Network-coding-based two-way relay cooperation with energy harvesting

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Abstract
For the relay cooperation systems or networks, in some scenarios, the relay is deployed in the hard-to-reach areas, such as on the remote mountains or in the sea. It is impractical for the relay to be powered by grid energy. And if the relay is powered by battery, it is difficult and high cost to replace the depleted battery. To overcome the power dependence of the relay, this article proposes the network-coding-based two-way relay cooperation with energy harvesting, where the relay is equipped with multiple antennas for information decoding and energy harvesting. Network coding is adopted at the relay to reduce the time slots, and low-density parity check codes are employed at the sources to improve the reliability. We introduce a maximal ratio combining–based decoding algorithm for the proposed system to achieve coding gain and diversity gain. Furthermore, we analyze the outage probability and bit error rate of the system when the optimal antenna selection algorithm is adopted at the relay to transmit data. Theoretical analysis and numerical simulation results show that the proposed system outperforms the corresponding point-to-point system under the same condition. The result also demonstrates that the relay should be deployed closer to the user whose outage probability is required to be lower.

Keywords
Relay cooperation, energy harvesting, network coding, maximal ratio combining, low-density parity check codes

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Introduction
Energy harvesting from ambient environment can potentially reduce the dependence on the supply of battery or grid energy. Recently, energy-harvesting communications and networks have attracted great attention from both academic and industrial communities. Based on the energy-harvesting technology, the communication nodes can benefit the energy saving and lower the carbon footprint. What is more important, because the nodes are powered by harvested energy, their lifetime is not limited by the battery or grid energy, and they can be deployed in hard-to-reach areas to enlarge the coverage and reduce the communication blind zones. Traditional energy-harvesting techniques rely on natural energy sources such as solar or wind. The energy harvested level is influenced by many factors, such as the time of the sunshine and the seasonal weather patterns. Since ambient radio frequency (RF) signals are widely available in the world, a promising harvesting technology is to use the RF energy. RF-based energy-harvesting communications can realize simultaneous information and power transfer (SWIPT), which generates great interest in the research of this area.

RF-based energy harvesting is extensively investigated in various communication scenarios, such as multiple-input multiple-output (MIMO) systems,
cognitive radio networks\textsuperscript{11,12} and relay cooperation.\textsuperscript{13–15} Relay cooperation\textsuperscript{16,17} enables single-antenna nodes to share the use of their antennas to form a virtual MIMO, which exploits the spatial diversity and improve the performance of wireless communication systems. Hence, relay cooperation with energy harvesting can not only achieve high performance but also break through the power limitation. Li et al.\textsuperscript{20} considered a non-convex regenerative two-way multi-antenna relay network with two-way relay cooperation scenarios. For a non-

The average symbol error rate performance is minimized through the MDP framework. Ku et al.\textsuperscript{18} investigated a cooperative system strategies are developed by a Markov decision process (MDP). Ku et al.\textsuperscript{18} investigated a cooperative system with energy harvesting. In order to maximize the long-term utility of the network, energy efficient scheduling and-forward relay cooperative network. In offline and online settings, optimal policies for transmission are obtained via maximizing the throughput. Some researchers extended the one-way cooperative systems or networks with energy harvesting\textsuperscript{4,18,19} to two-way relay cooperation scenarios. For a non-regenerative two-way multi-antenna relay network with energy harvesting, Li et al.\textsuperscript{20} considered a non-convex energy-harvesting-constrained relay beam-forming optimization problem. Based on semi-definite programming and rank-one decomposition theorem, an iterative algorithm is proposed to find the global optimal solution. Shah et al.\textsuperscript{21} proposed a two-way multiplicative relay with energy harvesting, where the relay node uses power splitting–based relaying protocol for energy harvesting and information processing. Du et al.\textsuperscript{22} presented a time switching–based network-coding relaying (TSNCR) protocol for the two-way relay system with energy harvesting. The outage probability for the proposed TSNCR protocol is derived and further minimized by a genetic optimization algorithm. All the scenarios considered in Li et al.,\textsuperscript{20} Shah et al.,\textsuperscript{21} and Du et al.\textsuperscript{22} ignore the direct link between the sources which may be blocked due to obstacles. However, when there are no obstacles between the sources, the direct link should be taken into account.

In this article, we investigate the network-coding-based two-way relay cooperation with energy harvesting. There are direct links between the sources and the relay is equipped with multiple antennas which are able to harvest energy. The main contributions of this article are summarized as follows:

- Network-coding-based two-way relay cooperation with energy harvesting is proposed. At the sources, low-density parity check (LDPC) codes are employed to improve the reliability, and at the relay, network coding is adopted to reduce the time slots and improve the average throughput.
- Maximal ratio combining (MRC)-based decoding algorithm for the network-coding-based two-way relay cooperation is introduced, via which coding gain and diversity gain are achieved.
- When the relay adopts the optimal antenna selection algorithm to transmit data, the outage probability and bit error rate (BER) of the network-coding-based two-way relay cooperation with energy harvesting are studied by theoretical analysis and numerical simulations.

The rest of this article is organized as follows. In section “System description,” the system description of the network-coding-based two-way relay cooperation with energy harvesting is presented. Section “MRC-based decoding algorithm for the proposed system” introduces the MRC-based decoding algorithm for the proposed system. Section “Performance analysis of the proposed system” analyzes the outage probability of the system. Simulation results are provided in section “Simulation results.” Finally, in section “Conclusion,” we conclude the whole paper.

**System description**

Network-coding-based two-way relay cooperation with energy harvesting is described as follows. Two users $S_1$ and $S_2$ exchange information with the help of relay $R$. $S_1$ and $S_2$ are equipped with single antenna with battery or grid power supply. The relay $R$ is equipped with $K$ antennas without external power supply, and it is powered by the energy harvested from the RF signals from $S_1$ and $S_2$. At the relay, some antennas are used to decode the incoming signal, and the rest antennas are used to harvest energy, which is used to broadcast the information to the users. To further improve the reliability of the system, LDPC codes\textsuperscript{23} are adopted at $S_1$ and $S_2$.

Figure 1 shows the three time slots of the network-coding-based two-way relay cooperation with energy harvesting, which is designed as follows:

- In time slot 1, the information bits at $S_1$ are encoded into a codeword $c_1 = \{c_1^{(1)}, \ldots, c_N^{(1)}\}$ by LDPC-1. $c_1$ is sent to $R$ and $S_2$ over a broadcast channel.
- In time slot 2, the information bits at $S_2$ are encoded into a codeword $c_2 = \{c_1^{(2)}, \ldots, c_N^{(2)}\}$ by LDPC-2. $c_2$ is sent to $R$ and $S_1$ over a broadcast channel.
- At the relay $R$, some antennas are used to decode the signals, and the rest antennas are used to harvest energy from the RF signals from $S_1$ and $S_2$. The relay combines the
MRC-based decoding algorithm for the proposed system

An MRC-based decoding algorithm for the network-coding-based two-way relay cooperation with energy harvesting is introduced. Because S1 and S2 are reciprocal, here, we just describe the decoding algorithm for S1. Binary phase-shift keying (BPSK) modulation is adopted. According to equation (1), the relationship between \( c_i^{(R)} \) and \( c_i^{(1)}, c_i^{(2)} \), is shown in Table 1.

At S1, there are two received signals: \( r_2 = (r_2^{(1)}, \ldots, r_2^{(N)}) \) from S2 and \( r_R = (r_R^{(1)}, \ldots, r_R^{(N)}) \) from R. S1 decodes \( c_2 \) based on \( r_2 \) and \( r_R \).

However, \( r_R \) corresponds to \( c_R \). It is not the same as \( r_2 \) which corresponds to \( c_2 \) directly. It is illustrated that

\[
c_i^{(R)} = \begin{cases} c_i^{(2)}, & \text{if } c_i^{(1)} = 0 \\ c_i^{(1)}, & \text{if } c_i^{(1)} = 1 \end{cases}, \quad i = 1, \ldots, N \quad (2)
\]

where \( c_i^{(2)} \) is the inversion of \( c_i^{(2)} \).

We assume \( r_3 = (r_3^{(1)}, \ldots, r_3^{(N)}) \). Since \( c_1 \) is known to S1, according to equation (2) and the property of BPSK modulation, we assign \( r_i^{(3)} \) as below

\[
r_i^{(3)} = \begin{cases} r_i^{(R)}, & \text{if } c_i^{(1)} = 0 \\ -r_i^{(R)}, & \text{if } c_i^{(1)} = 1 \end{cases}, \quad i = 1, \ldots, N \quad (3)
\]

Based on \( r_R \) and \( c_1 \), \( r_3 \) is achieved by equation (3), which corresponds to \( c_3 \) directly.

Because \( r_2 \) and \( r_1 \) are from S2 and R, respectively, they are over independent fading channels. Using MRC combination, we combine \( r_2 \) and \( r_1 \) which both correspond to \( c_2 \), and then put the combined signals into the LDPC-2 decoder at S1. Finally, information from S2 is decoded efficiently. This decoding scheme is called as MRC-based decoding algorithm, which can achieve coding gain and diversity gain.

Performance analysis of the proposed system

In this section, we investigate the outage probability performance of the network-coding-based two-way relay cooperation with energy harvesting. Suppose \( h_{12} \) and \( h_{21} \) represent S1-S2 channel in time slot 1 and S2-S1 channels in time slot 2, respectively. \( h_{R1}^{(k)} (k = 1, \ldots, K) \) and \( h_{R2}^{(k)} \) represent S1-R channel in time slot 1 and S2-R channel in time slot 2, respectively. All channels suffer from independent Rayleigh fading. \( h_{12}, h_{21}, h_{R1}^{(k)}, h_{R2}^{(k)}, h_{R1}^{(k)}, \) and \( h_{R2}^{(k)} \) are zero-mean complex Gaussian random variables with unit variance. \( d_{1R}^2, d_{2R}^2, \) and \( d_{12}^2 \) are the power attenuation factors of S1-R, S2-R, and S1-S2 channels due to different distances. Assume the transmission power at S1 and S2 is \( P \).


**Energy harvested at the relay**

At the relay, for the RF signals from S1, the number of energy-harvesting antennas is $K_1$, where $K - K_1$ antennas are applied for information decoding to recover the codewords. The energy harvested from S1 is calculated as

$$P_1 = \frac{P \sum_{k=1}^{K_1} |h_{1R}^{(k)}|^2}{d_{1R}^2} \tag{4}$$

For the RF signals from S2, the number of energy-harvesting antennas is $K_2$. Similarly, the energy harvested from S2 is calculated as

$$P_2 = \frac{P \sum_{k=1}^{K_2} |h_{2R}^{(k)}|^2}{d_{2R}^2} \tag{5}$$

Assuming the energy utilization ratio at the relay is $\eta(0 \leq \eta \leq 1)$, the total transmission energy at the relay is

$$\bar{P} = \eta(P_1 + P_2) = \frac{\eta P \sum_{k=1}^{K_1} |h_{1R}^{(k)}|^2}{d_{1R}^2} + \frac{\eta P \sum_{k=1}^{K_2} |h_{2R}^{(k)}|^2}{d_{2R}^2} \tag{6}$$

**Signals received at the sources**

We investigate only the outage probability of S1 due to the reciprocal of S1 and S2.

At S1, the received signals from S2 is

$$r_2 = \frac{\sqrt{\bar{P} h_{21}}}{d_{12}} x + n_2 \tag{7}$$

where $x$ is the BPSK modulation of codeword $c_2$. $n_2 = (n_{1}^{(2)}, \ldots, n_{N}^{(2)})$ is the additional noise. $n_{i}^{(2)} (i = 1, \ldots, N)$ are zero-mean complex Gaussian random variables with variance $\sigma^2$.

Assume the optimal antenna selection algorithm is adopted at the relay to select the optimal antenna $h_{R1}^{(o)}$ from $h_{R1}^{(1)}, \ldots, h_{R1}^{(K)}$.

$$|h_{R1}^{(o)}|^2 = \max \left\{ |h_{R1}^{(1)}|^2, \ldots, |h_{R1}^{(K)}|^2 \right\} \tag{8}$$

where $h_{R1}^{(k)} (k = 1, \ldots, K)$ represents R-S1 channel and $\max\{\cdot\}$ is the maximum function. The relay sends $\bar{x}$ over the antenna $h_{R1}^{(o)}$ with transmission power $\bar{P}$. $\bar{x}$ is the BPSK modulation of codeword $c_R$.

At S1, the received signals from R is

$$r_R = \frac{\sqrt{\bar{P}} d_{IR}}{d_{1R}} h_{R1}^{(o)} \bar{x} + n_R \tag{9}$$

where $n_R$ is defined the same as $n_2$. Substituting equation (6) into equation (9), we have

$$r_R = \frac{d_{2R} \eta P \sum_{k=1}^{K_1} |h_{1R}^{(k)}|^2 + d_{2R} \eta P \sum_{k=1}^{K_2} |h_{2R}^{(k)}|^2}{d_{1R}^2} h_{R1}^{(o)} \bar{x} + n_R \tag{10}$$

According to equation (3), we achieve $r_3 = (r_3^{(1)}, \ldots, r_3^{(N)})$ as below

$$r_3 = \left\{ \begin{array}{c}
\sqrt{d_{2R} \eta P \sum_{k=1}^{K_1} |h_{1R}^{(k)}|^2 + d_{2R} \eta P \sum_{k=1}^{K_2} |h_{2R}^{(k)}|^2}
\end{array} 
\right\}
$$

$$r_3^{(i)} = h_{R1}^{(o)} \bar{x}_i + n_i^{(R)}, \text{ if } c_i^{(1)} = 0, \quad i = 1, \ldots, N \tag{11}$$

By MRC combination, we have

$$y = [(h_{21})^* (h_{R1}^{(o)})^*] \begin{bmatrix} r_2 \\ r_3 \end{bmatrix} = (h_{21})^* r_2 + (h_{R1}^{(o)})^* r_3 \tag{12}$$

where $(\cdot)^*$ denotes the conjugate transpose. At S1, information from S2 is achieved by decoding $y$ via LDPC-2 decoder.

**Outage probability of the sources**

An outage event occurs when the instantaneous channel capacity falls below the data transmission rate. The probability of the outage event occurring is defined as the outage probability. At S1, the instantaneous channel capacity is

$$C = \log_2(1 + \gamma) \tag{13}$$

where $\gamma$ is the effective instantaneous signal-to-noise ratio (SNR). Based on equations (7), (11), and (12)
The outage probability can be calculated as

$$P_{\text{out}} = \Pr \{ C < R_c \} = \log_2 \left( 1 + \frac{P|h_{21}|^2}{d_{12}^2 \sigma^2} + \frac{\eta P|h_{R1}|^2}{d_{2R}^2 \sigma^2} \left( \frac{d_{1R}^2 \sum_{k=1}^{K_1} |h_{1R}^{(k)}|^2 + d_{2R}^2 \sum_{k=1}^{K_2} |h_{2R}^{(k)}|^2}{d_{1R}^2 d_{2R}^2 \sigma^2} \right) \right) < R_c \right) \tag{15}$$

where $R_c$ is the data transmission rate, which is regarded as the code rate of LDPC-2. For Rayleigh fading channels as described at the beginning of section “Performance analysis of the proposed system,” $|h_{21}|$, $|h_{1R}^{(k)}|$, $|h_{2R}^{(k)}|$, and $|h_{R1}|$ follow the Rayleigh distribution.

Hence, $|h_{21}|^2$, $|h_{1R}^{(k)}|^2$, $|h_{2R}^{(k)}|^2$, and $|h_{R1}|^2$ follow the exponential distribution $\varepsilon(1)$, whose common distribution function $F_X(x)$ and density function $f_X(x)$ are

$$F_X(x) = \begin{cases} 1 - e^{-x}, & x \geq 0 \\ 0, & x < 0 \end{cases}, \quad f_X(x) = \begin{cases} e^{-x}, & x \geq 0 \\ 0, & x < 0 \end{cases} \tag{16}$$

The density function of $Y = |h_{R1}|^2 = \max\left\{|h_{R1}^{(1)}|^2, \ldots, |h_{R1}^{(K)}|^2\right\}$ follows

$$f_Y(y) = K f_X(y) (F_X(y))^{K-1} = \begin{cases} Ke^{-y}(1-e^{-y})^{K-1}, & y \geq 0 \\ 0, & y < 0 \end{cases} \tag{17}$$

The outage probability will be further analyzed by simulations.

**Simulation results**

In this part, we present the outage probability performance of the proposed system with various numbers of antennas at the relay. Assume that the numbers of antennas $K = 2$ or 3, where the number of information decoding antennas is 1, and the number of energy-harvesting antennas $K_1 = K_2 = 1$ or 2. The energy utilization ratio at the relay $\eta = 1, 0.8, 0.6$. The data transmission rate is referred to as the overall code rate $R_c = 1/2$.

Figure 2 compares the outage probabilities of the proposed system and the point-to-point system. It is shown that the outage probability of the proposed system is much lower than that of the point-to-point system, and the diversity order is higher. This states that the proposed system can improve the performance without increasing the total power consumption. It is also demonstrated that the outage probability performance of the proposed system with $K = 3$ clearly outperforms that of the system with $K = 2$ under the same conditions. This can be contributed to the following fact: the more the antennas are equipped at the relay, the more the energy is harvested and the higher diversity gain is achieved with the optimal antenna configuration.
selection algorithm. Figure 2 also depicts that the higher the energy utilization ratio $\eta$, the lower the outage probability.

**Outage probability of the proposed system with various $d_{1R}, d_{2R}$**

We investigate the effect of the relay location on the outage probability of the proposed system. Assume $K = 3, K_1 = K_2 = 2, \eta = 1$, $d_{12} = 4$, and $d_{1R} + d_{2R} = d_{12}(d_{1R} \geq 1, d_{2R} \geq 1)$. Figure 3 shows the outage probability of the proposed system versus $d_{1R}$ with various SNRs. It is seen that when $d_{1R}$ is small which means the relay is close to $S_1$, the outage probability of the proposed system ($S_1$ is considered) is low. For instance, at SNR = 20 dB, when $d_{1R}$ decreases from 2 to 1, the outage probability drops from $10^{-5}$ to $3 \times 10^{-7}$. However, the relay is closer to $S_2$, whose outage probability will be increased. Hence, we need to decide the relay location based on the required outage probability of $S_1$ or $S_2$. The relay should be deployed closer to the user whose outage probability requires to be lower on the premise that the outage probability of the other user is satisfied.

**Outage probability of the proposed system with various antenna selection algorithms**

Assuming $K = 3, K_1 = K_2 = 2, \eta = 1$, we compare the outage probability of the proposed system with the optimal antenna selection, equal power allocation algorithm, and random antenna selection algorithm. It is shown in Figure 4 that the diversity orders of both optimal antenna selection algorithm and equal power allocation are higher than that of random antenna selection algorithm. Figure 4 also demonstrates that the outage probability of the system with the optimal antenna selection algorithm is lowest. However, these merits of the optimal antenna selection are at the cost of high implementation complexity and long time-delay. To select the optimal antenna from $K$ antennas using optimal antenna selection algorithm, $K - 1$ comparison times is needed. Hence, for a practical system, we should consider the trade-off between reliability performance and complexity or time-delay.

**BER of the proposed system with LDPC codes at the sources**

In this part, we investigate the BER performance of the proposed system with LDPC codes. Assume $K = 2$ or 3, $K_1 = K_2 = 1$ or 2, and $\eta = 1$. Random LDPC codes employed by $S_1$ and $S_2$ are with code rate $R_c = 1/2$, code length $N = 1000$, $d_v = 3$, and $d_c = 6$. Min-sum iterative decoding is adopted. For fair comparison, in the point-to-point system, the same LDPC code is adopted by the node. Figure 5 shows that the BER performance of the proposed system clearly outperforms that of the point-to-point system in various decoding iterations. This significant superiority owes to the following two facts. (1) At the user, MRC-based decoding algorithm combines the two signals from $S_2$ and $R$, which are through independent fading $S_2-S_1$ and $R-S_1$ channels. (2) At the relay, multiple antennas are equipped and the optimal antenna selection is adopted. Hence, high spatial diversity gain and coding gain are achieved.

**Comparison of the proposed system and the power splitting–based system**

In the proposed system, the relay adopts the antenna switching–based protocol for information decoding and energy harvesting, where some antennas are used...
to decode the incoming signal, and the rest antennas are used to harvest energy. In this part, we compare it with the system where the power splitting–based protocol is adopted by the relay as described in Ding et al. Random LDPC codes employed by $S_1$ and $S_2$ are the same as given in section “BER of the proposed system with LDPC codes at the sources.” Assume $K = 2$ and $K_1 = K_2 = 1$. For a fair comparison, because half of the antennas are used to harvested energy in the proposed system, we assume that half of the power for each antenna is used to harvested energy in the power splitting–based system.

Figure 6 compares the BER of the proposed system with that of the power splitting–based system with various energy utilization ratios $\eta$. It is shown that BER performance of the proposed system with $\eta = 1$ is inferior to that of the power splitting–based system with $\eta = 1$, however, superior to that of the system with $\eta = 0.6$ or $0.3$. Actually, for the power splitting–based system, the relay needs to first split the power for information decoding and energy harvesting at each antenna and then combine the harvested energy from all antennas. Hence, compared with the proposed system, its implementation complexity is much higher and the time-delay is longer. Furthermore, it is inevitable to decrease the energy utilization ratio.

**Conclusion**

In this article, we have studied the network-coding-based two-way relay cooperation with energy harvesting, which combines coded cooperation, network coding, and energy-harvesting technologies. It can achieve high diversity and coding gain, reduce the time slots, and overcome the dependence on the supply of battery or grid energy. An MRC-based decoding algorithm is introduced for the proposed system to combine signals from independent channels and combat the fading. When the optimal antenna selection algorithm is adopted at the relay to transmit data, the outage probability and BER of the proposed system are investigated by theoretical analysis and numerical simulations. The results show the superiority of the proposed system compared with the point-to-point system. For the relay, simulation result also shows that the performance of the scheme employing the optimal antenna selection algorithm is better than that of the random antenna selection algorithm or equal power allocation algorithm.

**Declaration of conflicting interests**

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