Physical Layer Security in a Hybrid TPSR Two-Way Half-Duplex Relaying Network over a Rayleigh Fading Channel: Outage and Intercept Probability Analysis

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Abstract: In this paper, the system performance of a hybrid time–power splitting relaying (TPSR) two-way half-duplex (HD) relaying network over a Rayleigh fading channel is investigated in terms of the outage probability (OP) and intercept probability (IP). The proposed model has two sources, A and B, which communicate with each other with the help of an intermediate relay (R) under the presence of an eavesdropper (E). The physical layer security (PLS) was considered in this case. Firstly, we derived the closed-form expressions of the exact and asymptotic IP in two cases, using MRC (maximal ratio combining) and SC (selection combining) techniques. The closed-form expressions of the system OP was then analyzed and derived. All the analytical expressions of the OP and IP of the system model were verified by a Monte Carlo simulation in connection with all the main system parameters. In the research results, the analytical and simulation values were in total agreement, demonstrating the correctness of the system performance analysis.

Keywords: physical layer security; half-duplex (HD); outage probability (OP); intercept probability (IP); relaying networks

1. Introduction

When energy harvesting (EH) from green environmental sources is considered, radio frequency (RF) signals can be seen as potential electrical sources for cooperative network devices. In comparison with other green environmental electrical sources, an RF signal’s source has excellent advantages, such as small dimensions, low cost, and independence with respect to time and location in urban areas. From this point of view, RF can be considered a novel solution for communication devices. In addition, RF signals can provide both information and energy in communication network nodes, using a well-known technique in the communication cooperative network called a wireless powered network (WPNs). Research in WPNs is therefore an important research direction in both academia and industry [1–4]. Furthermore, WPNs do not require as much charging, servicing, and maintenance as many battery-powered devices, and this is the great advantage of WPNs in comparison with other types of network. Instead, battery charging, recharging and replacing operations can take place through the air without physical cable connections. We can therefore state that WPNs are a novel...
solution for future applications of technology such as the Internet of Things (IoT) and the Internet of Everything (IoE) [1–8].

Security is increasingly considered a key area for further study on improving wireless communications, especially in the physical layer. Studies on information exchange security have already been extensively performed for the upper layers, but recently, the security of the physical layer has gained significant importance. Physical layer security (PLS) has recently attracted considerable attention, because it can prevent eavesdropping without data encryption in the upper layer. There is an ever-increasing interest in exploring the PLS of digital communications over fading channels. Due to its simple implementation (i.e., only exploiting characteristics of the wireless medium such as link distance and channel state information), PLS can be implemented efficiently in wireless communication networks, internet-of-things (IoT) networks, etc. [9–14]. The authors of [15] investigated a joint relay selection and power scheme to enhance the PLS of a cooperative network with a multiple-antenna source and a single-antenna destination in the presence of untrusted relays and passive eavesdroppers. In [16], secure downlink transmission from a controller to an actuator, with the help of a cooperative jammer to fight against multiple passive eavesdroppers and non-colluding eavesdroppers’ security, was studied, and cooperative jamming was explored to further enhance the PLS. Furthermore, [17] proposed and studied robust quality-of-service-based and secrecy-rate-based secure transmission designs for a multiple-input single-output (MIMO) system with multiple eavesdroppers and a cooperative jammer. A cooperative multi-hop-secured transmission protocol to underlie cognitive radio networks was proposed and considered in [18]. The PLS problem in cognitive decode-and-forward relay networks over a Nakagami-m fading channel is discussed in [19]. Moreover, [20] evaluated the secrecy performance of multi-hop cognitive wireless sensor networks. The secure cooperative transmissions in a dual-hop MIMO relay system (using a combined transmit antenna selection and a maximal-ratio combining scheme over the Nakagami-m fading channels, with an adaptive decode-and-forward relaying protocol and a multi-antenna eavesdropper) were considered in [21]. In [22], the authors investigated three innovative protocols, namely, the shortest path selection protocol, the random path selection protocol, and the best path selection protocol. These protocols enhanced the security of multi-hop multi-path randomize-and-forward cooperative wireless sensor networks, in the presence of eavesdroppers and hardware defects. The authors of [23] investigated the physical layer security of full-duplex two-way multiple AF relaying networks in the presence of an eavesdropper, in terms of the closed form expression of the approximate secrecy outage probability in maximizing the secrecy capacity. Furthermore, [24] proposed the physical layer secure transmission of a cooperative wireless communication system over a three-phase AF two-way relaying channel, and considered a cooperative jamming and multi-antenna relay beam forming scheme to improve the physical layer security of the system. A relay power allocation scheme was proposed in [25], the and information security of a cooperative wireless communication system over three-phase AF two-way relaying channels was investigated, as a way of improving system secrecy capacity. In [26], user selection coupled with an antenna selection (AS) scheme at the base station (BS) was employed in secure cellular multi-user two-way AF relay networks in the presence of a single-antenna passive eavesdropper to maximize the end-to-end signal-to-noise ratios. In addition, the authors of [27] and [28] proposed a novel wireless caching scheme to enhance the physical layer security of video streaming in cellular networks with limited backhaul capacity. Moreover, the authors of [29] studied and investigated the joint effect of fading and co-channel interference (CCI) on the secrecy performance of a wireless communications system when maximal ratio combining (MRC) is employed. From their point of view, the security issue remains unresolved and requires further study. This is the purpose of the present paper. In this paper, the system performance of a hybrid Time–Power Splitting Relaying (TPSR) two-way Half-Duplex (HD) relaying network over a Rayleigh fading channel is investigated, in terms of the Outage Probability (OP) and Intercept Probability (IP). The main contributions of this research are as follows:

(1) A system model of the hybrid TPSR two-way HD relaying communication network over Rayleigh fading channel is developed.
(2) The closed form expressions of the exact and asymptotic IP in two cases (with MRC (maximal ratio combining) techniques and SC (selection combining) techniques), and the closed form expression of the system OP, are derived.

(3) The correctness of the analytical expressions is verified using a Monte Carlo simulation.

The rest of this paper is organized as follows. The hybrid TPSR two-way HD relaying communication network is presented in the second section. The system OP and IP are analyzed and derived in the third section. The research results and some discussion are provided in the fourth section. Finally, the conclusion is proposed in the last section of the paper.

2. Network Model

In this section, a hybrid TPSR two-way HD relaying network over a Rayleigh fading channel is described (Figure 1). Two sources, A and B, communicate with each other with the help of a relay (R), in the presence of an eavesdropper (E). In this system model, all the block-fading channels are Rayleigh fading channels. The Energy Harvesting (EH) and Information Transmission (IT) phases in the interval T are displayed in Figure 2. In the first half-interval, αT, R harvests energy ((1−β)PA) from source A, and the source transfers the information βPA to R, where α is the time-switching factor, β is the power splitting factor, and 0 < α < 0.5 and 0 < β < 1. Actually, we can consider different values of β for A-to-R and B-to-R links, i.e., β1 for A-to-R and β2 for B-to-R. The analysis should be the same as it is here. However, the resulting formula may be more complex. Without loss of generality, we assume the same β for both A-to-R and B-to-R links, to make the result simpler and more readable.

In the next interval αT, R continues to harvest energy ((1-β)PB) from source B and transfers the information βPB to source A. In the last interval, (1−2α)T, R transfers information to sources A and B [30–34].

![Figure 1. The relaying network model.](image1)

![Figure 2. Energy harvesting (EH) and information transmission (IT) phases.](image2)
2.1. Energy Harvesting Phase

In the first phase, $aT$, A transmits the message $x_A$ with the power $P_A$ and the signal received at R can be calculated as follows:

$$y_{AR} = \sqrt{\alpha} h_{AR} x_A + n_R^1,$$

where $n_R^1$ is additive white Gaussian noise (AWGN) with variance $\sigma^2_A$, $h_{AR}$ is the channel gain of the A–R link, and $E\{x_A^2\} = P_A$ where $E\{\cdot\}$ is the expectation operator.

The EH relay employs a fixed power-splitting factor, $\beta$, to split the received RF power into two parts: $\sqrt{\beta} (h_{AR} x_A + n_R^1)$ is used for information transmission, and the remaining power, $\sqrt{1-\beta} (h_{AR} x_A + n_R^1)$, is used for EH.

The amount of harvested energy during the first and second phase can be formulated as

$$E_R = \eta(1-\beta)\alpha T \left( P_A |h_{AR}|^2 + P_B |h_{BR}|^2 \right),$$

(2)

where $0 < \eta \leq 1$ is the energy conversion efficiency, $P_B$ is the average transmitted power at the source B, and $h_{BR}$ is the channel gain of the B–R link. Moreover, $0 < \beta < 1$ and $0 < \alpha < 0.5$ are the power-splitting and time-switching factors, respectively.

If we assume that $P_A = P_B = P$, Equation (2) can be reformulated as the following:

$$E_R = \eta(1-\beta)\alpha T \left( P_A |h_{AR}|^2 + P_B |h_{BR}|^2 \right).$$

(3)

The average transmitted power at the relay can be calculated by

$$P_R = \frac{E_R}{T(1-2\alpha)} = \frac{\eta(1-\beta)\alpha TP_A |h_{AR}|^2 + P_B |h_{BR}|^2}{T(1-2\alpha)} = \kappa P(|h_{AR}|^2 + |h_{BR}|^2),$$

(4)

where $\kappa = \frac{\eta(1-\beta)\alpha}{1-2\alpha}$.

2.2. Information Transmission Phase

In the first phase, after completing EH, A will broadcast the information to the node R and to B with the remaining power $\sqrt{\beta} P_A$.

Hence, the signal received at R can be given as the below equation:

$$y_{AR} = \sqrt{\beta} h_{AR} x_A + n_R^1.$$

(5)

Similar to the first phase, the signal received at R in the second phase can be expressed as

$$y_{BR} = \sqrt{\beta} h_{BR} x_B + n_R^2,$$

(6)

Where $h_{BR}$ is the channel gain of the B–R link and $E\{x_B^2\} = P_B$ and $n_R^2$ is AWGN with variance $\sigma^2_B$.

Hence, the total signal received at R after nodes A and B transmit their signal can be calculated as

$$y_R = \sqrt{\beta} h_{AR} x_A + \sqrt{\beta} h_{BR} x_B + n_R,$$

(7)

where $n_R = n_R^1 + n_R^2$ denotes the total AWGN at R with variance $N_0$.

Finally, in the third phase, the signals received at the A and B nodes can be calculated, respectively, as
\[ y_A = h_{RA}x_B + n_A, \]
\[ y_B = h_{RB}x_R + n_B \]

where \( h_{RA}, h_{RB} \) is the channel gain of R–B and R–A links, respectively, \( n_A, n_B \) is AWGN with variance \( N_0 \) at the A and B nodes, and \( E\{x_R^2\} = P_R \).

In our proposed model, we considered the amplify and forward (AF) mode. In order to ensure that the transmission power at \( R \) is \( P_R \), the amplifying coefficient \( \mu \) was chosen as follows:

\[ \mu = \frac{P_R}{y_R} = \sqrt{\beta P_A|h_{AR}|^2 + P_B|h_{BR}|^2 + N_0} = \sqrt{\beta P|h_{AR}|^2 + |h_{BR}|^2 + N_0}. \]  

Combining Equation (7) with Equations (5) and (6), the received signal at the A node can be rewritten as

\[ y_A = \tilde{h}_{RA} \mu (y_{AR} + y_{BR}) + n_A. \]  

Substituting Equation (7) into Equation (10), we can obtain the following:

\[ y_A = h_{RA} \mu (\sqrt{\beta h_{AR} x_A} + \sqrt{\beta h_{BR} x_B} + n_R) + n_A = h_{RA} \mu \sqrt{\beta h_{BR} x_B} + h_{RA} \mu \sqrt{\beta h_{AR} x_A} + h_{RA} \mu n_R + n_A \]  

This signal contains both messages, \( x_A \) and \( x_B \), while only \( x_B \) is the desired signal at A. Since node A perfectly knows its own transmitted symbol \( x_A \), it can eliminate the corresponding self-interference term \( h_{RA} \mu \sqrt{\beta h_{AR} x_A} \) from \( y_A \).

Therefore, Equation (11) can be reformulated as

\[ y_A = h_{RA} \mu \left( \sqrt{\beta h_{BR} x_B} + h_{RA} \mu n_R + n_A \right). \]  

The signal to noise ratio (SNR) at node A can be formulated as

\[ \gamma_A = \frac{E[|\text{signal}|^2]}{E[|\text{noise}|^2]} = \frac{|h_{RA}||h_{BR}|^2 \mu^2 \beta P}{|h_{RA}|^2 \mu^2 N_0 + N_0}, \]  

Substituting Equation (5) into Equation (9) and then doing some algebra. In this paper, we assume that the channels are reciprocal, so \( h_{BR} = h_{RB} \) and \( h_{AR} = h_{RA} \). Hence, the end-to-end SNR at A can be obtained by

\[ \gamma_A \approx \frac{\kappa P \Psi |h_{BR}|^2}{\kappa |h_{AR}|^2 + \beta} , \]  

where \( \Psi = \frac{P}{N_0} \).

In the total information transmission phase, while R will receive both legitimated messages, \( x_A \) and \( x_B \), from source nodes A and B, E will also overhear the information transmitted by the A and B nodes. Thus, the signal received at E can be obtained by

\[ y_E^1 = h_{AE}x_A + h_{BE}x_B + n_E, \]  

where \( h_{AE} \) and \( h_{BE} \) are the channel gain of the A–E and B–E links, respectively, and \( n_E \) is AWGN with variance \( N_0 \).

During the broadcast signal phase, E also overhears the information from R. Hence, the received signal at E can be given by
\[ y_E^2 = h_{RE} x_R + n_E = h_{RE} \mu y_R + n_E \]
\[ = h_{RE} \mu \left( \sqrt{\beta h_{AR} x_A} + \sqrt{\beta h_{BR} x_B} + n_R \right) + n_E. \tag{16} \]

In our model, we analyzed the intercept (IP) at node A. Because our system model was symmetrical, we could analyze at either node A or node B. Therefore, using Equations (15) and (16), the SNR at E (when decoding a successful message from node A) in the two different phases can be determined, respectively, by

\[ y_E^1 = \frac{|h_{AE}|^2 P_A}{|h_{BE}|^2 P_B + N_0} = \frac{|h_{AE}|^2 \Psi}{|h_{BE}|^2 \Psi + 1}, \tag{17} \]

\[ y_E^2 = \frac{|h_{RE}|^2 \mu^2 \beta |h_{AR}|^2 P_A}{|h_{BE}|^2 \mu^2 \beta |h_{BR}|^2 P_B + |h_{RE}|^2 \mu^2 N_0 + N_0} = \frac{\beta |h_{BR}|^2 P_B + N_0}{|h_{BR}|^2 \Psi + 1}. \tag{18} \]

### 3. Outage Probability and Throughput Analysis

#### 3.1. Outage Probability (OP)

The outage probability at node A can be defined by

\[ OP = \Pr \left( C_A < C_{th} \right), \tag{19} \]

where \( C_A = \frac{(1-2\alpha)T}{3} \times \log_2 \left( 1 + y_A \right) \).

Using Equation (14), Equation (19) can be rewritten as

\[
OP = \Pr \left( y_A < \rho \right) = \Pr \left( \frac{k \rho^\Psi |h_{AR}|^2 |h_{BR}|^2}{\kappa |h_{AR}|^2 + \beta} < \rho \right) \\
= \int_0^\infty \Pr \left( |h_{BR}|^2 < \frac{\rho (k\Psi + \beta)}{k \rho^\Psi} \frac{|h_{AR}|^2}{\kappa} = x \right) \times f_{h_{AR}}(x)dx \\
= \int_0^\infty \Pr \left( |h_{BR}|^2 < \frac{\rho}{\kappa \Psi} + \frac{\rho}{\beta \Psi} \right) \times f_{h_{AR}}(x)dx \\
= \int_0^\infty F_{h_{AR}} \left( \frac{\rho}{\kappa \Psi} + \frac{\rho}{\beta \Psi} \right) \times f_{h_{AR}}(x)dx \\
= \lambda_{AR} \int_0^\infty \exp \left( - \frac{\lambda_{BR} \rho}{\kappa \Psi} - \frac{\lambda_{BR} \rho}{\beta \Psi} \right) \times \exp(-\lambda_{AR} x)dx \\
= 1 - \lambda_{AR} \int_0^\infty \exp \left( - \frac{\lambda_{BR} \rho}{\beta \Psi} \right) \times \exp \left( - \frac{\lambda_{BR} \rho \lambda_{AR}}{\kappa \Psi} \right) dx \\
= 1 - \lambda_{AR} \exp \left( - \frac{\lambda_{BR} \rho \lambda_{AR}}{\beta \Psi} \right) \times \exp \left( - \frac{\lambda_{BR} \rho \lambda_{AR}}{\kappa \Psi} \right) \times \int_0^\infty \exp \left( - \frac{\lambda_{BR} \rho \lambda_{AR}}{\beta \Psi} \right) dx.
\]

where \( \rho = \frac{3 \lambda_{AR}}{2(\alpha-\beta)^2} - 1 > 0 \).

Applying eq (3.324.1) to the table of the integral [35], Equation (20) can be reformulated as

\[ OP = 1 - 2 \exp \left( - \frac{\lambda_{BR} \rho \lambda_{AR}}{\beta \Psi} \right) \times \exp \left( - \frac{\lambda_{BR} \rho \lambda_{AR}}{\kappa \Psi} \right) \times \exp \left( - \frac{\lambda_{BR} \rho \lambda_{AR}}{\kappa \Psi} \right) \times \int_0^\infty \exp \left( - \frac{\lambda_{BR} \rho \lambda_{AR}}{\beta \Psi} \right) dx. \tag{21} \]

#### 3.2. Intercept Probability

**Case 1:** Instantaneous End-to-End SNR at E using the MRC Technique
Using the MRC technique, E combines the SNRs from Equations (17) and (18). Hence, the end-to-end SNR at E can be obtained by

$$\gamma_E^{MRC} = \gamma_E^1 + \gamma_E^2 = \frac{h_{AE}^2}{|h_{BE}|^2} + \frac{\beta |h_{AR}|^2}{|h_{BR}|^2}.$$

(22)

From Equations (14) and (12), we can now claim the capacities at node E are

$$C_E^{MRC} = \left(\frac{1 - (2\alpha_T)}{3}\right) \times \log_2 \left(1 + \gamma_E^{MRC}\right).$$

(23)

The IP can be calculated as

$$IP = \Pr\left(C_E^{MRC} \geq C_{th}\right),$$

(24)

where $C_{th}$ is a predetermined threshold.

Combining Equations (22) and (23), Equation (24) can be rewritten as

$$IP = \Pr\left(\frac{h_{AE}^2}{|h_{BE}|^2} + \frac{\beta |h_{AR}|^2}{|h_{BR}|^2} \geq \rho\right) = \Pr\left(X + Y \geq \rho\right) = 1 - \Pr\left(X + Y < \rho\right),$$

(25)

$$= 1 - \int_0^\rho F_X(\rho - Y) f_Y(y) dy,$$

where $\rho = 2^{1/T_{2\alpha_T}} - 1 > 0$ and $X = \frac{h_{AE}^2}{|h_{BE}|^2}, Y = \frac{\beta |h_{AR}|^2}{|h_{BR}|^2}.$

Comment: We assume that all of the channels are Rayleigh fading channels. Firstly, in order to find the IP in Equation (22), we have to determine the cumulative distribution function (CDF) and probability density function (PDF) of X, Y, respectively, as follows:

$$F_X(x) = \Pr(X < x) = \Pr\left(\frac{h_{AE}^2}{|h_{BE}|^2} < x\right) = \Pr\left(h_{AE} < x\frac{|h_{BE}|^2 + x}{|h_{BE}|^2} = l\right) \times f_{h_{AE}}(l) dt = 1 - \lambda_{BE} \exp\left[-\frac{\lambda_{AE} x}{\Psi}\right] \int_0^{\infty} \exp(-\lambda_{BE} t) \times \exp(-x\lambda_{AE} t) dt,$$

(26)

where $\lambda_{AE}$ and $\lambda_{BE}$ is the mean of the random variables (RVs) $|h_{AE}|^2$ and $|h_{BE}|^2$, respectively.

Similar to above, the CDF of Y can be obtained by

$$F_Y(y) = \Pr(Y < y) = \Pr\left(\frac{\beta |h_{AR}|^2}{|h_{BR}|^2} < y\right) = 1 - \frac{\lambda_{BR} \exp\left[-\frac{\lambda_{AR} y}{\beta \Psi}\right]}{\lambda_{BR} + y\lambda_{AR}}.$$

(27)

where $\lambda_{AR}$ and $\lambda_{BR}$ is the mean of RVs $|h_{AR}|^2$ and $|h_{BR}|^2$, respectively.
From Equation (24), the PDF of $Y$ can be formulated as

$$f_Y(y) = \frac{\partial F_Y(y)}{\partial y} = \frac{\lambda_{BR} \times \exp\left(-\frac{\lambda_{AR}y}{\beta\Psi}\right) \times \left[\frac{\lambda_{BR}\lambda_{AR}}{\beta\Psi} + \frac{(\lambda_{AR})^y + \lambda_{AR}}{\lambda_{BR} + y\lambda_{AR}}\right]}{\left(\lambda_{BR} + y\lambda_{AR}\right)^2}. \quad (28)$$

**Lemma 1. Exact Analysis**

Substituting Equations (26) and (28) into Equation (25), the IP can be claimed as

$$IP = 1 - \frac{\lambda_{BE} \times \exp\left[-\frac{\lambda_{AE}(\rho-y)}{\beta\Psi}\right] \times \exp\left(-\frac{\lambda_{AR}y}{\beta\Psi}\right) \times \left[\frac{\lambda_{BR}\lambda_{AR}}{\beta\Psi} + \frac{(\lambda_{AR})^y + \lambda_{AR}}{\lambda_{BR} + y\lambda_{AR}}\right]}{\left(\lambda_{BR} + y\lambda_{AR}\right)^2} \mathrm{d}y$$

$$= 1 - \frac{\rho \exp\left(-\frac{\lambda_{AR}y}{\beta\Psi}\right) \times \left[\frac{\lambda_{BR}\lambda_{AR}}{\beta\Psi} + \frac{(\lambda_{AR})^y + \lambda_{AR}}{\lambda_{BR} + y\lambda_{AR}}\right]}{\left(\lambda_{BR} + y\lambda_{AR}\right)^2} \mathrm{d}y$$

$$+ \frac{\lambda_{BR} \exp\left(-\frac{\lambda_{AE}\rho}{\beta\Psi}\right)}{\lambda_{AE} \beta\Psi} \int_0^\rho \left[\frac{\exp\left[-\frac{y(\lambda_{AR} - \lambda_{AE})}{\beta\Psi}\right]}{\lambda_{AE} \beta\Psi} \times \left[\frac{\lambda_{BR} + y}{\lambda_{AR} + y}\right]^2 \right] \mathrm{d}y \quad (29)$$

We can now solve for $P_1$ and $P_2$.

By using results from Equation (27), $P_1$ can be obtained as

$$P_1 = 1 - \frac{\lambda_{BR} \times \exp\left(-\frac{\lambda_{AR}\rho}{\beta\Psi}\right)}{\lambda_{BR} + \rho\lambda_{AR}}. \quad (30)$$

Next, we consider $P_2$. Using Equation (29), $P_2$ can be rewritten as

$$P_2 = \frac{\lambda_{BR}}{\lambda_{AE} \beta\Psi} \int_0^\rho \left[\exp\left[-\frac{\lambda_{AE}\rho}{\beta\Psi}\right] \times \left[\exp\left[-\frac{y(a + b)}{(c + y)^2(d - y)}\right]\right] \mathrm{d}y \right] \quad (31)$$

where $a = \frac{\lambda_{BR}}{\lambda_{AR}} \frac{\beta\Psi}{\lambda_{AR}}, b = \frac{\lambda_{AR}}{\beta\Psi} - \frac{\lambda_{AE}}{\lambda_{AR}} \frac{\beta\Psi}{\lambda_{AR}}, c = \frac{\lambda_{BR}}{\lambda_{AE}},$ and $d = \frac{\lambda_{BE}}{\lambda_{AE}} + \rho$. 

with

\[ \tilde{P}_2 = \int_0^\infty \exp\left[-by\right] (y + a) \, dy \]

\[ = \frac{1}{(c + d)^2 (c + x)} \times \left[ e^{bd} (c + x) \text{Ei}(bd - bx) + e^{bc} (c + d) \left( b(c + x) \text{Ei}(-bc - bx) + e^{-b(c + x)} \right) - \text{Ei}(bc - bx) \right] \]

\[ = \frac{1}{(c + d)^2 (c + x)} \times \left[ e^{bd} (c + x) \text{Ei}(bd - bx) + e^{bc} (c + d) \left( b(c + x) \text{Ei}(-bc - bx) + e^{-b(c + x)} \right) - \text{Ei}(bc - bx) \right] \]

where \( \text{Ei}(x) = -\int_{-x}^\infty \frac{e^{-t}}{t} \, dt \) is the exponential integral.

Finally, IP can be determined by

\[ IP = \frac{\lambda_{BR} \times \exp\left(-\frac{\lambda_{BR} \rho}{\beta \Psi}\right)}{\lambda_{BR} + \rho \lambda_{AR}} + \frac{\lambda_{BR}}{\rho \lambda_{AR}} \exp\left(-\frac{\lambda_{AR} \rho}{\Psi}\right) \times \tilde{P}_2 \] (33)

where \( \tilde{P}_2 \) was defined in Equation (32).

**Lemma 2. Asymptotic Analysis**

At the high SNR regime \( (\Psi \to +\infty) \), the IP can be approximated by

\[ IP\text{sym} = \Pr \left( \frac{|h_{AE}|^2}{|h_{BE}|^2} + \frac{|h_{AR}|^2}{|h_{BR}|^2} \geq \rho \right) = 1 - \Pr \left( \frac{|h_{AE}|^2}{|h_{BE}|^2} + \frac{|h_{AR}|^2}{|h_{BR}|^2} < \rho \right) \]

\[ = 1 - \int_0^\rho f_{X}^\rho (\rho - Y \mid Y = y) f_Y(y) \, dy \] (34)

It is easy to observe from Equations (26) and (27) that we can obtain the CDF of X and Y at a high SNR, respectively, as follows:
The PDF of \( Y \) can be obtained from Equation (35):

\[
f_Y^c(y) = \frac{\lambda_{AR} \lambda_{BR}}{(\lambda_{BR} + y \lambda_{AR})^2}.
\]

Substituting Equations (35) and (36) into Equation (34), the IP, in this case, can be determined by

\[
IP_{\text{asym}} = 1 - \frac{\int_{0}^{\rho} \frac{\lambda_{BE}}{\lambda_{BE} + (\rho - y) \lambda_{AE}} \times \frac{\lambda_{AR} \lambda_{BR}}{(\lambda_{BR} + y \lambda_{AR})^2} \, dy}{\lambda_{BR} + \rho \lambda_{AR}} + \frac{\lambda_{AR} \lambda_{AE}}{(\lambda_{BR} + y \lambda_{AR})^2} \, dy
\]

\[
= \frac{\lambda_{BE}}{\lambda_{BR} + \rho \lambda_{AR}} + \frac{\lambda_{AR} \lambda_{AE}}{\lambda_{BR} + y \lambda_{AR}} \times \frac{\lambda_{BR} + \rho \lambda_{AR}}{(\lambda_{BR} + y \lambda_{AR})^2}
\]

\[
= \frac{\lambda_{BE} \lambda_{AR}}{\lambda_{BR} + \rho \lambda_{AR}} \left[ c(d - \rho) \left( \frac{1}{c + d} \right)^2 \right]
\]

where \( c = \frac{\lambda_{BE}}{\lambda_{AR}} \), \( d = \frac{\lambda_{BE}}{\lambda_{AE}} + \rho \).

The integral in Equation (37) is not complicated and in easy to compute. Hence, we can obtain

\[
IP_{\text{asym}} = \frac{\lambda_{BE}}{\lambda_{BR} + \rho \lambda_{AR}} + c(d - \rho) \left( \frac{1 + \rho}{c(c + d)} - \frac{1}{d(c + d)} \right).
\]

**Case 2: Instantaneous End-to-End SNR at E under SC Technique**

With the SC technique, \( E \) will choose the max SNR from Equations (17) and (18). Hence, the end-to-end SNR at \( E \) can be expressed by

\[
\gamma_E^{SC} = \max \left( \gamma_E^1, \gamma_E^2 \right) = \max \left( \frac{| h_{AE} |^2 \Psi}{| h_{BE} |^2 \Psi + 1}, \frac{\beta | h_{AR} |^2 \Psi}{\beta | h_{BR} |^2 \Psi + 1} \right)
\]

**Lemma 3. Exact analysis**

The IP can be given by

\[
IP = \Pr \left( \gamma_E^{SC} \geq \rho \right) = \Pr \left[ \max \left( \frac{| h_{AE} |^2 \Psi}{| h_{BE} |^2 \Psi + 1}, \frac{\beta | h_{AR} |^2 \Psi}{\beta | h_{BR} |^2 \Psi + 1} \right) \geq \rho \right]
\]

\[
= 1 - \Pr \left( \frac{| h_{AE} |^2 \Psi}{| h_{BE} |^2 \Psi + 1} < \rho \right) \Pr \left( \frac{\beta | h_{AR} |^2 \Psi}{\beta | h_{BR} |^2 \Psi + 1} < \rho \right)
\]

From Equations (26) and (27), we have
Lemma 4. Asymptotic analysis

From Equation (31), the $\text{IP}^{\text{asym}}$ can be given by

$$\text{IP}^{\text{asym}} = 1 - \left(1 - \frac{\lambda_{BE} \exp \left(\frac{-\lambda_{AE}^\rho}{\psi}\right)}{\lambda_{BE} + \rho \lambda_{AE}}\right) \cdot \left(1 - \frac{\lambda_{BR} \exp \left(\frac{-\lambda_{AB}^\rho}{\beta \psi}\right)}{\lambda_{BR} + \rho \lambda_{AR}}\right).$$  \hfill (42)

Remark. The position of the E is integrated into the channel gains $h_{AE}, h_{BE}$ and $h_{RE}$. Communication between A and B with the assistance of R does not require knowledge about the position of the E. The position of E only affects the IP of E.

4. Numerical Results and Discussion

A Monte Carlo simulation was conducted to validate the correctness of the system performance analysis in terms of the derived IP and OP expressions [36–48]. The analytical and simulation results should match to verify the correctness of our analysis.

In Figure 3, the system IP is considered as a function of the time switching factor $\alpha$, with the main system parameters set as $C_0 = 0.5 \text{ bps/Hz}$, $\psi = 10 \text{ dB}$ and $\beta = 0.5, 0.85$, respectively. In this simulation stage, we vary the time switching factor $\alpha$ from 0 to 0.5, as shown in Figure 3. As shown in Figure 3, the system IP decreases to 0 as $\alpha$ changes from 0 to 0.3, and remains at 0 with further rises of $\alpha$. In Figure 3, we considered both cases using SC and MRC techniques. When $\alpha$ increases, SNR threshold also increases, because $\rho = 2^{(1-2\alpha)T} - 1 > 0$ (from Equation (23)). Therefore, IP decreases. The IP versus the power splitting factor $\beta$, is also plotted in Figure 4. In this figure, we set the primary system parameters as $C_0 = 0.5 \text{ bps/Hz}$, $\alpha = 0.3$, and $\psi = 10 \text{ dB}, 15 \text{ dB}$, respectively, and vary the power splitting factor $\beta$ from 0 to 1. From Figure 4, we can see that the system IP has a critical increase with the rising of $\beta$. It can be observed that when $\beta$ increases, the SNR at E in phase three (Equation (18)) increases. Therefore, IP increases. In addition, the system IP of the MRC technique is better than the system IP of the SC technique as shown in Figures 3 and 4. Moreover, the simulation produces an agreement between the analytical curves (drawn in Figures 3 and 4), demonstrating the correctness of the system performance analysis described in the above section.

![IP versus $\alpha$ with $C_0=0.5$ bps/Hz and $\psi=10$ dB](image_url)

Figure 3. Intercept probability (IP) versus $\alpha$. 
In Figure 5, we investigated the influence of \( \psi \) on the system IP, with the main system parameters as \( C_h = 0.5 \text{ bps/Hz} \), \( \beta = 0.5 \) in both cases, using SC and MRC techniques. From the research results, we can see that the exact system IP significantly rises while \( \psi \) varies from 0 to 25, and then retains a constant value near the asymptotic system IP. When SNR increases (i.e., when the power of sources A and B increases), the harvested energy at R also increases. Therefore, the transmit power of all sources and relays increases, leading to an increase in IP. This can be verified using Equations (17) and (18). As in Figures 3 and 4, we can see that the simulation and analytical values are the same, and the values obtained with the MRC technique are better than those obtained with the SC technique for verifying the correctness of the system performance analysis described in the third section.

Moreover, the system OP versus the time switching factors \( \alpha \) and \( \psi \) is displayed in Figures 5 and 6, respectively. Here, the main system parameters are set at \( C_h = 0.5 \text{ bps/Hz} \), \( \psi = 10 \text{ dB} \), \( \eta = 0.8 \), and \( \beta = 0.5, 0.85 \) for Figure 6, and \( C_h = 0.5 \text{ bps/Hz} \), \( \alpha = 0.3, \beta = 0.5 \) and \( \eta = 0.5, 1 \) for Figure 7, respectively. From Figure 6, it can be observed that the system OP decreases greatly with a rise of \( \alpha \) from 0.05 to 0.25 and then increases greatly as \( \alpha \) rises from 0.25 to 0.45. The optimal value for system OP is obtained with \( \alpha \) near 0.2–0.25, as shown in Figure 6. In the same way, the system OP decreases greatly with rising \( \psi \), as shown in Figure 7. In both Figures 6 and 7, we can state that the simulation and analytical curves do not differ, demonstrating the correctness of the analytical section of this paper.
Finally, the system OP versus $\beta$ is presented in Figure 8, with the main system parameters set as $C_n = 0.5$ bps/Hz, $\psi = 10$ dB, $\eta = 1$, and $\alpha = 0.3, 0.15$, respectively. In Figure 8, we can see that the system OP decreases greatly as $\alpha$ rises from 0 to 0.5 and then increases greatly as $\alpha$ rises from 0.5 to 1. The optimal value of the system OP is obtained with $\alpha$ near 0.5, as shown in Figure 8. Again, the simulation and analytical curves do not differ, demonstrating the correctness of the analysis.
5. Conclusions

In this paper, the system performance of a hybrid TPSR two-way HD relaying network over a Rayleigh fading channel was investigated, in terms of the system OP and IP. The closed form expressions of the exact and asymptotic IP in two cases (with MRC (maximal ratio combining) and SC (selecting combining) techniques) were derived to analyze the system performance. Moreover, the closed form expression of the system OP was analyzed and derived. The correctness of all the analytical expressions of OP and IP in the system model was verified using a Monte Carlo simulation, in connection with all main system parameters. The results show that the analytical and simulation values agree well with each other.

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