Secure Buffer-aided Scheme for Throughput Optimization in MIMO Full-duplex Relaying System

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***Abstract*—In this paper, the physical layer security is studied for a buffer-aided MIMO relaying system, which consists of a source, a destination, an eavesdropper and a multi-antenna relay. The relay adopts a hybrid half/full duplex mode based on the instantaneous channel state information of the legitimate links. The exact closed-form expression for the secrecy outage probability of the buffer-aided MIMO relaying system is derived. Unlike the existing work assuming a predetermined transmission rate, the optimal transmission rates of the source and relay in different duplex modes are designed. The average throughput is maximized under the intended secrecy outage probability constraint. Numerical results show that the analytical results of the secrecy outage probability agree with the simulation results perfectly. Compared with the conventional bufferless relaying schemes, the proposed buffer-aided relaying scheme achieves a higher throughput, as well as preserves the secrecy performance.**

Keywords*—*Buffer-aided relay; full-duplex; physical layer security; secrecy outage probability; throughput optimization.

I. Introduction

The relaying technique has been well-known to improve the communication reliability and expand the network coverage. However, the major disadvantage of conventional relaying system is that it usually adopts a fixed scheduling protocol. As a result, the transmission performance is restricted by the worst hop. In recent years, the buffer-aided relaying system has received more attentions due to its great flexibility in designing of the node transmission rate and the link scheduling protocol [1].

Solid work has been carried out about the buffer-aided half-duplex relaying system [2-3]. In [2], an adaptive link selection scheme was proposed according to the channel state information (CSI) of the link from source to relay and the link from relay to destination. It was concluded in [2] that the buffer-aided relaying system achieves significantly higher throughput compared with the conventional systems without buffer. In [3], an optimal scheduling protocol was further proposed for the buffer-aided relaying system with discrete transmission rates. Moreover, a hybrid half-duplex (HD)/full-duplex (FD) relaying scheme was presented in [4], where the throughput can be further improved owing to the property of the full-duplex mode. However, in all the researches mentioned above, the transmission rate of each node should be predetermined as either a constant value or a discrete set.

Physical layer security is another hot research topic in wireless systems. Since the reinforced signals from the relay can be eavesdropped, various work has been carried out to achieve higher security for the relaying system [5-7]. However, to achieve a higher throughput is also a challenging problem. In the initial work by Wyner [8], it is proven that a node has a maximal achievable rate in terms of the secrecy capacity to guarantee the perfect secrecy of the legitimate link. Hence, the system throughput may decrease dramatically when the channel condition of the eavesdropping link is good.

Due to its advantage, the physical layer security issue of the buffer-aided relaying system was studied. In [9], a link selection scheme was proposed for the buffer-aided HD relaying system by jointly considering the transmission efficiency and the security. It is concluded in [9] that the secrecy throughput can be significantly improved under a given secrecy outage probability constraint compared with the conventional bufferless relaying. A novel hybrid HD/FD scheme based on the prior work in [4] was proposed to enhance the relay channel security in [10].

However, in most of related work mentioned above [2-4, 9, 10], only the design of optimal scheduling protocols is focused on, while the node transmission rate is assumed to be a predetermined constant value. In addition, each node is equipped with single antenna.

In this paper, we study the buffer-aided hybrid HD/FD relaying system. Different from the work in [9] and [10], the relay is equipped with multiple antennas. The closed-form of the system performance in terms of the secrecy outage probability is derived. Furthermore, the transmission rates of the source node and the relay node in the HD mode and FD mode are designed to maximize the system throughput under a given secrecy constraint.

The remainder of this paper is organized as follows. Section II introduces the system model. Section III analyzes the buffer state. In Section IV, the closed-form of the secrecy outage probability is derived and the throughput optimization problem is formulated. Numerical results are given in Section V. We conclude the paper in Section VI.

II. System Model

We consider a relaying system consisting of a source node S, a destination node D, a decode-and-forward relay R and an eavesdropper E, as illustrated in Fig. 1. It is assumed that

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nodes S, D and E have single antenna, while node R has multiple antennas with N_{R} receive antennas and N_{T} transmit antennas. A typical scenario of the system model was given in [11], where a base station functioned as a relay and all other nodes were mobile terminals. It is also assumed that the relay is equipped with an infinite-size buffer and can operate in either HD mode or FD mode.

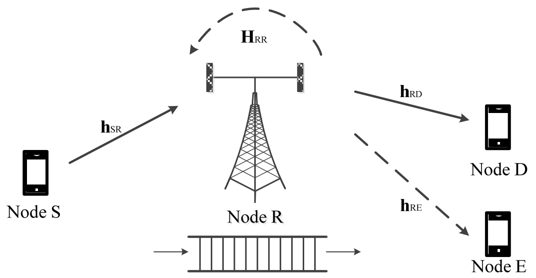

Fig. 1 Buffer-aided full-duplex relaying system, where the relay signal will be eavesdropped by node E

It is assumed that node S does not know the CSI of the S-D link. On the other hand, due to the particularity of node R, the exact CSIs of S-D link, R-D link and R-R self-interference link are available for the relay [11-12]. Since node E is a passive eavesdropper, node R cannot obtain the exact CSI of R-E link. However, it is still possible to obtain the statistical CSI when node E is a legitimate user in other communication phases.

During the communication phase, all the nodes transmit the encoded symbols in a time slot. First, node S transmits signals to node R with a fixed source rate, which is characterized by bits/symbol. The relay decodes the received symbols and stores the data into the buffer. At the same time, according to the instantaneous CSIs of the S-R link and R-D link, the relay decides to transmit to node D in the HD mode or FD mode. The received signals at nodes R, D and E can be expressed as

$$\mathbf{w}_{\mathrm{R}}^{H}\mathbf{y}_{\mathrm{R}}=\begin{cases}\mathbf{w}_{\mathrm{R}}^{H}\left(\mathbf{h}_{\mathrm{SR}}x_{\mathrm{S}}+\mathbf{n}_{\mathrm{R}}\right), & \mathrm{HD}\\ \mathbf{w}_{\mathrm{R}}^{H}\left(\mathbf{h}_{\mathrm{SR}}x_{\mathrm{S}}+\mathbf{H}_{\mathrm{RR}}\mathbf{w}_{\mathrm{T}}x_{\mathrm{R}}+\mathbf{n}_{\mathrm{R}}\right), & \mathrm{FD}\end{cases}, \tag{1}$$

$$y_{\mathrm{D}}=\mathbf{h}_{\mathrm{RD}}^{H}\mathbf{w}_{\mathrm{T}}x_{\mathrm{R}}+n_{\mathrm{D}}, \tag{2}$$

$$y_{\mathrm{E}}=\mathbf{h}_{\mathrm{RE}}^{H}\mathbf{w}_{\mathrm{T}}x_{\mathrm{R}}+n_{\mathrm{E}}, \tag{3}$$

where x_i is the transmit symbol of node i with power P_i, $i\in\{\mathrm{S},\mathrm{R}\}$; $\mathbf{h}_{\mathrm{SR}}$ and $\mathbf{h}_{\mathrm{RD}}$ denote the channel response of the S-R link and R-D link, respectively, $\mathbf{h}_{\mathrm{SR}}\in\mathbb{C}^{N_{\mathrm{R}}\times 1}$ and $\mathbf{h}_{\mathrm{RD}}\in\mathbb{C}^{N_{\mathrm{T}}\times 1}$; $\mathbf{H}_{\mathrm{RR}}$ denotes the self-interference channel response in FD mode, and $\mathbf{H}_{\mathrm{RR}}\in\mathbb{C}^{N_{\mathrm{R}}\times N_{\mathrm{T}}}$; n_i is the additive Gaussian noise with zero-mean and variance N_0 at node i; $\mathbf{w}_{\mathrm{R}}$ and $\mathbf{w}_{\mathrm{T}}$, which are designed to maximize the signal to noise ratio (SNR) of dual hops, denote the data combining and precoding vector at the relay, respectively. $(\cdot)^H$ denotes the Hermitian transpose of a matrix. In this paper, it is assumed that all the links experience the Rayleigh fading.

A. HD mode

In the HD mode, $\mathbf{w}_{\mathrm{R}}$ and $\mathbf{w}_{\mathrm{T}}$ can be expressed by $\mathbf{w}_{\mathrm{R}}^{HD}=\mathbf{h}_{\mathrm{SR}}/\|\mathbf{h}_{\mathrm{SR}}\|$ and $\mathbf{w}_{\mathrm{T}}^{HD}=\mathbf{h}_{\mathrm{RD}}/\|\mathbf{h}_{\mathrm{RD}}\|$, which are referred as the well-known maximal ratio combining (MRC) and maximal ratio transmission (MRT). The SNRs at nodes R and D can be calculated as $\gamma_{\mathrm{R}}^{HD}=\bar{\gamma}_{\mathrm{SR}}\|\mathbf{h}_{\mathrm{SR}}\|^2$ and $\gamma_{\mathrm{D}}^{HD}=\bar{\gamma}_{\mathrm{RD}}\|\mathbf{h}_{\mathrm{RD}}\|^2/N_{\mathrm{T}}$, where $\bar{\gamma}_{\mathrm{SR}}=P_{\mathrm{S}}/N_0$ and $\bar{\gamma}_{\mathrm{RD}}=P_{\mathrm{R}}/N_0$. The probability density functions (PDFs) of γ_{R}^{HD} and γ_{D}^{HD} can be expressed as

$$f_{\gamma_{\mathrm{R}}^{HD}}(x)=\frac{x^{N_{\mathrm{R}}-1}}{(N_{\mathrm{R}}-1)!\left(2b_{\mathrm{SR}}\bar{\gamma}_{\mathrm{SR}}\right)^{N_{\mathrm{R}}}}e^{-\frac{x}{2b_{\mathrm{SR}}\bar{\gamma}_{\mathrm{SR}}}} \tag{4}$$

and

$$f_{\gamma_{\mathrm{D}}^{HD}}(x)=\frac{x^{N_{\mathrm{T}}-1}}{(N_{\mathrm{T}}-1)!\left(2b_{\mathrm{RD}}\bar{\gamma}_{\mathrm{RD}}/N_{\mathrm{T}}\right)^{N_{\mathrm{T}}}}e^{-\frac{x}{2b_{\mathrm{SR}}\bar{\gamma}_{\mathrm{RD}}/N_{\mathrm{T}}}}, \tag{5}$$

respectively, where b_{SR} and b_{RD} are the Rayleigh fading parameters.

B. FD mode

In the FD mode, the relay will suffer from the self-interference when transmitting to node D and receiving from node S simultaneously. In this paper, we employ the interference cancellation technique proposed in [13] to achieve a suboptimal SNR at nodes R and D. $\mathbf{w}_{\mathrm{R}}$ and $\mathbf{w}_{\mathrm{T}}$ can be expressed as $\mathbf{w}_{\mathrm{R}}^{FD}=\mathbf{h}_{\mathrm{SR}}/\|\mathbf{h}_{\mathrm{SR}}\|$ and $\mathbf{w}_{\mathrm{T}}^{FD}=\mathbf{B}\mathbf{h}_{\mathrm{RD}}/\|\mathbf{B}\mathbf{h}_{\mathrm{RD}}\|$, where $\mathbf{B}$ is an idempotent orthogonal projection (null-space projection) matrix, and $\mathbf{B}=\mathbf{I}_{N_{\mathrm{T}}}-\frac{\mathbf{H}_{\mathrm{RR}}^{H}\mathbf{h}_{\mathrm{SR}}\left(\mathbf{H}_{\mathrm{RR}}^{H}\mathbf{h}_{\mathrm{SR}}\right)^{H}}{\left(\mathbf{H}_{\mathrm{RR}}^{H}\mathbf{h}_{\mathrm{SR}}\right)^{H}\mathbf{H}_{\mathrm{RR}}^{H}\mathbf{h}_{\mathrm{SR}}}$. The SNRs can be calculated by $\gamma_{\mathrm{R}}^{FD}=\bar{\gamma}_{\mathrm{SR}}\|\mathbf{h}_{\mathrm{SR}}\|^2$ and $\gamma_{\mathrm{D}}^{FD}=\bar{\gamma}_{\mathrm{RD}}\|\mathbf{B}\mathbf{h}_{\mathrm{RD}}\|^2/N_{\mathrm{T}}$, and their PDFs can be expressed as

$$f_{\gamma_{\mathrm{R}}^{FD}}(x)=\frac{x^{N_{\mathrm{R}}-1}}{(N_{\mathrm{R}}-1)!\left(2b_{\mathrm{SR}}\bar{\gamma}_{\mathrm{SR}}\right)^{N_{\mathrm{R}}}}e^{-\frac{x}{2b_{\mathrm{SR}}\bar{\gamma}_{\mathrm{SR}}}} \tag{6}$$

and

$$f_{\gamma_{\mathrm{D}}^{FD}}(x)=\frac{x^{N_{\mathrm{T}}-2}}{(N_{\mathrm{T}}-2)!\left(2b_{\mathrm{RD}}\bar{\gamma}_{\mathrm{RD}}/N_{\mathrm{T}}\right)^{N_{\mathrm{T}}-1}}e^{-\frac{x}{2b_{\mathrm{SR}}\bar{\gamma}_{\mathrm{RD}}/N_{\mathrm{T}}}}. \tag{7}$$

One finds that $\gamma_{\mathrm{R}}^{HD}=\gamma_{\mathrm{R}}^{FD}=\gamma_{\mathrm{R}}$. For simplicity, it is assumed $\bar{\gamma}_{\mathrm{SR}}=\bar{\gamma}_{\mathrm{RD}}=\bar{\gamma}$ in the following discussions.

III. Buffer State Analysis

It is assumed that node S transmits with a fixed rate $\mathcal{R}_{\mathrm{S}}$, and node R transmits with fixed rate $\mathcal{R}_{\mathrm{R}}^{HD}$ and $\mathcal{R}_{\mathrm{R}}^{FD}$ in the HD mode and FD mode, respectively. Hence, an outage event occurs in a given time slot i when the channel capacity falls below the node transmission rate.

TABLE I. SCHEDULING STRATEGY AT THE RELAY

	(i) $\mathcal{D}_{\mathrm{SR}}=0 \wedge \mathcal{D}_{\mathrm{RD}}^{FD}=1$	(ii) $\mathcal{D}_{\mathrm{SR}}=0 \wedge \mathcal{D}_{\mathrm{RD}}^{FD}=0$	(iii) $\mathcal{D}_{\mathrm{SR}}=1 \wedge \mathcal{D}_{\mathrm{RD}}^{HD}=0$	(iv) $\mathcal{D}_{\mathrm{SR}}=1 \wedge \mathcal{D}_{\mathrm{RD}}^{HD}=1$
Transmit	No	Yes	Yes	No
Receive	Yes	Yes	No	No

The outage event can be described by a variable defined as $\mathcal{D}_{\mathrm{SR}}[i]=\begin{cases}1, C_{\mathrm{SR}}[i]\le \mathcal{R}_{\mathrm{S}}\\ 0, C_{\mathrm{SR}}[i]>\mathcal{R}_{\mathrm{S}}\end{cases}$, $\mathcal{D}_{\mathrm{RD}}^{HD}[i]=\begin{cases}1, C_{\mathrm{RD}}^{HD}[i]\le \mathcal{R}_{\mathrm{R}}^{HD}\\ 0, C_{\mathrm{RD}}^{HD}[i]>\mathcal{R}_{\mathrm{R}}^{HD}\end{cases}$ and $\mathcal{D}_{\mathrm{RD}}^{FD}[i]=\begin{cases}1, C_{\mathrm{RD}}^{FD}[i]\le \mathcal{R}_{\mathrm{R}}^{FD}\\ 0, C_{\mathrm{RD}}^{FD}[i]>\mathcal{R}_{\mathrm{R}}^{FD}\end{cases}$, where $C_{\mathrm{SR}}=\log(1+\gamma_{\mathrm{SR}})$ and $C_{\mathrm{RD}}=\log(1+\gamma_{\mathrm{RD}})$ are the channel capacity of link S-R and link R-D, respectively. The instantaneous CSIs of link S-R and link R-D will affect the duplex mode of the relay. The scheduling strategy of node R is summarized in Table I.

With the assumption of the infinite buffer size, the actual transmission rate of the relay can be expressed as $\tilde{\mathcal{R}}_{\mathrm{R}}^{HD}(i)=\min\{\mathcal{R}_{\mathrm{R}}^{HD},Q(i-1)\}$ or $\tilde{\mathcal{R}}_{\mathrm{R}}^{FD}(i)=\min\{\mathcal{R}_{\mathrm{R}}^{FD},Q(i-1)\}$, where $Q(i-1)$ denotes the number of bits in the buffer at end of time slot $i-1$. According to Table I, the value of $Q(i)$ is time-variant, and can be calculated by

$$Q(i)=\begin{cases}Q(i-1)+\mathcal{R}_{\mathrm{S}}, & \text{(i)}\\ \max\left(Q(i-1)-\mathcal{R}_{\mathrm{R}}^{FD},0\right)+\mathcal{R}_{\mathrm{S}}, & \text{(ii)}\\ \max\left(Q(i-1)-\mathcal{R}_{\mathrm{R}}^{HD},0\right), & \text{(iii)}\\ Q(i-1), & \text{(iv)}\end{cases}. \tag{8}$$

Hence, the average receiving rate $\mathcal{T}_{\mathrm{in}}$ and average transmitting rate $\mathcal{T}_{\mathrm{out}}$ of node R can be expressed as

$$\mathcal{T}_{\mathrm{in}}=\lim_{N\to\infty}\frac{1}{N}\sum_{i=1}^{N}\mathcal{R}_{\mathrm{S}}\left(1-\mathcal{D}_{\mathrm{SR}}(i)\right) \tag{9}$$

and

$$\mathcal{T}_{\mathrm{out}}=\lim_{N\to\infty}\frac{1}{N}\sum_{i=1}^{N}\left[\tilde{\mathcal{R}}_{\mathrm{R}}^{HD}(i)\mathcal{D}_{\mathrm{SR}}(i)\left(1-\mathcal{D}_{\mathrm{RD}}^{HD}(i)\right)+\tilde{\mathcal{R}}_{\mathrm{R}}^{FD}(i)\left(1-\mathcal{D}_{\mathrm{SR}}(i)\right)\left(1-\mathcal{D}_{\mathrm{RD}}^{FD}(i)\right)\right] \tag{10}$$

where $\mathcal{T}_{\mathrm{out}}$ can also be regarded as the system throughput.

According to the law of conservation of flow, $\mathcal{T}_{\mathrm{in}}\ge\mathcal{T}_{\mathrm{out}}$ always holds. Considering the throughput maximization problem, we define that a buffer is in an absorbing state or a non-absorbing state, depending on whether $\mathcal{T}_{\mathrm{in}}$ equals to $\mathcal{T}_{\mathrm{out}}$ or not.

A. Absorbing state

The buffer is in the absorbing state when $\mathcal{T}_{\mathrm{in}}>\mathcal{T}_{\mathrm{out}}$. According to [2], the buffer length tends to grow infinitely in such a state, which leads to the following equation

$$\begin{aligned}&\mathcal{T}_{\mathrm{out}}\left(\mathcal{R}_{\mathrm{S}},\mathcal{R}_{\mathrm{R}}^{HD},\mathcal{R}_{\mathrm{R}}^{FD}\right)\\ &\cong\tilde{\mathcal{T}}_{\mathrm{out}}\left(\mathcal{R}_{\mathrm{S}},\mathcal{R}_{\mathrm{R}}^{HD},\mathcal{R}_{\mathrm{R}}^{FD}\right)\\ &\triangleq\lim_{N\to\infty}\frac{1}{N}\sum_{i=1}^{N}\left[\mathcal{R}_{\mathrm{R}}^{HD}\mathcal{D}_{\mathrm{SR}}(i)\left(1-\mathcal{D}_{\mathrm{RD}}^{HD}(i)\right)+\mathcal{R}_{\mathrm{R}}^{FD}\left(1-\mathcal{D}_{\mathrm{SR}}(i)\right)\left(1-\mathcal{D}_{\mathrm{RD}}^{FD}(i)\right)\right]\end{aligned}. \tag{11}$$

Utilizing the ergodicity of the channel fading, the time index i can be omitted. Hence, $\mathcal{T}_{\mathrm{in}}$ and $\tilde{\mathcal{T}}_{\mathrm{out}}$ can be rewritten as

$$\mathcal{T}_{\mathrm{in}}=\mathcal{R}_{\mathrm{S}}\left(1-P_{\mathrm{SR}}\right) \tag{12}$$

and

$$\begin{aligned}&\tilde{\mathcal{T}}_{\mathrm{out}}\left(\mathcal{R}_{\mathrm{S}},\mathcal{R}_{\mathrm{R}}^{HD},\mathcal{R}_{\mathrm{R}}^{FD}\right)\\ &=P_{\mathrm{SR}}\left(1-P_{\mathrm{RD}}^{HD}\right)\mathcal{R}_{\mathrm{R}}^{HD}+\left(1-P_{\mathrm{SR}}\right)\left(1-P_{\mathrm{RD}}^{FD}\right)\mathcal{R}_{\mathrm{R}}^{FD},\end{aligned} \tag{13}$$

where P_{SR} represents the outage probability of link S-R, and $P_{\mathrm{SR}}=\Pr\left[C_{\mathrm{SR}}<\mathcal{R}_{\mathrm{S}}\right]$. In the same way, we obtain P_{RD}^{HD} and P_{RD}^{FD}. The closed-form expressions of the link outage probability can be calculated with (4)-(7) as

$$P_{\mathrm{SR}}=1-\frac{1}{(N_{\mathrm{R}}-1)!}\Gamma\left(N_{\mathrm{R}},\frac{2^{\mathcal{R}_{\mathrm{S}}}-1}{2b_{\mathrm{SR}}\bar{\gamma}}\right), \tag{14}$$

$$P_{\mathrm{RD}}^{HD}=1-\frac{1}{(N_{\mathrm{T}}-1)!}\Gamma\left(N_{\mathrm{T}},\frac{2^{\mathcal{R}_{\mathrm{R}}^{HD}}-1}{2b_{\mathrm{RD}}\bar{\gamma}/N_{\mathrm{T}}}\right), \tag{15}$$

$$P_{\mathrm{RD}}^{FD}=1-\frac{1}{(N_{\mathrm{T}}-2)!}\Gamma\left(N_{\mathrm{T}}-1,\frac{2^{\mathcal{R}_{\mathrm{R}}^{FD}}-1}{2b_{\mathrm{RD}}\bar{\gamma}/N_{\mathrm{T}}}\right). \tag{16}$$

where $\Gamma(\,,\,)$ denotes the incomplete gamma function.

It is revealed in (11) that maximizing the throughput is equivalent to maximize $\tilde{\mathcal{T}}_{\mathrm{out}}$ when the buffer is in the absorbing state. Based on (12) and (14), $\mathcal{T}_{\mathrm{in}}$ is a one-dimensional function with respect to $\mathcal{R}_{\mathrm{S}}$, $\mathcal{T}_{\mathrm{in}}(0)=0$ and $\lim_{\mathcal{R}_{\mathrm{S}}\to\infty}\mathcal{T}_{\mathrm{in}}(\mathcal{R}_{\mathrm{S}})=0$. Hence, the intersection point of $\mathcal{T}_{\mathrm{in}}$ and $\tilde{\mathcal{T}}_{\mathrm{out}}$ must exist, with the optimal transmission rates $\left(\mathcal{R}_{\mathrm{S}}^{*},\mathcal{R}_{\mathrm{R}}^{HD*},\mathcal{R}_{\mathrm{R}}^{FD*}\right)$ satisfying $\tilde{\mathcal{T}}_{\mathrm{out}}=\mathcal{T}_{\mathrm{in}}$.

B. Non-absorbing state

In the non-absorbing state, as opposed to (11), we have

$$\mathcal{T}_{\mathrm{in}}\left(\mathcal{R}_{\mathrm{S}}\right)=\mathcal{T}_{\mathrm{out}}\left(\mathcal{R}_{\mathrm{S}},\mathcal{R}_{\mathrm{R}}^{HD},\mathcal{R}_{\mathrm{R}}^{FD}\right)\le\tilde{\mathcal{T}}_{\mathrm{out}}\left(\mathcal{R}_{\mathrm{S}},\mathcal{R}_{\mathrm{R}}^{HD},\mathcal{R}_{\mathrm{R}}^{FD}\right). \tag{17}$$

In this case, the system throughput is restricted by $\mathcal{T}_{\mathrm{in}}$. Hence, the optimal source rate $\mathcal{R}_{\mathrm{S}}^{*}$ must be an extreme point of the function $\mathcal{T}_{\text{in}}$ or the maximal point if $\mathcal{T}_{\text{in}}$ is a unimodal function. Calculating the derivative of (12) with respect to $\mathcal{R}_{\text{S}}$, and setting the result to be zero, the optimal $\mathcal{R}_{\text{S}}^*$ should satisfy

$$\Gamma\left(N_{\text{R}}, \frac{2^{\mathcal{R}_{\text{S}}^*}-1}{2b_{\text{SR}}\bar{\gamma}}\right) = \left(\frac{2^{\mathcal{R}_{\text{S}}^*}-1}{2b_{\text{SR}}\bar{\gamma}}\right)^{N_{\text{R}}-1} \frac{2^{\mathcal{R}_{\text{S}}^*}\mathcal{R}_{\text{S}}^*}{2b_{\text{SR}}\bar{\gamma}\ln 2} e^{-\frac{2^{\mathcal{R}_{\text{S}}^*}-1}{2b_{\text{SR}}\bar{\gamma}}}, \quad (18)$$

which is a transcendental equation and can be solved by numerical methods.

With a given $\mathcal{R}_{\text{S}}^*$, the values of $\mathcal{R}_{\text{R}}^{HD*}$ and $\mathcal{R}_{\text{R}}^{FD*}$ will be determined as long as (17) is satisfied without additional constraints.

IV. Throughput Optimization

In the previous section, the eavesdropper E has not been under consideration during the throughput analysis. Because the exact CSI of the R-E link is not available, we cannot ensure all the information transmitted to node D is perfectly secure. Hence, a secrecy constraint should be satisfied in the designed relaying scheme in addition to the rate constraint presented in Section III.

A. Secrecy outage probability

The secrecy capacity is defined as the difference between the capacity of the legitimate channel (R-D) and the eavesdropping channel (R-E). In this paper, we define a secrecy outage event is that the transmission rate of node R exceeds the secrecy capacity under the condition that the link R-D is not in outage. Hence, the secrecy outage probability P_{sec} is closely related to the transmission rate, and can be calculated by

$$P_{\text{sec}}\left(\mathcal{R}_{\text{S}}, \mathcal{R}_{\text{R}}^{HD}, \mathcal{R}_{\text{R}}^{FD}\right) = \Pr\left[\mathcal{R}_{\text{R}} > C_{\text{RD}} - C_{\text{RE}} \mid \text{R sends}\right], \quad (19)$$

where C_{RE} denotes the capacity of the eavesdropping channel, and $C_{\text{RE}} = \log(1+\gamma_{\text{E}})$. Based on Section II, γ_{E} is dependent on the duplex mode of the relay, $\gamma_{\text{E}}^{HD} = \frac{\bar{\gamma}\left\|\mathbf{h}_{\text{RE}}^H \mathbf{h}_{\text{RD}}\right\|^2}{N_{\text{T}}\left\|\mathbf{h}_{\text{RD}}\right\|^2}$ and $\gamma_{\text{E}}^{FD} = \frac{\bar{\gamma}\left\|\mathbf{h}_{\text{RE}}^H \mathbf{B}\mathbf{h}_{\text{RD}}\right\|^2}{N_{\text{T}}\left\|\mathbf{B}\mathbf{h}_{\text{RD}}\right\|^2}$.

With the basics of probability theory, (19) can be expanded as

$$\begin{aligned} &P_{\text{sec}}\left(\mathcal{R}_{\text{S}}, \mathcal{R}_{\text{R}}^{HD}, \mathcal{R}_{\text{R}}^{FD}\right) \\ &= \frac{P_{\text{SR}} \cdot \Pr\left[\gamma_{\text{E}}^{HD} > \frac{1+\gamma_{\text{D}}^{HD}}{2^{\mathcal{R}_{\text{R}}^{HD}}} - 1, \gamma_{\text{D}}^{HD} > 2^{\mathcal{R}_{\text{R}}^{HD}} - 1\right]}{P_{\text{SR}} \cdot \left(1 - P_{\text{RD}}^{HD}\right) + \left(1 - P_{\text{SR}}\right) \cdot \left(1 - P_{\text{RD}}^{FD}\right)} \\ &+ \frac{\left(1 - P_{\text{SR}}\right) \cdot \Pr\left[\gamma_{\text{E}}^{FD} > \frac{1+\gamma_{\text{D}}^{FD}}{2^{\mathcal{R}_{\text{R}}^{FD}}} - 1, \gamma_{\text{D}}^{FD} > 2^{\mathcal{R}_{\text{R}}^{FD}} - 1\right]}{P_{\text{SR}} \cdot \left(1 - P_{\text{RD}}^{HD}\right) + \left(1 - P_{\text{SR}}\right) \cdot \left(1 - P_{\text{RD}}^{FD}\right)}, \end{aligned} \quad (20)$$

where joint probabilities in (20) can be calculated according to [14, Eq. (8)], (5) and (7), as

$$\begin{aligned} &\Pr\left[\gamma_{\text{E}}^{HD} > \frac{1+\gamma_{\text{D}}^{HD}}{2^{\mathcal{R}_{\text{R}}^{HD}}} - 1, \gamma_{\text{D}}^{HD} > 2^{\mathcal{R}_{\text{R}}^{HD}} - 1\right] \\ &= \int_{2^{\mathcal{R}_{\text{R}}^{HD}}-1}^{\infty} e^{-\frac{1+x-2^{\mathcal{R}_{\text{R}}^{HD}}}{2b_{\text{RE}}\bar{\gamma}/N_{\text{T}} 2^{\mathcal{R}_{\text{R}}^{HD}}}} f_{\gamma_{\text{D}}^{HD}}(x)\,\mathrm{d}x \\ &= \frac{e^{\frac{1-2^{-\mathcal{R}_{\text{R}}^{HD}}}{2b_{\text{RE}}\bar{\gamma}/N_{\text{T}}}}}{\left(2b_{\text{RE}}\bar{\gamma}/N_{\text{T}}\right)^{N_{\text{T}}}} \frac{\Gamma\left(N_{\text{T}}, \mu\left(2^{\mathcal{R}_{\text{R}}^{HD}}-1\right)\right)}{\left(N_{\text{T}}-1\right)!\,\mu^{N_{\text{T}}}}, \end{aligned} \quad (21)$$

$$\begin{aligned} &\Pr\left[\gamma_{\text{E}}^{FD} > \frac{1+\gamma_{\text{D}}^{FD}}{2^{\mathcal{R}_{\text{R}}^{FD}}} - 1, \gamma_{\text{D}}^{FD} > 2^{\mathcal{R}_{\text{R}}^{FD}} - 1\right] \\ &= \frac{e^{\frac{1-2^{-\mathcal{R}_{\text{R}}^{FD}}}{2b_{\text{RE}}\bar{\gamma}/N_{\text{T}}}}}{\left(2b_{\text{RE}}\bar{\gamma}/N_{\text{T}}\right)^{N_{\text{T}}-1}} \frac{\Gamma\left(N_{\text{T}}-1, \nu\left(2^{\mathcal{R}_{\text{R}}^{FD}}-1\right)\right)}{\left(N_{\text{T}}-2\right)!\,\nu^{N_{\text{T}}-1}}, \end{aligned} \quad (22)$$

where $\mu = \frac{b_{\text{RE}} + b_{\text{RD}} 2^{-\mathcal{R}_{\text{R}}^{HD}}}{2b_{\text{RE}}b_{\text{RD}}\bar{\gamma}/N_{\text{T}}}$ and $\nu = \frac{b_{\text{RE}} + b_{\text{RD}} 2^{-\mathcal{R}_{\text{R}}^{FD}}}{2b_{\text{RE}}b_{\text{RD}}\bar{\gamma}/N_{\text{T}}}$.

B. Problem formulation

The objective is to maximize the system throughput under the constraint of a given secrecy outage target $P_{\text{sec}} \le \eta$, by designing the source and relay transmission rates. Without loss of generality, it is assumed that $\mathcal{R}_{\text{R}}^{FD} \le \mathcal{R}_{\text{R}}^{HD}$ holds.

Based on Section III, it is necessary to divide the problem into two parts according to the buffer state. Generally, the original problem can be solved through the following two steps.

1) Checking the extreme point of $\mathcal{T}_{\text{in}}$

In such a case the buffer will not enter the absorbing state and the throughput is exactly the extreme value of $\mathcal{T}_{\text{in}}$. First, equation (18) is solved to get the solution $\mathcal{R}_{\text{S}}^*$. Then, substitute $\mathcal{R}_{\text{S}}^*$ into $\tilde{\mathcal{T}}_{\text{out}}$, the problem is formulated as

$$\min_{\mathcal{R}_{\text{R}}^{HD}, \mathcal{R}_{\text{R}}^{FD}} P_{\text{sec}}\left(\mathcal{R}_{\text{S}}^*, \mathcal{R}_{\text{R}}^{HD}, \mathcal{R}_{\text{R}}^{FD}\right), \quad \text{(P1)}$$

s.t.

$$\mathcal{T}_{\text{in}}\left(\mathcal{R}_{\text{S}}^*\right) \le \tilde{\mathcal{T}}_{\text{out}}\left(\mathcal{R}_{\text{S}}^*, \mathcal{R}_{\text{R}}^{HD}, \mathcal{R}_{\text{R}}^{FD}\right), \quad \text{(23a)}$$

$$0 \le \mathcal{R}_{\text{R}}^{FD} \le \mathcal{R}_{\text{R}}^{HD}. \quad \text{(23b)}$$

Solving (P1), the solution ($\mathcal{R}_{\text{R}}^{HD*}$, $\mathcal{R}_{\text{R}}^{FD*}$) and the object value P_{sec}^* are obtained.

If $P_{\text{sec}}^* \le \eta$, it means that the original problem has infinite solutions to guarantee the secrecy constraint.

Among all the solutions, $\left(\mathcal{R}_S^*, \mathcal{R}_R^{HD*}, \mathcal{R}_R^{FD*}\right)$ is the optimal one to achieve the largest throughput and secrecy at the same time. The original problem is solved.

However, if $P_{sec}^* > \eta$, one should go to the next step.

2) Checking the throughput balanced point of relay

It is a more general case where both the flow conservation constraint and the secrecy constraint should be satisfied. The problem can be formulated as

$$\max_{\mathcal{R}_S, \mathcal{R}_R^{HD}, \mathcal{R}_R^{FD}} \tilde{\mathcal{T}}_{out}\left(\mathcal{R}_S, \mathcal{R}_R^{HD}, \mathcal{R}_R^{FD}\right), \tag{P2}$$

s.t.

$$\mathcal{T}_{in}\left(\mathcal{R}_S\right) = \tilde{\mathcal{T}}_{out}\left(\mathcal{R}_S, \mathcal{R}_R^{HD}, \mathcal{R}_R^{FD}\right), \tag{24a}$$

$$P_{sec}\left(\mathcal{R}_S, \mathcal{R}_R^{HD}, \mathcal{R}_R^{FD}\right) \le \eta, \tag{24b}$$

$$0 \le \mathcal{R}_R^{FD} \le \mathcal{R}_R^{HD}. \tag{24c}$$

Through a numerical search, the optimal throughput $\tilde{\mathcal{T}}_{out}^*$ and the solution $\left(\mathcal{R}_S^*, \mathcal{R}_R^{HD*}, \mathcal{R}_R^{FD*}\right)$ are obtained.

V. Numerical Results

The Rayleigh fading parameters of each link are set as b_{SR}=b_{RD}=1 and b_{RE}=0.5. Other parameters are set as N_R=2, η=0.1 [9].

The secrecy outage probability versus the average transmitted SNR $\bar{\gamma}$ is shown in Fig. 2, where $\mathcal{R}_S$=3 bits/symbol, and $\mathcal{R}_R^{HD} = \mathcal{R}_R^{FD} = 2$ bits/symbol. From Fig. 2, one finds that the analytical results agree with Monte Carlo simulation results vey well, which means that the secrecy analysis in Section IV is correct. As the transmitted SNR increases, the relaying system will finally reach a secrecy outage floor. This is because a fixed transmission rate is adopted. According to (19), when $\bar{\gamma}$ increases, the channel fading gain becomes much dominant. Therefore, one can expect that the secrecy outage probability converges to a constant value.

Moreover, it can be observed that when N_T=5, the secrecy of the relaying system cannot be fulfilled even if the transmitted SNR is sufficiently high. Hence, it is necessary to design the optimized transmission rate to satisfy the secrecy constraint.

Fig. 3 shows the impact of $\bar{\gamma}$ on the average throughput. From Fig. 3, one finds that the proposed buffer-aided relaying scheme achieves a considerable average throughput under the given secrecy constraint. Moreover, the average throughput of the proposed scheme increases as N_T increases.

Next, we compare the proposed buffer-aided relaying scheme with the conventional relaying scheme, where the relay is also equipped with multiple antennas and without buffer in the conventional relaying scheme.

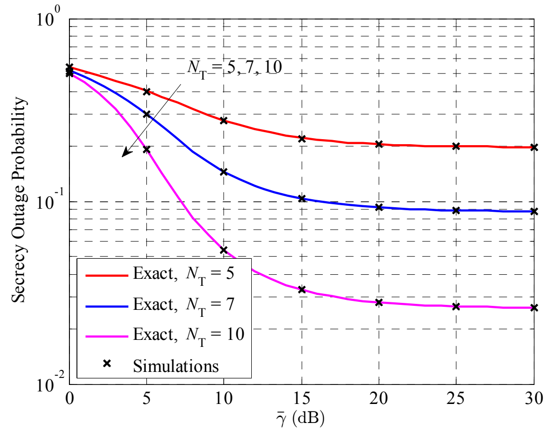

Fig. 2 Secrecy outage probability versus the average transmitted SNR, where b_{SR}=b_{RD}=1, b_{RE}=0.5, $\mathcal{R}_S$=3 bits/symbol, $\mathcal{R}_R^{HD} = \mathcal{R}_R^{FD} = 2$ bits/symbol, N_R=2.

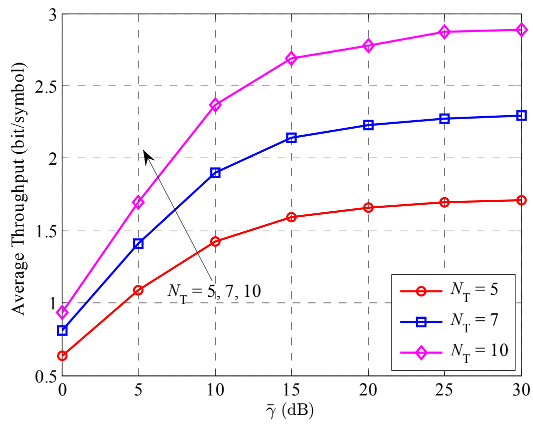

Fig. 3 Average throughput versus the average transmitted SNR, where b_{SR}=b_{RD}=1, b_{RE}=0.5, η=0.1, N_R=2.

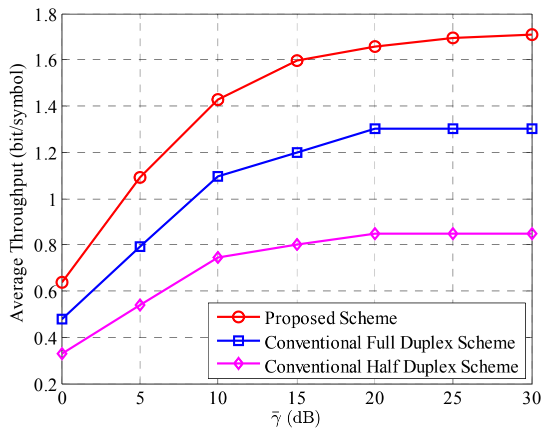

Fig. 4 Throughput comparison between the proposed scheme and the conventional bufferless schemes, where b_{SR}=b_{RD}=1, b_{RE}=0.5, η=0.1, N_R=2, N_T=5.

Fig. 4 shows the comparison of the average throughput of the proposed scheme, the conventional FD scheme and the conventional HD scheme, where N_T=5. For the conventional schemes, the transmission rates of the source and the relay are identical, and have been optimized to maximize the throughput under the secrecy constraint.

From Fig. 4, it can be observed that the proposed scheme outperforms the conventional schemes over the whole range of SNR. It is because that the transmission rate of each node is optimized owing to the deployment of buffer, while the hybrid HD/FD relaying scheme can also bring performance improvement. On the other hand, the conventional HD scheme achieves the worst performance due to the rate penalty multiplied by 1/2.

VI. CONCLUSIONS

In this paper, the physical layer security in a buffer-aided HD/FD relaying system is studied. The closed-form of the secrecy outage probability is derived. The transmission rates of all the nodes and in all the duplex modes are optimized to maximize the average system throughput under a given secrecy constraint. Numerical results show that the analytical curves agree with the simulation results quite well, which means the secrecy performance analysis is correct. Under a secrecy outage probability constraint, the proposed buffer-aided relaying scheme achieves much higher throughput compared with the conventional bufferless relaying schemes.

In the future, the rate optimization and power control will be jointly considered for the buffer-aided relaying system. To solve the optimization problem efficiently, novel numerical methods will be addressed.

REFERENCES

[1] B. Xia, Y. Fan, J. Thompson, and H. V. Poor, “Buffering in a three-node relay network,” *IEEE Trans. Wireless Communications*, vol. 7, no. 11, pp. 4492–4496, Nov. 2008.

[2] N. Zlatanov, R. Schober and P. Popovski, "Buffer-aided relaying with adaptive link selection," *IEEE Journal on Selected Areas in Communications,* vol. 31, pp. 1530-1542, Aug. 2013.

[3] W. Wicke, N. Zlatanov, V. Jamali, and R. Schober, "Buffer-aided relaying with discrete transmission rates for the two-hop half-duplex relay network," *IEEE Trans. on Wireless Communications,* vol. 16, pp. 967-981, Feb. 2017.

[4] M. G-Khafagy, A. E-Shafie, A. Sultan, and M. S-Alouini, "Throughput maximization for buffer-aided hybrid half-/full-duplex relaying with self-interference," in *Proc. IEEE ICC*, Jun. 2015, pp. 1926-1931.

[5] H. M-Wang and X. G-Xia, "Enhancing wireless secrecy via cooperation: signal design and optimization," *IEEE Communications Magazines,* vol. 53, pp. 47-53, Dec. 2015.

[6] J. Lee, "Full-Duplex relay for enhancing physical layer security in multi-hop relaying systems," *IEEE Communications Letters,* vol. 19, pp. 525-528, Feb. 2015.

[7] E. Nosrati, X. Wang and A. Khabbazibasmenj, "Secrecy capacity enhancement in two-hop DF relaying systems in the presence of eavesdropper," in *Proc. IEEE ICC*, Jun. 2015, pp. 7365-7369.

[8] A. D. Wyner, “The wire-tap channel,” *Bell Syst. Tech. J.*, vol. 54, pp. 1355–1387, Oct. 1975.

[9] J. Huang and A. L-Swindlehurst, "Buffer-aided relaying for two-hop secure communication," *IEEE Trans. on Wireless Communications,* vol. 14, pp. 152-164, Jan. 2015.

[10] A. El-Shafie, A. Sultan and N. Al-Dhahir, "Physical-layer security of a buffer-aided full-duplex relaying system," *IEEE Communications Letters,* vol. 20, pp. 1856-1859, Sep. 2016.

[11] F. Zhu, F. Gao, T. Zhang, K. Sun, and M. Yao, "Physical-layer security for full duplex communications with self-interference mitigation," *IEEE Trans. on Wireless Communications,* vol. 15, pp. 329-340, Jan. 2016.

[12] R. Zhao, Y. Huang, W. Wang, and V. K-N-Lau, "Ergodic secrecy capacity of dual-hop multiple-antenna AF relaying systems," in *Proc. IEEE GLOBECOM*, Dec. 2015, pp. 1-6.

[13] A. Almradi and K. Hamdi, "MIMO full-duplex relaying in the presence of co-channel interference," *IEEE Trans. on Vehicular Technology*. vol. PP, 2016, p. 1-1.

[14] J. Xiong, K. K-Wong, D. Ma, and J. Wei, "A closed-form power allocation for minimizing secrecy outage probability for MISO wiretap channels via masked beamforming," *IEEE Communications Letters,* vol. 16, pp. 1496-1499, Sep. 2012.