Research Article

Performance Analysis in DF Energy Harvesting Full-Duplex Relaying Network with MRC and SC at the Receiver under Impact of Eavesdropper

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This paper investigates the decode-and-forward (DF) full-duplex (FD) relaying system under the presence of an eavesdropper. Moreover, the relay node is able to harvest energy from a transmitter, and then it uses the harvested energy for conveying information to the receiver. Besides, both two-hop and direct relaying links are taken into consideration. In the mathematical analysis, we derived the exact expressions for intercept probability and outage probability (OP) by applying maximal ratio combining (MRC) and selection combining (SC) techniques at the receiver. Next, the Monte Carlo simulation is performed to validate the mathematical analysis. The results show that the simulation curves match the mathematical expressions, which confirms the analysis section.

1. Introduction

Radio frequency- (RF-) enabled wireless power transfer (WPT) has recently become a promising technique to overcome the energy limitation for wireless communication networks [1–10]. Moreover, because RF signal is able to carry both energy and information, one attractive direction is to transmit information and energy simultaneously (SWIPT) jointly. The SWIPT relaying networks have been intensively studied in [11–16]. Besides energy harvesting, physical layer security for relay networks received great attention from researchers [17–22]. Recent advances in self-interference cancellation (SIC)

techniques achieve high SI reduction. Therefore, FD relaying communications become a promising solution to overcome the spectrum scarcity of wireless systems [23–25].

In this paper, we consider a new system model to investigate the trade-off between physical layer security (PLS) and reliability for an energy-constrained FD relaying network. Further, the direct link between transmitter and receiver is taken into account to improve the total network performance. Moreover, the maximal ratio combining (MRC) and selection combining (SC) protocols are exploited at the eavesdropper and destination to enhance their received rate. The research contributions are summarized as follows:

- (i) We present an FD- and SWIPT-assisted relaying network in decode-and-forward (DF) under the presence of a direct link. Particularly, an eavesdropper is able to overhear the information transmission from source to destination via a relay. Moreover, an FD-enabled relay node is able to get energy from a transmitter and use it to transfer signals to the a receiver. Notably, the relay node can simultaneously receive information from the source and transmit it to the destination using the FD technique.
- (ii) We derive closed-form expressions of intercept probability (IP) at the eavesdropper E and outage probability (OP) at the destination D in maximal ratio combining (MRC) and selection combining (SC) techniques.
- (iii) The correctness of the developed analysis is validated through the Monte Carlo simulation. On one hand, we investigate the security perspective in terms of intercept probability. On the other hand, system reliability is also studied through outage probability. Consequently, a trade-off between IP and OP can provide many insightful and useful perspectives for system designers.

2. System Model

In Figure 1, we consider a relaying network where a relay R aids in conveying data from a transmitter S to a receiver D in the presence of one eavesdropper E. In particular, an eavesdropper is trying to get the information from S and R by applying maximal ratio combining (MRC) and selection combining (SC) techniques. In Figure 2, the relay R can harvest energy from the source during αT . In the remaining time, $(1 - \alpha)T$, the information process is executed.

We assume that the channel between two users follows block Rayleigh fading, where channel coefficients are unchanged during a time frame and change independently across time frames. Moreover, let us denote h_{XY} for $XY \in \{SR, RD, RR, SD, RE, SE\}$ as the channel coefficient of the link between nodes X and Y. Because the channels are Rayleigh distribution, the channel gains such as $|h_{RD}|^2$ and $|h_{SD}|^2$ are exponential random variables (RVs) whose cumulative distribution function (CDF) and probability density function (PDF) are, respectively, represented as

$$F_X(x) = 1 - \exp(-\lambda x),$$

$$f_X(x) = \frac{\partial F_X(x)}{\partial x} = \lambda \exp(-\lambda x), \quad (1)$$

where λ is rate parameter of exponential distribution.

The received signal at the relay can be expressed as

$$y_R = h_{SR}x_S + h_{RR}x_R + n_R, \quad (2)$$

where x_S is the energy symbol and $E\{|x_S|^2\} = P_S$, x_R is the loopback interference due to full-duplex relaying and satisfies $E\{|x_R|^2\} = P_R$, where $E\{\cdot\}$ denotes the expectation operation. n_R denotes the zero mean additive white Gaussian noise (AWGN) with variance N_0 .

FIGURE 1: System model.

FIGURE 2: IT and EH processes.

At the first phase, the harvested energy at the relay can be computed by

$$E_R = \eta \alpha T P_S |h_{SR}|^2, \quad (3)$$

where $0 < \eta \leq 1$ denotes the energy conversion efficiency.

From (3), the average transmit power of the relay node can be obtained as

$$P_R = \frac{E_R}{(1 - \alpha)T} = \frac{\eta \alpha P_S |h_{SR}|^2}{(1 - \alpha)} = \kappa P_S |h_{SR}|^2, \quad (4)$$

where $\kappa = \eta \alpha / (1 - \alpha)$.

Next, in the second phase, the eavesdropper E may intercept signals from both relay R and source S. Nevertheless, source S also generates artificial noise $\tilde{x}_S$ to prevent E from overhearing the source information. Moreover, since the relay R and destination D are legitimate users, they are assumed to know the artificial noise created by S. Consequently, they can cancel the artificial noise at the receiver circuit. Therefore, the received signal at E from relay R and source S can be, respectively, expressed as

$$y_E^I = h_{RE}x_R + n_E^I, y_E^{II} = h_{SE}x_S + h_{SE}\tilde{x}_S + n_E^{II}, \quad (5)$$

where $n_E = n_E^I = n_E^{II}$ is the AWGN with variance N_0 .

Since we adopt the decode-and-forward (DF) protocol, the signal to interference noise ratios (SINR) at the eavesdropper in the second phase from (5) are, respectively, given by

$$\gamma_E^I = \frac{|h_{RE}|^2 P_R}{N_0} = \kappa \Psi |h_{SR}|^2 |h_{RE}|^2, \gamma_E^{II} = \frac{\Psi |h_{SE}|^2}{\Psi |h_{SE}|^2 + 1}, \quad (6)$$

where $\Psi = P_S / N_0$.

As mentioned in the above discussion, the destination D can cancel the artificial noise from source S. Consequently, the received signal at the destination from relay R and source S during the second phase can be expressed as

$$y_D^I = h_{RD}x_R + n_D^I, y_D^{II} = h_{SD}x_S + n_D^{II}, \quad (7)$$

where $n_D = n_D^I = n_D^{II}$ is the AWGN with variance N_0 .

3. Intercept Probability (IP) Analysis

Destination D will be intercepted if E can successfully wiretap signal; that is, $\gamma_E \geq \gamma_{th}$, where $\gamma_{th} = 2^R - 1$ and R is the target rate.

Therefore, the IP of the system can be expressed as

$$IP = \Pr(\gamma_E \geq \gamma_{th}). \quad (8)$$

3.1. Instantaneous End-to-End SNR at E Using the MRC Technique. In this case, the end-to-end SNR at E from (6) can be given by

$$\gamma_E^{MRC} = \gamma_E^I + \gamma_E^{II} = \kappa\Psi|h_{SR}|^2|h_{RE}|^2 + \frac{\Psi|h_{SE}|^2}{\Psi|h_{SE}|^2 + 1}. \quad (9)$$

Then, the IP in (7) can be rewritten as

$$\begin{aligned} IP_{MRC} &= \Pr\left(\kappa\Psi|h_{SR}|^2|h_{RE}|^2 + \frac{\Psi|h_{SE}|^2}{\Psi|h_{SE}|^2 + 1} \geq \gamma_{th}\right) \\ &= \Pr(X + Y \geq \gamma_{th}) = 1 - \int_0^{\gamma_{th}} F_X(\gamma_{th} - y) \times f_Y(y) dy, \end{aligned} \quad (10)$$

where $X = \kappa\Psi|h_{SR}|^2|h_{RE}|^2$, $Y = \Psi|h_{SE}|^2/\Psi|h_{SE}|^2 + 1$.

In order to find the probability in (10), we have to find the CDF of X and PDF of Y. So, the CDF of X can be calculated by

$$\begin{aligned} F_X(x) &= \Pr(X < x) = \Pr(\kappa\Psi|h_{SR}|^2|h_{RE}|^2 < x) \\ &= \Pr\left(|h_{SR}|^2 < \frac{x}{\kappa\Psi|h_{RE}|^2}\right) = \int_0^\infty F_{|h_{SR}|^2}\left(\frac{x}{\kappa\Psi y} \mid |h_{RE}|^2 = y\right) \times f_{|h_{RE}|^2}(y) dy \\ &= 1 - \int_0^\infty \lambda_{RE} \exp\left(-\frac{\lambda_{SR}x}{\kappa\Psi y} - \lambda_{RE}y\right) dy. \end{aligned} \quad (11)$$

By applying (Eq. 3.324.1, [26]), (11) can be obtained by

$$F_X(x) = 1 - 2\sqrt{\frac{\lambda_{SR}\lambda_{RE}x}{\kappa\Psi}} \times K_1\left(2\sqrt{\frac{\lambda_{SR}\lambda_{RE}x}{\kappa\Psi}}\right). \quad (12)$$

Next, the CDF of Y can be formulated as

$$\begin{aligned} F_Y(y) &= \Pr(Y < y) = \Pr\left(\frac{\Psi|h_{SE}|^2}{\Psi|h_{SE}|^2 + 1} < y\right) \\ &= \Pr\left(|h_{SE}|^2 < \frac{y}{\Psi(1-y)}\right) = 1 - \exp\left(-\frac{\lambda_{SE}y}{\Psi(1-y)}\right), \text{ with } 0 < y < 1. \end{aligned} \quad (13)$$

The PDF of Y is given by

$$f_Y(y) = \frac{\partial F_Y(y)}{\partial y} = \frac{\lambda_{SE}}{\Psi} \times \frac{\exp(-\lambda_{SE}y/\Psi(1-y))}{(1-y)^2}. \quad (14)$$

Applying (12) and (14), the IP, in this case, can be claimed by

$$\begin{aligned} IP_{MRC} &= 1 - \int_0^{\gamma_{th}} \left\{ 1 - 2\sqrt{\frac{\lambda_{SR}\lambda_{RE}(\gamma_{th}-y)}{\kappa\Psi}} \times K_1\left(2\sqrt{\frac{\lambda_{SR}\lambda_{RE}(\gamma_{th}-y)}{\kappa\Psi}}\right) \right\} \\ &\quad \times \frac{\lambda_{SE}}{\Psi} \times \frac{\exp(-\lambda_{SE}y/\Psi(1-y))}{(1-y)^2} dy. \end{aligned} \quad (15)$$

3.2. Instantaneous End-to-End SNR at E Using the SC Technique. In this case, the end-to-end SNR at E can be given by

$$\begin{aligned}\gamma_E^{SC} &= \max(\gamma_E^I, \gamma_E^{II}) = \max\left(\kappa\Psi|h_{SR}|^2|h_{RE}|^2, \frac{\Psi|h_{SE}|^2}{\Psi|h_{SE}|^2 + 1}\right) \\ &= \max(X, Y).\end{aligned}\quad (16)$$

Then, the IP can be expressed as

$$\begin{aligned}\text{IP}_{SC} &= \Pr(\gamma_E^{SC} \geq \gamma_{th}) = \Pr(\max(X, Y) \geq \gamma_{th}) \\ &= 1 - \Pr(X < \gamma_{th})\Pr(Y < \gamma_{th}).\end{aligned}\quad (17)$$

By applying (12) and (13), the expression of IP_{SC} can be expressed as

$$\text{IP}_{SC} = 1 - \left\{1 - \exp\left(-\frac{\lambda_{SE}\gamma_{th}}{\Psi(1 - \gamma_{th})}\right)\right\} \times \left\{1 - 2\sqrt{\frac{\lambda_{SR}\lambda_{RE}\gamma_{th}}{\kappa\Psi}} \times K_1\left(2\sqrt{\frac{\lambda_{SR}\lambda_{RE}\gamma_{th}}{\kappa\Psi}}\right)\right\}.\quad (18)$$

4. Outage Probability (OP) Analysis

The OP can be defined by

$$\text{OP} = \Pr(\gamma_D < \gamma_{th}).\quad (19)$$

4.1. Instantaneous End-to-End SNR at D Using the MRC Technique. From (2) and (7), outage probability of relay link can be computed at

$$\begin{aligned}\text{OP}_1 &= \Pr(\text{source} - \text{relay or relay} - \text{destination is in outage}) \\ &= \Pr\left(\min\left(\frac{1}{\kappa|h_{RR}|^2}, \kappa\Psi|h_{SR}|^2|h_{RD}|^2\right) < \gamma_{th}\right).\end{aligned}\quad (20)$$

From (20), we can see that, to successfully receive data at the destination D, the system needs to decode in the first and second hop.

Equivalently, we can represent the end-to-end SINR of the relay path by

$$T = \min\left(\frac{1}{\kappa|h_{RR}|^2}, \kappa\Psi|h_{SR}|^2|h_{RD}|^2\right).\quad (21)$$

By using MRC technique, the received SINR at destination can be given as

$$\gamma_D^{MRC} = \min\left(\frac{1}{\kappa|h_{RR}|^2}, \kappa\Psi|h_{SR}|^2|h_{RD}|^2\right) + \Psi|h_{SD}|^2 = T + Z,\quad (22)$$

where $Z = \Psi|h_{SD}|^2$.

The OP, in this case, can be expressed by

$$\text{OP}_{MRC} = \Pr(T + Z < \gamma_{th}) = \int_0^\infty F_T(\gamma_{th} - z) \times f_Z(z) dz.\quad (23)$$

From (21), $F_T(t)$ can be calculated as

$$\begin{aligned}F_T(t) &= \Pr(T < t) = \Pr\left(\min\left(\frac{1}{\kappa|h_{RR}|^2}, \kappa\Psi|h_{SR}|^2|h_{RD}|^2\right) < t\right) \\ &= 1 - \underbrace{\Pr(1/\kappa|h_{RR}|^2 \geq t)}_{P_1} \underbrace{\Pr(\kappa\Psi|h_{SR}|^2|h_{RD}|^2 \geq t)}_{P_2},\end{aligned}\quad (24)$$

where

$$P_1 = \Pr\left(\frac{1}{\kappa|h_{RR}|^2} \geq t\right) = \Pr\left(|h_{RR}|^2 \leq \frac{1}{\kappa t}\right) = 1 - \exp\left(-\frac{\lambda_{RR}}{\kappa t}\right),\quad (25)$$

$$P_2 = 1 - \Pr(\kappa\Psi|h_{SR}|^2|h_{RD}|^2 < t) = 2\sqrt{\frac{\lambda_{SR}\lambda_{RD}t}{\kappa\Psi}} \times K_1\left(2\sqrt{\frac{\lambda_{SR}\lambda_{RD}t}{\kappa\Psi}}\right).\quad (26)$$

Substituting (23) and (24) into (22), $F_T(t)$ can be mathematically calculated as

$$\begin{aligned}F_T(t) &= 1 - 2\left\{1 - \exp\left(-\frac{\lambda_{RR}}{\kappa t}\right)\right\} \times \sqrt{\frac{\lambda_{SR}\lambda_{RD}t}{\kappa\Psi}} \\ &\quad \times K_1\left(2\sqrt{\frac{\lambda_{SR}\lambda_{RD}t}{\kappa\Psi}}\right).\end{aligned}\quad (27)$$

By substituting (25) into (21), OP_{MRC} can be given by

$$\text{OP}_{\text{MRC}} = \int_0^{\infty} \left\{ \frac{1 - 2 \left\{ 1 - \exp\left(-\frac{\lambda_{\text{RR}}}{\kappa(\gamma_{\text{th}} - z)}\right) \right\}}{\sqrt{\frac{\lambda_{\text{SR}}\lambda_{\text{RD}}(\gamma_{\text{th}} - z)}{\kappa\Psi}} \times K_1\left(2\sqrt{\frac{\lambda_{\text{SR}}\lambda_{\text{RD}}(\gamma_{\text{th}} - z)}{\kappa\Psi}}\right)} \right\} \times \frac{\lambda_{\text{SD}}}{\Psi} \exp\left(-\frac{\lambda_{\text{SD}}z}{\Psi}\right) dz. \quad (28)$$

4.2. *Instantaneous End-to-End SNR at D Using the SC Technique.* Similar to MRC technique as mentioned above, the overall SNR at D can be given by

$$\gamma_D^{\text{SC}} = \max \left\{ \min \left(\frac{1}{\kappa|h_{\text{RR}}|^2}, \kappa\Psi|h_{\text{SR}}|^2|h_{\text{RD}}|^2 \right), \Psi|h_{\text{SD}}|^2 \right\}. \quad (29)$$

Hence, the OP can be calculated as

$$\begin{aligned} \text{OP}_{\text{SC}} &= \Pr(\gamma_D^{\text{SC}} < \gamma_{\text{th}}) = \Pr \left[\max \left\{ \min \left(\frac{1}{\kappa|h_{\text{RR}}|^2}, \kappa\Psi|h_{\text{SR}}|^2|h_{\text{RD}}|^2 \right), \Psi|h_{\text{SD}}|^2 \right\} < \gamma_{\text{th}} \right] \\ &= \Pr \left[\underbrace{\min \left(\frac{1}{\kappa|h_{\text{RR}}|^2}, \kappa\Psi|h_{\text{SR}}|^2|h_{\text{RD}}|^2 \right) < \gamma_{\text{th}}}_{P_3} \right] \underbrace{\Pr(\Psi|h_{\text{SD}}|^2 < \gamma_{\text{th}})}_{P_4}, \end{aligned} \quad (30)$$

where

$$\begin{aligned} P_3 &= \Pr \left[\min \left(\frac{1}{\kappa|h_{\text{RR}}|^2}, \kappa\Psi|h_{\text{SR}}|^2|h_{\text{RD}}|^2 \right) < \gamma_{\text{th}} \right] \\ &= 1 - \Pr \left(\frac{1}{\kappa|h_{\text{RR}}|^2} \geq \gamma_{\text{th}} \right) \Pr(\kappa\Psi|h_{\text{SR}}|^2|h_{\text{RD}}|^2 \geq \gamma_{\text{th}}) \\ &= 1 - 2 \left\{ 1 - \exp\left(-\frac{\lambda_{\text{RR}}}{\kappa\gamma_{\text{th}}}\right) \right\} \times \sqrt{\frac{\lambda_{\text{SR}}\lambda_{\text{RD}}\gamma_{\text{th}}}{\kappa\Psi}} \times K_1 \left(2\sqrt{\frac{\lambda_{\text{SR}}\lambda_{\text{RD}}\gamma_{\text{th}}}{\kappa\Psi}} \right), \\ P_4 &= 1 - \exp\left(-\frac{\lambda_{\text{SD}}\gamma_{\text{th}}}{\Psi}\right). \end{aligned} \quad (31)$$

Finally, substituting (28) and (29) into (27), the OP in this scenario can be expressed as

$$\begin{aligned} \text{OP}_{\text{SC}} &= \left\{ 1 - \exp\left(-\frac{\lambda_{\text{SD}}\gamma_{\text{th}}}{\Psi}\right) \right\} \\ &\times \left\{ 1 - 2 \left\{ 1 - \exp\left(-\frac{\lambda_{\text{RR}}}{\kappa\gamma_{\text{th}}}\right) \right\} \times \sqrt{\frac{\lambda_{\text{SR}}\lambda_{\text{RD}}\gamma_{\text{th}}}{\kappa\Psi}} \times K_1 \left(2\sqrt{\frac{\lambda_{\text{SR}}\lambda_{\text{RD}}\gamma_{\text{th}}}{\kappa\Psi}} \right) \right\}. \end{aligned} \quad (32)$$

5. Simulation Results

The simulation results are given to validate the performance, that is, IP and OP, of our proposed schemes under maximal ratio combining (MRC) and selection combining (SC) techniques. The results are obtained by averaging 10^5 Rayleigh channels [27–29].

In Figures 3 and 4, we investigate the IP and OP as functions of Ψ (dB), where $\gamma_{th} = 1$, $\alpha = 0.5$, $\eta = 1$. One can observe from Figure 3 that as Ψ increases from -5 to 20 dB, the IP performance improves accordingly. The source's transmit power is proportional to Ψ value, since Ψ is defined as a ratio between source transmit power and additive white Gaussian noise. Thus, the higher the Ψ value is, the better the SNR at eavesdropper can be obtained. Furthermore, the IP of the MRC technique outperforms that of the SC technique. It is because the eavesdropper can overhear information from both source S and relay R using MRC while only receiving signals from the source with the SC technique. In Figure 4, the outage performance of MRC is superior to that of the SC method. It is because the destination can combine signals from relay and source in MRC, which only receives this information from relay user in the SC method. As shown from Figures 3 and 4, the performances of both destination D and eavesdropper E can be continuously improved by increasing the transmit power. Thus, the designer should select a suitable value of Ψ when designing in practice for trade-off between security and reliability of the system.

Figures 5 and 6 show the IP and OP as a function of α for the time-switching relaying (TSR) protocol, where $\gamma_{th} = 1$, $\Psi = 3$ dB, $\eta = 1$. The value of α is crucial, since it influences both the harvested energy at the relay and the information transmission from the relay to the destination. As a result, the higher the value of α is, the more energy the relay can harvest. However, there is less time for information transmission to the destination. Therefore, the OP can obtain the best value at the optimal point of α ; then the performance worsens. Notably, when the value of α is small, the eavesdropper has a low probability of intercepting the information. For instance, the IPs of MRC and SC are 0.073 and 0.0068, respectively, when α equals 0.05. When α is higher than the optimal value, the outage performance and system security are worse. It provides useful information for designing a practical system.

In Figures 7 and 8, we investigate the IP and OP as a function of rate threshold requirement to decode the signal successfully, where $\alpha = 0.85$, $\Psi = 5$ dB, $\eta = 1$. As observed from Figures 7 and 8, as the rate threshold increases from 0.25 to 4 bps/Hz, the IP and OP performance degrades accordingly. It is expected since when the rate requirement is higher, the eavesdropper and destination need to obtain a higher transmission rate to decode the signal. However, the transmission rate is limited by many factors such as channel gain and allocated time for data transmission. One more interesting point is that the IP and OP performances of MRC and SC are converged to a saturation value when the rate threshold increases.

In Figures 9 and 10, we study the influences of energy conversion efficiency on the network performance, that is, IP

FIGURE 3: IP versus Ψ (dB).

FIGURE 4: OP versus Ψ (dB).

FIGURE 5: IP versus α .

FIGURE 6: OP versus α .

FIGURE 7: IP versus R (bps/Hz).

FIGURE 8: OP versus R (bps/Hz).

FIGURE 9: IP versus η . FIGURE 10: OP versus η .

and OP. It can be seen that both IP and OP are improved with higher values of IP and OP. This can be explained by the fact that the higher the conversion rate is, the more transmit power at the relay R can be obtained, which improves the channel gain to eavesdropper and destination. Moreover, similar to Figures 3–8, the IP and OP performance of the MRC is better than that of the SC, which shows the superiority of the MRC technique. However, the MRC technique requires more complicated hardware, which is not always suitable in practice. Thus, the evaluations in our work give different scenarios for the designer to build a system in reality.

6. Conclusion

This paper investigated the decode-and-forward (DF) full-duplex (FD) relaying networks under the presence of a direct

link. Specifically, the relay node can harvest energy from the source and use it to transmit information to the destination. By considering the above discussions, we derive the closed-form expressions of the intercept probability (IP) and the outage probability (OP) in both maximal ratio combining (MRC) and selection combining (SC) techniques at the receiver. Besides, the simulation results show the exactness of the mathematical results compared to simulation ones. Besides, the IP and OP of the MRC technique obtain better performance in comparison to those of the SC technique. In particular, the system security is improved significantly when the time splitting factor value is small. We can extend this work to the case where the source and eavesdropper are equipped with multiple antennas.

Data Availability

No data were used in this paper. The authors just proposed the system and simulated it by MATLAB.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Phu Tran Tin (phutrantin@iuh.edu.vn) was the main performer, while Dong Si Thien Chau (dongsithienchau@tdtu.edu.vn), Van-Duc Phan (duc.pv@vlu.edu.vn), Tan N. Nguyen (nguyennhattan@tdtu.edu.vn), and Phu X. Nguyen (phunx4@fpt.edu.vn, phunx4@fe.edu.vn) worked as the advisors of Phu Tran Tin.

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