

Physical layer security in DF full-duplex relaying network: performance analysis

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ABSTRACT

In this letter, the system performance of the DF full-duplex (FD) relaying communication network is investigated with physical layer security (PLS). In this system model, the source (S) and the destination (D) communicate via a helping relay (R) in the presence of the eavesdropper (E). From the system model, we derive the closed-form expressions for intercept probability (IP) and secrecy outage probability (SOP). For verifying the correctness of the analytical analysis, the Monte Carlo simulation is conducted. In addition, the influence of the main system parameter on the system performance is investigated. Finally, the results show that the analytical and the simulation values agree well with each other.

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1. INTRODUCTION

In the comparison with the conventional communication network, the wireless communication network the power supply from the nodes to nodes can be done via RF to avoid the process battery replacement with some disadvantages, such as inconvenient, infeasible for some applications [1-10]. In the last few years, wireless energy transfer (WET) technologies by supplying continuous and stable energy over the air is a proposed solution for avoiding disadvantages. This method could significantly reduce the maintenance cost and the frequency of energy outage events due to battery depletion [6-15]. Authors in [16] investigated the outage probability and the throughput of an amplify-and-forward relaying system using energy harvesting, and an amplify-and-forward (AF) relaying network is considered in [17], where an energy-constrained relay node harvests energy from the received RF signal and uses that harvested energy to forward the source information to the destination. Furthermore, authors in [18] proposed a dual-hop decode-and-forward (DF) relaying network, where relays operate based on harvested energy from radio frequency (RF) radiation and authors in [19] considered the generalized diversity combining of an energy-constrained multiple antenna decode-and-forward relay network. Moreover, authors in [20] proposed and investigated simultaneous wireless information and power transfer in two-way decode-and-forward (DF) relay networks,

where the relay is an energy-constrained node but is capable of harvesting energy from the radio frequency signal transmitted by the source nodes for forwarding its information [21-26].

In this letter, the system performance of the DF full-duplex (FD) Relaying communication network is investigated with physical layer security (PLS). In this system model, the source (S) and the destination (D) communicate via a helping relay (R) in the presence of the eavesdropper (E). From the system model, we derive the closed-form expressions for intercept probability (IP) and Secrecy Outage Probability (SOP). For verifying the correctness of the analytical analysis, the Monte Carlo simulation is conducted. In addition, the influence of the main system parameter on the system performance is investigated. Finally, the results show that the analytical and the simulation values agree well with each other. The main contribution of the paper can be summarized as the following:

- a) The system model of the DF full-duplex (FD) Relaying communication network is investigated with Physical layer security (PLS) is proposed.
- b) The closed-form expressions for intercept probability (IP) and secrecy outage probability (SOP) are derived.
- c) The influence of the main system parameter on the system performance is investigated.
- d) The Monte Carlo simulation is conducted for verifying the analytical analysis.

The rest of the manuscript can be provided as the following. The system model of the DF full-duplex (FD) Relaying communication network is investigated with physical layer security (PLS) is drawn in the Section 2. The IP and SOP analysis are presented in the Section 3. Then, the numerical results and some discussions are presented in the Section 4. Finally, the Section 5 concludes this manuscript.

2. SYSTEM MODEL

In Figure 1, a source S communicates with a destination D via the help of a FD relay denoted by R and one eavesdropper, which denoted by E want to overhear the information at the relay R [27-30]. Let us denote h_{SR} , h_{RD} and h_{RE} as the channel coefficients of the $S \rightarrow R$, $R \rightarrow D$ and $R \rightarrow E$ links, respectively. We also denote h_{RR} as the self-interference between the transmit antenna and the receive antenna of the relay R.

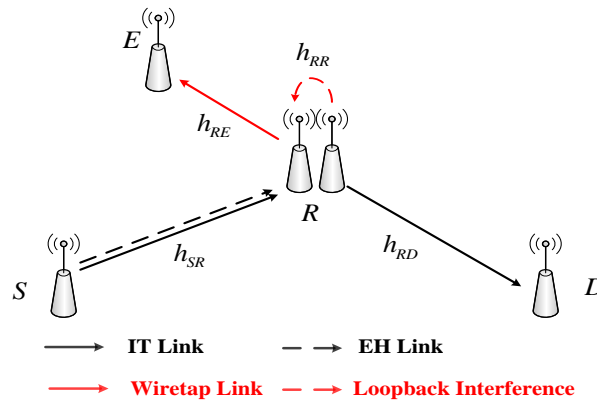


Figure 1. P_{out} versus the transmit power P_3 with different P_1 and P_2 (P_1, P_2)

Cumulative distribution function (CDF) is given as

$$F_{\varphi_i}(x) = 1 - \exp(-\lambda_i x) \tag{1}$$

Where $i \in (SR, RD, RR, RE)$,

Here,

$$\lambda_i = (d_i)^\beta \tag{2}$$

where d_i is link distance between correspondence nodes.

Then, the probability density function (PDF) of φ_i is expressed as,

$$f_{\varphi_i}(x) = \lambda_i \exp(-\lambda_i x) \tag{3}$$

As shown in Figure 2, T denotes the total time interval, which is used for energy harvesting and information transferring from S to D. In the first interval time αT ($0 < \alpha < 1$), the relay R harvests energy from the source. In the remaining interval $(1-\alpha)T$, the source transfers the information to the destination D via the helping relay R.

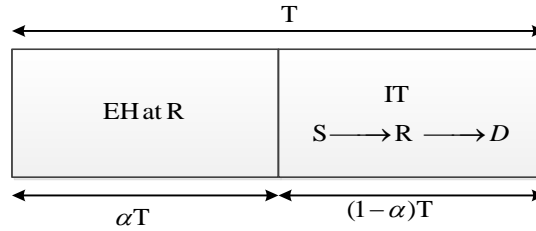


Figure 2. EH and IT phases

2.1. Energy harvesting and Information transmission phase

In this phase, the received signal at the relay can be formulated as,

$$y_R = h_{SR}x_S + h_{RR}x_R + n_R \tag{4}$$

And $E\{|x_S|^2\} = P_S$, $E\{|x_R|^2\} = P_R$, $E\{\bullet\}$ is an expectation operator in which P_S is average transmit power at the source and P_R is average transmit power at the relay. As [28], the harvested power at the relay can be calculated as,

$$P_R = \frac{E_h}{T} = \frac{\eta \alpha T P_S |h_{SR}|^2}{(1-\alpha)T} = \kappa P_S |h_{SR}|^2 = \kappa P_S \varphi_{SR} \tag{5}$$

Where $\kappa = \frac{\eta \alpha}{1-\alpha}$ in which $0 < \eta \leq 1$.

The received signal at the destination can be expressed as:

$$y_D = h_{RD}x_R + n_D \tag{6}$$

Where h_{RD} is the relay to destination channel gain and n_D is the AWGN with variance N_0 .

In our proposed system, we consider the decode and forward scheme as [29]. So, from (4), the signal to noise ratio (SNR) at the relay can be formulated by,

$$\gamma_R = \frac{P_S |h_{SR}|^2}{|h_{RR}|^2 P_R + N_0} \tag{7}$$

Substituting (5) into (7), we obtain:

$$\gamma_R = \frac{P_S |h_{SR}|^2}{\kappa P_S |h_{RR}|^2 |h_{SR}|^2 + N_0} \approx \frac{1}{\kappa |h_{RR}|^2} = \frac{1}{\kappa \varphi_{RR}} \tag{8}$$

From (6), the SNR at the destination can be computed as,

$$\gamma_D = \frac{P_R |h_{RD}|^2}{N_0} = \frac{\kappa P_S |h_{SR}|^2 |h_{RD}|^2}{N_0} = \kappa \Psi |h_{SR}|^2 |h_{RD}|^2 = \kappa \Psi \varphi_{SR} \varphi_{RD} \quad (9)$$

Where $\Psi = \frac{P_S}{N_0}$

The end to end SNR can be claimed by,

$$\gamma_{DF} = \min(\gamma_R, \gamma_D) \quad (10)$$

Next, the eavesdropper overhears the information of the relay. Hence, the received signal at the eavesdropper can be expressed by,

$$y_E = h_{RE} x_R + n_E \quad (11)$$

E successfully decodes the information from the relay with the following SNR.:

$$\gamma_E = \frac{P_R |h_{RE}|^2}{N_0} = \kappa \Psi |h_{SR}|^2 |h_{RE}|^2 = \kappa \Psi \varphi_{SR} \varphi_{RE} \quad (12)$$

Here, the data rate for the data and eavesdropping links can be formulated, respectively by,

$$\begin{aligned} C_{DF} &= (1 - \alpha) \times \log_2(1 + \gamma_{DF}) \\ C_E &= (1 - \alpha) \times \log_2(1 + \gamma_E) \end{aligned} \quad (13)$$

3. PERFORMANCE ANALYSIS

3.1. Intercept probability (IP) analysis

As [31], the IP can be defined by

$$IP = \Pr(C_E \geq C_{th}) \quad (14)$$

Where C_{th} is the predetermined data rate threshold.

Substituting (13) into (14) and then combining with (12), we can obtain:

$$\begin{aligned} IP &= \Pr(\kappa \Psi \varphi_{SR} \varphi_{RE} \geq \gamma_{th}) = 1 - \Pr(\kappa \Psi \varphi_{SR} \varphi_{RE} < \gamma_{th}) \\ &= 1 - \Pr\left(\varphi_{SR} < \frac{\gamma_{th}}{\kappa \Psi \varphi_{RE}}\right) = 1 - \int_0^{\infty} F_{\varphi_{SR}}\left(\frac{\gamma_{th}}{\kappa \Psi \varphi} \mid \varphi_{RE} = \varphi\right) \times f_{\varphi_{RE}}(\varphi) d\varphi \end{aligned} \quad (15)$$

Where $\gamma_{th} = 2^{\frac{C_{th}}{1-\alpha}} - 1$

Using results from (1) and (3), (15) can be reformulated by,

$$IP = 1 - \int_0^{\infty} \left[1 - \exp\left(-\frac{\gamma_{th} \lambda_{SR}}{\kappa \Psi \varphi}\right)\right] \times \lambda_{RE} \exp(-\lambda_{RE} \varphi) d\varphi = \lambda_{RE} \int_0^{\infty} \exp\left(-\frac{\gamma_{th} \lambda_{SR}}{\kappa \Psi \varphi}\right) \times \exp(-\lambda_{RE} \varphi) d\varphi \quad (16)$$

Applying (3.324,1) of [32], we obtain:

$$IP = 2 \sqrt{\frac{\gamma_{th} \lambda_{SR} \lambda_{RE}}{\kappa \Psi}} \times K_1\left(2 \sqrt{\frac{\gamma_{th} \lambda_{SR} \lambda_{RE}}{\kappa \Psi}}\right) \quad (17)$$

Where $K_v(\bullet)$ is the modified Bessel function of the second kind and v^{th} order.

3.2. Secrecy outage probability (SOP) analysis

The secrecy capacity can be defined as,

$$C_{e2e}^{Sec} = \max[0, C_{DF} - C_E] \tag{18}$$

So, the SOP of the system can be formulated by,

$$SOP = \Pr(C_{e2e}^{Sec} < C_{th}) = \Pr\left(\frac{1 + \gamma_{DF}}{1 + \gamma_E} < 2^{C_{th}}\right) = \Pr(\gamma_{DF} < \gamma_1 + \gamma_2 \gamma_E) \tag{19}$$

Where $\gamma_1 = 2^{C_{th}} - 1$ and $\gamma_2 = 2^{C_{th}}$

In the high SNR regime, (19) can be approximated by,

$$SOP \approx \Pr\left(\frac{\gamma_{DF}}{\gamma_E} < 2^{C_{th}}\right) = \Pr(\gamma_{DF} < \gamma_2 \gamma_E) \tag{20}$$

Combining (8), (9), (10) and (12), (20) can be rewritten as,

$$\begin{aligned} SOP &= \Pr\left\{\min\left(\frac{1}{\kappa\varphi_{RR}}, \kappa\Psi\varphi_{SR}\varphi_{RD}\right) < \kappa\Psi\gamma_2\varphi_{SR}\varphi_{RE}\right\} \\ &= \int_0^\infty \Pr\left\{\min\left(\frac{1}{\kappa\varphi_{RR}}, \kappa\Psi x\varphi_{RD}\right) < \kappa\Psi\gamma_2 x\varphi_{RE}\right\} \times f_{\varphi_{SR}}(x) dx \end{aligned} \tag{21}$$

The probability in (21) can be written by,

$$P_1 = \Pr(\gamma_{DF}^1 < \kappa\Psi\gamma_2 x\varphi_{RE}) = \int_0^\infty F_{\gamma_{DF}^1}(\kappa\Psi\gamma_2 x\varphi_{RE} | \varphi_{RE} = \varphi) \times f_{\varphi_{RE}}(\varphi) d\varphi \tag{22}$$

Where
$$\gamma_{DF}^1 = \min\left(\frac{1}{\kappa\varphi_{RR}}, \kappa\Psi x\varphi_{RD}\right)$$

Next, we find the CDF of γ_{DF}^1 . We can express as:

$$F_{\gamma_{DF}^1}(y) = \Pr(\gamma_{DF}^1 < y) = \Pr\left\{\min\left(\frac{1}{\kappa\varphi_{RR}}, \kappa\Psi x\varphi_{RD}\right) < y\right\} = 1 - \Pr\left(\frac{1}{\kappa\varphi_{RR}} \geq y\right) \times \Pr(\kappa\Psi x\varphi_{RD} \geq y) \tag{23}$$

The first term of (23) can be calculated by,

$$P_{11} = \Pr\left(\varphi_{RR} \leq \frac{1}{\kappa y}\right) = 1 - \exp\left(-\frac{\lambda_{RR}}{\kappa y}\right) \tag{24}$$

Next, P_{12} can be computed by,

$$P_{12} = 1 - \Pr(\kappa\Psi x\varphi_{RD} < y) = 1 - \Pr\left(\varphi_{RD} < \frac{y}{\kappa\Psi x}\right) = \exp\left(-\frac{y\lambda_{RD}}{\kappa\Psi x}\right) \tag{25}$$

Substituting (24), (25) into (23), we have:

$$F_{\gamma_{DF}^1}(y) = 1 - \left\{1 - \exp\left(-\frac{\lambda_{RR}}{\kappa y}\right)\right\} \times \exp\left(-\frac{y\lambda_{RD}}{\kappa\Psi x}\right) = 1 - \exp\left(-\frac{y\lambda_{RD}}{\kappa\Psi x}\right) + \exp\left(-\frac{y\lambda_{RD}}{\kappa\Psi x} - \frac{\lambda_{RR}}{\kappa y}\right) \tag{26}$$

Substituting (26) into (22), we claim:

$$\begin{aligned}
 P_1 &= \int_0^{\infty} \left\{ 1 - \exp(-\gamma_2 \varphi \lambda_{RD}) + \right. \\
 &\quad \left. \exp\left(-\gamma_2 \varphi \lambda_{RD} - \frac{\lambda_{RR}}{\kappa^2 \Psi \gamma_2 x \varphi}\right) \right\} \times f_{\varphi_{RE}}(\varphi) d\varphi \\
 &= 1 - \lambda_{RE} \int_0^{\infty} \exp(-\gamma_2 \varphi \lambda_{RD} - \lambda_{RE} \varphi) d\varphi + \lambda_{RE} \int_0^{\infty} \exp\left(-\gamma_2 \varphi \lambda_{RD} - \frac{\lambda_{RR}}{\kappa^2 \Psi \gamma_2 x \varphi} - \lambda_{RE} \varphi\right) d\varphi
 \end{aligned} \quad (27)$$

From (27), the first integral can be easily calculated by,

$$I_1 = \lambda_{RE} \int_0^{\infty} \exp\{-\varphi(\lambda_{RD} \gamma_2 + \lambda_{RE})\} d\varphi = \frac{\lambda_{RE}}{\lambda_{RD} \gamma_2 + \lambda_{RE}} \quad (28)$$

Next, the second integral can be obtained as,

$$I_2 = \lambda_{RE} \int_0^{\infty} \exp\left(-\varphi[\gamma_2 \lambda_{RD} + \lambda_{RE}] - \frac{\lambda_{RR}}{\kappa^2 \Psi \gamma_2 x \varphi}\right) d\varphi \quad (29)$$

Applying (3.324,1) of [32], we have,

$$I_2 = 2\lambda_{RE} \sqrt{\frac{\lambda_{RR}}{\kappa^2 \Psi \gamma_2 x (\gamma_2 \lambda_{RD} + \lambda_{RE})}} \times K_1 \left(2\sqrt{\frac{\lambda_{RR} (\gamma_2 \lambda_{RD} + \lambda_{RE})}{\kappa^2 \Psi \gamma_2 x}} \right) \quad (30)$$

Then, substituting (28) and (30) into (27), we have:

$$P_1 = 1 - \frac{\lambda_{RE}}{\lambda_{RD} \gamma_2 + \lambda_{RE}} + 2\lambda_{RE} \sqrt{\frac{\lambda_{RR}}{\kappa^2 \Psi \gamma_2 x (\gamma_2 \lambda_{RD} + \lambda_{RE})}} \times K_1 \left(2\sqrt{\frac{\lambda_{RR} (\gamma_2 \lambda_{RD} + \lambda_{RE})}{\kappa^2 \Psi \gamma_2 x}} \right) \quad (31)$$

Finally, substituting (31) into (21), we obtain:

$$SOP = 1 - \frac{\lambda_{RE}}{b^2} + \frac{2\lambda_{RE} \lambda_{SR} a}{b} \int_0^{\infty} x^{-1/2} \times \exp(-\lambda_{SR} x) \times K_1 \left(\frac{2ab}{\sqrt{x}} \right) dx \quad (32)$$

Where $a = \sqrt{\frac{\lambda_{RR}}{\kappa^2 \Psi \gamma_2}}$ and $b = \sqrt{\gamma_2 \lambda_{RD} + \lambda_{RE}}$

Using result from (26) of [33], the SOP can be claimed as,

$$SOP = 1 - \frac{\lambda_{RE}}{b^2} + \frac{\sqrt{\lambda_{SR} \lambda_{RE}} a}{b} \times G_{0,3}^{3,0} \left(a^2 b^2 \lambda_{SR} \mid \frac{-1}{2}, \frac{1}{2}, \frac{1}{2} \right) \quad (33)$$

Where $G_{p,q}^{m,n} \left(z \mid \begin{matrix} a_1, \dots, a_p \\ b_1, \dots, b_q \end{matrix} \right)$ is the Meijer G function.

4. NUMERICAL RESULTS AND DISCUSSION

The system IP and SOP versus α are investigated in Figures 3 and 4, respectively. In Figure 3, the main system parameters are set as the following $\psi = 5$ dB, $C_{th} = 0.25$, and $\eta = 0.5, 0.85, 1$, respectively. From Figure 3, we can see that the system IP has a huge increase when α varies from 0 to 0.7 and the decreases significantly. The maximum value of the system IP can be obtained with α near 0.7. Furthermore, the main system parameters are set as $C_{th} = 0.25$, $\psi = 10$ dB, and $\eta = 0.5, 0.85, 1$, respectively. As shown in Figure 4, the system SOP increase

massively with rising of α from 0 to 1. In Figures 3 and 4, it can be observed that the simulation and analytical curves are the same to verify the correctness of the analytical above section [27-36].

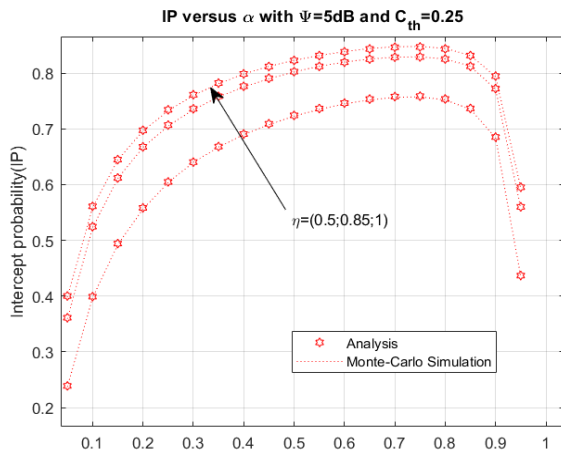


Figure 3. IP versus α

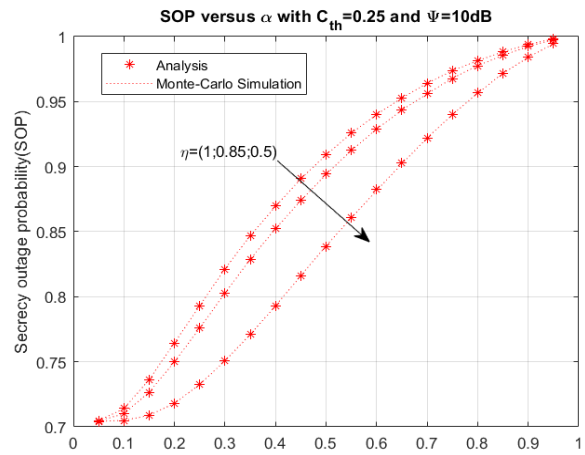


Figure 4. SOP versus α

In addition, the effect of C_{th} on the system IP is illustrated in Figure 5 with the primary system parameter as $\psi=10$ dB, $\eta=1$, and $\alpha=0.3, 0.5, 0.85$, respectively. From the result, the system IP falls considerably with the increase of C_{th} from 0 to 1 bit/s/Hz. Moreover, we considered the system SOP as the function of η with the main system parameters as $C_{th}=0.25, \psi=10$ dB, $\alpha=0.3, 0.5, 0.85$ as proposed in Figure 6. As drawn in Figure 6, the system SOP increases significantly while η rises from 0 to 1. As shown in Figures 5 and 6, the simulation curve agrees well with the analytical curve to convince the correctness of the analytical section.

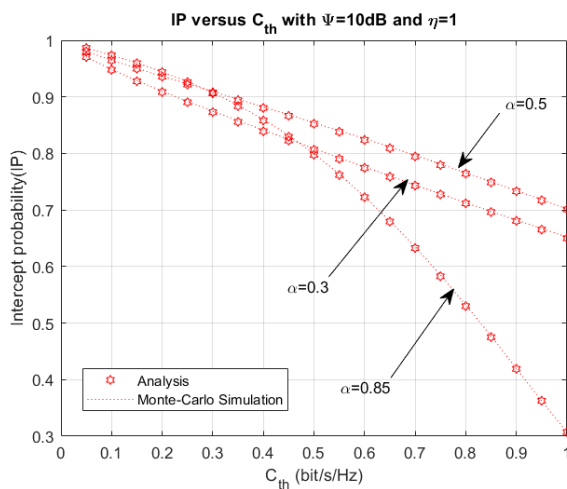


Figure 5. IP versus C_{th}

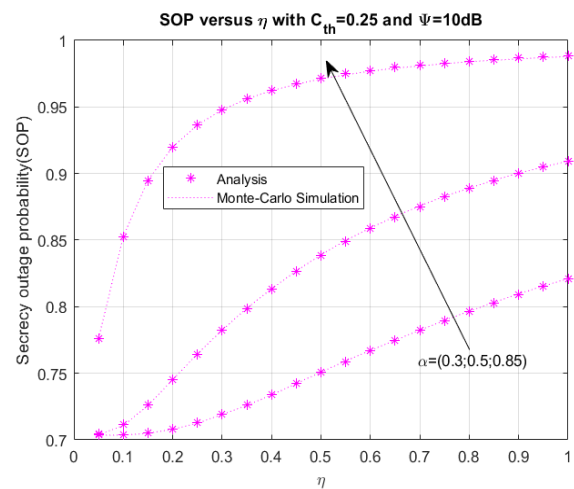
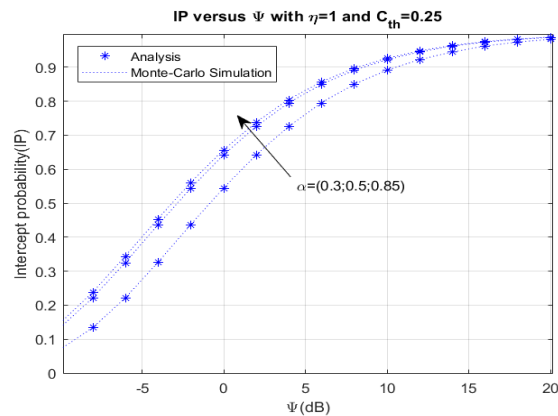
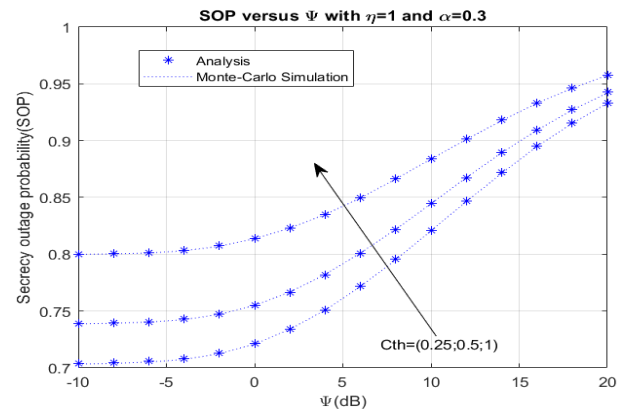


Figure 6. SOP versus η

Finally, the system IP and SOP versus ψ are presented in Figures. 7 and 8, respectively. In Figures 7 and 8, we set $\eta=1, \alpha=0.3, C_{th}=0.24, 0.5$ and 1. As shown in Figures 7 and 8, the system IP and SOP has a massive increase while ψ rises from -10 dB to 20 dB. From the research results, we can see that the analytical are the same with the simulation values.

Figure 7. IP versus ψ Figure 8. SOP versus ψ

5. CONCLUSION

In this letter, the system performance of the DF FD Relaying communication network is investigated with PLS. From the system model, we derive the closed-form expressions for IP and SOP. For verifying the correctness of the analytical analysis, the Monte Carlo simulation is conducted. Moreover, the influence of the main system parameter on the system performance is investigated. Finally, the results show that the analytical and the simulation values agree well with each other.

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