Opportunistic Routing Algorithm for Relay Node Selection in Wireless Sensor Networks

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***Abstract*—Energy savings optimization becomes one of the major concerns in the wireless sensor network (WSN) routing protocol design, due to the fact that most sensor nodes are equipped with the limited nonrechargeable battery power. In this paper, we focus on minimizing energy consumption and maximizing network lifetime for data relay in one-dimensional (1-D) queue network. Following the principle of opportunistic routing theory, multihop relay decision to optimize the network energy efficiency is made based on the differences among sensor nodes, in terms of both their distance to sink and the residual energy of each other. Specifically, an Energy Saving via Opportunistic Routing (ENS_OR) algorithm is designed to ensure minimum power cost during data relay and protect the nodes with relatively low residual energy. Extensive simulations and real testbed results show that the proposed solution ENS_OR can significantly improve the network performance on energy saving and wireless connectivity in comparison with other existing WSN routing schemes.**

***Index Terms*—Energy efficiency, one-dimensional (1-D) queue network, opportunistic routing, relay node, wireless sensor network (WSN).**

I. INTRODUCTION

WIRELESS sensor network (WSN) offers a wide range of applications in areas such as traffic monitoring, medical care, inhospitable terrain, robotic exploration, and agriculture surveillance [1]. The advent of efficient wireless communications and advancement in electronics has enabled the development of low-power, low-cost, and multifunctional wireless sensor nodes that are characterized by miniaturization and integration.

In WSNs, thousands of physically embedded sensor nodes are distributed in possibly harsh terrain and in most applications, it is impossible to replenish energy via replacing batteries. In order to cooperatively monitor physical or environmental conditions, the main task of sensor nodes is to collect and transmit data. It is well known that transmitting data consumes much more energy than collecting data [2]. To improve the energy efficiency for transmitting data, most of the existing energy-efficient routing protocols attempt to find the minimum energy path between a source and a sink to achieve optimal energy consumption [3]–[5]. However, the task of designing an energy-efficient routing protocol, in case of sensor networks, is multifold, since it involves not only finding the minimum energy path from a single sensor node to destination, but also balancing the distribution of residual energy of the whole network [6]. Furthermore, the unreliable wireless links and network partition may cause packet loss and multiple retransmissions in a preselected good path [7]. Retransmitting packet over the preselected good path inevitably induces significant energy cost. Therefore, it is necessary to make an appropriate tradeoff between minimum energy consumption and maximum network lifetime.

We focus on one-dimensional (1-D) queue network, which has been designed and developed for a wide variety of industrial and civilian applications, such as pipeline monitoring, electrical power line monitoring, and intelligent traffic. Fig. 1 shows an example, illustrating a pervasive traffic information acquisition system based on 1-D queue network platform, where the nodes are linearly deployed along the road. Most of the existing traditional traffic information acquisition systems are implemented without power-saving management. With the demands of various sustainable developments in smart city, an energy saving optimization solution for smart traffic information acquisition should be taken into account. In our solution, when a motion sensor node detects a vehicle in its sensing range, it will acquire traffic information, such as traffic volume, vehicle velocity, and traffic density. Sensor nodes will send the collected data to relay sensor nodes, and then the relay sensor nodes forward traffic information along the energy-efficient path to the sink node that is one or more hops away. Finally, comprehensive traffic information will be established by the sink node and sent to the traffic management center. Meanwhile, traffic management center will select appropriate information and offer it to the clients via the network. This smart traffic information acquisition solution can be used to extend the lifetime of 1-D queue network in the need of energy saving in WSN-based Information Technology (IT) infrastructure.

In this paper, we propose an energy-efficient routing algorithm for above 1-D queue network, namely, Energy Saving via Opportunistic Routing (ENS_OR). ENS_OR adopts a new concept called energy equivalent node (EEN), which selecting relay nodes based on opportunistic routing theory, to virtually derive the optimal transmission distance for energy saving and maximizing the lifetime of whole network. Since sensor nodes are usually static, each sensor's unique information, such as the

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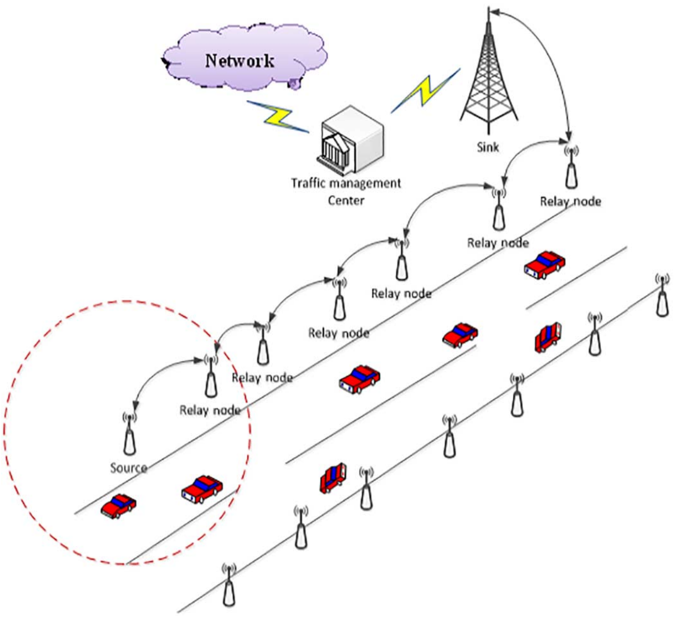

Fig. 1. Smart traffic information acquisition system.

distance of the sensor node to the sink and the residual energy of each node, are crucial to determine the optimal transmission distance; thus, it is necessary to consider these factors together for opportunistic routing decision. ENS_OR selects a forwarder set and prioritizes nodes in it, according to their virtual optimal transmission distance and residual energy level. Nodes in this forwarder set that are closer to EENs and have more residual energy than the sender can be selected as forwarder candidates. Our scheme is targeted for relatively dense 1-D queue networks, and can improve the energy efficiency and prolong the lifetime of the network.

The main contributions of this paper include the following.

1) We calculate the optimal transmission distance under the ideal scenarios and further modify the value based on the real conditions.
2) We define the concept of EEN to conduct energy optimal strategy at the position based on the optimal transmission distance.
3) We introduce the forwarder list based on the distances to EEN and the residual energy of each node into EEN for the selection of relay nodes.
4) We propose ENS_OR algorithm to maximize the energy efficiency and increase the network lifetime.

The remainder of this paper is organized as follows. Section II describes the related work. Section III introduces 1-D queue network and an energy models. Section IV proposes the concept of EEN and initiates theoretical analysis of the optimal transmission distance. To address the problem of unbalanced distribution of residual energy, a new opportunistic routing mechanism based on optimal energy strategy is devised in Section V. While Section VI evaluates the integrated performance of ENS_OR algorithm compared with existing routing protocols. Finally, the conclusion and future directions are drawn in Section VII.

II. RELATED WORK

In recent years, there are several studies on routing-related parameters, like connectivity-related parameters and density of the distributed nodes, in 1-D queue networks. Previous works [8] and [9] studied the connectivity probability of two certain nodes versus the entire network. Other work in [10], [11] investigated on uniformly and independently distribution under the assumption that the transmission range is fixed among sensor nodes.

Some energy-efficient approaches have been explored in the literature [12]–[14]. As transmitting data consumes much more energy than other tasks of sensor nodes, energy savings optimization is realized by finding the minimum energy path between the source and sink in WSNs. In [12], the theoretical analysis about the optimal power control and optimal forwarding distance of each single hop was discussed. There is a tradeoff between using high power and long hop lengths and using low power and shorter hop lengths. With this in mind, minimum energy consumption can be achieved when each sensor node locates with the optimal transmission distance away from others in dense multihop wireless network. The most forward within range (MFR) [13] routing approach has also been considered in 1-D queue networks, which chooses the farthest away neighboring node as the next forwarder, and eventually results in less multihop delay, less power consumption. Another approach proposed in [14] reduces the total consumed energy based on two optimization objectives, i.e., path selection and bit allocation. Packets with the optimum size are relayed to the fusion node from sensor nodes in the best intermediate hops. Surprisingly, the benefit of optimal bit allocation among the sensor node has not been investigated in 1-D queue networks.

The unreliable wireless links makes routing in wireless networks a challenging problem. In order to overcome this problem, the concept of opportunistic routing was proposed in [15]. Compared with traditional best path routing, opportunistic routings, such as extremely opportunistic routing (ExOR) [16], geographic random orwarding (GeRaF) [17], and efficient QoS-aware geographic opportunistic routing (EQGOR) [18], take advantage of the broadcast nature of the wireless medium, and allow multiple neighbors that can overhear the transmission to participate in forwarding packets. However, these routing protocols did not address exploiting OR for selecting the appropriate forwarding list to minimize the energy consumption, and optimize the design of an energy-efficient OR protocol for wireless networks. However, these routing protocols did not address exploiting OR for selecting the appropriate forwarding list to minimize the energy consumption, and optimize the design of an energy-efficient OR protocol for wireless networks. Mao *et al.* [19] introduced an energy-efficient opportunistic routing strategy called energy-efficient opportunistic routing (EEOR), which selects a forwarder set and prioritizes them using energy savings optimization solution of forwarding data to the sink node in WSNs.

While all of these routing methods to improve the energy efficiency of individual node or the whole network can minimize energy consumption, it is equally important to focus on other objectives such as network lifetime and residual energy of

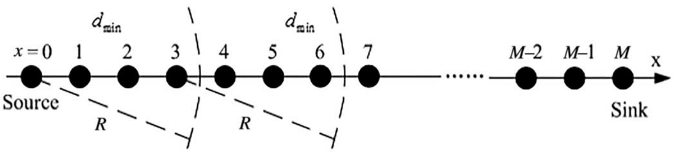

Fig. 2. Queuing model of relay with maximal transmission range of R and minimal transmission range $d_{\min}$.

relay nodes. Therefore, it is reasonable to take residual energy of sensor nodes as a primary metric into consideration.

III. NETWORK AND ENERGY MODELS

In this section, the network model and energy model will be described.

A. Network Model

We consider a multihop WSN in a 1-D queue model as shown in Fig. 2. We assume that our scheme is targeted for relatively dense network, i.e., each relay node has plenty of neighboring nodes. Nodes have some knowledge of the location information of their direct neighboring nodes and the position of the source node and the sink node. Every wireless sensor node has fixed maximum transmission range R and minimal transmission range $d_{\min}$. The 1-D queue network is then constructed by a connected graph $G = (V, E)$, where V is a set of sensor nodes aligned on a single line and E is a set of directed links between communication nodes. We set the indices $\{0, 1, 2, \ldots, h, n, \ldots, M-1, M\}$ from left to right, and two specific nodes with index 0 and index M among them as the source node and the sink node. Let $N(h)$ represents as the neighbor set of a node h, i.e., $n \in N(h)$. Each directed link (h, n) has a nonnegative weigh $w(h, n)$, which denotes the total energy dissipation in transmission and receiving required by node h to its neighboring node n.

B. Energy Model

In this work, we refer to a simplified power model of radio communication as it is used in [20] and [21]. The energy consumption can be expressed as follows:

$$E_T = \left(E_{\text{elec}} + \varepsilon_{\text{amp}} d^{\tau}\right) B \tag{1}$$

where E_{elec} is the basic energy consumption of sensor board to run the transmitter or receiver circuitry, and ε_{amp} is its energy dissipated in the transmit amplifier. d is the distance between transmitter and receiver, τ is the channel path-loss exponent of the antenna, which is affected by the radio frequency (RF) environment and satisfies $2 \le \tau \le 4$. E_T denotes the energy consumption to transmit a B-bit message in a distance d.

On the other hand, the energy consumption of receiver E_R can be calculated as follows:

$$E_R = E_{\text{elec}} B. \tag{2}$$

In our model, since the noise and environmental factor are constant, only the transmitter can adjust its transmission power to make E_T reach a minimum value.

IV. OPTIMAL TRANSMISSION SCHEMES

In this section, energy consumption analysis is conducted on the proposed 1-D model, where data are delivered to sink node through hop-by-hop connected relay nodes. Our objective is to design an energy-efficient opportunistic routing strategy for each relay node that ensures minimum power cost and protects the nodes with relatively low residual energy. Theorem 1 proves the optimal transmission distance d_{op} of sensor node under large-scale 1-D queue network.

Theorem 1: In a large-scale WSN where nodes are uniformly and independently distributed in a 1-D queuing model, the position of the sensor nodes h is x_h $(x_h \ll M)$, according to (1) and (2), the optimal transmission distance d_{op} for node h is $d_{\text{op}} = \frac{M - x_h}{n_{\text{op}}} = \{(2E_{\text{elec}})/[(\tau-1)\,\varepsilon_{\text{amp}}]\}^{1/\tau}$.

Proof: To illustrate this point, consider node h shown in Fig. 2, the distance between hth node and the sink node is $d(h, m) = M - x_h = \sum_{i=1}^{n} (x_i - x_{i-1})$, where n represents the number of hops that hth node relay data to sink. Thus, the total consumed energy (C_h) of node h can be expressed as follows:

$$\begin{aligned} C_h &= \sum_{i=1}^{n} E_T + \sum_{i=1}^{n-1} E_R \\ &= \sum_{i=1}^{n} \left\{\left[E_{\text{elec}} + \varepsilon_{\text{amp}}(x_i - x_{i-1})^{\tau}\right] B\right\} + \sum_{i=1}^{n-1} \left(E_{\text{elec}} B\right). \end{aligned} \tag{3}$$

In order to minimize C_h, we use the average value inequality to derive inequality

$$C_h \ge (2n-1)\, E_{\text{elec}} B + \frac{\varepsilon_{\text{amp}} \left[\sum_{i=1}^{n} (x_i - x_{i-1})\right]^{\tau} B}{n^{\tau-1}}. \tag{4}$$

According to inequality (4), we have

$$C_h^{\min}(n) = (2n-1)\, E_{\text{elec}} B + \frac{\varepsilon_{\text{amp}} (M - x_h)^{\tau} B}{n^{\tau-1}}. \tag{5}$$

One way to optimize the overall energy consumption during data relay is to take a derivative with respect to hop. We take the first derivative of $C_h^{\min}$ with respect to n as

$$\partial C_h^{\min} / \partial n = 2E_{\text{elec}} B - (\tau-1)\, \frac{\varepsilon_{\text{amp}} (M - x_h)^{\tau} B}{n^{\tau}} = 0. \tag{6}$$

This global minimum/maximum can be calculated as follows:

$$n_{\text{op}} = \frac{\left[(\tau-1)\,\varepsilon_{\text{amp}}\right]^{1/\tau} (M - x_h)}{\left(2E_{\text{elec}}\right)^{1/\tau}}. \tag{7}$$

Then, we take the second derivative of $C_h^{\min}$ with respect to n as

$$\begin{aligned} &\left.\frac{\partial^2 C_h^{\min}}{\partial n^2}\right|_{n = \frac{[(\tau-1)\varepsilon_{\text{amp}}]^{1/\tau}(M - x_h)}{(2E_{\text{elec}})^{1/\tau}}} \\ &\quad = \tau(\tau-1)\, \frac{\varepsilon_{\text{amp}} (M - x_h)^{\tau} B}{n^{\tau+1}} > 0. \end{aligned} \tag{8}$$

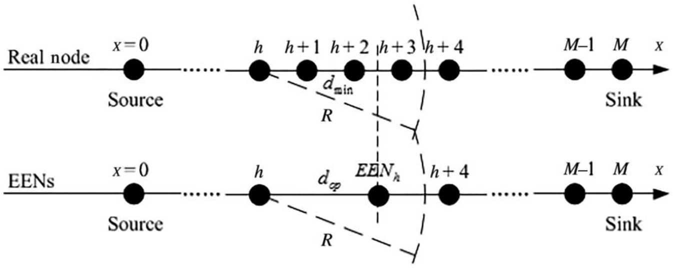

Fig. 3. Real nodes and EEN in 1-D queue model.

From (8), we deduced that (7) is the global minimum with respect to the energy consumption of node h. Hence, the corresponding optimal transmission distance d_{op} for node h is given by

$$\begin{aligned} &d_{\text{op}} = \frac{M - x_h}{n_{\text{op}}} = \{(2E_{\text{elec}})/[(\tau - 1)\varepsilon_{\text{amp}}]\}^{1/\tau} \\ &d_{\min} < d_{\text{op}} \leq R. \end{aligned} \tag{9}$$

Therefore, the proof of Theorem 1 is finished. However, Theorem 1 is an ideal model for multihop 1-D queue network. However, the distance between optimal next relay node to source node could not actually equal to d_{op}. Fig. 3 depicts a realistic environment, where the optimal next relay node of node h based on Theorem 1 would possibly be set between two real relay nodes. To solve the problem, we further address Theorem 1 that uses the idea of EEN to select the optimal next relay nodes.

Definition 1: EEN is a virtual relay node that the relay function is realized by several real nodes and its energy consumption equals to the total amount of energy of these real nodes.

In this paper, we only focus on the behavior of transmitter for data relay in our model. We replace real nodes with EENs and then obtain the minimum relay energy consumption of each node according to Theorem 1. The illustration of this process is shown in Fig. 3.

V. OPPORTUNISTIC ROUTING ALGORITHM FOR RELAY NODE SELECTION

In this section, we further analyze the energy consumption of large-scale network under 1-D model.

A. *Problem of Optimal Energy Strategy*

In order to acquire the minimum energy consumption during data transmission in whole network, we introduce the concept of EEN to conduct energy optimal strategy at the position based on the optimal transmission distance d_{op}. However, the optimal energy strategy does not explicitly takes care of the residual energy of relay nodes in the network. For instance, in the case of hop-by-hop transmissions toward the sink node, the relay nodes lying closer to the EENs tend to deplete their energy faster than the others, since d_{op} is a constant. As a consequence, this uneven energy depletion dramatically reduces the network lifetime and quickly exhausts the energy of these relay nodes. Furthermore, such imbalance of energy consumption eventually results in a network partition, although there may be still significant amounts of energy left at the nodes farther away. Therefore, we should readdress the optimal energy strategy for large-scale network from Theorem 1. Inspired from the opportunity routing approach, EEN is formed by jointly considering the distribution of real nodes and their relay priority. The specific algorithm to choose EEN is described in the following section.

B. *Forwarder Set Selection for Optimal Energy Strategy*

In the proposed Theorem 1, we conclude that the energy consumption function (5) is convex with respect to the number of hops n. We can achieve optimal energy strategy by choosing optimal hops n_{op} to determine optimal transmission distance d_{op}. In addition, factors such as energy-balanced of a network and the residual energy of nodes are also considered while selecting the available next-hop forwarder.

We assume that node h is sending a data packet to sink, and $h + i$ is one of neighbors of node h. If it is closer to the estimated result in (9) and has more residual energy, the neighboring node $h + i$ can be a forwarding candidate, then the network can obtain better energy usage. Moreover, these eligible candidates rank themselves according to their distances from the EEN and the residual energy of each node as

$$P(h+i) = \begin{cases} (d_{h+i} - d_h)\left[\frac{1}{|d_{h+i} - d_{\text{op}}|} + (E_{h+i} - \zeta)\right] \\ (h+i) \in F(h), \quad -R \leq i \leq R \end{cases} \tag{10}$$

where $d_{h+i} - d_h$ is the distance between node h and neighbor node $h + i$, E_{h+i} denotes the residual energy of node $h + i$, and ζ denotes the value of energy threshold. $F(h)\,(F(h) \subseteq N(h))$ is the selected forwarding candidate set of node h. The larger the value of $P(h + i)$ is, the higher priority of the node will be. Only the forwarder candidate with the highest priority is selected as the next forwarder.

We use above forwarding candidate set to decide corresponding energy saving strategy, which is specifically achieved through the following opportunistic routing algorithm, called ENS_OR.

C. *ENS_OR Algorithm*

In this section, we will describe how to select and prioritize the forwarder set using optimal energy strategy on each node, and how to choose the optimal relay node among potential forwarders that respond in a priority order. In addition, the transmitted data can be naturally classified into two categories: 1) the former is the collected data of its own; and 2) the latter is the relay data from other nodes. Obviously, we should distinguish incoming data (the data of second category) by tracing the ID of sender. Eventually, we introduce ENS_OR algorithm for energy saving to select the next relay node which has the highest priority in forwarder set to forward the incoming ENS_OR algorithm. Algorithm 1 depicts the pseudocode of ENS_OR algorithm.

```
Algorithm 1. ENS_OR Algorithm
Require: $d_i,\ d_h,\ d_{\rm op},\ E_i,\ \zeta$, where $i \in F\,(h)$
Ensure: the position of next forwarder $d_n$.

    Event: Node $h$ has a data packet to send to the sink node.
    $/ * $ Steps $ * /$
1: start a retransmission timer
2: select the forwarder set $F(h)$ from neighboring nodes
   $N\,(h)$;
3: for each node $i \in N\,(h)$ do
4:     if $((d(i, d_{\rm op}) < d(h, d_{\rm op})) \cup (E_i > \zeta))$ then
5:         add $i$ to $F(h)$;
6:     end if
7: end for
8: prioritize the forwarder set using Optimal Energy Strategy;
9: for each node $i \in F\,(h)$ do
10:     $P(i) = (d_i - d_h)\left[\frac{1}{|d_i - d_{\rm op}|} + (E_i - \zeta)\right]$
11: end for
12: broadcast the data packet;
13: for each node $i \in F\,(h)$ do
14:     receive the data packet;
15:     checks the sender ID and start a timer and $time(i) = \frac{\alpha}{P(i)}$;
16: end for
17: if node $n$ which has the highest-priority receives the data
    packet successfully then
18:     reply an ACK to notify the sender;
19:     for each node $i \in F\,(h)$ except $n$ do
20:         discard the data packet and close timer;
21:     end for
22: else
23:     if the priority timer expire then
24:         set $n = n'$, node $n'$ has the lower-priority;
25:         goto 17;
26:     end if
27: end if
28: if no forwarding candidate has successfully received the
    packet then
29:     if the retransmission timer expire then
30:         drop the data packet;
31:     else
32:         goto 2;
33:     end if
34: end if
35: return
```

VI. PERFORMANCE EVALUATION IN DIFFERENT METRICS

A. Simulation Scenario Experiments

1) Simulation Environment: We conduct the simulation experiments using MATLAB with 100 nodes uniformly and independently distributed over a line. Each node has the same frequency $B = 1$ Mbit/s, and firmware character $E_{\rm elec}$ and $\varepsilon_{\rm amp}$ in (1) is set as 50×10^{-9} J/bit and 100×10^{-12} J/bit/m^2, respectively. Path-loss exponent of environment τ is 2. Hence, the value of optimal transmission distance $d_{\rm op}$ in (9) is approximately equal to 31.6 m. Since $E_{\rm elec}$ and $\varepsilon_{\rm amp}$, τ are fixed, no matter how the distance between two nearest nodes changes, $d_{\rm op}$ still will be 31.6 m, without change. The longest transmission distance of a single hop is 50 m and the initial energy is 720 mJ. Other simulation parameters are listed in Table I. In this one-source-one-sink topology, a node can only act as a relaying node. In this paper, we ignore the interference among the generated signals of each node. To fully analyze the performance of ENS_OR, we compared it with the methods GeRaF and minimum transmission energy (MTE) which represent the transmission power strategy with minimum transmission power, to satisfy quality of service (QoS) requirement of reception. The abbreviations and corresponding full names are listed in Table II.

TABLE I
SIMULATION PARAMETERS

Parameter	Parameter's value
Deployment area	$50\,\mathrm{m} \times 2500\,\mathrm{m}$
Deployment distribution	Uniform
Distance between two adjacent nodes	$5 - 25\,\mathrm{m}$
Number of nodes	100
Source node	1
Sink node	1
Relay nodes	98
The longest transmission distance	50 m
Sending rate	1 packet/s
Packet size	1024 bit
Testing time	900 s

TABLE II
ABBREVIATIONS AND CORRESPONDING FULL NAMES

Abbreviation	Full name
EEN	Energy equivalent node
ENS_OR	Energy saving via opportunistic routing
GeRaF	Geographic random forwarding
MTE	Minimum transmission energy
ARE	Average of residual energy
SRE	Standard deviation of residual energy
RPR	Receiving packets ratio
FDN	First dead node
NL	Network lifetime

2) Performance Metrics: We define four main measurable metrics to evaluate the effectiveness of ENS_OR algorithm for data forwarding in 1-D queue networks.

1) Average of residual energy (ARE): Relay nodes left with more average residual energy indicates that all the relay nodes are alive for longer time, which would help to prolong network lifetime.
2) Standard deviation of residual energy (SRE): We use SRE as a metric to quantify the energy balance characteristic of the routing protocol, we have noticed that high standard deviation in the estimations of residual energy implies the unbalanced energy dissipation among sensor nodes, and lowering SRE is important for the routing protocol.
3) Receiving packets ratio (RPR): RPR is defined as the ratio of the amount of packets received by the sink to the total amount of packets sent by the source. In order to effectively avoid the network partition, the sink should receive most of the packets sent from the source, and eventually results in a good connectivity of the network.

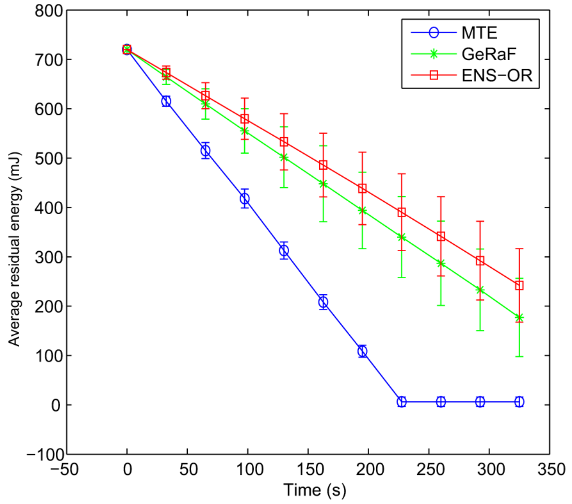

Fig. 4. Comparison of ARE according to time.

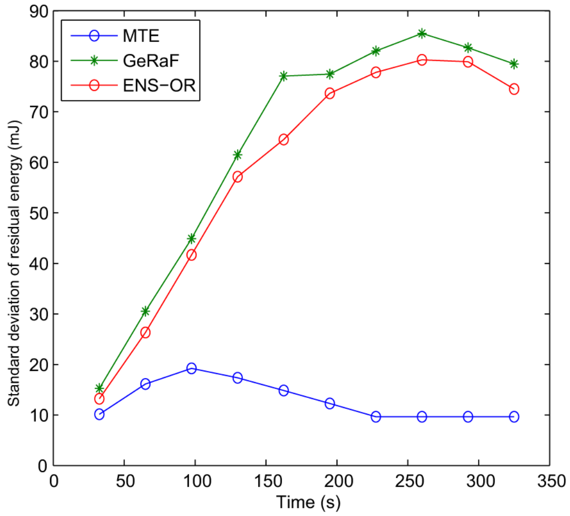

Fig. 5. Comparison of SRE according to time.

4) First dead node (FDN): We define this metric to evaluate the influence of the network connectivity. As the first energy exhausted node appears, the probability of network partition increases, and the connectivity of the network goes bad.

5) Network lifetime (NL): The network lifetime of a 1-D queue network is defined as the time when the sink is unable to receive packet sent from the source. The network lifetime is closely related to the energy consumption and network partition. The higher the network lifetime is, the more effectively the balance of energy consumption will be achieved, and the more likely the network partition is going to happen.

3) Evaluation of Relay Algorithm: Fig. 4 describes the average residual energy as a function of time, when system is fully operated. As we can see, in general, the total residual energy decreases as the simulation time increases. This can be explained by (1) and (2), where packet size grows incrementally over time can communicate with more energy over a given distance. ENS_OR can achieve higher average residual energy compared with GeRaF and MTE, because of its energy optimal strategy and opportunistic routing scheme. ENS_OR always keeps the energy consumption at the lowest level. Due to the lower energy consumption, a longer lifetime can be achieved as well by ENS_OR method.

From Fig. 5, we notice that ENS_OR has a lower standard deviation of residual energy compared with GeRaF. MTE has the lowest value, because MTE always deliver data to sink node hop-by-hop, which implies that energy dissipation of MTE strategy is balanced among relay nodes. However the total energy consumption of delivery is maximal as shown in Fig. 4. Thus, according to Figs. 4 and 5, we can also infer that ENS_OR strategy is a better equilibrium energy strategy.

Fig. 6 reports the RPR under different minimum distance between two nearest nodes. Here we also observe from Fig. 6 that initially data received at sink node in ENS_OR is greater than that in GeRaF. However, when the distance between two nearest nodes exceeds 15 m, the difference between two methods is rather small. Thus, ENS_OR receive more packets sent from the source than GeRaF, which can effectively avoid the network partition and has a good connectivity of the network. The more the number of data is transmitted means more energy will be consumed. So there is a direct relationship between the number of data received and energy consumption. Therefore, the results are cross-checked by plotting (Fig. 4) energy consumed in network over time.

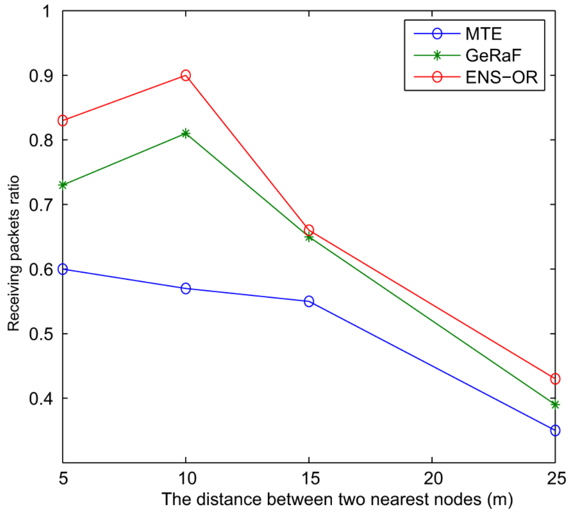

Fig. 6. Comparison of RPR according to the minimum distance between two nearest nodes.

There is a very strong correlation between FDN and NL. The longer the network lifetime is, and the more slowly the first dead node is going to appear. As shown in Figs. 7 and 8, the result shows that the time that the first dead node appears in ENS_OR is much later than that in MTE and GeRaF, and the life time of ENS_OR is much longer. Since the optimal energy strategy will especially protect the low energy nodes, ENS_OR performs the best. Thus, ENS_OR guarantees both the extensive lifetime and the largest conservation of energy.

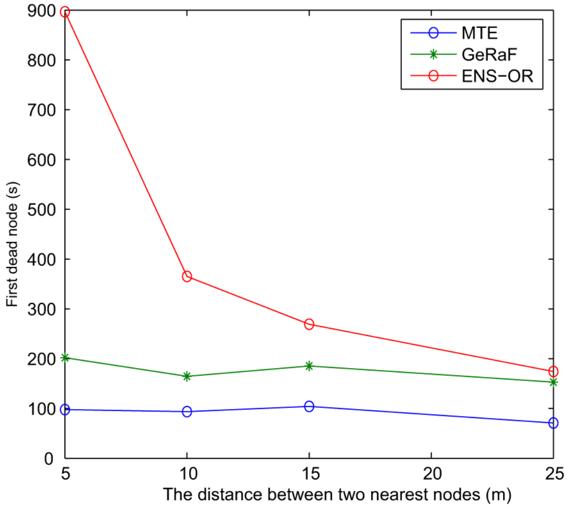

Fig. 7. Comparison of FDN according to the minimum distance between two nearest nodes.

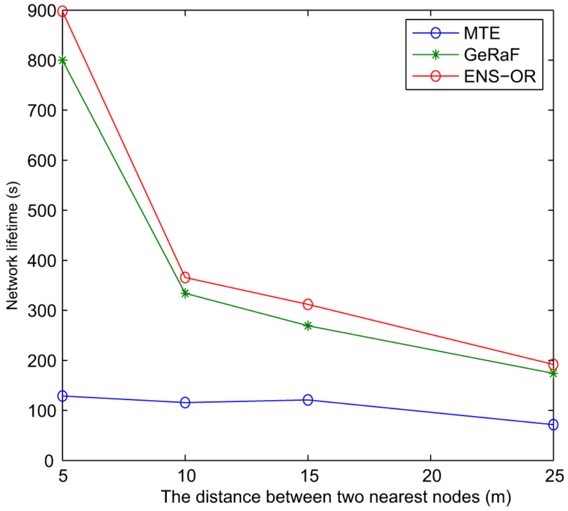

Fig. 8. Comparison of NL according to the minimum distance between two nearest nodes.

Fig. 9. Network topology in the outdoor test.

Fig. 10. Network topology in the indoor test.

B. *Realistic Scenario Experiments*

Characterized by a true system-on-a-chip (SOC) solution tailored for IEEE 802.15.4/Zigbee applications, CC2530 is used to enable ZigBee nodes to be built to implement our opportunistic routing algorithm in realistic testing environment. In order to acquire accurate measurements of targets, the wireless sensor nodes are tested outdoor and indoor separately. As shown in Figs. 9 and 10, we deploy ZigBee nodes along the road in the 1-D queue network. ZigBee nodes in our network are divided into three types, including coordinator, router and end device. There is only one end device (source node) residing at the head of 1-D queue network, and only one coordinator (sink node) is set at the tail of 1-D queue network, others are all router nodes (relay nodes). Through the multihop routing algorithm, the end device transmits data packet every 1 s to the coordinator. The detailed parameters and corresponding values used in real testbed experiments are summarized in Table III.

To validate and evaluate the performance of our ENS_OR algorithm in real testbed experiments, we compared it with the GeRaF and MTE routing algorithm by using the open-circuit voltage method to measure the residual capacity on battery. In this paper, we mainly focus on the energy consumption of router nodes (relay nodes) for data forwarding in our network model, and give no considerations to the temperature and aging of battery. Since our energy model only involves packets transmitting and receiving, we turn off the sleep mode on ZigBee nodes.

As shown in Fig. 11, the effect of time on the discharge processes in battery has been investigated by the measured voltage method over a 5-h period starting from 13:20. The parameters of the test circuit are given in Table IV. According to Fig. 11, the discharge curve decreases rapidly after 0.8 V. This means the low cutoff voltage of our test battery is 0.8 V. Therefore, we assume that when the battery voltage of node reaches 0.8 V, this

TABLE III
PARAMETERS AND CORRESPONDING VALUES USED IN REAL TESTBED EXPERIMENTS

Parameter	Parameter's value
(a) Outdoor experiments	
Deployment area	50 m × 500 m
Deployment distribution	Uniform
Distance between two adjacent nodes	20 m
Number of nodes	50
End device	1
Coordinator	1
Router	48
Transmitted power	4.5 dBm
Sending rate	1 packet/s
Packet size	120 bit
Outdoor temperature	$30^{\circ}\mathrm{C} \pm 5^{\circ}\mathrm{C}$
(b) Indoor experiments	
Deployment area	20 m × 40 m
Deployment distribution	Uniform
Distance between two adjacent nodes	2 m
Number of nodes	20
End device	1
Coordinator	1
Router	18
Transmitted power	2.5 dBm
Sending rate	1 packet/s
Packet size	120 bit
Indoor temperature	$25^{\circ}\mathrm{C} \pm 5^{\circ}\mathrm{C}$

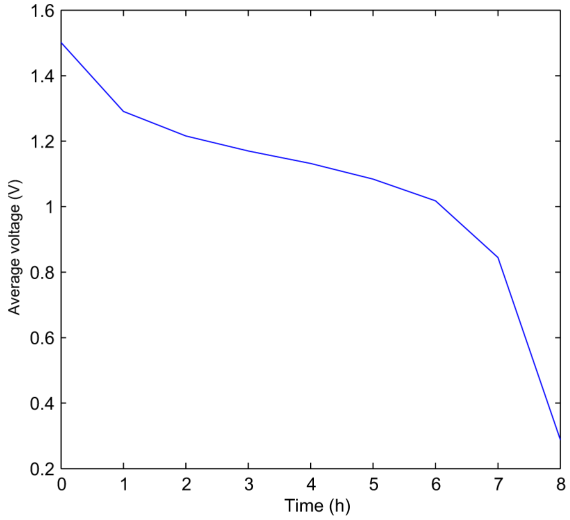

Fig. 11. Effect of time on the discharge processes.

TABLE IV
PARAMETERS AND CORRESPONDING VALUES USED IN DISCHARGE EXPERIMENT

Parameter	Parameter's value
Initial discharge voltage of battery	1.603 V
Test resistance	4 Ω
Internal resistance of battery	34.9 mΩ
Discharge time	8 h

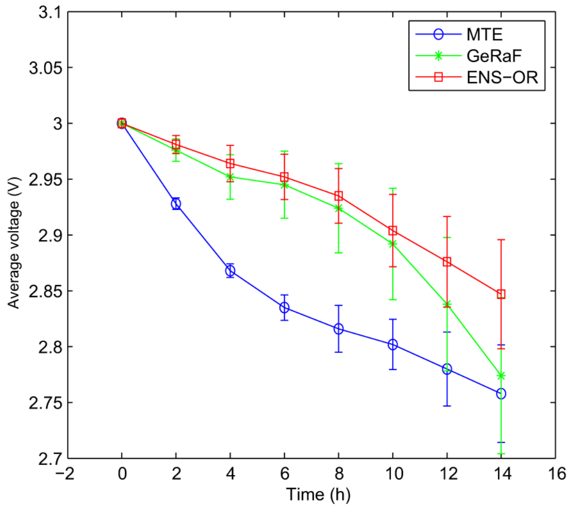

Fig. 12. Average voltage of the batteries according to time in the outdoor test.

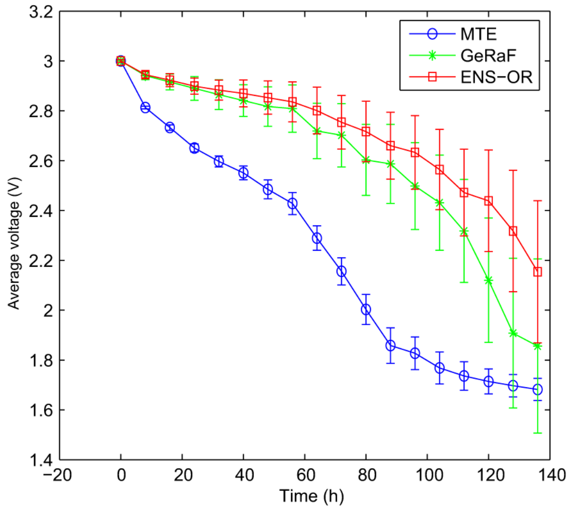

Fig. 13. Average voltage of the batteries according to time in the indoor test.

node may run out of energy, and define 0.8 V as the voltage of first dead node.

Fig. 12 shows the average voltage measured on router nodes with varying time. The initial average voltage is 3 V. At the end of the experiment, the initial average voltage of ENS_OR is 2.847 V, which is the highest value compared with others. GeRaF is following behind ENS_OR as 2.774 V, and MTE has the lowest value 2.758 V. As we can see, the energy efficiency of ENS_OR is better than GeRaF and MTE, which implies the more average residual energy is left. So far, we have evidences to conclude that ENS_OR can improve the energy efficiency of individual node or the whole network, and prolong the lifetime of whole network even in the realistic scenario.

In Fig. 13, the measured voltage of ENS_OR algorithm is shown and compared to the measured voltage of other two algorithms. From this figure, it is clear that the proposed algorithm demonstrates desirable performance in prolonging the network lifetime. Since the optimal energy strategy will especially protect the low energy nodes and balance the energy consumption, ENS_OR performs well. Both GeRaF and MTE give no consideration to the residual energy of relay nodes, and their performance is much worse than that of ENS_OR because low residual energy of relay nodes would run out more quickly for transmitting large amount of data.

Furthermore, Figs. 12 and 13 display the average voltage together with the associated confidence interval. As shown in

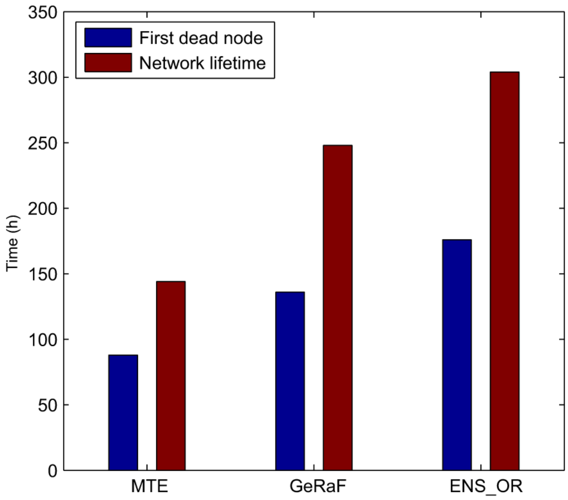

Fig. 14. Times of FND and NL.

Fig. 12, confidence intervals for ENS_OR, GeRaF, and MTE increase over time, as well as the magnitude of the sample sizes. However, confidence interval for MTE in Fig. 13 decreases after 88 h. This means that the difference between the voltage variation of nodes becomes smaller.

Fig. 14 depicts the times of first dead node and network lifetime in the whole network. It is noticed that the time when the dead node first appeared in ENS_OR is later than that in MTE and GeRaF as well as the network lifetime. Because of the increasing number of the energy exhausted nodes, the end device (sink) is unable to receive packet sent from the coordinator (source), i.e., 1-D queue network is not working, packet data cannot be forwarded through other routers (relay nodes). ENS_OR has the energy optimal strategy and opportunistic routing scheme to reduce the number of energy exhausted nodes, and can prolong the lifetime of the network.

VII. CONCLUSION

WSN has been widely used for monitoring and control applications in our daily life due to its promising features, such as low cost, low power, easy implementation, and easy maintenance. However, most of sensor nodes are equipped with the limited nonrechargeable battery power. Energy savings optimization, therefore, becomes one of major concerns in the WSN routing protocol design.

In this paper, we focus on minimizing energy consumption and maximizing network lifetime of 1-D queue network where sensors' locations are predetermined and unchangeable. For this matter, we borrow the knowledge from opportunistic routing theory to optimize the network energy efficiency by considering the differences among sensor nodes in terms of both their distance to sink and residual energy of each other. We implement opportunistic routing theory to virtually realize the relay node when actual relay nodes are predetermined which cannot be moved to the place according to the optimal transmission distance. This will prolong the lifetime of the network. Hence, our objective is to design an energy-efficient opportunistic routing strategy that ensures minimum power is cost and protects the nodes with relatively low residual energy. Numerous simulation results and real testbed results show that the proposed solution ENS_OR makes significant improvements in energy saving and network partition as compared with other existing routing algorithms.

In the future, the proposed routing algorithm will be extended to sleep mode and therefore a longer network lifetime can be achieved. Apart from that, an analytical investigation of the new energy model include sleep mode will be performed.

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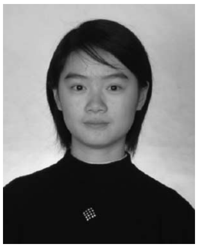

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