# Exact Outage Probability of Two-Way Decode-and-Forward Scheme with Energy Harvesting from Intermediate Relaying Station

Tan-Phuoc Huynh[1](✉), Pham Ngoc Son[2], and Miroslav Voznak[3]

[1] Eastern International University (EIU), Thu Dau Mot, Vietnam
phuoc.huynh@eiu.edu.vn
[2] Ho Chi Minh City University of Technology and Education, Ho Chi Minh City, Vietnam
sonpndtvt@hcmute.edu.vn
[3] VSB Technical University of Ostrava, Ostrava, Czech Republic
miroslav.voznak@vsb.cz

**Abstract.** In this paper, we propose a two-way energy-harvesting scheme (called a TWEH protocol) in which an intermediate full-power relay provides energy for two source nodes and implements digital network coding to compress received data from these source nodes. In the proposed TWEH protocol, two source nodes do not have enough energy to exchange data with each other, they have to collect energy from the intermediate relay through wireless signals before transmitting their data. We analyze and evaluate the system performance in terms of exact closed-form outage probabilities over Rayleigh fading channels. For comparison purposes, a conventional two-way scheme without using digital network coding and energy harvesting (called a TWNEH protocol) is also obtained. Results show that the proposed TWEH protocol outperforms the TWNEH protocol. In addition, the theoretical analyses are verified by performing Monte Carlo simulation.

**Keywords:** Energy harvesting · Two-way scheme · Cooperative communication Decode-and-forward · Digital network coding · Outage probability

## 1 Introduction

Cooperative relaying is very essential to increase diversity capacity and thus to improve range of wireless communication. The aim of the cooperative relaying is to help wireless source nodes to transmit their data to destinations. During the first (broadcast) phase, the source nodes broadcast their data to relays while in the second (cooperation) phase, the relays help the sources to forward the received data to the destinations. In other to transfer data from the sources to the destinations through the relays, cooperative solutions are considered as: Amplify-and-Forward (AF) and Decode-and-Forward (DF) techniques [1–6].

There are many studied cases in cooperative networks about energy harvesting [7–11]. The researchers in [7] studied about the throughput maximization based on the assumptions of both causal and non-causal knowledge of the harvested energy in the


Y. Chen and T. Q. Duong (Eds.): INISCOM 2017, LNICST 221, pp. 155–166, 2018.
https://doi.org/10.1007/978-3-319-74176-5_15

energy harvesting two-hop AF relaying network. In addition, the authors assumed that the channel state information was well recognized before the data were transmitted to the destination by the collaboration of the single relay node and the transmitter.

In [12], the author studied about power transmission policies for the energy harvesting two-way relay which maximize the sum throughput. The energy harvesting relay can perform AF, DF, compress-and-forward, or compute-and-forward relaying.

Most of the above researchers, the authors have considered the situation that the source nodes have enough power in the initial phase of the transmission processes. Exceptionally, in [13], the source nodes do not have enough energy which operate in the one-way scheme. None of the researchers considers two-way relaying networks with limited energies at the source and the destination nodes.

Inspired by the above ideas, in this paper, we propose a two-way energy-harvesting scheme (called a TWEH protocol) in which an intermediate relay supports power to two source nodes and apply digital network coding to compress received data from the source nodes. There are two main considerations as folows. Firstly, we suppose that both sources have insufficiently energy to transmit as well as to receive the data. Hence, each source has to collect energy from the RF signals of the relay. For example in real wireless systems, source nodes sometimes do not have enough energy to transmit and get signals from other sources and relays while original stations have fully energy. In other to set up these systems, we assume that the source nodes get energy from the RF signals of the nodes with full energy (original stations) to charge their battery so that these source nodes have sufficiently energy. The second consideration is the analysis and comparison of the proposed TWEH protocol with a conventional two-way DF scheme without using digital network coding and energy harvesting (called a TWNEH protocol).

This paper is organized as follows: Sect. 2 describes a two-way system model with the energy harvesting architecture and operation principles of the proposed TWEH protocol; Sect. 3 analyzes and calculates the exact outage probabilities of the source nodes, and infers the sum outage probabilities of the protocols TWEH and TWNEH; the simulation results are presented in Sect. 4 and Sect. 5 summarizes our conclusions.

## 2 System Model

As illustrated in Fig. 1, in this paper, we investigate a system model of a DF two-way energy-harvesting scheme with a relay R and two source nodes $S_1$ and $S_2$ in which $S_1$ and $S_2$ are energy harvesting source nodes. In this figure, we assume that two sources $S_1$ and $S_2$ have not enough energy in the transmitting-receiving process of the pilot messages in the set-up phase,and each source harvests energy from the RF signals of the relay R. After the sources harvest energy from the relay, the packets of two source nodes $S_1$ and $S_2$ are carried to the intermediate relay node R.

There are some assumptions as follows. Firstly, each node has a private antenna. Secondly, variances of Zero-mean White Gaussian Noises (AWGNs) are equal, denoted similarly as $N_0$. Thirdly, all channels are designated to flat and block Rayleigh fading. Finally, Channel State-Information (CSI) are recognized at the source nodes $S_1$ and $S_2$ [14].

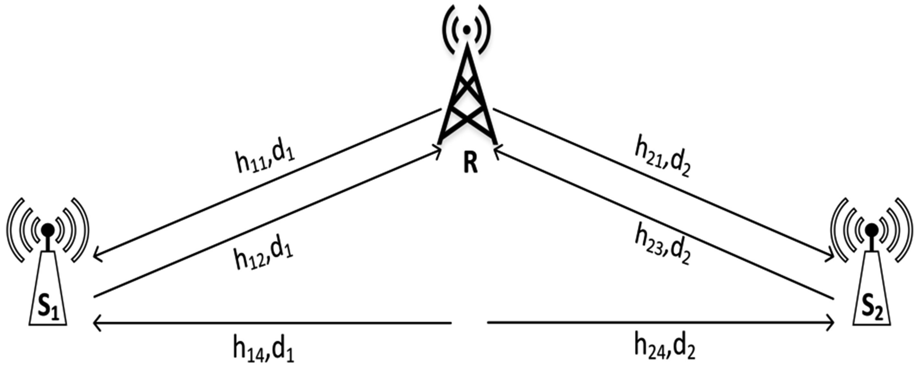


**Fig. 1.** System model of a DF two-way energy-harvesting scheme

In Fig. 1, ($h_{1i}$, $d_1$) and ($h_{2i}$, $d_2$) are Rayleigh fading channel coefficients and the link distances of R-$S_1$, R-$S_2$, respectively, where $i \in \{1,2,3,4\}$, where the first subscript of the Rayleigh fading channel coefficients denotes the hop index whereas the remaining second subscript presents the time slot index. Hence, the random variables $g_{1i} = |h_{1i}|^2$ and $g_{2i} = |h_{2i}|^2$ have exponential distributions with the parameters $\lambda_1 = d_1^{\beta}$ and $\lambda_2 = d_2^{\beta}$, respectively, where $\beta$ is a path-loss exponent. The respectively distances $d_1$ and $d_2$ from the source $S_1$ and $S_2$ to the relay R have considered in [14].

The Cumulative Distribution Function (CDF) and probability density function (pdf) of random variables $g_{ji}$ are expressed as $F_{g_{ji}}(x) = 1 - e^{-\lambda_i x}$ and $f_{g_{ji}}(x) = \lambda_i e^{-\lambda_i x}$, respectively, where $j \in \{1,2\}$.

As above assumptions, the fading channel $h_{ji}$ do not change during a block time $T$, and are independent and identically distributed between two consecutive block times, $j \in \{1,2\}$.

Based on a time division channel model and each source harvests energy from the RF signals of the relay, the operation principle of the DF two-way energy-harvesting scheme (called the TWEH protocol) is split into four time slots as follows. In the initial time slot, an energy-provided packet of the relay is transmitted to all of the sources. In the next time slot, after harvesting energy from the relay, $S_1$ sends an information-carrying packet $x_1$ to the relay. Similar to $S_1$, $S_2$ also dispatches an information-carrying packet $x_2$ to the relay R in the third time slot. Finally, in the last time slot, a coded packet is based on digital network coding by an XOR operation ($x = x_1 \oplus x_2$) is broadcasted to the source nodes $S_1$ and $S_2$.

The mathematical expressions and outage probability analyses of the TWEH and TWNEH protocols will be discussed in the next section.

## 3 Outage Probability Analysis

To analyze the outage probability of the DF two-way schemes (the TWEH and TWNEH protocols), we assume that a node successfully decodes the received packet if its achievable data rate is larger than a target data rate $R_t$.

### 3.1 The TWEH Protocol

Because the system model in Fig. 1 is symmetric, the outage probability of the source node $S_2$ is calculated in the same way as that of the source node $S_1$. Hence, we only present the outage probability of the source node $S_1$, and then we will infer the outage probability of the source node $S_2$.

At the first time slot point of the block time $T$, the relay R broadcasts energy signals $e$ to the source nodes $S_1$ and $S_2$ with a transmitting power $P$, where $E\{|e|^2\} = 1$(E{x} is notated for the expectation process of x). The energy-carried signals received at the source nodes $S_j$ are given, respectively, as

$$y_{S_j}^{(1)} = \sqrt{P}h_{j1}e + n_{S_j} \quad (1)$$

where $n_{S_j}$ denote the AWGNs at receiving antennas of the source nodes $S_j$, respectively, with the same variance $N_0$, $j \in \{1,2\}$. The harvested energies at the source nodes $S_j$ over a time interval $T$ are obtained from (1), as

$$E_{S_j} = P|h_{j1}|^2 T\eta_j \quad (2)$$

where $\eta_i$ are energy conversion efficiencies at the source nodes $S_j$, $0 < \eta_j \leq 1$. Assuming that the source nodes $S_j$ has the same constructions, then the energy conversion efficiencies $\eta_j$ are constant, denoted as $\eta_j = \eta$.

In the second time slot, the signal received at the relay R from the source node $S_1$ is given by

$$y_R^{(2)} = \sqrt{P_{S_1}}h_{12}x_1 + n_R \quad (3)$$

The power $P_{S_1}$ in (3) can be achieved from the harvested energy $E_{S_1}$ as in (2) for sending the signal $x_1$ to the cooperative relay R over a time interval $T$ as follows

$$P_{S_1} = \frac{E_{S_1}}{T} \quad (4)$$

Substituting the harvested energy $E_{S_1}$ from (2) into (4), we obtain the following result:

$$P_{S_1} = P|h_{11}|^2\eta \quad (5)$$

With the same way, at the third time slot, the signal received at the relay R from the source node $S_2$ is given by

$$y_R^{(3)} = \sqrt{P_{S_2}} h_{23} x_2 + n_R \tag{6}$$

Similarly as from (3), over a time interval *T*, the power $P_{S_2}$ can be obtained from the harvested energy $E_{S_2}$ as in (4) for transmitting the signal $x_2$ from the source $S_2$ to the cooperative relay R as follows

$$P_{S_2} = P|h_{21}|^2 \eta \tag{7}$$

The received Signal-to-Noise Ratio (SNR) $SNR_{S_2R}$ at the relay R for decoding the information signal $x_2$ is obtained as follows

$$SNR_{S_2R} = \frac{P_{S_2}|h_{23}|^2}{N_0} = \frac{P\eta|h_{21}|^2|h_{23}|^2}{N_0} = \gamma\eta g_{21} g_{23} \tag{8}$$

where $\gamma$ is defined as a transmit SNR, $\gamma = \frac{P}{N_0}$.

The achievable data rate at the relay R to decode the information signal $x_2$ of the source $S_2$ is given as:

$$R_{S_2R} = \frac{1}{4}\log_2(1 + SNR_{S_2R}) \tag{9a}$$

where a ratio ¼ denotes that the TWEH protocol operates in four time slots.

Substituting the received $SNR_{S_2R}$ from (8) into (9a), $R_{S_2R}$ is expressed as:

$$R_{S_2R} = \frac{1}{4}\log_2(1 + \gamma\eta g_{21} g_{23}) \tag{9b}$$

Decoding operation of the information signal $x_1$ of the source node $S_1$ was performed at the relay R in the second time slot. After receiving the packets $x_1$ and $x_2$, the relay R codes these packets using the digital network coding as $x = x_1 \oplus x_2$. Then, in the fourth time slot, the relay broadcasts the coded packet *x*, thus the received signals at the source nodes $S_j$ is expressed, respectively, as

$$y_{S_j}^{(4)} = \sqrt{P} h_{j4} x + n_{S_j} \tag{10}$$

The received $SNR_{RS_1}$ at the source $S_1$ for decoding the information signal x is obtained from (10) as follows

$$SNR_{RS_1} = \frac{P|h_{14}|^2}{N_0} = \gamma g_{14} \tag{11}$$

We have $SNR_{RS_1}$ in hand, the achievable data rate at the source node $S_1$ from the transmission *x* of the relay R is given as:

$$R_{RS_1} = \frac{1}{4}\log_2(1 + SNR_{RS_1}) \tag{12a}$$

Substituting the $SNR_{RS_1}$ from (11) into (12a), we obtain the following result:

$$R_{RS_1} = \frac{1}{4}\log_2(1 + \gamma g_{14}) \tag{12b}$$

The outage probability of the source node $S_1$ in the TWEH protocol in which the source node $S_1$ does not receive signal from the source node $S_{2,}$ is obtained by a math expression as follows

$$P_{TWEH}^{out\_S_1} = \underbrace{\Pr[R_{S_2R} < R_t]}_{\Pr 1} + \underbrace{\Pr[R_{S_2R} \geq R_t, R_{RS_1} < R_t]}_{\Pr 2} \tag{13}$$

Pr1 is calculated by substituting (9b) into the expression of Pr1 in (13), we obtain the following result:

$$\Pr 1 = \Pr\left[\frac{1}{4}\log_2(1 + \gamma\eta g_{21}g_{23}) < R_t\right] = \int_0^\infty f_{g_{21}}(x)F_{g_{23}}(a/x)dx \tag{14a}$$

where a = $\frac{2^{4R_t}-1}{\gamma\eta}$.

Applying the pdf of the random variable $g_{21}$ and the CDF of the random variable $g_{23}$ into (14a), Pr1 is solved in a closed form expression as

$$\Pr 1 = \int_0^\infty \lambda_2 e^{-\lambda_2 x}\left(1 - e^{-\lambda_2(a/x)}\right)dx = 1 - u_1 \times K_1(1, u_1) \tag{14b}$$

where $u_1 = 2\lambda_2\sqrt{a}$ and $K_1(.)$ is the modified Bessel function [15, Eq. (8.432.6)].

Similarly as Pr1, Pr2 is manipulated by substituting (9b) and (12b) into the formula of Pr2 in (13), Pr2 is rewritten as

$$\begin{aligned}\Pr 2 &= \Pr\left[\frac{1}{4}\log_2(1 + \gamma\eta g_{21}g_{23}) \geq R_t, \frac{1}{4}\log_2(1 + \gamma g_{14}) < R_t\right] \\ &= \underbrace{\Pr\left[\frac{1}{4}\log_2(1 + \gamma\eta g_{21}g_{23}) \geq R_t\right]}_{\Pr 2.1} \underbrace{\times \Pr\left[\frac{1}{4}\log_2(1 + \gamma g_{14}) < R_t\right]}_{\Pr 2.2}\end{aligned} \tag{15}$$

The probability Pr2.1 is calculated as

$$\Pr 2.1 = 1 - \Pr\left[\frac{1}{4}\log_2(1 + \gamma\eta g_{21}g_{23}) < R_t\right] = 1 - \Pr 1 = u_1 \times K_1(1, u_1) \tag{16}$$

The probability Pr2.2 is solved as follows:

$$\Pr 2.2 = \Pr\left[g_{14} < \frac{2^{4R_t} - 1}{\gamma}\right] = \Pr[g_{14} < a\eta] = F_{g_{14}}(a\eta) = 1 - e^{-\lambda_1 a\eta} \tag{17}$$

From (16) and (17), Pr2 is obtained as follows:

$$\Pr 2 = \Pr 2.1 \times \Pr 2.2 = u_1 \times K_1(1, u_1) \times \left(1 - e^{-\lambda_1 a\eta}\right) \tag{18}$$

Finally, owing Pr1 in (14b) and Pr2 in (18) in hand, the outage probability of the source node $S_1$ in the TWEH protocol $P_{TWEH}^{out\_S_1}$ is obtained in the closed-form expression as

$$\begin{aligned} P_{TWEH}^{out\_S_1} &= \Pr 1 + \Pr 2 \\ &= 1 - u_1 \times e^{-\lambda_1 a\eta} \times K_1(1, u_1) \end{aligned} \tag{19}$$

Similarly, the outage probability of the source node $S_2$ in the TWEH protocol $P_{TWEH}^{out\_S_2}$ is inferred by changing $\lambda_2$ to $\lambda_1$ and vice versa as

$$P_{TWEH}^{out\_S_2} = 1 - u_2 \times e^{-\lambda_2 a\eta} \times K_1(1, u_2) \tag{20}$$

where $u_2 = 2\lambda_1\sqrt{a}$

From (19) and (20), the sum outage probability $P_{TWEH}^{out\_sum}$ in the TWEH protocol is obtained to evaluate the asymmetric two-way energy-harvesting scheme as

$$\begin{aligned} P_{TWEH}^{out\_sum} &= P_{TWEH}^{out\_S_1} + P_{TWEH}^{out\_S_2} \\ &= 2 - u_1 \times e^{-\lambda_1 a\eta} \times K_1(1, u_1) - u_2 \times e^{-\lambda_2 a\eta} \times K_1(1, u_2) \end{aligned} \tag{21}$$

## 3.2 The TWNEH Protocol

In the TWNEH protocol, the two source nodes $S_1$ and $S_2$ have enough power. At first, the packet $x_1$ of source node $S_1$ is transmitted to the relay R. This packet is decoded and then is transferred to the source node $S_2$ through the relay R in the next time slot. After receiving the packet from the relay, the source node $S_2$ transmits its own packet $x_2$ to the relay R. In the fourth time slot, the relay also decodes and forwards the packet $x_2$ to the source node $S_1$.

The outage probability of the source node $S_1$ in the TWNEH is expressed as

$$P_{TWNEH}^{out\_S_1} = \underbrace{\Pr[R_{S_2R}^{NEH} < R_t]}_{\Pr 3} + \underbrace{\Pr[R_{S_2R}^{NEH} \geq R_t, R_{RS_1}^{NEH} < R_t]}_{\Pr 4} \tag{22}$$

where $R_{S_2R}^{NEH}$ and $R_{RS_1}^{NEH}$ are achievable data rates at the relay R and the source node $S_1$, respectively.

In the TWNEH protocol, the sum energy equals to $4 \times T \times P_{NEH}$, where $P_{NEH}$ is the same power of the nodes $S_1$, $S_2$ and R, whereas the sum energy in the TWEH is $2 \times T \times P$. With fair comparison purpose about used energy, we set as $4 \times T \times P_{NEH} = 2 \times T \times P$, then $P_{NEH} = P/2$.

The achievable data rates at the relay R and the source node $S_1$ to decode the information signal $x_2$ of the source node $S_2$ are given, respectively, as:

$$R_{S_2R}^{NEH} = \frac{1}{4}\log_2\left(1 + SNR_{S_2R}^{NEH}\right) = \frac{1}{4}\log_2\left(1 + \frac{\gamma g_{23}}{2}\right) \tag{23}$$

$$R_{RS_1}^{NEH} = \frac{1}{4}\log_2\left(1 + SNR_{RS_1}^{NEH}\right) = \frac{1}{4}\log_2\left(1 + \frac{\gamma g_{14}}{2}\right) \tag{24}$$

By substituting $R_{S_2R}^{NEH}$ from (23) into the formula of Pr3 in (22), Pr3 is solved as follows

$$\begin{aligned} \Pr 3 &= \Pr\left[\frac{1}{4}\log_2\left(1 + \frac{\gamma g_{23}}{2}\right) < R_t\right] = \Pr\left[g_{23} < 2\frac{2^{4R_t} - 1}{\gamma}\right] \\ &= \Pr[g_{23} < 2a\eta] = F_{g_{23}}(2a\eta) = 1 - e^{-2\lambda_2 a\eta} \end{aligned} \tag{25}$$

Similarly as Pr3, Pr4 are obtained by substituting $R_{S_2R}^{NEH}$ from (23) and $R_{RS_1}^{NEH}$ from (24) into the formula of Pr4 in (22) as

$$\begin{aligned} \Pr 4 &= \left[1 - \Pr\left(g_{23} < 2\frac{2^{4R_t} - 1}{\gamma}\right), \Pr\left(g_{14} < 2\frac{2^{4R_t} - 1}{\gamma}\right)\right] \\ &= e^{-2\lambda_2 a\eta} \times \left(1 - e^{-2\lambda_1 a\eta}\right) \end{aligned} \tag{26}$$

From (25) and (26), the outage probability of the source node $S_1$ in the TWNEH protocol $P_{TWNEH}^{out\_S_1}$ is also obtained in the closed-form expression as

$$P_{TWNEH}^{out\_S_1} = \Pr 3 + \Pr 4 = 1 - e^{-(\lambda_1 + \lambda_2)2a\eta} \tag{27}$$

Because of identical effects of the relay R on the transmission between the source node $S_1$ and $S_2$ in the TWNEH protocol, the outage probability $P_{TWNEH}^{out\_S_2}$ of the source node $S_2$ is equal to $P_{TWNEH}^{out\_S_1}$ and the sum outage probability $P_{TWNEH}^{out\_sum}$ in the TWNEH protocol is $2 \times P_{TWNEH}^{out\_S_1}$.

## 4 Simulation Results

In this section, the system performance of two protocols TWEH and TWNEH is analyzed and evaluated using the exact theoretical analyses and the Monte Carlo simulations of the (sum) outage probabilities. In the two-dimensional plane, the coordinates of $S_1$, $S_2$, and R are $S_1$ (0, 0), $S_2$ (1, 0) and R (x, y), respectively, satisfying

0 < x < 1. Therefore, $d_1 = \sqrt{x^2 + y^2}$ and $d_2 = \sqrt{(1-x)^2 + y^2}$. We assume that the path-loss exponent β is set to 3, and the SNR on the *x*-axis is defined as SNR = $P/N_0$.

Figure 2 presents the outage probabilities of the source nodes $S_1$ and $S_2$ in the protocols TWEH and TWNEH versus the SNR (dB) when the symmetric network model is considered with $x = 0.5$, y = 0, $R_t = 1$ (bit/s/Hz) and $\eta = 0.9$. Due to the symmetric network model, the outage probabilities of the source nodes $S_1$ and $S_2$ are identical. As shown in Fig. 2, the outage probabilities of the source nodes $S_1$ and $S_2$ in both protocols decrease when the SNRs increase because the harvested energies as in formulas (21) and (27), the decoding capacities at the nodes $S_1$, $S_2$ and R are larger at the higher SNRs. In addition, the performance of the proposed TWEH protocol outperforms the conventional TWNEH protocol because the proposed TWEH protocol applies the digital network coding to compensate the loss of the bandwidth for the energy harvesting phase (the first time slot). Lastly, we can see that the simulation results fit well to the theoretical results. Hence, we can conclude that the derived formulas during analyzing are accurate.

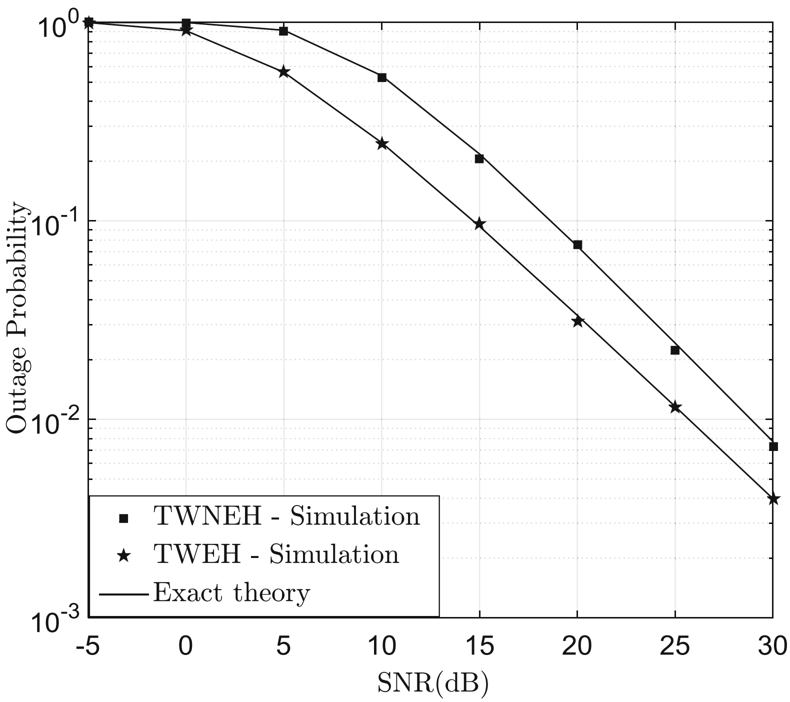


**Fig. 2.** The outage probabilities of the source nodes $S_1$ and $S_2$ in the protocols TWEH and TWNEH versus SNR (dB) when x = 0.5, $R_t = 1$ (bit/s/Hz), $\eta = 0.9$.

Figure 3 presents the sum outage probabilities versus $\eta$ in the asymmetric network scheme of the protocols TWEH and TWNEH with $R_t$ = *1*(bit/s/Hz), $x$ = 0.5, y = 0, $\eta$ is changed from 0.1 to 1, and the SNR values are set to 10 and 20 (dB). In Fig. 3, the TWEH protocol has the smaller sum outage probability in comparison with TWNEH protocol at SNR = 10 dB. At SNR = 20 dB, the sum outage probability values of the TWEH protocol are greater than those of the TWNEH protocol when $\eta < 0.2$ (small energy conversion efficiency). Nevertheless, when the energy conversion efficiency increases from 0.2 to 1, the sum outage probability of the TWEH protocol also goes down and lower than the sum outage probability of the TWNEH protocol. We note that the protocol TWNEH does not apply the energy harvesting so that the sum outage probability does not depend on $\eta$ and is constant versus $\eta$.

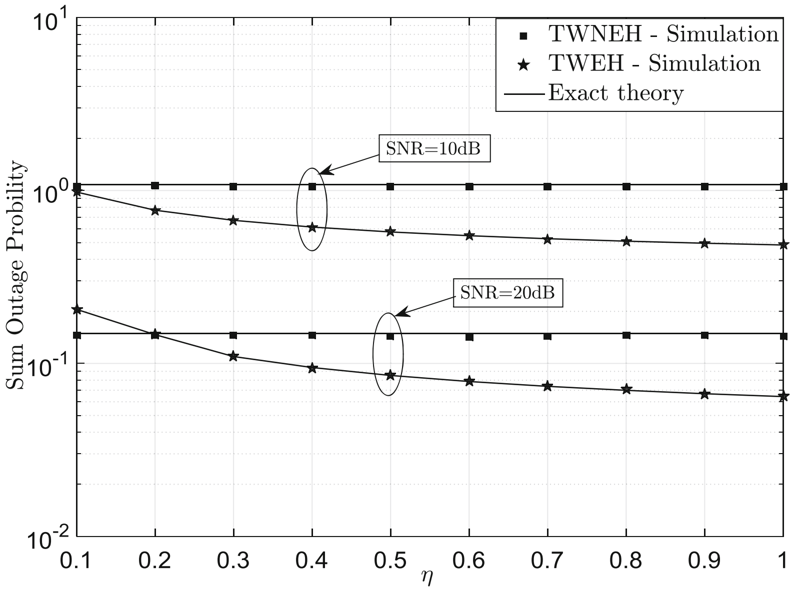


**Fig. 3.** The sum outage probabilities of the scheme in the TWEH and TWNEH protocols versus $\eta$ when x = 0.5, y = 0, $R_t$ = 1 (bit/s/Hz) and SNR is considered at 10 and 20 (dB).

Figure 4 illustrates the sum outage probability of the protocols TWEH and TWNEH in the asymmetric network scheme as a function of $R_t$ when x = 0.5, y = 0, SNR values are set to 10 (dB) and 20 (dB). It can be seen that when target data rate $R_t$ goes up, the system performance of the protocols TWEH and TWNEH decreases and then moves to the worst regions (about $R_t > 2.5$).

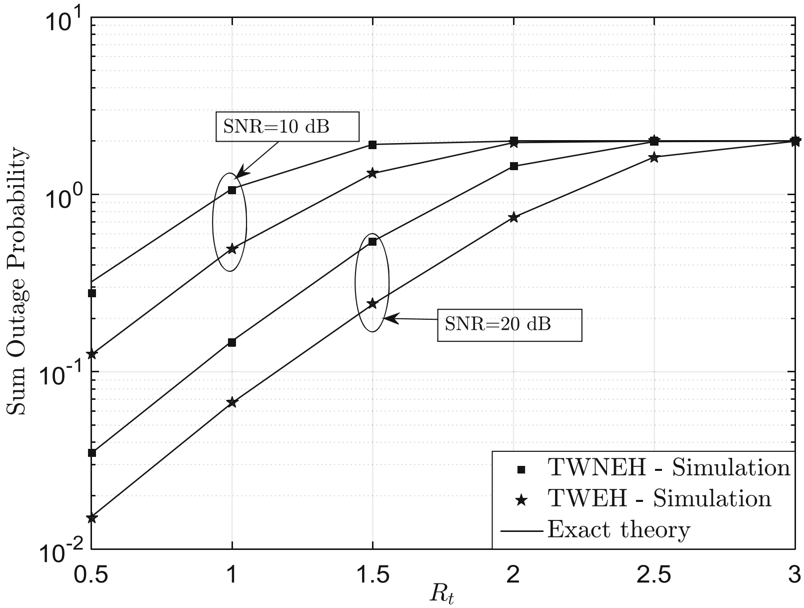


**Fig. 4.** The sum outage probabilities of the scheme in the TWEH and TWNEH protocols versus $R_t$ when x = 0.5, y = 0, and SNR is considered at 10 and 20 (dB).

## 5 Conclusions

In this paper, we propose the two-way energy-harvesting scheme (called the TWEH protocol) in which the intermediate relay provides power to two source nodes and applies the digital network coding to compress received data from the source nodes. In the proposed TWEH protocol, during the first time slot, each source has to collect energy from the RF signals of the relay to have sufficiently energy to transmit as well as to receive the data in the next three time slots. The exact closed-form outage probability expressions are used to evaluate the system performance of the proposed protocol and are verified by the Monte Carlo simulation method. The results show that the proposed TWEH protocol achieves higher performance when comparing with the conventional two-way DF scheme without using digital network coding and energy harvesting (called the TWNEH protocol), and both protocols reach the smallest sum outage probabilities when the relay is located at the midpoint of the two sources. In addition, the closed-form theory expressions of the (sum) outage probabilities match well with the Monte Carlo simulation results.

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