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Exploiting direct link in EH based two-way DF half-duplex relaying network: Outage probability analysis

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## Article Info

ABSTRACT

Relay communication is considered as a popular solution for expanding the coverage, increasing the transmission capacity and reducing the power consumption of the communication networks. In this paper, we proposed and investigated the two-way decode-and-forward (DF) half-duplex (HD) relaying network with the direct link between two sources S_1 and S_2. Firstly, the system model, energy harvesting (EH) and information transmission (IT) are presented. The closed-form analytical expression of the system outage probability (OP) is analyzed and derived in the next stage. Finally, the correctness of the analytical expressions is verified by Monte Carlo simulation. The research results show that the analytical and simulation are the same in connection with the primary system parameters.
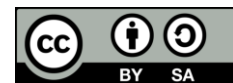
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1. INTRODUCTION

Nowadays, the fifth-generation (5G) wireless networks is considered as a hot research area in academic and industrial based on the increasing data rate transmission. Relay communication, in which the relay forwards the signal received by a source to a destination, has a massive consideration in research, due to its ability to expand the coverage, increase the capacity, and reduce the power consumption [1-4]. Moreover, relaying the communication network is an effective way to combat the performance degradation caused by fading, shadowing, path loss, and is an efficient way to improve spectrum efficiency and extend coverage [1-6]. On another way, two-way relaying, where two users exchange information with each other via a single or multiple relays, provides improved spectral efficiency compared to conventional one-way relaying by using either superposition coding or physical layer network coding at relays. Furthermore, to satisfy the 5G requirements, relaying schemes with high spectrum efficiency, such as two-way, and full-duplex, etc., have been recently attracted considerable attention [7-10]. In [7], the authors investigate one-way full-duplex (FD) relaying and two-way half-duplex (HD) relaying to minimize the spectral efficiency loss associated with one-way HD relaying. In [8] and [9], the authors proposed and investigated one-way FD relaying with multiple antennas to provide a solution to overcome the spectral efficiency loss. In [10], the authors investigate one-way FD relaying with opportunistic relay selection to enhance the performance.

In this research, the two-way decode-and-forward (DF) HD relaying network with the direct link between two sources S_1 and S_2 is proposed and investigated. The system model, energy harvesting (EH) and information transmission (IT) are presented in the first stage. After that, we derived the closed-form of the system outage probability (OP) in the next stage. Finally, the correctness of the analytical expressions is verified by Monte Carlo simulation in connection with the primary system parameters. The research results show that the analytical and simulation are the same in connection with the primary system parameters. In this research, we focus on some problems:

a. The two-way DF HD relaying network with the direct link between two sources S_1 and S_2 is proposed and investigated.
b. The closed-form expression of the system OP is analyzed and derived.
c. All the results are convinced by Monte Carlo simulation in connection with all primary system parameters.

The structure of the rest of the paper can be drawn as follows. We provide the system model, the energy and information transfer phases in section 2. The closed-form expression of system OP analysis is derived in section 3. We introduce the results and have some discussions in section 4. In the last section, some conclusions are proposed.

2. RESEARCH METHOD

In this section, the two-way DF HD relaying network with the direct link between two sources S_1 and S_2 is drawn in Figure 1. The energy harvesting (EH) and information transformation (IT) for this proposed model system are proposed in Figure 2. In this protocol, the transmission interval time is T, which consists of three-time slots T/3. In the first time slot T/3, the R harvests energy ρP_1 from the source node S_1, and the source uses the energy $(1-\rho)P_1$ for information transmission to R and S_2 (here $0 < \rho < 1$ is the power splitting factor). In the second interval time T/3, the R harvests energy ρP_2 from the source node S_2, and the source S_2 uses the energy $(1-\rho)P_2$ for information transmission to R and S_1. Finally, the remaining time slot T/3 is used for information transferring from the R to the nodes S_1 and S_2 [11-16].
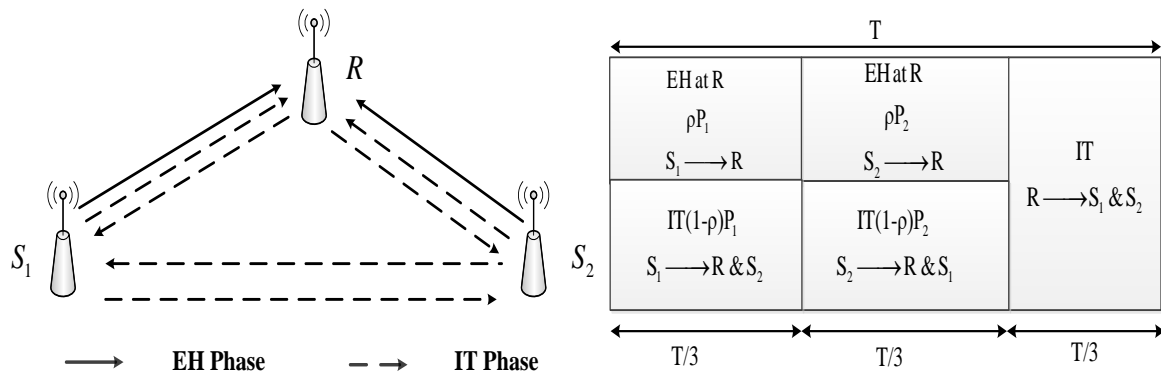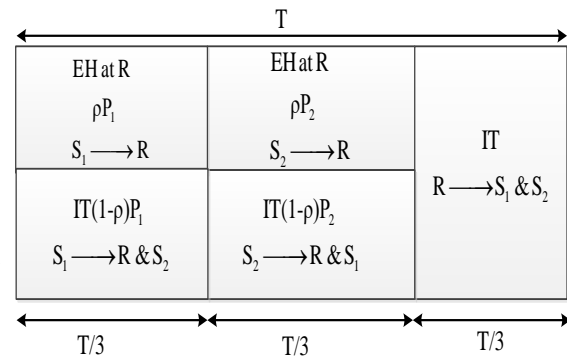

Figure 1. System model

Figure 2. The energy harvesting (EH) and information transmission (IT) processes

2.1. Energy harvesting phase

Let S_1 transmits the symbol x_1 in the first interval time. We define the received signal at the R node R and the S node S_2 as:

$$y_{1,R}^I = h_{1,R} x_1 + n_r^I$$
$$y_{1,2}^I = h_{1,2} x_1 + n_2^I \qquad (1)$$

Where $E\left\{|x_1|^2\right\} = P_1, E\{\bullet\}$ is expectation operator and P_1 represents the average transmit power at the S_1. Further, n_r^I and n_2^I denote the zero-mean additive white Gaussian noise (AWGN) with variance N_0. Then, the harvested energy at the R node can be formulated as the following:

$$E_h^I = \frac{\eta \rho P_1 \left|h_{1,R}\right|^2 T}{3} \tag{2}$$

In the second interval time, the source node S_2 transmits the signal x_2 to the nodes R and S_1. Therefore, the received signals at the R and S_1 can be expressed, respectively, as:

$$y_{2,R}^{II} = h_{2,R} x_2 + n_r^{II},$$
$$y_{2,1}^{II} = h_{2,1} x_2 + n_1^{II} \tag{3}$$

Where $E\left\{\left|x_2\right|^2\right\} = P_2$, P_2 is the average transmit power at the S_2. And we assume that n_r^{II} and n_1^{II} are the zero-mean additive white Gaussian noise (AWGN) with variance N_0. Here, the total harvested energy at the R node can be defined as:

$$E_h = \frac{\eta \rho \left(P_1 \left|h_{1,R}\right|^2 + P_2 \left|h_{2,R}\right|^2 \right) T}{3} \tag{4}$$

In this model, the average transmits power from source S_1 and S_2 is assumed to equal. So, the (4) can be rewritten as the following:

$$E_h = \frac{\eta \rho \left(P_1 \left|h_{1,R}\right|^2 + P_2 \left|h_{2,R}\right|^2 \right) T}{3} = \frac{\eta \rho P \left(\left|h_{1,R}\right|^2 + \left|h_{2,R}\right|^2 \right) T}{3} \tag{5}$$

Where we denote $P_1 = P_2 = P$. Therefore, we have the average transmit power at the R as:

$$P_R = \frac{E_h}{(T/3)} = \eta \rho P \left(\left|h_{1,R}\right|^2 + \left|h_{2,R}\right|^2 \right) \tag{6}$$

2.2. Information transmission phase

In the first interval time, after doing EH, S_1 broadcasts the information to the R node and S_2 with remaining power $(1-\rho)P$. From that, we have the received signal at the R node and S_2 as:

$$y_{1,R}^I = \sqrt{1-\rho} h_{1,R} x_1 + n_r^I,$$
$$y_{1,2}^I = h_{1,2} x_1 + n_2^I \tag{7}$$

Similar to the first case, the received signal at node and S_1 node can be given as the following:

$$y_{2,R}^{II} = \sqrt{1-\rho} h_{2,R} x_2 + n_r^{II},$$
$$y_{2,1}^{II} = h_{2,1} x_2 + n_1^{II} \tag{8}$$

Finally, in the third interval time, the received signal at the sources S_1 and S_2 can be expressed, respectively, as:

$$y_1^{III} = h_{R,1} x_R + n_1^{III},$$
$$y_2^{III} = h_{R,2} x_R + n_2^{III} \tag{9}$$

Where $E\left\{\left|x_R\right|^2\right\} = P_R$. The received signal at the source node S_1 or S_2 can be formulated as:

$$y_1^{DF} = \sqrt{P_R} h_{R,i} (x_1 \oplus x_2) + n \quad y_1^{DF} = \sqrt{P_R} h_{R,i} (x_1 \oplus x_2) + n \quad y_1^{DF} = \sqrt{P_R} h_{R,i} (x_1 \oplus x_2) + n_1 \tag{10}$$

Where $i \in (1, 2)$. Once again, after applying the canceling the self-interference method and combine with (6) the SNR at S_1 can be defined as:

$$\gamma_1^{DF} = \frac{P_R |h_{R,1}|^2}{N_0} = \eta\rho\psi \left(|h_{1,R}|^2 + |h_{2,R}|^2 \right) |h_{R,1}|^2 = \eta\rho\psi\varphi_1 [\varphi_2 + \varphi_4] \tag{11}$$

Where $\varphi_4 = |h_{1,R}|^2$

3. SYSTEM PERFORMANCE ANALYSIS

Hence, the outage probability (OP) of DF mode at the S_1 can be formulated as:

$$\begin{aligned} OP_{DF} &= \Pr\left\{ \gamma_{e2e}^{DF} < \gamma_{th} \right\} = \Pr\left\{ \max\left\{ \eta\rho\psi\varphi_1 \left[\varphi_2 + \varphi_4 \right], \psi\varphi_3 \right\} < \gamma_{th} \right\} \\ &= \Pr\left\{ \eta\rho\psi\varphi_1 \left[\varphi_2 + \varphi_4 \right] < \gamma_{th} \right\} \times \Pr\left\{ \psi\varphi_3 < \gamma_{th} \right\} \end{aligned} \tag{12}$$

Where we denote:

$$\Pr\left\{ \psi\varphi_3 < \gamma_{th} \right\} = \Pr\left\{ \varphi_3 < \frac{\gamma_{th}}{\psi} \right\} = 1 - \exp\left(-\frac{\gamma_{th}}{\lambda_3 \psi} \right) \tag{13}$$

Which λ_3 is mean of the random variable (RV) φ_3. Here we have:

$$\begin{aligned} P_3 &= \Pr\left\{ \eta\rho\psi\varphi_1\varphi < \gamma_{th} \right\} = \Pr\left\{ \varphi_1 < \frac{\gamma_{th}}{\eta\rho\psi\varphi} \right\} \\ &= \int_0^\infty F_{\varphi_1}\left(\frac{\gamma_{th}}{\eta\rho\psi\varphi} | \varphi \right) f_\varphi(\varphi) d\varphi \end{aligned} \tag{14}$$

Where $\varphi = \varphi_2 + \varphi_4$ For calculating the probability in (13), the probability density function (PDF) and cumulative density function (CDF) of φ is calculated as in Lemma 1

Lemma 1.

The CDF of $(\varphi_2 + \varphi_4)$ can be formulated as:

$$\begin{aligned} F_\varphi(x) &= \Pr[\varphi < x] = \Pr[\varphi_2 < x - \varphi_4] \\ &= \int_0^x f_{\varphi_4}(\varphi_4) d\varphi_4 \int_0^{x - \varphi_4} f_{\varphi_2}(\varphi_2) d\varphi_2 = \int_0^x F_{\varphi_2}(x - \varphi_4) f_{\varphi_4}(\varphi_4) d\varphi_4 \\ &= \frac{1}{\lambda_4} \int_0^x \left[1 - \exp\left(-\frac{x - \varphi_4}{\lambda_2} \right) \right] \exp\left(-\frac{\varphi_4}{\lambda_4} \right) d\varphi_4 \\ &= 1 - \exp\left(-\frac{x}{\lambda_4} \right) - \frac{\exp\left(-\frac{x}{\lambda_2} \right)}{\lambda_4} \int_0^x \exp\left(\varphi_4 \left[\frac{1}{\lambda_2} - \frac{1}{\lambda_4} \right] \right) d\varphi_4 \end{aligned} \tag{15}$$

Where λ_4 is the mean of RV φ_4.

Case 1: $\lambda_2 = \lambda_4 = \lambda$

From (28), we have:

$$F_\varphi(x) = 1 - \exp\left(-\frac{x}{\lambda} \right) - \frac{x \exp\left(-\frac{x}{\lambda} \right)}{\lambda} \tag{16}$$

And the PDF of φ can be computed as:

$$f_\varphi(x) = \frac{\partial F_\varphi(x)}{\partial x} = \frac{x \exp\left(-\frac{x}{\lambda}\right)}{\lambda^2} \tag{17}$$

Case 2: $\lambda_2 \neq \lambda_4$

Similar, we can obtain CDF and PDF of φ as followings respectively:

$$F_\varphi(x) = 1 - \exp\left(-\frac{x}{\lambda_4}\right) - \frac{\lambda_2}{\lambda_4 - \lambda_2}\left[\exp\left(-\frac{x}{\lambda_4}\right) - \exp\left(-\frac{x}{\lambda_2}\right)\right] \tag{18}$$

$$f_\varphi(x) = \frac{1}{\lambda_4 - \lambda_2}\left[\exp\left(-\frac{x}{\lambda_4}\right) - \exp\left(-\frac{x}{\lambda_2}\right)\right] \tag{19}$$

We can calculate the probability P_3 into 2 case

Case 1: $\lambda_2 = \lambda_4 = \lambda$

Substituting (14) into (16), we can obtain:

$$\begin{aligned} P_3 &= 1 - \int_0^\infty \exp\left[-\frac{\gamma_{th}}{\eta\rho\psi\varphi\lambda_1}\right] \times \frac{\varphi \exp\left(-\frac{\varphi}{\lambda}\right)}{\lambda^2} d\varphi \\ &= 1 - \frac{1}{\lambda^2}\int_0^\infty \varphi \times \exp\left[-\frac{\gamma_{th}}{\eta\rho\psi\varphi\lambda_1}\right] \times \exp\left(-\frac{\varphi}{\lambda}\right) d\varphi \end{aligned} \tag{20}$$

Apply (3.471,9) in [17], (20) can be rewritten as:

$$P_3 = 1 - \frac{2\gamma_{th}}{\eta\rho\psi\lambda\lambda_1} K_2\left(2\sqrt{\frac{\gamma_{th}}{\eta\rho\psi\lambda\lambda_1}}\right) \tag{21}$$

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

Also, finally, substituting (13), (21) into (12), the system OP at the source S_1 in the first interval time can be obtained as:

$$OP_{DF}^1 = \left\{1 - \exp\left(-\frac{\gamma_{th}}{\lambda_3\psi}\right)\right\}\left\{1 - \frac{2\gamma_{th}}{\eta\rho\psi\lambda\lambda_1} K_2\left(2\sqrt{\frac{\gamma_{th}}{\eta\rho\psi\lambda\lambda_1}}\right)\right\} \tag{22}$$

Case 2: $\lambda_2 \neq \lambda_4$

Substituting (19) into (14), the probability P_3 can be expressed as:

$$\begin{aligned} P_3 &= 1 - \int_0^\infty \exp\left[-\frac{\gamma_{th}}{\eta\rho\psi\varphi\lambda_1}\right] \times \frac{1}{\lambda_4 - \lambda_2}\left[\exp\left(-\frac{\varphi}{\lambda_4}\right) - \exp\left(-\frac{\varphi}{\lambda_2}\right)\right] d\varphi \\ &= 1 - \frac{1}{\lambda_4 - \lambda_2}\int_0^\infty \exp\left[-\frac{\gamma_{th}}{\eta\rho\psi\varphi\lambda_1}\right] \times \left[\exp\left(-\frac{\varphi}{\lambda_4}\right) - \exp\left(-\frac{\varphi}{\lambda_2}\right)\right] d\varphi \\ &= 1 - \frac{1}{\lambda_4 - \lambda_2}\int_0^\infty \exp\left[-\frac{\gamma_{th}}{\eta\rho\psi\varphi\lambda_1}\right] \times \exp\left(-\frac{\varphi}{\lambda_4}\right) d\varphi \\ &\quad + \frac{1}{\lambda_4 - \lambda_2}\int_0^\infty \exp\left[-\frac{\gamma_{th}}{\eta\rho\psi\varphi\lambda_1}\right] \times \exp\left(-\frac{\varphi}{\lambda_2}\right) d\varphi \end{aligned} \tag{23}$$

Apply eq (3.324,1) in [17], (23) can be rewritten as:

$$P_3 = 1 - \frac{2}{\lambda_4 - \lambda_2} \sqrt{\frac{\gamma_{th}}{\eta \rho \psi \lambda_1}} \times \left\{ \begin{array}{c} \sqrt{\lambda_4} \times K_1\left(2\sqrt{\frac{\gamma_{th}}{\eta \rho \psi \lambda_1 \lambda_4}} \right) \\ -\sqrt{\lambda_2} \times K_1\left(2\sqrt{\frac{\gamma_{th}}{\eta \rho \psi \lambda_1 \lambda_2}} \right) \end{array} \right\} \tag{24}$$

And then substituting (13), (24) into (12), the OP at the source S_1 in the second case can be obtained as:

$$OP_{DF}^2 = \left[1 - \exp\left(-\frac{\gamma_{th}}{\lambda_3 \psi} \right) \right] \left[1 - \frac{2}{\lambda_4 - \lambda_2} \sqrt{\frac{\gamma_{th}}{\eta \rho \psi \lambda_1}} \times \left\{ \begin{array}{c} \sqrt{\lambda_4} \times K_1\left(2\sqrt{\frac{\gamma_{th}}{\eta \rho \psi \lambda_1 \lambda_4}} \right) \\ -\sqrt{\lambda_2} \times K_1\left(2\sqrt{\frac{\gamma_{th}}{\eta \rho \psi \lambda_1 \lambda_2}} \right) \end{array} \right\} \right] \tag{25}$$

4.   NUMERICAL RESULTS AND DISCUSSION

In this section, we investigate the system OP using Monte Carlo simulation in connection with the primary system parameters [18-25]. In Figure 3, the effect of the energy coefficient η on the system OP is plotted with the primary system parameters as ρ=0.8, R=0.5 bps/Hz, ψ=0.5 dB. From the results, we can see that the OP of S_1 significantly decreases with the rising of η. Here, we consider both cases with and without a direct link between the sources S_1 and S_2. From Figure 3, we can see that the system OP with the direct link is better than the system OP without the direct link between the sources. Furthermore, the simulation results agree well with the analytical results. In the same way, the system OP versus ψ is drawn in Figure 4. In this simulation, we set η=0.5, R=0.5bps/Hz, ρ=0.5, and consider both cases with and without a direct link between the sources. As shown in Figure 4, we can state that the system OP has a considerable decrease when ψ varies from -10 to 10. In Figure 4, the simulation and analytical results are the same with all values of α and b_2, and again, the OP with the direct link is better than the cases without.
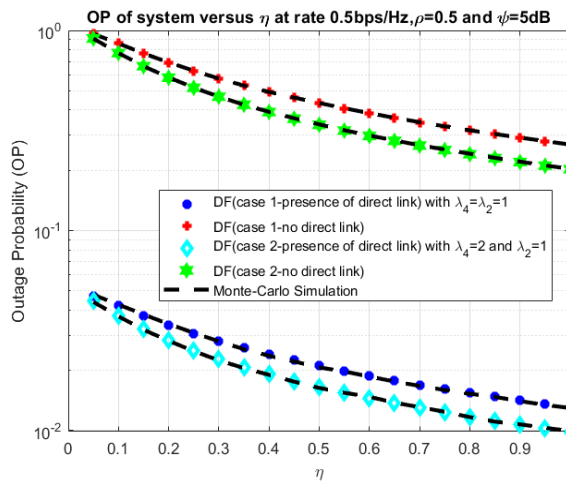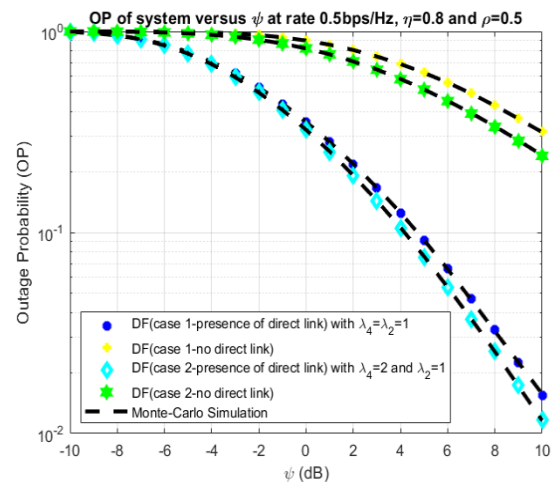

Figure 3. OP versus η

Figure 4. OP versus ψ

Furthermore, we investigate the effect of R and ρ on the OP of the model system, as plotted in Figures 5 and 6. In these Figures, we set the primary parameters, as shown in these Figures. From Figures 5 and 6, it can be observed that OP has a slight decrease when ρ varies from 0 to 1, and the system OP crucially increases with the rising of R from 0.5 to 5. In all two Figures, the analytical and simulation results agree well with each other. On another hand, the comparison of the system OP of both cases with and without a direct link between these sources is demonstrated in all Figures. From the results, we can state that the system OP with the direct link is better than another case.
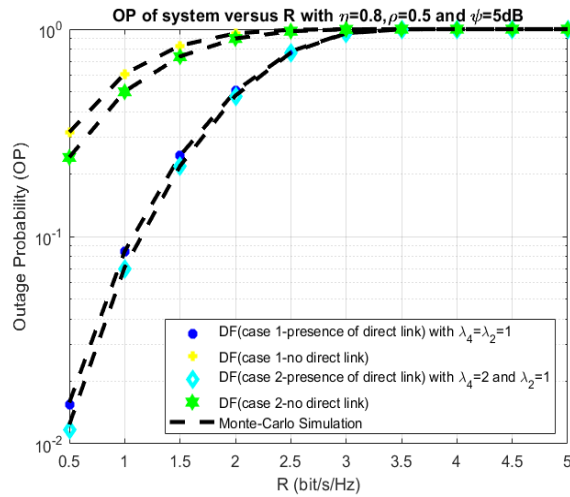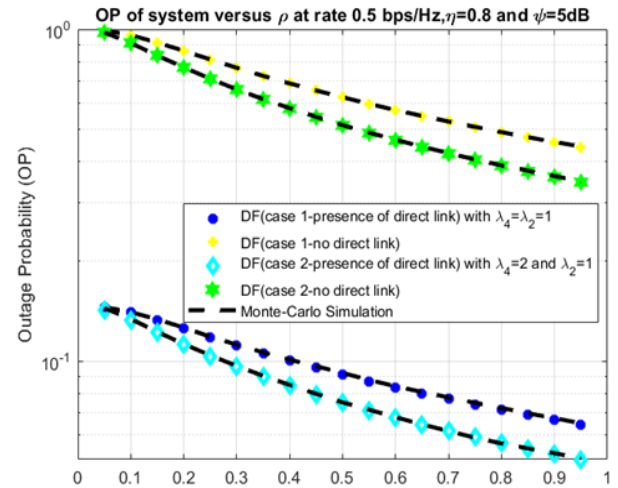
Figure 5. OP versus R

Figure 6. OP versus ρ

5.   CONCLUSION

In this research, the two-way DF HD relaying network with the direct link between two sources S_1 and S_2 is proposed and investigated. The system model, EH and IT are presented in the first stage. After that, we derived the closed-form expression of the system OP in the next stage. Finally, the correctness of the analytical expressions is verified by Monte Carlo simulation in connection with the primary system parameters. The research results show that the analytical and simulation are the same as the primary system parameters. The results can provide a critical recommendation for the relaying communication network.

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