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Energy Collaboration for Non-Homogeneous Energy Harvesting in Cooperative Wireless Sensor Networks

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ABSTRACT In wireless sensor networks, energy harvesting is developed as an effective way to solve energy drain problem of nodes which powered by battery, just like that cooperative communication is used to improve transmission reliability. In some energy harvesting networks, the nodes' energy harvested from ambient environment is disequilibrium. For example, nodes exposed to sunlight collect more solar energy than those shaded. Impoverished energy will reduce transmission reliability because some nodes have not enough energy to send data or are forced to decrease transmission power to save energy. In this paper, energy collaboration is taken into consideration for non-homogeneous energy harvesting in cooperative wireless sensor networks, where all sensor nodes harvest solar energy and then store it in rechargeable battery. And an energy cooperative protocol is proposed for energy inhomogeneity to enhance transmission reliability among relay nodes through radio frequency, where the nodes with abundant energy share excess power to other nodes which undertake the forwarding task but store insufficient energy. By exploiting ACK/NACK frame fed back from the destination node and No Enough Energy (NEE) frame advertised by the forwarding relays in the active set, each candidate node forms its energy supply set when all of them are lack of energy for transmitting. For the relay selection, three strategies are presented for choosing the pair of the best forwarding relay and the optimal energy supply relay, which are respectively named Best Channel Strategy, Nearest Distance Strategy and Minimum Energy Sharing Strategy. Furthermore, the outage probability of cooperative transmission under energy collaboration is derived. Simulation results show that energy collaboration for cooperative wireless sensor networks can significantly reduce the outage probability of the system and improve transmission reliability of the network.

INDEX TERMS Cooperative communication, energy harvesting, relay selection, wireless sensor networks.

I. INTRODUCTION

Cooperative communication is widely used in wireless sensor networks to improve transmission reliability due to the simple configuration of nodes [1]. As an effective and low-complexity method, selection cooperation has attracted great attention, which chooses one relay node called the best relay from multiple candidates to assist the source node forwarding data. It was proposed in [2], and outage probability under different signal-to-noise ratios with typical channel models was derived in it. Literature [3] introduced the feedback mechanism into the selection cooperation and raised a lightweight selection cooperation protocol based on feedback frame from destination node, which effectively improved the reliability of data transmission and also provided more than one best relay. The above literatures, including many related studies, assumed that the energy supply of nodes was infinite. In other words, nodes' actions were not influenced by energy. However, in the actual networks, nodes are often powered by batteries. Once a node exhausts energy, it will exit the network and interrupt transmission task. Therefore, various energy-saving protocols and strategies were developed to reduce node's energy consumption and prolong network lifetime, such as sleep mode, network clustering, packet aggregation, etc. [4]–[7]. On the other hand, diverse energy collection schemes from ambient environment and power allocation

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methods were put forward to provide sustainable energy supply for nodes in wireless sensor networks [8]–[10].

Energy harvesting is a growing tendency that providing a potential solution for energy-constrained networks. Solar, wind, thermal and mechanical vibrations are the common green energy resources [11]–[14]. These various kinds of energy existing in the natural environment are widely distributed and inexhaustible. Using energy harvesting technology, these natural energy sources can supply power for sensor nodes so as to prolong the lifetime of wireless sensor networks. Among them, solar energy had the highest power density, which could provide power at milliwatt level per cubic centimeter of volume in bright sunny day [15]. Therefore, it was used widely for wireless sensor networks where the total power cost of sensor nodes had been reduced to μW level with the low-power design [16]. Although these natural resources can provide endless energy, their collection depends heavily on the environment. For example, the nodes harvest more solar energy where the sun shines, but less energy indoors or at night or on rainy days. Considering the impacts of energy collection, different energy storage and management schemes were proposed to provide reliable and stable energy supply for sensor nodes [17].

Additionally, radio frequency (RF) energy is an emerging supply and has attracted a lot of attention in recent years. RF energy harvesting technology mainly includes wireless power transfer (WPT), wireless powered communication network (WPCN), and simultaneous wireless information and power transfer (SWIPT) [18]–[20]. Literature [21] applied WPT to medical and radio networks, where RF was only used for energy transmission without information interaction. WPCN allowed node to harvest RF energy and then used it for data transmission, which showed great application prospects in the industrial Internet of Things [22]. SWIPT technology could simultaneously transmit information and energy with RF signals, in other words, decoding and harvesting energy were in the same time slot [23]. Enabling SWIPT technology to be implemented in existing receiver circuitry, [24] proposed two receiver architectures based on Time Switching (TS) and Power Splitting (PS). On this basis, [25] developed two protocols for SWIPT in the amplify-and-forward networks, which were called as time switching-based relaying (TSR) and power splitting-based relaying (PSR), and derived the throughput and outage probability of the two protocols. Moreover, some studies have taken radio frequency energy collection into cooperative networks. [26] studied system performance of ultra-reliable cooperative communication networks for wireless energy harvesting by transmitting test information to evaluate the channel quality among nodes, and optimized transmit power of the test information as the energy harvesting increases. In [27], SWIPT was implemented in the amplify-and-forward multi-relay cooperative network powered by battery, and outage probability of the system and the maximum combination ratio of the destination node were obtained. [28] discussed the optimal transmission power and optimal sharing time of the relay nodes to minimize the energy consumption of the whole network in cooperative networks with RF energy harvesting. Zhiguo Ding et al. took a wireless cooperative network into consideration, where multiple source-destination pairs communicated with each other via an energy harvesting relay, and focused on the relay's strategies to distribute the harvested energy among the multiple users and their impact on the system performance in [29]. Literature [30] developed a partial relay selection protocol (PRS) based on partial channel state information and an opportunistic relay selection (ORS) method by taking the harvested energy into account to enhance system performance in terms of outage probability and diversity gain. On this basis, considering the impact of hardware noises, hybrid partial relay selection (H-PRS) and best opportunistic relay selection (B-ORS) protocols were proposed to improve transmission reliability and throughput in [31], where instantaneous signal to noise ratio (SNR) replaced channel gain to select the best relay.

Berk Gurakan et al. firstly studied energy cooperation in energy harvesting wireless networks, in which the nodes could realize energy cooperation through radio frequency, and proposed energy management strategies to maximize the throughput of the system in [32]. PS-DSM and ER-DSM protocols based on Distributed Spatial Modulation (DSM) were put forward in wireless energy harvesting networks, where inactive nodes shared part of the energy to other activated source nodes to prolong network survival time [33]. Two scenarios were analyzed in [34]: data cooperation and energy cooperation, especially the latter. In energy cooperation scenario, system performance formulated by the packet delivery ratio was derived and optimized over the amount of energy transferred to the source. [35] proposed an energy cooperation scheme to minimize the overall latency of the given battery-free wireless network with radio frequency energy harvesting.

Most of the above literatures consider a single type of energy collection, but in some applications, such as bridge health monitoring networks powered by solar, only one energy source can't make the network run reliably. That is because the nodes located inside the bridge or shaded by other objects collect so little energy that they can't transmit data to the destination. Energy disequilibrium will increase transmission interruption. Literature [34] developed energy cooperation by transferring a portion of the relay's energy to the source in form of RF signal to optimize the packet delivery ratio. However, if the relay's energy harvested from surroundings is insufficient, how to implement energy collaboration?

Inspired by this, the paper introduces data cooperation and energy collaboration simultaneously to communication protocol in energy harvesting wireless sensor networks and proposes a cooperative scheme for both data and energy to improve transmission reliability. A wireless sensor network powered by harvested solar is taken into consideration. There are three cases for the communication process: direct transmission, cooperative transmission and data cooperation with energy collaboration. We focus on the third case, in which all of the relays have not enough residual energy to assist the source forwarding data to the destination. In order to continue the forwarding, the relays need energy collaboration. For simplicity, we devote this kind of relays as the forwarding relays, and another kind of relays which have abundant energy but don't have to forward data as energy supply relays. We present three selection strategies of the best forwarding relay and the optimal energy supply relay pair. In energy collaboration, the optimal energy supply relay transfer a portion of its energy to the best forwarding relay by radio frequency, so that the forwarding relay can continue its transmission. We also analyze the system performance of energy collaboration and derive the outage probability of the network. Simulations are carried out to evaluate the energy cooperation performance.

The main contributions of this paper are summarized as follows.

1) In order to solve energy drain of the relays and ensure reliable transmission in non- homogeneous energy harvesting networks, we consider data and energy cooperation, and propose a cooperative protocol with energy collaboration. In our scheme, the energy supply relays share their excess energy to the forwarding relays by radio frequency, so that the forwarding relays can harvest desired energy to complete the cooperative transmission.

2) In energy collaboration, we develop an energy supply set for every forwarding relay. In the energy supply set, each member can transfer its energy to the forwarding relay by radio frequency when needed. Based on the energy supply set, we present three selection strategies of the best forwarding relay and the optimal energy supply relay pair.

3) We analyze the system performance and derive the outage probability of the network with energy collaboration.

4) For evaluating the energy collaboration performance, we verify the outage probability of the proposed protocol and compare it with related works. Furthermore, we simulate transmission power, the harvested energy and the lost energy for various required energy in three relay pair selection strategies. Numerical results show the effectiveness of the proposed scheme with energy collaboration.

The rest of this paper is organized as follows. Section II describes system model, and section III presents the cooperative protocol with energy collaboration. Outage probability of the cooperative network with energy collaboration is derived in section IV and simulation results are provided in section V. Section VI summarizes the paper.

II. SYSTEM MODEL

We consider a multi-source single-destination cooperative network as shown in Fig. 1, which consists of M source nodes $s_i\,(i = 1, 2, \ldots, M)$ and a destination node d. There is no special relay, and the source nodes serve as the relays when needed. For clarity of description, when the node i acts as a source, it is devoted as s_i, and r_i as a relay. The channels among the nodes obey the flat quasi-static Rayleigh fading, and the channels remain independent. Defining the channel gains between the source node s_i and the destination node d, the source node s_i and the relay r_j, two relays r_j and r_k $(k \neq j)$, the relay r_j and the destination node d as $h_{s_i,d}$, h_{s_i,r_j}, h_{r_j,r_k}, $h_{r_j,d}$ respectively. Their variances are $1/\lambda_{s_i,d}$, $1/\lambda_{s_i,r_j}$, $1/\lambda_{r_j,r_k}$, $1/\lambda_{r_j,d}$, separately.

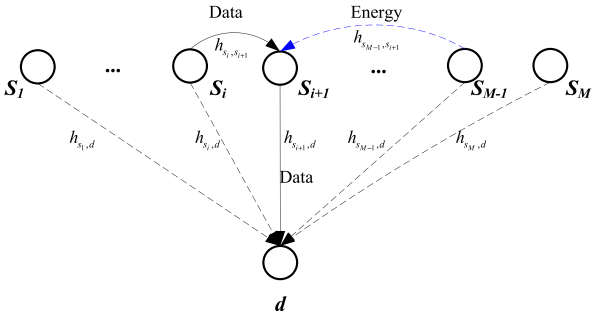

FIGURE 1. System model.

It is assumed that it is reciprocity between channels, and the channel state does not change during a transmission round. The noises at each receiver are additive white Gaussian noise (AWGN) with mean 0 and variance σ^2, and without specification, the average signal-to-noise ratio (SNR) is denoted as: $\rho = P/\sigma^2$. All nodes in the network are configured with single antenna and work in half-duplex. The transmission rate for all of nodes is R (b/s). The channel state information (CSI) can be estimated by the ACK/NACK frame fed back from the destination node. It is assumed that each relay can detect its remaining energy and calculate the required energy value of forwarding data to the destination according to received ACK/NACK frame.

All nodes are equipped both with solar and RF energy harvesting modules. Like [34], it is assumed that each node has a rechargeable battery with infinite capacity. Under normal conditions, nodes harvest solar energy and store it to the rechargeable battery for data transmission. Only when energy collaboration is triggered, RF energy collection is turned on. In other words, only when all of the forwarding relays detect that their remaining energy are lower than the required energy for successfully forwarding data to the destination, energy collaboration will begin. Then a frame called No Enough Energy (NEE) is advertised for energy assistant. When NEE frame is received by a node, it is assumed that the requested energy value, the distance, and the channel quality between the two nodes are obtained.

III. COOPERATIVE PROTOCOL WITH ENERGY COLLABORATION

A. PROTOCOL DESCRIPTION

Similar to literature [3], we utilize ACK/NACK feedback frame from destination to estimate channel quality. Beyond that, NEE frame is added to broadcast energy request in our proposal. And from it, the receiver can calculate the requested energy value, the distance, and the channel value to the transmitter. In our protocol, data cooperation and energy collaboration is not necessary for every data transmission.

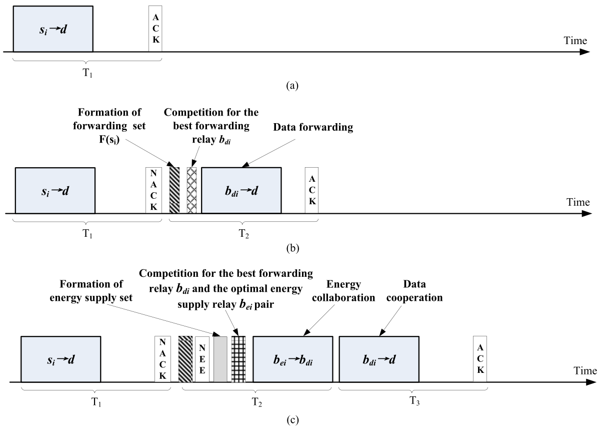

FIGURE 2. Communication process of a message in different cases. (a) Direct transmission; (b) Cooperative transmission; (c) Data cooperation with energy collaboration.

If a source node sends data successfully to the destination, there is no need for data cooperation. Energy collaboration is for the same reason. If a node has enough energy to communicate with others, energy collaboration is so unnecessary. Therefore, for a message sending, there are three cases for the proposed protocol: direct transmission, cooperative transmission and data cooperation with energy collaboration, and the number of time slot required is not the same in different cases. Communication process of a message in three cases is shown in Fig. 2.

Taking s_i as an example, the communication process of a message is as follows.

Case 1: direct transmission. The source node s_i send data to the destination node, at the same time, the other source s_k $(k = 1, 2, \ldots, M, k \neq i)$ listens and tries to decode the information sent by s_i. If the destination node can receive the data correctly, it feeds back an ACK frame to all nodes, as shown in Fig. 2(a). That means the data has been transferred successfully, it is the turn of next source node to send its data.

Case 2: cooperative transmission. In direct transmission, if the destination node fails to decode the data, it will broadcast a NACK frame shown in Fig. 2(b), which indicates the need for cooperative transmission. Like [3], the nodes which can decode both the data from s_i and the NACK frame from the destination join in the forwarding set $F(s_i)$. Each node in the set $F(s_i)$ detects its own remaining energy and calculates the minimum required energy for successfully forwarding the data to the destination according to the length of the data and the received NACK frame. If the remaining energy is more than the required energy, the node will get into the forwarding set $B(s_i)$. If $B(s_i)$ is empty, interruption will occur. Otherwise, similar to [3], a distributed relay competition will begin, which takes up a very short period of the current time slot, shown in Fig. 2(b). Each relay in $B(s_i)$ starts a timer and sets the initial value which is inversely proportional to the instantaneous channel value to the destination. Each relay participating in the competition keeps listening until its own timer reduces to zero or someone captures the channel. The relay who has the best instantaneous channel wins the competition because it has the smallest initial value. The best forwarding relay b_{di} selected from $B(s_i)$ sends the data to the destination. The cooperative transmission of this data finishes, and then the next source begins its data.

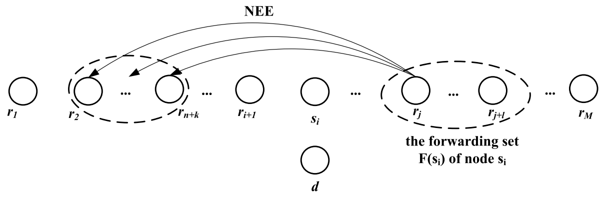

FIGURE 3. Energy collaboration request by broadcasting a NEE frame.

Case 3: data cooperation with energy collaboration. If direct transmission fails and $B(s_i)$ is empty, in other words, all of the forwarding relays in cooperative transmission have insufficient energy, energy collaboration will start. Each relay in the forwarding set $F(s_i)$, called as r_j, sequentially broadcasts a NEE frame for energy collaboration. The nodes which have received the NEE frame correctly form the energy supply set $E\left(r_j\right)$ of the forwarding node s_j, details about this can be seen in the following Subsection B. As a result, after the advertisement, every relay in $F(s_i)$ has its own energy supply set. Adopting the distributed relay competition mechanism mentioned in case 2, the optimal energy supply relay for each one in $F(s_i)$ can stand out. According to selection strategy of the best forwarding relay and the optimal power supply relay pair in Subsection C, the best forwarding relay b_{di} and the optimal power supply relay b_{ei} are selected. Then the optimal energy supply relay b_{ei} transfers a portion of its energy to the best forwarding relay b_{di} through radio frequency. After energy collection is completed, in the following time slot, the best forwarding relay b_{di} transmits the data of s_i to the destination, shown in Fig. 2(c). If the best forwarding relay can't harvest the required minimum energy, outage event will occur.

B. FORMATION OF ENERGY SUPPLY SET

In data cooperation and energy collaboration, when none of the nodes in the forwarding set has sufficient energy to forward data, they take their turn to advertise NEE frame for energy assistance request. Each forwarding node forms its own energy supply set according to the following steps.

1) Each relay in the forwarding set $F(s_i)$, defined as r_j, broadcasts a NEE frame, requesting energy assistance from other nodes. Fig. 3 shows that the node r_j advertises a NEE frame to other nodes for energy collaboration.

2) The node r_p $(p = 1, \ldots, M, p \neq i, j)$ that received the NEE frame estimates the channel value h_{r_p,r_j} to r_j, calculates the actual distance d_{r_p,r_j} between r_p and r_j, and obtains the minimum energy required by r_j. The minimum energy required by r_j consists of three parts: the minimum energy for successfully forwarding data to the destination in the current time slot $E_{r_j}(t)$, the remaining energy of r_j in the previous

time slot $E_{r_j}(t-1)$ and the energy consumed in broadcasting NEE frame $E_{nee\_r_j}$. If the node r_j can forward data to the destination successfully, its harvested energy $E_{h\_r_j}(t)$ must satisfy with formula (1).

$$E_{h\_r_j}(t) \geq E_{r_j}(t) + E_{nee\_r_j} - E_{r_j}(t-1) \tag{1}$$

It is noted that the energy $E_{nee\_r_j}$ can be calculated by transmission power and the length of NEE frame before broadcasting. For details, see formula (5) in literature [36].

According to the literature [25], the RF energy value collected during a time slot T is $E_{h\_r_j}(t)$. It is expressed

$$E_{h\_r_j}(t) = \frac{\eta P_{r_p} \left| h_{r_p,r_j} \right|^2}{d^m{}_{r_p,r_j}} \cdot T \tag{2}$$

Here, η is the efficiency of the forwarding node receiving the RF energy, T is the duration of RF energy, $P_{r_p}$is the transmission power of r_p when energy collaboration is performed, and m is the fading coefficient. Substituting (2) into (1), we get

$$\frac{\eta P_{r_p} \left| h_{r_p,r_j} \right|^2}{d^m{}_{r_p,r_j}} \cdot T \geq E_{r_j}(t) + E_{nee\_r_j} - E_{r_j}(t-1) \tag{3}$$

Defining the sharing energy by the node r_p as $E_{share}(t) = P_{r_p} \times T$, the maximum theoretical distance between the forwarding relay r_j and the energy supply relay r_p is

$$\tilde{d}_{r_p,r_j} = \sqrt[m]{\frac{\eta \left| h_{r_p,r_j} \right|^2 E_{share}(t)}{E_{r_j}(t) + E_{nee\_r_j} - E_{r_j}(t-1)}} \tag{4}$$

If r_p wants to transfer the required minimum energy to r_j, the distance d_{r_p,r_j} between r_p and r_j must be less than or equal to the maximum theoretical distance. That is

$$d_{r_p,r_j} \leq \tilde{d}_{r_p,r_j} \tag{5}$$

Substituting (4) into (5), that is

$$d_{r_p,r_j} \leq \sqrt[m]{\frac{\eta \left| h_{r_p,r_j} \right|^2 E_{share}(t)}{E_{r_j}(t) + E_{nee\_r_j} - E_{r_j}(t-1)}} \tag{6}$$

3) The node r_p compares the actual distance d_{r_p,r_j} to the maximum theoretical distance $\tilde{d}_{r_p,r_j}$. If d_{r_p,r_j} is not greater than the maximum theoretical distance $\tilde{d}_{r_p,r_j}$, it will join in the energy supply set $E\left(r_j\right)$ of r_j.

After all of the forwarding relay in $F(s_i)$ complete the creation of their own energy supply sets shown in Fig. 4, each member in its set and the forwarding relay become a candidate pair of the best forwarding relay and the optimal energy supply relay.

C. SELECTION STRATEGY OF THE BEST FORWARDING RELAY AND THE OPTIMAL POWER SUPPLY RELAY PAIR

Before energy collaboration, we must choose the optimal power supply relay. There are two ways to do it. The one is to select the best forwarding relay first, and then the optimal energy supply relay. The other is to select the best forwarding relay and the optimal energy supply relay pair at the same time. For the following reasons, we develop the latter. It was proved in [3] that any forwarding relay in $F(s_i)$ had good channel quality to the destination, and could ensure successful transmission if its energy was sufficient. Selecting any one of them could achieve the same outage probability. However, energy collaboration indicates that none of relays in $F(s_i)$ has enough energy for data forwarding. If the best forwarding relay is selected first, but its energy supply relay set is empty, an outage event will occur and the outage probability will increase. Furthermore, from Subsection B in section III, the latter traverses all pairs of the forwarding relays in $F(s_i)$ and its energy supply relays. When forming the candidate relay pairs, it actually excludes the case, in which the energy supply relay cannot provide the required energy to its forwarding relay. Therefore, selecting relay pair ensures that the selected energy supply relay can provide the required energy to its forwarding relay, and the forwarding relay can transmit the data to the destination successfully.

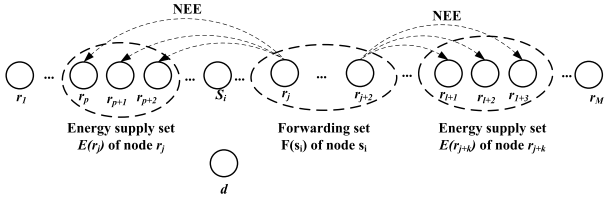

FIGURE 4. Energy supply set formation of relay r_j and r_{j+2}.

Since any forwarding relay in $F(s_i)$ has good channel quality to the destination, choosing any one can ensure transmission reliability. So, we focus our selection criteria on the parameters of candidate pairs. Three selection strategies for the best forwarding relay and the optimal energy supply relay pair are presented as follows.

1) Best Channel (BC) Strategy. The pair with the best channel value between them are selected as the best forwarding relay b_{di} and the optimal energy supply relay b_{ei}.

2) Nearest Distance (ND) Strategy. According to the distance between relays, the closest pair are elected as the best forwarding relay b_{di} and the optimal energy supply relay b_{ei}.

3) Minimum Energy Sharing (MES) Strategy. To avoid excessive waste of energy, transferring desired energy to forwarding relay is reasonable. From (1), (2) and $E_{share}(t) = P_{r_p} \times T$, we get

$$E_{share}(t) \geq \frac{d^m_{r_p,r_j} \cdot \left[E_{r_j}(t) + E_{nee\_r_j} - E_{r_j}(t-1)\right]}{\eta \cdot \left| h_{r_p,r_j} \right|^2} \tag{7}$$

For every candidate pair, we calculate the shared energy by the energy supply relay, and then choose the minimum energy sharing relay as the optimal energy supply relay b_{ei}, the corresponding forwarding relay as the best forwarding relay b_{di}.

It is worth mentioning that among all of the relay selection strategies in this paper, the distributed competition mechanism is adopted. The difference is that the initial value of the timer is set according to selection criteria.

TABLE 1. Definitions of the sets.

Set name	Definitions
$D(s_i)$	The set of nodes which can decode information from the source s_i
$D(d)$	The set of nodes which can decode ACK/NACK from the destination d
$CD(sd)$	Complementary set of the union of $D(s_i)$ and $D(d)$
$F(s_i)$	The set of nodes which can decode both information from the source s_i and ACK/NACK from the destination d
$CF(s_i)$	Complementary set of $F(s_i)$
$E(r_j)$	The energy supply set of the forwarding relay r_j

IV. OUTAGE PROBABILITY WITH ENERGY COLLABORATION

In this section, we derive the outage probability performance of the proposed scheme. It is noted that the system outage probability is the sum of outage probabilities of all nodes. That is

$$P_{out} = \sum_{i=1}^{M} P_{out}(s_i) \tag{8}$$

In the following, we show the outage probability of a single node and the proof. For ease of explanation, we list the set definitions in Table 1, shown on the top of this page.

Additionally, the transmission power is fixed to P except NEE frame and energy assistance which changes according to its residual energy.

Theorem 1: The outage probability of data cooperation with energy collaboration for source node s_i is given by (9), as shown at the bottom of this page, where $g = \frac{2^R-1}{\rho}$.

Proof: Like [3], we use the characteristic of exponential order to simplify the deduction, that is, if $\lim_{\rho\to\infty} \frac{\log_2(f(\rho))}{\log_2(\rho)} = b$ is established, b is the exponential order of $f(\rho)$ and written as $f(\rho) \doteq \rho^b$. In our proposed cooperative protocol with energy collaboration, only when the direct transmission, cooperative transmission and the energy cooperation all fail, an interruption will occur. The failure of data cooperation with energy collaboration is defined as δ, which includes event α and event β. Event α is that cooperative transmission fails. Event β is that data cooperation with energy collaboration is unsuccessful. Considering event δ, the outage probability of s_i is expressed as

$$P_{out}(s_i) = \Pr\left\{I_E < \frac{R}{3} | \delta\right\} \Pr\{\delta\} \tag{10}$$

In equation (10), I_E is the mutual information between the source node and the destination for energy collaboration. Since the cooperative transmission is performed on the basis of the direct transmission, when the event δ occurs, the channel between the source node s_i and the destination d cannot support the data transmission with the spectral efficiency R, thereby the first part of (10) is obtained

$$\begin{aligned}\Pr\left\{I_E < \frac{R}{3} | \delta\right\} &= \Pr\left\{\frac{1}{3}\log_2\left(1+\rho\left|h_{s_i,d}\right|^2\right) < \frac{R}{3}\right\} \\ &= 1 - e^{-\lambda_{s_i,d}\cdot g}\end{aligned} \tag{11}$$

Next, the second part $\Pr\{\delta\}$ in the equation (10) is further solved. The probability of event δ can be expressed by the total probability law as

$$\Pr\{\delta\} = \sum_{F(s_i)} \Pr\{\delta | F(s_i)\} \mathrm{P}_r\{F(s_i)\} \tag{12}$$

Since anyone in the set $F(s_i)$ can decode both the source node information and the NACK frame, the probability that

$$\begin{aligned}P_{out}(s_i) = {}&(1-e^{-\lambda_{s_i,d}\cdot g}) \times \sum_{F(s_i)} \Bigg[\prod_{r_j\in F(s_i)} e^{-\lambda_{s_i,r_j}\cdot g} e^{-\lambda_{r_j,d}\cdot g}(1-e^{-\lambda_{r_j,d}\cdot g}) \times \prod_{\substack{r_k\in D(s_i)\\ r_k\notin F(s_i)}} e^{-\lambda_{s_i,r_k}\cdot g}(1-e^{-\lambda_{r_k,d}\cdot g}) \\ &\times \prod_{\substack{r_l\in D(d)\\ r_l\notin F(s_i)}} (1-e^{-\lambda_{s_i,r_l}\cdot g}) e^{-\lambda_{r_l,d}\cdot g} \times \prod_{r_m\in CD(sd)} (1-e^{-\lambda_{s_i,r_m}\cdot g})\cdot(1-e^{-\lambda_{r_m,d}\cdot g}) \\ &\times \sum_{E(r_j)\in CF(s_i)} \Bigg[\prod_{\substack{r_j\in F(s_i)\\ r_p\in E(r_j)}} (1-e^{-\lambda_{r_p,r_j}\frac{2^R-1}{\rho_{r_p}}}) \times \prod_{r_p\in E(r_j)} e^{-\lambda_{r_j,r_p}\frac{2^R-1}{\rho_{r_j}}} \times \prod_{r_q\notin E(r_j)} (1-e^{-\lambda_{r_j,r_q}\frac{2^R-1}{\rho_{r_j}}}) \Bigg]\Bigg]\end{aligned} \tag{9}$$

$$\begin{aligned}\Pr\{F(s_i)\} = \sum_{F(s_i)} \Bigg[&\prod_{r_j\in F(s_i)} e^{-\lambda_{s_i,r_j}\cdot g} e^{-\lambda_{r_j,d}\cdot g} \times \prod_{\substack{r_k\in D(s_i)\\ r_k\notin F(s_i)}} e^{-\lambda_{s_i,r_k}\cdot g}(1-e^{-\lambda_{r_k,d}\cdot g}) \\ &\times \prod_{\substack{r_l\in D(d)\\ r_l\notin F(s_i)}} (1-e^{-\lambda_{s_i,r_l}\cdot g}) e^{-\lambda_{r_l,d}\cdot g} \times \prod_{r_m\in CD(sd)} (1-e^{-\lambda_{s_i,r_m}\cdot g})\cdot(1-e^{-\lambda_{r_m,d}\cdot g}) \Bigg]\end{aligned} \tag{17}$$

the node r_j goes into $F(s_i)$ is

$$\begin{aligned}\Pr\left\{r_j \in F(s_i)\right\} &= \Pr\left\{\log_2\left(1+\rho\left|h_{s_i,r_j}\right|^2\right) \geq R\right\}\\ &\quad\cdot \Pr\left\{\log_2\left(1+\rho\left|h_{r_j,d}\right|^2\right) \geq R\right\}\\ &= e^{-\lambda_{s_i,r_j}\cdot g}\cdot e^{-\lambda_{r_j,d}\cdot g} \end{aligned}\tag{13}$$

If the relay r_j is absent in $F(s_i)$, it is maybe in $D(s_i)$, $D(d)$ or $CD(sd)$, the corresponding probabilities are

$$\begin{aligned}&\Pr\left\{r_j \in D(s_i), r_j \notin F(s_i)\right\}\\ &\quad= \Pr\left\{\log_2\left(1+\rho\left|h_{s_i,r_j}\right|^2\right) \geq R\right\}\\ &\qquad\cdot \Pr\left\{\log_2\left(1+\rho\left|h_{r_j,d}\right|^2\right) < R\right\}\\ &\quad= e^{-\lambda_{s_i,r_j}\cdot g}\cdot(1-e^{-\lambda_{r_j,d}\cdot g}) \end{aligned}\tag{14}$$

$$\begin{aligned}&\Pr\left\{r_j \in D(d), r_j \notin F(s_i)\right\}\\ &\quad= \Pr\left\{\log_2\left(1+\rho\left|h_{s_i,r_j}\right|^2\right) < R\right\}\\ &\qquad\cdot \Pr\left\{\log_2\left(1+\rho\left|h_{r_j,d}\right|^2\right) \geq R\right\}\\ &\quad= (1-e^{-\lambda_{s_i,r_j}\cdot g})\cdot e^{-\lambda_{r_j,d}\cdot g} \end{aligned}\tag{15}$$

$$\begin{aligned}&\Pr\left\{r_j \in CD(sd), r_j \notin F(s_i)\right\}\\ &\quad= \Pr\left\{\log_2\left(1+\rho\left|h_{s_i,r_j}\right|^2\right) < R\right\}\\ &\qquad\cdot \Pr\left\{\log_2\left(1+\rho\left|h_{r_j,d}\right|^2\right) < R\right\}\\ &\quad= (1-e^{-\lambda_{s_i,r_j}\cdot g})\cdot(1-e^{-\lambda_{r_j,d}\cdot g}) \end{aligned}\tag{16}$$

Combining (13)-(16), we can get (17), as shown at the bottom of the previous page.

Since event α and β are independent of each other, the first part of equation (12) can be written as

$$\Pr\{\delta|F(s_i)\} = \Pr\{\alpha|F(s_i)\} \times \Pr\{\beta|F(s_i)\} \tag{18}$$

When event α occurs, none of the relays in $F(s_i)$ can communicate with the destination, and the outage probability is

$$\begin{aligned}\Pr\{\alpha|F(s_i)\} &= \prod_{r_j\in F(s_i)} \Pr\left\{\log_2(1+\rho\left|h_{r_j,d}\right|^2) < R\right\}\\ &= \prod_{r_j\in F(s_i)} (1-e^{-\lambda_{r_j,d}\cdot g}) \end{aligned}\tag{19}$$

The event β occurs when the energy of the relay r_j is still insufficient after the energy cooperation. In other words, the forwarding relay r_j can't harvest the required energy from the energy supply relay r_p in $E(r_j)$.The second part of (18) is written as

$$\Pr\{\beta|F(s_i)\} = \sum_{E(r_j)\in CF(s_i)} \Pr\left\{\beta, F(s_i)\,|E(r_j)\right\} \times \Pr\left\{E\left(r_j\right)\right\} \tag{20}$$

The outage probability of energy collaboration from r_p to r_j can be expressed as

$$\Pr\left\{\beta, F(s_i)|E(r_j)\right\} = \prod_{\substack{r_j\in F(s_i)\\ r_p\in E(r_j)}} (1-e^{-\lambda_{r_p,r_j}\frac{2^R-1}{\rho_{r_p}}}) \tag{21}$$

Applying the total probability law, we can get the outage probability of the energy supply set $E\left(s_j\right)$. That is

$$\begin{aligned}\Pr\left\{E\left(r_j\right)\right\} &= \prod_{r_p\in E(r_j)} e^{-\lambda_{r_j,r_p}\frac{2^R-1}{\rho_{r_j}}}\\ &\quad\times \prod_{r_q\notin E(r_j)} (1-e^{-\lambda_{r_j,r_q}\frac{2^R-1}{\rho_{r_j}}}) \end{aligned}\tag{22}$$

Substituting (20) and (21) into (19), the probability of event β is obtained

$$\begin{aligned}&\Pr\{\beta|F(s_i)\}\\ &= \sum_{E(r_j)\in CF(s_i)} \left[\prod_{\substack{r_j\in F(s_i)\\ r_p\in E(r_j)}} (1-e^{-\lambda_{r_p,r_j}\frac{2^R-1}{\rho_{r_p}}})\right.\\ &\quad\left.\times \prod_{r_p\in E(r_j)} e^{-\lambda_{r_j,r_p}\frac{2^R-1}{\rho_{r_j}}} \times \prod_{r_q\notin E(r_j)} (1-e^{-\lambda_{r_j,r_q}\frac{2^R-1}{\rho_{r_j}}})\right] \end{aligned}\tag{23}$$

Substituting (17), (19), (23) into (12), the probability of event δ is reprensented as (24), as shown at the bottom of this page.

Substituting (11), (24) into (10), we obtain (9).

$$\begin{aligned}\Pr\{\delta\} = \sum_{F(s_i)} &\left[\prod_{r_j\in F(s_i)} e^{-\lambda_{s_i,r_j}\cdot g} e^{-\lambda_{r_j,d}\cdot g}(1-e^{-\lambda_{r_j,d}\cdot g}) \times \prod_{\substack{r_k\in D(s_i)\\ r_k\notin F(s_i)}} e^{-\lambda_{s_i,r_k}\cdot g}(1-e^{-\lambda_{r_k,d}\cdot g})\right.\\ &\times \prod_{\substack{r_l\in D(d)\\ r_l\notin F(s_i)}} (1-e^{-\lambda_{s_i,r_l}\cdot g})e^{-\lambda_{r_l,d}\cdot g} \times \prod_{r_m\in CD(sd)} (1-e^{-\lambda_{s_i,r_m}\cdot g})\cdot(1-e^{-\lambda_{r_m,d}\cdot g})\\ &\left.\times \sum_{E(r_j)\in CF(s_i)} \left[\prod_{\substack{r_j\in F(s_i)\\ r_p\in E(r_j)}} (1-e^{-\lambda_{r_p,r_j}\frac{2^R-1}{\rho_{r_p}}}) \times \prod_{r_p\in E(r_j)} e^{-\lambda_{r_j,r_p}\frac{2^R-1}{\rho_{r_j}}} \times \prod_{r_q\notin E(r_j)} (1-e^{-\lambda_{r_j,r_q}\frac{2^R-1}{\rho_{r_j}}})\right]\right] \end{aligned}\tag{24}$$

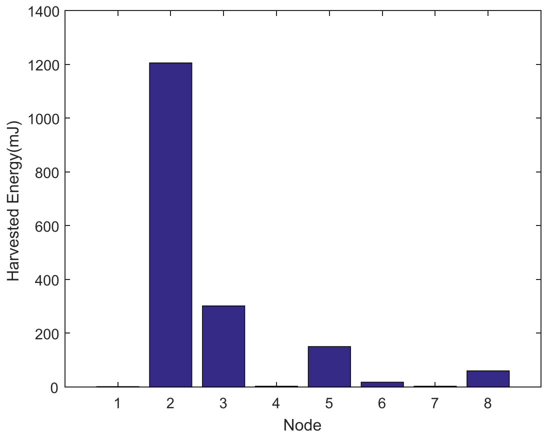

FIGURE 5. **Harvested solar energy of the source nodes.**

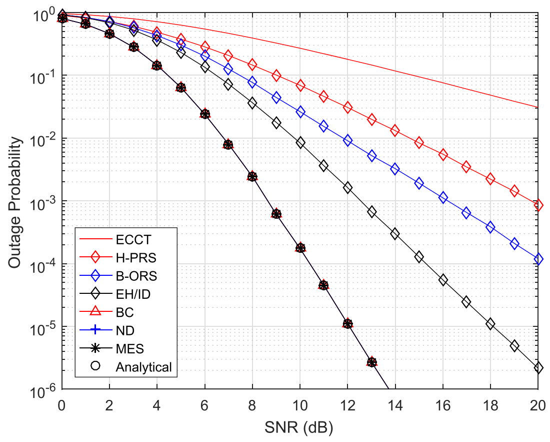

FIGURE 6. **Outage probability comparison for different schemes.**

V. SIMULATION RESULTS

In this section we simulate and discuss the cooperative scheme with energy collaboration for energy harvesting networks, observe and verify the outage probability of the system, energy consumption of the nodes. In the simulation, all channels obey Rayleigh fading, the transmission rate R per hertz between two nodes is set to 1b/s/Hz, a time slot is set to $T = 0.001s$, energy efficiency of relays $\eta = 0.4$. The number of source nodes is $M = 8$. Like [25], path fading coefficient m is equal to 2.7. The distance of two nodes is subject to a random distribution with a mean of 1, and simulation round is set to 100,000.

Fig. 5 shows the solar energy harvested by each node. The average rates of solar energy collected by source nodes are 0.05, 40, 10, 0.1, 5, 0.6, 0.1, 2, respectively. Among them, node 1, 4 and 7 collect little energy, almost equal to 0, while node 2 harvests the most energy, which is about 1200mJ. In such a sensor network, the energy harvested by each node is disequilibrium. Node 2 has enough energy to complete data acquisition and transmission, while node 1 often has insufficient energy to perform its task. Therefore, implementing energy collaboration among nodes is an attractive way to enhance system performance.

Fig. 6 verifies the theoretical and simulated outage probability of the proposed protocol. In this simulation, the channel parameters between nodes $\lambda_{s,d}$, λ_{s,r_i}, $\lambda_{r_i,d}$ and λ_{r_i,r_j} are set to 1. It can be seen from Fig. 6 that the simulation curves under the three selection strategies proposed almost coincide with the theoretical one. That indicates the correctness of Equation (9). For the sake of contrast, we give the outage probability of cooperative transmission with no energy collaboration for energy constrained networks (ECCT) in [4]. Fig. 6 shows that our proposal has a significantly lower outage probability than cooperative schemes without energy collaboration. The reason is obvious. When the node energy is used up, the transmission cannot be carried out and an outage event occurs.

Furthermore, in order to compare the performance of different energy cooperation schemes, we simulated hybrid partial relay selection (H-PRS), best opportunistic relay selection (B-ORS) in [31], where the relays employ power splitting to harvest energy from radio frequency signal of the sources and then to forward data to the destination, and energy harvesting or information decoding (EH/ID) in [34], in which the relay transfers a portion of its energy to the source as an energy provider or cooperates with the source to transmit data to the destination as a relay. Like [31], in the H-PSR and H-OSR simulation, the fraction of the total energy used for EH is set to 0.2 ($\alpha = 0.2$). The results are shown in Fig. 6. From Fig. 6, we can observe that our proposed scheme has the lowest outage probability, followed by EH/ID. They outperform better than H-PRS and B-ORS. There are three reason for above. The first is the power splitting ratio. In H-PRS and B-ORS, α is fixed by 0.2, while in EH/ID, it is an optimized value from 0 to 1. In the process of information decoding and energy cooperation, the larger the power splitting ratio is, the more energy the node harvests. Our scheme allocates a separate time slot for energy cooperation, that is, our power splitting ratio is equal to 1 in the time slot. Therefore, in the same time slot, the relay nodes in our scheme can collect the most energy, EH/ID is the second, H-PRS and B-OSR are the least. The second reason is the transmission power of energy cooperation transfered by the energy supply relay. In H-PRS, B-OSR and EH/ID, the energy of the relay comes from the source, while the transmission power of the source is fixed. In our proposal, the optimal energy supply relay can adjust the transmission power according to the needs of the best forwarding relay to ensure that the best forwarding relay can harvest as much energy as possible. Sufficient energy can enhance reliable transmission. Thirdly, the number of relay nodes in the three compared methods is different. EH/ID has only one relay, H-PRS and B-OSR have multiple relays but one energy supply node, while our scheme has multiple relays and multiple energy supply nodes. This makes it possible to select the optimal energy supply relay to transfer sufficient energy and the best forwarding relay to transmit data from a group of candidates. The more relay nodes, the more chance for data cooperation and energy collaboration. The above factors lead to a great improvement in transmission reliability.

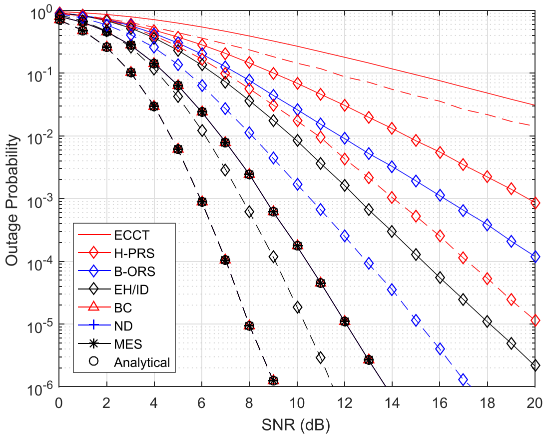

FIGURE 7. Outage probability comparison with different source nodes ($M = 8$ marked with solid line and $M = 16$ with dash line).

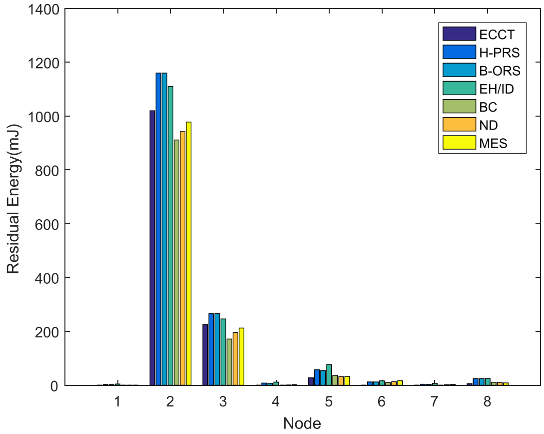

FIGURE 8. Residual energy of the source nodes.

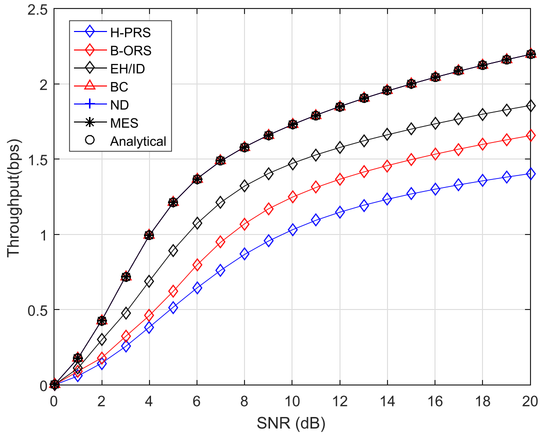

FIGURE 9. Throughput comparison for different schemes.

So, we can obtain the lowest outage probability than the compared schemes.

In order to further investigate the impact of the number of relays on system performance, we give the comparison of outage probabilities with different relay nodes, as shown in Fig. 7. The numbers of source nodes are $M = 8$ marked with solid line and $M = 16$ with dash line. Simulation results show that all curves of cooperative transmission decrease as the number of relays increases. This is because in cooperative transmission, the increase of the source number means that there are more potential relays participating in collaboration. Hence, the outage probability of cooperative transmission decreases with the number of source nodes increasing. For the same reason, in our data cooperation with energy collaboration, increasing the source number leads more energy supply relays to participate in cooperation, which reduces the outage events.

Fig. 8 gives the residual energy of source nodes in different schemes. It is noted that except for ECCT, the energy of other methods comes from two aspects: solar energy and RF energy. ECCT energy is only from solar. In the compared schemes, the harvested solar energy is same, while the collected RF energy is different. Since there is no energy cooperation, the energy consumption of H-PRS and O-BRS is mainly in transmitting information as a source node or forwarding data as a relay. As a source node, H-PRS and O-BRS use the same transmission power as other methods to send data. As a relay, they have always been the receiver of RF energy, which make they have the most residual energy. In our scheme, in addition to the above consumption, there is also the consumption caused by energy cooperation. When the node has enough energy, it is more likely to transmit energy by RF to other nodes, and when the energy is less, it has more chance to be the energy receiver. So, as can be seen from Fig. 8, H-PRS and O-BRS have the most residual energy. However, for node 2, the residual energy of BC, ND and MES is lower than that of ECCT. While for node 5, BC, ND and MES are higher than ECCT, which indicates that they act more as energy receivers than as energy transmitter.

Throughput comparison of different cooperative schemes is shown in Fig. 9. For the definition of throughput, see formula (19) in literature [31]. From Fig. 9, we can find that the curves of our proposal are higher than other compared ones, which indicates that our scheme can achieve greater throughput. The reason is that our scheme makes full use of energy cooperation, so that nodes with insufficient energy can collect the required energy to transmit data when needed. This reduces the outage probability of networks and improves system throughput. H-PRS and B-ORS use a fixed proportion to collect energy and forward information. The harvested energy by them is limited, and the outage probability is higher. EH/ID tradeoffs and optimizes the ratio of energy harvesting and information decoding, and its throughput is higher than H-PRS and B-ORS.

In order to evaluate the energy collaboration performance, we simulate the transmission power and the lost energy for various required energy with proposed relay pair selection strategies. The distance of two nodes is subject to a random distribution with a mean of 1 and 2. They are expressed as $d_1 = 1$ and $d_2 = 2$ respectively. Fig. 10 compares the transmission power of three relay pair selection strategies. As shown in Fig. 10, when the required energy is equal, the transmission power of Best Channel (BC) strategy is

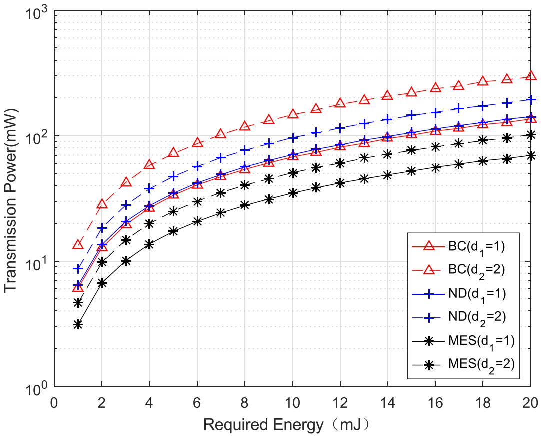

FIGURE 10. **Transmission power of proposed three relay pair selection strategies.**

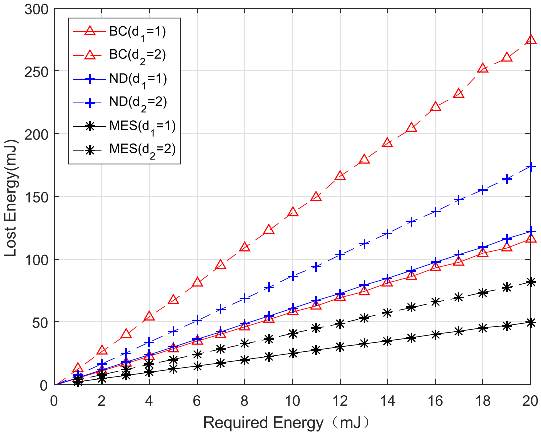

FIGURE 11. **Lost energy comparison of proposed three relay pair selection strategies.**

the largest, followed by Nearest Distance (ND) strategy and Minimum Energy Sharing (MES) strategy. From formula (2), we know when the required harvested energy is fixed, the transmission power of the energy supply relay is proportional to the increase of the channel value and the decrease of the transmission distance. In other words, the larger the channel value, the smaller the transmitting power. And the shorter the distance, the smaller the transmitting power. Increasing channel quality and reducing transmission distance can both contribute to reducing transmission power. It is noted that the exponents of the distance and channel value are 2.7 and 2, which makes that in reducing the transmission power, decreasing distance is more effective than increasing channel value. That is why the curve of BC is higher than that of ND. Since one factor above can affect the transmission power, combining the two parameters will further reduce the transmission power. So the MES has the lowest curve for considering both the distance and the channel quality simultaneously. It also can be seen from Fig. 10 that the transmission power increases as the nodes get further away. Transmitting a signal to a node with a distance of 2 requires more power than to a node with a distance of 1. Therefore, the curves of $d_1 = 1$ are lower than those of $d_2 = 2$.

Fig. 11 presents the lost energy of three relay pair selection strategies. The lost energy is the difference between the energy transmitted by the optimal energy supply relay and the energy received by the best forwarding relay. Transmission energy is directly proportional to transmission power. In a certain period of time, when the required energy is constant, the higher the transmission power is, the more energy is lost. From Fig. 10, we obtain that MES strategy has the lowest transmission power. Therefore, in Fig. 11, MES loses the least energy, and its curve lies at the bottom. ND curve is in the middle and BC is on the top. In addition, as the transmission distance increases, the energy loss increases. The lost energy curves of $d_1 = 1$ are lower than those of $d_2 = 2$.

VI. CONCLUSION

In this paper, a cooperative scheme with energy collaboration between relay nodes is proposed in non-homogeneous energy harvesting networks. The proposed protocol solves energy drain of relay nodes in cooperative transmission. When none of the forwarding relays has sufficient energy to perform transmission, other relays transfer a portion of their energy to them to ensure reliable transmission. In relay selection, we develop an energy supply set for each forwarding relay and present three relay pair selection strategies to choose the best forwarding relay and the optimal energy supply relay pair. Also, we derive the outage probability of the cooperative protocol with energy collaboration. Simulation results verify the effectiveness of the proposed scheme.

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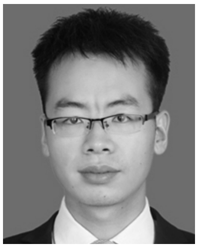

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