IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received 3 November 2022, accepted 14 November 2022, date of publication 17 November 2022, date of current version 22 November 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3222843

RESEARCH ARTICLE

An Opportunistic Routing for Energy-Harvesting Wireless Sensor Networks With Dynamic Transmission Power and Duty Cycle

QIAN REN[1] **AND GUANGSHUN YAO**[1,2]
[1]School of Computer and Information Engineering, Chuzhou University, Chuzhou, Anhui 239000, China
[2]School of Computer Science and Engineering, Southeast University, Nanjing, Jiangsu 211189, China

Corresponding author: Guangshun Yao (yaogshun@chzu.edu.cn)

This work was supported in part by the China Postdoctoral Science Foundation under Grant 2018M632209, in part by the Anhui Provincial Natural Science Foundation under Grant 1808085MF177, in part by the Anhui Provincial Education Department Project under Grant KJ2021ZD0129, in part by the Anhui Provincial University Outstanding Talents Program under Grant gxgnfx2020103 and Grant gxyq2021216, and in part by the Chuzhou University Research Foundation under Grant 2022XJZD15 and Grant 2022XJYB04.

ABSTRACT Opportunistic routing (OR) is widely used in energy-harvesting wireless sensor networks (EH-WSNs). The transmission power of sensor nodes in EH-WSNs is usually adjusted dynamically to make full use of the harvested energy. Many OR algorithms with dynamic transmission power adjustment have been proposed for EH-WSNs. However, fewer studies consider the non-bidirectional communication and the increase in packet retransmission and delay caused by the heterogeneous transmission power/radii. To this end, we propose an opportunistic routing algorithm for EH-WSNs with dynamic transmission power and duty cycle (ORDPD). It adjusts the transmission power of the sensor nodes at the end of each time slot, according to the predicted available energy. It also adjusts the transmission power and duty cycle of the sensor nodes in time slots if the nodes receive packets from other nodes outside their current transmission range. ORDPD also adopts an improved transmission model and information exchange mechanism to dynamically update relay sets and forwarding paths. A series of experiments were conducted to verify the effectiveness of the proposed algorithm. The experimental results demonstrate that the proposed ORDPD reduces non-bidirectional communication and retransmission significantly and performs better than its corresponding competitors.

INDEX TERMS Energy-harvesting wireless sensor networks, transmission power, duty cycle, non-bidirectional communication.

I. INTRODUCTION

The limited battery power capacity is one of the major constraints in the application of traditional wireless sensor networks [1], [2], [3]. Energy harvesting (EH) technology has become a promising solution to this problem [4], [5], [6], [7]. By equipping energy harvesting modules, the sensor nodes in energy-harvesting wireless sensor networks (EH-WSNs) can harvest energy from ambient energy, such as solar, wind, and vibrations. In theory, they can work permanently until hardware failures occur if the consumed energy is less than the harvested energy [8], [9]. However, the available ambient energy is usually uncontrollable, dynamic, and unbalanced among the nodes [8], [10]. In this case, designing a suitable routing protocol is crucial for realizing efficient and sustainable data transmission in EH-WSNs.

Previous studies have proven that opportunistic routing (OR) performs well in EH-WSNs [11], [12], [13]. Unlike traditional routing protocols that select predetermined paths for data forwarding, OR exploits the broadcast nature of wireless transmissions and does not require a priori knowledge of the network topology [14]. It selects a set of nodes (the relay set) for data forwarding. As long as one node in the relay set receives the data, it can forward the data to the next relay set,

The associate editor coordinating the review of this manuscript and approving it for publication was Stefano Scanzio.

effectively reducing the delay and packet loss rate. Moreover, it has high flexibility and can adapt to network changes in EH-WSNs [12].

Because the harvested energy is uncontrollable, dynamic, and unbalanced, many studies adjust the transmission parameters of sensor nodes dynamically to keep EH-WSNs working sustainably [1], [12]. The transmission power is an adjustable parameter of the nodes [15]. When the energy of the nodes is sufficient, increasing the transmission power of the nodes can improve data transmission efficiency. When the energy of the nodes is insufficient, decreasing the transmission power of the nodes can keep the nodes in the EH-WSNs working continuously. In recent decades, many efficient OR algorithms with dynamic transmission power adjustment strategies have been proposed for EH-WSNs such as ORDTP [12] and ECTRA [16]. The nodes in these algorithms dynamically adjust their transmission power according to the available energy. The different transmission powers of nodes result in heterogeneous transmission radii and non-bidirectional communication between nodes, which leads to an increase in retransmission and delay. However, few studies have considered the impact of heterogeneous transmission radii and non-bidirectional communication between nodes on network system performance.

In this study, we propose an OR algorithm with dynamic transmission power and dynamic duty cycle (ORDPD) in EH-WSNs. Both the transmission power and duty cycle of the nodes are adjusted dynamically in ORDPD. At the end of each time slot, ORDPD adjusts the transmission power of each sensor node for the next slot according to the predicted available energy in the next slot and its energy utilization in the previous slots to ensure efficient and sustainable working. In each time slot, ORDPD adjusts the transmission power and duty cycle of the nodes if they receive packets from other nodes beyond their transmission range. Thereafter, the nodes update their relay sets and forwarding paths timely to reduce packet transmission delays and retransmissions. The major contributions of this study are as follows.

(1) An OR algorithm with dynamic transmission power and dynamic duty cycle scheme is proposed to decrease the retransmission and delay caused by the heterogeneous transmission power/radii of the nodes. Besides adjusting the transmission power of sensor nodes at the end of each time slot, the algorithm adjusts the transmission power and duty cycle of the sensor nodes in each slot if necessary.
(2) An improved transmission model and a novel information exchange mechanism are designed to dynamically update the relay sets and forwarding paths.

The remainder of this paper is organized as follows. Related work is discussed in Section II. Section III describes the system models and the research problems of this study. After introducing the transmission model and information exchange mechanism, the proposed ORDPD, including the relay set (re)selection stage, the opportunistic packet (re)transmission stage and the transmission power adjustment stage, is presented in Section IV. The evaluation of our algorithm and the analysis of the obtained results are presented in Section V. Finally, we present the main conclusions and future work in Section VI.

II. RELATED WORKS

We briefly review the designed OR strategies for EH-WSNs in this section.

In the last few decades, many OR algorithms have been proposed for EH-WSNs to efficiently utilize the harvested energy. Eu et al. proposed two OR protocols, AOR [17] and EHOR [18], for EH-WSNs. Both AOR and EHOR use geographical location to group the nodes in the relay sets in different regions. The nodes in the different groups are assigned different transmission priorities. Both the available energy and distance from the sink are considered in the AOR and EHOR to determine the priority for transmission. Recently, Li et al. [19] proposed an energy-aware OR protocol for EH-WSNs by deploying an LSTM neural network to predict the harvested energy. It considers the nodes' current residual energy and harvesting energy in a short term as key factors in forwarding candidates selection process. It assigns relay priority by considering the residual energy and sleep history of candidates to balance the energy consumption among nodes. Shafieirad et al. [20] designed a novel and energy-aware OR called Max-SNR for large scale EH-WSNs. Max-SNR comprehensively considers the energy available at the sensor nodes, the distance to the sink, and the amount of data to be transmitted to select the best forwarding node. However, the transmission parameters of the nodes, such as the transmission power and duty cycle, are fixed in these OR strategies, and a large amount of harvested energy is wasted.

Recently, some studies have combined opportunistic routing with other techniques to improve system performance, such as cognitive radio [21] and wireless energy transfer [22], [23]. However, the transmission parameters are still fixed in these studies.

In contrast to the above schemes with fixed transmission parameters, some studies have been devoted to designing OR approaches with dynamic transmission parameters for EH-WSNs. The transmission power and the duty cycle of sensor nodes are two adjustable parameters. Zhang et al. [1] designed an OR scheme called OPEH with dynamic and heterogeneous duty cycles for EH-WSNs. The scheme adjusts the duty cycle of the nodes at the end of each time slot, based on the predicted harvested energy in the next slot. However, the dynamic and heterogeneous duty cycle cannot guarantee that a sender node has relay nodes available at all times. Chen et al. [12] designed an OR scheme called ORDTP for EH-WSNs. Similar to the scheme in [1], ORDTP also adjusts the transmission parameter at the end of each timeslot based on the predicted harvested energy in the next slot. The difference is that ORDTP adjusts the transmission power of nodes, whereas the scheme in [1] adjusts the duty cycle. Ju X et al. [16] proposed an energy conserving and transmission radius adaptive scheme called ECTRA for

EH-WSNs to make full use of the harvested energy and reduce delay and network deployment costs. The ECTRA rotates the transmission radii of the nodes by adjusting the transmission power to balance the energy consumption and reduce the maximum energy consumption. It also increases the transmission radii to forward data in turns when the nodes harvest sufficient energy from the environment. The heterogeneous transmission power of nodes inevitably leads to heterogeneous transmission radii and non-bidirectional communication between nodes, which results in an increase in retransmission and delay. However, none of these schemes addresses this problem.

Table 1 simply compares the existing OR strategies for EH-WSNs with the proposed algorithm. To the best of our knowledge, the problem considered in this study has not yet been studied, even though it occurs widely when dynamically adjusting the transmission power of sensors in EH-WSNs in practice.

III. SYSTEM MODELS AND PROBLEM DESCRIPTION

A. NETWORK MODEL FOR EH-WSNs

The EH-WSNs considered in this study contain multiple stationary sensor nodes and a resource-rich sink. The sink node has no energy constraints and is deployed at the center of the monitoring area. The sensor nodes in the monitoring area collect the data of interest and transmit them to the sink via multi-hop forwarding. Each node is equipped with a rechargeable battery and an ambient energy harvester model that can harvest ambient energy and store the harvested energy in the rechargeable battery. We use solar energy as externally accessible energy in this study. We assume that each node has a unique ID and knows its position and that of the sink node. The location can be obtained using GPS at deployment or localization protocols, which are beyond the scope of this study. We also assume that each node knows the distance between itself and the sender if it receives a packet sent from the sender. The working process of each node is divided into multiple time slots of equal length and the slot time length of node i is denoted as T_i. The sensor node can adjust its transmission power based on its available energy. The transmission power set is denoted as $TP = \{TP_0, \cdots, TP_{L-1} = \{(tp_0, d_0), \cdots, (tp_{L-1}, d_{L-1})\}$, where TP_l is the l-th transmission mode with tp_l transmission power and d_l transmission distance, $tp_0 < tp_1 < \cdots < tp_l < \cdots < tp_{L-1}$, $d_0 < d_1 < \cdots < d_l < \cdots < d_{L-1}$. Therefore, in this study, the transmission power of nodes in EH-WSNs is adjusted dynamically and is thus heterogeneous.

B. ENERGY CONSUMTION AND HARVESTING MODEL

Let d_{ij} denote the distance between nodes i and j. The first-order radio model is adopted to descript the energy consumed for packet forwarding in this study. The energy consumed for node i sending k-bit data to node j is

$$E_{tx}\left(k, d_{ij}\right) = k \times E_{ele} + \begin{cases} \varepsilon_{fs} \times d_{ij}^2 d_{ij} < d_0 \\ \varepsilon_{mf} \times d_{ij}^4 d_{ij} \geq d_0, \end{cases} \quad (1)$$

and the energy consumed for receiving k bit data is

$$E_{rx}\left(k, d_{ij}\right) = k \times E_{ele}. \quad (2)$$

where E_{ele} is the electronics circuit of the sensor nodes, ε_{fs} and ε_{mf} are the propagation loss coefficients and $d_0 = \sqrt{\varepsilon_{fs}/\varepsilon_{mf}}$.

Similar to [24], [25], we model the energy harvested from sunlight by a harvested energy prediction model because ambient resources are uncontrollable and change dynamically [26]. An accurate harvest energy prediction algorithm can effectively improve network performance [27]. Many solar energy prediction models have been proposed in recent decades, such as the LSTM neural network [19], accurate solar energy allocation (ASEA) [27], exponential weighted moving average (EWMA) [28], profile energy prediction (Pro-Energy) [29], and weather conditioned moving average (WCMA) [30], [31], [32]. Owing to the advantages of high prediction accuracy and wide application range, WCMA is adopted to predict the harvested energy in this study.

The WCMA combines solar radiation values with weather data of the current day to make predictions. A $(D \times N)$ matrix E is used to store the measured energy values for the past D days. It uses K previously observed samples for the current day and the average values of the past D days to predict the harvested energy. The predicted energy $E_{har}(d, t+1)$ for time slot $t+1$ of the current day d is expressed by (3).

$$E_{har}(d, t+1) = \beta \times E_{har}(d, t) + GAP_K \times (1-\beta) \times M_D(d, t+1), \quad (3)$$

where β is a weighting factor and $M_D(l, t+1)$ represents the average value of the energy obtained at time slot $t+1$ in the past D days. GAP_K is a weighting factor used to calculate the relationship between the current day and the previous days and is calculated by (4).

$$GAP_K = \frac{V \times P}{\sum P}, \quad (4)$$

where both V and P are vectors with K elements, that is, $V = \{v_1, v_2, \cdots, v_K\}, P = \{p_1, p_2, \cdots, p_K\}$. $v_k (1 \leq k \leq K)$ is the quotient of the past K samples and the average solar energy available during the previous D days for those samples, and is calculated by (5).

$$v_k = \frac{E(d, t-K+k+1)}{M_D(d, t-K+k+1)}. \quad (5)$$

$p_k (1 \leq k \leq K)$ is a parameter that indicates the importance of the sample v_k and is calculated by (6).

$$p_k = \frac{k}{K} \quad (6)$$

C. PROBLEM DESCRIPTION

In the OR, a sender node stops its data retransmission only when it receives an ACK signal from one receiver node in the relay set. However, the heterogeneous transmission power

TABLE 1. Comparisons between the proposed ORDPD with the existing OR based studies for EH-ESNs.

Studies	OR Model	Adjust parameter dynamically		Considering non-bidirectional communication
		Transmission power	Duty cycle	
[17]	√	×	×	×
[18]	√	×	×	×
[19]	√	×	×	×
[20]	√	×	×	×
[21]	√	×	×	×
[22]	√	×	×	×
[23]	√	×	×	×
[1]	√	×	√	×
[12]	√	√	×	×
[16]	√	√	×	×
ORDPD	√	√	√	√

among nodes results in heterogeneous transmission radii and non-bidirectional communication between the sender and receiver, which increases the retransmission and packet delivery delay.

We consider a simple example, as shown in Fig. 1, to explain the non-bidirectional communication in EH-WSNs. Node S is a sender node, whereas nodes 1 and 2 are receiver nodes. They dynamically adjust their transmission power and operate in different transmission models. Nodes 1 and 2 are within the transmission range of node S, whereas node S is outside the transmission range of node 2, as shown in Fig. 1(a). In this scenario, both nodes 1 and 2 can receive the data sent by node S. However, the data from node S can only be forwarded by node 1 because node S cannot receive the ACK signal from node 2. As a result, the transmission hops and packet delivery delay increase. An opposite scenario is shown in Fig. 1(b), where nodes S and 1 are within the transmission range of node 2 and node 2 is outside the transmission range of node S. In this case, node S can only forward its data by node 1 because node 2 cannot receive data from node S.

IV. ALGORITHM IMPLEMENTATION

In this section, we first introduce the transmission model and information exchange mechanism. Thereafter, we present the proposed ORDPD in detail, which is divided into three stages: relay set (re)selection, opportunistic packet (re)transmission, and transmission power adjustment.

A. THE TRANSMISSION MODEL AND INFORMATION EXCHANGE MECHANISM

To maintain sustainable operation, the sensor nodes in the ORDPD adjust their transmission model at the end of each time slot, and the network status changes dynamically. The transmission radii are heterogeneous for all nodes in the same time slot and for the same node in different slots. Therefore, an effective information exchange mechanism is required for the timely exchange of messages among nodes.

Receiver-initiated MAC (RI-MAC) [33] is a type of MAC protocol widely used in WSNs. As in [1] and [12], we consider RI-MAC as the fundamental information exchange mechanism and make some improvements. At the beginning of each time slot, node i broadcasts an initial beacon packet IB_i to inform potential sender j of its current status information. After receiving IB_i, the potential sender j obtains the status information of node i. When the potential sender j has data to send, it can forward the data packet to node i directly, which will send an ACK signal ACK_i after receiving the packet successfully. In each time slot, the receive node i adjusts its transmission power and duty cycle if it receives a message from another potential sender outside of its current transmission range. Thereafter, node i broadcasts an updated beacon packet UB_i. After receiving UB_i, the potential sender j updates its relay set and forwarding paths in a timely manner to reduce information transmission delay and retransmission. At the end of each time slot, each node adjusts its transmission model for the next slot according to its available energy and energy utilization in previous slots.

The beacon packet used in ORDPD includes the node ID, transmission model TP_k, metric value, packet type, and the remaining valid time. The metric value is used for selecting the relay nodes and is introduced in Section 4.2. Two types of beacon packets are used in ORDPD: the initial beacon packet and the updated beacon packet. The type of packet is set to 0 if the packet is an initial beacon packet and 1 otherwise. The remaining valid time is set as 100% if the packet is an initial beacon packet and is decided by the current transmission model, and available energy otherwise. The details of deciding the remaining valid time are introduced in Section 4.4.

We consider the scenario in Fig. 1(a) as an example to explain the transmission model and information exchange mechanism, as shown in Fig. 2. In Fig. 1(a), node S is a sender node, while nodes 1 and 2 are receiver nodes that broadcast initial beacon packets at the beginning of each time slot. However, node S can only receive the initial beacon packet from

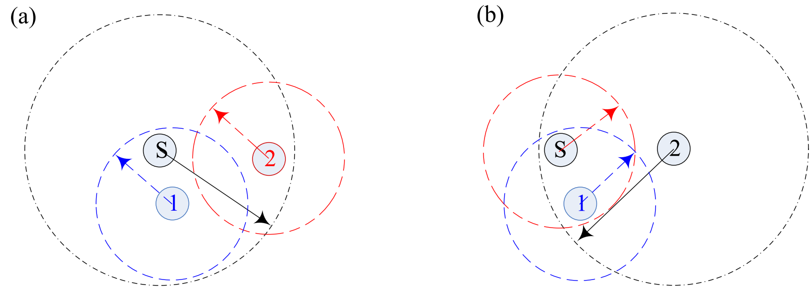

FIGURE 1. Non-bidirectional communication in EH-WSNs: (a) the transmission radius of node S is greater than that of node 2 and (b) the transmission radius of node 2 is greater than that of node S.

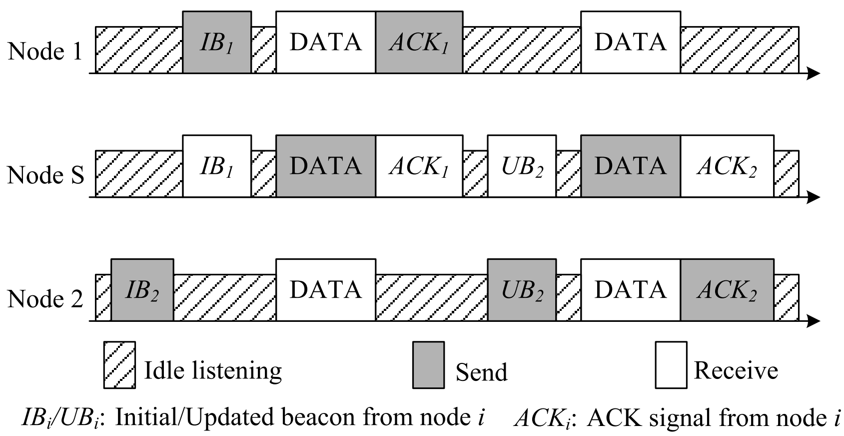

FIGURE 2. Transmission model.

node 1, as shown in Fig. 1(a), and then obtain the information of node 1. Therefore, the data packet from node S can only be forwarded by node 1 in this scenario, and the transmission delay increases owing to the limited transmission distance. However, node 2 also receives data from node S simultaneously. Furthermore, node 2 also finds that node S is out of its transmission range by the received signal strength indication (RSSI). Thereafter, node 2 adjusts its transmission power and duty cycle according to its available residual energy in the current time slot, and broadcasts an updated beacon packet. After receiving the updated beacon packet from node 2, node S updates its relay set and can transmit data packets to both nodes 1 and 2 when it has a data packet to send.

B. THE RELAY SET (RE)SELECTION STAGE

For one node in ORDPD, its available relay set for data forwarding changes dynamically because the transmission power and duty cycle of its neighbors are adjusted dynamically. Therefore, designing an effective relay set selection scheme is desirable for OR in this scenario. In this study, we improve the multistage relay set selection scheme proposed in [12] to select the forwarding set for each node.

For node i, ORDPD first selects a group of candidate nodes based on the gradient decrease in geographical location information to form a candidate forwarding set S_i^C. According to the current transmission power and distance to each candidate node, ORDPD estimates the corresponding link quality of node i and further filters out the candidate nodes in S_i^C whose link quality is lower than a predefined threshold α. Thereafter, the remaining candidate nodes in S_i^C constitute the actual forwarding set S_i^A. Similar to [12], we take the packet acceptance rate (PAR), as shown in (7), to measure the link quality. The larger the PAR, the better the link quality.

$$PAR\left(d_{ij}\right) = (1 - \frac{1}{2}exp(-\frac{SNR(d_{ij})}{2} \times \frac{B_N}{V_s}))^{8f}, \tag{7}$$

where d_{ij} is the distance between nodes i and j, $j \in S_i^C$, B_N is the noise bandwidth, V_s is the packet sending rate, SNR denotes the current signal-to-noise ratio and f denotes the size of the forwarding packet. We use the model proposed in [34] to estimate SNR by (8).

$$SNR\left(d_{ij}\right) = P_{tr}(i) - P_n - PL\left(d_{ij}\right), \tag{8}$$

where $P_{tr}\ (i)$ is the current transmission power of node i, P_n denotes the environmental noise, and $PL\left(d_{ij}\right)$ is the propagation path loss, which can be estimated by (9).

$$PL\left(d_{ij}\right) = PL\left(d_0\right) + 10n \times \lg\left(\frac{d_{ij}}{d_0}\right) + X_\sigma, \tag{9}$$

where d_0 and n denote the reference distance and path loss index, respectively, $PL(d_0)$ denotes the propagation path loss at a reference distance d_0.

After obtaining S_i^A, we take the metric used in [1] and [12], that is, the expected dynamic transmission cost ($EDTC$), to denote the transmission cost and prioritize the nodes in S_i^A. The transmission cost of a single hop from node i to j in S_i^A at time slot t, i.e., $EDTC_{ij}^{singlehop}(t)$, is the expected time interval between the sender beginning to send a packet and the receiver beginning to forward the packet. Therefore, it is mainly composed of the communication cost $T_{ij}^{com}(t)$ and waiting cost T_{ij}^{wait}, that is,

$$EDTC_{ij}^{singlehop}(t) = T_{ij}^{com}(t) + T_{ij}^{wait}(t). \quad (10)$$

According to [12], $T_{ij}^{com}(t) = \frac{1}{PAR(d_{ij},t)} \times T_{com\_pre}$, where $PAR(d_{ij}, t)$ denotes the link quality between nodes i and j at time slot t and T_{com_pre} denotes the average time required to transmit a packet to its neighbors by the perfect link. $T_{ij}^{wait}(t)$ can be estimated by the mean of the waiting cost of the prior m time slots, that is, $T_{ij}^{wait}(t) = \frac{\sum_{k=t-1-m}^{t-1} T_{ij}^{wait}(k)}{m}$.

Because packets usually require multiple hops to reach the sink node, we calculate the multi-hop $EDTC$ using the single-hop $EDTC$ and the average $EDTC$ of subsequent relay nodes. Therefore, if a sender node i selects node j in S_i^A for data forwarding at time slot t, the multihop $EDTT$ is calculated by (11) as follows:

$$EDTC_{ij}(t) = EDTC_{ij}^{singlehop}(t) + \frac{\sum_{k \in S_j^C} EDTC_{jk}(t)}{size(S_j^C)}. \quad (11)$$

Thereafter, all nodes in S_i^A are resorted by increasing $EDTC(t)$ value. The larger the$EDTC$, the higher the transmission cost. All nodes update their $EDTC$s at the end of each time slot, and broadcast the updated $EDTC$s to their neighbors at the beginning of the next time slot. Therefore, the sender node can prioritize the nodes in S^A by current $EDTC$s, and nodes with smaller $EDTC$ values have more opportunities to forward packets.

We consider Fig. 3 as an example to explain this process. Node i in Fig. 3 first obtains its candidate forwarding set S_i^C according to the gradient decrease in the geographical location information. $S_i^C = \{node1, node2, node3, node4, node5\}$. Thereafter, the link quality for the link between each node in S_i^C and node i is calculated using (7). Nodes 4 and 5 are filtered out because their link quality is lower than the predefined threshold α. The remaining nodes, that is, nodes 1, 2, and 3, constitute the actual forwarding set, S_i^A. Then, the transmission cost $EDTC$ for each node in S_i^A is calculated by (11), and node 1 is assigned the highest priority for data forwarding because it obtains the smallest value of $EDTC$ among all nodes in S_i^A.

In contrast to the sensor nodes in [12], which only adjust the transmission power at the end of each time slot, the sensor nodes in this study also adjust their transmission power and duty cycle, if necessary, in each time slot. A forwarding node adjusts its transmission power and duty cycle (increasing the transmission power and decreasing the duty cycle) if it receives a packet from a sender, as shown in Fig. 1(a). Subsequently, it broadcasts an updated beacon packet. A sender node also adjusts its transmission power and duty cycle if it receives an initial beacon packet from a candidate relay node, as shown in Fig. 1(b). The details of adjusting the transmission power and duty cycle are introduced in Section 4.4. The adjustment of the node transmission power and duty cycle also leads to a change in the link quality and communication cost. Therefore, the relay sets are reselected if the above adjustments occur, and the priority of nodes in S^A is also updated. It is worth noting that not all nodes can continue working for the entire time slot after adjustment. The adjustments also result in a heterogeneous duty cycle for the nodes. The node goes to sleep and is moved out from the actual forwarding set S^A if its active time in the current slot is exhausted.

The relay set (re)selection procedure for node i is described formally in Algorithm 1.

C. THE OPPORTUNISTIC PACKET (RE)TRANSMISSION STAGE

Opportunistic packet (re)transmission is used to select appropriate forwarding paths for sender nodes. In this stage, we adopt the packet (re)transmission strategy proposed in [12], and its main process is as follows.

After (re)sorting the nodes in S^A by increasing $EDTC$ value, as described in Section 4.2, the node with a smaller $EDTC$ value is stored in front of the S^A and has a higher priority for packet forwarding. Conversely, the node with a higher $EDTC$ value is stored at the back of S^A and has a lower priority for packet forwarding. When node i has data packets to send, it selects the node in S_i^A in order of priority for forwarding. The node with the lower priority retransmits the packet only when the transmission by the node with the higher priority fails. If the retransmission by the node with the lowest priority in S_i^A also fails, a new round of retransmission starts from the node with the highest priority in S_i^A. If the lasted retransmission in the maximal allowable rounds fails, the packet is dropped. More details about the opportunistic packet (re)transmission strategy are provided in [12].

D. THE TRANSMISSION POWER ADJUSTMENT STAGE

The transmission power adjustment stage in the ORDPD adjusts the transmission power of the nodes based on the harvested energy prediction at the end of each time slot. Moreover, it also adjusts the transmission power and duty cycle of the nodes in each time slot based on the residual available energy in the current time slot if the scenarios shown in Fig. 1 occur.

After predicting the harvested energy available in the next slot by (3), the node adjusts its transmission power for the next slot. For node i. $E_{har}^i(d, t+1)$ denotes the available energy

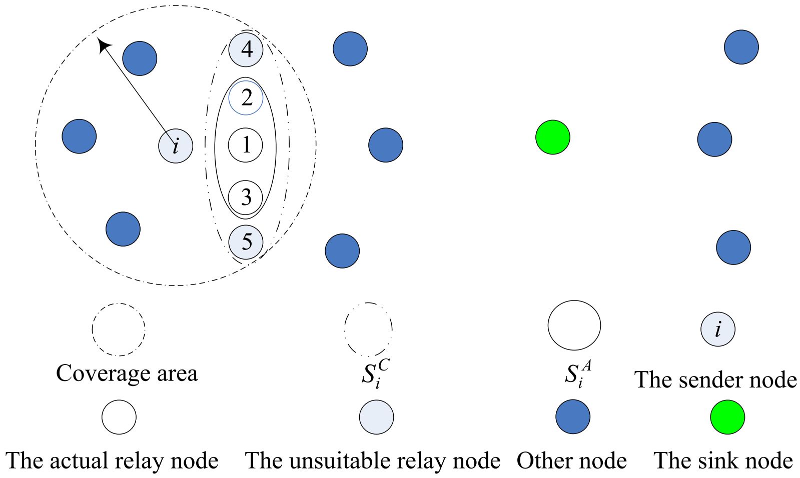

FIGURE 3. Relay set selection example.

Algorithm 1: RSRS()

1 get S_i^C for node i based on the gradient decreasing of geographical location information;
2 *for (each node* $j \in S_i^C$) do
3 calculate $PAR(j, d_{ij})$ by (7);
4 *if* ($PAR(j, d_{ij}) < \alpha$)
5 $S_i^C \leftarrow S_i^C - \{j\}$;
6 $S_i^A \leftarrow S_i^C$;
7 *for (each node* $j \in S_i^A$) do
8 calculate $EDTC_{ij}(t)$ by (11);
9 sort nodes of set S_i^A in increasing $EDTC(t)$ value;
10 *for (each node* $j \in S_i^C$) do
11 *if ((node j receives the packet from node i) && (node i is out of the current transmission range of node j))*
12 adjust tp_j to tp_i;
13 broadcast an updated beacon packet;
14 *if (node i receives an updated beacon packet from node* $j \in S_i^C$)
15 calculate $PAR(j, d_{ij})$ by (7);
16 *if* ($PAR(j, d_{ij}) \geq \alpha$)
17 $S_i^A \leftarrow S_i^A + \{j\}$;
18 calculate $EDTC_{ij}(t)$ by (11);
19 resort nodes of set S_i^A in increasing $EDTC(t)$ value;
20 *if ((node i receives an initial beacon packet from node* $j \in S_i^C$) *&& (node* $j \notin S_i^A$))
21 adjust tp_i to tp_j;
22 repeat lines 15-19;
23 *for (each node* $j \in S_i^A$) do
24 *if (the active time of node j is exhausted)*
25 $S_i^A \leftarrow S_i^A - j$;

---

predicted in time slot $t+1$ of the current day d by the WCMA model. $E_{res}^i(d,t)$ denotes the residual energy at the end of the time slot t. $E_{tr\_max}^i$ denotes the energy consumed by node i at the maximum transmission power in a slot. Therefore, the adjustable energy for node i in slot $t+1$, that is, $E_{tr}^i(d,t+1)$, is calculated by (12).

$$E_{tr}^i(d,t+1) = min(max\left(E_{har}^i(d,t+1) + E_{res}^i(d,t) - E_{th}^i, 0\right), E_{tr\_max}^i) \tag{12}$$

where E_{th}^i denotes the threshold energy for node i keeping basic computation and sensing. According to $E_{tr}^i(d,t+1)$ and slot length T_i, the ideal transmission power for node i in slot $t+1$ is determined by (13).

$$P_{tr}^i(d,t+1) = \frac{E_{tr}^i(d,t+1)}{T_i}. \tag{13}$$

Thereafter, node i adjusts its transmission power in slot $t+1$ by selecting the transmission mode $tp_l \in TP$ that is less than $P_{tr}^i(d,t+1)$ but closest to $P_{tr}^i(d,t+1)$. Node i informs its neighbors of the adjusted transmission power by broadcasting the initial beacon packet at the beginning of slot $t+1$. Moreover, the duty cycle is set to 100%.

From (3) and (13), we know that the transmission power mainly depends on the harvested energy, which is uncontrollable, dynamic, and unbalanced in EH-WSNs. Therefore, the transmission power of all nodes is heterogeneous after adjustment. In each time slot, node i also adjusts its transmission power and duty cycle if it receives a packet from a sender node j beyond the current transmission range of node i as shown in Fig. 1. Suppose node i receives the packet from node j with transmission model tp_j at ζ, $t \leq \zeta \leq t+T_i$. To reduce information transmission delay and retransmission, node i increases its transmission power to tp_j by adjusting its duty cycle in slot $[\zeta, t+T_i]$. The energy consumed in slot $[t,\zeta]$ is $tp_l \times (\zeta - t)$. The residual available energy for time slot $[\zeta, t+T_i]$ is $E_{har}^i(d,t+1) + E_{res}^i(d,t) - E_{th}^i - tp_l \times (\zeta - t)$. Therefore, the duty cycle in slot $[\zeta, t+T_i]$, that is,

$T^i_{active}(\zeta, t+T_i)$ is determined by (14) as follows:

$$T^i_{active}(\zeta, t+T_i) = \frac{E^i_{har}(d, t+1) + E^i_{res}(d, t) - E^i_{th} - tp_l \times (\zeta - t)}{tp_j \times (t + T_i - \zeta)}. \quad (14)$$

If node i is a relay node such as node 2 in Fig. 1(a), it adjusts its transmission power and duty cycle and then broadcasts an updated beacon packet to its neighbors. The potential sender node updates its actual forwarding set S^A and reassigns the transmission priority of the nodes in S^A by the updated *EDTCs* after receiving the updated beacon packet. If node i is a sender node such as node S in Fig. 1(b), it adjusts its transmission power and duty cycle and then reassigns the transmission priority of nodes in S^A by the updated *EDTCs*.

V. PERFORMANCE EVALUATION

A. SIMULATION SETUP

To evaluate the performance of the proposed ORDPD, we conduct a series of experiments and compare ORDPD with OPEH [1], ORDTP [12] and ECTRA [16]. OPEH adjusts the duty cycle of sensor nodes dynamically to improve the network performance while both ORDTP and ECTRA adjust the transmission power of nodes in EH-WSNs. Moreover, both OPEH and ORDTP are OR based schemes. OPEH forwards packets with fixed transmission power. It adjusts the duty cycle of the nodes at the end of each time slot, based on the predicted harvested energy in the next slot. Different from OPEH, ORDTP works with fixed duty cycle. It adjusts the transmission power of the nodes at the end of each time slot. ECTRA rotates the transmission radii of the nodes by adjusting the transmission power to balance the energy consumption among the nodes and to reduce the maximum energy consumption. It also increases the transmission radii to forward data in turns when the nodes harvest sufficient energy from the environment. However, non-bidirectional communication between nodes caused by the heterogeneous transmission radii of nodes has not been studied in these algorithms. The following metrics are used to evaluate the performance of all the tested algorithms:

(1) End-to-End Delay (EED) is the delay from the sensor node to the sink node for transmitting data packets, reflecting the tardiness of packet forwarding.
(2) Packet Delivery Ratio (PDR) represents the success rate of transmitting data packets from the sensor node to the sink node, reflecting the reliability of data forwarding.
(3) Packet Redundancy Ratio (PRR) is the ratio of redundant data packets received by the sink node to the data packets sent by the sensor nodes, reflecting the redundancy rate of data forwarding.
(4) Energy Consumption Ratio (ECR) is the ratio of energy consumed to the number of packets received by the sink node successfully, reflecting the efficiency of energy consumption.

The performance of all algorithms is evaluated in NS-3, which is a discrete event driven network simulator and produces results that are highly similar to real environments [8], [10]. For the simulation, the energy harvesting sensor nodes are deployed in a two-dimensional area (200m $\times$ 200m) and one sink node at (100 m, 100 m). During the simulation, the sensor nodes periodically forward packets to the sink node. Each sensor node is also equipped with a rechargeable battery with a maximal capacity of 100 J and a solar panel with dimensions 10mm $\times$ 10mm. The updated National Solar Radiation Database statistical summaries [35], which hold solar and meteorological data for 1454 locations in the United States, are used as the solar power harvesting characteristic during the simulation. All parameters for the simulations are listed in Table 2.

B. EVALUATION OF EXPERIMENTAL RESULTS

The impact on EED as a function of the number of sensor nodes is shown in Fig. 4, which indicates that the EEDs of all algorithms first maintain high values and then have a decreasing trend with an increase in the number of sensor nodes. This phenomenon occurs because the number of available relay nodes for a sender node increases with an increase in the number of sensor nodes in EH-WSNs. The increase of available relay nodes significantly reduces the waiting time for packet transmission. Fig. 4 also shows that the proposed ORDPD obtains the best results for EED among all the compared algorithms. This result can be explained as follows: In addition to adjusting the transmission power of sensor nodes at the end of each time slot, ORDPD adjusts both the transmission power and duty cycle of sensors dynamically in each time slot according to the available residual energy if these nodes receive packets from other nodes beyond their transmission range. The adjustments in the time slots adopted by ORDPD effectively remove the non-bidirectional communication caused by heterogeneous transmission radii. However, all the other compared algorithms do not consider the phenomenon of non-bidirectional communication, which results in more retransmission and delay.

The impact on PDR as a function of the number of sensor nodes is shown in Fig. 5. It can be observed that the PDRs of all algorithms have a increasing trend with an increase in the number of sensor nodes and the proposed ORDPD gets the best results among all algorithms. The average transmission distance between nodes decreases with an increase in the number of sensor nodes, which increases the transmission reliability and PDRs. The nodes with higher link quality are selected to join the actual forwarding sets in the algorithms except ECTRA, which further increases the transmission reliability and PDRs. However, ORDTP and OPEH forward packet with fixed duty cycle and fixed transmission power, respectively, while only the proposed ORDPD adjusts both the transmission power and duty cycle dynamically. On this basis, the adjustments of both the transmission power and duty cycle in the time slots adopted by ORDPD

TABLE 2. Simulation parameters setting.

Parameter	Value
The minimum/maximum transmission radius of nodes	4m/20 m
The size of data packet	100 bytes
The size of initial/updated beacon packet	30 bytes
T_{com_pre}	5 ms
α, β	0.7, 0.5
B_N	30 kHz
V_s	19.2 kbps
P_n	-115 dBm
d_0	1 m
n	4
$PL(d_0)$	55 dB
E_{tr_max}	0.05J
E_{th}	0.01J

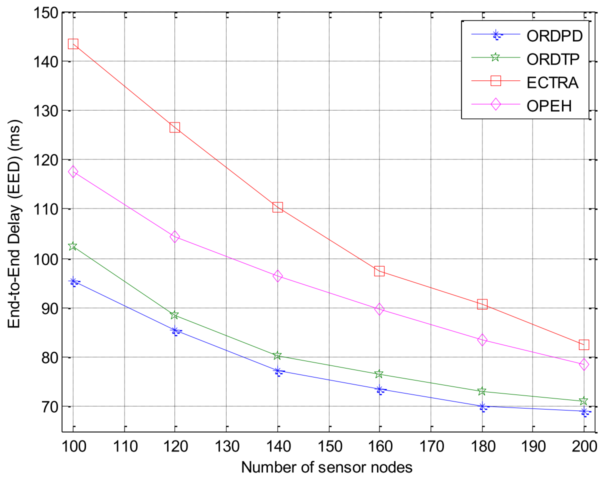

FIGURE 4. The impact on EED as a function of the number of sensor nodes.

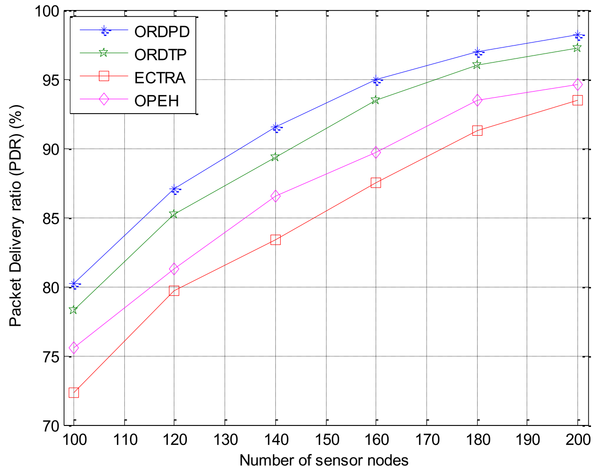

FIGURE 5. The impact on PDR as a function of the number of sensor nodes.

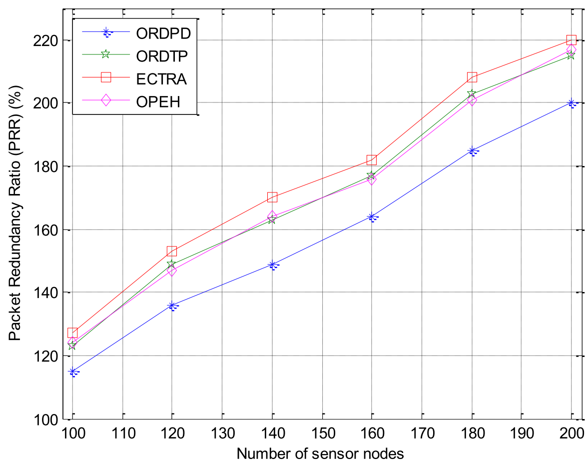

FIGURE 6. The impact on PRR as a function of the number of sensor nodes.

further enhance transmission reliability. Therefore, the proposed ORDPD obtains the best results for the PDR among all algorithms.

The impact on the PRR as a function of the number of sensor nodes is presented in Fig. 6, which shows that the PDRs of all algorithms maintain an increasing trend with the increase in the number of sensor nodes, and the proposed ORDPD obtains the best results among all algorithms. This phenomenon is due to similar reasons for Figs. 4 and 5. More sensor nodes take part in data forwarding with the increase in the number of sensor nodes. Therefore, the chance of the same packet being sent by different nodes increases, which results in a more redundant packet being transmitted, thus increasing their PRRs. By only adjusting the transmission power or the duty cycle of the sensor nodes, ORDTP and OPEH obtain the similar PRR results. By adjusting both the transmission power and the duty cycle of the sensor nodes in the time slots, the non-bidirectional communication is significantly reduced in the proposed ORDPD. Therefore, ORDPD obtains the best PRR results among all the algorithms.

The impact on the ECR as a function of the number of sensor nodes is presented in Fig. 7. It can be observed that the ECRs of all algorithms maintain an increasing trend with the increase in the number of sensor nodes, and the proposed ORDPD obtains the best results among all algorithms. This phenomenon happens because the number of available relay nodes for a sender node increases and the average transmission distance between nodes decreases with an increase in the number of sensor nodes in EH-WSNs. Therefore, more and more sensor nodes are involved in packet forwarding when the sender nodes transmit data to the sink and more energy is consumed, which brings up the ECRs of all compared algorithms. However, the proposed ORDPD gets the best results on EED, PDR, and PRR as shown in Fig.4, Fig.5, and Fig.6, respectively, which results that ORDPD consumes less energy than the other algorithms and gets the best results on ECR. ECTRA is not an OR based algorithm for EH-ESNs and adjusts the transmission power of nodes dynamically for

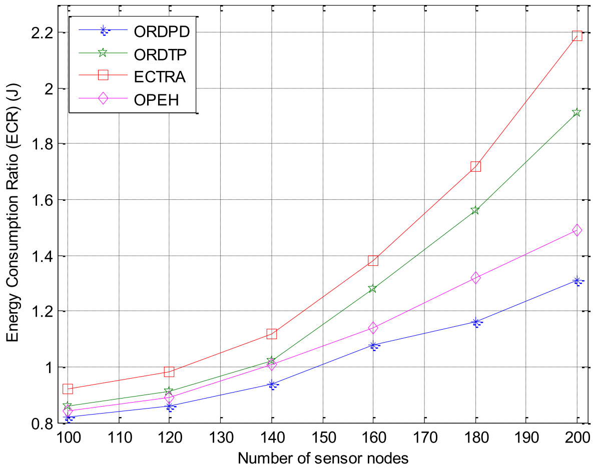

FIGURE 7. The impact on ECR as a function of the number of sensor nodes.

balancing the energy consumption among the nodes. However, the dynamic change of node transmission radius in ECTRA results in the continuous eatablishing of data transmission routes, which brings up its ECR values. Moreover, the unconsidered non-bidirectional communication further increases its ECR values.

When considering EED, PDR, PRR, and ECR simultaneously, it can be found that the proposed ORDPD obtains lower EEDs, PRRs, and ECRs with higher PDRs and performs better than other competitors.

VI. CONCLUSION

In this study, we proposed an OR scheme called ORDPD to solve the non-bidirectional communication between nodes caused by the heterogeneous transmission power of nodes in EH-WSNs. ORDPD dynamically adjusts both the transmission power and the dynamic duty cycle of the nodes. It adjusts the transmission power of each sensor node at the end of each time slot for the next slot, according to the predicted available energy. In each time slot, to decrease the retransmission and delay caused by non-bidirectional communication between nodes, ORDPD adjusts the transmission power and duty cycle of sensor nodes according to their residual available energy in the current slot if the nodes receive packets from other nodes outside of their transmission ranges. ORDPD also adopts an improved transmission model and information exchange mechanism to dynamically update relay sets and forwarding paths. The simulation results verify that the proposed ORDPD provides effective performance for EH-WSNs and has superior performance to its competitors.

The main limitation of this study is that it did not consider unbalanced energy consumption among nodes. The ambient harvestable energy for the sensor nodes in the same area is basically the same. However, the energy consumption among nodes is unbalanced. If some nodes, especially the sensor nodes near the sink node, consume more energy than those harvested in a given period of time, these nodes will tend to perish and then cause the network to die prematurely. Therefore, we intend to design another OR scheme by considering the unbalanced energy consumption. Moreover, only one sink node was considered, and the location of the sink node was fixed. Recently, mobile devices, such as mobile phones and unmanned aerial vehicles, have become increasingly popular in our daily lives. We also plan to use multiple mobile devices as sinks in EH-WSNs to enhance system performance.

REFERENCES

[1] X. Zhang, C. Wang, and L. Tao, "An opportunistic packet forwarding for energy-harvesting wireless sensor networks with dynamic and heterogeneous duty cycle," *IEEE Sensors Lett.*, vol. 2, no. 3, pp. 1–4, Sep. 2018.

[2] M. Gamal, N. E. Mekky, H. H. Soliman, and N. A. Hikal, "Enhancing the lifetime of wireless sensor networks using fuzzy logic LEACH technique-based particle swarm optimization," *IEEE Access*, vol. 10, pp. 36935–36948, 2022.

[3] W. Osamy, A. M. Khedr, A. Salim, A. I. A. Ali, and A. A. El-Sawy, "Coverage, deployment and localization challenges in wireless sensor networks based on artificial intelligence techniques: A review," *IEEE Access*, vol. 10, pp. 30232–30257, 2022.

[4] G. Ardeshiri and A. Vosoughi, "On adaptive transmission for distributed detection in energy harvesting wireless sensor networks with limited fusion center feedback," *IEEE Trans. Green Commun. Netw.*, vol. 6, no. 3, pp. 1764–1779, Sep. 2022.

[5] B. Han, F. Ran, J. Li, L. Yan, H. Shen, and A. Li, "A novel adaptive cluster based routing protocol for energy-harvesting wireless sensor networks," *Sensors*, vol. 22, no. 4, p. 1564, Feb. 2022.

[6] T. Sanislav, G. D. Mois, S. Zeadally, and S. C. Folea, "Energy harvesting techniques for Internet of Things (IoT)," *IEEE Access*, vol. 9, pp. 39530–39549, 2021.

[7] F. Liu, C. Jiang, and W. Xiao, "Multistep prediction-based adaptive dynamic programming sensor scheduling approach for collaborative target tracking in energy harvesting wireless sensor networks," *IEEE Trans. Autom. Sci. Eng.*, vol. 18, no. 2, pp. 693–704, Apr. 2021.

[8] Q. Ren and G. Yao, "An energy-efficient cluster head selection scheme for energy-harvesting wireless sensor networks," *Sensors*, vol. 20, no. 1, p. 187, Dec. 2019.

[9] C. Tang, Q. Tan, Y. Han, W. An, H. Li, and H. Tang, "An energy harvesting aware routing algorithm for hierarchical clustering wireless sensor networks," *KSII T. Internet. Inf.*, vol. 10, no. 2, pp. 504–521, Feb. 2016.

[10] Q. Ren and G. Yao, "Enhancing harvested energy utilization for energy harvesting wireless sensor networks by an improved uneven clustering protocol," *IEEE Access*, vol. 9, pp. 119279–119288, 2021.

[11] M. Abdollahi, F. Eshghi, M. Kelarestaghi, and M. Bag-Mohammadi, "Opportunistic routing metrics: A timely one-stop tutorial survey," *J. Netw. Comput. Appl.*, vol. 171, Dec. 2020, Art. no. 102802.

[12] H. Cheng, C. Wang, and X. Zhang, "An opportunistic routing in energy-harvesting wireless sensor networks with dynamic transmission power," *IEEE Access*, vol. 7, pp. 180652–180660, 2019.

[13] M. M. I. Rajib and A. Nasipuri, "Predictive retransmissions for intermittently connected sensor networks with transmission diversity," *ACM Trans. Embedded Comput. Syst.*, vol. 17, no. 1, pp. 1–25, Jan. 2018.

[14] H. Shafieirad, R. S. Adve, and S. ShahbazPanahi, "Opportunistic routing in large-scale energy harvesting sensor networks," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Washington DC, USA, Dec. 2016, pp. 1–6.

[15] H. U. Yildiz, S. Kurt, and B. Tavli, "Comparative analysis of transmission power level and packet size optimization strategies for WSNs," *IEEE Syst. J.*, vol. 13, no. 3, pp. 2264–2274, Sep. 2019.

[16] X. Ju, W. Liu, C. Zhang, A. Liu, T. Wang, N. N. Xiong, and Z. Cai, "An energy conserving and transmission radius adaptive scheme to optimize performance of energy harvesting sensor networks," *Sensors*, vol. 18, no. 9, p. 2885, Aug. 2018.

[17] Z. A. Eu and H.-P. Tan, "Adaptive opportunistic routing protocol for energy harvesting wireless sensor networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Ottawa ON, Canada, Jun. 2012, pp. 318–322.

[18] Z. A. Eu, H.-P. Tan, and W. K. G. Seah, "Opportunistic routing in wireless sensor networks powered by ambient energy harvesting," *Comput. Netw.*, vol. 54, no. 17, pp. 2943–2966, Dec. 2010.

[19] Y. Li, X. He, and C. Yin, "Energy aware opportunistic routing for energy harvesting wireless sensor networks," in *Proc. IEEE 31st Annu. Int. Symp. Pers., Indoor Mobile Radio Commun.*, London, U.K., Aug. 2020, pp. 1–6.
[20] H. Shafieirad, R. S. Adve, and S. Shahbazpanahi, "Max-SNR opportunistic routing for large-scale energy harvesting sensor networks," *IEEE Trans. Green Commun. Netw.*, vol. 2, no. 2, pp. 506–516, Jun. 2018.
[21] P. Spachos and D. Hatzinakos, "Poster–SEA-OR: Spectrum and energy aware opportunistic routing for self-powered wireless sensor networks," in *Proc. 20th Annu. Int. Conf. Mobile Comput. Netw.*, Maui, HI, USA, Sep. 2014, pp. 429–432.
[22] J. Hu, J. Luo, Y. Zheng, and K. Li, "Graphene-grid deployment in energy harvesting cooperative wireless sensor networks for green IoT," *IEEE Trans. Ind. Informat.*, vol. 15, no. 3, pp. 1820–1829, Mar. 2019.
[23] J. Hu, J. Luo, and K. Li, "Opportunistic energy cooperation mechanism for large Internet of Things," *Mobile Netw. Appl. J.*, vol. 23, no. 3, pp. 489–502, Jun. 2018.
[24] D. K. Sah and T. Amgoth, "A novel efficient clustering protocol for energy harvesting in wireless sensor networks," *Wireless Netw.*, vol. 26, no. 6, pp. 4723–4737, May 2020.
[25] I. U. Haq, Q. Javaid, Z. Ullah, Z. Zaheer, M. Raza, M. Khalid, G. Ahmed, and S. Khan, "E^2-MACH: Energy efficient multi-attribute based clustering scheme for energy harvesting wireless sensor networks," *Int. J. Distrib. Sensor Netw.*, vol. 16, no. 10, Oct. 2020, Art. no. 1550147720968047.
[26] J. Zheng, Y. Cai, X. Shen, Z. Zheng, and W. Yang, "Green energy optimization in energy harvesting wireless sensor networks," *IEEE Commun. Mag.*, vol. 53, no. 11, pp. 150–157, Nov. 2015.
[27] D. K. Noh and K. Kang, "Balanced energy allocation scheme for a solar-powered sensor system and its effects on network-wide performance," *J. Comput. Syst. Sci.*, vol. 77, no. 5, pp. 917–932, Sep. 2011.
[28] A. Kansal, J. Hsu, S. Zahedi, and M. B. Srivastava, "Power management in energy harvesting sensor networks," *ACM Trans. Embedded Comput. Syst.*, vol. 6, no. 4, p. 32, Sep. 2007.
[29] A. Cammarano, C. Petrioli, and D. Spenza, "Pro-energy: A novel energy prediction model for solar and wind energy-harvesting wireless sensor networks," in *Proc. IEEE 9th Int. Conf. Mobile Ad-Hoc Sensor Syst. (MASS)*, Las Vegas NV, USA, Oct. 2012, pp. 75–83.
[30] J. R. Piorno, C. Bergonzini, D. Atienza, and T. S. Rosing, "Prediction and management in energy harvested wireless sensor nodes," in *Proc. 1st Int. Conf. Wireless Commun., Veh. Technol., Inf. Theory Aerosp. Electron. Syst. Technol.*, Aalborg, Denmark, May 2009, pp. 6–10.
[31] J. C. López-Ardao, R. F. Rodríguez-Rubio, A. Suárez-González, M. Rodríguez-Pérez, and M. E. Sousa-Vieira, "Current trends on green wireless sensor networks," *Sensors*, vol. 21, no. 13, p. 4281, May 2021.
[32] S. Avlani, D.-H. Seo, B. Chatterjee, and S. Sen, "EICO: Energy-harvesting long-range environmental sensor nodes with energy-information dynamic co-optimization," *IEEE Internet Things J.*, vol. 9, no. 21, pp. 20932–20944, Nov. 2022, doi: 10.1109/JIOT.2022.3178422.
[33] Y. Sun, O. Gurewitz, and D. B. Johnson, "RI-MAC: A receiver-initiated asynchronous duty cycle MAC protocol for dynamic traffic loads in wireless sensor networks," in *Proc. 6th ACM Conf. Embedded Netw. Sensor Syst. (SenSys)*, Raleigh NC, USA, 2008, pp. 1–14.
[34] A. Akbas, H. U. Yildiz, B. Tavli, and S. Uludag, "Joint optimization of transmission power level and packet size for WSN lifetime maximization," *IEEE Sensors J.*, vol. 16, no. 12, pp. 5084–5094, Jun. 2016.
[35] (2010). *The National Solar Radiation Database*. [Online]. Available: https://rredc.nrel.gov/solar/olddata/nsrdb/1991-2010/

QIAN REN received the M.S. degree from the Hefei University of Technology, Hefei, China, in 2012. She is currently a Lecturer at the College of Computer and Information Engineering, Chuzhou University, China. Her research interests include wireless sensor networks and the Internet of Things.

GUANGSHUN YAO received the Ph.D. degree from Donghua University, China, in 2016. He is currently a Professor at the College of Computer and Information Engineering, Chuzhou University, China. He is also working as a Postdoctoral Researcher with Southeast University, China. He is the author or coauthor over more than 20 academic articles, some of which have been published in international journals such as IEEE TRANSACTIONS ON PARALLEL AND DISTRIBUTED SYSTEMS, IEEE TRANSACTIONS ON SERVICES COMPUTING, IEEE ACCESS, *Information Sciences*, *Knowledge-Based Systems*, and *Soft Computing*. His research interests include cloud computing and the Internet of Things.