_2\lambda\}}.$$  (27)

Furthermore, it can be shown that $R_{BD-DF-FDN, Case 2.3}(\lambda)$ is a monotonically increasing function of $R_2(\lambda)$. Hence, if we assign to User 2 its maximum transmission rate for the period preceding the residual period, we arrive at the MAEFDR of Case 2.3, which may be formulated as

$$R_{max}^{BD-DF-FDN} = \lim_{\lambda \to \lambda_0} R_{BD-DF-FDN, Case 2.3}(\lambda) = \frac{C(\gamma_1 + \gamma_2)(\gamma_1^3 + \gamma_2^3)}{C(\gamma_1 + \gamma_2) + \frac{1}{2}C(\gamma_1 + \gamma_2) - C(\frac{\gamma_1^3 + \gamma_2^3}{\gamma_1 + \gamma_2})},$$

if $\gamma_1 + \left(\frac{1}{\gamma_1 + 1}\right)\gamma_1^2 > \gamma_2 \geq \gamma_1 \cap \lambda \in (\lambda_0, 1].$  (28)

Apparently, (28) is equivalent to (22). Then, it can be formally shown that the MAEFDR of our BD-DF-FDN obtained for Case 2.1 is always lower than that obtained for Case 2.2 or 2.3. Hence, we finally arrive at Theorem 4.1.

**Theorem 4.1:** The MAEFDR of BD-DF-FDN is given by

$$R_{max}^{BD-DF-FDN} = \begin{cases} 
\frac{C(\gamma_1 + \gamma_2)(\gamma_1^3 + \gamma_2^3)}{C(\gamma_1 + \gamma_2) + \frac{1}{2}C(\gamma_1 + \gamma_2) - C(\frac{\gamma_1^3 + \gamma_2^3}{\gamma_1 + \gamma_2})}, & \text{if } \gamma_2 \geq \gamma_1 + \left(\frac{1}{\gamma_1 + 1}\right)\gamma_1^2 \\
\frac{C(\gamma_1 + \gamma_2)(\gamma_1^3 + \gamma_2^3)}{C(\gamma_1 + \gamma_2) + \frac{1}{2}C(\gamma_1 + \gamma_2) - C(\frac{\gamma_1^3 + \gamma_2^3}{\gamma_1 + \gamma_2})}, & \text{if } \gamma_1 + \left(\frac{1}{\gamma_1 + 1}\right)\gamma_1^2 > \gamma_2 \geq \gamma_1 
\end{cases}.$$  (29)

where $\gamma_i, i \in \{1, 2, 3\}$ is the relevant SNR defined in (3). Apparently, according to the analysis stated in Section IV, particularly to (29), depending on different channel conditions and transmit power levels, i.e., different relationships among $\gamma_i, i \in \{1, 2, 3\}$, the algebraic representation of MAEFDR of our BD-DF-FDN will be categorized into two different formulas.

**V. Simulation Results**

First, it is assumed that the distance between User 2 and User 1 is normalized to unity. Then, the distance between User 2 and the RN is denoted by $D_2$ and that between User 1 and the RN is denoted by $D_1$. Hence, we have $D_2 + D_1 = 1.0$. Then, each sum rate demonstrated in the following figures is an average over simulating $10^8$ random fading channels.

We first investigate the effects of both the SI and the RN’s geographic location on the MAEFDR of BD-DF-FDN. The relevant simulation results are displayed in Fig. 5, where the parameters employed can be found in Table I. Furthermore, to demonstrate the advantages of the proposed BD-DF-FDN, the performance of the FD-based direct transmission (FD-DT) regime, which is summarized in Table II, is also shown in Fig. 5 as a benchmark.

It was reported in [19], [20] that contemporary FD transceiver techniques are capable of reducing the SI close to the noise floor. Hence, according to (2), it is achievable that $|h_3|^2 \sigma^2 \approx \sigma^2$, which is identical to $G_{SI} \geq \text{SNR}$. Hence, when $G_{SI}$ the SNR value employed in Fig. 5 is 10 dB, it is reasonable to assume that we have $G_{SI} \in \{0, 3, 6, 10\}$ dB for modeling. 553
Fig. 6. Effect of the SNR value on the MAEFDR of BD-DF-FDN, which is evaluated according to (29) in Theorem 4.1. The parameters employed can be found in Table I.

As observed in Fig. 5, when we have $G_{SI} = 0$ or 3 dB, the sum rate of our BD-DF-FDN always exceeds that of the FD-DT regime, regardless of the RN positions. However, when $G_{SI}$ increases to 6 dB, the range of the RN’s position, where our BD-DF-FDN outperforms the FD-DT regime, is reduced to the area between the two triangular legends shown in Fig. 5. More severely, when we have sufficiently high values of $G_{SI} = 10$ dB, the predominant region of our BD-DF-FDN, with respect to its FD-DT counterpart, is further reduced to the area between the two square legends. Hence, it may be concluded from Fig. 5 that, for most practical SI suppression capabilities, our BD-DF-FDN has the potential of significantly improving the performance of an FD communication system. This is more suitable for FD-based communication scenarios, where the employment of powerful SI suppression cannot always be guaranteed.

Moreover, the MAEFDR of our BD-DF-FDN is also affected by the RN’s position, as shown in Fig. 5. If the RN roams too close to one of the users, the system’s sum rate will rapidly drop. This tendency can be evidenced again by comparing the sum rate of our BD-DF-FDN associated with $G_{SI} = 10$ dB to that of the FD-DT regime, particularly when considering the curve segments between the two square legends in Fig. 5 in contrast to those outside these two square legends.

Similarly, in Fig. 6, we investigate the effect of different SNR values on the MAEFDR of BD-DF-FDN, when the SI suppression factor $G_{SI}$ is fixed. Observe in Fig. 6 that, regardless of the SNR, the proposed BD-DF-FDN always outperforms its FD-DT regime-based counterpart, except when the RN is located too close to one of the users. Furthermore, the optimum performance is obtained in high-SNR scenarios.

Then, the comparisons between our BD-DF-FDN and the bidirectional AF-relaying-aided FD network (BD-AF-FDN) [21], which is also described in Table II, are demonstrated in Figs. 7 and 8. According to Figs. 7 and 8, in general, in contrast to its AF-based counterpart, the proposed BD-DF-FDN is capable of achieving a higher spectral efficiency during low-SNR regions. Specifically, when the SI suppression ability of the FD transceiver is enhanced to $G = 10$ dB, the DF-aided performance is improved.

It is equivalent to having $\Omega = 0.1$ in [21].
system can still outperform its AF-based counterpart within the low-SNR region of \((-\infty, 3)\) dB. Bearing the green radio concept in mind, with the aid of powerful forward error correction (FEC) techniques, in a mount of literatures, practical relaying systems tend to be operated in increasingly lower SNR scenarios [30]. Hence, the BD-DF-FDN may better adapt to the application scenarios, where powerful FEC receivers are employed.

In more detail, observe in Fig. 7 that the spectral gain of BD-DF-FDN, with respect to its AF-based counterpart, increases upon incurring higher SI. Then, observe in Fig. 8 that, when we fix the SI suppression ability of the FD transceiver, lower path-loss reduction effect will result in higher performance gain of the proposed DF-aided system compared with its AF-based counterpart. Based on these phenomena, it may be concluded that, in contrast to BD-AF-FDN [21], [22], our BD-DF-FDN seems to be more appropriate to low-SNR, high-SI, and low-PLRG application scenarios.

Finally, the spectral efficiency of our BD-DF-FDN regime versus that of other typical networking regimes is shown in Fig. 9, where the FDR-based system [10], [13] and the HD-TW-based system [8] characterized in Table II are also invoked as benchmarks. Observe in Fig. 9 that, benefiting from the intelligent relaying strategy, the BD-DF-FDN is capable of significantly outperforming its DT-based counterpart, which also explores the advanced FD technology, except the situation that the RN roams extremely close to one of the users. Further-more, the BD-DF-FDN is capable of achieving salient spectral gain, with regard to either the DF-FDR relaying or the HD-DF-TW relaying, which evidences the high spectral efficiency of combining a complete FD network with the intelligent two-way relaying strategy.

Fig. 9. Comparison among different regimes. The parameters employed can be found in Table I.

VI. CONCLUSION

In this paper, we have proposed the novel concept of bidirectional DF relaying. We considered a challenging FD communication scenario and conceived a bidirectional relaying-aided full-duplex network, where an optimum rate allocation scheme was designed for improving the system’s spectral efficiency.

The simulation results provided in Section V have confirmed that the proposed BD-DF-FDN is capable of achieving a significantly higher spectral efficiency than the other typical net-working regimes listed in Table II. However, the performance of the BD-DF-FDN solution is dominated by the system’s interference suppression capability, as well as by the RN’s geographic location. Hence, in some scenarios where the system either has a weak or powerful interference suppression capability or if the RN is extremely close to one of the users, it may not be necessary to activate the proposed BD-DF-FDN.

REFERENCES


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