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Research Article

On the Performance of Power Splitting Energy Harvested Wireless Full-Duplex Relaying Network with Imperfect CSI over Dissimilar Channels

Tan N. Nguyen,[1] Minh Tran ,[2] Phuong T. Tran,[3] Phu Tran Tin,[1] Thanh-Long Nguyen,[4] Duy-Hung Ha,[1] and Miroslav Voznak [1]

[1] *VSB-Technical University of Ostrava, 17. listopadu 15/2172, 708 33 Ostrava-Poruba, Czech Republic*
[2] *Optoelectronics Research Group, Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam*
[3] *Wireless Communications Research Group, Faculty of Electrical & Electronics Engineering, Ton Duc Thang University, Vietnam*
[4] *Center for Information Technology, Ho Chi Minh City University of Food Industry, Ho Chi Minh City, Vietnam*

Correspondence should be addressed to Minh Tran; tranhoangquangminh@tdtu.edu.vn

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The energy harvesting amplify-and-forward full-duplex relaying network over the dissimilar fading environments in imperfect CSI condition is investigated. In this system model, the energy, and information are transferred from the source to the relay nodes by the power splitting protocol with helping of the full-duplex relay node. Firstly, the outage probability, achievable throughput, and the optimal power splitting factor in terms of the analytical mathematical expressions were proposed, analyzed, and demonstrated. Furthermore, the system performance of the proposed model on the connection with all system parameters is rigorously studied. Finally, the numerical results demonstrated and convinced one that the analytical and the simulation results are matched well with each other for all system parameter values using Monte-Carlo simulation. The results show that the system performance degrades significantly but is still in a permissible interval while the channel estimation error increases and the system performance of the mixing scenarios is better in comparison with the Rayleigh-Rayleigh scenario.

1. Introduction

In the last few decades, traditional energy-constrained communication network (ECN) systems have such a limited operational lifetime. Periodical battery recharging or replacement is necessary to propose in order to maintain network connectivity and performance, which caused some disadvantages such as high cost and inconvenient and sometimes impossible realization [1, 2]. Nowadays, energy harvesting (EH) from the environment is a prospective direction for enhancing the lifetime of energy-constrained communication networks (ECN). In comparison with other renewable energy sources, the radio frequency (RF) signals could be promised innovative sources for wireless powered communication network (WPCN). It can be easily realized in connection with this that RF signals can carry both information and energy. Hence energy constrained nodes can harvest energy from the received RF signals. This solution seems to be a promising solution for applications where battery-limited devices are not easily accessible, and replacing or recharging their batteries is inconvenient such as devices embedded inside human bodies and sensors placed in dangerous areas [1–6]. However, energy harvesting and information processing from the source node to the destination node may be interrupted because of the performance degradation caused by fading, shadowing, and path loss. In this case, the intermediate helping relay node between the source node and the destination node can become an excellent solution [7]. There are many types of research focused on the WCPN with helping of the intermediate relay perfect and imperfect channel state information (CSI) [8–10]. Moreover, a hybrid EH single relay network with channel and energy state uncertainties in optimizing system throughput over a limited number of transmission intervals is proposed. Fault-tolerant schemes were analyzed in the presence of imperfect CSI [11].

Half-duplex (HD) and full-duplex (FD) are considered as the primary architectures, which are popularly used in the relaying network. In the HD relaying model, the relay node cannot receive and transmit data simultaneously in the same frequency band. The HD model is popularly proposed in traditional WPCN due to simple of the system design and implementation. However, the HD led to significant spectrum efficiency loss [12–14]. On another way, an FD scheme, where the reception and the transmission processes occur on the same channel at the same time, can achieve up to double the capacity in comparison with the HD scheme. FD relaying, in which the relay node receives and transmits simultaneously in the same frequency band, is considered as the main direction in the last decades. Hence, FD can reduce the spectral loss, based on innovative antenna technology and signal processing capability [15–17]. However, not many papers have considered the application of FD relaying network in the imperfect CSI condition over the different fading channel [18, 19]. This paper can entirely fill this remaining gap. In some practical applications, the relay should be close to energy station, which is also the source node in our model. Hence, line-of-sight (LOS) should exist between the source and the relay, whereas the channel between the relay and the destination might not necessarily be LOS. The dissimilar channel model has been considered in many previous works, for example, in [17–19].

In this research, the system performance analysis (in the term the outage probability and the achievable throughput) of the amplify-and-forward (AF) FD relaying network over different fading environments in the imperfect CSI condition is proposed, analyzed, and demonstrated. In this case, the energy and information are transferred from the source to the relay nodes by the power splitting protocol. Firstly, the outage probability, achievable throughput, and the optimal power splitting factor in terms of the analytical mathematical expressions were proposed, analyzed, and demonstrated. Furthermore, the system performance of the proposed model on the connection with all system parameters is rigorously studied. Finally, the numerical results demonstrated and convinced one that the analytical and the simulation results are matched well with each other for all system parameter values using Monte-Carlo simulation. The main contributions of the paper are summarized as follows:

(1) The system model of FD relaying network over different fading channels in the imperfect CSI condition with the power splitting protocol is proposed and investigated in two cases: (a) S-R link is Rician Fading Channel, and R-D link is Rayleigh Fading Channel; (b) S-R link is Rayleigh Fading Channel, and R-D link is Rician Fading Channel.

(2) The closed-form of the throughput and outage probability over different fading environments for FD relay system is derived.

(3) The influence of the main parameters on the system performance is demonstrated entirely.

(4) The optimal power splitting factor is investigated and calculated in connection with the main system parameters.

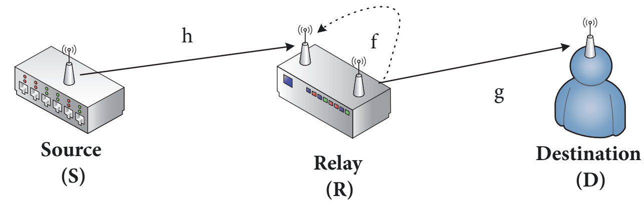

Figure 1: System model, in which a source, a relay, and destination nodes are denoted by S, R, and D, respectively.

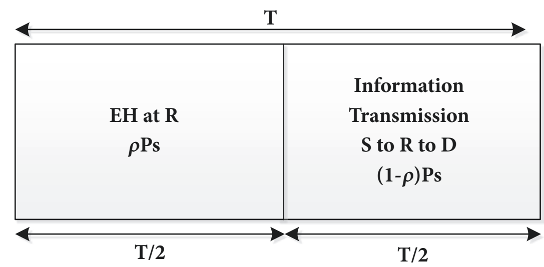

Figure 2: The energy harvesting and information processing by the power splitting protocol.

The rest of this paper is presented as follows. Section 2 proposes the system model of the model system. Section 3 proposes and demonstrates the analytical mathematical expressions of the outage probability, throughput, and the optimal power splitting factor of the system. Section 4 presents the numerical results and some discussions. Finally, Section 5 concludes the paper.

2. System Model

In this section, the amplify-and-forward (AF) full-duplex (FD) relaying wireless communications network in an imperfect CSI condition is proposed and illustrated in Figure 1. In Figure 1, the information is transferred from the source (S) node to the destination (D) node, through energy constrained intermediate relay (R) [7, 20, 21]. In this model, the following set of assumptions are considered:

(1) There is no connection between S and R in the results of elimination transmission information (too poor connection between S and R). In particular, an intermediate FD relay is used for transferring the information from the source to the destination in imperfect CSI condition [16, 17].

(2) The required power of the data decoding process at the relay is negligible in comparison to the signal transmission energy from the relay to the destination. In this paper, the energy harvesting and information processing at the relay node are proposed with the power splitting protocol at the relay node [7].

The energy harvesting and information processing at the relay node by the power splitting protocol are proposed in Figure 2. In reality, the power-splitting protocol is more effective because it does not waste the time resource for transmission, so the transmission rate is higher than the time-switching protocol. In Figure 2, T is the block time of the energy harvesting and information process. In this model, half of the time, T/2 is used for the source to relay energy harvesting and in the remaining half, T/2 is used for the source to the relay node to the destination node information transmission. During the all-time interval, in the fraction of the received signal power, ρP_S is used for energy harvesting and in the remaining received power, $(1-\rho)P_S$ is used for transmitting source information to the destination node via the full-duplex helping relay (where ρ is the power splitting factor, $\rho \in (0,1)$ and P_s is transmission power from the source) [7, 20, 21]. As introduced before, we consider the case that the channel state information is obtained with an error. The effect of CSI error on the performance of the model of interest is the main concentration of this paper. In this system model, the gain channel factors are denoted as follows:

$$h = \hat{h} + \Delta h$$
$$g = \hat{g} + \Delta g \qquad (1)$$
$$f = \hat{f} + \Delta f$$

where h and g denote the channel gains from the source to the relay and the relay to the destination, respectively, and f denotes the loopback interference channel at the relay (Figure 1). Moreover, Δh, Δg, and Δf are the channel estimation error corresponding to h, g, and f, respectively. These estimation errors are all assumed to be Gaussian distributed with zero means.

2.1. Energy Harvesting. In the energy harvesting process, the RF signal received from the source S at the FD helping relay R is calculated as

$$y_r = hx_e + n_r \qquad (2)$$

where h is the channel gain factor from S to R and x_e is the energy symbol with $E\{|x_e|^2\} = P_s$, where $E\{\bullet\}$ denotes the expectation operation. n_r is the zero-mean additive white Gaussian noise (AWGN) with variance N_0.

Hence, the harvested energy can be calculated as

$$E_h = \eta P_s \left(\left|\hat{h}\right|^2 + \delta^2_{\Delta h}\right)\rho\frac{T}{2} \qquad (3)$$

In this case, the relay transmits power can be computed as

$$P_r = \frac{\eta\rho P_S\left(\left|\hat{h}\right|^2 + \delta^2_{\Delta h}\right)(T/2)}{T/2} = \eta\rho P_S\left(\left|\hat{h}\right|^2 + \delta^2_{\Delta h}\right) \qquad (4)$$

where $0 < \eta < 1$ is a constant and denotes the energy conversion efficiency and $\delta^2_{\Delta h}$ is the standard deviation of the channel estimation error Δh, which is a zero-mean Gaussian random variable as mentioned above.

2.2. Information Transmission. Now the information transmission phase is investigated in more details. Here, the received signal at the relay is calculated by

$$y_r = \sqrt{1-\rho}hx_s + fx_r + n_r \qquad (5)$$

where x_s is the transmitted signal, which satisfies $E\{|x_s|^2\} = P_s$, x_r is the loopback interference due to full-duplex relaying and satisfies $E\{|x_r|^2\} = P_r$, f denotes the loopback interference channel, and n_r is the zero-mean AWGN with variance N_0. After applying interference cancellation methods to mitigate the loopback interference [22], we have

$$\hat{y}_r = y_r - \hat{f}x_r = \sqrt{1-\rho}\left(\hat{h} + \Delta h\right)x_s + \Delta f x_R + n_r \qquad (6)$$

In this step, the amplifier factor could be present by

$$\beta = \frac{x_r}{\hat{y}_r} = \sqrt{\frac{P_r}{(1-\rho)\left(\left|\hat{h}\right|^2 + \delta^2_{\Delta h}\right)P_s + \delta^2_{\Delta f}P_r + N_0}} \qquad (7)$$

Finally, the received signal at the destination node is

$$\begin{aligned} y_d &= gx_r + n_d = (\hat{g} + \Delta g)x_r + n_d \\ &= \hat{g}\beta\left\{\sqrt{1-\rho}\left(\hat{h} + \Delta h\right)x_s + \Delta f x_R + n_r\right\} \\ &\quad + \Delta g\beta\left\{\sqrt{1-\rho}\left(\hat{h} + \Delta h\right)x_s + \Delta f x_R + n_r\right\} + n_d \end{aligned} \qquad (8)$$

where g is the channel gain factor from R to D.

Also, the end-to-end signal to noise ratio (SNR) can formulate as

$$\gamma_{e2e} = \frac{E\left\{|signal|^2\right\}}{E\left\{|noise|^2\right\}} = \frac{A}{B} \qquad (9)$$

where $A = (1-\rho)|\hat{g}|^2|\hat{h}|^2P_S$ and

$$\begin{aligned} B &= (1-\rho)P_s\delta^2_{\Delta h}\left|\hat{g}\right|^2 + P_r\left|\hat{g}\right|^2\delta^2_{\Delta f} + \left|\hat{g}\right|^2 N_0 \\ &\quad + (1-\rho)P_s\delta^2_{\Delta g}\left|\hat{h}\right|^2 + (1-\rho)P_s\delta^2_{\Delta g}\delta^2_{\Delta h} \\ &\quad + \delta^2_{\Delta g}P_r\delta^2_{\Delta f} + \delta^2_{\Delta g}N_0 + \frac{N_0}{\beta^2} \end{aligned} \qquad (10)$$

Combined with (4), (7) and some algebra helping (9), (9) can be rewritten as

$$\gamma_{e2e} = \frac{C}{D} \qquad (11)$$

In which, we denote $C = (1-\rho)\varphi_1\varphi_2\gamma_0$, and $D = (1-\rho)\gamma_0\delta^2_{\Delta h}\varphi_2 + \eta\rho\gamma_0(\varphi_1 + \delta^2_{\Delta h})\varphi_2\delta^2_{\Delta f} + \varphi_2 + (1-\rho)\gamma_0\delta^2_{\Delta g}\varphi_1 + (1-\rho)\gamma_0\delta^2_{\Delta g}\delta^2_{\Delta h} + \delta^2_{\Delta g}\eta\rho\gamma_0(\varphi_1+\delta^2_{\Delta h})\delta^2_{\Delta f} + \delta^2_{\Delta g} + (1-\rho)/\eta\rho + \delta^2_{\Delta f}$.

In the above equation, we denote $\varphi_1 = |\hat{h}|^2$, $\varphi_2 = |\hat{g}|^2$, and $\gamma_0 = P_s/N_0$.

More details of the analytical mathematical model of the achievable throughput, outage probability, and optimal power splitting factor in FD relaying system in the imperfect CSI condition over different fading channels are proposed and presented in details in the following sections.

3. System Performance

Based on the system model on the above section, the system performance analysis of FD relay network is presented, analyzed, and demonstrated with power splitting protocols in details in this sections. In this analysis, two Scenarios are proposed. In the first Scenario, S-R link is Rician Fading Channel; R-D link is Rayleigh Fading Channel. In another way, S-R link is the Rayleigh Fading Channel; R-D link is the Rician Fading Channel in the second Scenario.

3.1. Scenario 1: S-R Link Is Rician Fading Channel and R-D Link Is Rayleigh Fading Channel

3.1.1. The Exact Outage Probability. The probability density function (PDF) of a random variable (RV) φ_1 can be calculated as

$$f_{\varphi_1}(x) = \frac{(K+1)e^{-K}}{\lambda_1} e^{-(K+1)x/\lambda_i} I_0\left(2\sqrt{\frac{K(K+1)x}{\lambda_1}}\right) \quad (12)$$

Here λ_1 is the mean value of RV φ_1. K is the Rician K-factor defined as the ratio of the power of the line-of-sight (LOS) component to the scattered components and $I_0(\bullet)$ is the zero-th order modified Bessel function of the first kind [23].

Equation (12) can be reconstructed as follows:

$$f_{\varphi_1}(x) = \omega \sum_{l=0}^{\infty} \frac{(bK)^l}{(l!)^2} x^l e^{-\theta x} \quad (13)$$

where $\omega = (K+1)e^{-K}/\lambda_1$, $\theta = (K+1)/\lambda_1$, and $I_0(x) = \sum_{l=0}^{\infty}(x^{2l}/2^{2l}(l!)^2)$.

Like in [7] the cumulative density function (CDF) of RV φ_1 can be computed as

$$F_{\varphi_1}(\varsigma) = \int_0^{\varsigma} f_{\varphi_1}(x)\,dx = 1 - \frac{\omega}{\theta}\sum_{l=0}^{\infty}\sum_{m=0}^{l} \frac{K^l \theta^m}{l!m!} \varsigma^m e^{-\theta\varsigma} \quad (14)$$

In the same way, the probability density function (PDF) of a random variable (RV) φ_2 can be expressed as

$$f_{\varphi_2}(x) = \lambda_2 e^{-x\lambda_2} \quad (15)$$

where λ_2 is the mean value of RV φ_2.

Moreover, the cumulative density function (CDF) of RV φ_2 can be computed as

$$F_{\varphi_2}(\psi) = \int_0^{\omega} f_{\varphi_1}(x)\,dx = 1 - e^{-\psi\lambda_2} \quad (16)$$

The outage probability of the model system is given by

$$\begin{aligned} P_{out} &= F_{\gamma_{e2e}}(\gamma_{th}) = \Pr\{\gamma_{e2e} \le \gamma_{th}\} \\ &= \Pr[\varphi_2(a_1\varphi_1 - a_2) \le b_1\varphi_1 + b_2] \end{aligned} \quad (17)$$

where we denote

$$\begin{aligned} a_1 &= (1-\rho)\gamma_0 - \gamma_{th}\eta\rho\gamma_0\delta_{\Delta f}^2, \\ a_2 &= \gamma_{th}\left[(1-\rho)\gamma_0\delta_{\Delta h}^2 + \eta\rho\gamma_0\delta_{\Delta h}^2\delta_{\Delta f}^2 + 1\right] \\ b_1 &= \gamma_{th}\left[(1-\rho)\gamma_0\delta_{\Delta g}^2 + \eta\rho\gamma_0\delta_{\Delta g}^2\delta_{\Delta f}^2\right], \\ b_2 &= \gamma_{th}\left[(1-\rho)\gamma_0\delta_{\Delta h}^2\delta_{\Delta g}^2 + \eta\rho\gamma_0\delta_{\Delta h}^2\delta_{\Delta g}^2\delta_{\Delta f}^2 + \delta_{\Delta g}^2 \right. \\ &\quad \left. + \delta_{\Delta f}^2 + \frac{(1-\rho)}{\eta\rho}\right] \end{aligned} \quad (18)$$

In these equations, $\gamma_{th} = 2^R - 1$ is the system threshold with the source rate R. Now we have

$$\begin{aligned} &\Pr[\varphi_2(a_1\varphi_1 - a_2) \le b_1\varphi_1 + b_2] \\ &= \left\{\begin{matrix} \Pr\left\{\varphi_2 \le \dfrac{b_1\varphi_1 + b_2}{a_1\varphi_1 - a_2},\ if\ \varphi_1 > \dfrac{a_2}{a_1}\right\} \\ 1,\ if\ \varphi_1 \le \dfrac{a_2}{a_1} \end{matrix}\right\} \\ &= \int_0^{a_2/a_1} f_{\varphi_1}(\varphi_1)\,d\varphi_1 \\ &\quad + \int_{a_2/a_1}^{\infty} F_{\varphi_2}\left(\frac{b_1\varphi_1 + b_2}{a_1\varphi_1 - a_2}\right) f_{\varphi_1}(\varphi_1)\,d\varphi_1 \end{aligned} \quad (19)$$

Using (13) and (14) the outage probability can be rewritten as

$$\begin{aligned} P_{out} &= 1 - \int_{a_2/a_1}^{\infty} \exp\left(-\lambda_2 \frac{b_1\varphi_1 + b_2}{a_1\varphi_1 - a_2}\right) \\ &\quad \times \omega \sum_{l=0}^{\infty} \frac{(\theta K)^l}{(l!)^2} \varphi_1^l e^{-\theta\varphi_1} d\varphi_1 \end{aligned} \quad (20)$$

By changing variable and set: $t = a_1\varphi_1 - a_2$, (20) can be changed into

$$\begin{aligned} P_{out} &= 1 - \frac{\omega}{a_1} e^{-\theta a_2/a_1 - \lambda_2 b_1/a_1} \times \int_0^{\infty} \sum_{l=0}^{\infty} \frac{(\theta K)^l}{(l!)^2} \left(\frac{t + a_2}{a_1}\right)^l \\ &\quad \times e^{-\theta t/a_1} \times e^{-\xi/t} dt \end{aligned} \quad (21)$$

where $\xi = \lambda_2(a_1 b_2 + a_2 b_1)/a_1$.

After that, by applying the equation, $(x + y)^m = \sum_{n=0}^{m} \binom{m}{n} x^{m-n} y^n$, we have

$$P_{out} = 1 - \frac{\omega}{a_1} e^{-\theta a_2/a_1 - \lambda_2 b_1/a_1} \times \int_0^\infty \sum_{l=0}^{\infty} \frac{(\theta K)^l a_2^n}{a_1^l (l!)^2} \sum_{n=0}^{l} \binom{l}{n} \times t^{l-n} \times e^{-\theta t/a_1} \times e^{-\xi/t} dt \quad (22)$$

$$P_{out} = 1 - \frac{\omega}{a_1} e^{-\theta a_2/a_1 - \lambda_2 b_1/a_1} \times \sum_{l=0}^{\infty} \sum_{n=0}^{l} \frac{(\theta K)^l a_2^n}{l! n! (l-n)! a_1^l} \times \int_0^\infty t^{l-n} \times e^{-\theta t/a_1} \times e^{-\xi/t} dt \quad (23)$$

Using Table of Integral Equation [3.471, 9] [24], the final exact-form of the outage probability can be expressed as

$$P_{out} = 1 - \frac{2\omega}{a_1} e^{-\theta a_2/a_1 - \lambda_2 b_1/a_1} \times \sum_{l=0}^{\infty} \sum_{n=0}^{l} \frac{(\theta K)^l a_2^n}{l! n! (l-n)! a_1^l} \times \left(\frac{\xi a_1}{\theta}\right)^{(l-n+1)/2} \times K_{l-n+1}\left(2\sqrt{\frac{\xi\theta}{a_1}}\right)$$

$$P_{out} = 1 - 2\omega \times e^{-\theta a_2/a_1 - \lambda_2 b_1/a_1} \times \sum_{l=0}^{\infty} \sum_{n=0}^{l} \frac{K^l \theta^{(l+n-1)/2} a_2^n \xi^{(l-n+1)/2}}{l! n! (l-n)! a_1^{(l+n+1)/2}} \times K_{l-n+1}\left(2\sqrt{\frac{\xi\theta}{a_1}}\right) \quad (24)$$

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

3.1.2. Average Throughput. From the above analysis, the average throughput can be calculated by

$$\tau = (1 - P_{out}) \frac{R}{2} = 2\omega \times e^{-\theta a_2/a_1 - \lambda_2 b_1/a_1} \times \sum_{l=0}^{\infty} \sum_{n=0}^{l} \frac{K^l \theta^{(l+n-1)/2} a_2^n \xi^{(l-n+1)/2}}{l! n! (l-n)! a_1^{(l+n+1)/2}} \times K_{l-n+1}\left(2\sqrt{\frac{\xi\theta}{a_1}}\right) \times \frac{R}{2} \quad (25)$$

3.1.3. Asymptotic Outage Probability and Average Throughput. In high SNR regime, (11) can be recomputed as

$$\gamma_{e2e}^{\infty} = \frac{E}{F} \quad (26)$$

where $E = (1-\rho)\varphi_1\varphi_2$ and

$$F = (1-\rho)\,\delta_{\Delta h}^2 \varphi_2 + \eta\rho\left(\varphi_1 + \delta_{\Delta h}^2\right)\varphi_2 \delta_{\Delta f}^2 + (1-\rho)\,\delta_{\Delta g}^2 \varphi_1 + (1-\rho)\,\delta_{\Delta g}^2 \delta_{\Delta h}^2 + \delta_{\Delta g}^2 \eta\rho\left(\varphi_1 + \delta_{\Delta h}^2\right)\delta_{\Delta f}^2 \quad (27)$$

In this case, the outage probability at the high SNR can be formulated as

$$P_{out}^{\infty} = F_{\gamma_{e2e}}^{\infty}(\gamma_{th}) = \Pr\left\{\gamma_{e2e}^{\infty} \le \gamma_{th}\right\} = \Pr\left[\varphi_2 (a_3\varphi_1 - a_4) \le b_3\varphi_1 + b_4\right] \quad (28)$$

In which, we denoted $a_3 = (1-\rho) - \gamma_{th}\eta\rho\delta_{\Delta f}^2$, $a_4 = \gamma_{th}[(1-\rho)\delta_{\Delta h}^2 + \eta\rho\delta_{\Delta h}^2\delta_{\Delta f}^2]$, and

$$b_3 = \gamma_{th}\left[(1-\rho)\,\delta_{\Delta g}^2 + \eta\rho\delta_{\Delta g}^2\delta_{\Delta f}^2\right], \quad b_4 = \gamma_{th}\left[(1-\rho)\,\delta_{\Delta h}^2\delta_{\Delta g}^2 + \eta\rho\delta_{\Delta h}^2\delta_{\Delta g}^2\delta_{\Delta f}^2\right]. \quad (29)$$

Similar to the exact case, we have:

$$P_{out}^{\infty} = 1 - 2\omega \times e^{-\theta a_4/a_3 - \lambda_2 b_3/a_3} \times \sum_{l=0}^{\infty} \sum_{n=0}^{l} \frac{K^l \theta^{(l+n-1)/2} a_4^n \mu^{(l-n+1)/2}}{l! n! (l-n)! a_3^{(l+n+1)/2}} \times K_{l-n+1}\left(2\sqrt{\frac{\mu\theta}{a_3}}\right) \quad (30)$$

where $\mu = \lambda_2(a_3 b_4 + a_4 b_3)/a_3$.

Moreover, the average throughput is

$$\tau^{\infty} = (1 - P_{out}) \frac{R}{2} = 2\omega \times e^{-\theta a_4/a_3 - \lambda_2 b_3/a_3} \times \sum_{l=0}^{\infty} \sum_{n=0}^{l} \frac{K^l \theta^{(l+n-1)/2} a_4^n \mu^{(l-n+1)/2}}{l! n! (l-n)! a_3^{(l+n+1)/2}} \times K_{l-n+1}\left(2\sqrt{\frac{\mu\theta}{a_3}}\right) \times \frac{R}{2} \quad (31)$$

3.2. Scenario 2: S-R Link Is Rayleigh Fading Channel and R-D Link Is Rician Fading Channel

3.2.1. Exact Probability and Average Throughput. Similar to scenario 1, the cumulative density function (CDF) of RV φ_2 can be computed as

$$F_{\varphi_2}(\varsigma) = \int_0^{\varsigma} f_{\varphi_2}(x)\,dx = 1 - \frac{a}{b}\sum_{l=0}^{\infty}\sum_{m=0}^{l} \frac{K^l b^m}{l! m!} \varsigma^m e^{-b\varsigma} \quad (32)$$

where $a = (K+1)e^{-K}/\lambda_2$, $b = (K+1)/\lambda_2$.

The probability density function (PDF) of a random variable (RV) φ_1 is

$$f_{\varphi_1}(x) = \lambda_1 e^{-x\lambda_1} \quad (33)$$

Also, the outage probability can be formulated as

$$P_{out} = \int_0^{a_2/a_1} f_{\varphi_1}(\varphi_1)\,d\varphi_1 + \int_{a_2/a_1}^{\infty} F_{\varphi_2}\left(\frac{b_1\varphi_1 + b_2}{a_1\varphi_1 - a_2}\right) f_{\varphi_1}(\varphi_1)\,d\varphi_1 \quad (34)$$

Using (32) and (33) we can reformulate (21) as

$$P_{out} = 1 - \lambda_1 \times \int_{a_2/a_1}^{\infty} \frac{a}{b} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \frac{K^l b^m}{l! m!} \left(\frac{b_1 \varphi_1 + b_2}{a_1 \varphi_1 - a_2} \right)^m \cdot e^{-b((b_1\varphi_1 + b_2)/(a_1\varphi_1 - a_2))} \times e^{-\lambda_1 \varphi_1} d\varphi_1 \quad (35)$$

By changing the variable, $t = 1/(a_1\varphi_1 - a_2)$ (35) can be rewritten as

$$\begin{aligned} P_{out} &= 1 - \frac{a}{a_1 b} \lambda_1 \int_0^{\infty} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \frac{K^l b^m}{l! m!} \left(\frac{b_1}{a_1} + \kappa t \right)^m \cdot t^{-2} e^{-b(b_1/a_1 + \kappa t)} \times e^{-\lambda_1 (1/a_1 t + a_2/a_1)} dt \\ P_{out} &= 1 - \frac{a\lambda_1}{a_1 b} \times e^{-bb_1/a_1 - \lambda_1 a_2/a_1} \int_0^{\infty} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \frac{K^l b^m}{l! m!} \cdot \left(\frac{b_1}{a_1} + \kappa t \right)^m t^{-2} e^{-b\kappa t} \times e^{-\lambda_1/a_1 t} dt \end{aligned} \quad (36)$$

where $\kappa = b_1 a_2/a_1 + b_2$.

Equation (36) becomes as follows:

$$\begin{aligned} P_{out} &= 1 - \frac{a\lambda_1}{a_1 b} \times e^{-bb_1/a_1 - \lambda_1 a_2/a_1} \int_0^{\infty} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \frac{K^l b^m \kappa^n}{l! m!} \sum_{n=0}^{m} \binom{m}{n} \cdot \left(\frac{b_1}{a_1} \right)^{m-n} \times t^{n-2} e^{-b\kappa t} \times e^{-\lambda_1/a_1 t} dt \\ P_{out} &= 1 - \frac{a\lambda_1}{a_1} \times e^{-bb_1/a_1 - \lambda_1 a_2/a_1} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \sum_{n=0}^{m} \frac{K^l b^{m-1} \kappa^n}{l! n! (m-n)!} \left(\frac{b_1}{a_1} \right)^{m-n} \cdot \int_0^{\infty} t^{n-2} \times e^{-b\kappa t} \times e^{-\lambda_1/a_1 t} dt \end{aligned} \quad (37)$$

Using Table of Integral Equation [3.471, 9] in [24], (37) can be changed into

$$\begin{aligned} P_{out} &= 1 - \frac{2a\lambda_1}{a_1} \times e^{-bb_1/a_1 - \lambda_1 a_2/a_1} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \sum_{n=0}^{m} \frac{K^l b^{m-1} \kappa^n}{l! n! (m-n)!} \left(\frac{b_1}{a_1} \right)^{m-n} \cdot \left(\frac{\lambda_1}{a_1 b \kappa} \right)^{(n-1)/2} \times K_{n-1} \left(2\sqrt{\frac{\lambda_1 b \kappa}{a_1}} \right) \\ P_{out} &= 1 - 2a \times e^{-bb_1/a_1 - \lambda_1 a_2/a_1} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \sum_{n=0}^{m} \frac{K^l b^{(2m-n-1)/2} \kappa^{(n+1)/2} b_1^{m-n} (\lambda_1)^{(n+1)/2}}{l! n! (m-n)! (a_1)^{(2m-n+1)/2}} \times K_{n-1} \left(2\sqrt{\frac{\lambda_1 b \kappa}{a_1}} \right) \end{aligned} \quad (38)$$

Then the average throughput can be calculated as

$$\tau = (1 - P_{out}) \frac{R}{2} = 2a \times e^{-bb_1/a_1 - \lambda_1 a_2/a_1} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \sum_{n=0}^{m} \frac{K^l b^{(2m-n-1)/2} \kappa^{(n+1)/2} b_1^{m-n} (\lambda_1)^{(n+1)/2}}{l! n! (m-n)! (a_1)^{(2m-n+1)/2}} \times K_{n-1} \left(2\sqrt{\frac{\lambda_1 b \kappa}{a_1}} \right) \times \frac{R}{2} \quad (39)$$

3.2.2. Asymptotic Outage Probability and Average Throughput. Similar proof as scenario 1 we have

$$P_{out}^{\infty} = 1 - 2a \times e^{-bb_3/a_3 - \lambda_1 a_4/a_3} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \sum_{n=0}^{m} \frac{K^l b^{(2m-n-1)/2} \vartheta^{(n+1)/2} b_3^{m-n} (\lambda_1)^{(n+1)/2}}{l! n! (m-n)! (a_3)^{(2m-n+1)/2}} \times K_{n-1} \left(2\sqrt{\frac{\lambda_1 b \vartheta}{a_3}} \right) \quad (40)$$

where $\vartheta = b_3 a_4/a_3 + b_4$.

Moreover, the average throughput can formulate as

$$\tau^{\infty} = (1 - P_{out}) \frac{R}{2} = 2a \times e^{-bb_3/a_3 - \lambda_1 a_4/a_3} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \sum_{n=0}^{m} \frac{K^l b^{(2m-n-1)/2} \vartheta^{(n+1)/2} b_3^{m-n} (\lambda_1)^{(n+1)/2}}{l! n! (m-n)! (a_3)^{(2m-n+1)/2}} \times K_{n-1} \left(2\sqrt{\frac{\lambda_1 b \vartheta}{a_3}} \right) \times \frac{R}{2} \quad (41)$$

3.3. Optimal Power Splitting Factor. The optimal value ρ^* can be obtained by solving the equation $d\tau(\rho)/d\rho = 0$. Given the average throughput expression in (25) and (39), this optimization problem does not admit a closed-form solution. However, the optimal ρ^* is efficiently solved via numerical calculation, as illustrated below [25–27].

Here, we can use the Golden section search algorithm to find the optimal factor ρ^*. This algorithm has been used in many global optimization problems in communications, for example, in [25]. The detailed algorithm, as well as the related theory, is described in [25–27].

4. Numerical Results and Discussion

In this section, the system performance (the throughput and the outage probability) of FD relaying network are validated in details by using the Monte Carlo simulation. The system performance is analyzed in connection with α, ρ, P_s/N_0, and R. The system network is considered with one source, one relay, and one destination nodes, where source-relay and relay-destination distances are both normalized to unit value. The channel gains are generated from Rayleigh/Rician distributed random variables with parameters as given in Table 1. The number of generated samples for each simulation is 10^6. Other simulation parameters are also listed in Table 1. These parameters are chosen specifically to illustrate the correctness of the derived formulas. In fact, these parameters can be

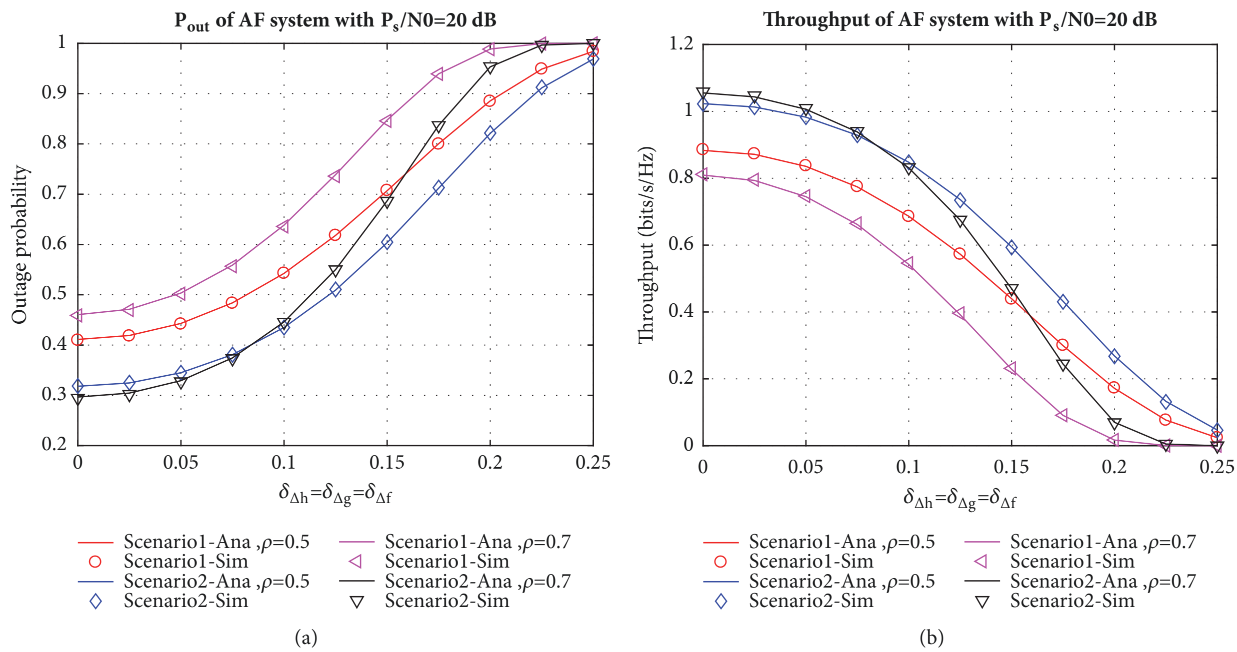

Figure 3: Outage probability (a) and achievable throughput (b) of the system model versus δ.

Table 1: Simulation parameters.

Symbol	Name	Values
η	Energy harvesting efficiency	0.7
λ_1	Mean of $\lvert\hat{h}\rvert^2$	0.5
λ_2	Mean of $\lvert\hat{g}\rvert^2$	0.5
K	Rician K-factor	3
γ_{th}	SNR threshold	7
Ps/N0	Source power to noise ratio	0-50dB
$\delta_0 = \delta_{\Delta h} = \delta_{\Delta g} = \delta_{\Delta f}$	Channel estimation error	0; 0,1
R	Source rate	3 bit/s/Hz

varied depending on practical systems, but the simulation methods presented here are still applicable.

In this analysis, Figures 3(a) and 3(b) show the influence of the standard deviation of the channel estimation error on the outage probability and throughput of the model system for two scenarios, respectively. In this simulation process, the standard deviations of the channel estimation error are set the same for all links $\delta_{\Delta h} = \delta_{\Delta g} = \delta_{\Delta f}$ and $\rho = 0.5$ and 0.7. The results show that the outage probability increased and the throughput decreased crucially while the standard deviation of channel estimation error $\delta_{\Delta h} = \delta_{\Delta g} = \delta_{\Delta f}$ increases from 0 to 0.25. From that point of view, the system performance degrades significantly after the error exceeds specific threshold value. Furthermore, the analytical results agree well with the Monte Carlo simulation results, validating the theoretical derivations.

On another hand, Figures 4(a) and 4(b) illustrate the influence of the power splitting ratio ρ on the achievable throughput and the outage probability at the destination node. Here, δ_0 is set at 0 and 0.1 at rate 3 bps and the ratio P_s/N_0 at 20 dB. From the simulation, it is clear fond that the achievable throughput increases and the outage probability decrease significantly at the destination node while the ratio ρ varies from 0 to the optimal value (0.5-0.6). After the optimal value, both decreased with ratio ρ from 0.6 to 1.0. The optimal value ρ is about 0.5-0.6 as shown in Figure 4 and the corresponding maximum throughput and minimum outage probability are shown in Table 2. Moreover, the analytical and the Monte Carlo simulation results are the same in these cases.

Moreover, Figures 5(a) and 5(b) present the influence of the ratio P_s/N_0 on the outage probability and the achievable throughput with δ_0 at 0 and 0.1, at rate 3 bps and $\rho = 0.5$ for the two scenarios. From the results, it is shown that the achievable throughput increases and the outage probability decreases significantly at the destination node while the ratio P_s/N_0 increased from 0 to 50 dB. Furthermore, the exact and the asymptotical throughput and outage probability get close to each other at the end of the interval of the ratio P_s/N_0. In two scenarios, all the analytical and the simulation results agreed well with each other. Furthermore, it is confirmed that, in the low SNR regime, the channel estimation error has little effect on system performance (the outage probability and the throughput). However, when the transmit power increases to the significant value, the channel estimation error has an increasing impact on both achievable throughput and outage probability.

In the same way, the influence of the system rate R on the outage probability and the achievable throughput with $P_s/N_0 = 20$ dB and $\rho = 0.5$ are illustrated in Figures 6(a) and 6(b). Figure 6(a) showed that the outage probability increase crucially with increasing the rate R. However, the system throughput only increased in the interval R from 0 to the optimal value of around 3. After that, it significantly

Table 2: The maximum throughput and minimum outage probability.

	Scenario 1- $\delta_0 = 0$	Scenario 2- $\delta_0 = 0$	Scenario 1- $\delta_0 = 0.1$	Scenario 2- $\delta_0 = 0.1$
Optimal $\rho*$	0.55	0.65	0.45	0.6
Minimum outage	0.4110	0.2957	0.5412	0.4284
Maximum throughput	0.8835	1.0565	0.6882	0.8574

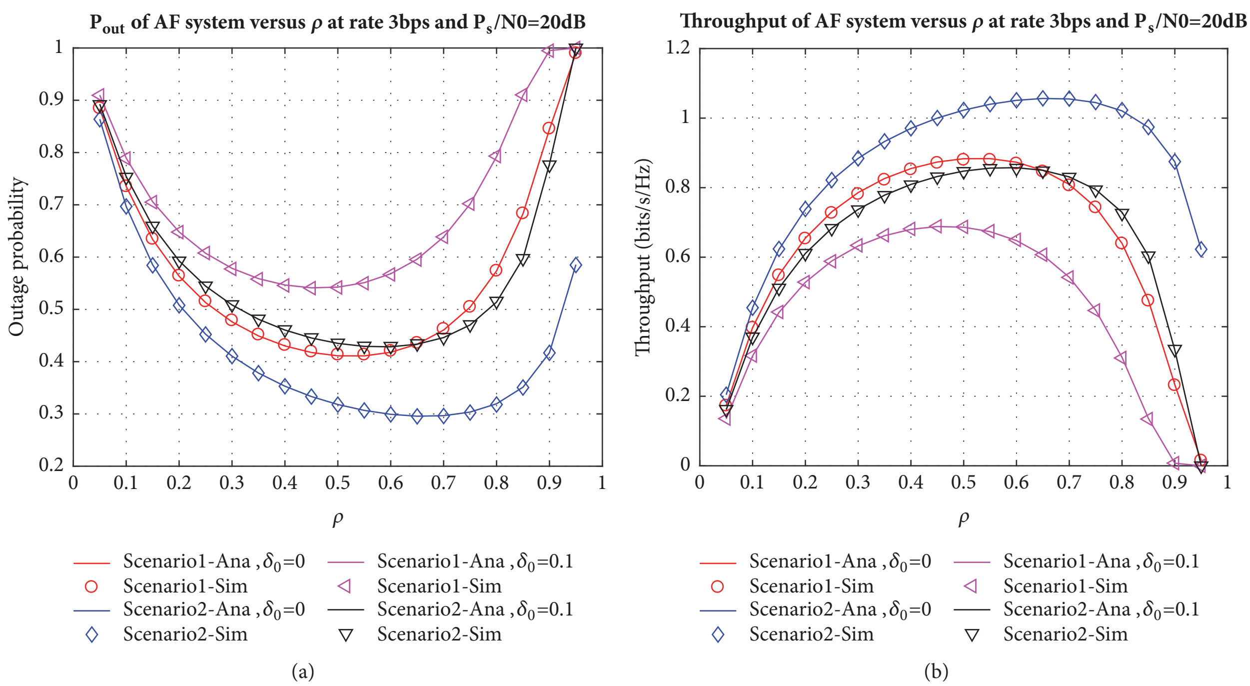

Figure 4: Outage probability (a) and achievable throughput (b) of the system model versus ρ.

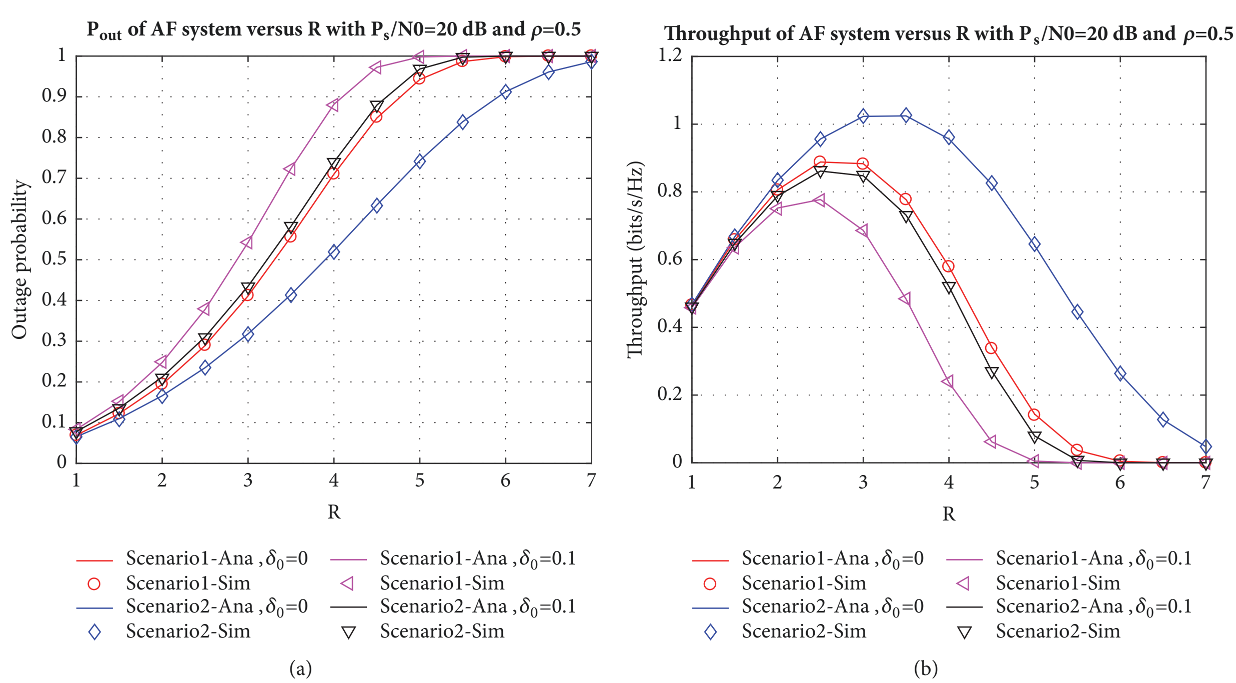

Figure 5: Outage probability (a) and achievable throughput (b) of the system mode versus ratio PS/N0.

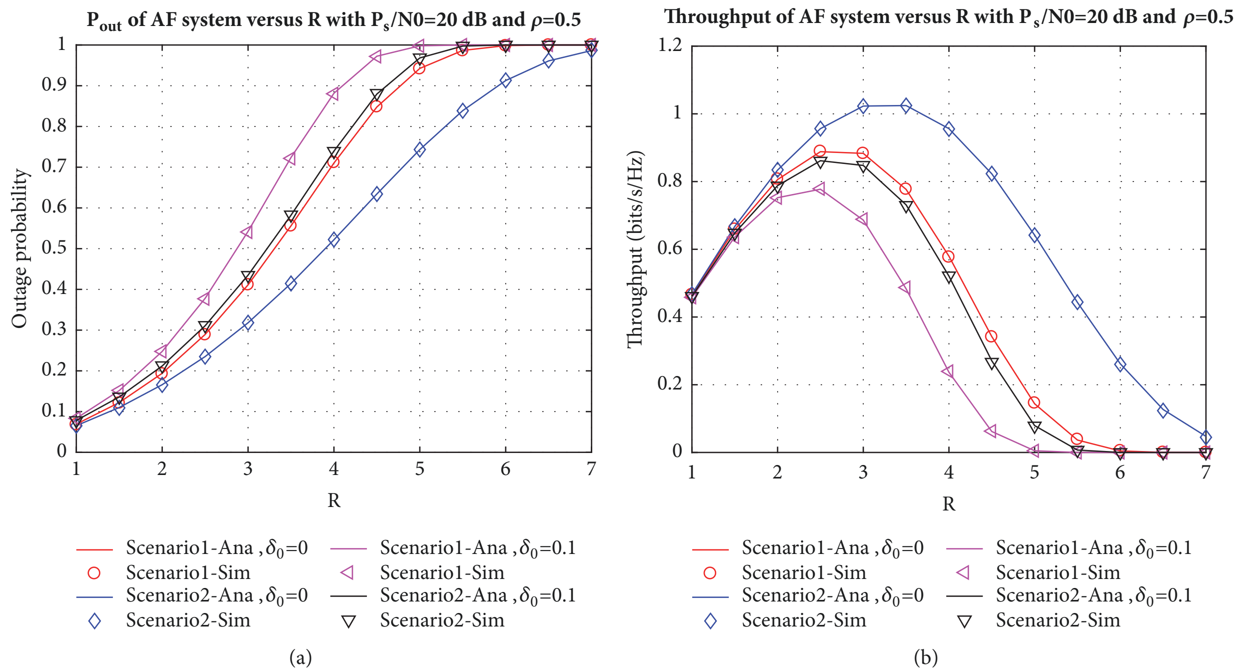

Figure 6: Outage probability (a) and achievable throughput (b) of the system mode versus R.

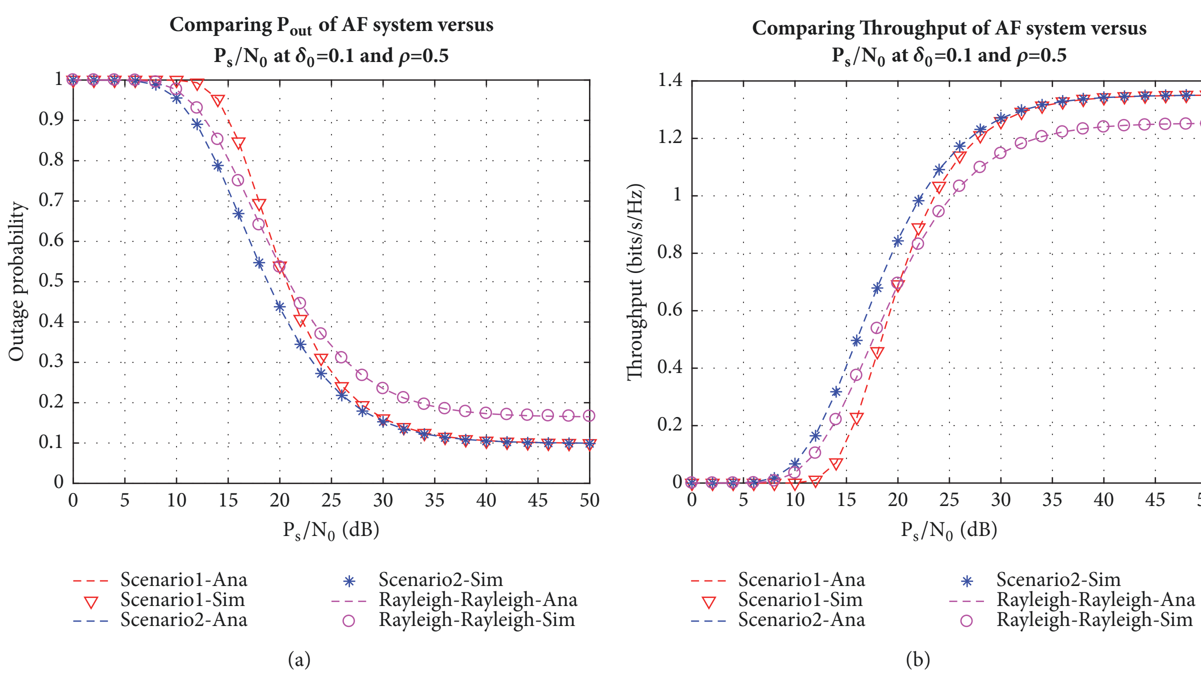

Figure 7: Scenarios 1 and 2 versus the Rayleigh-Rayleigh scenario.

fell to 0 at the rate around 7. In particular, the simulation lines wholly matched with the analytical lines in Figures 1–6. Moreover, the comparison between our dissimilar channel model (Scenarios 1 and 2) and the similar channel model that means both source-relay and relay-destination links is assumed to be Rayleigh fading channels, in Figure 7(a) for throughput analysis and Figure 7(b) for outage probability analysis, respectively. From the simulation results, we show that the system performance of the scenarios 1 and 2 is better in comparison with the Rayleigh-Rayleigh scenario. Finally, the optimal power splitting factor versus the ratio P_s/N_0 in the two scenarios is proposed in Figures 8 and 9, respectively.

5. Conclusions

In this paper, the wireless communication network with FD relaying in imperfect condition with the power splitting protocol is proposed and demonstrated. In this system model,

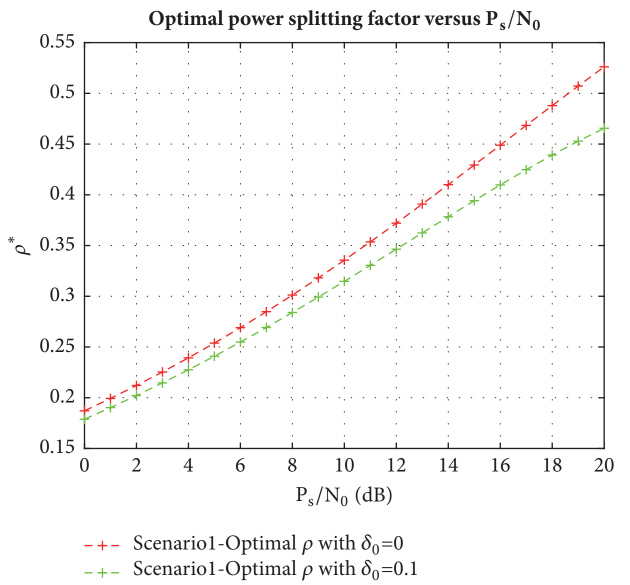

Figure 8: The optimal splitting factor versus Ps/N0 for the first case.

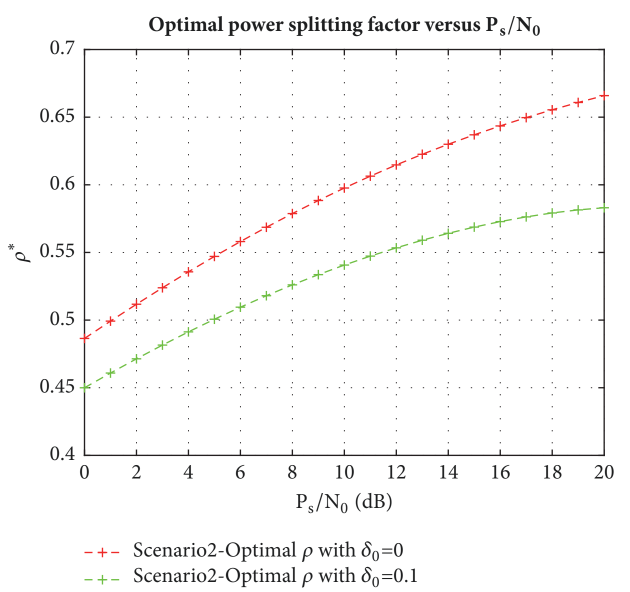

Figure 9: The optimal splitting factor versus Ps/N0 for the second case.

the two scenarios with the dissimilar fading channels are presented and analyzed. To analyze the system performance at the destination node, analytical expressions for the outage probability, the throughput, and optimal power splitting factor are proposed and investigated. The numerical results show that the analytical mathematical expression and the simulation results using Monte Carlo method totally matched each other. Moreover, this paper has provided practical insights into the effect of various system parameters on the system performance. The results show that the system performance degrades significantly but is still in a permissible interval while the channel estimation error increases. Finally, the system performance of the mixing scenarios is better in comparison with the Rayleigh-Rayleigh scenario. The results could be providing the prospective solution for the communication network.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] S. Bi, C. K. Ho, and R. Zhang, "Wireless powered communication: opportunities and challenges," *IEEE Communications Magazine*, vol. 53, no. 4, pp. 117–125, 2015.

[2] N. Zhao, S. Zhang, F. R. Yu, Y. Chen, A. Nallanathan, and V. C. M. Leung, "Exploiting Interference for Energy Harvesting: A Survey, Research Issues, and Challenges," *IEEE Access*, vol. 5, pp. 10403–10421, 2017.

[3] D. Niyato, D. I. Kim, M. Maso, and Z. Han, "Wireless powered communication networks: research directions and technological approaches," *IEEE Wireless Communications Magazine*, vol. 24, no. 6, pp. 88–97, 2017.

[4] K. Tutuncuoglu and A. Yener, "Cooperative energy harvesting communications with relaying and energy sharing," in *Proceedings of the IEEE Information Theory Workshop (ITW '13)*, IEEE, Angeles, Calif, USA, September 2013.

[5] N. Zhao, F. R. Yu, and V. C. M. Leung, "Opportunistic communications in interference alignment networks with wireless power transfer," *IEEE Wireless Communications Magazine*, vol. 22, no. 1, pp. 88–95, 2015.

[6] S. Li, C. Li, S. Jin, M. Wei, and L. Yang, "SINR balancing technique for robust beamforming in V2X-SWIPT system based on a non-linear EH model," *Physical Communication*, vol. 29, pp. 95–102, 2018.

[7] A. A. Nasir, X. Zhou, S. Durrani, and R. A. Kennedy, "Relaying protocols for wireless energy harvesting and information processing," *IEEE Transactions on Wireless Communications*, vol. 12, no. 7, pp. 3622–3636, 2013.

[8] D. Choi and J. H. Lee, "Outage Probability of Two-Way Full-Duplex Relaying With Imperfect Channel State Information," *IEEE Communications Letters*, vol. 18, no. 6, pp. 933–936, 2014.

[9] M. Soysa, H. A. Suraweera, C. Tellambura, and H. K. Garg, "Partial and opportunistic relay selection with outdated channel estimates," *IEEE Transactions on Communications*, vol. 60, no. 3, pp. 840–850, 2012.

[10] Z. Ding, C. Zhong, D. W. K. Ng et al., "Application of smart antenna technologies in simultaneous wireless information and

power transfer," *IEEE Communications Magazine*, vol. 53, no. 4, pp. 86–93, 2015.

[11] K. Tourki, K. A. Qaraqe, and M. Alouini, "Outage Analysis for Underlay Cognitive Networks Using Incremental Regenerative Relaying," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 2, pp. 721–734, 2013.

[12] A. A. Okandeji, M. R. Khandaker, and K. Wong, "Wireless information and power transfer in full-duplex communication systems," in *Proceedings of the ICC 2016 - 2016 IEEE International Conference on Communications*, pp. 1–6, Kuala Lumpur, Malaysia, May 2016.

[13] A. A. Nasir, X. Zhou, S. Durrani, and R. A. Kennedy, "Throughput and ergodic capacity of wireless energy harvesting based DF relaying network," in *Proceedings of the IEEE International Conference on Communications (ICC '14)*, pp. 4066–4071, Sydney, Australia, June 2014.

[14] M. W. Baidas and E. A. Alsusa, "Power allocation, relay selection and energy cooperation strategies in energy harvesting cooperative wireless networks," *Wireless Communications and Mobile Computing*, vol. 16, no. 14, pp. 2065–2082, 2016.

[15] H. A. Suraweera, I. Krikidis, G. Zheng, C. Yuen, and P. J. Smith, "Low-complexity end-to-end performance optimization in MIMO full-duplex relay systems," *IEEE Transactions on Wireless Communications*, vol. 13, no. 2, pp. 913–927, 2014.

[16] C. Zhong, H. A. Suraweera, G. Zheng, I. Krikidis, and Z. Zhang, "Wireless information and power transfer with full duplex relaying," *IEEE Transactions on Communications*, vol. 62, no. 10, pp. 3447–3461, 2014.

[17] G. Chen, P. Xiao, J. R. Kelly, B. Li, and R. Tafazolli, "Full-Duplex Wireless-Powered Relay in Two Way Cooperative Networks," *IEEE Access*, vol. 5, pp. 1548–1558, 2017.

[18] D. H. Ha, D. Tran, V. Tran-Ha, and E. Hong, "Performance of Amplify-and-Forward Relaying with Wireless Power Transfer over Dissimilar Channels," *Elektronika ir Elektrotechnika*, vol. 21, no. 5, 2015.

[19] H. A. Suraweera, R. H. Y. Louie, Y. Li, G. K. Karagiannidis, and B. Vucetic, "Two hop amplify-and-forward transmission in mixed Rayleigh and Rician fading channels," *IEEE Communications Letters*, vol. 13, no. 4, pp. 227–229, 2009.

[20] T. Nguyen, T. Quang Minh, P. Tran, and M. Vozňák, "Energy Harvesting over Rician Fading Channel: A Performance Analysis for Half-Duplex Bidirectional Sensor Networks under Hardware Impairments," *Sensors*, vol. 18, no. 6, p. 1781, 2018.

[21] T. N. Nguyen, T. H. Q. Minh, P. T. Tran, and M. Voznak, "Adaptive Energy Harvesting Relaying Protocol for Two-Way Half-Duplex System Network over Rician Fading Channels," *Wireless Communications and Mobile Computing*, vol. 2018, Article ID 7693016, 10 pages, 2018.

[22] T. Riihonen, S. Werner, and R. Wichman, "Hybrid full-duplex/half-duplex relaying with transmit power adaptation," *IEEE Transactions on Wireless Communications*, vol. 10, no. 9, pp. 3074–3085, 2011.

[23] H. Suraweera, G. K. Karagiannidis, and P. J. Smith, "Performance analysis of the dual-hop asymmetric fading channel," *IEEE Transactions on Wireless Communications*, vol. 8, no. 6, pp. 2783–2788, 2009.

[24] Z. Daniel, *Table of Integrals, Series, and Products*, Elsevier Science, 2014.

[25] T. Q. Duong, T. T. Duy, M. Matthaiou, T. Tsiftsis, and G. K. Karagiannidis, "Cognitive cooperative networks in dual-hop asymmetric fading channels," in *Proceedings of the 2013 IEEE Global Communications Conference (GLOBECOM 2013)*, pp. 955–961, Atlanta, GA, December 2013.

[26] D. Ha and N. Yo, "Physical layer secrecy performance with transmitter antenna selection over dissimilar fading channels," in *Proceedings of the 2014 International Conference on Computer, Communications, and Control Technology (I4CT)*, pp. 140–144, Langkawi, Malaysia, September 2014.

[27] A. Emad and N. C. Beaulieu, "On the Performance of an Automatic Frequency Control Loop in Dissimilar Fading Channels in the Presence of Interference," *IEEE Transactions on Communications*, vol. 59, no. 12, pp. 3234–3239, 2011.