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Outage Performance of a Two-branch Cooperative Energy-constrained Relaying Network with Selection Combining at Destination

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Abstract

In this paper, we investigate two-branch cooperative DF relaying networks with selection combining at the destination. Two intermediate relay-clusters (a conventional relay cluster and an energy-constrained relay cluster) are utilized to aid the communication between the source and the destination. We study two cases: direct link (DR) and no direct link (NDR) between the source and the destination. In each case, we consider two relay selection schemes: best sourceâĂŞrelay channel gain (BSR) and random relay selection (RAN). Thus, we have 4 protocols: DR-BSR, DR-RAN, NDR-BSR, and NDR-RAN. For the performance evaluation, we derive a closed-form expression for the outage probability of each of the four protocols. Our analysis is substantiated via a Monte Carlo simulation. As expected, the results show that the DR case outperforms the NDR case, and the BSR scheme outperforms the RAN scheme. The outage performances of the protocols are evaluated based on the system parameters, including the transmit power, the number of relays in each cluster, the energy harvesting efficiency, the position of the two clusters, and the target rate. The outage performance of the system is improved when the transmit power increases, the energy harvesting efficiency increases, the distance between the two clusters and the source and destination decreases, or the target rate decreases. We found good matches between the theoretical and Monte Carlo simulation results, verifying our mathematical analysis.

Keywords: Cooperative communication, Energy harvesting, Decode-and-forward, Power splitting, Selection combining

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1. Introduction

In wireless communication, cooperative diversity is a promising technique used to enhance data rates and reliability, in which a source transmits data to a destination with the help of relays leading to acquire benefits from both relayed communications and space diversity [1]. The concept of cooperative communication was first investigated in [2]. Cooperation expands the coverage area of a cellular system, compared to non-cooperation, as demonstrated in [3]. Two well-known relaying protocols are used in cooperative communication: decode and forward (DF) and amplify and forward (AF). In the AF protocol, the cooperating node or relay node amplifies and forwards the source signal to the destination, whereas in the DF protocol, the signal is decoded at the relay node, and it is then re-encoded and forwarded to the destination. The implementation of the AF protocol is simpler than the DF protocol, but along with the signal, the noise is also amplified and forwarded to the destination. In [4] and [5], the authors derived closed-form expressions for symbol error probability (SEP), bit error rate (BER), achievable spectral efficiency, and outage probability of a dual-hop DF relaying network over a Rayleigh fading channel and a Nakgami-m fading channel, respectively. The analysis of a dual-hop two-way semi-blind AF relay network (partial channel state information (CSI)) was investigated in terms of average sum-rate, outage probability, and average symbol error rate over Rayleigh fading channels [6], Nakagami-m fading channels [7], and generalized-k fading channels [8]. The authors in [9] studied the hybrid AF-DF protocol, in which some relays amplify the received signal and others decode and forward the signal, for mutltihop relaying networks. The authors in [10] investigated the performance of dual-hop DF relaying networks under the joint impact of hardware impairment and co-channel interference.

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Diversity combining is a practical technique to efficiently combine multiple received signals at the destination receiver in both source-destination and relay-destination communication links. Selection combining (SC) and maximal ratio combining (MRC) are two advantageous and popular linear combining schemes [11]-[12]. The MRC scheme achieves full diversity by compiling the signal-to-noise ratios (SNRs) of all received signals, but its implementation requires many multipliers and adders, leading to higher implementation complexity and cost for mobile devices than the SC schemes that choose only the strongest diversity path (the received signal with the highest SNR). The performance of the DF relaying system with selection combining has been widely studied [13]-[17].

Recently, wireless information and power transfer technology has become an attractive solution for prolonging the lifetime of energy-constrained wireless devices by enabling each of them to simultaneously harvest energy and process information from the ambient radio frequency (RF) signals [18]-[21], [27], [28]. Two practical energy harvesting architectures for simultaneous wireless information and power transfer are power-splitting (PS) and time-switching (TS). The PS receiver splits the received signal into two parts according to a power splitting ratio, one part for harvesting the energy and the other one for information processing. The TS receiver harvests energy from the received signal during an initial interval in a time block and then switches to processing the information during the remaining interval of this time block. Several works have investigated the application of energy harvesting techniques in energy-constrained relay nodes in cooperative wireless networks. In [22], the authors evaluated the performance of a dual-hop AF relaying system under both PS and TS architectures in terms of outage probability, throughput, and ergodic capacity. In [23], the authors analyzed the throughput performance of three proposed wireless power transfer policies in two-way energy-constrained AF relaying networks. The performance of an energy-harvesting relaying network with the assistance of multiple relay nodes was studied in [24]. In [25], the authors derived the exact outage probability for a DF energy-harvesting relaying network with N-th best relay selection and considering both PS and TS architectures.

To the best of our knowledge, no study has considered a cooperative system model aided by two groups of relays: conventional relay and energy-constrained relay, and applying diversity combining at the destination. This motivates us to analyze the closed-form outage probability for this model. In this model, we consider the communication between a source and a destination assisted via two groups of DF relays (two relay clusters), in which the first group consists of multiple conventional relay nodes, and the second group includes multiple energy-constrained relay nodes. We also consider the direct source-destination link. Two relay selection schemes, i.e., best source-relay channel gain selection (BSR) and random selection (RAN), are presented in this paper. The best relay in each cluster is selected following the BSR or RAN strategy to help relay the source information to the destination: the best relay in the conventional relay cluster decodes the source signal, re-encodes, and then forwards to the destination; the best relay in the energy-constrained relay cluster harvests the energy, decodes the information from the received signal, and then re-encodes and forwards it to the destination. We present both cases: direct link (DR) and no direct link (NDR) between the source and destination. Therefore, we have four protocols: DR-RAN, DR-BSR, NDR-RAN, and NDR-BSR. At the destination, the selection-combining (SC) technique is utilized to combine three received signals in the DR case, or to combine two received signals in the NDR case. To conduct performance evaluation and comparison, we derive closed-from expressions for the outage probabilities of the four protocols, and we verify these analyses via Monte Carlo simulations.

This paper is arranged as follows. A description of the system model is presented in Section 2. Section 3 presents the operation principles. In Section 4, the closed form expressions for the RAN and BSR schemes in the DR case are derived. The closed-form expressions for the NDR case are presented in Section 5. Numerical and simulation results are discussed in Section 6. Section 7 provides the conclusions for this work.

Notation: The notation $\mathcal{CN}(a,b)$ denotes a circularly symmetric complex Gaussian random variable (RV) with mean a and variance b. $\mathcal{E}\{.\}$ denotes mathematical expectation. The functions $f_X(.)$ and $F_X(.)$ present the probability density function (PDF) and cumulative distribution function (CDF) of RV X. The function $\Gamma(x,y)$ is an incomplete Gamma function [26, Eq. (8.350.2)]. $C_b^a = \frac{b!}{a!(b-a)!}$.

2. System model

As shown in Figure 1, we consider a cooperative two-branch relaying network, which includes a source node S, an energy-constraint relay cluster comprising M nodes R_m $(m = 1, 2, ..., M)$, a conventional relay cluster comprising N nodes R_n $(n = 1, 2, ..., N)$, and a destination node D. Here, there is a direct link available from S to D. Thus, the communication from S to D can occur via three paths: direct transmission, via R_m, and via R_n. In the network, all nodes are equipped with a single antenna operating in half-duplex mode [25]

In Fig. 1, (h_{1m}, d_{1m}), (h_{2n}, d_{2n}), (h_{3m}, d_{3m}), (h_{4n}, d_{4n}), and (h_5, d_5) denote the Rayleigh fading channel coefficients and distances of the links $S - R_m$, $S - R_n$, $R_m - D$, $R_n - D$, and $S - D$, respectively, where

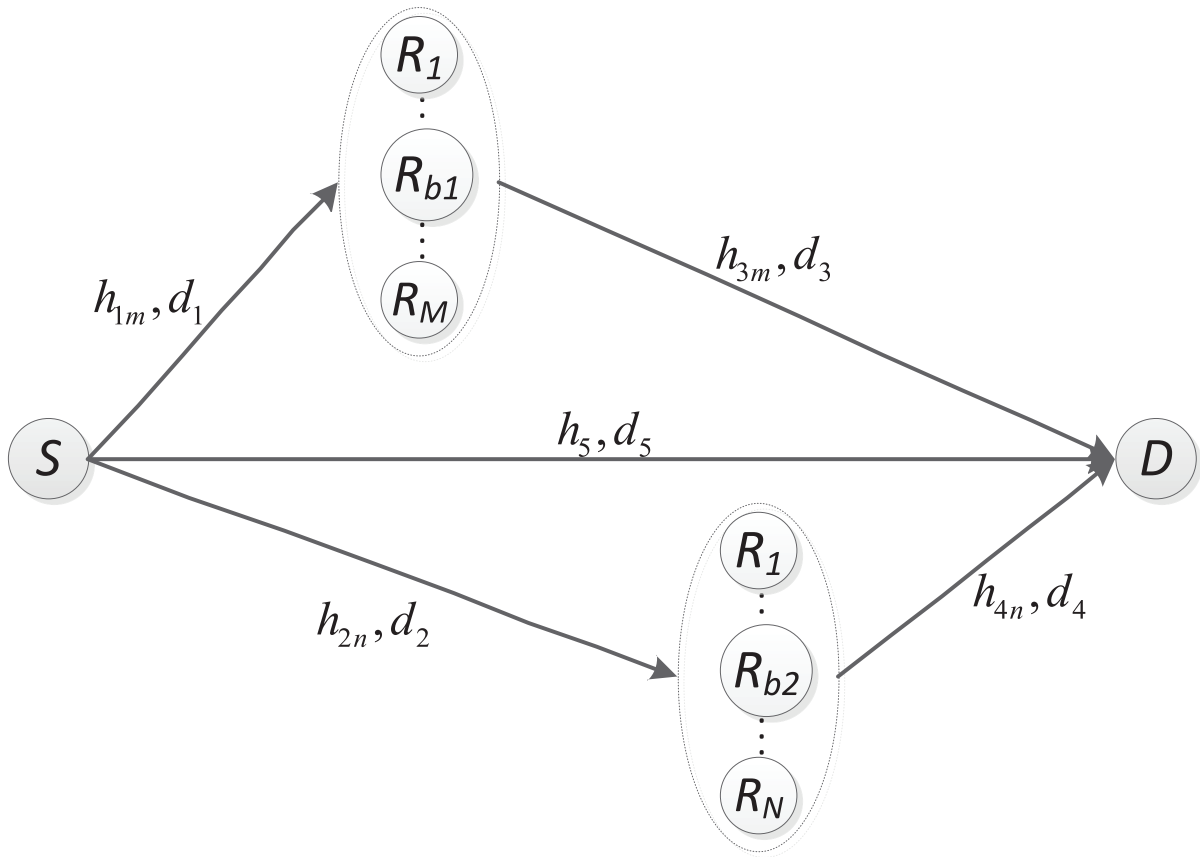

Figure 1. System model

$d_\omega = \frac{\tilde{d}_\omega}{D_\omega}$, $\omega \in \{1m, 2n, 3m, 4n, 5\}$, where $\tilde{d}_\omega$ is the actual distance and D_ω is the reference distance. Thus, the corresponding channel gains $g_\omega = |h_\omega|^2$ are exponential random variables (RVs) with parameter $\lambda_\omega = (d_\omega)^\beta$, where β denotes the path-loss exponent (from 2 to 6). We obtain the corresponding cumulative distribution function (CDF) and probability density function (PDF) as $F_{g_\omega}(x) = 1 - e^{-\lambda_\omega x}$ and $f_{g_\omega}(x) = \lambda_\omega e^{-\lambda_\omega x}$. We note that the distances between two nodes in a cluster are insignificant compared to the distance between a node inside and a node outside a cluster. Thus, we denote $d_{1m} = d_1$, $d_{2n} = d_2$, $d_{3m} = d_3$, and $d_{4n} = d_4$ and then $\lambda_{1m} = \lambda_1$, $\lambda_{2n} = \lambda_2$, $\lambda_{3m} = \lambda_3$, and $\lambda_{4n} = \lambda_4$, where $m = 1, 2, ..., M$ and $n = 1, 2, ..., N$. The best relays in an energy-constraint relay cluster and conventional relay cluster, which are denoted as R_{b1} and R_{b2}, are selected by the destination D, because D can obtain all fading channel coefficients in the setup phase [25].

3. Operation principles

In the first time slot, the source S broadcasts its signal $x(t)$, where $\mathcal{E}\left\{|x(t)|^2 = 1\right\}$, with transmit power P to all relays in the two clusters and destination D. The received radio frequency (RF) signals at all relays and the destination are expressed as follows:

$$y_{1m}(t) = \sqrt{P} h_{1m} x(t) + n_{1m}^a(t) \quad (1)$$

$$y_{2n}(t) = \sqrt{P} h_{2n} x(t) + n_{2n}^a(t) \quad (2)$$

$$y_5(t) = \sqrt{P} h_5 x(t) + n_5^a(t) \quad (3)$$

where $y_{1m}(t)$ and $n_{1m}^a(t)$, $y_{2n}(t)$ and $n_{2n}^a(t)$, and $y_5(t)$ and $n_5^a(t)$ are the received RF signal and additive white Gaussian noise (AWGN) at the m-th relay in the energy-constraint relay cluster, at the n-th relay in the conventional relay cluster, and at the destination D, respectively; $n_{1m}^a, n_{2n}^a, n_5^a \sim \mathcal{CN}(0, N_0)$.

At the energy-constrained relay cluster, the best relay is selected from the M nodes, denoted as R_{b1}, to split the received RF signal $y_{1b}(t) = \sqrt{P}h_{1b}x(t) + n_{1b}^a(t)$ into two components, i.e., one for harvesting the energy $(y_{1b,eh}(t))$ and one for decoding the information $(y_{1b,di}(t))$. These two components are expressed respectively as [25]

$$y_{1b,eh}(t) = \sqrt{\rho} \times y_{1b}(t) = \sqrt{\rho P}h_{1b}x(t) + \sqrt{\rho}n_{1b}^a(t) \quad (4)$$

$$y_{1b,di}(t) = \sqrt{1-\rho} \times y_{1b}(t) = \sqrt{(1-\rho)P} \times h_{1b}x(t) + \sqrt{1-\rho} \times n_{1b}^a(t) \quad (5)$$

where h_{1b} is the Rayleigh fading channel coefficient of the link $S - R_{b1}$, and ρ is the power-splitting ratio, $\rho \in (0, 1)$.

The signal $y_{1b,di}(t)$ is converted to a sampled baseband signal $y_{1b,di}(k)$ [25] as

$$y_{1b,di}(k) = \sqrt{(1-\rho)P} \times h_{1b}x(k) + \sqrt{1-\rho} \times n_{1b}^a(k) + n_{1b}^c(k) \quad (6)$$

where $n_{1b}^c \sim (0, N_0)$ denotes the noise from the converting process.

In the conventional relay cluster, the best relay is selected from the N nodes, denoted as R_{b2}, to receive the RF signal from the source $y_{2b}(t) = \sqrt{P}h_{2b}x(t) + n_{2b}^a(t)$. Similar to (6), the sampled baseband signals at R_{b2} and D, e.g., $y_{2b}(k)$ and $y_5(k)$, are obtained by down converting the received RF as

$$y_{2b}(k) = \sqrt{P}h_{2b}x(k) + n_{2b}^a(k) + n_{2b}^c(k) \quad (7)$$

$$y_5(k) = \sqrt{P}h_5x(k) + n_5^a(k) + n_5^c(k) \quad (8)$$

where h_{2b} is the Rayleigh fading channel coefficient of the link $S - R_{b2}$; $n_{2b}^c, n_5^c \sim \mathcal{CN}(0, N_0)$.

The received SNRs at R_{b1}, R_{b2}, and D in the first time slot can be obtained from three sampled baseband signals in (6), (7), and (8), respectively, as follows:

$$\psi_1 = \frac{(1-\rho)P|h_{1b}|^2}{(2-\rho)N_0} = \omega_1 g_{1b} \quad (9)$$

$$\psi_2 = \frac{P|h_{2b}|^2}{2N_0} = \omega_2 g_{2b} \quad (10)$$

$$\psi_5 = \frac{P|h_5|^2}{2N_0} = \omega_2 g_5 \quad (11)$$

where $\omega_1 \triangleq \frac{(1-\rho)P}{(2-\rho)N_0}$, $\omega_2 \triangleq \frac{P}{2N_0}$.

The harvested energy at R_{1b} can be obtained from the energy harvesting component (4) as

$$E_{1b} = \eta\rho P|h_{1b}|^2 T \quad (12)$$

where η is the energy conversion efficiency, $\eta \in (0, 1)$; T is the time duration for the first time slot.

In the second time slot (duration time T), R_{1b} forwards the source data to the destination D with transmit power P_{1b} obtained from the harvested energy in Eq. 12 as $P_{1b} = E_{1b}/T = \eta\rho P|h_{1b}|^2 = \eta\rho P g_{1b}$. Here, R_{2b} uses its own power, i.e., P, to forward the data. The received sampled baseband signals at D that are converted from the received RF signals transmitted by R_{1b} and R_{2b} are respectively expressed as

$$y_{3b}(k) = \sqrt{P_{1b}}h_{3b}x(k) + n_{3b}^a(k) + n_{3b}^c(k) \quad (13)$$

$$y_{4b}(k) = \sqrt{P}h_{4b}x(k) + n_{4b}^a(k) + n_{4b}^c(k) \quad (14)$$

where h_{3b} and h_{4b}, respectively, are the Rayleigh fading channel coefficients of the links $R_{b1} - D$ and $R_{b2} - D$; $n_{3b}^a, n_{3b}^c, n_{4b}^a, n_{4b}^c \sim CN(0, N_0)$.

The received SNRs of the two links $R_{b1} - D$ and $R_{b2} - D$ can be obtained respectively as

$$\psi_3 = \frac{P_{1b}|h_{3b}|^2}{2N_0} = \omega_3 g_{1b} g_{3b} \quad (15)$$

$$\psi_4 = \frac{P|h_{4b}|^2}{2N_0} = \omega_2 g_{4b} \quad (16)$$

where $\omega_3 \triangleq \frac{\eta\rho P}{2N_0}$.

In this paper, we consider two relay selection methods. One is random relay selection (RAN), in which the two best relays R_{b1} and R_{b2} are randomly selected from the M nodes in the energy-constrained relay cluster and from the N nodes in the conventional relay cluster, respectively. In this scheme, the PDFs of the 5 RVs g_{1b}, g_{2b}, g_{3b}, g_{4b} and g_5 are respectively expressed as $f_{g_{1b}}(x) = \lambda_1 e^{-\lambda_1 x}$, $f_{g_{2b}}(x) = \lambda_2 e^{-\lambda_2 x}$, $f_{g_{3b}}(x) = \lambda_3 e^{-\lambda_3 x}$, $f_{g_{4b}}(x) = \lambda_4 e^{-\lambda_4 x}$, and $f_{g_5}(x) = \lambda_5 e^{-\lambda_5 x}$. And their CDFs are $F_{g_{1b}}(x) = 1 - e^{-\lambda_1 x}$, $F_{g_{2b}}(x) = 1 - e^{-\lambda_2 x}$, $F_{g_{3b}}(x) = 1 - e^{-\lambda_3 x}$, $F_{g_{4b}}(x) = 1 - e^{-\lambda_4 x}$, and $F_{g_5}(x) = 1 - e^{-\lambda_5 x}$.

The other relay selection method is BSR, in which the best relay at each cluster is selected based on maximizing the channel gain between the relays in each cluster and the source, expressed as follows:

$$\begin{cases} R_{b1} = \max\limits_{m=1,2,\dots,M} |h_{1m}|^2 = \max\limits_{m=1,2,\dots,M} g_{1m} \\ R_{b2} = \max\limits_{n=1,2,\dots,N} |h_{2n}|^2 = \max\limits_{n=1,2,\dots,N} g_{2n} \end{cases} \quad (17)$$

In the BSR scheme, the PDFs and CDFs of the two RVs g_{1b} and g_{2b} are changed and expressed as $f_{g_{1b}}(x) = M\lambda_1 \sum\limits_{m=0}^{M-1} C_{M-1}^m (-1)^m e^{-(m+1)\lambda_1 x}$, $F_{g_{1b}}(x) = \left(1 - e^{-\lambda_1 x}\right)^M$, $f_{g_{2b}}(x) = N\lambda_2 \sum\limits_{n=0}^{N-1} C_{N-1}^n (-1)^n e^{-(n+1)\lambda_2 x}$, $F_{g_{2b}}(x) = \left(1 - e^{-\lambda_2 x}\right)^N$.

4. Performance evaluation

In this section, we derive the closed-form expressions of the outage probabilities for the two considered relay selection schemes. Diversity selection combining is used at the destination D; thus, the outage probability expression can be formulated as

$$\begin{aligned} P_{out} = & \underbrace{\Pr\left[\psi_1<\psi_t,\psi_2<\psi_t,\psi_5<\psi_t\right]}_{\Pr 1} \\ & +\underbrace{\Pr\left[\psi_1\ge\psi_t,\psi_2<\psi_t,max\left(\psi_3,\psi_5\right)<\psi_t\right]}_{\Pr 2} \\ & +\underbrace{\Pr\left[\psi_1<\psi_t,\psi_2\ge\psi_t,max\left(\psi_4,\psi_5\right)<\psi_t\right]}_{\Pr 3} \\ & +\underbrace{\Pr\left[\psi_1\ge\psi_t,\psi_2\ge\psi_t,max\left(\psi_3,\psi_4,\psi_5\right)<\psi_t\right]}_{\Pr 4} \end{aligned} \quad (18)$$

First, the term Pr 1 in Eq. 18 can be rewritten as

$$\begin{aligned} \Pr 1 &= \Pr\left[g_{1b}<\frac{\psi_t}{\omega_1},g_{2b}<\frac{\psi_t}{\omega_2},g_5<\frac{\psi_t}{\omega_2}\right] \\ &= F_{g_{1b}}\left(\frac{\psi_t}{\omega_1}\right)F_{g_{2b}}\left(\frac{\psi_t}{\omega_2}\right)F_{g_5}\left(\frac{\psi_t}{\omega_2}\right) \end{aligned} \quad (19)$$

By using the PDF of the RVs g_{1b}, g_{2b}, and g_5 for the two relay selection schemes RAN and BSR, we obtain term Pr 1 for each scheme, as follows:

$$\Pr 1_{\text{RAN}} = \left(1-e^{-\frac{\lambda_1\psi_t}{\omega_1}}\right)\left(1-e^{-\frac{\lambda_2\psi_t}{\omega_2}}\right)\left(1-e^{-\frac{\lambda_5\psi_t}{\omega_2}}\right) \quad (20)$$

$$\Pr 1_{\text{BSR}} = \left(1-e^{-\frac{\lambda_1\psi_t}{\omega_1}}\right)^M\left(1-e^{-\frac{\lambda_2\psi_t}{\omega_2}}\right)^N\left(1-e^{-\frac{\lambda_5\psi_t}{\omega_2}}\right) \quad (21)$$

Second, we calculate the term Pr 2 in Eq. 18 as

$$\begin{aligned} \Pr 2 &= \Pr\left[g_{1b}\ge\frac{\psi_t}{\omega_1},g_{2b}<\frac{\psi_t}{\omega_2},max\left(\omega_3g_{1b}g_{3b},\omega_2g_5\right)<\psi_t\right] \\ &= F_{g_{2b}}\left(\frac{\psi_t}{\omega_2}\right)\left\{\begin{array}{l}\underbrace{\Pr\left[g_{1b}\ge\frac{\psi_t}{\omega_1},\omega_3g_{1b}g_{3b}<\psi_t,\omega_3g_{1b}g_{3b}>\omega_2g_5\right]}_{\Pr 2.1} \\ +\underbrace{\Pr\left[g_{1b}\ge\frac{\psi_t}{\omega_1},\omega_2g_5<\psi_t,\omega_3g_{1b}g_{3b}<\omega_2g_5\right]}_{\Pr 2.2}\end{array}\right\} \end{aligned} \quad (22)$$

The terms Pr 2.1 and Pr 2.2 are expressed as

$$\Pr 2.1 = \int_{\frac{\psi_t}{\omega_1}}^{\infty} f_{g_{1b}}\left(x_1\right)\int_0^{\frac{\psi_t}{\omega_3x_1}} f_{g_{3b}}\left(x_3\right)\int_0^{\frac{\omega_3}{\omega_2}x_1x_3} f_{g_5}\left(x_5\right)dx_5dx_3dx_1 \quad (23)$$

$$\begin{aligned} \Pr 2.2 &= \Pr\left[g_{1b}\ge\frac{\psi_t}{\omega_1},g_5<\frac{\psi_t}{\omega_2},g_{3b}<\frac{\omega_2g_5}{\omega_3g_{1b}}\right] \\ &= \int_{\frac{\psi_t}{\omega_1}}^{\infty} f_{g_{1b}}\left(x_1\right)\int_0^{\frac{\psi_t}{\omega_2}} f_{g_5}\left(x_5\right)\int_0^{\frac{\omega_2x_5}{\omega_3x_1}} f_{g_{3b}}\left(x_3\right)dx_3dx_5dx_1 \end{aligned} \quad (24)$$

Using the PDFs of the three RVs g_{1b}, g_{3b} and g_5 for the RAN and BSR schemes, we obtain

$$\begin{aligned} \Pr 2.1_{\text{RAN}} &= \int_{\frac{\psi_t}{\omega_1}}^{\infty}\lambda_1e^{-\lambda_1x_1}\int_0^{\frac{\psi_t}{\omega_3x_1}}\lambda_3e^{-\lambda_3x_3}dx_3dx_1 \\ &- \int_{\frac{\psi_t}{\omega_1}}^{\infty}\lambda_1e^{-\lambda_1x_1}\int_0^{\frac{\psi_t}{\omega_3x_1}}\lambda_3e^{-\left(\lambda_3+\frac{\lambda_5\omega_3}{\omega_2}x_1\right)x_3}dx_3dx_1 \\ &= \lambda_1\Omega_1\left(\lambda_1,\frac{\lambda_3\psi_t}{\omega_3},\frac{\psi_t}{\omega_1}\right)-\lambda_1\lambda_3\frac{\omega_2}{\lambda_5\omega_3}\Omega_2\left(\lambda_1,\frac{\lambda_5\psi_t}{\omega_2},\frac{\lambda_3\psi_t}{\omega_3},\frac{\lambda_3\omega_2}{\lambda_5\omega_3},\frac{\psi_t}{\omega_1}\right) \end{aligned} \quad (25)$$

$$\begin{aligned} \Pr 2.1_{\text{BSR}} &= M\lambda_1\sum_{m=0}^{M-1}C_{M-1}^m(-1)^m \\ &\left[\begin{array}{l}\int_{\frac{\psi_t}{\omega_1}}^{\infty}e^{-(m+1)\lambda_1x}\int_0^{\frac{\psi_t}{\omega_3x_1}}\lambda_3e^{-\lambda_3x_3}dx_3dx_1 \\ -\int_{\frac{\psi_t}{\omega_1}}^{\infty}e^{-(m+1)\lambda_1x}\int_0^{\frac{\psi_t}{\omega_3x_1}}\lambda_3e^{-\left(\lambda_3+\frac{\lambda_5\omega_3}{\omega_2}x_1\right)x_3}dx_3dx_1\end{array}\right] \\ &= M\lambda_1\sum_{m=0}^{M-1}C_{M-1}^m(-1)^m \\ &\left[\begin{array}{l}\Omega_1\left(\left(m+1\right)\lambda_1,\frac{\lambda_3\psi_t}{\omega_3},\frac{\psi_t}{\omega_1}\right) \\ -\lambda_3\frac{\omega_2}{\lambda_5\omega_3}\Omega_2\left(\left(m+1\right)\lambda_1,\frac{\lambda_5\psi_t}{\omega_2},\frac{\lambda_3\psi_t}{\omega_3},\frac{\lambda_3\omega_2}{\lambda_5\omega_3},\frac{\psi_t}{\omega_1}\right)\end{array}\right] \end{aligned} \quad (26)$$

$$\begin{aligned} \Pr 2.2_{\text{RAN}} &= \int_{\frac{\psi_t}{\omega_1}}^{\infty}\lambda_1e^{-\lambda_1x_1}\int_0^{\frac{\psi_t}{\omega_2}}\lambda_5\left(e^{-\lambda_5x_5}-e^{-\left(\lambda_5+\frac{\lambda_3\omega_2}{\omega_3x_1}\right)x_5}\right)dx_3dx_1 \\ &= \left(1-e^{-\frac{\lambda_5\psi_t}{\omega_2}}\right)e^{-\frac{\lambda_1\psi_t}{\omega_1}}-\lambda_1\Omega_3\left(\lambda_1,\frac{\lambda_5\psi_t}{\omega_2},\frac{\lambda_3\psi_t}{\omega_3},\frac{\lambda_3\omega_2}{\lambda_5\omega_3},\frac{\psi_t}{\omega_1}\right) \end{aligned} \quad (27)$$

$$\begin{aligned} \Pr 2.2_{\text{BSR}} &= M\lambda_1\sum_{m=0}^{M-1}C_{M-1}^m(-1)^m \\ &\int_{\frac{\psi_t}{\omega_1}}^{\infty}e^{-(m+1)\lambda_1x}\int_0^{\frac{\psi_t}{\omega_2}}\lambda_5\left(e^{-\lambda_5x_5}-e^{-\left(\lambda_5+\frac{\lambda_3\omega_2}{\omega_3x_1}\right)x_5}\right)dx_3dx_1 \\ &= M\sum_{m=0}^{M-1}C_{M-1}^m(-1)^m\left\{\begin{array}{l}\left(1-e^{-\frac{\lambda_5\psi_t}{\omega_2}}\right)\frac{e^{-\frac{(m+1)\lambda_1\psi_t}{\omega_1}}}{m+1} \\ -\lambda_1\Omega_3\left(\left(m+1\right)\lambda_1,\frac{\lambda_5\psi_t}{\omega_2},\frac{\lambda_3\psi_t}{\omega_3},\frac{\lambda_3\omega_2}{\lambda_5\omega_3},\frac{\psi_t}{\omega_1}\right)\end{array}\right\} \end{aligned} \quad (28)$$

where $\Omega_1\left(\varphi_1,\varphi_2,\varphi_3\right) = -\sum_{p=1}^{\infty}\frac{(-\varphi_2)^p}{p!}{\varphi_1}^{p-1}\Gamma\left(1-p,\varphi_1\varphi_3\right)$ (see **Appendix A**),

$\Omega_2\left(\varphi_1,\varphi_2,\varphi_3,\varphi_4,\varphi_5\right) = \left(1-e^{-\varphi_2}\right)e^{\varphi_1\varphi_4}\Gamma\left(0,\varphi_1\left(\varphi_5+\varphi_4\right)\right)$
$-e^{-\varphi_2}\sum_{q=1}^{\infty}\frac{(-\varphi_3)^q}{q!}\left[\begin{array}{l}\sum_{l=1}^{1}\theta_{l,q}{\varphi_1}^{l-1}\Gamma\left(1-l,\varphi_1\varphi_5\right) \\ +\vartheta_qe^{\varphi_1\varphi_4}\Gamma\left(0,\varphi_1\left(\varphi_5+\varphi_4\right)\right)\end{array}\right]$
(see **Appendix B**),

$\Omega_3\left(\varphi_1,\varphi_2,\varphi_3,\varphi_4,\varphi_5\right) = \left(1-e^{-\varphi_2}\right)\varphi_4e^{\varphi_1\varphi_4}\Gamma\left(-1,\varphi_1\varphi_4\right)+$
$e^{-\varphi_2}\varphi_3e^{\varphi_1\varphi_4}\Gamma\left(0,\varphi_1\left(\varphi_5+\varphi_4\right)\right)-$

$$e^{-\varphi_2}\sum_{t=1}^{\infty}\frac{(-\varphi_3)^{t+1}}{(t+1)!}\left[\begin{array}{l}\sum\limits_{l=1}^{t}\theta_{l,t}{\varphi_1}^{l-1}\Gamma(1-l,\varphi_1\varphi_5)\\ +\vartheta_t e^{\varphi_1\varphi_4}\Gamma(0,\varphi_1(\varphi_5+\varphi_4))\end{array}\right]$$

(see **Appendix C**).

Then, we can obtain the term Pr 2 for the RAN and BSR schemes by substituting Eqs. 25-28 into 22:

$$\Pr 2_{\mathrm{RAN}} = \left(1-e^{-\frac{\lambda_2\psi_t}{\omega_2}}\right)\{\Pr 2.1_{\mathrm{RAN}}+\Pr 2.2_{\mathrm{RAN}}\} \quad (29)$$

$$\Pr 2_{\mathrm{BSR}} = \left(1-e^{-\frac{\lambda_2\psi_t}{\omega_2}}\right)^{N}\{\Pr 2.1_{\mathrm{BSR}}+\Pr 2.2_{\mathrm{BSR}}\} \quad (30)$$

Third, we calculate the term Pr 3 in Eq. 18 as

$$\begin{aligned}\Pr 3 &= \Pr[\psi_2\ge\psi_t]\Pr[\psi_1<\psi_t]\Pr[max(\psi_4,\psi_5)<\psi_t]\\ &= \Pr\left[g_{2b}\ge\frac{\psi_t}{\omega_2}\right]\Pr\left[g_{1b}<\frac{\psi_t}{\omega_1}\right]\left\{\begin{array}{l}\underbrace{\Pr[\omega_2 g_{4b}<\psi_t, g_{4b}>g_5]}_{\Pr 3.1}\\ +\underbrace{\Pr[\omega_2 g_5<\psi_t, g_{4b}<g_5]}_{\Pr 3.2}\end{array}\right\}\end{aligned} \quad (31)$$

Because the PDFs of the RVs g_{4b} and g_5 in the two schemes RAN and BSR are the same, e.g., $F_{g_{4b},\mathrm{RAN}}(x) = F_{g_{4b},\mathrm{BSR}}(x) = 1-e^{-\lambda_4 x}$ and $f_{g_5,\mathrm{RAN}}(x) = f_{g_5,BSR}(x) = 1-e^{-\lambda_5 x}$, we obtain:

$$\begin{aligned}\Pr 3.1_{\mathrm{RAN}} = \Pr 3.1_{\mathrm{BSR}} &= \int_0^{\frac{\psi_t}{\omega_2}} f_{g_{4b}}(x_4)\int_0^{x_4} f_{g_5}(x_5)dx_5dx_4\\ &= \left(1-e^{-\frac{\lambda_4\psi_t}{\omega_2}}\right)-\frac{\lambda_4}{\lambda_4+\lambda_5}\left(1-e^{-\frac{(\lambda_4+\lambda_5)\psi_t}{\omega_2}}\right)\end{aligned} \quad (32)$$

$$\begin{aligned}&\Pr 3.2_{\mathrm{RAN}} = \Pr 3.2_{\mathrm{BSR}}\\ &= \left(1-e^{-\frac{\lambda_5\psi_t}{\omega_2}}\right)-\frac{\lambda_5}{\lambda_4+\lambda_5}\left(1-e^{-\frac{(\lambda_4+\lambda_5)\psi_t}{\omega_2}}\right)\end{aligned} \quad (33)$$

By substituting Eqs 32 and 33 into 31, we obtain the term Pr 3 for the two relay selection schemes:

$$\Pr 3_{\mathrm{RAN}} = \left(1-e^{-\frac{\lambda_1\psi_t}{\omega_1}}\right)e^{-\frac{\lambda_2\psi_t}{\omega_2}}\left\{1-e^{-\frac{\lambda_4\psi_t}{\omega_2}}-e^{-\frac{\lambda_5\psi_t}{\omega_2}}+e^{-\frac{(\lambda_4+\lambda_5)\psi_t}{\omega_2}}\right\} \quad (34)$$

$$\begin{aligned}\Pr 3_{\mathrm{BSR}} = &\left(1-e^{-\frac{\lambda_1\psi_t}{\omega_1}}\right)^{M}\left[1-\left(1-e^{-\frac{\lambda_2\psi_t}{\omega_2}}\right)^{N}\right]\\ &\left\{1-e^{-\frac{\lambda_4\psi_t}{\omega_2}}-e^{-\frac{\lambda_5\psi_t}{\omega_2}}+e^{-\frac{(\lambda_4+\lambda_5)\psi_t}{\omega_2}}\right\}\end{aligned} \quad (35)$$

Fourth, we calculate the term Pr 4 in Eq. 18 as

$$\begin{aligned}\Pr 4 &= \Pr\left[\begin{array}{l}\omega_1 g_{1b}\ge\psi_t, \omega_2 g_{2b}\ge\psi_t,\\ max(\omega_3 g_{1b}g_{3b}, \omega_2 g_{4b}, \omega_2 g_5)<\psi_t\end{array}\right]\\
&= \left[1-F_{g_{2b}}\left(\frac{\psi_t}{\omega_2}\right)\right]\left\{\begin{array}{l}\Pr\left[\begin{array}{l}\omega_1 g_{1b}\ge\psi_t, \omega_3 g_{1b}g_{3b}<\psi_t,\\ \omega_3 g_{1b}g_{3b}\ge\omega_2 g_{4b}, g_{4b}\ge g_5\end{array}\right]\\
+\Pr\left[\begin{array}{l}\omega_1 g_{1b}\ge\psi_t, \omega_2 g_{4b}<\psi_t,\\ \omega_3 g_{1b}g_{3b}<\omega_2 g_{4b}, g_{4b}\ge g_5\end{array}\right]\\
+\Pr\left[\begin{array}{l}\omega_1 g_{1b}\ge\psi_t, \omega_3 g_{1b}g_{3b}<\psi_t,\\ \omega_3 g_{1b}g_{3b}\ge\omega_2 g_5, g_{4b}<g_5\end{array}\right]\\
+\Pr\left[\begin{array}{l}\omega_1 g_{1b}\ge\psi_t, \omega_2 g_5<\psi_t,\\ \omega_3 g_{1b}g_{3b}<\omega_2 g_5, g_{4b}<g_5\end{array}\right]\end{array}\right\}\\
&= \left[1-F_{g_{2b}}\left(\frac{\psi_t}{\omega_2}\right)\right]\left\{\begin{array}{l}\underbrace{\Pr\left[\begin{array}{l}g_{1b}\ge\frac{\psi_t}{\omega_1}, g_{3b}<\frac{\psi_t}{\omega_3 g_{1b}},\\ \frac{\omega_3 g_{1b}g_{3b}}{\omega_2}\ge g_{4b}, g_{4b}\ge g_5\end{array}\right]}_{\Pr 4.1}\\
+\underbrace{\Pr\left[\begin{array}{l}g_{1b}\ge\frac{\psi_t}{\omega_1}, g_4<\frac{\psi_t}{\omega_2},\\ g_{3b}<\frac{\omega_2}{\omega_3}\frac{g_{4b}}{g_{1b}}, g_{4b}\ge g_5\end{array}\right]}_{\Pr 4.2}\\
+\underbrace{\Pr\left[\begin{array}{l}g_{1b}\ge\frac{\psi_t}{\omega_1}, g_{3b}<\frac{\psi_t}{\omega_3 g_{1b}},\\ \frac{\omega_3 g_{1b}g_{3b}}{\omega_2}\ge g_5, g_{4b}<g_5\end{array}\right]}_{\Pr 4.3}\\
+\underbrace{\Pr\left[\begin{array}{l}g_{1b}\ge\frac{\psi_t}{\omega_1}, g_5<\frac{\psi_t}{\omega_2},\\ g_{3b}<\frac{\omega_2}{\omega_3}\frac{g_5}{g_{1b}}, g_{4b}<g_5\end{array}\right]}_{\Pr 4.4}\end{array}\right\}\end{aligned} \quad (36)$$

The terms Pr 4.1 and Pr 4.2 in Eq. (36) can be expressed in the multiple integrals form, as follows:

$$\begin{aligned}\Pr 4.1 = &\int_{\frac{\psi_t}{\omega_1}}^{\infty} f_{g_{1b}}(x_1)\int_0^{\frac{\psi_t}{\omega_3 x_1}} f_{g_{3b}}(x_3)\int_0^{\frac{\omega_3 x_1 x_3}{\omega_2}} f_{g_{4b}}(x_4)\\ &\int_0^{x_4} f_{g_5}(x_5)dx_5dx_4dx_3dx_1\end{aligned} \quad (37)$$

$$\begin{aligned}\Pr 4.2 = &\int_{\frac{\psi_t}{\omega_1}}^{\infty} f_{g_{1b}}(x_1)\int_0^{\frac{\psi_t}{\omega_2}} f_{g_{4b}}(x_4)\int_0^{\frac{\omega_2}{\omega_3}\frac{x_4}{x_1}} f_{g_{3b}}(x_3)\\ &\int_0^{x_4} f_{g_5}(x_5)dx_5dx_3dx_4dx_1\end{aligned} \quad (38)$$

By applying the PDFs for the four RVs g_{1b}, g_{3b}, g_{4b}, and g_5 for the two schemes RAN and BSRs into Eqs. 37 and

38, we obtain:

$$\begin{aligned}
\Pr 4.1_{\text{RAN}} &= \int_{\frac{\psi_t}{\omega_1}}^{\infty} \lambda_1 e^{-\lambda_1 x_1} \int_{0}^{\frac{\psi_t}{\omega_3 x_1}} \lambda_3 e^{-\lambda_3 x_3} \\
&\left[\left(1 - e^{-\frac{\lambda_4 \omega_3 x_1 x_3}{\omega_2}}\right) - \frac{\lambda_4}{\lambda_4+\lambda_5}\left(1 - e^{-\frac{(\lambda_4+\lambda_5)\omega_3 x_1 x_3}{\omega_2}}\right)\right] dx_3 dx_1 \\
&= \left(1 - \frac{\lambda_4}{\lambda_4+\lambda_5}\right) \int_{\frac{\psi_t}{\omega_1}}^{\infty} \lambda_1 e^{-\lambda_1 x_1} \int_{0}^{\frac{\psi_t}{\omega_3 x_1}} \lambda_3 e^{-\lambda_3 x_3} dx_3 dx_1 \\
&- \int_{\frac{\psi_t}{\omega_1}}^{\infty} \lambda_1 e^{-\lambda_1 x_1} \int_{0}^{\frac{\psi_t}{\omega_3 x_1}} \lambda_3 e^{-\lambda_3 x_3} e^{-\frac{\lambda_4 \omega_3 x_1 x_3}{\omega_2}} dx_3 dx_1 \\
&+ \frac{\lambda_4}{\lambda_4+\lambda_5} \int_{\frac{\psi_t}{\omega_1}}^{\infty} \lambda_1 e^{-\lambda_1 x_1} \int_{0}^{\frac{\psi_t}{\omega_3 x_1}} \lambda_3 e^{-\lambda_3 x_3} e^{-\frac{(\lambda_4+\lambda_5)\omega_3 x_1 x_3}{\omega_2}} dx_3 dx_1 \\
&= \lambda_1 \left(1 - \frac{\lambda_4}{\lambda_4+\lambda_5}\right) \Omega_1\left(\lambda_1, \frac{\lambda_3 \psi_t}{\omega_3}, \frac{\psi_t}{\omega_1}\right) \\
&- \lambda_1 \lambda_3 \frac{\omega_2}{\lambda_4 \omega_3} \Omega_2\left(\lambda_1, \frac{\lambda_4 \psi_t}{\omega_2}, \frac{\lambda_3 \psi_t}{\omega_3}, \frac{\lambda_3 \omega_2}{\lambda_4 \omega_3}, \frac{\psi_t}{\omega_1}\right) \\
&+ \lambda_1 \lambda_3 \frac{\lambda_4}{\lambda_4+\lambda_5} \frac{\omega_2}{(\lambda_4+\lambda_5)\omega_3} \Omega_2\left(\lambda_1, \frac{(\lambda_4+\lambda_5)\psi_t}{\omega_2}, \frac{\lambda_3 \psi_t}{\omega_3}, \frac{\lambda_3 \omega_2}{(\lambda_4+\lambda_5)\omega_3}, \frac{\psi_t}{\omega_1}\right)
\end{aligned} \tag{39}$$

$$\begin{aligned}
\Pr 4.1_{\text{BSR}} &= M \lambda_1 \sum_{m=0}^{M-1} C_{M-1}^{m} (-1)^m \int_{\frac{\psi_t}{\omega_1}}^{\infty} e^{-(m+1)\lambda_1 x_1} \\
&\int_{0}^{\frac{\psi_t}{\omega_3 x_1}} \lambda_3 e^{-\lambda_3 x_3} \left[\begin{array}{l} \left(1 - e^{-\frac{\lambda_4 \omega_3 x_1 x_3}{\omega_2}}\right) \\ -\frac{\lambda_4}{\lambda_4+\lambda_5}\left(1 - e^{-\frac{(\lambda_4+\lambda_5)\omega_3 x_1 x_3}{\omega_2}}\right) \end{array}\right] dx_3 dx_1 \\
&= M \lambda_1 \left(1 - \frac{\lambda_4}{\lambda_4+\lambda_5}\right) \sum_{m=0}^{M-1} C_{M-1}^{m} (-1)^m \Omega_1\left((m+1)\lambda_1, \frac{\lambda_3 \psi_t}{\omega_3}, \frac{\psi_t}{\omega_1}\right) \\
&+ \frac{M \lambda_1 \lambda_3 \lambda_4 \omega_2}{(\lambda_4+\lambda_5)^2 \omega_3} \sum_{m=0}^{M-1} C_{M-1}^{m} (-1)^m \\
&\Omega_2\left((m+1)\lambda_1, \frac{(\lambda_4+\lambda_5)\psi_t}{\omega_2}, \frac{\lambda_3 \psi_t}{\omega_3}, \frac{\lambda_3 \omega_2}{(\lambda_4+\lambda_5)\omega_3}, \frac{\psi_t}{\omega_1}\right)
\end{aligned} \tag{40}$$

$$\begin{aligned}
\Pr 4.2_{\text{RAN}} &= \int_{\frac{\psi_t}{\omega_1}}^{\infty} \lambda_1 e^{-\lambda_1 x_1} \int_{0}^{\frac{\psi_t}{\omega_2}} \lambda_4 e^{-\lambda_4 x_4} \\
&\left(1 - e^{-\lambda_5 x_4}\right)\left(1 - e^{-\frac{\lambda_3 \omega_2}{\omega_3} \frac{x_4}{x_1}}\right) dx_4 dx_1 \\
&= e^{-\frac{\lambda_1 \psi_t}{\omega_1}}\left(1 - e^{-\frac{\lambda_4 \psi_t}{\omega_2}}\right) - \frac{\lambda_4}{\lambda_4+\lambda_5} e^{-\frac{\lambda_1 \psi_t}{\omega_1}}\left(1 - e^{-\frac{(\lambda_4+\lambda_5)\psi_t}{\omega_2}}\right) \\
&- \lambda_4 \lambda_1 \int_{\frac{\psi_t}{\omega_1}}^{\infty} e^{-\lambda_1 x_1} \frac{\left[1 - e^{-\left(\frac{\lambda_4 \psi_t}{\omega_2} + \frac{\lambda_3 \psi_t}{\omega_3 x_1}\right)}\right]}{\lambda_4 + \frac{\lambda_3 \omega_2}{\omega_3 x_1}} dx_1 \\
&+ \lambda_4 \lambda_1 \int_{\frac{\psi_t}{\omega_1}}^{\infty} e^{-\lambda_1 x_1} \frac{\left[1 - e^{-\left(\frac{(\lambda_4+\lambda_5)\psi_t}{\omega_2} + \frac{\lambda_3 \psi_t}{\omega_3 x_1}\right)}\right]}{\lambda_4 + \lambda_5 + \frac{\lambda_3 \omega_2}{\omega_3 x_1}} dx_1 \\
&= e^{-\frac{\lambda_1 \psi_t}{\omega_1}}\left(1 - e^{-\frac{\lambda_4 \psi_t}{\omega_2}}\right) - \frac{\lambda_4}{\lambda_4+\lambda_5} e^{-\frac{\lambda_1 \psi_t}{\omega_1}}\left(1 - e^{-\frac{(\lambda_4+\lambda_5)\psi_t}{\omega_2}}\right) \\
&- \lambda_1 \Omega_3\left(\lambda_1, \frac{\lambda_4 \psi_t}{\omega_2}, \frac{\lambda_3 \psi_t}{\omega_3}, \frac{\lambda_3 \omega_2}{\lambda_4 \omega_3}, \frac{\psi_t}{\omega_1}\right) \\
&+ \frac{\lambda_4 \lambda_1}{(\lambda_4+\lambda_5)} \Omega_3\left(\lambda_1, \frac{(\lambda_4+\lambda_5)\psi_t}{\omega_2}, \frac{\lambda_3 \psi_t}{\omega_3}, \frac{\lambda_3 \omega_2}{(\lambda_4+\lambda_5)\omega_3}, \frac{\psi_t}{\omega_1}\right)
\end{aligned} \tag{41}$$

$$\Pr 4.2_{\text{BSR}} = M \sum_{m=0}^{M-1} C_{M-1}^{m} (-1)^m \left\{\begin{array}{l}
\frac{e^{-\frac{(m+1)\lambda_1 \psi_t}{\omega_1}}}{m+1}\left(1 - e^{-\frac{\lambda_4 \psi_t}{\omega_2}}\right) \\
-\frac{e^{-\frac{(m+1)\lambda_1 \psi_t}{\omega_1}}}{m+1} \frac{\lambda_4}{\lambda_4+\lambda_5}\left(1 - e^{-\frac{(\lambda_4+\lambda_5)\psi_t}{\omega_2}}\right) \\
-\lambda_1 \Omega_3\left((m+1)\lambda_1, \frac{\lambda_4 \psi_t}{\omega_2}, \frac{\lambda_3 \psi_t}{\omega_3}, \frac{\lambda_3 \omega_2}{\lambda_4 \omega_3}, \frac{\psi_t}{\omega_1}\right) \\
+\frac{\lambda_4 \lambda_1}{(\lambda_4+\lambda_5)} \Omega_3\left((m+1)\lambda_1, \frac{(\lambda_4+\lambda_5)\psi_t}{\omega_2}, \frac{\lambda_3 \psi_t}{\omega_3}, \frac{\lambda_3 \omega_2}{(\lambda_4+\lambda_5)\omega_3}, \frac{\psi_t}{\omega_1}\right)
\end{array}\right\} \tag{42}$$

In Eq. 36, we see that the terms $\Pr 4.3$ and $\Pr 4.4$ can be derived from $\Pr 4.1$ and $\Pr 4.2$, respectively, by replacing the RV g_{4b} with g_5 and g_5 with g_{4b}. In addition, their PDFs are $F_{g_{4b},\text{RAN}}(x) = F_{g_{4b},\text{BSR}}(x) = 1 - e^{-\lambda_4 x}$ and $f_{g_5,\text{RAN}}(x) = f_{g_5,BSR}(x) = 1 - e^{-\lambda_5 x}$. Thus, we obtain the following expressions:

$$\begin{aligned}
\Pr 4.3_{\text{RAN}} &= \Pr 4.1_{\text{RAN}}\big|_{\lambda_4 \leftrightarrow \lambda_5} = \\
&= \lambda_1 \left(1 - \frac{\lambda_5}{\lambda_4+\lambda_5}\right) \Omega_1\left(\lambda_1, \frac{\lambda_3 \psi_t}{\omega_3}, \frac{\psi_t}{\omega_1}\right) \\
&- \lambda_1 \lambda_3 \frac{\omega_2}{\lambda_5 \omega_3} \Omega_2\left(\lambda_1, \frac{\lambda_5 \psi_t}{\omega_2}, \frac{\lambda_3 \psi_t}{\omega_3}, \frac{\lambda_3 \omega_2}{\lambda_5 \omega_3}, \frac{\psi_t}{\omega_1}\right) \\
&+ \lambda_1 \lambda_3 \frac{\lambda_5}{\lambda_4+\lambda_5} \frac{\omega_2}{(\lambda_4+\lambda_5)\omega_3} \\
&\Omega_2\left(\lambda_1, \frac{(\lambda_4+\lambda_5)\psi_t}{\omega_2}, \frac{\lambda_3 \psi_t}{\omega_3}, \frac{\lambda_3 \omega_2}{(\lambda_4+\lambda_5)\omega_3}, \frac{\psi_t}{\omega_1}\right)
\end{aligned} \tag{43}$$

$$\Pr 4.3_{\mathrm{BSR}} = \Pr 4.1_{\mathrm{BSR}}|_{\lambda_4 \leftrightarrow \lambda_5} = M\lambda_1\left(1 - \frac{\lambda_5}{\lambda_4+\lambda_5}\right)\sum_{m=0}^{M-1} C_{M-1}^{m}(-1)^m \Omega_1\left((m+1)\lambda_1, \frac{\lambda_3\psi_t}{\omega_3}, \frac{\psi_t}{\omega_1}\right) - M\lambda_1\lambda_3\frac{\omega_2}{\lambda_5\omega_3}\sum_{m=0}^{M-1} C_{M-1}^{m}(-1)^m \Omega_2\left((m+1)\lambda_1, \frac{\lambda_5\psi_t}{\omega_2}, \frac{\lambda_3\psi_t}{\omega_3}, \frac{\lambda_3\omega_2}{\lambda_5\omega_3}, \frac{\psi_t}{\omega_1}\right) + \frac{M\lambda_1\lambda_3\lambda_5\omega_2}{(\lambda_4+\lambda_5)^2\omega_3}\sum_{m=0}^{M-1} C_{M-1}^{m}(-1)^m \Omega_2\left((m+1)\lambda_1, \frac{(\lambda_4+\lambda_5)\psi_t}{\omega_2}, \frac{\lambda_3\psi_t}{\omega_3}, \frac{\lambda_3\omega_2}{(\lambda_4+\lambda_5)\omega_3}, \frac{\psi_t}{\omega_1}\right) \tag{44}$$

$$\Pr 4.3_{\mathrm{BSR}} = \Pr 4.1_{\mathrm{BSR}}|_{\lambda_4 \leftrightarrow \lambda_5} = M\lambda_1\left(1 - \frac{\lambda_5}{\lambda_4+\lambda_5}\right)\sum_{m=0}^{M-1} C_{M-1}^{m}(-1)^m \Omega_1\left((m+1)\lambda_1, \frac{\lambda_3\psi_t}{\omega_3}, \frac{\psi_t}{\omega_1}\right) - M\lambda_1\lambda_3\frac{\omega_2}{\lambda_5\omega_3}\sum_{m=0}^{M-1} C_{M-1}^{m}(-1)^m \Omega_2\left((m+1)\lambda_1, \frac{\lambda_5\psi_t}{\omega_2}, \frac{\lambda_3\psi_t}{\omega_3}, \frac{\lambda_3\omega_2}{\lambda_5\omega_3}, \frac{\psi_t}{\omega_1}\right) + \frac{M\lambda_1\lambda_3\lambda_5\omega_2}{(\lambda_4+\lambda_5)^2\omega_3}\sum_{m=0}^{M-1} C_{M-1}^{m}(-1)^m \Omega_2\left((m+1)\lambda_1, \frac{(\lambda_4+\lambda_5)\psi_t}{\omega_2}, \frac{\lambda_3\psi_t}{\omega_3}, \frac{\lambda_3\omega_2}{(\lambda_4+\lambda_5)\omega_3}, \frac{\psi_t}{\omega_1}\right) \tag{45}$$

$$\Pr 4.4_{\mathrm{BSR}} = \Pr 4.2_{\mathrm{BSR}}|_{\lambda_4 \leftrightarrow \lambda_5} = M\sum_{m=0}^{M-1} C_{M-1}^{m}(-1)^m \left\{ \begin{array}{l} \frac{e^{-\frac{(m+1)\lambda_1\psi_t}{\omega_1}}}{m+1}\left(1 - e^{-\frac{\lambda_5\psi_t}{\omega_2}}\right) - \frac{e^{-\frac{(m+1)\lambda_1\psi_t}{\omega_1}}}{m+1}\frac{\lambda_5}{\lambda_4+\lambda_5}\left(1 - e^{-\frac{(\lambda_4+\lambda_5)\psi_t}{\omega_2}}\right) \\ -\lambda_1\Omega_3\left((m+1)\lambda_1, \frac{\lambda_5\psi_t}{\omega_2}, \frac{\lambda_3\psi_t}{\omega_3}, \frac{\lambda_3\omega_2}{\lambda_5\omega_3}, \frac{\psi_t}{\omega_1}\right) \\ +\frac{\lambda_5\lambda_1}{(\lambda_4+\lambda_5)}\Omega_3\left((m+1)\lambda_1, \frac{(\lambda_4+\lambda_5)\psi_t}{\omega_2}, \frac{\lambda_3\psi_t}{\omega_3}, \frac{\lambda_3\omega_2}{(\lambda_4+\lambda_5)\omega_3}, \frac{\psi_t}{\omega_1}\right) \end{array} \right\} \tag{46}$$

The term Pr 4.4 for the relay selection schemes RAN and BSR can be obtained by substituting Eqs. 39-46 into 36:

$$\Pr 4_{\mathrm{RAN}} = e^{-\frac{\lambda_2\psi_t}{\omega_2}} \left\{ \begin{array}{l} \Pr 4.1_{\mathrm{RAN}} + \Pr 4.2_{\mathrm{RAN}} \\ + \Pr 4.3_{\mathrm{RAN}} + \Pr 4.4_{\mathrm{RAN}} \end{array} \right\} \tag{47}$$

$$\Pr 4_{\mathrm{BSR}} = \left[1 - \left(1 - e^{-\frac{\lambda_2\psi_t}{\omega_2}}\right)^N\right] \left\{ \begin{array}{l} \Pr 4.1_{\mathrm{BSR}} + \Pr 4.2_{\mathrm{BSR}} \\ + \Pr 4.3_{\mathrm{BSR}} + \Pr 4.4_{\mathrm{BSR}} \end{array} \right\} \tag{48}$$

Finally, we obtain the outage probabilities of the proposed system model with the two relay selection schemes RAN and BSR, respectively, as follows:

$$P_{out,\mathrm{RAN/BSR}} = \Pr 1_{\mathrm{RAN/BSR}} + \Pr 2_{\mathrm{RAN/BSR}} + \Pr 3_{\mathrm{RAN/BSR}} + \Pr 4_{\mathrm{RAN/BSR}} \tag{49}$$

5. No direct link

In this section, we consider the case of no direct link between the source S and the destination D due to deep fading. In this case, ψ_5 is not present in the outage probability expression, which is given by

$$P_{out}^{\mathrm{NDR}} = \underbrace{\Pr[\psi_1 < \psi_t, \psi_2 < \psi_t]}_{\Pr 5} + \underbrace{\Pr[\psi_1 \geq \psi_t, \psi_2 < \psi_t, \psi_3 < \psi_t]}_{\Pr 6} + \underbrace{\Pr[\psi_1 < \psi_t, \psi_2 \geq \psi_t, \psi_4 < \psi_t]}_{\Pr 7} + \underbrace{\Pr[\psi_1 \geq \psi_t, \psi_2 \geq \psi_t, max(\psi_3, \psi_4) < \psi_t]}_{\Pr 8} \tag{50}$$

The terms Pr 5 and Pr 7 under the two relay selection schemes are easily obtained as

$$\Pr 5_{\mathrm{RAN}} = \left(1 - e^{-\frac{\lambda_1\psi_t}{\omega_1}}\right)\left(1 - e^{-\frac{\lambda_2\psi_t}{\omega_2}}\right) \tag{51}$$

$$\Pr 5_{\mathrm{BSR}} = \left(1 - e^{-\frac{\lambda_1\psi_t}{\omega_1}}\right)^M\left(1 - e^{-\frac{\lambda_2\psi_t}{\omega_2}}\right)^N \tag{52}$$

$$\Pr 7_{\mathrm{RAN}} = \left(1 - e^{-\frac{\lambda_1\psi_t}{\omega_1}}\right)e^{-\frac{\lambda_2\psi_t}{\omega_2}}\left(1 - e^{-\frac{\lambda_4\psi_t}{\omega_2}}\right) \tag{53}$$

$$\Pr 7_{\mathrm{BSR}} = \left(1 - e^{-\frac{\lambda_1\psi_t}{\omega_1}}\right)^M\left[1 - \left(1 - e^{-\frac{\lambda_2\psi_t}{\omega_2}}\right)^N\right]\left(1 - e^{-\frac{\lambda_4\psi_t}{\omega_2}}\right) \tag{54}$$

The term Pr 6 in Eq. 54 is obtained as

$$\Pr 6 = \Pr\left[g_{1b} \geq \frac{\psi_t}{\omega_1}, g_{2b} < \frac{\psi_t}{\omega_2}, \omega_3 g_{1b} g_{3b} < \psi_t\right] = F_{g_{2b}}\left(\frac{\psi_t}{\omega_2}\right)\int_{\frac{\psi_t}{\omega_1}}^{\infty} f_{g_{1b}}(x_1) \int_0^{\frac{\psi_t}{\omega_3 x_1}} f_{g_{3b}}(x_3) \tag{55}$$

Then, substituting the PDFs of the three RVs g_{1b}, g_{2b} and g_{3b} of the two schemes RAN and BSR, we obtain

$$\Pr 6_{\mathrm{RAN}} = \left(1 - e^{-\frac{\lambda_2\psi_t}{\omega_2}}\right)\lambda_1\Omega_1\left(\lambda_1, \frac{\lambda_3\psi_t}{\omega_3}, \frac{\psi_t}{\omega_1}\right) \tag{56}$$

$$\Pr 6_{\mathrm{BSR}} = \left(1 - e^{-\frac{\lambda_2\psi_t}{\omega_2}}\right)^N M\lambda_1\sum_{m=0}^{M-1} C_{M-1}^{m}(-1)^m \Omega_1\left((m+1)\lambda_1, \frac{\lambda_3\psi_t}{\omega_3}, \frac{\psi_t}{\omega_1}\right) \tag{57}$$

The term Pr 8 is rewritten as

$$\Pr 8 = \Pr\left[g_{1b} \geq \frac{\psi_t}{\omega_1}, g_{2b} \geq \frac{\psi_t}{\omega_2}, max(\omega_3 g_{1b} g_{3b}, \omega_2 g_{4b}) < \psi_t\right] = \left[1 - F_{g_{2b}}\left(\frac{\psi_t}{\omega_2}\right)\right] \left\{ \begin{array}{l} \underbrace{\Pr\left[g_{1b} \geq \frac{\psi_t}{\omega_1}, \omega_3 g_{1b} g_{3b} < \psi_t, \omega_3 g_{1b} g_{3b} > \omega_2 g_{4b}\right]}_{\Pr 8.1 = \Pr 2.1|_{g_5 \to g_{4b}}} \\ + \underbrace{\Pr\left[g_{1b} \geq \frac{\psi_t}{\omega_1}, \omega_2 g_5 < \psi_t, \omega_3 g_{1b} g_{3b} < \omega_2 g_{4b}\right]}_{\Pr 8.2 = \Pr 2.2|_{g_5 \to g_{4b}}} \end{array} \right\} \tag{58}$$

The terms Pr 8.1 and Pr 8.2 can be derived in the same way as Pr 2.1 and Pr 2.2 in Eqs. 23 and 24, respectively, by changing the RV g_5 to g_{4b}. Thus, Pr 8.1 and Pr 8.2 for the two schemes RAN and BSR are obtained from the results in Eqs. 25-28 by replacing λ_5 with λ_4 because the PDFs of g_5 and g_{4b} with the two relay selection schemes are $F_{g_{4b},\mathrm{RAN}}(x) = F_{g_{4b},\mathrm{BSR}}(x) = 1 - e^{-\lambda_4 x}$ and $f_{g_5,\mathrm{RAN}}(x) = f_{g_5,BSR}(x) = 1 - e^{-\lambda_5 x}$

$$\begin{array}{l}\Pr 8.1_{\mathrm{RAN}} = \lambda_1 \Omega_1\left(\lambda_1, \frac{\lambda_3\psi_t}{\omega_3}, \frac{\psi_t}{\omega_1}\right)\\ -\lambda_1\lambda_3\frac{\omega_2}{\lambda_5\omega_3}\Omega_2\left(\lambda_1, \frac{\lambda_4\psi_t}{\omega_2}, \frac{\lambda_3\psi_t}{\omega_3}, \frac{\lambda_3\omega_2}{\lambda_4\omega_3}, \frac{\psi_t}{\omega_1}\right)\end{array} \tag{59}$$

$$\begin{array}{l}\Pr 8.1_{\mathrm{BSR}} = M\lambda_1 \sum\limits_{m=0}^{M-1} C_{M-1}^{m}(-1)^m\\ \left[\begin{array}{l}\Omega_1\left((m+1)\lambda_1, \frac{\lambda_3\psi_t}{\omega_3}, \frac{\psi_t}{\omega_1}\right)\\ -\lambda_3\frac{\omega_2}{\lambda_4\omega_3}\Omega_2\left((m+1)\lambda_1, \frac{\lambda_4\psi_t}{\omega_2}, \frac{\lambda_3\psi_t}{\omega_3}, \frac{\lambda_3\omega_2}{\lambda_4\omega_3}, \frac{\psi_t}{\omega_1}\right)\end{array}\right]\end{array} \tag{60}$$

$$\begin{array}{l}\Pr 8.2_{\mathrm{RAN}} = \left(1 - e^{-\frac{\lambda_4\psi_t}{\omega_2}}\right) e^{-\frac{\lambda_1\psi_t}{\omega_1}}\\ -\lambda_1\Omega_3\left(\lambda_1, \frac{\lambda_4\psi_t}{\omega_2}, \frac{\lambda_3\psi_t}{\omega_3}, \frac{\lambda_3\omega_2}{\lambda_4\omega_3}, \frac{\psi_t}{\omega_1}\right)\end{array} \tag{61}$$

$$\begin{array}{l}\Pr 8.2_{\mathrm{BSR}} = M \sum\limits_{m=0}^{M-1} C_{M-1}^{m}(-1)^m\\ \left\{\begin{array}{l}\left(1 - e^{-\frac{\lambda_4\psi_t}{\omega_2}}\right)\frac{e^{-\frac{(m+1)\lambda_1\psi_t}{\omega_1}}}{m+1}\\ -\lambda_1\Omega_3\left((m+1)\lambda_1, \frac{\lambda_4\psi_t}{\omega_2}, \frac{\lambda_3\psi_t}{\omega_3}, \frac{\lambda_3\omega_2}{\lambda_4\omega_3}, \frac{\psi_t}{\omega_1}\right)\end{array}\right\}\end{array} \tag{62}$$

Substituting Eqs. 59-62 into 58, the term Pr 8 for the two schemes can be obtained as

$$\Pr 8_{\mathrm{RAN}} = e^{-\frac{\lambda_2\psi_t}{\omega_2}}\left(\Pr 8.1_{\mathrm{RAN}} + \Pr 8.2_{\mathrm{RAN}}\right) \tag{63}$$

$$\Pr 8_{\mathrm{BSR}} = \left[1 - \left(1 - e^{-\frac{\lambda_2\psi_t}{\omega_2}}\right)^N\right]\left(\Pr 8.1_{\mathrm{BSR}} + \Pr 8.2_{\mathrm{BSR}}\right) \tag{64}$$

The outage probabilities for the two schemes in the case of no direct link $S - D$ are expressed as follows:

$$\begin{array}{l}P_{out,\mathrm{RAN/BSR}}^{\mathrm{NDR}} = \Pr 5_{\mathrm{RAN/BSR}} + \Pr 6_{\mathrm{RAN/BSR}}\\ + \Pr 7_{\mathrm{RAN/BSR}} + \Pr 8_{\mathrm{RAN/BSR}}\end{array} \tag{65}$$

6. Numerical results

In this section, we present Monte Carlo simulations to verify our derivations and compare the outage performances of the considered protocols for the system model in Fig. 1 and the system with no direct link $S - D$. Consider a network in a two-dimensional plane with the following coordinates for the source S, the destination D, the energy-constrained relay cluster $R1$, and the conventional relay cluster $R2$: $(0, 0)$, $(1, 0)$, (x_{R1}, y_{R1}), and (x_{R2}, y_{R2}), respectively. Then, the distances of the links $S - R1$, $S - R2$, $R1 - D$, $R2 - D$, and $S - D$ are, respectively, $d_1 = \sqrt{(x_{R1})^2 + (y_{R1})^2}$, $d_2 = \sqrt{(x_{R2})^2 + (y_{R2})^2}$, $d_3 = \sqrt{(1 - x_{R1})^2 + (y_{R1})^2}$, $d_4 = \sqrt{(1 - x_{R1})^2 + (y_{R2})^2}$, and $d_5 = 1$. In all the simulations, we assume the path loss $\beta = 3$ and the noise $N_0 = 1$. For ease of presentation, we call the two protocols in Section 4 DR-RAN and DR-BSR, and the two protocols in Section 5 NDR-RAN and NDR-BSR.

Fig. 2 shows our evaluation and comparison of the performances of the four protocols, i.e., DR-RAN, DR-BSR, NDR-RAN, and NDR-BSR, versus the transmit power P from -5 dB to 10 dB. We observe that, as expected, the outage performances of all the protocols are significantly improved when the transmit power P increases. In Fig. 3, the outage performances of all protocols are presented versus the power splitting ratio ρ varying from 0.1 to 0.9. The performances are the worst when ρ is at 0.1 or 0.9. This phenomenon can be explained as follows. When $\rho = 0.1$, the harvested energy at the best relay in cluster R1 is insignificant; thus, it is difficult to use that amount of energy to successfully forward the source data to the destination. And when $\rho = 0.9$, the harvested energy is large, but the decoding performance at the best relay in cluster R1 is low. Therefore, there is an optimal value of ρ that balances the decoding performance and the harvested energy at the best relay in cluster R1. For example, the optimal value of ρ in this scenario is around 0.6; at this point, the outage performances of all the protocols achieve their best.

We observe in Figs. 2 and 3 that the DR-BSR and NDR-BSR protocols improve in performance when the number of relays is increased in cluster $R1$ $(M = 2, 4)$ and/or cluster $R2$ $(N = 2, 4)$ due to increasing the decoding performance and the amount of harvested energy at the best relay in cluster $R1$, and increasing the decoding performance at the best relay in cluster $R2$, while the DR-RAN and NDR-RAN protocols have unchanged performance because the best relay is randomly selected. In addition, as expected, the DR-RAN and DR-BSR protocols achieve higher performance than the NDR-RAN and NDR-BSR, respectively. And the outage performances of the DR-BSR and NDR-BSR protocols are higher than those of the DR-RAN and NDR-RAN, respectively. Thus, we do not show the DR-RAN and NDR-RAN in the next figures. Moreover, we see that the gaps between the curves $M = 2$ and $M = 4$ of the protocol DR/NDR-BSR shown in Figure 2 are bigger than those between the curves $N = 2$ and $N = 4$ in Fig. 3. Therefore, the system is improved more when we increase the number of relays in cluster $R1$ (M) than when we increase the number of relays in cluster $R2$ (N). This finding is shown again in Fig. 6.

In Fig. 4, the impact of the position of cluster $R1$ on the outage performance is shown. It can be

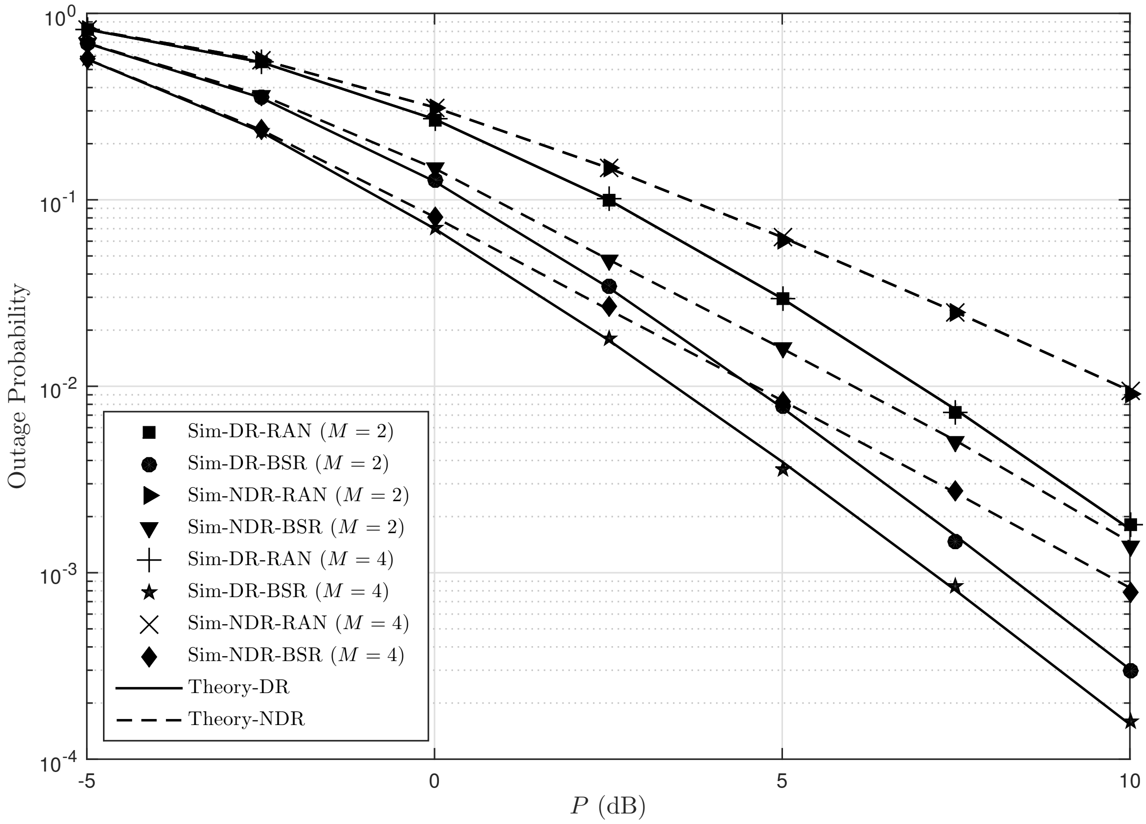

Figure 2. Outage probability versus transmit power P in dB for the four protocols and for M of 2 and 4 with $(x_{R1}, y_{R1}) = (0.5, 0.3)$, $(x_{R2}, y_{R2}) = (0.5, -0.3)$, $\psi_t = 1$ bit/s/Hz, $\rho = 0.5$, $\eta = 0.5$, and $N = 2$.

observed that the outage performance is the worst when the cluster $R1$ is farthest away from the source and destination ($y_{R1} = 0.7$), and it changes very slightly when x_{R1} is changed from 0.1 to 0.9. This can be explained as follows. When $y_{R1} = 0.7$, for all values of x_{R1} from 0.1 to 0.9, the distances from the source to cluster $R1$ and from the destination to cluster $R1$ are relatively long, so the decoding performance and energy harvesting of the link from S to cluster $R1$, as well as the decoding performance of the link from cluster $R1$ to D, are too low. In this case, successful transmission occurs almost via the links $S - D$ and S−cluster$R2$−D; hence, the outage performance changes slightly as x_{R1} changes. When cluster $R1$ is positioned nearer to the source and destination, e.g., $y_{R1} = 0.4$, the outage performances of the DR-BSR and NDR-BSR increases. As cluster $R1$ continues moving nearer ($y_{R1} = 0.1$), their outage performances continue to improve. Additionally, there is a big change in the outage performance when x_{R1} changes. For instance, the outage performance is the best when $x_{R1} = 0.1$ because, at this position, the best relay in cluster $R1$ can easily decode the source data and harvest enough energy for forwarding the data to the destination. The performance is decreased significantly when $x_{R1} = 0.9$. In addition, the DR-BSR protocol achieves higher performance than the NDR-BSR protocol for all values of x_{R1} and y_{R1}.

Fig. 5 shows the impact of the position of cluster $R2$ on the outage performance. As expected, the DR-BSR protocol outperforms the NDR-BSR protocol for the same position of cluster $R2$, and they both achieve higher performance when cluster $R2$ is closer to the source and destination. For example, the performance when $y_{R2} = -0.1$ is higher than when $y_{R2} = -0.4$ and $y_{R2} = -0.7$, for all values of x_{R2}. Especially, the two protocols achieve their highest performances when x_{R2} is around 0.7 because this is the optimal position for balancing between decoding the information of the two links $S - R2$ and $R2 - D$.

Fig. 6 presents comparisons of the outage probabilities of the DR-BSR and NDR-BSR protocols versus η for $(M, N) = (2, 4)$ and $(M, N) = (4, 2)$. As we can see in Fig. 6, the outage performance of the DR-BSR or NDR-BSR

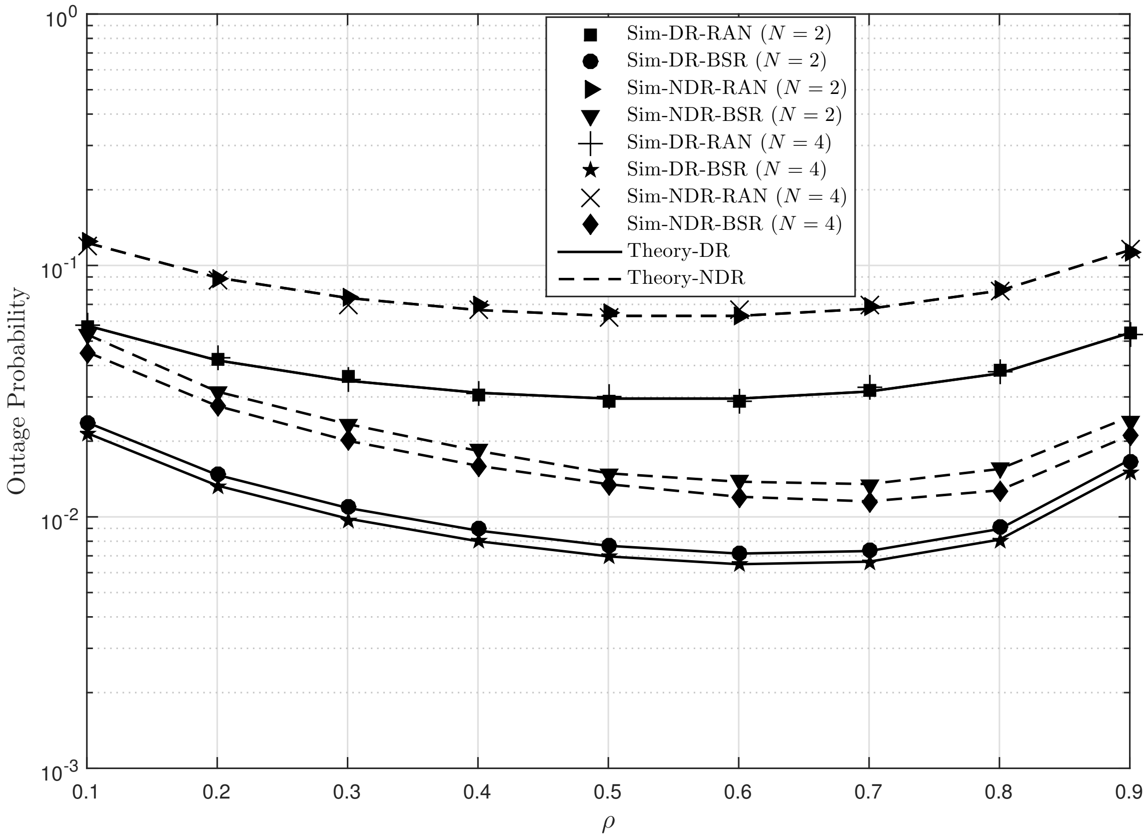

Figure 3. Outage probability versus power splitting ratio ρ for the four protocols and for N of 2 and 4 with $(x_{R1}, y_{R1}) = (0.5, 0.3)$, $(x_{R2}, y_{R2}) = (0.5, -0.3)$, $P = 5$ dB, $\psi_t = 1$ bits/s/Hz, $\rho = 0.5$, $\eta = 0.5$, and $M = 2$.

protocols in the case of $(M, N) = (4, 2)$ is better than in the case of $(M, N) = (2, 4)$. In addition, the effect of the direct link $S - D$ on the system performance is large. As we can see, the DR-BSR protocol (considering the presence of direct link $S - D$) gains higher performance than the NDR-BSR protocol (no direct link $S - D$) for both cases of $(M, N) = (2, 4)$ and $(M, N) = (4, 2)$. Furthermore, as shown in this figure, the outage performances of all protocols increase significantly when η increases, due to increasing the amount of harvested energy as well as the decoding performance at the best relay in cluster $R1$.

Fig. 7 presents the outage probabilities of the DR-BSR and NDR-BSR protocols with respect to transmit power P in dB for ψ_t of 0.3, 0.7, and 1. The performance of the system is high when the requirement for the outage rate is low, i.e., the outage performances increase when the target rate ψ_t decreases.

Finally, as we can see in Figs. 2 to 7, the theoretical results match very well with the simulation results, verifying our derivations in Section 4 and 5.

7. Conclusions

In this paper, we investigate the selection-combining technique at the destination for a system model of a 2-branch cooperative communication system including one energy-constrained relaying branch and one conventional relaying branch. We study two relay-selection schemes (RAN and BSR) for two cases, one with the existence of a direct link (DR) and the other without (NDR) between the source and destination. Thus we considered four protocols: DR-RAN, DR-BSR, NDR-RAN, and NDR-BSR. We derived the closed-form expressions of the outage probabilities for evaluation and comparison of the performances of the four protocols. We derived these theoretical expressions using the Monte Carlo simulation method. From the simulation and theoretical results, we discovered the following. 1) The outage performance of the DR/NDR-RAN protocols do not depend on the number of relays in the two cluster. 2) The DR/NDR-BSR protocols improve the system performance when the number of relays in the two clusters increase; moreover, the system achieves higher performance by increasing M than by

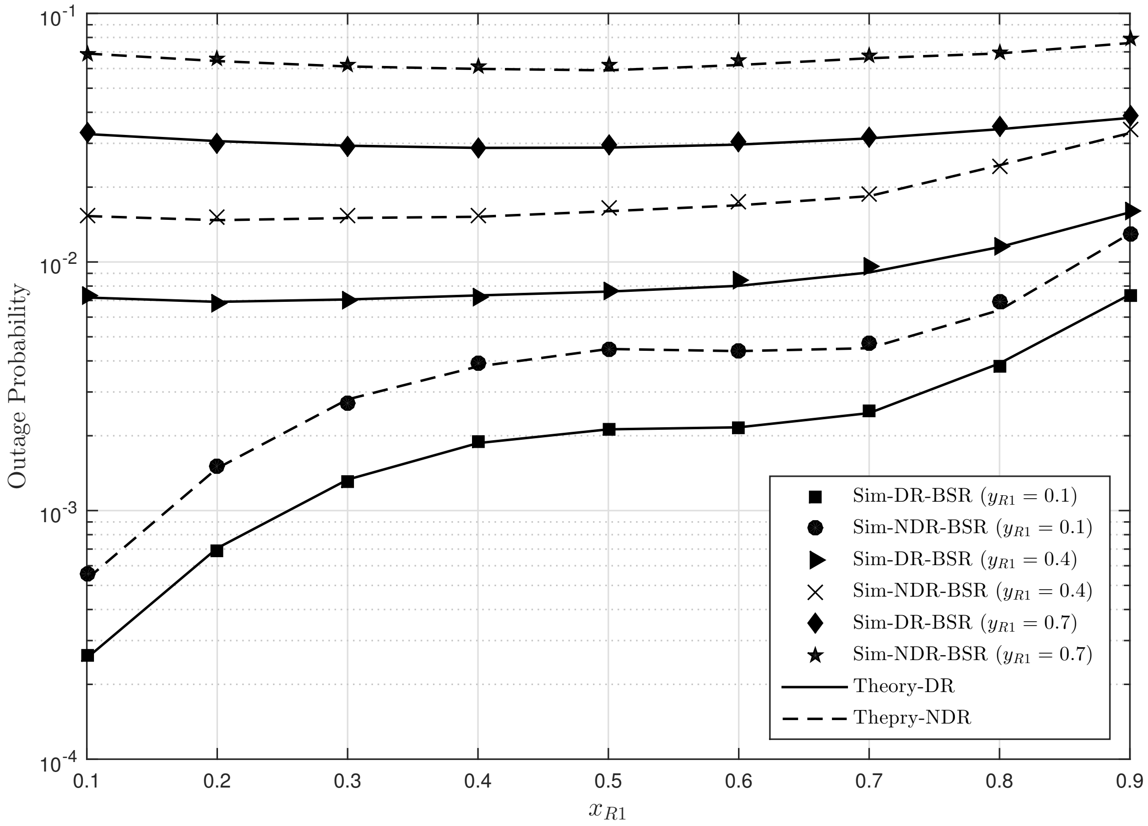

Figure 4. Outage probability versus x_{R1} of the DR-BSR and NDR-BSR protocols for y_{R1} of 0.1, 0.4, and 0.7 with $(x_{R2}, y_{R2}) = (0.5, -0.3)$, $P = 5$ dB, $\psi_t = 1$ bits/s/Hz, $\rho = 0.5$, $\eta = 0.5$, $M = 3$, and $N = 3$.

increasing N. 3) The DR model outperformed the NDR model, and the BSR scheme outperformed the RAN scheme. 4) The outage performances of all protocols improved when the transmit power P increased, the energy harvesting efficiency η increased, the distances between the two clusters and the source and the destination decreased, or the target rate ψ_t decreased. 5) The theoretical results match the simulation results well.

Appendix A: Finding $\Omega_1(\varphi_1, \varphi_2, \varphi_3) = \int\limits_{\varphi_3}^{\infty} e^{-\varphi_1 x}\left(1 - e^{-\varphi_2/x}\right)dx$

We can express the integral as following

$$\begin{aligned}
&\int\limits_{\varphi_3}^{\infty} e^{-\varphi_1 x}\left(1 - e^{-\varphi_2/x}\right)dx = \int\limits_{\varphi_3}^{\infty} e^{-\varphi_1 x}dx - \int\limits_{\varphi_3}^{\infty} e^{-\varphi_1 x}e^{-\varphi_2/x}dx\\
&= \int\limits_{\varphi_3}^{\infty} e^{-\varphi_1 x}dx - \int\limits_{\varphi_3}^{\infty} e^{-\varphi_1 x}\left(1 + \sum_{p=1}^{\infty}\frac{(-\varphi_2)^p}{p!}\frac{1}{(x)^p}\right)dx\\
&= -\int\limits_{\varphi_3}^{\infty} e^{-\varphi_1 x}\left(\sum_{p=1}^{\infty}\frac{(-\varphi_2)^p}{p!}\frac{1}{(x)^p}\right)dx
\end{aligned} \tag{A1}$$

Using [26, Eq. 3.381.3]: $\int\limits_{u}^{\infty} x^{v-1}e^{-\mu x}dx = \mu^{-v}\Gamma(v, \mu u)$, we obtain:

$$\begin{aligned}
&\Omega_1(\varphi_1, \varphi_2, \varphi_3) = \int\limits_{\varphi_3}^{\infty} e^{-\varphi_1 x}\left(1 - e^{-\varphi_2/x}\right)dx = \\
&-\sum_{p=1}^{T\to\infty}\frac{(-\varphi_2)^p}{p!}{\varphi_1}^{p-1}\Gamma(1-p, \varphi_1\varphi_3)
\end{aligned} \tag{A2}$$

We note that, in the **Numerical results** part, we choose the value for T is large enough, i.e., $T \sim 20$m to obtain the closed form results.

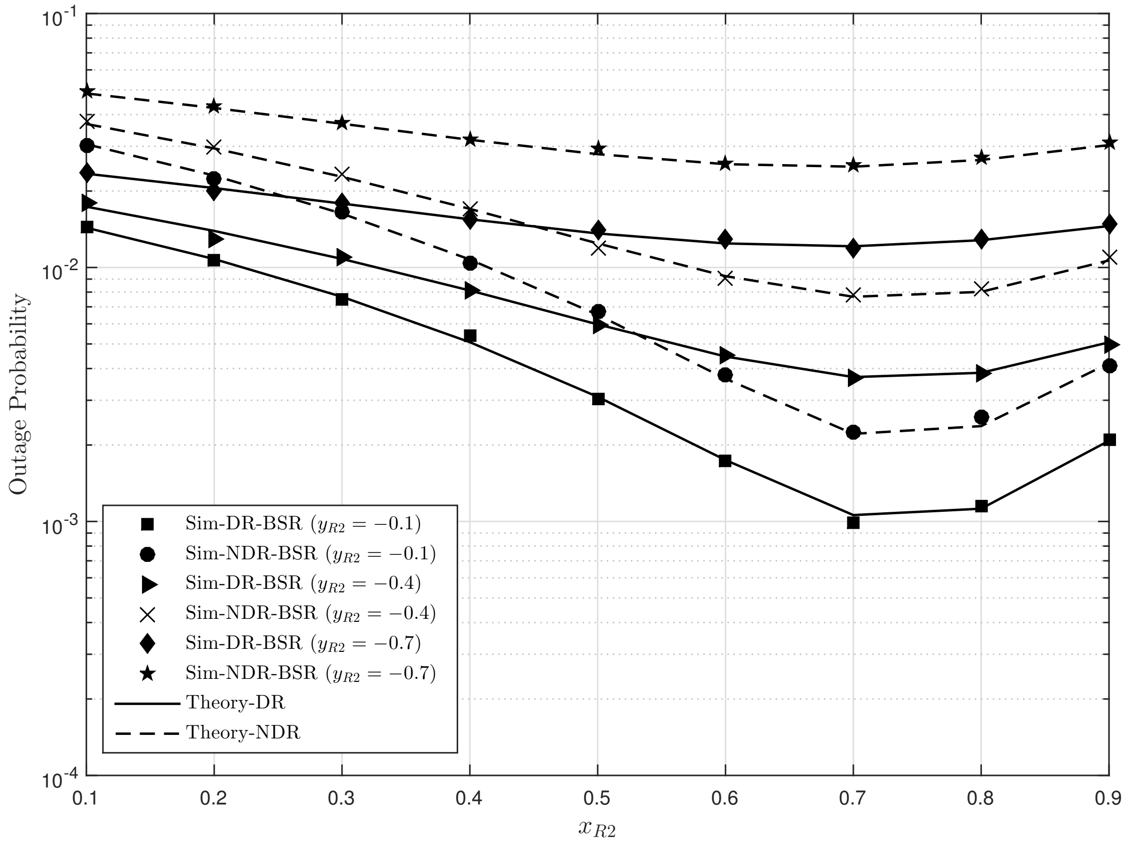

Figure 5. Outage probability versus x_{R2} of the DR-BSR and NDR-BSR protocols and for y_{R2} of -0.1, -0.4, and -0.7 with $(x_{R1}, y_{R1}) = (0.5, 0.3)$, $P = 5$ dB, $\psi_t = 1$ bits/s/Hz, $\rho = 0.5$, $\eta = 0.5$, $M = 3$, and $N = 3$.

Appendix B: Finding $\Omega_2(\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5) = \int\limits_{\varphi_5}^{\infty} e^{-\varphi_1 x}\frac{(1-e^{-\varphi_2}e^{-\varphi_3/x})}{x+\varphi_4}dx$

We can express the integral as following

$$\begin{aligned}
&\int\limits_{\varphi_5}^{\infty} e^{-\varphi_1 x}\frac{(1-e^{-\varphi_2}e^{-\varphi_3/x})}{x+\varphi_4}dx \\
&= \int\limits_{\varphi_5}^{\infty} \frac{e^{-\varphi_1 x}}{x+\varphi_4}dx - e^{-\varphi_2}\int\limits_{\varphi_5}^{\infty} \frac{e^{-\varphi_1 x}\left[1+\sum\limits_{q=1}^{\infty}\frac{(-\varphi_3)^q}{q!}\frac{1}{(x)^q}\right]}{x+\varphi_4}dx \\
&= (1-e^{-\varphi_2})\underbrace{\int\limits_{\varphi_5}^{\infty}\frac{e^{-\varphi_1 x}}{x+\varphi_4}dx}_{I_1} - e^{-\varphi_2}\sum_{q=1}^{\infty}\frac{(-\varphi_3)^q}{q!}\underbrace{\int\limits_{\varphi_5}^{\infty}\frac{e^{-\varphi_1 x}}{(x)^q(x+\varphi_4)}dx}_{U_q}
\end{aligned} \tag{B1}$$

First, we calculate I_1. By setting $u = x + \varphi_4$, the integral I_1 can be expressed as

$$\begin{aligned}
I_1 &= \int\limits_{\varphi_5}^{\infty}\frac{e^{-\varphi_1 x}}{x+\varphi_4}dx = \int\limits_{\varphi_5+\varphi_4}^{\infty}\frac{e^{-\varphi_1(u-\varphi_4)}}{u}du \\
&\overset{(B2.1)}{=} e^{\varphi_1\varphi_4}\int\limits_{\varphi_5+\varphi_4}^{\infty}\frac{e^{-\varphi_1 u}}{u}du \overset{(B2.2)}{=} e^{\varphi_1\varphi_4}\Gamma(0, \varphi_1(\varphi_5+\varphi_4))
\end{aligned} \tag{B2}$$

where (B2.2) can be obtained from (B2.1) by using [26, Eq. 3.381.3].

Next, we calculate U_q as following

$$\begin{aligned}
U_q &= \int\limits_{\varphi_5}^{\infty}\frac{e^{-\varphi_1 x}}{(x)^q(x+\varphi_4)}dx = \left(\sum_{l=1}^{q}\theta_{l,q}\int\limits_{\varphi_5}^{\infty}\frac{e^{-\varphi_1 x}}{(x)^l}dx\right) + \vartheta_q\int\limits_{\varphi_5}^{\infty}\frac{e^{-\varphi_1 x}}{x+\varphi_4}dx \\
&= \sum_{l=1}^{1}\theta_{l,q}\varphi_1^{\,l-1}\Gamma(1-l, \varphi_1\varphi_5) + \vartheta_q e^{\varphi_1\varphi_4}\Gamma(0, \varphi_1(\varphi_5+\varphi_4))
\end{aligned} \tag{B3}$$

where $\theta_{l,q} = \frac{1}{(q-l)!}\frac{\partial^{(q-l)}}{dx}\left[\frac{1}{x+\varphi_4}\right]\Big|_{x=0}$, $\vartheta_q = \left[\frac{1}{(x)^q}\right]\Big|_{x=-\varphi_4} = \frac{1}{(-\varphi_4)^q}$.

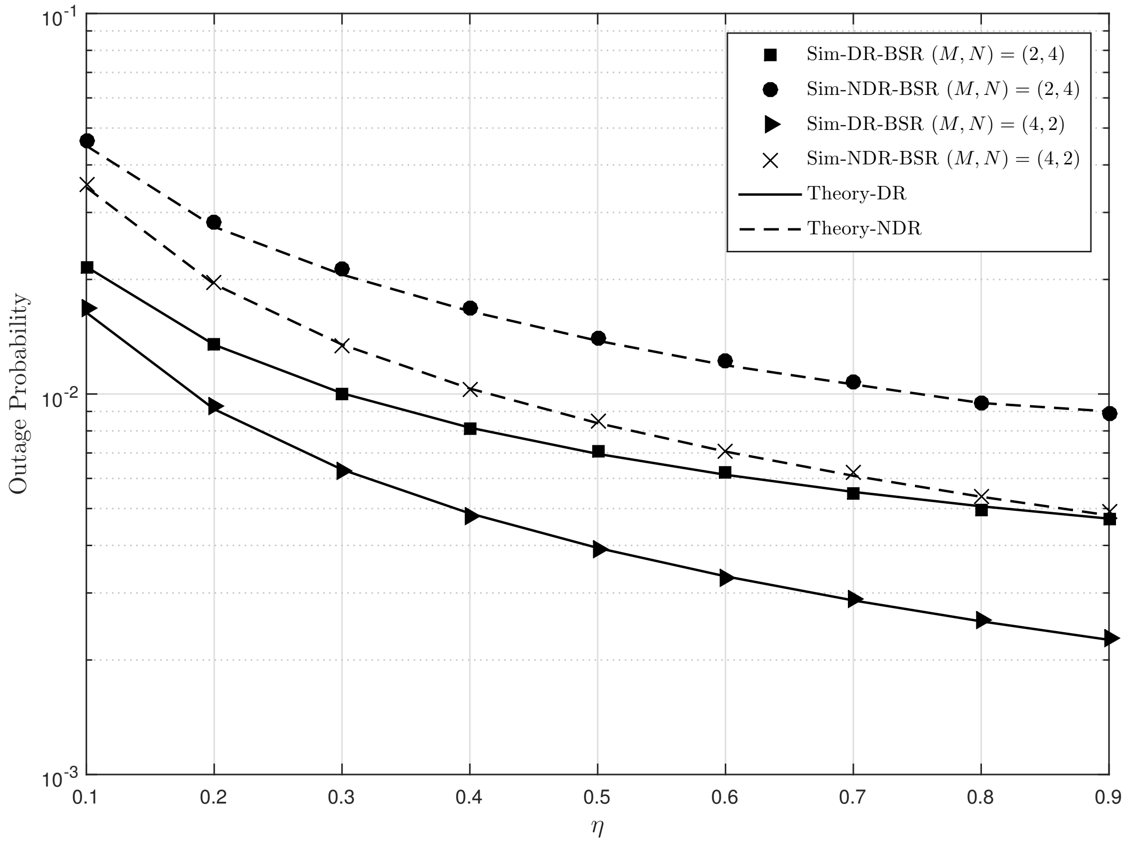

Figure 6. Outage probability versus η of the DR-BSR and NDR-BSR protocols and for $(M, N) = (2, 4)$, and $(M, N) = (4, 2)$ with $(x_{R1}, y_{R1}) = (0.5, 0.3)$, $(x_{R2}, y_{R2}) = (0.5, -0.3)$, $P = 5$ dB, $\psi_t = 1$ bits/s/Hz, and $\rho = 0.5$.

Substituting (B2) and (B3) into (B1), we obtain:

$$\begin{aligned}\Omega_2(\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5) &= \left(1 - e^{-\varphi_2}\right) e^{\varphi_1 \varphi_4} \Gamma\left(0, \varphi_1(\varphi_5 + \varphi_4)\right) - e^{-\varphi_2} \sum_{q=1}^{\infty} \frac{(-\varphi_3)^q}{q!} \\ &\left[\sum_{l=1}^{1} \theta_{l,q} {\varphi_1}^{l-1} \Gamma\left(1 - l, \varphi_1 \varphi_5\right) + \vartheta_q e^{\varphi_1 \varphi_4} \Gamma\left(0, \varphi_1(\varphi_5 + \varphi_4)\right)\right]\end{aligned} \tag{B4}$$

Appendix C: Finding $\Omega_3(\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5) = \int_{\varphi_5}^{\infty} x e^{-\varphi_1 x} \frac{\left(1 - e^{-\varphi_2} e^{-\varphi_3/x}\right)}{x + \varphi_4} dx$

We can express the integral as following

$$\begin{aligned}&\int_{\varphi_5}^{\infty} x e^{-\varphi_1 x} \frac{\left(1 - e^{-\varphi_2} e^{-\varphi_3/x}\right)}{x + \varphi_4} \\ &= \int_{\varphi_5}^{\infty} \frac{x e^{-\varphi_1 x}}{x + \varphi_4} dx - \left\{ e^{-\varphi_2} \int_{\varphi_5}^{\infty} \frac{x e^{-\varphi_1 x}\left[1 + \frac{-\varphi_3}{x} + \sum_{k=2}^{\infty} \frac{(-\varphi_3)^k}{k!} \frac{1}{(x)^k}\right]}{x + \varphi_4} dx \right\} \\ &= \left(1 - e^{-\varphi_2}\right) \underbrace{\int_{\varphi_5}^{\infty} \frac{x e^{-\varphi_1 x}}{x + \varphi_4} dx}_{I_2} + e^{-\varphi_2} \varphi_3 \underbrace{\int_{\varphi_5}^{\infty} \frac{e^{-\varphi_1 x}}{x_1 + \varphi_4} dx}_{I_3} \\ &\quad \underbrace{- e^{-\varphi_2} \sum_{k=2}^{\infty} \frac{(-\varphi_3)^k}{k!} \underbrace{\int_{\varphi_5}^{\infty} \frac{e^{-\varphi_1 x}}{(x)^{k-1}(x + \varphi_4)} dx}_{V_{k-1}}}_{T}\end{aligned} \tag{C1}$$

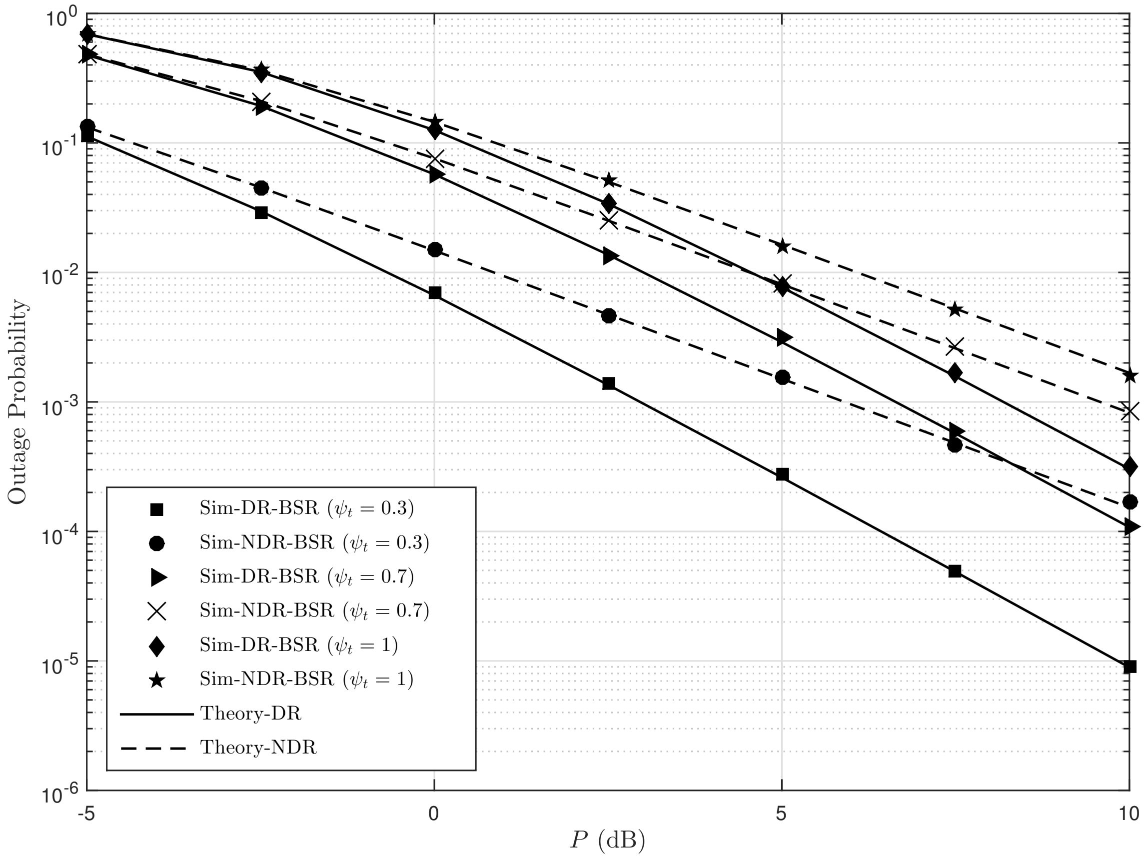

Figure 7. Outage probability versus transmit power P in dB for the DR-BSR and NDR-BSR protocols and for ψ_t of 0.3, 0.7, and 1 with $(x_{R1}, y_{R1}) = (0.5, 0.3)$, $(x_{R2}, y_{R2}) = (0.5, -0.3)$, $\rho = 0.5$, $\eta = 0.5$, $M = 2$, and $N = 2$.

By setting $u = x + \varphi_4$, the integral $I_2 = \int\limits_{\varphi_5}^{\infty} \frac{x e^{-\varphi_1 x}}{x + \varphi_4} dx$ can be rewritten as

$$\begin{aligned} I_2 &= \int\limits_{\varphi_5+\varphi_4}^{\infty} \frac{(x-\varphi_4) e^{\varphi_1 \varphi_4} e^{-\varphi_1 u}}{u} du \\ &= \int\limits_{\varphi_5+\varphi_4}^{\infty} \frac{(x-\varphi_4-\varphi_5) e^{\varphi_1 \varphi_4} e^{-\varphi_1 u}}{u} du + \int\limits_{\varphi_5+\varphi_4}^{\infty} \frac{\varphi_5 e^{\varphi_1 \varphi_4} e^{-\varphi_1 u}}{u} du \end{aligned} \tag{C2}$$

Using [26, Eq. 3.383.9]: $\int\limits_{u}^{\infty} \frac{(x-u)^v e^{-\mu x}}{x} dx = u^v \Gamma(v+1) \Gamma(-v, u\mu)$, and [26, Eq. 3.381.3], the integral I_2 is derived as

$$\begin{aligned} I_2 &= e^{\varphi_1 \varphi_4} (\varphi_4 + \varphi_5) \\ &\Gamma(-1, \varphi_1 (\varphi_4 + \varphi_5)) + \varphi_5 e^{\varphi_1 \varphi_4} \Gamma(0, \varphi_1 (\varphi_4 + \varphi_5)) \end{aligned} \tag{C3}$$

The integral I_3 is expressed from (B2) as:

$$I_3 = \int\limits_{\varphi_5}^{\infty} \frac{e^{-\varphi_1 x}}{x_1 + \varphi_4} dx = e^{\varphi_1 \varphi_4} \Gamma(0, \varphi_1 (\varphi_4 + \varphi_5)) \tag{C4}$$

The integral V_{k-1} can be expressed as following

$$\begin{aligned} V_{k-1} &= \int\limits_{\varphi_5}^{\infty} \frac{e^{-\varphi_1 x}}{(x)^{k-1} (x+\varphi_4)} dx = \\ &\left(\sum_{t=1}^{k-1} \tau_{t,k-1} \int\limits_{\varphi_5}^{\infty} \frac{e^{-\varphi_1 x}}{(x)^t} dx \right) + \upsilon_{k-1} \int\limits_{\varphi_5}^{\infty} \frac{e^{-\varphi_1 x}}{x+\varphi_4} dx \\ &= \left[\sum_{t=1}^{k-1} \tau_{t,k-1} {\varphi_1}^{t-1} \Gamma(1-t, \varphi_1 \varphi_5) \right] \\ &+ \upsilon_{k-1} e^{\varphi_1 \varphi_4} \Gamma(0, \varphi_1 (\varphi_5 + \varphi_4)) \end{aligned} \tag{C5}$$

where $\tau_{t,k-1} = \frac{1}{(k-1-t)!} \frac{\partial^{(k-1-t)}}{dx} \left[\frac{1}{x+\varphi_4} \right] \Big|_{x=0}$, $\upsilon_{k-1} = \left[\frac{1}{(x)^{k-1}} \right] \Big|_{x=-\varphi_4} = \frac{1}{(-\varphi_4)^{k-1}}$ Finally, substituting (C2), (C4), and (C5) into (C1), we obtain

$$\begin{aligned}
&\Omega_3(\varphi_1,\varphi_2,\varphi_3,\varphi_4,\varphi_5) = \\
&(1-e^{-\varphi_2})\, e^{\varphi_1\varphi_4} \left\{ \begin{array}{l} (\varphi_4+\varphi_5)\,\Gamma(-1,\varphi_1(\varphi_4+\varphi_5)) \\ +\varphi_5\Gamma(0,\varphi_1(\varphi_4+\varphi_5)) \end{array} \right\} \\
&+e^{-\varphi_2}\varphi_3 e^{\varphi_1\varphi_4}\Gamma(0,\varphi_1(\varphi_4+\varphi_5)) \\
&-e^{-\varphi_2}\sum_{k=2}^{\infty}\frac{(-\varphi_3)^k}{k!} \left\{ \begin{array}{l} \left[\sum\limits_{t=1}^{k-1}\tau_{t,k-1}{\varphi_1}^{t-1}\Gamma(1-t,\varphi_1\varphi_5)\right] \\ +\upsilon_{k-1}e^{\varphi_1\varphi_4}\Gamma(0,\varphi_1(\varphi_5+\varphi_4)) \end{array} \right\}
\end{aligned} \tag{C6}$$

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