Outage Performance of Multi-relay System with Energy Harvesting and Storage

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Abstract

This paper analyzes the performance of a two-hop half-duplex multi-relay system based on energy harvesting. The relay has energy harvesting and storage functions, and adopts an adaptive AF/DF transmission strategy and PS protocol. Based on three relay selection schemes, namely Energy Optimal Selection (EOS), Channel Gain Optimal Selection (GOS), and Energy and Channel Gain Optimal Selection (EGOS), the outage performance is compared. First, the finite state Markov chain (FSMC) is used to model the energy arrival and use status of each relay, and the energy transfer steady-state matrix is obtained. Then we use the Gauss Chebyshev formula to derive the analytical expression of the communication outage probability (COP). Finally, an optimization model for minimizing the COP for three relay selection schemes is constructed. The EOS and GOS schemes optimize power allocation for energy harvesting and information transmission, and the EGOS scheme jointly optimizes power allocation and energy thresholds. We use a one-dimensional search algorithm based on the golden section and a two-dimensional search algorithm based on iteration to solve these optimization problems. The simulation results show that the EGOS is the best among the three relay selection schemes.

Keywords: Adaptive AF/DF, FSMC, Multi-relay, Relay selection, SWIPT

1 Introduction

With the development of wireless communication technology, the application of wireless services has become more and more extensive, resulting in high energy consumption and a large amount of carbon emissions. Therefore, the research of green communication has become the focus. Energy harvesting technology can obtain energy from the surrounding environment [1], using renewable natural resources such as solar energy and wind energy. In the simultaneous wireless information and power transmission (SWIPT) system, nodes can collect energy from wireless signals for signal processing and forwarding, which extends the life of energy self-sufficient equipment [2]. Therefore, the new energy harvesting technology of obtaining energy from wireless signals has caused a wide range of people [3].

The performance analysis of the wireless system has important reference value for the design and optimization of the network. In [4], it derives the outage probability of a single-relay system in TS mode, and analyzes the influence of different time slot division ratios on the outage probability. The authors of [5] proposed a modified time-switching relaying (TSR) protocol, derived the outage probability, and compared it with the traditional TSR protocol and power-splitting relaying (PSR) protocol. With a three-node half-duplex relay system with two source nodes and one relay node, a non-linear amplifier-based two-way relay system outage probability analysis framework is proposed in [6]. Authors in [7] proposed an adaptive maximum ratio combining (MRC) protocol on the basis of TSR and PSR protocols, which used interrupt probability to characterize throughput, and analyzed the throughput performance during transmission. However, the above-mentioned literatures only study the single-relay system, and do not consider the multi-relay system.

Multiple relays can improve system capacity because the channel state has a direct impact on system performance. The channel state depends on the relay location and small-scale fading. Multiple relays can generate multiple different channels, and select a relatively good channel to complete information transmission, thereby improving the quality of information transmission. In addition, compared with the single-relay system, the energy harvesting efficiency of the multi-relay system will be higher. In [8], it adopts the relay selection scheme with the most harvested energy, and derives the outage probability of the amplify and forward (AF) strategy based on the multi-relay system. Under the framework of decode and forward (DF) strategy with multiple relays, based on the channel gain optimal selection scheme, a new closed expression of the outage probability under the time switch protocol of the energy harvesting relay network is derived in [9]. Authors in [10] studied the downlink cooperative multiple-input single-output wireless sensor network of non-orthogonal multiple access technology, and proposed a power split ratio optimization algorithm and an optimal antenna-relay-target selection algorithm. The authors of [11] studied the SWIPT two-way relay non-orthogonal multiple access system, and derived the analytical expressions of outage probability and ergodic capacity. However, the above literatures only consider the optimal energy or the optimal channel gain to select a relay, and do not consider both at the same time. In addition, they also do not consider energy storage, which would cause the relay to clear its energy at the beginning of the next time slot even if it is not involved in

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communication. This does not match the actual situation, because most devices are now equipped with rechargeable batteries that can store energy.

This paper considers a two-hop half-duplex multi-relay system and derives the outage probability based on energy storage and an adaptive AF/DF transmission strategy under three relay selection schemes. For clarity, we list the contributions as follows:

・A two-hop half-duplex multi-relay system model based on energy harvesting and storage is constructed, in which the PS protocol is used to complete the SWIPT, and the relay forwarding adopts an adaptive AF/DF transmission strategy. The relays are very close to each other therefore the source to relay channel links are identical besides being independent. The relay selection scheme adopts the Energy Optimal Selection (EOS), the Channel Gain Optimal Selection (GOS), and the Energy and Channel Gain Optimal Selection (EGOS). The destination node combines the direct signal and the relay signal with the MRC criterion.

・The finite state Markov chain (FSMC) is used to model the change of the relay energy storage state caused by energy harvesting and information transmission, and the energy transfer steady-state matrix for multiple relays is obtained. The Gauss Chebyshev formula is used to derive the analytical expressions about the communication outage probability (COP) of the adaptive AF/DF transmission strategy under the three relay selection schemes. For both the EOS and GOS solutions, an optimization model that optimizes the power splitting factor to minimize the COP is constructed, which is solved by a one-dimensional search algorithm based on the golden section. For the EGOS scheme, an optimization model is constructed to minimize the COP by jointly optimizing the energy level threshold and the power splitting factor, which is solved by a two-dimensional search algorithm based on iteration.

・The simulation results show that the EGOS scheme is the best among the three schemes, and an optimal value can be obtained by adjusting the energy level threshold and the power splitting factor. We compared the adaptive AF/DF transmission strategy, AF transmission strategy and DF transmission strategy, and proved the superior performance of the adaptive AF/DF transmission strategy. In addition, the simulation results also show that the outage performance of the multi-relay selection system is better than that of the single-relay system. The farther the relay is from the source node, the COP decreases first, then increases, and finally tends to balance.

The rest of this paper is organized as follows. In Section 2, the system model is described. In Section 3, the relay selection and forwarding mechanism is introduced. In Section 4, the energy transfer state matrix and the analytical expressions of the COP are derived. In Section 5, the simulation results are presented and analyzed. Finally, Section 6 concludes the paper.

2 Problem Formulation

As shown in Figure 1, we consider a two-hop half-duplex SWIPT multi-relay system, including a source node S, a destination node D, and N relay nodes R_i, $i \in \{1, 2, \ldots, N\}$. Relay can harvest and store energy. Assuming that there is a direct link between the S and the D, the corresponding channel of each relay is independent of each other, which h_{SD} represents the Rayleigh fading coefficients of the channel link from the S to the D, h_{SR_i} represents the Rayleigh fading coefficients of the channel link from the S to the R_i, and h_{R_iD} represents the Rayleigh fading coefficients of the channel link from the R_i to the D. The channel links are all subject to independent flat Rayleigh fading, and the distance between relays is very close, so the corresponding channel gains $|h_{SD}|^2$, $|h_{SR_i}|^2$, and $|h_{R_iD}|^2$ respectively satisfy the exponential distribution that satisfies the parameters $1/\lambda_0 = d_{SD}^{-\beta}$, $1/\lambda_1 = d_{SR}^{-\beta}$, $1/\lambda_2 = d_{RD}^{-\beta}$, where $d_{SD} = d_{SR} + d_{RD}$ represents the distance relationship, β is the path loss coefficient. Because the path gain obeys an exponential random distribution, the probability distribution function is $f(x) = \lambda e^{-\lambda x}$.

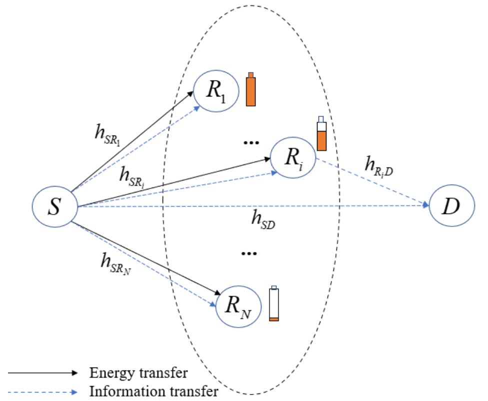

Figure 1. The relay network model

The energy harvesting of the relay adopts the PSR protocol, as shown in Figure 2. Within $\frac{T}{2}$ in each time slot, the source node sends information to the relay node and the destination node, where the relay node divides the received signal power into two parts according to the proportional relationship of $1-\rho:\rho$, one part enters the information processing module, and the other part enters the energy harvesting module, where ρ is the power division factor, which satisfies $0 \le \rho \le 1$. Assume that both channel information and node state information are known. The relay selection is performed at the source node, and the adaptive AF/DF selection strategy is completed by the relay node. After relay selection and adaptive AF/DF transmission strategy selection, the selected relay R transmits information to the destination node within $\frac{T}{2}$.

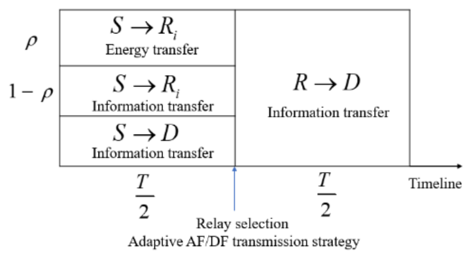

Figure 2. The relay working mode

3 Relay Selection and Forwarding Mechanism

After all relays have completed energy harvesting, an optimal relay needs to be selected among N relays to complete information transmission. There are three relay selection schemes in this article, namely the EOS, GOS, and EGOS, will be introduced in Section 3.1. After selecting the relay to participate in the communication, for the relay transmission strategy, this article considers adaptive AF/DF transmission, which will be introduced in detail in Section 3.2.

3.1 Relay Selection

According to the relay selection scheme, an optimal relay R is selected for information transmission, and the information is forwarded to the destination node. Assuming that b_i denotes the level of energy stored by the relay node R_i at the current moment. There are three relay selection schemes:

- EOS

In this scheme, R_i with the most energy stored at the current moment among the relay nodes is selected as the optimal relay R, which can be expressed as

$$R = \underset{i\in\{1,2,\ldots,N\}}{\arg\max}\, b_i \ . \quad \textbf{(1)}$$

- GOS

In this scheme, R_i with the largest channel gain between R_i and D is selected as the optimal relay R, which can be expressed as

$$R = \underset{i\in\{1,2,\ldots,N\}}{\arg\max} \left|h_{R_iD}\right|^2 . \quad \textbf{(2)}$$

- EGOS

In this scheme, when the energy stored by R_i is greater than the energy threshold τ, the relay node belongs to a qualified set Φ, denoted as $\Phi=\{R_i \mid b_i > \tau\}$, and R_i with the largest channel gain between R_i and D in Φ is selected as the optimal relay R. If the set $\Phi = \varnothing$ is qualified, it means that the remaining energy of all relay nodes is too small. At this time, R_i with the most energy stored at the current moment is selected as the optimal relay R. The expression is

$$R = \begin{cases} \underset{i\in\Phi}{\arg\max} \left|h_{R_iD}\right|^2, \Phi \neq \varnothing \\ \underset{i\in\{1,2,\ldots,N\}}{\arg\max}\, b_i, \Phi = \varnothing \end{cases} . \quad \textbf{(3)}$$

In order to reduce the outage probability as much as possible, the selected relay R will transmit information with the highest transmission power P_R .Therefore, once R is selected, all the stored energy will be used up, namely

$$P_R = \frac{2b_R}{T} \ . \quad \textbf{(4)}$$

3.2 Forwarding Mechanism

There are multiple strategies for relay forwarding, the most common of which are DF and AF. DF means that the relay first decodes the received source signal, and then sends the decoded signal to the destination node. AF means that the relay itself does not decode the source signal, but only receives the received signal. The signal is amplified by a certain amplification factor and sent to the destination node. Both strategies have certain advantages and disadvantages. This paper adopts an adaptive AF/DF transmission strategy [12]. If R is selected for information transmission, R determines the forwarding transmission strategy according to the decoding situation. The process is shown in Figure 3.

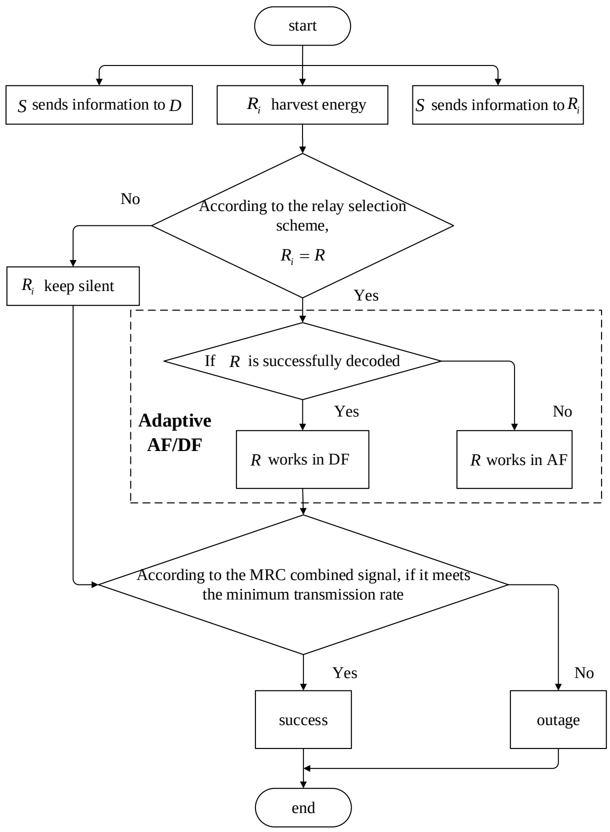

Figure 3. The relay workflow

First, R_i harvest energy from the RF signal sent by S and store it in the battery. The harvested energy is expressed as

$$E_i = \eta\rho P_S \left|h_{SR_i}\right|^2 \cdot \frac{T}{2} \ , \quad \textbf{(5)}$$

where η is the energy conversion factor, P_S is the transmit power of the S.

In the first time slot, S uses the transmit power P_S to send signal x_S to R_i and D. Assuming that $n_R \sim CN(0,\ \sigma_R^2)$

and $n_D \sim CN(0, \sigma_D^2)$ are the additive white Gaussian noise at R_i and D respectively. The received signal of R is $y_R = \sqrt{(1-\rho)P_S} h_{SR} x_S + n_R$, and the received signal of D is $y_D = \sqrt{P_S} h_{SD} x_S + n_D$. Therefore, the received signal-to-noise ratio (SNR) of R_i and D are

$$\gamma_R = \frac{(1-\rho)P_S |h_{SR}|^2}{\sigma_R^2}. \tag{6}$$

$$\gamma_0 = \frac{P_S |h_{SD}|^2}{\sigma_D^2}. \tag{7}$$

In the second time slot, R uses the transmit power P_R to send signal x_R to D. If the R can be successfully decoded, the DF transmission strategy is adopted. At this time, the received signal of D is $y_D = \sqrt{P_R} h_{RD} x_R + n_D$. Therefore, the received SNR of the D with respect to the R in the DF mode is

$$\gamma_1 = \frac{P_R |h_{RD}|^2}{\sigma_D^2}. \tag{8}$$

If the R cannot be successfully decoded, the AF transmission strategy is adopted. At this time, the received signal of D is $y_D = \sqrt{P_R} h_{RD} \beta y_R + n_D$, where the amplifying and forwarding factor is $\beta = \frac{1}{\sqrt{(1-\rho)P_S |h_{SR}|^2 + \sigma_R^2}}$. Therefore, the received SNR of the D with respect to the R in the AF mode is

$$\gamma_2 = \frac{(1-\rho)P_S P_R |h_{SR}|^2 |h_{RD}|^2}{P_R |h_{RD}|^2 \sigma_R^2 + (1-\rho)P_S |h_{SR}|^2 \sigma_D^2 + \sigma_R^2 \sigma_D^2}. \tag{9}$$

According to the MRC criterion [13], the total received SNR of the D under the two relay transmission strategies can be obtained as

$$\gamma_D^{DF} = \gamma_0 + \min(\gamma_R, \gamma_1). \tag{10}$$

$$\gamma_D^{AF} = \gamma_0 + \gamma_2. \tag{11}$$

4 Performance Analysis

Because R is selected from the set of qualified energy storage states, in order to analyze the communication performance, it is necessary to track the energy storage evolution process of all relays. To facilitate analysis, the energy storage of each relay is discretely divided into $L+1$ energy levels, denoted as $\{\varepsilon_l\}_0^L$, where $\varepsilon_l = lC/L$, and C are the maximum storage capacity of the battery.

The energy storage state of the R_i is modeled as a finite state Markov chain [14], where each storage state corresponds to the battery state when the R_i selects the optimal relay R after energy harvesting. It is assumed that the current state of the battery is only related to the state of the battery for relay selection in the last time slot, and has nothing to do with the state in the past, so the Markov chain has a memoryless characteristic. Suppose the state of FSMC is $\vec{s}_m = (s_1, s_2, \ldots, s_N), m \in \{1, 2, \ldots, (L+1)^N\}$, where s_i represents the energy storage state of the R_i, which satisfies $s_i \in \{\varepsilon_0, \varepsilon_1, \ldots, \varepsilon_L\}$.

Let $P = [p_{mn}]$ represent the transition probability matrix (TPM) of FSMC, where p_{mn} represents the transition probability from $\vec{s}_m$ to $\vec{s}_n$. According to [15], it can be proved that the transition probability matrix is irreducible and row random, and there is a unique steady-state probability vector π satisfies $\pi = P^T \pi$, we can get

$$\pi = [\pi_m] = (P^T - I + B)^{-1} b, \tag{12}$$

where I is the identity matrix, B is a matrix with all elements of 1, $b = (1, 1, \ldots, 1)^T$.

The communication outage probability (COP) refers to the probability of communication interruption during the communication process. The total probability formula can be used to obtain the COP under the adaptive AF/DF strategy as

$$P_{COP}(\gamma_{th}^R, \gamma_{th}^D) = \sum_m P_{con}(\gamma_{th}^R, \gamma_{th}^D) \cdot \pi_m, \tag{13}$$

where γ_{th}^R and γ_{th}^D are the outage threshold for successful relay decoding and the outage threshold for successful information transmission, $P_{con}(\gamma_{th}^R, \gamma_{th}^D)$ is the conditional outage probability when the energy storage state is π_m, which can be expressed as

$$P_{con}(\gamma_{th}^R, \gamma_{th}^D) = \begin{cases} \Pr\{\gamma_0 < \gamma_{th}^D \mid \pi_m\}, P_R = 0 \\ \Pr\{\gamma_R \geq \gamma_{th}^R, \gamma_D^{DF} < \gamma_{th}^D \mid \pi_m\} \\ + \Pr\{\gamma_R < \gamma_{th}^R, \gamma_D^{AF} < \gamma_{th}^D \mid \pi_m\}, P_R > 0 \end{cases}. \tag{14}$$

4.1 Energy Transfer Matrix

Because this paper assumes that the channels experience independent fading and the relays are close to each other, all relays have the same energy state transition. For convenience, we introduce an indicator function to indicate whether the R_i is selected, that is

$$\varphi_i = \begin{cases} 1, R_i = R \\ 0, R_i \neq R \end{cases}. \tag{15}$$

Let's study the energy storage changing from ε_j to ε_k in the energy storage state s_i, where $p_{j,k}$ represents the energy storage state transition probability from ε_j to ε_k. The energy storage changing is determined by the R_i working mode, and the R_i has only two working modes: forwarding information and keeping silent.

- $\varepsilon_j = 0, \varepsilon_k < \varepsilon_j$: In this case, the relay has no energy for information forwarding. If it is selected, it will be interrupted directly and energy will not be transferred. If it is not selected, the relay only uses energy, does not consume energy, and the energy level will not drop. Consequently, $p_{j,k} = 0$.

- $\varepsilon_j = 0, \varepsilon_j \le \varepsilon_k \le L$: In this case, if the relay is selected, then interruption occurs directly, and no energy transfer occurs. If the relay is not selected, the energy accumulation is repeated in the EH phase of the next time slot, and the transition probability is

$$\begin{aligned} p_{j,k} &= (1-\varphi_i)\Pr\left\{\frac{kC}{L} \le E_i < \frac{(k+1)C}{L}\right\} \\ &= (1-\varphi_i)\left[e^{-\lambda_1 \frac{2kC}{\eta\rho P_S TL}} - e^{-\lambda_1 \frac{2(k+1)C}{\eta\rho P_S TL}}\right] \end{aligned}. \tag{16}$$

- $0 < \varepsilon_j \le L, 0 \le \varepsilon_k < \varepsilon_j$: In this case, the relay is selected, consumes all energy in the current time slot to transmit information, and then re-accumulates energy in the EH phase of the next time slot, the transition probability is

$$\begin{aligned} p_{j,k} &= \varphi_i \Pr\left\{\frac{kC}{L} \le E_i < \frac{(k+1)C}{L}\right\} \\ &= \varphi_i\left[e^{-\lambda_1 \frac{2kC}{\eta\rho P_S TL}} - e^{-\lambda_1 \frac{2(k+1)C}{\eta\rho P_S TL}}\right] \end{aligned}. \tag{17}$$

- $0 < \varepsilon_j < L, \varepsilon_j \le \varepsilon_k < L$: In this case, the relay may be selected or not. If the relay is selected, all energy is consumed in the current time slot to transmit information, and then the energy accumulation is performed again in the EH phase of the next time slot, and the accumulated energy at this time reaches at least the energy of the current time slot. If the relay is not selected, the relay keeps silent and only harvests energy instead of consuming energy. In summary, the transition probability is

$$\begin{aligned} p_{j,k} &= \varphi_i \Pr\left\{\frac{kC}{L} \le E_i < \frac{(k+1)C}{L}\right\} \\ &\quad + (1-\varphi_i)\Pr\left\{\frac{(k-j)C}{L} \le E_i < \frac{(k-j+1)C}{L}\right\} \\ &= \varphi_i\left[e^{-\lambda_1 \frac{2kC}{\eta\rho P_S TL}} - e^{-\lambda_1 \frac{2(k+1)C}{\eta\rho P_S TL}}\right] \\ &\quad + (1-\varphi_i)\left[e^{-\lambda_1 \frac{2(k-j)C}{\eta\rho P_S TL}} - e^{-\lambda_1 \frac{2(k-j+1)C}{\eta\rho P_S TL}}\right] \end{aligned}. \tag{18}$$

- $0 < \varepsilon_j < L, \varepsilon_k = L$ or $\varepsilon_j = L, \varepsilon_k = L$: In this case, the relay may be selected or not, in short, the battery is fully charged at the end. Similarly, the transition probability is

$$\begin{aligned} p_{j,k} &= \varphi_i \Pr\{E_i \ge C\} + (1-\varphi_i)\Pr\left\{E_i \ge \frac{(L-j)C}{L}\right\} \\ &= \varphi_i e^{-\lambda_1 \frac{2C}{\eta\rho P_S T}} + (1-\varphi_i) e^{-\lambda_1 \frac{2(L-j)C}{\eta\rho P_S TL}} \end{aligned}. \tag{19}$$

Remark: For EOS, $\varphi_i = 1$ is satisfied only when the energy level of R_i is the maximum value among all relays at the current moment. If it is not the maximum value, then the relay only harvests energy and does not consume energy, that is, $\varphi_i = 0$. For GOS, the relay selection is only related to the channel gain, not the energy level of the current time slot. Therefore, each relay has an equal chance of being selected, that is, all relays may be selected. For EGOS, because the battery capacity is quantified, the relay qualified set Φ is re-expressed as $\Phi = \left\{R_i \mid b_i > \frac{\tau C}{L}\right\}$, where τ is the energy level threshold. Only the relay in Φ can be selected, and the other relays cannot, that is, the above five conditions of energy storage changing should be changed to: $0 \le \varepsilon_j \le \tau, \varepsilon_k < \varepsilon_j$; $0 \le \varepsilon_j \le \tau, \varepsilon_j \le \varepsilon_k$; $\tau < \varepsilon_j \le L, 0 \le \varepsilon_k < \varepsilon_j$; $\tau < \varepsilon_j < L, \varepsilon_j \le \varepsilon_k < L$; $\tau < \varepsilon_j < L, \varepsilon_k = L$ or $\varepsilon_j = L, \varepsilon_k = L$.

Through the above analysis, we can get the energy state transition probability of any relay according to the role of the relay in the information transmission block, that is, information forwarding or keeping silent. According to the construction method of the FSMC transition probability matrix (TPM) in [16], we can obtain the transition probability p_{mn} from $\vec{s}_m$ to $\vec{s}_n$ by multiplying the energy state transition probabilities corresponding to all relays, thereby obtaining the transition probability matrix *P*. After P is given, the steady-state probability matrix π can be calculated according to (12).

4.2 Outage Probability

In the communication process, the relay set whose relay energy is interrupted is $\Omega = \{m \mid P_{R,m} = 0\}$. At this time, the selected relay cannot participate in the communication, and the D only receives the information from the directly connected link. Because $|h_{SD}|^2$ obeys the exponential distribution of $1/\lambda_0$, $\gamma_0 = a_0|h_{SD}|^2$ obeys the exponential distribution of a_0/λ_0, where $a_0 = \frac{P_S}{\sigma_D^2}$. So the outage probability of the direct link is

$$P_{con0} = \Pr\{\gamma_0 < \gamma_{th}^D \mid \pi_m\} = 1 - e^{-\frac{\lambda_0\gamma_{th}^D}{a_0}}. \tag{20}$$

If the relay can be decoded successfully, that is, the relay forwarding adopts the DF transmission strategy, then the outage probability is

$$\begin{aligned} P_{con1} &= \Pr\{\gamma_R \ge \gamma_{th}^R, \gamma_D^{DF} < \gamma_{th}^D \mid \pi_m\} \\ &= \Pr\{\gamma_R \ge \gamma_{th}^R, \gamma_0 < \gamma_{th}^D, \gamma_1 < \gamma_{th}^D - \gamma_0 \mid \pi_m\} \end{aligned}. \tag{21}$$

If the relay decoding fails, that is, the relay forwarding adopts the AF transmission strategy, then the outage probability is

$$\begin{aligned} P_{con2} &= \Pr\left\{\gamma_R < \gamma_{th}^R, \gamma_D^{AF} < \gamma_{th}^D \mid \pi_m\right\} \\ &= \Pr\left\{\gamma_R < \gamma_{th}^R, \gamma_0 < \gamma_{th}^D, \gamma_2 < \gamma_{th}^D - \gamma_0 \mid \pi_m\right\} \end{aligned} \quad \textbf{(22)}$$

4.2.1 EOS

This scheme selects the relay with the most energy stored at the current moment among the relay nodes as the optimal relay *R*. According to (14), if $P_R = 0$, the conditional outage probability P_{con} of the scheme is expressed by (20), otherwise it is composed of (21) and (22).

When the relay can be successfully decoded, because $|h_{SR}|^2$ and $|h_{RD}|^2$ obey the exponential distribution of $1/\lambda_1$ and $1/\lambda_2$ respectively, $\gamma_R = a_1|h_{SR}|^2$ and $\gamma_1 = a_2|h_{RD}|^2$ obey the exponential distribution of a_1/λ_1 and a_2/λ_2 respectively, where $a_1 = \frac{(1-\rho)P_S}{\sigma_R^2}$ and $a_2 = \frac{P_R}{\sigma_D^2}$. Therefore, the outage probability of relay forwarding using DF transmission strategy is

$$\begin{aligned} P_{con1}^{EOS} &= \int_{\gamma_{th}^R}^{\infty} \frac{\lambda_1}{a_1} e^{-\frac{\lambda_1 Y}{a_1}} dY \cdot \int_0^{\gamma_{th}^D} \frac{\lambda_0}{a_0} e^{-\frac{\lambda_0}{a_0}X} \left(1 - e^{-\frac{\lambda_2(\gamma_{th}^D - X)}{a_2}}\right) dX \\ &= e^{-\frac{\lambda_1 \gamma_{th}^R}{a_1}} \cdot \left[1 - \frac{\lambda_2 a_0}{\lambda_2 a_0 - \lambda_0 a_2} e^{-\frac{\lambda_0 \gamma_{th}^D}{a_0}} + \frac{\lambda_0 a_2}{\lambda_2 a_0 - \lambda_0 a_2} e^{-\frac{\lambda_2 \gamma_{th}^D}{a_2}}\right] \end{aligned} \quad \textbf{.(23)}$$

When the relay cannot be successfully decoded, substituting (6) and (8) into $\gamma_2 < \gamma_{th}^D - \gamma_0$ can get $\left(A_1|h_{SR}|^2 + A_2|h_{SD}|^2 - A_3\right)|h_{RD}|^2 < A_4|h_{SR}|^2 - A_5|h_{SD}|^2|h_{SR}|^2 - A_6|h_{SD}|^2 + A_7$, where $A_1 = (1-\rho)P_S P_R \sigma_D^2$, $A_2 = P_S P_R \sigma_R^2$, $A_3 = P_R \sigma_R^2 \sigma_D^2 \gamma_{th}^D$, $A_4 = (1-\rho)P_S \sigma_D^2 \sigma_D^2 \gamma_{th}^D$, $A_5 = (1-\rho)P_S P_S \sigma_D^2$, $A_6 = P_S \sigma_R^2 \sigma_D^2$, $A_7 = \sigma_D^2 \gamma_{th}^D \sigma_R^2 \sigma_D^2$. Because of $\gamma_0 < \gamma_{th}^D$, $A_4|h_{SR}|^2 - A_5|h_{SD}|^2|h_{SR}|^2 - A_6|h_{SD}|^2 + A_7 > 0$ always holds. If $A_1|h_{SR}|^2 + A_2|h_{SD}|^2 - A_3 \le 0$, i.e., $|h_{SR}|^2 \le \frac{A_3 - A_2|h_{SD}|^2}{A_1}$, we have that $\gamma_2 < \gamma_{th}^D - \gamma_0$ holds with probability 1; if $A_1|h_{SR}|^2 + A_2|h_{SD}|^2 - A_3 > 0$, i.e., $|h_{SR}|^2 > \frac{A_3 - A_2|h_{SD}|^2}{A_1}$, we have that $\gamma_2 < \gamma_{th}^D - \gamma_0$ holds with probability $\Pr\left\{|h_{RD}|^2 < \frac{A_4|h_{SR}|^2 - A_5|h_{SD}|^2|h_{SR}|^2 - A_6|h_{SD}|^2 + A_7}{A_1|h_{SR}|^2 + A_2|h_{SD}|^2 - A_3}\right\}$.

Therefore, the outage probability of using the AF transmission strategy for relay forwarding is

$$\begin{aligned} P_{con2}^{EOS} &= \Pr\left\{|h_{SD}|^2 < \frac{\gamma_{th}^D}{a_0}, |h_{SR}|^2 \le \frac{A_3 - A_2|h_{SD}|^2}{A_1}\right\} \\ &+ \Pr\left\{\begin{aligned} &|h_{SD}|^2 < \frac{\gamma_{th}^D}{a_0}, \frac{A_3 - A_2|h_{SD}|^2}{A_1} < |h_{SR}|^2 < \frac{\gamma_{th}^R}{a_1}, \\ &|h_{RD}|^2 < \frac{A_4|h_{SR}|^2 - A_5|h_{SD}|^2|h_{SR}|^2 - A_6|h_{SD}|^2 + A_7}{A_1|h_{SR}|^2 + A_2|h_{SD}|^2 - A_3} \end{aligned}\right\}. \\ &= P_{21} + P_{22} \end{aligned} \quad \textbf{(24)}$$

According to the exponential distribution characteristics, we have

$$\begin{aligned} P_{21} &= \int_0^{\frac{\gamma_{th}^D}{a_0}} \left(1 - e^{-\frac{\lambda_1(A_3 - A_2 x)}{A_1}}\right) \lambda_0 e^{-\lambda_0 x} dx, \\ &= 1 - e^{-\frac{\lambda_0 \gamma_{th}^D}{a_0}} + \frac{\lambda_0 A_1}{\lambda_1 A_2 - \lambda_0 A_1} e^{-\frac{\lambda_0 A_3}{A_1}} \left(1 - e^{-\frac{(\lambda_0 A_1 - \lambda_1 A_2)\gamma_{th}^D}{a_0 A_1}}\right) \end{aligned}$$

$$\begin{aligned} P_{22} &= \int_0^{\frac{\gamma_{th}^D}{a_0}} \int_{\frac{A_3 - A_2 x}{A_1}}^{\frac{\gamma_{th}^R}{a_1}} \left(1 - e^{-\lambda_2 \frac{A_4 y - A_5 xy - A_6 x + A_7}{A_1 y + A_2 x - A_3}}\right) \lambda_0 \lambda_1 e^{-\lambda_0 x - \lambda_1 y} dxdy \\ &= \int_0^{\frac{\gamma_{th}^D}{a_0}} \left(e^{-\lambda_1 \frac{A_3 - A_2 x}{A_1}} - e^{-\lambda_1 \frac{\gamma_{th}^R}{a_1}}\right) \lambda_0 e^{-\lambda_0 x} dx \\ &\quad - \int_0^{\frac{\gamma_{th}^D}{a_0}} \int_{\frac{A_3 - A_2 x}{A_1}}^{\frac{\gamma_{th}^R}{a_1}} e^{-\lambda_2 \frac{A_4 y - A_5 xy - A_6 x + A_7}{A_1 y + A_2 x - A_3}} \lambda_0 \lambda_1 e^{-\lambda_0 x - \lambda_1 y} dxdy \\ &= \frac{\lambda_0 A_1}{\lambda_0 A_1 - \lambda_1 A_2} e^{-\lambda_1 \frac{A_3}{A_1}} \left(1 - e^{-\frac{(\lambda_0 A_1 - \lambda_1 A_2)\gamma_{th}^D}{a_0 A_1}}\right) - e^{-\lambda_1 \frac{\gamma_{th}^R}{a_1}} \left(1 - e^{-\lambda_0 \frac{\gamma_{th}^D}{a_0}}\right) - I \end{aligned}$$

.

Because of the complexity of the integrand function in *I*, we use the Gauss Chebyshev formula to find an approximate solution [17]. Let $f_{n_1} = \cos(\frac{2n_1 - 1}{N_1}\pi)$, $f_{n_2} = \cos(\frac{2n_2 - 1}{N_2}\pi)$, $w_{n_1} = \frac{\pi}{N_1}$, $w_{n_2} = \frac{\pi}{N_2}$, $x_{n_1} = \frac{\gamma_{th}^D}{2a_0}\left(f_{n_1} + 1\right)$, $x_{n_2} = \left(\frac{\gamma_{th}^R}{2a_1} - \frac{A_3 - A_2 x_{n_1}}{2A_1}\right) f_{n_2} + \left(\frac{\gamma_{th}^R}{2a_1} + \frac{A_3 - A_2 x_{n_1}}{2A_1}\right)$, where N_1, N_2 represent the parameters of complexity and accuracy, then

$$\begin{aligned} I &= \lambda_0 \lambda_1 \int_0^{\frac{\gamma_{th}^R}{a_1}} \int_{\frac{A_3 - A_1 y}{A_2}}^{\frac{\gamma_{th}^D}{a_0}} e^{-\lambda_0 x - \lambda_1 y - \frac{\lambda_2 A_4 y - \lambda_2 A_5 xy - \lambda_2 A_6 x + \lambda_2 A_7}{A_1 y + A_2 x - A_3}} dxdy, \\ &= \sum_{n_1=1}^{N_1} \sum_{n_2=1}^{N_2} w_{n_1} w_{n_2} \sqrt{1 - f_{n_1}^2} \sqrt{1 - f_{n_2}^2} \frac{\gamma_{th}^D}{2a_0} \left(\frac{\gamma_{th}^R}{2a_1} - \frac{A_3 - A_2 x_{n_1}}{2A_1}\right) I_e \end{aligned} \quad \textbf{(25)}$$

where $I_e = \lambda_0 \lambda_1 e^{-(\lambda_0 x_{n_1} + \lambda_1 x_{n_2} + \frac{\lambda_2 A_4 x_{n_2} - \lambda_2 A_5 x_{n_1} x_{n_2} - \lambda_2 A_6 x_{n1} + \lambda_2 A_7}{A_1 x_{n_2} + A_2 x_{n1} - A_3})}$.

In a given state $\vec{s}_m$, the remaining energy of the optimal relay R can be found as $b_R(m) = \frac{\max[s_1, s_2, \ldots, s_N] \cdot C}{L}$, and $P_{R,m} = \frac{2b_R(m)}{T}$ can be obtained according to (4). Therefore, the outage probability of the EOS scheme is

$$P_{COP}^{EOS} = \sum_{m \in \Omega} P_{con0} \cdot \pi_m + \sum_{m \notin \Omega} \left(P_{con1}^{EOS}(P_{R,m}) + P_{con2}^{EOS}(P_{R,m}) \right) \cdot \pi_m \ . \quad \textbf{(26)}$$

4.2.2 GOS

This scheme selects the relay with the maximum channel gain between the relay node and the destination node as the optimal relay *R*. At any time, there are N relays that can be selected. At this time, the cumulative distribution function (CDF) of $|h_{RD}|^2$ and $\gamma_1 = a_2 |h_{RD}|^2$ are respectively

$$F_{|h_{RD}|^2}(x) = \left(1 - e^{-\lambda_2 x}\right)^N = \sum_{n=0}^{N} \binom{N}{n} (-1)^n e^{-n\lambda_2 x} \ . \quad \textbf{(27)}$$

$$F_{\gamma_1}(x) = \left(1 - e^{-\frac{\lambda_2}{a_2}x}\right)^N = \sum_{n=0}^{N} \binom{N}{n} (-1)^n e^{-n\frac{\lambda_2}{a_2}x} \ . \quad \textbf{(28)}$$

The outage probability of relay forwarding using DF transmission strategy is

$$\begin{aligned} P_{con1}^{GOS} &= \Pr\left\{\gamma_R \geq \gamma_{th}^R, \gamma_D^{DF} < \gamma_{th}^D \mid \pi_m\right\} \\ &= \Pr\left\{\gamma_R \geq \gamma_{th}^R, \gamma_0 < \gamma_{th}^D, \gamma_1 \leq \gamma_{th}^D - \gamma_0\right\} \\ &= \int_{\gamma_{th}^R}^{\infty} \frac{\lambda_1}{a_1} e^{-\frac{\lambda_1}{a_1}y} dy \int_0^{\gamma_{th}^D} \frac{\lambda_0}{a_0} e^{-\frac{\lambda_0}{a_0}x} \left(\sum_{n=0}^{N} \binom{N}{n} (-1)^n e^{-\frac{\lambda_2}{a_2} n(\gamma_{th}^D - x)} \right) dx \ . \\ &= \sum_{n=0}^{N} \binom{N}{n} \frac{(-1)^n \lambda_0 a_2}{n\lambda_2 a_0 - \lambda_0 a_2} \left(e^{-\frac{\lambda_0 \gamma_{th}^D}{a_0} - \frac{\lambda_1 \gamma_{th}^R}{a_1}} - e^{-\frac{\lambda_1 \gamma_{th}^R}{a_1} - \frac{\lambda_2 n \gamma_{th}^D}{a_2}} \right) \end{aligned} \quad \textbf{(29)}$$

The outage probability of relay forwarding using AF transmission strategy is

$$\begin{aligned} P_{con2}^{GOS} &= \Pr\left\{ |h_{SD}|^2 < \frac{\gamma_{th}^D}{a_0}, |h_{SR}|^2 \leq \frac{A_3 - A_2 |h_{SD}|^2}{A_1} \right\} + \\ &\Pr\left\{ \begin{aligned} &|h_{SD}|^2 < \frac{\gamma_{th}^D}{a_0}, \frac{A_3 - A_2 |h_{SD}|^2}{A_1} < |h_{SR}|^2 < \frac{\gamma_{th}^R}{a_1}, \\ &|h_{RD}|^2 < \frac{A_4 |h_{SR}|^2 - A_5 |h_{SD}|^2 |h_{SR}|^2 - A_6 |h_{SD}|^2 + A_7}{A_1 |h_{SR}|^2 + A_2 |h_{SD}|^2 - A_3} \end{aligned} \right\} . \\ &= P_{21} + \sum_{n=0}^{N} \binom{N}{n} (-1)^n \cdot I' \end{aligned} \quad \textbf{(30)}$$

In the same way, the Gauss Chebyshev formula can be used to obtain

$$\begin{aligned} I' &= \int_0^{\frac{\gamma_{th}^D}{a_0}} \int_{\frac{A_3 - A_2 x}{A_1}}^{\frac{\gamma_{th}^R}{a_1}} \lambda_0 \lambda_1 e^{-\lambda_0 x - \lambda_1 y - \lambda_2 n \frac{A_4 y - A_5 xy - A_6 x + A_7}{A_1 y + A_2 x - A_3}} dxdy \\ &= \lambda_0 \lambda_1 \sum_{n_1=1}^{N_1} \sum_{n_2=1}^{N_2} w_{n_1} w_{n_2} \sqrt{1 - f_{n_1}^2} \sqrt{1 - f_{n_2}^2} \cdot \frac{\gamma_{th}^D}{2a_0} \cdot \left(\frac{\gamma_{th}^R}{2a_1} - \frac{A_3 - A_2 x_{n_1}}{2A_1} \right) \cdot \\ &\cdot e^{-(\lambda_0 x_{n_1} + \lambda_1 x_{n_2} + \frac{\lambda_2 n A_4 x_{n_2} - \lambda_2 n A_5 x_{n_1} x_{n_2} - \lambda_2 n A_6 x_{n1} + \lambda_2 n A_7}{A_1 x_{n_2} + A_2 x_{n1} - A_3})} \end{aligned}$$

In a given state $\vec{s}_m$, the remaining energy of the relay node can be found as $b_{R_i}(m) = \frac{s_i \cdot C}{L}$, and $P_{R_i,m} = \frac{2b_{R_i}(m)}{T}$ can be obtained according to (4). Because N relay nodes have the same chance of being selected as the optimal relay R, we need to calculate the average of the conditional outage probability under all circumstances. Therefore, the outage probability of the GOS scheme is

$$\begin{aligned} P_{COP}^{GOS} &= \sum_{m \in \Omega} P_{con0} \cdot \pi_m \\ &+ \sum_{m \notin \Omega} \left[\frac{1}{N} \sum_i \left(P_{con1}^{GOS}(P_{R_i,m}, N) + P_{con2}^{GOS}(P_{R_i,m}, N) \right) \right] \cdot \pi_m \end{aligned} \ . \quad \textbf{(31)}$$

4.2.3 EGOS

In a given state $\vec{s}_m$, the qualified set of relays is Φ_m, and a factor ϕ_m is introduced. If $\Phi_m = \{R_i \mid b_i(j) > \tau\} \neq \varnothing$, then $\phi_m = 1$, there are $|\Phi_m|$ relays that can be selected according to GOS, otherwise $\Phi_m = \{R_i \mid \arg\max b_i(j)\}$, at this time, $\phi_m = 0$ represents the optimal relay R to be selected according to EOS. If the relay participates in the communication, the outage probability is

$$\begin{aligned} P_{con}^{EGOS} &= \phi_m \left(\frac{1}{|\Phi_m|} \sum_i \left(P_{con1}^{GOS}(P_{R_i,m}, |\Phi_m|) + P_{con2}^{GOS}(P_{R_i,m}, |\Phi_m|) \right) \right) \\ &+ (1 - \phi_m) \left(P_{con1}^{EOS}(P_{R,m}) + P_{con2}^{EOS}(P_{R,m}) \right) \end{aligned} . \quad \textbf{(32)}$$

Therefore, the outage probability of the EGOS scheme is

$$P_{COP}^{EGOS} = \sum_{m \in \Omega} P_{con0} \cdot \pi_m + \sum_{m \notin \Omega} P_{con}^{EGOS} \cdot \pi_m \ . \quad \textbf{(33)}$$

4.3 Optimization Problem

For the theoretical analysis of (26), (31) and (33), it can be seen that the COP of EOS and GOS schemes has a minimum value with respect to the power splitting factor ρ, and the COP of the EGOS scheme also has a minimum value with respect to the energy level threshold τ and power splitting factor ρ. Through the simulation results, the above conclusions can be proved. Therefore, this paper constructs the COP minimization problem of three relay selection schemes respectively, which is expressed as follows:

$$\begin{aligned} &\min_{\rho} P_{COP}^{EOS} \\ &s.t. 0 \le \rho \le 1 \end{aligned} . \tag{34}$$

$$\begin{aligned} &\min_{\rho} P_{COP}^{GOS} \\ &s.t. 0 \le \rho \le 1 \end{aligned} . \tag{35}$$

$$\begin{aligned} &\min_{\tau,\rho} P_{COP}^{EGOS} \\ &s.t. 0 \le \tau \le L . \\ &0 \le \rho \le 1 \end{aligned} \tag{36}$$

For EOS and GOS schemes, the minimum COP can be obtained by optimizing the power splitting factor ρ. This paper proposes a one-dimensional search algorithm based on the golden section, represented by Algorithm 1. For the EGOS scheme, due to the need to jointly optimize the energy level threshold τ and the power splitting factor ρ to obtain the minimum COP, this paper uses a two-dimensional search algorithm based on iteration, represented by Algorithm 2. Among them, $\dagger \in \{EOS, GOS, EGOS\}$.

Algorithm 1. One-dimensional search algorithm based on golden section

1: Initialize the maximum iterations $I_{\max}$, $i = 0$, $a = 0$, $b = 1$, $\varepsilon = 10^{-4}$
2: $\rho_1 = a + 0.382*(b-a)$, $\rho_2 = a + 0.618*(b-a)$
3: repeat
4: if $P_{COP}^{\dagger}(\rho_1, \tau) > P_{COP}^{\dagger}(\rho_2, \tau)$
5: $a = \rho_1, \rho_1 = \rho_2, \rho_2 = a + 0.618*(b-a), i{+}{+}$
8: else
9: $b = \rho_2, \rho_2 = \rho_1, \rho_1 = a + 0.382*(b-a), i{+}{+}$
10: end if
11: until $|a-b| < \varepsilon$ or $i > I_{\max}$
12: $\rho^* = \frac{a+b}{2}$, $P_{COP}^{*} = P_{COP}^{\dagger}(\rho^*, \tau)$

Algorithm 2. Two-dimensional search algorithm based on iteration

1: Initialize $P_{COP}^{opt} = 1$
2: for $\tau = 0 : L$
3: Substitute τ into Algorithm 1 to get P_{COP}^{*}, ρ^*
4: if $P_{COP}^{opt} < P_{COP}^{*}$
5: $P_{COP}^{opt} = P_{COP}^{*}$, $\tau^{opt} = \tau$, $\rho^{opt} = \rho^*$
6: end if
7: end for

5 Simulations

In this section, a Monte Carlo simulation experiment is conducted to discuss the influence of different parameters on the outage probability of the adaptive AF/DF transmission strategy under different relay selections. The basic parameters available from [9, 16] are as follows: the number of relays $N = 4$, the upper limit of battery storage capacity $C = 0.001J$, the number of energy levels $L = 6$, the predefined energy level threshold $\tau = 2$, the total length of the time slot $T = 1s$, the energy conversion factor $\eta = 0.5$, the power splitting factor $\rho = 0.7$, transmission rate threshold $R_{th} = 1bps/Hz$, SNR threshold $\gamma_{th}^R = \gamma_{th}^D = 2^{2R_{th}} - 1$, noise power $\sigma_R^2 = \sigma_D^2 = -20dBm$, distance $d_{SD} = 6m$, $d_{SR} = 2m$, $d_{RD} = 4m$, the path loss coefficient $\beta = 2.7$. Assume $SNR = \frac{P_S}{\sigma_R^2}$.

Figure 4 shows the variation of the COP in the three relay selection schemes with the transmit power of the *S*. First of all, the theoretical value and the simulation value are in good agreement, which verifies the correctness of the derivation of the outage probability formula for the three relay selection schemes in this paper. Secondly, it can be seen that under the same parameters, the EGOS scheme is the best scheme among the three schemes. This is because the scheme not only considers energy and sets an energy threshold, thereby effectively reducing the COP, but also considers the channel gain, which further helps to reduce the COP. However, the other two schemes only unilaterally provide limiting conditions for the reduction of COP. Therefore, the EGOS scheme is the optimal scheme.

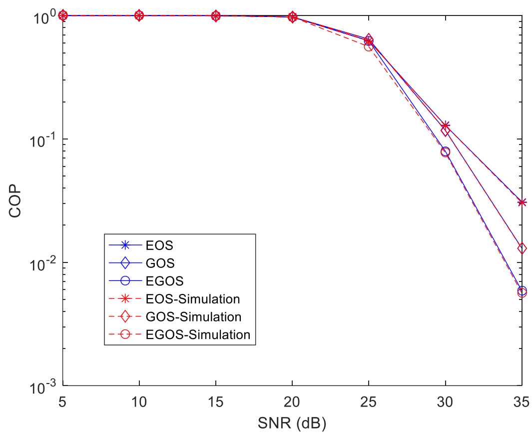

Figure 4. COP versus the transmit power of the *S* in the three relay selection schemes

Figure 5 shows the variation of the COP in the EGOS scheme with the energy level threshold τ. It can be seen that as the τ increases, the COP first decreases and then increases, which means that there is an optimal energy level threshold τ_{opt} in this scheme. This is because as the τ increases, the energy storage status in the energy qualified set $\Phi = \left\{ R_i \mid b_i > \frac{\tau C}{L} \right\}$ is higher, and then the optimal selection of channel gain can effectively reduce the COP. But with the further increase of the energy level threshold τ, the number of nodes in $\Phi = \left\{ R_i \mid b_i > \frac{\tau C}{L} \right\}$ gradually decreases, resulting in the energy qualified set becoming $\Phi_m = \{ R_i \mid \arg\max b_i \}$. At this time, the relay selects only according to the energy storage state without considering the merits of the channel gain, so that the COP increases. Figure

6 shows the variation of the COP with the power splitting factor ρ. It can be seen that the COP first decreases and then increases with the increase of the ρ in the three relay selection schemes, indicating that there is an optimal power splitting factor ρ_{opt} to optimize the outage performance. The above two figures prove that the optimization problems (34), (35), (36) have optimal solutions. And Figure 7 shows that the algorithm proposed in this paper can obtain the optimal COP of the three schemes.

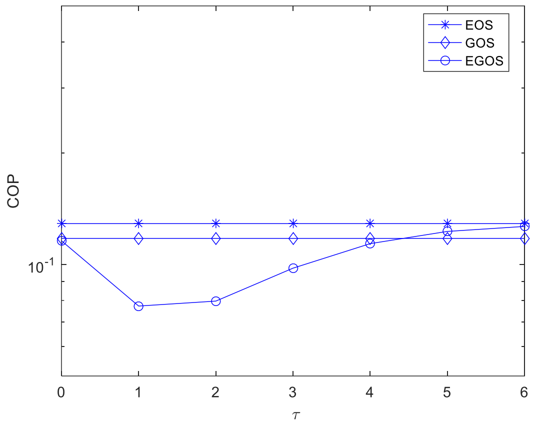

Figure 5. COP versus the energy level threshold τ in the EGOS scheme

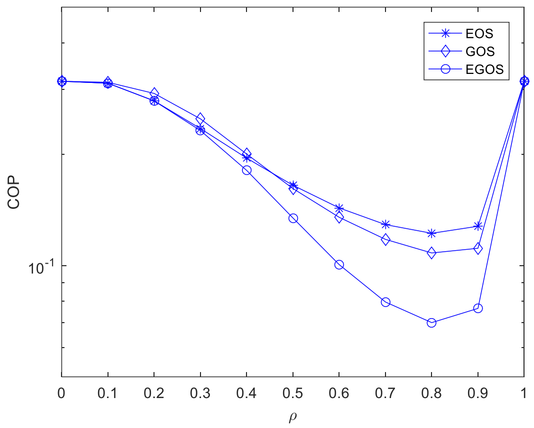

Figure 6. COP versus the power splitting factor ρ in the three relay selection schemes

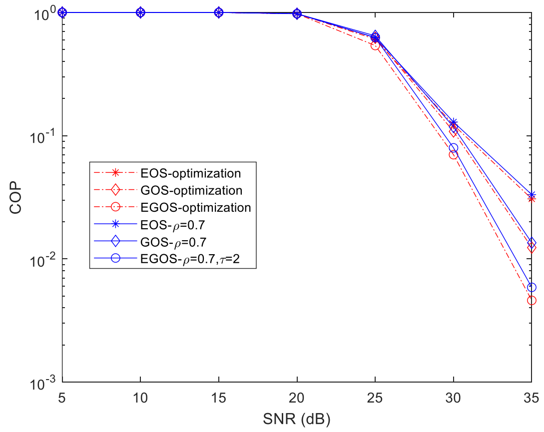

Figure 7. COP after the three relay selection schemes optimization

Figure 8 compares the COP of AF transmission strategy, DF transmission strategy and adaptive AF/DF transmission strategy in the EGOS scheme. It can be seen that the COP of the three transmission strategies all gradually decrease with the increase in the transmit power of the S. This is because its growth not only increases the SNR of the direct link, but also benefits the relay energy harvesting. As a result, the energy stored by the relay increases, thereby reducing the probability that all relays have no energy, and increasing the probability that the relay transmission power P_R is at a larger energy level. In addition, compared with the AF transmission strategy in [8] and the DF transmission strategy in [9], the adaptive AF/DF transmission strategy has superior performance under the condition of high SNR.

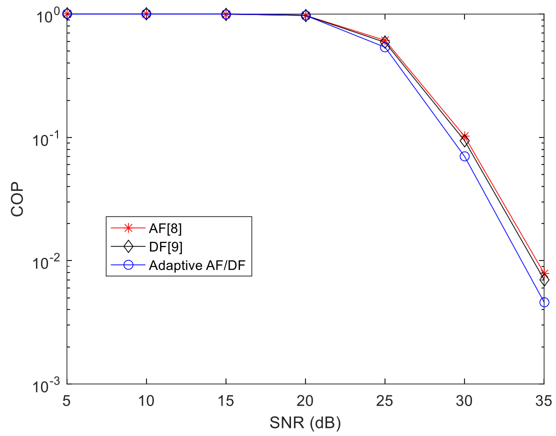

Figure 8. COP versus the transmit power of the S in the three transmission strategies

Figure 9 shows the variation of the COP with the transmission rate threshold R_{th}. It can be seen that as R_{th} increases, the COP increases significantly. This is because the increase in R_{th} will make it more difficult for the SNR obtained under the same conditions to reach the threshold, which will more easily lead to communication outage. In addition, by comparing with the single-relay system in [7], the simulation results prove the superiority of the multi-relay selection system in this paper. The more relays, the lower the probability of being selected for each relay, the more opportunities the relay will have for energy harvesting, so that it will transmit information with greater power and reduce the COP when it is selected.

Figure 10 shows the variation of the COP with the relay location. It can be seen that as the relay is farther from the S, the COP of the GOS scheme gradually increases, while the EOS and EGOS schemes first decrease and then increase. This is because the outage performance of the GOS scheme is completely dependent on the channel gain, regardless of energy, and the closer the relay is to the S, the more energy is harvested, which improves the outage performance. The EOS scheme itself does not consider the influence of channel gain on the outage performance. Although the closer the relay is to the D, the harvested energy decreases, but the channel gain increases. Therefore, when the scheme has sufficient energy, the increase in channel gain will decrease COP. But if the energy is insufficient, even if the channel gain increases, the COP will be improved. The EGOS scheme is a balance between the EOS scheme and the GOS scheme, so it has the characteristics of two schemes. In addition, when the relay is far away from the S, the relay will not be able to carry out cooperative communication due to serious insufficient energy storage. At this time, only the direct link is working, so the results of the three schemes are consistent.

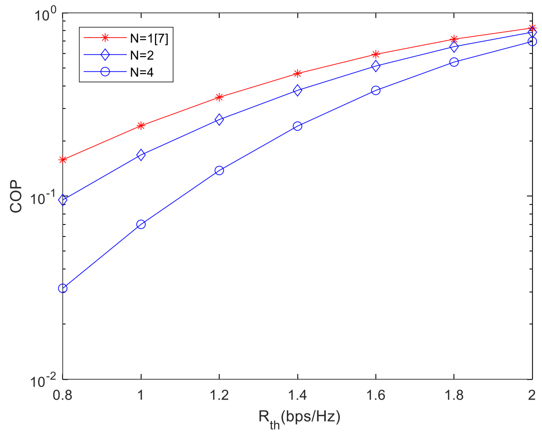

Figure 9. COP versus the transmission rate threshold R_{th}

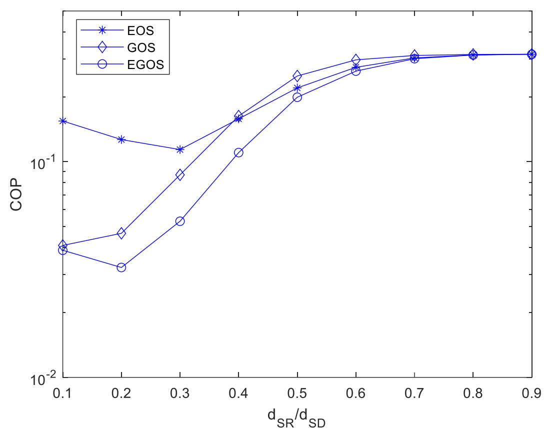

Figure 10. COP versus the relay location

6 Conclusion

For the two-hop half-duplex multi-relay system, this paper proposes three relay selection schemes based on energy storage, namely EOS, GOS, and EGOS. First, the finite state Markov chain and the Gauss Chebyshev formula are used to derive the analytical expressions of the communication outage probability. Then the optimization models for minimizing the communication outage probability of the three relay selection schemes are constructed, and we use a one-dimensional search algorithm based on the golden section and a two-dimensional search algorithm based on iteration to solve these optimization models. The simulation results show that the EGOS is the optimal scheme.

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