ON THE PERFORMANCE OF FULL-DUPLEX RELAYING UNDER PHY SECURITY CONSTRAINTS

Hirley Alves[*†], *Glauber Brante*[†], *Richard Demo Souza*[†], *Daniel B. da Costa*[‡], *and Matti Latva-aho*[*]

[*] CWC, University of Oulu, Oulu, Finland
[†] CPGEI, Federal University of Technology – Paraná, Curitiba, PR, Brazil
[‡] UFC, Federal University of Ceará, Fortaleza, Brazil
halves@ee.oulu.fi, gbrante@utfpr.edu.br, richard@utfpr.edu.br, danielbcosta@ieee.org, matla@ee.oulu.fi

ABSTRACT

In this paper we investigate the performance of a cooperative network in the presence of an eavesdropper (Eve). Alice and Bob communicate with the help of a relay, which can operate either in half-duplex (HD) or full-duplex (FD) mode. We account for the self interference at the relay when operating under FD mode. Our analysis focus in the case that the CSI of Eve is not available at Alice. Thus, we derive closed-form expressions for secrecy outage probability. Our results allow us to compare the performance of FD and HD cooperative scenarios under secrecy constraints and, despite the additional interference at the relay, show the advantages of FD relaying over HD. In addition, we also show that a cooperative network is more vulnerable if Eve is closer to Alice than to the relay.

***Index Terms*—** Physical layer security, full-duplex relaying, secrecy outage probability.

1. INTRODUCTION

Security is one of the main concerns in wireless networks since in the wireless medium the transmissions are naturally vulnerable to eavesdropping and hostile attacks [1, 2]. Moreover, due to the growth and to the ad hoc nature of modern wireless networks, we face a challenge in key distribution for traditional cryptographic techniques, usually applied in upper layers of the network [1]. In this context securing the wireless medium at the physical layer (PHY) has gained considerable attention in the recent years as a low complexity alternative to increase security [1, 2].

The wire-tap channel is composed of two legitimate users, Alice and Bob, communicating in the presence of an eavesdropper, Eve, which sees a degraded version of the message sent by Alice. It has been demonstrated that the secrecy capacity on a Gaussian wire-tap channel can be defined as the difference between the capacity of the main channel and the eavesdropper channel, being the capacity of the former greater than the latter [3,4]. Moreover, it has been proven that there are codes for the wire-tap channel that guarantee both low error probabilities and a certain degree of confidentiality [4, 5]. Diversity techniques, in which Alice, Bob and/or Eve may be equipped with multiple antennas, are investigated in [5–8]. Recently, cooperative communication schemes have also been analyzed in the context of PHY security [9–12], and more recently [13] gives a summary of recent advances in cooperative security at the physical layer.

A common characteristic to [10–12] is that all nodes operate in the half-duplex (HD) mode, so that transmission and reception occur in orthogonal channels. On the other hand, in full-duplex (FD) mode the transmission and reception are performed at the same time and at the same frequency band, so that ideal FD relaying can achieve higher capacity than HD relaying [14]. However, the self-interference at the relay must be taken into account in a practical FD approach [15,16]. Nevertheless, even though experiencing relatively strong self-interference levels, FD relaying is still feasible, as it has been shown in [15, 16].

In this work we assume a cooperative network in the presence of a single antenna eavesdropper. We consider that Alice communicates to Bob with the help of a FD relay, and that the self interference is taken into account at the relay. To the best of our knowledge, such analysis is not available in the literature yet. We assume that the channel state information (CSI) of Eve is not available. Thus, we employ the secrecy outage probability as the main security metric, since perfect secrecy cannot be guaranteed at all times [2]. We derive closed-form expressions for the secrecy outage probability of FD and HD relaying based on the decode-and-forward (DF) protocol. Furthermore, we demonstrate the feasibility of FD relaying under secrecy outage constraints and self interference, as great gains can be achieved over HD relaying.

The remainder of this paper is organized as follows. Section 2 introduces the system model. In Section 3 we present the passive eavesdropping analysis. Section 4 gives some numerical results and discussions. Finally, Section 5 concludes the paper.

Notations and Functions Mathematical expectation is denoted by $\mathrm{E}[\cdot]$, $\Pr[\cdot]$ stands for probability, $f_W(\cdot)$ and $F_W(\cdot)$ represent the probability density function (PDF) and cumulative distribution function (CDF) of a given random variable (RV) W, respectively.

2. SYSTEM MODEL

Consider a cooperative network operating in the presence of a single antenna eavesdropper, Eve (E). As shown in Fig. 1, Alice (A) plays the role of the source, while Bob (B) represents the destination and the relay (R) is a known node to Alice which is chosen as a helper.

The received signal between any two nodes $i \in \{\mathrm{A}, \mathrm{R}\}$ and $j \in \{\mathrm{R}, \mathrm{B}, \mathrm{E}\}$ can be represented by

$$\mathbf{y}_{ij} = \sqrt{P_i d_{ij}^{-\nu}}\, h_{ij} \cdot x + w_{ij}, \tag{1}$$

where h_{ij} is the quasi-static block fading channel channel gain, which is independent and identically distributed assuming Rayleigh distribution, P_i is the transmit power, while d_{ij} represents the distance between nodes i and j, and ν denotes the path loss exponent. Additionally, x is the unity energy transmitted symbol, and w_{ij} is zero-mean complex Gaussian noise with unity variance.

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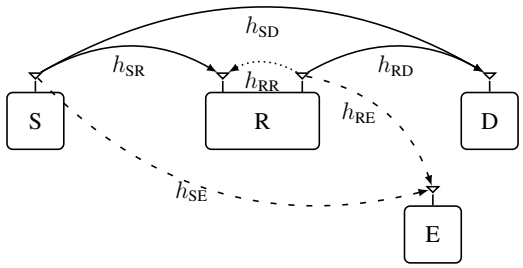

Fig. 1. Cooperative network composed of Alice (A), relay (R) and Bob (B) in the presence of Eve (E).

The instantaneous SNR at the receiver is $\gamma_{ij} = |h_{ij}|^2 \lambda_{ij}$, where $\lambda_{ij} = P_i\, d_{ij}^{-\nu}$ is the average SNR. Moreover, since all nodes are single antenna and the links are subject to Rayleigh fading, the instantaneous SNR is exponentially distributed, which we represent by the RV $\Gamma_{ij} \sim \mathsf{Exp}\left(\lambda_{ij}^{-1}\right)$.

We assume that the relay operates in a FD mode and therefore suffers from self-interference, since the isolation of transmitted and received signals is an intricate task [14, 17]. However, FD relaying is a promising technology to boost performance of cooperative networks, since recent works have shown that even though suffering from self-interference FD relaying is feasible [16–19]. Even though employing advanced interference cancellation techniques there still remains a residual self-interference level at the relay [15–18]. Such residual interference is dominated by the scattering component, once the line-of-sight component is considerably reduced by antenna isolation [15]. As a consequence, the self-interference can be modelled as a fading channel [15, 16, 19], which is denoted as h_{RR}.

We assume a selective DF (SDF) cooperative protocol, so that the relay only operates if the message received from Alice is free of errors [19]. The protocol can be simply described as follows: Alice broadcasts its message to the relay and Bob; simultaneously the relay forwards the received message to Bob if free of errors. Therefore, Bob employs joint decoding (JD) on the signals received from Alice and the relay. Moreover, if the A-R link is in outage, the relay remains silent [19].

3. COOPERATIVE SECRECY OUTAGE PROBABILITY

We assume that Alice does not know Eve's CSI and that the receivers have CSI of their own channels only. In this context, secrecy outage probability is the appropriated metric to evaluate the performance of a block fading wiretap channel [2, 16]. Alice uses a secrecy rate $\mathcal{R}$ in order to protect the transmission against potential eavesdropping, so that secrecy outage probability is defined $\Pr[C_s < \mathcal{R}]$. Thus, the overall secrecy outage probability of SDF-FD is [3, 14]

$$\begin{aligned}\mathcal{O}_{\mathrm{FD}} &= \Pr\left[\log_2\left(\frac{1+\gamma_{\mathrm{AB}}}{1+\gamma_{\mathrm{AE}}}\right) < \mathcal{R}\right] \cdot \Pr\left[\log_2\left(1+\gamma'_{\mathrm{AR}}\right) < \mathcal{R}\right] \\ &+ \Pr\left[\log_2\left(\frac{1+\gamma_{\mathrm{AB}}+\gamma_{\mathrm{RB}}}{1+\gamma_{\mathrm{AE}}+\gamma_{\mathrm{RE}}}\right) < \mathcal{R}\right] \cdot \Pr\left[\log_2\left(1+\gamma'_{\mathrm{AR}}\right) \geq \mathcal{R}\right] \\ &= \mathcal{O}_{\mathrm{NC}} \cdot \mathcal{O}_{\mathrm{AR}} + \mathcal{O}_{\mathrm{JD}} \cdot (1 - \mathcal{O}_{\mathrm{AR}}), \end{aligned} \tag{2}$$

where $\gamma'_{\mathrm{AR}} = \frac{\gamma_{\mathrm{AR}}}{1+\gamma_{\mathrm{RR}}}$, with γ_{RR} representing the self-interference at the relay. It is worth noting that the first term in (2), $\mathcal{O}_{\mathrm{NC}} \cdot \mathcal{O}_{\mathrm{AR}}$, refers to the non-cooperative case (when the A-R link is in outage), while the second term represents the cooperative case. Then, let us first define the outage probability of the A-R link as

$$\begin{aligned}\mathcal{O}_{\mathrm{AR}} &= \Pr\left[\log_2\left(1+\gamma'_{\mathrm{AR}}\right) < \mathcal{R}\right] \\ &= 1 - \frac{\exp\left(-\frac{\xi-1}{\lambda_{\mathrm{AR}}}\right)\lambda_{\mathrm{AR}}}{\lambda_{\mathrm{AR}} + (\xi-1)\lambda_{\mathrm{RR}}}, \end{aligned} \tag{3}$$

where $\xi = 2^{\mathcal{R}}$.

Next, we define the secrecy outage probability of the non-cooperative case as

$$\begin{aligned}\mathcal{O}_{\mathrm{NC}} &= \Pr\left[\log_2\left(\frac{1+\gamma_{\mathrm{AB}}}{1+\gamma_{\mathrm{AE}}}\right) < \mathcal{R}\right] \\ &= \int_0^{\infty}\int_0^{\xi(\gamma_{\mathrm{AE}}+1)-1} f_{\Gamma_{\mathrm{AB}}}(\gamma_{\mathrm{AB}})\, f_{\Gamma_{\mathrm{AE}}}(\gamma_{\mathrm{AE}})\, \mathrm{d}\gamma_{\mathrm{AB}}\, \mathrm{d}\gamma_{\mathrm{AE}} \\ &= 1 - \frac{\exp\left(-\frac{\xi-1}{\lambda_{\mathrm{AB}}}\right)\lambda_{\mathrm{AB}}}{\lambda_{\mathrm{AB}} + \xi\lambda_{\mathrm{AE}}}. \end{aligned} \tag{4}$$

The cooperative case in (2) can be written as

$$\begin{aligned}\mathcal{O}_{\mathrm{JD}} &= \Pr\left[\log_2\left(\frac{1+\gamma_{\mathrm{AB}}+\gamma_{\mathrm{RB}}}{1+\gamma_{\mathrm{AE}}+\gamma_{\mathrm{RE}}}\right) < \mathcal{R}\right] \\ &= \Pr\left[\log_2\left(\frac{1+\gamma_{\mathrm{B}}}{1+\gamma_{\mathrm{E}}}\right) < \mathcal{R}\right] \\ &= \int_0^{\infty}\int_0^{\xi(\gamma_{\mathrm{E}}+1)-1} f_{\Gamma_{\mathrm{B}}}(\gamma_{\mathrm{B}}) f_{\Gamma_{\mathrm{E}}}(\gamma_{\mathrm{E}})\, \mathrm{d}\gamma_{\mathrm{B}}\, \mathrm{d}\gamma_{\mathrm{E}}, \end{aligned} \tag{5}$$

where Γ_i, $i = \{\mathrm{B}, \mathrm{E}\}$, is the sum of two exponentially distributed RVs, whose PDF is

$$f_{\Gamma_i}(\gamma_i) = \begin{cases} \frac{\exp\left(-\frac{\gamma_i}{\lambda_{\mathrm{R}i}}\right) - \exp\left(-\frac{\gamma_i}{\lambda_{\mathrm{A}i}}\right)}{\lambda_{\mathrm{R}i} - \lambda_{\mathrm{A}i}}, & \lambda_{\mathrm{A}i} \neq \lambda_{\mathrm{R}i} \\ \frac{\exp\left(-\frac{\gamma_i}{\lambda_{\mathrm{A}i}}\right)}{\lambda_{\mathrm{A}i}^2}, & \text{otherwise.} \end{cases} \tag{6}$$

We can divide the cooperative case in to four sub-cases: *i)* $\lambda_{\mathrm{AB}} \neq \lambda_{\mathrm{RB}}$ and $\lambda_{\mathrm{AE}} \neq \lambda_{\mathrm{RE}}$; *ii)* $\lambda_{\mathrm{AB}} = \lambda_{\mathrm{RB}}$ and $\lambda_{\mathrm{AE}} \neq \lambda_{\mathrm{RE}}$; *iii)* $\lambda_{\mathrm{AB}} \neq \lambda_{\mathrm{RB}}$ and $\lambda_{\mathrm{AE}} = \lambda_{\mathrm{RE}}$; and *iv)* $\lambda_{\mathrm{AB}} = \lambda_{\mathrm{RB}}$ and $\lambda_{\mathrm{AE}} = \lambda_{\mathrm{RE}}$, which, with the help of [20, Eq. 6.455-2], yields

$$\mathcal{O}_{\mathrm{JD}} = \begin{cases} \Phi_1, & \lambda_{\mathrm{AB}} \neq \lambda_{\mathrm{RB}}\,,\ \lambda_{\mathrm{AE}} \neq \lambda_{\mathrm{RE}} \\ \Phi_2, & \lambda_{\mathrm{AB}} = \lambda_{\mathrm{RB}}\,,\ \lambda_{\mathrm{AE}} \neq \lambda_{\mathrm{RE}} \\ \Phi_3, & \lambda_{\mathrm{AB}} \neq \lambda_{\mathrm{RB}}\,,\ \lambda_{\mathrm{AE}} = \lambda_{\mathrm{RE}} \\ \Phi_4, & \lambda_{\mathrm{AB}} = \lambda_{\mathrm{RB}}\,,\ \lambda_{\mathrm{AE}} = \lambda_{\mathrm{RE}} \end{cases}. \tag{7}$$

For the first sub-case, and with help of [20, Eq. 6.455-2], we attain

$$\begin{aligned}\Phi_1 = 1 - \frac{1}{\lambda_{\mathrm{RB}} - \lambda_{\mathrm{AB}}}\Bigg[&\frac{\exp\left(-\frac{\xi-1}{\lambda_{\mathrm{RB}}}\right)\lambda_{\mathrm{RB}}^3}{(\lambda_{\mathrm{RB}} + \xi\lambda_{\mathrm{RE}})(\lambda_{\mathrm{RB}} + \xi\lambda_{\mathrm{AE}})} \\ &+ \frac{\exp\left(-\frac{\xi-1}{\lambda_{\mathrm{AB}}}\right)\lambda_{\mathrm{AB}}^3}{(\lambda_{\mathrm{AB}} + \xi\lambda_{\mathrm{RE}})(\lambda_{\mathrm{AB}} + \xi\lambda_{\mathrm{AE}})}\Bigg]. \end{aligned} \tag{8}$$

Next, when $\lambda_{\mathrm{B}} = \lambda_{\mathrm{AB}} = \lambda_{\mathrm{RB}}$,

$$\begin{aligned}\Phi_2 = 1 - \Bigg\{&\exp\left(-\frac{\xi-1}{\lambda_{\mathrm{B}}}\right)\lambda_{\mathrm{B}}\Big[\lambda_{\mathrm{B}}^3 - \lambda_{\mathrm{B}}(\lambda_{\mathrm{RE}} + \lambda_{\mathrm{AE}})\xi \\ &+ \lambda_{\mathrm{B}}(\lambda_{\mathrm{RE}} + \lambda_{\mathrm{AE}} + 3\lambda_{\mathrm{RE}}\lambda_{\mathrm{AE}})\xi^2 + \lambda_{\mathrm{RE}}\lambda_{\mathrm{AE}}(\xi-1)\xi^2 \\ &+ \lambda_{\mathrm{B}}^2(\xi - 1 + 2\xi\lambda_{\mathrm{RE}} + 2\xi\lambda_{\mathrm{AE}})\Big]\Bigg\} \\ &\times \left[(\xi\lambda_{\mathrm{AE}} + \lambda_{\mathrm{B}})^2(\lambda_{\mathrm{B}} + \xi\lambda_{\mathrm{AE}})^2\right]^{-1}. \end{aligned} \tag{9}$$

When $\lambda_{\text{AB}} \neq \lambda_{\text{RB}}$ and $\lambda_{\text{E}} = \lambda_{\text{AE}} = \lambda_{\text{RE}}$,

$$\Phi_3 = 1 - \frac{\exp\left(-\frac{\xi-1}{\lambda_{\text{RB}}}\right)\lambda_{\text{RB}}^2}{(\lambda_{\text{RB}}-\lambda_{\text{AB}})(\lambda_{\text{RB}}+2\xi\lambda_{\text{E}})} + \frac{\exp\left(-\frac{\xi-1}{\lambda_{\text{AB}}}\right)\lambda_{\text{AB}}^2}{(\lambda_{\text{RB}}-\lambda_{\text{AB}})(\lambda_{\text{AB}}+2\xi\lambda_{\text{E}})}. \tag{10}$$

The last sub-case is

$$\Phi_4 = 1 - \left[\exp\left(-\frac{\xi-1}{\lambda_{\text{B}}}\right)\lambda_{\text{B}}\left(\lambda_{\text{B}}^2 + \lambda_{\text{E}}(\xi-1)\xi + \lambda_{\text{B}}(\xi-1+3\xi\lambda_{\text{E}})\right)\right] \times \left[\lambda_{\text{B}}+\xi\lambda_{\text{E}}\right]^{-3}. \tag{11}$$

Finally, the overall secrecy outage probability of the SDF-FD scheme can be written by putting (3), (4) and (7) into (2).

HD Relaying The overall outage probability of the SDF-HD scheme can be defined as in (2). However, we must replace ξ by $\varrho = 2^{2\mathcal{R}}$ in (4) and (7), due to the multiplexing loss. Moreover, since there is no self interference in the HD mode, $\mathcal{O}_{\text{AR}}$ simplifies to

$$\Pr\left[\log_2(1+\gamma_{\text{AR}}) < 2\mathcal{R}\right] = 1 - \exp\left(-\frac{\varrho-1}{\lambda_{\text{AR}}}\right), \tag{12}$$

so that $\mathcal{O}_{\text{HD}}$ is found by including (4) and (7), with the proper replacement of ξ by $\varrho = 2^{2\mathcal{R}}$, as well as (12), into (2).

4. NUMERICAL RESULTS

We assume that Alice, Bob and the relay are in a straight line, with R positioned at the center. The distance between Alice and Bob is normalized to the unity. Moreover, the path loss exponent is $\nu = 4$, $\lambda_{\text{RR}} = 10^{-4}$ and the attempted secrecy rate is $\mathcal{R} = 2$ bits/s/Hz. The secrecy outage probability of the FD and HD schemes as a function of the SNR of the A-B link is shown in Fig. 2. We consider that $\lambda_{\text{AE}} = \lambda_{\text{RE}} = \{10, 20, 30\}$ dB. We can notice from the figure that the FD protocol considerably outperforms the HD protocol, even when the average SNR of Eve is high. For instance, for a secrecy outage probability of 10^{-4}, the FD scheme presents approximately 5 dB of gain over the HD scheme. Additionally, it is worth noting from the figure that Monte Carlo simulations match well with the theoretical curves, validating the accuracy of our derivations.

Fig. 3 shows the secrecy outage probability of the FD scheme for different values of λ_{RR} and for $\lambda_{\text{E}} = \lambda_{\text{AE}} = \lambda_{\text{RE}} = \{0, 20\}$ dB. Notice that even in the presence of the strong self interference ($\lambda_{\text{RR}} = 10^{-1}$), the FD scheme already achieves a secrecy outage probability in the order of 10^{-5}, and even better performance can be achieved when $\lambda_{\text{RR}} \to 0$ (ideal FD case). Notice that, in practice, even though self interference cannot be completely mitigated, it can be considerably attenuated, which provides low values of λ_{RR} [17].

The outage probability as a function of $\mathcal{R}$ is shown in Fig. 4 for different values of $\lambda_{\text{AB}} = \lambda_{\text{RB}} = \{10, 20, 30\}$ dB and $\lambda_{\text{E}} = 10$ dB. Note that the performance degrades as $\mathcal{R}$ grows, which was also observed in non-cooperative scenarios [7, 8]. Notice also that much higher rates can be achieved if the average SNR of the legitimate link is much stronger than at Eve. We can also see from Fig. 4 that the FD scheme considerably outperforms the HD one, since much higher transmission rates can be employed for a given secrecy outage probability threshold.

Finally, Fig. 5 plots the secrecy outage probability as a function of the distance between Alice and the relay. We assume two scenarios for this analysis. First, Eve is assumed to follow the relay at a fixed distance, so that we set $d_{\text{RE}} = 1/2$ and calculate $d_{\text{AE}} = (d_{\text{RE}}^2 + d_{\text{AR}}^2)^{1/2}$. In a second scenario, the distance between

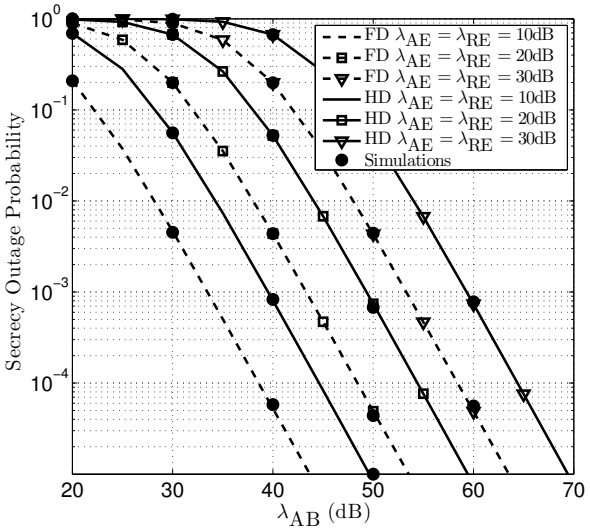

Fig. 2. Secrecy outage probability as a function of the SNR of the direct link (λ_{AB}) with $\lambda_{\text{AB}} = \lambda_{\text{AR}} = \lambda_{\text{RB}}$.

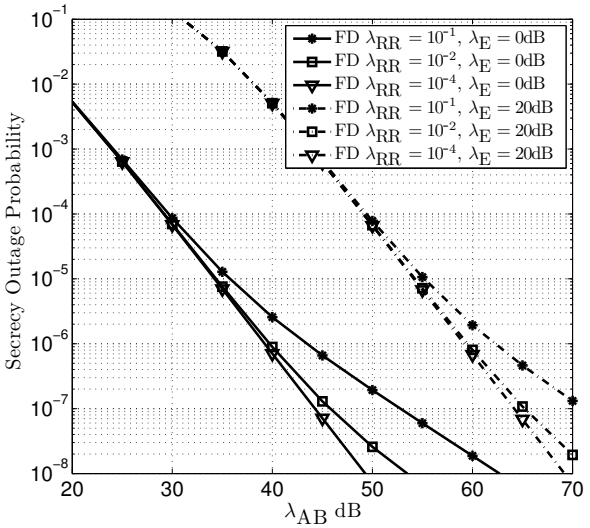

Fig. 3. Secrecy outage probability as a function of the SNR of the direct link (λ_{AB}).

Eve and Alice is fixed, at $d_{\text{AE}} = 1/2$, and $d_{\text{RE}} = (d_{\text{AE}}^2 + d_{\text{AR}}^2)^{1/2}$. From the figure, we can observe that Eve may be much harmful if positioned closer to the Alice rather than closer to the relay. In addition, regardless of Eve's position, the cooperative schemes enhance performance if the relay is positioned closer to Bob.

5. CONCLUSIONS

We investigate the performance of FD relaying when the cooperative nodes communicate in the presence of a single antenna eavesdropper. We focus on the case when the CSI of Eve is not known. Therefore, we derive closed-form expressions for the secrecy outage probability. Our results allow us to compare the performance of

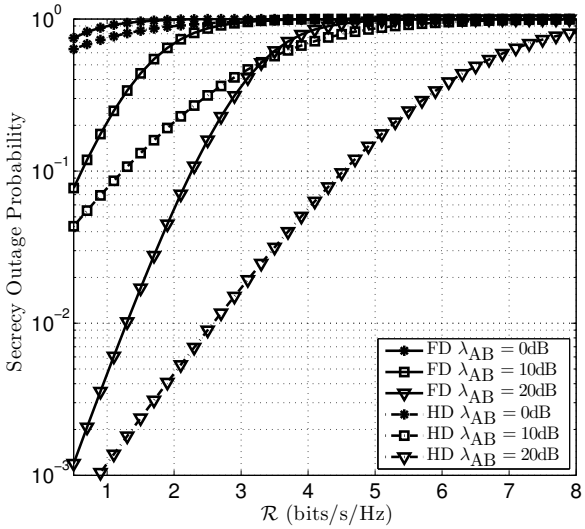

Fig. 4. Secrecy outage probability as a function of the attempted rate ($\mathcal{R}$) with $\lambda_{\rm B} = \{10, 20, 30\}$ dB and $\lambda_{\rm E} = 10$ dB.

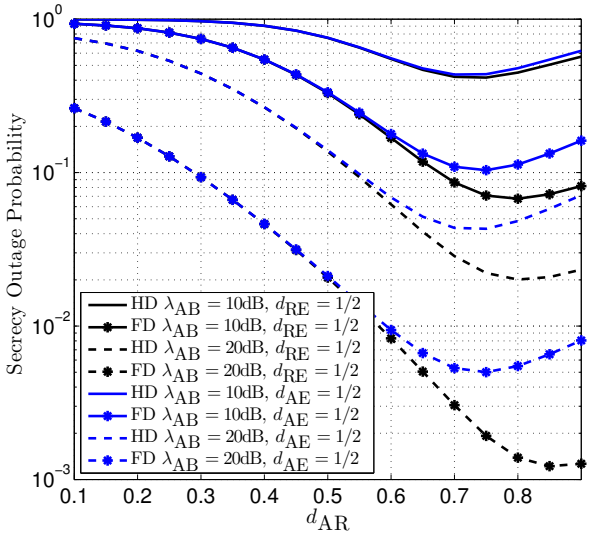

Fig. 5. Secrecy outage probability as a function of the distance from Alice to the relay, $d_{\rm AR}$.

FD and HD cooperative scenarios under secrecy constrains, and we show that, despite the additional interference at the relay (the self-interference inherent to the FD mode), FD relaying can considerably outperform HD relaying. Moreover, we also show that Eve would perform a more efficient attack if positioned closer to Alice rather than to the relay.

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