# Relay Selection Scheme for Energy Harvesting Cooperative Networks

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**Abstract.** Harvesting energy from the radio-frequency signal is an appealing approach to replenish energy in energy-constrained networks. In this paper, relay selection (RS) in a half-duplex decode-and-forwarding multi-relay network with an energy harvesting source is investigated. Without relying on dedicated wireless power transfer, in our system the source is powered by salvaging energy from the relaying signals. In this network, RS will affect both the current transmission quality and the source energy state in the following transmission block, which is not considered in the traditional RS schemes. Thus, a two-step distributed RS scheme is proposed to improve the system performance and is compared with the max-min signal-to-noise ratio strategy. In our proposed RS scheme, the system outage probability is derived in a closed form, and the diversity gain is shown to achieve the full diversity order. Finally, numerical results are given to evaluate the performance and verify the analysis.

**Keywords:** Cooperative communications · Energy harvesting · Relay selection · DF-relay · Distributed

## 1 Introduction

Harvesting energy from wireless radio frequency (RF) signals, which is a very promising technology to realize green communications, has recently drawn considerable attention [1]. Since RF signal carries information as well as energy, simultaneous wireless information and power transfer (SWIPT) was first introduced in [2,3], where the tradeoff between harvested energy and information was investigated. Considering practical limitations, two realizable circuit designs for SWIPT were proposed as time switching (TS) and power splitting (PS), respectively [4].

In several practical wireless networks, such as sensor networks and wireless body area networks, a sensor node as the information source is powered by batteries which are inconvenient or even impossible to be replaced. Therefore, energy harvesting (EH) is a meaningful technology for power supply in networks with an energy-constrained source node [5]. In [6], the authors considered a three-node cooperative network performing wireless power transfer (WPT) where the source is wireless-powered by the access point before the data transmission.


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In all the above works, additional time or power resources compared with traditional networks are consumed for power transfer. For the PS structure, the received signal is split into two streams for EH and information decoding separately, whereas for the TS and WPT structure, a part of transmission time is sacrificed for EH. In contrast, an appealing solution for half-duplex cooperative networks with an energy-constrained source is to salvage energy during the relaying interval and use the harvested energy for information transfer in the following transmission. Due to the broadcast nature of wireless medium, the relaying signals can be received and further converted to usable DC power by the source without additional time or power consumption. The transmission outage performance for such an EH cooperative network was analyzed in [7], and the optimal power allocation scheme to maximize the system throughput was proposed in [8]. However, both the works in [7,8] assume the single-relay scenario.

Considering the multi-relay scenario, optimal relay selection (RS) is an easy implemented and effective approach for developing system performance, and the max-min signal-to-noise ratio (SNR) criterion is the outage optimal RS scheme in the traditional cooperative networks [9]. However, in the scenario where source salvages energy from the relaying signals, RS affects both the current transmission quality and the source energy state in the next transmission block, which is not considered in existing RS schemes. For example, to select a relay merely minimizing the outage probability in the current transmission may cause a low transmit power of the source in the following transmission, and on the other hand, to select a relay which can maximize the harvested energy may lead to a high outage probability of the current transmission. The reason is that the data transmission is influenced by both the two hops channel qualities, while EH only depends on the channel gain of the first hop. Thus, RS in this considered system should take into account both the current performance and the future evolution of the network. Beyond that, since in practical networks the future channel coefficients can not be known in the current transmission, it is difficult to find the exact tradeoff of the system performance between the current and the future transmissions.

In this paper, we investigate the decode-and-forwarding (DF) multi-relay two-hop network where an energy-constrained source salvages energy from the relaying signals during the current transmission block and will utilize the harvested energy for information transfer in the following transmission. Motivated by above observations, we propose a two-step RS scheme to improve the system performance in this considered network, and the RS scheme is performed in the distributed mechanism to decrease the complexity and energy consumption of the energy-constrained source. The system performance achieved by our proposed RS scheme is evaluated in outage probability and is compared with the max-min SNR scheme. Furthermore, we derive the closed-form outage probability expressions for the proposed RS scheme and analyze the achievable diversity order in high-SNR regime. Analytical results show that the proposed scheme achieves the full diversity order.

## 2 System Model

Consider a half-duplex DF relay-assisted network which consists of an RF-EH source $S$, a destination $D$, and $M$ DF-relays $R_i$ $i = 1, 2, ..., M$, as shown in Fig. 1. There is no direct link between $S$ and $D$. The transmission is performed with the help of one selected relay. We assume that all channels experience independent Rayleigh fading, and $M$ relays are clustered relatively close together. Consequently, the coefficients of source-to-relay and relay-to-destination links, denoted as $\{h_1, h_2, ..., h_M\}$ and $\{g_1, g_2, ..., g_M\}$, are independent and identically distributed (i.i.d.) complex Gaussian random variables, i.e., $h_i \sim \mathcal{CN}(0, \Omega_h)$ and $g_i \sim \mathcal{CN}(0, \Omega_g)$. Moreover, the block-fading channel model is considered which means the channel coefficients remain constant during one transmission block but change independently from one block to another. In addition, let $h_i(k)$ and $g_i(k)$ denote the channel coefficients in the $k$-th block.

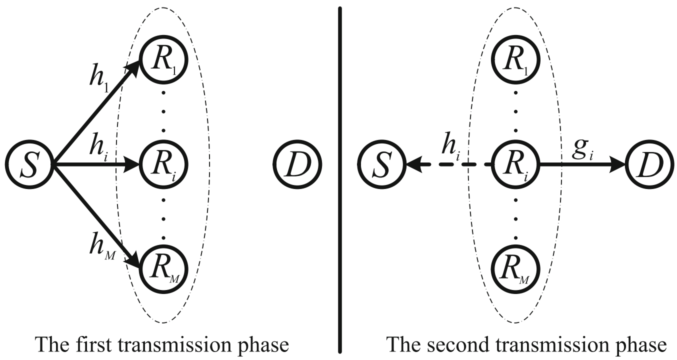


**Fig. 1.** System model with illustration of the two transmission phases in a transmission block.

Similar to the traditional relay-assisted communication, a transmission block is performed in two phases. In the first phase of $(k-1)$-th block, $S$ broadcasts information with a transmit power $P_S(k-1)$, which depends on the harvested energy in the previous transmission. After that, a selected relay $R_i$ decodes and forwards the information powered by a stabilized power source $P_R$ in the second phase. Meanwhile, $S$ harvests energy from the forwarding signal transmitted by $R_i$ for further data transmission in the $k$-th block. Considering the channel reciprocity, the harvested energy at $S$ in the $(k-1)$-th block is given by

$$E_S(k-1) = \eta P_R |h_i(k-1)|^2 T/2, \tag{1}$$

where $\eta$, $0 < \eta \leq 1$, denotes the conversion efficiency of EH and $T$ denotes the time duration of a transmission block. In addition, we assume there is a dedicated power transfer from the relay to the source in order to guarantee the initial transmission. In $k$-th block, the received signal at $R_i$ is expressed as

$$y_i^R(k) = \sqrt{\eta P_R |h_i(k-1)|^2} x(k) h_i(k) + n_i(k), \tag{2}$$

where $x(k)$ is the information signal with unity energy and $n_i(k)$ is baseband additive white Gaussian noise (AWGN) with zero mean and variance $\sigma_i^2$. The signal observation at $D$ via relay $R_i$ is given by

$$y_i^D(k) = \sqrt{P_R}x(k)g_i(k) + n_d(k), \tag{3}$$

where $n_d(k)$ is AWGN at $D$ and $n_d(k) \sim \mathcal{CN}(0, \sigma_d^2)$. We assume both $\sigma_i^2$ and $\sigma_d^2$ are equal to $\sigma_o^2$ for simplicity.

From Eq. (2), the first-hop received SNR at relay $R_i$ is expressed as

$$\gamma_i^R(k) = \frac{\eta P_R |h_i(k-1)|^2 |h_i(k)|^2}{\sigma_o^2}. \tag{4}$$

According to Eq. (3), the SNR at $D$ with the help of the $i$-th relay is given by

$$\gamma_i^D(k) = \frac{P_R |g_i(k)|^2}{\sigma_o^2}. \tag{5}$$

Setting the target transmission rate as $\mathbf{R}$ bps/Hz, the SNR threshold at each receiver is given by

$$\gamma_{\text{th}} = 2^{2\mathbf{R}} - 1. \tag{6}$$

## 3 Relay Selection Schemes

Aiming at improving the system outage performance, a two-step relay selection scheme for the source-energy-constrained cooperative network is described as follows:

- Construct a set, denoted by $\mathcal{R}(k)$, containing all the relays by which the signal transmitted can be successfully decoded at $D$ in the $k$-th block, i.e., $\mathcal{R}(k) \triangleq \{R_i \mid \gamma_i^D(k) \geq \gamma_{\text{th}}, i = 1, 2, ..., M\}$.
- A relay in $\mathcal{R}(k)$ which will maximize the received SNR of the first hop will be selected, i.e., $R^*(k) = \arg \max\limits_{R_i \in \mathcal{R}(k)} \{\gamma_i^R(k)\}$. In the case that $\mathcal{R}(k) = \varnothing$, all nodes will keep silence in the k-th block for saving energy due to an inevitable outage.

To simplify the notations, denote the channel gains of link $S - R^*(k)$ and link $R^*(k) - D$ as $|h^*(k)|^2$ and $|g^*(k)|^2$, respectively. By substituting Eq. (4), we have

$$R^*(k) = \arg \max_{R_i \in \mathcal{R}(k)} \left\{ \frac{\eta P_R |h^*(l)|^2 |h_i(k)|^2}{\sigma_o^2} \right\}, \tag{7}$$

where $l$ is the index of a recent block, in which $\mathcal{R}(l)$ is not a null set. Since the random variable $|h^*(l)|^2$ has produced a sample value in the $k$-th block, Eq. (7) can be simplified as

$$R^*(k) = \arg \max_{R_i \in \mathcal{R}(k)} \{|h_i(k)|^2\}. \tag{8}$$

Eqs. (7) and (8) indicate an important feature that the instantaneous energy state information of $S$ is not demanded in the proposed RS scheme which leads to the lower system overhead compared with the max-min SNR scheme [9].

The above RS process can be performed in a distributed RS mechanism based on timing structure. At the beginning of a transmission block, relays estimate all the channel coefficients via pilot packets transmitted by $S$ and $D$. Afterwards, each relay $R_i$ sets the initial value of its countdown timer as $1/|h_i(k)|^2$. The relay which counts to zero first, will broadcast one bit signal to announce itself the best relay. Due to space limitations, more details about distributed RS mechanism can be seen in [10].

## 4 Performance Analysis

In this section, the performance of the proposed RS scheme is studied in terms of the outage probability.

For the proposed two-step RS scheme, the outage probability can be written as

$$P_{\text{out}}^{\text{Pro}} = \Pr\{|\mathcal{R}(k)| = 0\} + \underbrace{\Pr\{|\mathcal{R}(k)| > 0, |h^*(l)|^2|h^*(k)|^2 < \frac{\varepsilon}{\eta}\}}_{P_1}, \tag{9}$$

where $\varepsilon = (2^{2\mathbf{R}}-1)\sigma_o^2/P_R$ and $|\mathcal{R}(k)|$ denotes the cardinality of set $\mathcal{R}(k)$. Recall that $\{|h_i(k)|^2 \mid i = 1, 2, ..., M\}$ and $\{|g_i(k)|^2 \mid i = 1, 2, ..., M\}$ follow independent and identically exponential distribution with mean $\Omega_h$ and $\Omega_g$, respectively. The corresponding cumulative distribution function (CDF) of $|h_i(k)|^2$ is given as $F_{|h_i(k)|^2}(x) = 1 - e^{-x/\Omega_h}$, and that of $|g_i(k)|^2$ is $F_{|g_i(k)|^2}(x) = 1 - e^{-x/\Omega_g}$. According to order statistics, the probability of $|\mathcal{R}(k)| = m$ is given as

$$\begin{aligned}\Pr\{|\mathcal{R}(k)| = m\} =& \binom{M}{m}(\Pr\{|g_i(k)|^2 \geq \varepsilon\})^m(\Pr\{|g_i(k)|^2 < \varepsilon\})^{M-m} \\ =& \frac{M!}{(M-m)!m!}e^{-m\varepsilon/\Omega_g}(1 - e^{-\varepsilon/\Omega_g})^{M-m}.\end{aligned} \tag{10}$$

On the other hand, by using the Total Probability Theorem, $P_1$ can be calculated as follows:

$$\begin{aligned}P_1 =& \sum_{m=1}^{M}\Pr\{|\mathcal{R}(k)| = m\}\Pr\{|h^*(l)|^2|h^*(k)|^2 < \frac{\varepsilon}{\eta}||\mathcal{R}(k)| = m\} \\ =& \sum_{m=1}^{M}\sum_{n=1}^{M}\Pr\{|\mathcal{R}(k)| = m\}\frac{\Pr\{|\mathcal{R}(l)| = n\}}{1 - \Pr\{|\mathcal{R}(l)| = 0\}} \\ & \times \underbrace{\Pr\{|h^*(l)|^2|h^*(k)|^2 < \frac{\varepsilon}{\eta}||\mathcal{R}(k)| = m, |\mathcal{R}(l)| = n\}}_{P_2},\end{aligned} \tag{11}$$

where the denominator is for probability normalization due to the fact that the transmission happens only when $\mathcal{R}(k)$ is not a null set. The factor $P_2$ can be calculated as

$$P_2 = \int_0^\infty \Pr\{|h^*(k)|^2 < \frac{\varepsilon}{\eta y}\big||\mathcal{R}(k)| = m\}\Pr\{|h^*(l)|^2 = y\big||\mathcal{R}(l)| = n\}dy. \tag{12}$$

The condition, $|\mathcal{R}(k)| = m$, has no effect on $|h_i(k)|^2$ which is still exponentially distributed. Thus, from Eq. (8), the conditional CDF of $|h^*(k)|^2$ and the probability distribution function (PDF) of $|h^*(l)|^2$ are given as

$$F_{|h^*(k)|^2\big||\mathcal{R}(k)|=m}(x) = (\Pr\{|h_i(k)|^2 < x\})^m = (1 - e^{-x/\Omega_h})^m, \tag{13}$$

$$\Pr\{|h^*(l)|^2 = y\big||\mathcal{R}(l)| = n\} = \frac{n}{\Omega_h}(1 - e^{-y/\Omega_h})^{n-1}e^{-y/\Omega_h}. \tag{14}$$

Therefore, $P_2$ can be calculated as

$$\begin{aligned}
P_2 &= \int_0^\infty \frac{n}{\Omega_h}(1 - e^{-\varepsilon/(\Omega_h \eta y)})^m(1 - e^{-y/\Omega_h})^{n-1}e^{-y/\Omega_h}dy \\
&\overset{(e)}{=} \frac{n}{\Omega_h}\sum_{a=0}^{m}\sum_{b=0}^{n-1}\binom{m}{a}\binom{n-1}{b}(-1)^{a+b}\int_0^\infty e^{-a\varepsilon/(\Omega_h\eta y)-(b+1)y/\Omega_h}dy \\
&= n\sum_{a=1}^{m}\sum_{b=0}^{n-1}\binom{m}{a}\binom{n-1}{b}(-1)^{a+b}\frac{1}{b+1}\sqrt{\frac{4a(b+1)\varepsilon}{\Omega_h^2\eta}}\mathbf{K}_1\left(\sqrt{\frac{4a(b+1)\varepsilon}{\Omega_h^2\eta}}\right) \\
&\quad + n\sum_{b=0}^{n-1}\binom{n-1}{b}(-1)^b\frac{1}{b+1},
\end{aligned} \tag{15}$$

where $\mathbf{K}_1(x)$ is the first-order modified Bessel function of the second kind [11, Eq. (3.324.1)], and the equal sign $(e)$ is obtained by binomial expansions. Furthermore, by changing the variable, we have

$$n\sum_{b=0}^{n-1}\binom{n-1}{b}(-1)^b\frac{1}{b+1} = -\sum_{b=1}^{n}\binom{n}{b}(-1)^b = 1. \tag{16}$$

Thus, $P_2$ can be expressed as

$$P_2 = 1 - \sum_{a=1}^{m}\sum_{b=1}^{n}\binom{m}{a}\binom{n}{b}(-1)^{a+b}\sqrt{\frac{4ab\varepsilon}{\Omega_h^2\eta}}\mathbf{K}_1\left(\sqrt{\frac{4ab\varepsilon}{\Omega_h^2\eta}}\right). \tag{17}$$

By plugging Eqs. (10), (11) and (17) into Eq. (9), the analytical expression for the outage probability of the proposed RS scheme is given as

$$\begin{aligned}P_{\text{out}}^{\text{Pro}} =& (1-e^{-\varepsilon/\Omega_g})^M + \frac{1}{1-(1-e^{-\varepsilon/\Omega_g})^M}\\ &\times \sum_{m=1}^{M}\sum_{n=1}^{M}\binom{M}{m}\binom{M}{n}(1-e^{-\varepsilon/\Omega_h})^{2M-m-n}e^{-(m+n)\varepsilon/\Omega_h}\\ &\times \left(1-\sum_{a=1}^{m}\sum_{b=1}^{n}\binom{m}{a}\binom{n}{b}(-1)^{a+b}\sqrt{\frac{4ab\varepsilon}{\Omega_h^2\eta}}\mathbf{K}_1\left(\sqrt{\frac{4ab\varepsilon}{\Omega_h^2\eta}}\right)\right). \end{aligned} \tag{18}$$

In addition, Eq. (18) can be used for the analysis of the diversity gain achieved by the proposed RS scheme. To clarify the analytical results, we set constant coefficients $\eta = \Omega_h = \Omega_g = 1$, which have no impact on diversity order obtained at high SNR. When $x \to 0$, the following approximations can be established: [6]

$$x\mathbf{K}_1(x) \approx 1 + \frac{x^2}{2}\ln\frac{x}{2}, \tag{19}$$

$$1-e^{-x} \approx x. \tag{20}$$

Thus, in high SNR regime, i.e., $\varepsilon \to 0$, by applying (19), $P_2$ can be approximated as

$$\begin{aligned}P_2 &\approx 1-\sum_{a=1}^{m}\sum_{b=1}^{n}\binom{m}{a}\binom{n}{b}(-1)^{a+b}(1+ab\varepsilon\ln(ab\varepsilon))\\ &= \sum_{a=1}^{m}\binom{m}{a}(-1)^a a\sum_{b=1}^{n}\binom{n}{b}(-1)^b b\varepsilon\big(\ln\frac{1}{ab}+\ln\frac{1}{\varepsilon}\big)\\ &\approx \varepsilon\ln\frac{1}{\varepsilon}\left(\sum_{a=1}^{m}\binom{m}{a}(-1)^a a\right)\left(\sum_{b=1}^{n}\binom{n}{b}(-1)^b b\right)\\ &= \varepsilon\ln\frac{1}{\varepsilon}\left(\sum_{a=1}^{m}\binom{m}{a}(-1)^{a+1} a\right)\left(\sum_{b=1}^{n}\binom{n}{b}(-1)^{b+1} b\right). \end{aligned} \tag{21}$$

Using (20) and (21), the outage probability in high SNR regime can be approximated as follow:

$$\begin{aligned}P_{\text{out}}^{\text{Pro}} \approx& \varepsilon^M + \sum_{m=1}^{M}\sum_{n=1}^{M}\binom{M}{m}\binom{M}{n}\varepsilon^{2M-m-n+1}\ln\frac{1}{\varepsilon}\\ &\times\left(\sum_{a=1}^{m}\binom{m}{a}(-1)^{a+1}a\right)\left(\sum_{b=1}^{n}\binom{n}{b}(-1)^{b+1}b\right), \end{aligned} \tag{22}$$

Recall the following property about the sums of binomial coefficients: [11, Eq. (0.154.2)]

$$\sum_{k=1}^{K}\binom{K}{k}(-1)^{k+1}k = 0, \tag{23}$$

for $K \geq 2$. By applying (23), the approximated outage probability can be simplified as

$$P_{\text{out}}^{\text{Pro}} \approx \varepsilon^M + M^2 \varepsilon^{2M-1} \ln \frac{1}{\varepsilon} = \varepsilon^M + M^2 \varepsilon^M \big(\varepsilon^{M-1} \ln \frac{1}{\varepsilon}\big), \tag{24}$$

where $\varepsilon^{M-1} \ln(1/\varepsilon) \to 0$ when $\varepsilon \to 0$ and $M \geq 2$. Therefore, we have $\frac{\log P_{\text{out}}^{\text{Pro}}}{\log \varepsilon} \to M$, which indicates that the proposed RS scheme achieves a full diversity gain.

## 5 Numerical Results

In this section, numerical results are presented to verify the analysis and evaluate the performance of our proposed RS scheme. And as a benchmark, the simulation results of the outage performance achieved by max-min SNR criterion are shown in Figs. 1 and 3. We set the noise variance as $\sigma_i^2 = \sigma_d^2 = \sigma_o^2 = 1$, and the average channel gain as $\Omega_h = \Omega_g = 1$. The energy conversion efficiency is assumed as $\eta = 1$. Throughout this section, the term "SNR" represents the transmitted SNR at relays i.e., $\text{SNR} = P_R/\sigma_o^2$.

Figure 2 shows the outage probabilities as a function of SNR where the target rate is $\mathbf{R} = 3\,\text{bps/Hz}$ and the number of relays is 3 or 6. The accuracy of our closed-form expressions of the outage probability is verified by simulation results. Moreover, it is demonstrated that the outage performance gains of our proposed scheme is advanced with the increase of SNR. The reason is that, for the proposed RS scheme, more relays are active due to high SNR. It means a better source-to-relay link can be selected, which improves the energy state of source in the following block.

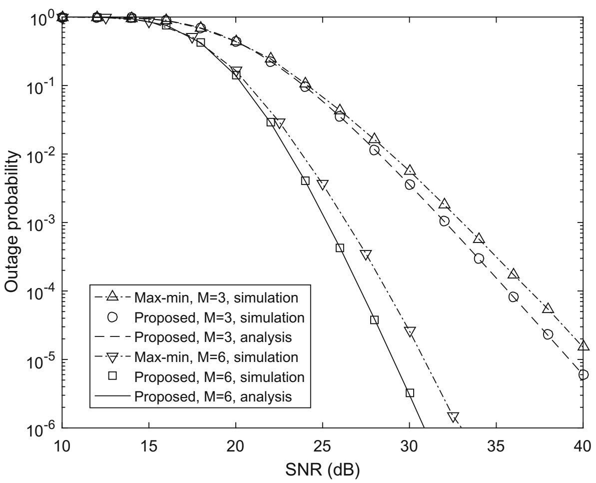


**Fig. 2.** Outage probability vs. SNR for $\mathbf{R} = 3\,\text{bps/Hz}$.

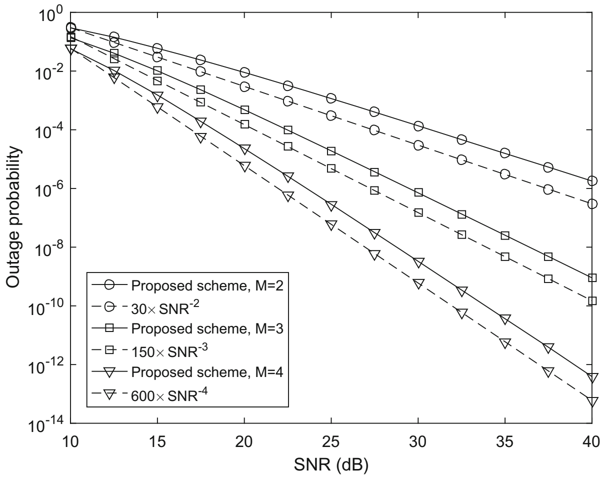


**Fig. 3.** Verification of the diversity order for the proposed RS scheme when $\mathbf{R} = 1\,\mathrm{bps/Hz}$.

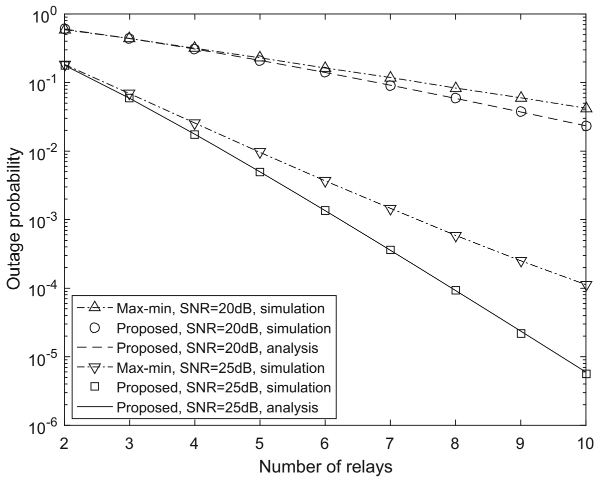


**Fig. 4.** Outage probability vs. number of relays for $\mathbf{R} = 3\,\mathrm{bps/Hz}$.

In Fig. 3, the analysis about the diversity gains is verified. The full curves are generated by analytical results, and the dot-dash lines are drawn as auxiliary lines with the diversity order of $M$. It can be seen that the full curves tend to straight lines and get parallel to the auxiliary lines with the increase of SNR. Therefore, our proposed scheme is verified to achieve the full diversity order, as is derived by the analytical results.

Figure 4 shows the performance gap versus the number of relays when the target rate is $\mathbf{R} = 3\,\mathrm{bps/Hz}$ and SNR is 20 dB or 25 dB. It is obvious that the gap of outage performance between the proposed scheme and the max-min SNR scheme extends as $M$ increases.

## 6 Conclusion

In this paper, we investigated RS in a cooperative network with an energy-constrained source node. We proposed a two-step RS scheme which improves the system outage performance and incurs lower system overhead since the energy state information is not required. To evaluate the proposed scheme, we derived the closed-form expression of outage probability for the proposed scheme. We further analyzed the diversity order of the proposed scheme and showed that the scheme achieves the full diversity order. Numerical results verified our theoretical analysis and demonstrated the advantages over the max-min SNR scheme.

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