

Energy-balanced cooperative transmission based on relay selection and power control in energy harvesting wireless sensor network



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ABSTRACT

Energy harvesting can be leveraged by Wireless Sensor Network (WSN) to address its energy-scarcity problem, giving rise to Energy Harvesting Wireless Sensor Network (EHWSN). Residual energy balancing of sensors is the key issue to avoid sensors' failure and promise the network function of EHWSN. In this paper, by exploiting the sensors around the source and sink as relays, we propose a distributed relay selection and power control scheme to balance sensors' residual energy in EHWSN. To achieve the optimal power control of each relay, we formulate a maximization of minimum value problem which can be efficiently solved by utilizing its linear structure. The optimal relay is selected in a distributed manner by setting the highest priority to the relay which can maximize the minimum residual energy of sensors. Through extensive performance evaluations, we verify that DEBS can be applied to effectively balance the residual energy of sensors.

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1. Introduction

Wireless Sensor Network (WSN) is a salient technique for information gathering with a wide range of applications including habitat monitoring, battlefield surveillance, intelligent building, etc [1]. In general, the small-sized and battery-powered sensors are deployed and intended to operate unattended for a long operation time. Due to the limitation of battery capacity, the depletion of sensors' energy may lead to coverage hole and network partition [2]. Recently, the energy harvesting (EH) technology proposes a promising solution to prolong sensors' lifetime by enabling the sensors to harvest energy from the ambient energy sources, such as thermal, wind and Radio Frequency (RF) [3,4]. The typical application of the Energy Harvesting Wireless Sensor Network (EHWSN) is reported in [5], where Dutta et al. deploy a solar-powered sensor network to monitor the outdoor environment for more than four months. Although, the ambient energy can be harvested and stored for later use, the availability of ambient energy sources is temporally and spatially changing [6,7]. Therefore, the energy harvested and consumed by sensors should be well balanced to promise the sensors' sustainability and functioning [8].

With the emerging of virtual Multiple-Input-Multiple-Output (MIMO), i.e., the cooperative transmission technique, the small wireless devices can distributively coordinate their antennas to emulate the functionality of multi-antenna systems for data transmission [9]. The signals from the small wireless devices are constructively combined at the destination [10]. By exploiting the cooperative transmission in EHWSN, the sensors with low EH capability are able to leverage the energy of other sensors to transmit data, such that sensors' energy consumption and harvesting can be balanced according to their EH capabilities.

Utilizing cooperative transmission in EHWSN, sensors play two energy consuming roles, where one role is to serve as the source with a data packet destined to the sink, and the other role is to serve as the relay to cooperate with the source. Since the energy consumption of cooperative transmission may impact the relay's operation, the relay selection, i.e., which relay is selected to cooperate with the source, and the power control, i.e., how do the relay and source adjust their transmission power, are both the key issues to make a balanced use of sensors' energy. Furthermore, due to the decentralized nature of EHWSN, the relay selection and power control should be realized in a distributed manner.

In this paper, we investigate the distributed single relay selection and power control for an EHWSN to balance the residual energy of sensors. In the EHWSN, the sink locates in the maximal transmission range of all sensors. In each data transmission, the sensor with the data packet is referred to as the source, while

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other sensors are referred to as the relays. Each relay resolves the power control problem to maximize the minimum residual energy of sensors. Then the relay sends a JOIN message to the source for cooperative transmission after a backoff time. The value of the backoff time is inversely correlated with the maximized minimum residual energy, such that the relay selection can be realized in a distributed manner. Specifically, the contributions are summarized as follows:

1. Considering the EH capability and instantaneous channel gain, we design a relay selection and power control scheme that can be unified into the signaling procedure of the MAC layer for EHWSN, called Distributed Energy Balancing Scheme (DEBS), to maximize the residual energy of sensors using cooperative transmission.
2. In DEBS, we formulate a maximization of minimum value problem to maximize the minimum residual energy of sensors in each data transmission, and efficiently solve the problem by exploiting its linear structure. The extensive simulation results are conducted to confirm that DEBS can remarkably optimize the residual energy of sensors comparing to other two classic relay selection schemes.

The remainder of this paper is organized as follows. The related works are reviewed in Section 2. Section 3 describes the system model. Then we propose DEBS in Section 4. Section 5 provides the performance evaluation. Finally, Section 6 concludes this paper and outlines the future work.

2. Related works

Virtual MIMO-based cooperative transmission has been widely investigated for the sake of energy efficiency in the literature [11–15]. Cui et al. analyze the best modulation and transmission strategy for a single-hop sensor network to minimize the energy consumption that is required to send a given number of bits [11]. It is revealed that much transmission energy can be saved through sensors' cooperation, especially for long-distance transmission. In [12], Jayaweera extends the analysis in [11] by taking the training overhead of MIMO system into account. In [13], Qu et al. investigate the relay selection to minimize the bit-error-rate in data transmission while considering the constraints on energy consumption and data rate. To this end, the authors optimize multiple system parameters, such as the power level and the constellation size of each selected relay. For multi-hop sensor networks using cooperative transmission, Xu et al. study the energy-efficient topology control in [14] and [15]. The topology construction and routing are jointly determined to minimize the energy consumption of sensed data collection in the entire network.

The above-mentioned cooperative transmission schemes are mainly proposed for battery-powered sensor networks, with the objective to either minimize the energy consumption while guaranteeing a certain QoS, or optimize the QoS with the constraint on energy consumption. Notably, these schemes may lead to remarkably uneven energy distribution among sensors [16]. Unlike these schemes, our proposed scheme focuses on maximizing the residual energy of EH-powered sensors to guarantee their sustainability while considering the diverse EH capabilities.

There are also works exploiting the EH technologies to support cooperative transmission for sensor networks [17–20]. Li et al. [17] analyze the outage performance of an EH relay-aided sensor network under slow fading channel. Ku et al. [18] consider a single relay scenario in which our source transmits data to a destination with the assistance of an EH-powered decode-and-forward (DF) relay. The authors minimize the long-term average symbol error rate by adapting the relay's power control to the changes of EH process and battery states. Medapally et al. [19] analyze the symbol

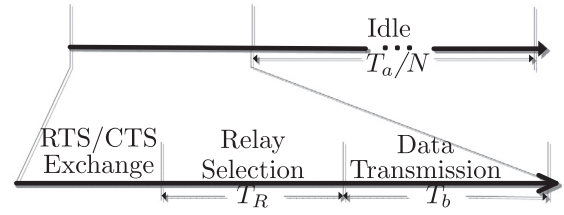


Fig. 1. The illustration of one operation cycle in the EHWSN.

error rate performance of a sensor network consisting of multiple EH-powered relays. The relay that maximizes the end-to-end signal-to-noise-ratio volunteers to serve the source for data transmission using amplify-and-forward (AF). Huang et al. [20] propose a power control scheme for a DF relaying-enhanced sensor network in which the relay serves as the renewable energy source for the source. The proposed scheme maximize the overall throughput by jointly allocate the power of the source and relay. The works mentioned above consider either AF or DF-based relaying. Unlike these works, our paper investigate the relay selection and power control using Virtual MIMO-based cooperative transmission, which can achieve better performance in residual energy balancing.

3. System model

We consider an EHWSN consisting of one sink, and N sensors equipped with EH modules and a rechargeable battery with capacity B_{max} . The sensors can communicate with the sink directly with the maximal transmission power. The sensors collect data from the area of interest, and transmit the data packet to the sink. Furthermore, the following assumptions stand through the paper:

1. The sensors are equipped with omni-directional antennas. Therefore, we assume the wireless channels between all sensors are symmetric, i.e., the channel condition from the transmitter to the receiver is the same as the reciprocal channel condition, as in [21]. In case the channels are asymmetric due to other environmental factors, the learning functions introduced in [22] can be used to train the sensors. Such that the sensors can know the asymmetric features of the wireless channels, and operate over them by adjusting the transmission power.
2. Similar to [9] and [23], we assume that the transmission power of sensors is continuously adjustable between $[0, P_{max}]$. Taking in to consideration the sensors with discrete power setting (e.g., Intel Mote [24] and Mica Mote [25]) the optimal transmission power that is obtained by the proposed scheme can be "rounded" to closest available discrete power level [26].

3.1. Operation cycle

One operation cycle of the considered EHWSN starts at the time when one sensor (the source) has a data packet to transmit, and ends when a new data packet arrives to a sensor in the network. Each operation cycle consists of four phases (Fig. 1). In the following, we explain the four phases in detail:

1. RTS/CTS exchange phase: When a sensor has a data packet to transmit as the source, it first sends a control message called RTS (Ready-To-Send) to the sink [27]. Each relay, a neighbour of the source and sink, overhears the information in RTS and estimates instantaneous channel gain $\beta_{S,R}$ of the channel between the source and the relay by channel estimation techniques [28]. If the channel is clear, the sink feedbacks a control message called CTS (Clear-To-Send) to the source. Similarly, each relay

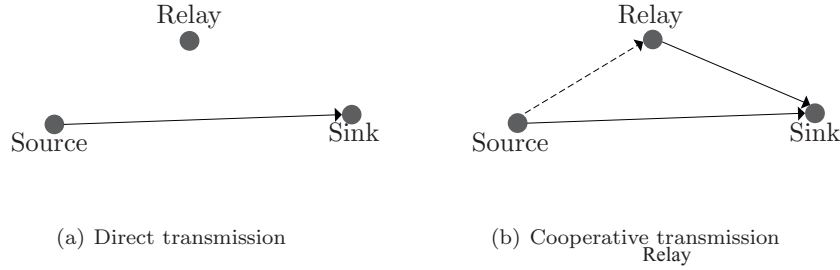


Fig. 2. Direct and cooperative transmission.

can estimate the instantaneous channel gain $\beta_{R,D}$ between itself and the sink, as well as channel gain $\beta_{S,D}$ between the source and sink.

2. Relay selection phase: In relay selection phase with time duration T_R , the relay sends a control message called JOIN message to the source, if the relay decides to cooperate with the source. Furthermore, to select the optimal relay which can maximize the minimum residual energy, each relay sends the JOIN message to the source after a backoff time $t_R \leq T_R$, where t_R is inversely correlated to the residual energy of the source and relay. Therefore, the optimal relay sends the JOIN message to the source earlier than other relays.
3. Data transmission phase: In the data transmission phase with time duration T_b , the data packet at the source is transmitted to the sink with data rate R_t . If the source does not receive any JOIN message in the relay selection phase, i.e., no relay cooperates, the source transmits the data packet to the sink by itself using direct transmission, as shown in Fig. 2(a). Otherwise, the source first transmits the data packet to the relay as shown in the dashed line of Fig. 2(b); then the source and relay collaborate their antennas and transmit the data packet using cooperative transmission, as shown in the solid line of Fig. 2(b).
4. Idle phase: All the sensors harvest energy and sense data from the area of interest in the idle phase. The sensing rate is the same for all sensors, as in [29] and [30]. Let T_a denote the time duration for each sensor to have a data packet for transmission. Because there are N sensors in the EHWSN, the time duration of idle phase evaluates to T_a/N .

For simplicity, we do not take into account the collisions of RTS messages and transmission failure of data packets. However, if multiple sources have data packet to transmit at the same time, their RTS messages may collide with each other. Under such circumstances, the sources can back off according to the exponential back off algorithm [31]. The collision of RTS messages implies the temporally heavy network load. To account for this case, the interval of successive data transmissions, i.e., T_a/N , can be updated according to the current network load. Furthermore, if the data packet transmission fails, it should be scheduled for retransmission which increases the network load. Similar to the RTS collision case, T_a/N should also be decreased, because the data packet retransmission increase the network load.

3.2. Residual energy

In each operation cycle, the relay attempts to maximize the minimum residual energy of itself and the source by adjusting the transmission power, with the objective to maximize the minimum residual energy of sensors. Let E_S and E_R denote the initial energy in the source and relay at the beginning of the operation cycle, respectively. Moreover, we use C_S and C_R to denote the energy consumption of the source and relay caused by data transmission, respectively. The EH rate of the source and relay are denoted

by P_S^h and P_R^h , respectively. Since the EH process evolves slowly in time compared to the interval of successive data transmissions and channel fading, e.g., solar power remains constant in 30 minutes [32], the EH rate of sensors is assumed to be constant during the current operation cycle. Furthermore, the EH rate can be obtained by the sensors through estimation techniques or historical information, such as the ones proposed in [33] and [34].

The source piggybacks its initial energy E_S and EH rate P_S^h in the RTS message, such that the relay can obtain these information. At the end of the operation cycle, the amount of residual energy in the source and relay can be expressed by:

$$\begin{cases} B_S = E_S - C_S + P_S^h \frac{T_a}{N}, \\ B_R = E_R - C_R + P_R^h \frac{T_a}{N}. \end{cases} \quad (1)$$

The minimum residual energy is determined by $\min\{B_S, B_R\}$, which is the minimum amount of energy between the source and relay at the end of the operation cycle.

We neglect the energy consumption of the control messages in the analysis due to the following two reasons. Firstly, the power consumption of the control messages is more or less fixed, regardless of which relay is selected. Secondly, the control message length is in general much less than the data packet [9]; hence, the data packet transmission takes the major part of sensors' energy consumption.

4. Distributed energy balancing scheme: DEBS

Considering the channel gain and EH capabilities of the relays, the design of distributed relay selection and power control becomes challenging. In this section, we propose the DEBS for each relay to decide whether it should cooperate with the source, and the setting of backoff time t_R . By assigning a shorter backoff time to the relay which can achieve higher minimum residual energy, the relay selection can be distributively realized.

4.1. Overview of DEBS

The proposed scheme DEBS aims at balancing the residual energy among sensors to guarantee their sustainability. By executing DEBS in the relay selection phase, the relay can decide whether to cooperate with the source for data transmission and the optimal power control.

To achieve these goals, the relay first analyzes the residual energy of the source using direct transmission. Then, it analyzes the optimal power control to maximize the minimum residual energy by adjusting the transmission power in cooperative transmission. If the cooperative transmission can achieve higher minimum residual energy, i.e., $\min\{B_S, B_R\}$, the relay sets a backoff time t_R , which is inversely correlated to $\min\{B_S, B_R\}$. After this backoff time, the relay sends JOIN message to the source for cooperative transmission. Meanwhile, if the relay overhears any JOIN message from other relays in the relay selection phase, it cancels the scheduled JOIN

message. By this setting, the relay which can make a better balance of the residual energy among sensors sends the JOIN message first, such that the relay selection can be distributedly realized.

In the following, we analyze the residual energy in direct and cooperative transmission, respectively. Notably, the analysis is only based on the information that the relay can obtain from the RTS/CTS exchange between the source and sink.

4.2. Residual energy using direct transmission

We first derive the residual energy of the relay and source in direct transmission, in which the source transmits the data packet to the sink without any relay's cooperation. Since the required data rate is R_t , the transmission power of the source to the sink $P_{S,D}^{DRT}$ in direct transmission should satisfy [9]:

$$R_t = W \log_2 \left(1 + \frac{\beta_{S,D} P_{S,D}^{DRT}}{N_0 W} \right), \quad (2)$$

where W denote the bandwidth of the wireless channel, N_0 denote the noise power, $\beta_{S,D}$ is the channel gain between the source and sink, and $P_{S,D}^{DRT}$ is the transmission power of the source to the sink in direct transmission. By rearranging Eq. (2), we can derive the transmission power $P_{S,D}^{DRT}$ to be:

$$P_{S,D}^{DRT} = \frac{(2^{R_t/W} - 1)N_0 W}{\beta_{S,D}}. \quad (3)$$

Since the time duration of the data transmission phase is T_b and the energy consumption of the relay is 0 in direct transmission, we have:

$$\begin{cases} B_S^{DRT} = E_S - P_{S,D}^{DRT} T_b + P_S^h \frac{T_a}{N}, \\ B_R^{DRT} = E_R + P_R^h \frac{T_a}{N}, \end{cases} \quad (4)$$

where B_S^{DRT} and B_R^{DRT} denote the residual energy of the source and relay if the source directly transmit the data packet to the sink, respectively.

4.3. Residual energy using cooperative transmission

In this subsection, we analyze the optimal power control of the source and relay in cooperative transmission, in which the source first shares the data packet to the relay data rate $2R_t$ in time duration $\frac{1}{2}T_b$, then the source and relay collaborate their antennas to simultaneously transmit the data packet to the sink with the same data rate and time duration [9].

We use B_S^{CPT} and B_R^{CPT} to denote the residual energy of the source and relay in cooperative transmission, respectively. The residual energy of the source and relay in cooperative transmission can be determined by:

$$\begin{cases} B_S^{CPT} = E_S - P_{S,R}^{CPT} \frac{T_b}{2} - P_{S,D}^{CPT} \frac{T_b}{2} + P_S^h \frac{T_a}{N}, \\ B_R^{CPT} = E_R - P_{R,D}^{CPT} \frac{T_b}{2} + P_R^h \frac{T_a}{N}. \end{cases} \quad (5)$$

where $P_{S,R}^{CPT}$ denotes the transmission power from the source to the relay. $P_{S,D}^{CPT}$ and $P_{R,D}^{CPT}$ denote the transmission power from the source and relay to the sink, respectively.

We adjust the transmission power of the source and relay, i.e., $P_{S,D}^{CPT}$ and $P_{R,D}^{CPT}$, to maximize the minimum residual energy $\min\{B_S^{DRT}, B_R^{DRT}\}$, while the transmission power is subject to the maximum power P_{max} . To find the optimal transmission power, we mathematically formulate the problem to:

$$\begin{aligned} (\text{REB}) \quad & \max_{P_{S,D}^{CPT}, P_{R,D}^{CPT}} \min\{B_S^{CPT}, B_R^{CPT}\} \\ \text{s.t.} \quad & \begin{cases} 0 \leq P_{S,D}^{CPT} \leq P_{max}, \\ 0 \leq P_{R,D}^{CPT} \leq P_{max}. \end{cases} \end{aligned}$$

To solve problem **REB**, we first show that the transmission power from the source to the sink, i.e., $P_{S,D}^{CPT}$, can be replaced by an equation of the transmission power from the relay to the sink, i.e., $P_{R,D}^{CPT}$. Therefore, we can transform **REB** to a problem with only $P_{R,D}^{CPT}$ as the variable. Then, by exploiting the linear structure of the new problem, we derive the optimal $P_{R,D}^{CPT*}$, as given in **Theorem 1**.

In the following, we derive the residual energy B_S^{CPT} and B_R^{CPT} with respect to the transmission power $P_{S,D}^{CPT}$ and $P_{R,D}^{CPT}$. Similarly to Eq. (3), the transmission power from the source to the relay $P_{S,R}^{CPT}$ is given by:

$$P_{S,R}^{CPT} = \frac{(2^{2R_t/W} - 1)N_0 W}{\beta_{S,R}}, \quad (6)$$

After the relay receive the data packet, the source and the relay cooperatively transmit the data packet to the sink which uses MRC (Maximal Rate Combining) to decode the received data packet. Therefore, the transmission power $P_{S,D}^{CPT}$ and $P_{R,D}^{CPT}$ should satisfy [35]:

$$2R_t = W \log_2 \left(1 + \frac{\beta_{S,D} P_{S,D}^{CPT} + \beta_{R,D} P_{R,D}^{CPT}}{N_0 W} \right), \quad (7)$$

By rearranging Eq. 7, we have

$$\beta_{S,D} P_{S,D}^{CPT} + \beta_{R,D} P_{R,D}^{CPT} = (2^{2R_t/W} - 1)N_0 W. \quad (8)$$

Then, we can obtain the relationship between $P_{S,D}^{CPT}$ and $P_{R,D}^{CPT}$ as:

$$P_{S,D}^{CPT} = \frac{(2^{2R_t/W} - 1)N_0 W - \beta_{R,D} P_{R,D}^{CPT}}{\beta_{S,D}}. \quad (9)$$

Substituting Eq. (9) into (5), we can replace transmission power $P_{S,D}^{CPT}$ by the equation of $P_{R,D}^{CPT}$ and obtain:

$$\begin{cases} B_S^{CPT} = E_S - \left(P_{S,R}^{CPT} + \frac{(2^{2R_t/W} - 1)N_0 W - \beta_{R,D} P_{R,D}^{CPT}}{\beta_{S,D}} \right) \frac{T_b}{2} + P_S^h \frac{T_a}{N}, \\ B_R^{CPT} = E_R - P_{R,D}^{CPT} \frac{T_b}{2} + P_R^h \frac{T_a}{N}. \end{cases} \quad (10)$$

To simplify the presentation, we use the notations $k_S = \frac{T_b \beta_{R,D}}{2\beta_{S,D}}$, $k_R = -\frac{T_b}{2}$, $b_S = E_S - (P_{S,R}^{CPT} + \frac{(2^{2R_t/W} - 1)N_0 W}{\beta_{S,D}}) \frac{T_b}{2} + P_S^h \frac{T_a}{N}$ and $b_R = E_R + P_R^h \frac{T_a}{N}$. Then we can transform Eq. (10) to

$$\begin{cases} B_S^{CPT} = k_S P_{R,D}^{CPT} + b_S, \\ B_R^{CPT} = k_R P_{R,D}^{CPT} + b_R. \end{cases} \quad (11)$$

By exploiting the linear structure of B_S^{CPT} and B_R^{CPT} with respect to $P_{R,D}^{CPT}$, we derive the optimal value of $P_{R,D}^{CPT}$ to maximize the minimum residual energy in the relay and source, in **Theorem 1**.

Theorem 1. Let the optimal transmission power $P_{R,D}^{CPT*}$ be the solution for problem **(REB)**, the value of $P_{R,D}^{CPT*}$ must satisfy:

$$\begin{cases} P_{R,D}^{CPT*} = 0, & \text{if } \frac{b_R - b_S}{k_S - k_R} < 0 \\ P_{R,D}^{CPT*} = \frac{b_R - b_S}{k_S - k_R}, & \text{if } \frac{b_R - b_S}{k_S - k_R} \in [0, P_{max}] \\ P_{R,D}^{CPT*} = P_{max}, & \text{if } \frac{b_R - b_S}{k_S - k_R} > P_{max} \end{cases} \quad (12)$$

Proof. As we see from Eq. (11), both the residual energy in the source and relay, i.e., B_S^{CPT} and B_R^{CPT} , are linear functions of $P_{R,D}^{CPT}$. Since the value of $k_S > 0$ and $k_R < 0$, the value of B_S^{CPT} and B_R^{CPT} monotonically increases and decreases with increasing $P_{R,D}^{CPT}$, respectively. Therefore, maximizing $\min\{B_S^{DRT}, B_R^{DRT}\}$ is equivalent to minimize the difference between B_S^{DRT} and B_R^{DRT} . Then, we can transform problem **REB** to:

$$\begin{aligned} & \min_{P_{R,D}^{CPT}} |B_S^{CPT} - B_R^{CPT}| \\ \text{s.t.} \quad & 0 \leq P_{R,D}^{CPT} \leq P_{min}. \end{aligned}$$

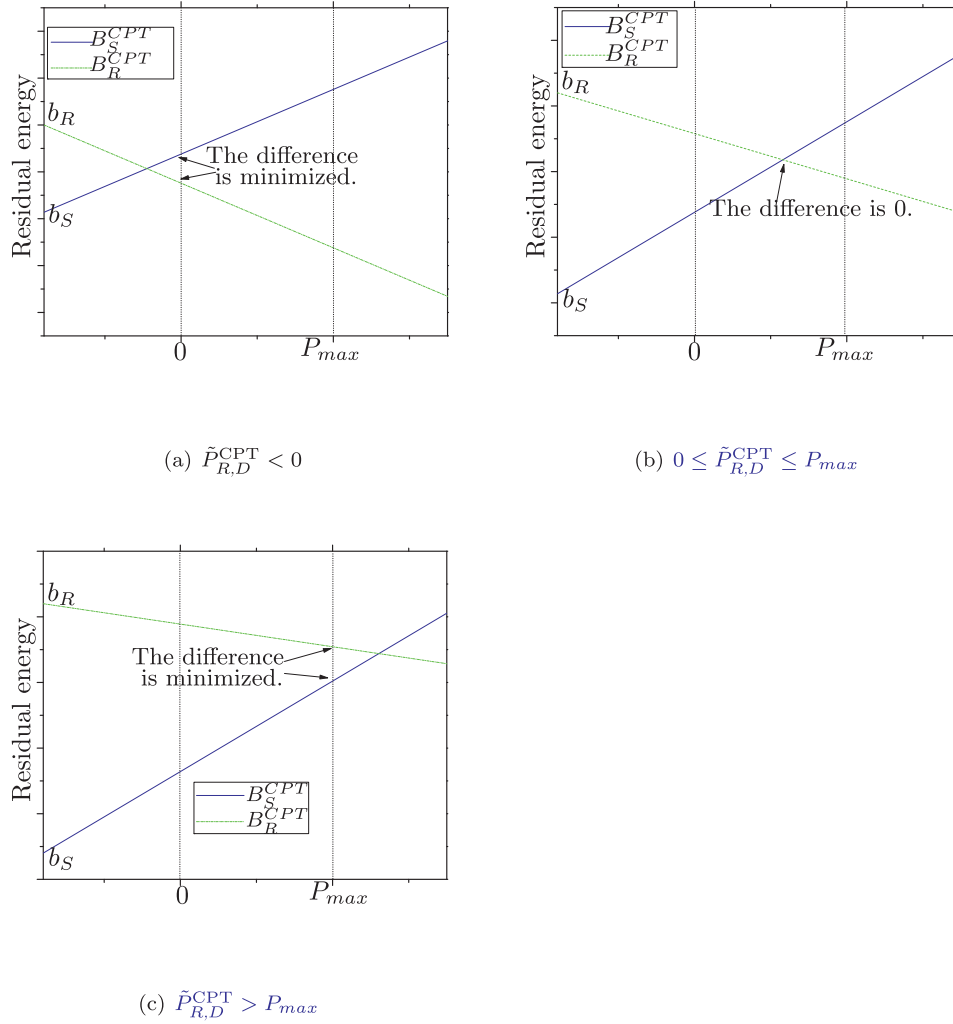


Fig. 3. Maximization of minimum residual energy.

Obviously, $|B_S^{CPT} - B_R^{CPT}|$ can be minimized when the source and relay have the same residual energy, i.e., $B_S^{CPT} = B_R^{CPT}$. Let $\tilde{P}_{R,D}^{CPT}$ be the value when $B_S^{CPT} = B_R^{CPT}$, we can derive $\tilde{P}_{R,D}^{CPT}$ to be

$$\tilde{P}_{R,D}^{CPT} = \frac{b_R - b_S}{k_S - k_R}. \quad (13)$$

Considering that the transmission power is bounded in $[0, P_{max}]$, we separately analyze the cases according to the value of $\tilde{P}_{R,D}^{CPT}$:

- Case 1: $\tilde{P}_{R,D}^{CPT} < 0$.
The value of $|B_S^{CPT} - B_R^{CPT}|$ monotonically increases when $\tilde{P}_{R,D}^{CPT} \in [0, P_{max}]$. In this case, the optimal transmission power $P_{R,D}^{CPT*}$ is 0, as shown in Fig. 3(a). It happens when the relay's initial energy and EH capability cannot support the cooperative data transmission or the channel fading between the relay and the sink is severe. Therefore, the relay does not send the JOIN message to the source.
- Case 2: $\tilde{P}_{R,D}^{CPT} \in [0, P_{max}]$.
The value of $P_{R,D}^{CPT*} = \tilde{P}_{R,D}^{CPT}$ is achievable, as shown in Fig. 3(b). In this case, the relay cooperatively transmit the data packet with power $\tilde{P}_{R,D}^{CPT}$.
- Case 3: $\tilde{P}_{R,D}^{CPT} > P_{max}$.
The value of $|B_S^{CPT} - B_R^{CPT}|$ monotonically decreases when $\tilde{P}_{R,D}^{CPT} \in [0, P_{max}]$, as shown in Fig. 3(c). Therefore the optimal transmission power $P_{R,D}^{CPT*}$ is P_{max} . This means that the relay has suffi-

cient energy for data transmission, i.e., $E_R + P_R^h \frac{T_a}{N}$ is large. In this case, the relay uses power P_{max} in cooperative transmission.

Summarily, we get Eq. (12). $\square$

Taking Eq. (12) into Eq. (10) yields the optimal transmission power of the source $P_{S,D}^{CPT}$.

4.4. Procedure of DEBS

To balance the residual energy of all sensors in the EHWSN, each relay executes DEBS according to the information that is extracted from the RTS/CTS messages, i.e., the initial energy in the source E_S , channel gain $\beta_{S,D}$, $\beta_{R,D}$, and the energy harvesting rate of the source P_S^h . The detail of DEBS is given in Algorithm 1.

To decide whether the relay should cooperate with the source, the relay first analyzes the residual energy of the source and itself in direct and cooperative transmission, respectively. If cooperative transmission can achieve higher minimum residual energy, the relay obtains the backoff time t_R , as well as the optimal transmission power $P_{S,D}^{CPT*}$ and $P_{R,D}^{CPT*}$. The backoff time t_R is inversely correlated with the maximized minimum residual energy that can be achieved by cooperation of the relay, as shown in Eq. (14), in such a way that the optimal relay sends the JOIN message to the source before other relays.

Notably, the operation of DEBS only requires the information in the RTS/CTS messages, such as the channel gain, EH rate, and

Algorithm 1 Distributed Energy Balancing Scheme (DEBS)

Require: Channel gain $\beta_{S,D}$, $\beta_{R,D}$ and $\beta_{S,R}$; energy harvesting rate p_S^h , p_R^h ; initial energy E_S , E_R ; upper bound of transmission power P_{max} ; time duration of relay selection phase T_R ; battery capacity of sensors B_{max} .

Ensure: Backoff time t_R , optimal transmission power $P_{S,D}^{CPT*}$ and $P_{R,D}^{CPT*}$.

1: Solve equation (4) to obtain B_S^{DRT} and B_R^{DRT} in direct transmission.

2: Solve problem (REB) to obtain residual energy B_S^{CPT} and B_R^{CPT} , as well as optimal transmission power $P_{S,D}^{CPT*}$ and $P_{R,D}^{CPT*}$ in cooperative transmission.

3: **if** $\min\{B_S^{CPT}, B_R^{CPT}\} > \min\{B_S^{DRT}, B_R^{DRT}\}$ and $P_{R,D}^{CPT*} > 0$ **then**

4: Set

$$t_R = \frac{B_{max} - \min\{B_S^{CPT*}, B_R^{CPT*}\}}{B_{max}} T_R. \quad (14)$$

5: **else**

6: Set $t_R = \infty$.

7: **end if**

8: **if** $t_R < \infty$ **then**

9: Output t_R , $P_{S,D}^{CPT*}$ and $P_{R,D}^{CPT*}$.

10: **else**

11: Do not send the JOIN message.

12: **end if**

initial energy. Therefore, DEBS can distributively realize the relay selection and power control.

If multiple relays achieve the same maximized minimum residual energy, their JOIN message may collide with each other. Under such circumstances, other relays still transmit the JOIN messages according to the scheduled backoff time t_R , because they cannot decode the collided messages. For the extreme case that all JOIN messages collide in the relay selection phase, the source transmits the data packet to the sink using direct transmission. Furthermore, if the power settings in the radios are discrete, the continuous transmission power control decision determined by DEBS, i.e., $P_{S,D}^{CPT*}$ and $P_{R,D}^{CPT*}$, can be discretized according to the available power settings.

5. Performance evaluation

This section evaluates the performance of the proposed scheme. The transmission of control messages and data packets is built in the widely-used Omnet++ discrete event simulator [36]. The considered EHWSN consists of $N = 81$ sensors and one sink. The sensors randomly distribute around a circular area with radius 120 m. In each data transmission, the sensor with a data packet to transmit acts as the source, while other sensors act as relays. The relay sends the JOIN message to the source for cooperative transmission based on the outcome of DEBS. The initial energy of the source is $E_S = 0.3$ J, and the initial energy of the relays uniformly distributes in $[0.1, 0.5]$ J.

The required data rate is $R_t = 2$ Kb/s and time duration of the data transmission phase is $T_b = 1$ s. The average interval time of two data transmission is 5 s, i.e., $T_a/N = 5$ s. The bandwidth of the channel is $W = 1$ M Hz. The channel gain is given as $d^{-3}|h|^2$, where d is the distance between the transmitter and receiver, and $|h|^2$ is the exponentially distributed channel fading factor [28]. The upper bound of EH rates for all the sensors is $P^h = 5 \mu W$, which can represent the EH rates of typical ambient energy sources, such as RF and indoor illumination [37]. The EH rate of each sensor uniformly distributes between $0 \mu W$ to $5 \mu W$.

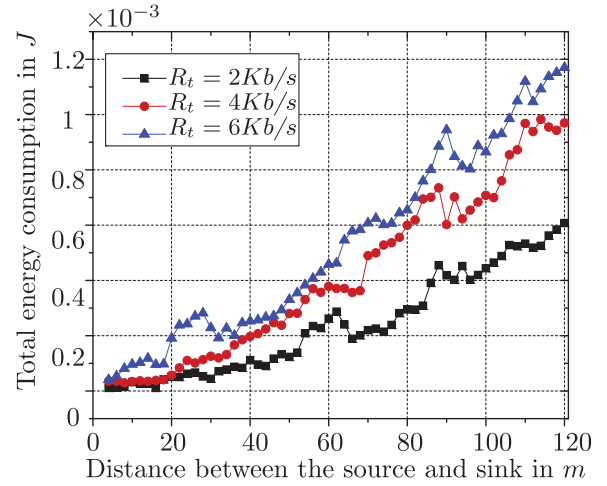


Fig. 4. Total energy consumption for different data rate R_t .

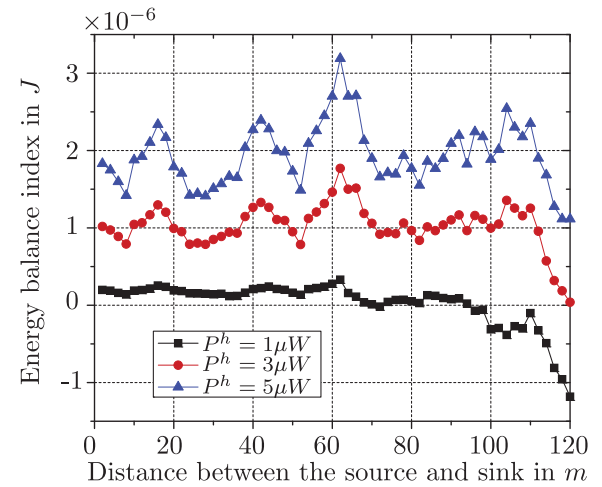


Fig. 5. Comparison of energy balance index for different energy harvesting rate.

Fig. 4 shows the energy consumption performance of DEBS with data rate R_t ranging from 2 Kb/s to 6 Kb/s. As we can see from the figure, the energy consumption of data transmission increases with higher data rate R_t . However, due to the impact of the exponentially distributed channel fading, the total energy consumption of the source and relay does not monotonically increase with the distance between the source and sink for a given data transmission rate.

As we can see from Fig. 4, the energy consumption of one data transmission is much smaller than the initial energy ($1 \times 10^{-3} \text{ J} \ll 0.3 \text{ J}$). To clearly show the energy balancing performance of DEBS, we use the energy balance index $B^* - E_S$, i.e., the difference between the minimum residual energy of the source and the relay B^* , and the initial energy in the source E_S , as the performance metric. The larger the value of energy balance index $B^* - E_S$, the better residual energy balancing can be achieved.

In Fig. 5, we show the energy balance index of DEBS with different upper bound of EH rate ranging from $1 \mu W$ to $5 \mu W$. As we see from the figure, the energy balance index exceeds zero when the minimum residual energy exceeds the initial energy at the source. It means that the energy consumed by the data transmission can be compensated by the harvested energy. Furthermore, the value of the energy balance index increases with higher energy harvesting rate. Moreover, with a large distance

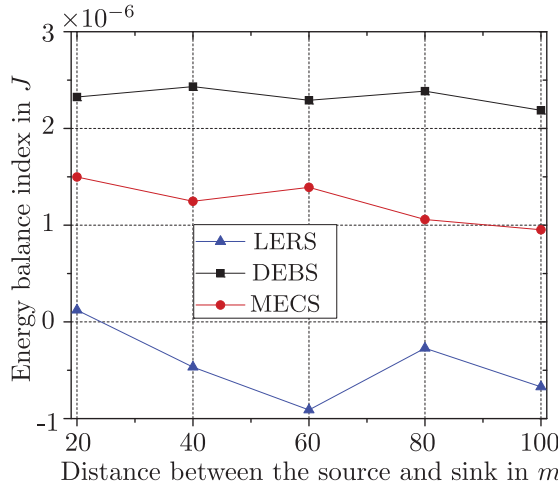


Fig. 6. Comparison of energy balance index versus the distance between the source and sink.

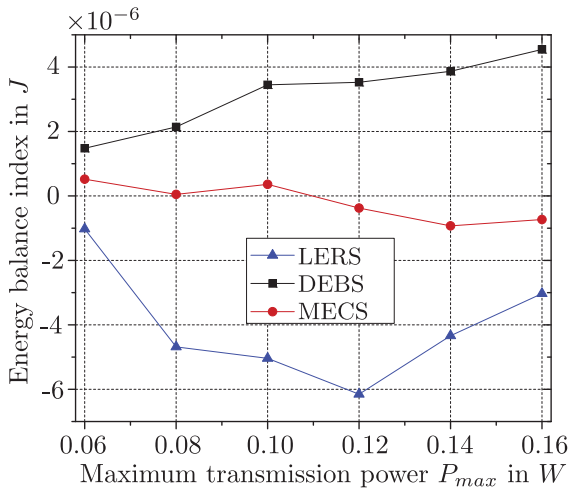


Fig. 7. Energy balance index versus various maximum transmission power P_{max} .

between the source and sink (≥ 110 m), the energy balance index decreases since longer distance causes more energy consumption.

To verify the effectiveness of DEBS, we compare DEBS to other two classic schemes called Largest E_R Scheme (LERS) and Minimum Energy Consumption Scheme (MECS) [38], respectively. In LERS, the backoff time of each relay to send the JOIN message is set according to the initial energy of the relay, i.e., the higher the relay's initial energy, the sooner the relay sends the JOIN message to the source. Meanwhile, in MECS, the relays calculate the minimized energy consumption of the cooperative transmission, and the relay which minimizes the total energy consumption sends the JOIN message to the source before other relays.

In Fig. 6, we compare the energy balance index of DEBS with that of LERS and MECS. As we can see from the figure, comparing to MECS, the energy balance index of DEBS increases $1 \mu\text{J}$, which is the lower bound of the amount of sensor's harvested energy in one second. Furthermore, since LERS does not consider the impact of channel gain, the energy balance index of MECS exceeds that of LERS.

Fig. 7 shows the comparisons of energy balance index in different schemes with maximum transmission power P_{max} ranging from 0.06 W to 0.16 W, and the distance between the source and sink is set to 40 m. As we can see from the figure, comparing with LERS and MECS, DEBS maximizes the energy balance index. Fur-

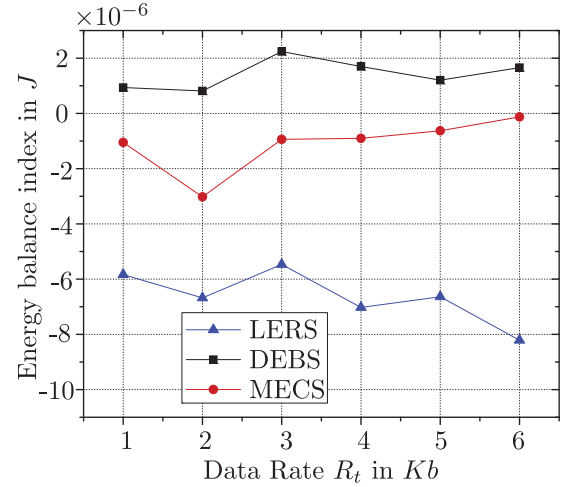


Fig. 8. Energy balance index versus data rate R_t .

thermore, similar to Fig. 6, the energy balance index of MECS is also larger than that of LERS with different maximum transmission power.

Fig. 8 shows the comparisons of energy balance index in different schemes with data rate R_t ranging from 1 Kb to 6 Kb, and the distance between the source and sink is 40 m. Similar to Fig. 7, the energy balance index of DEBS is larger than that of LERS and MECS with various data rate R_t , since DEBS considers both the energy harvesting capability of each sensor and channel gain between the source, relay and sink.

6. Conclusion

In this paper, we have proposed a cooperative transmission scheme for EHWSN, where the relay selection and power control are jointly designed to balance the residual energy of sensors. The proposed scheme operates in a distributed manner in which the optimal relay, i.e., the relay that can maximize the sensors' residual energy, is selected to cooperate with the source for data transmission. The outcomes of this paper can provide some insights for residual energy balancing design in EHWSN, by exploiting cooperative transmission. Performance evaluation has shown that the proposed scheme can outperform other classic schemes, from the perspective of residual energy balancing.

For our future work, we plan to investigate the multiple relay selection in EHWSN to balance the residual energy distribution of sensors.

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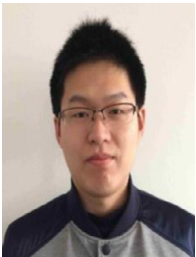
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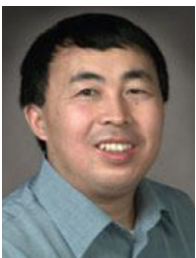
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