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Rendezvous Cost-Aware Opportunistic Routing in Heterogeneous Duty-Cycled Wireless Sensor Networks

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ABSTRACT This paper analyzes the packet transmission cost in asynchronous heterogeneous duty-cycled wireless sensor network systems (WSNs). We discover limitations of conventional opportunistic routing protocols when they are applied to asynchronous heterogeneous duty-cycled WSNs. The key reason is that the conventional opportunistic routing protocols overlook the rendezvous cost in calculating the packet transmission cost. To solve the above issue, we introduce a novel routing metric, expected transmission cost (ETC), which is designed with the rendezvous cost-aware. The proposed metric, ETC, appropriately captures the packet transmitting cost in heterogeneous duty-cycled WSN environments by incorporating the estimation for both expected communication as well as rendezvous cost. We then design an efficient ETC-based opportunistic routing protocol (EoR) which selects the best forwarding candidates with the least packet transmission cost to reduce the actual energy consumption of sensors in packet transmission. We conduct comprehensive testbed experiments and simulations with Telosb motes for the performance evaluation of EoR in comparison with the state-of-the-art routing protocols. Obtained experimental results indicate that EoR achieves significant improvements in terms of packet latency, delivery ratio, and energy efficiency, in comparison with the state-of-the-art protocols.

INDEX TERMS Information centric wireless sensor networking, energy efficiency, sensor cloud, IoT cloud, interactive sensor data prediction, machine learning, sensor quality of information, sdn/nfv.

I. INTRODUCTION

Low duty cycle operation [2] has been widely deployed for energy saving in traditional asynchronous wireless sensor networks [3]–[6] where nodes are expected to operate at low duty cycle (i.e., a few percents). With the recent advancement of energy harvesting technologies, sensor nodes may be able to operate at a higher duty cycle to achieve better performance [7]–[9] (e.g., Everlast nodes with 50% duty cycle [7], [10], and Trior nodes with 20-40% [11]). The duty cycle of an energy harvesting sensor is usually designed to be proportional to its energy availability, harvesting capability, and energy storage capability [7], [12]. Different nodes may have different energy levels due to harvested from different energy sources (e.g., RF, solar, and wind). Even from the same energy source, the amount of energy harvested for each node will be different due to the non-uniform energy distribution of the source. As a result, the duty cycle of an energy harvesting node may be different from that of others in a network [7]–[9]. In addition, we have seen many sensor networks where heterogeneous nodes with different energy saving requirements (e.g., cluster heads, different levels of relay nodes, gateways, and nodes with different tasks) co-exist. This is known as *Heterogeneous Duty Cycled Wireless Sensor Networks* where sensor nodes operate at different duty cycles in the same network [13]–[16].

We argue that existing routing protocols for duty-cycled WSNs (e.g., CTP [17] and ORW [18]) may not work efficiently when applying to heterogeneous duty-cycled WSNs, especially when duty cycles of nodes are significantly

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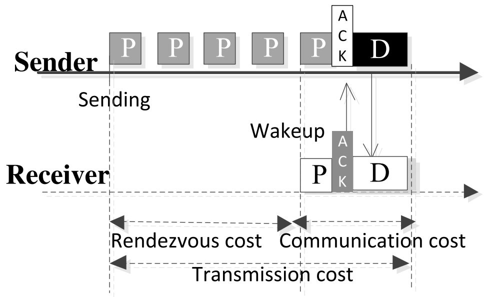

FIGURE 1. **The transmission cost in asynchronous duty-cycled WSNs.**

different from each other. We identify their limitations by analyzing the packet transmission cost and investigating existing routing metrics. As illustrated in Fig. 1, the actual packet transmission cost of a node (i.e., sender) in an asynchronous duty-cycled WSN consists of communication cost (i.e., the time cost for transmitting a packet by a sender through a link when both the sender and its receiver are active), and rendezvous cost (i.e., the time cost of transmitting preambles or waiting by a sender until its receiver wakes up). In receiver-initiated MAC protocols [19], the rendezvous cost is considered as the listening time cost of the sender. In this paper, we illustrate the rendezvous cost with X-MAC [5], a sender initiated asynchronous MAC. The communication cost of the sender is decided by the link quality with its receiver. During the rendezvous waiting period of a sender (i.e, waiting for the receiver waking up), there is no link between it and its receiver. Therefore, the rendezvous cost of the sender doesn't depend on related link parameters. Instead, the rendezvous cost is decided by when the sender's packet transmitting time aligns with the wakeup time of the receiver. Considering the heterogeneous duty-cycled WSN environments, because nodes may run with different duty cycle, the expected rendezvous cost of neighbor nodes may be different. Moreover, in many cases, as discussed in section III, the rendezvous cost can be a dominant factor in the packet transmission cost [4].

However, in existing duty-cycled routing protocols, their routing metrics do not sufficiently capture the rendezvous cost in heterogeneous duty-cycled WSNs. In particular, ETX [20] used in CTP [17] basically considers only link reliability of possible routes. This implies that only communication cost is captured. In the most recent opportunistic routing protocol (ORW) [18], although the EDC metric (expected duty cycled wakeups) proposed by the authors is to capture the expected time duration for transmitting a packet (i.e., the number of wakeups is used as the unit), EDC takes into account the reliability of related links only. Therefore, EDC is considered as the adaptation of ETX metric for opportunistic routing. EDC doesn't capture the rendezvous cost properly. Both ETX and EDC fail to capture the rendezvous cost appropriately in heterogeneous duty-cycled WSN environments. As a result, CTP and ORW may suffer from inefficiency problems in routing and forwarding priority assignment. For an instant, the selection of a set of forwarding candidates having the least EDC value may not result in the least transmission cost actually. We provide the detailed analysis in section III.A.

To address the limitation of the existing routing metrics in heterogeneous duty-cycled WSNs, we first propose a novel routing metric, named expected transmission cost (ETC) which is designed with the rendezvous cost-aware and captures properly both rendezvous cost and communication cost. We also propose and implement a lightweight algorithm to calculate ETC for each node. We design EoR, the ETC-based opportunistic routing protocol, to address the inefficiency and duplicate data packet forwarding problems of ORW [18]. In EoR, a node selects a number of forwarding candidates which minimize its total transmission cost. Based on ETC, each node selects its best path with the least actual transmission cost to forward packets.

For performance evaluation, We implemented the proposed EoR protocol in TinyOS-2.1.2 incorporating a cross-layer method in which preamble transmissions at the MAC layer are exploited to transmit necessary information utilized to select the opportunistic forwarders. We conduct comprehensive testbed experiments with Telosb motes and TOSSIM simulations to evaluate the performance of EoR in comparison to state-of-the-art routing protocols (i.e., CTP, ORW, DOF [21], and COF [22]) under various network conditions. The results show that EoR achieves over 20% improvement in terms of packet transmission latency, energy efficiency, and packet delivery ratio in comparison to CTP, ORW, DOF, and COF. We also conduct scalability tests which show EoR achieving a better scalability compared to ORW.

In summary, the contribution points of this paper are as follows.

- We discover limitations of existing routing metrics in heterogeneous duty-cycled WSNs. (section III.A)
- We propose a novel routing metric – ETC which captures properly both rendezvous cost and communication cost. We then design EoR to address the inefficiency and duplicate data packet forwarding problems of ORW [18]. (section III.B and III.C)
- We conduct comprehensive testbed and TOSSIM simulations under different network conditions to evaluate the performance of EoR. The experimental results show that the proposed protocol achieves a significant improvement in terms of packet transmission latency, energy efficiency, and packet delivery ratio compared to the state-of-the-art protocols. (section IV)

II. RELATED WORK

In this section, we present related works. In the literature, studies in WSNs proposed different routing metrics such as energy-based routing, link-based routing, to distance-based routing [23], [24]). Among the routing metrics, the link-based routing metric like ETX [20] is used most popularly, which is the core of well-known routing protocols like CTP [17]. Besides conventional deterministic routing, opportunistic routing (for example, ExOR [25] and

MORE [26]) was studied for improving the network throughput in wireless mesh networks [27]–[30]. GeRaF [26] and CMAC [31] are the two routing protocols which utilize geographic information for routing. However, the study [32] showed that geographic information might not be available in resource-constrained nodes in WSNs [33], [34]. In other works, EAX and EATT [26] are proposed as adaptations of ETX for opportunistic routing operations. In DSF [35], the authors proposed to use wakeup schedule as well as different metrics like energy consumption and reliability [36]–[38] for selecting forwarders. However, DSF requires to work in synchronized networks that have a high control overhead compared to asynchronous networks [39]. A number of papers investigated time-independent schemes [40], [41] but those studies are limited to theoretical study only. Recently, the authors [18] proposed a practical routing protocol, namely ORW, for duty-cycled WSN environments. ORW is built on EDC, a routing metric which is designed based on adapting ETX for opportunistic routing for duty-cycled sensors. Although ORW runs effectively in low duty cycled WSN environments, section III shows limitations of ORW in heterogeneous duty-cycled WSN environments.

Recently, energy harvesting for wireless sensor networks is studied actively. In a WSN, some sensors may be equipped with energy harvesting capability. Their energy harvesting capability may also be different depending on their types of nodes and locations. As a result, they may have different duty cycles and wakeup patterns in comparison with conventional battery only nodes. Sensors having high effective energy may wake up more frequently and be awake for a longer period of time depending on their duty cycle [7]–[9], [42]. Conventional sensors normally wake up only on-demand to receive packets when they detect energy on the channel based on CCA (clear channel assessment) [5].

Duty cycle of sensors are normally set proportionally to their energy storage capability, energy availability, and harvesting capability [7], [12]. Different sensors have different harvesting capability based different sources of energy harvesting (e.g., solar, RF, wind, and heat) and their location. As a result, the duty cycle of a node may be different from other nodes [7]. There are two main approaches in calculating the optimal duty cycle for an energy harvesting sensor. The first one [12] proposes to adapt the duty cycle over time. The second approach enables a sensor to run with a stable duty cycle over time [43], [44]. In this paper, we assume a sensor run with a stable periodic duty cycle (i.e., D %). Comprehensive literature studies for protocols used in asynchronous WSNs can be found in our previous work [39] and in survey studies [4], [26].

III. EOR ROUTING PROTOCOL DESIGN

A. MOTIVATION

1) REVISITING ORW

We review ORW [18], the state-of-the-art opportunistic routing scheme designed for duty-cycled WSNs. ORW uses EDC (expected duty cycled wakeups) routing metric, which is calculated as follows. We denote EDC_i as the EDC of node i.

$$EDC_i = \frac{1}{\sum_{j\in F(i)} p(i,j)} + \frac{\sum_{j\in F(i)} p(i,j).EDC(j)}{\sum_{j\in F(i)} p(i,j)} + w \qquad (1)$$

where $p(i,j)$ denotes the EDC value for a single hop. $p(i,j)$ is calculated based on the reliability of the link between i and j which are two nodes in F_i, the set of forwarding candidates of node i. EDC metric is considered as an adaptation of the ETX metric for opportunistic routing. In particular, instead of considering the parameters of a single link like ETX, EDC takes into account link parameters of multiple forwarding candidates. The second part in the above formulation indicates the subsequent packet latency to the sink node. w is the weight which is a constant number. In ORW, a node picks out a set of forwarding candidates based on EDC. When the node transmits a packet, the packet is forwarded to the first wakeup node in the set. Experimental results [18] show that EDC works effectively in traditional low duty cycled WSNs. However, we observe that EDC has limitations and is inefficient when it is used in heterogeneous duty cycled WSNs.

2) LIMITATIONS OF ORW

We now discuss limitations of EDC with ORW, and motivations of this work through examples. First, we specify definitions of several technical terms used below.

Cycle (L_i): a cycle of a node i indicates its time period between two consecutive periodic wake-ups of i.

Forwarder candidates' active ratio per cycle (FAR) of a node: FAR of a node is the ratio between the total time period in a cycle that one of its forwarding candidates is wakeup, and the the cycle length.

Periodic duty cycle (D_i%) and periodic wakeup period (T_a^j): D_i is the ratio between the periodic wakeup period of the node and the cycle length. In each cycle, node i wakes up and remains awake for a periodic wakeup period $T_a^j = D_i * L$. Note that the total duty cycle of a node can be larger than D_j as a node may extend its wakeup period upon receiving or transmitting packets [39].

According to our experiments and observations, the rendezvous cost of a node in duty-cycled WSNs can be the dominant factor of its total packet transmission cost in many cases. For example, we assume that a sender node i picks up node j as its forwarder because the link between node i and the forwarder has perfect reliability (i.e., ETX = 1). It means that when the link between node i and j are available, only one transmission is required for node i to send a packet to node j. However, node j operates with a low duty cycle (i.e., < 1 %). In this case, the expected communication cost of node i is as small as the cost to transmit one packet (i.e., 20 ms). On the contrary, its expected rendezvous cost is approximate $L_j/2$ on average and the worst case is approximate L_j [4], [39]. If we assume L_j is 1 s, which is popularly used in WSNs, the expected rendezvous cost is about 500 ms. Then the total packet transmission cost of node i is about 520 ms. The above example shows that if a node considers only the link parameters for selecting forwarding candidates, its communication cost can be very low, but its total packet transmission cost can be very high due to a high rendezvous cost.

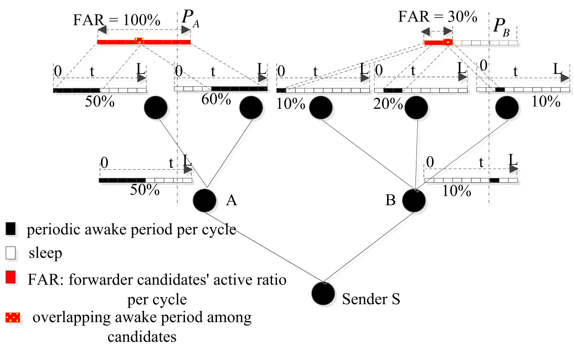

FIGURE 2. An illustration for heterogeneous duty cycled WSNs.

Figure 2 illustrates how ORW may make inefficient route selections. To keep it tractable, we assume that all nodes have L of 1 s and the link quality p is 1 for all links unless otherwise specified.

In the figure, A and B are the neighbor nodes of the sender node S. The periodic duty cycle of A is 50%, and the periodic duty cycle of B is 10%. The links from S to A and B have the reliability of 1. Following the design of ORW, EDC of A and B is equal, so the sender S considers A and B equally for forwarder selection. In our observation, A and B have the same communication cost, but their actual transmission is totally different. The reason is that A has the rendezvous cost up to 500 ms (i.e., 50% of L) while B has the rendezvous cost up to 900 ms (i.e., 90% of L). For that reason, considering A and B equally is inefficient and may lead to suboptimal routing path selection because A provides significantly a lower expected packet transmission cost in comparison to B.

We now discuss a more complicated example in figure 2 to provide understanding inside into the limitations of ORW. In figure 2, A has 2 forwarding candidates whose periodic duty cycles are 60% and 50%, respectively. As a result, FAR of A is 100%, as shown in figure 2. In other words, node A always has at least one forwarding candidate which is awake. This indicates that A can forward its packet anytime without a rendezvous cost. On the other hand, node B has 3 forwarding candidates whose periodic duty cycles are 10%, 20%, and 10%, respectively. FAR value of B is 30% as shown in figure 2. In other words, about 70 % of the time in a cycle L, forwarding candidates of B are not available due to sleeping. Once B wants to send a packet, B has to wait for a period up to 70% of L (i.e., 0.7s) until one of its forwarders wakes up. Above results show that the path through A obviously provides a much lower packet transmission cost in comparison to B. However, following the EDC calculation of ORW, the one hop EDC value of A is 0.5 cycle (i.e., $1/(1+1) = 0.5$) while that of B is 0.33 cycle ($1/(1+1+1) = 1/3$). ORW considers B is the better forwarding candidate in comparison to A while the fact is the opposite.

This limitation of ORW leads to inefficient route selections. In section III.C, we discuss another duplicate packet forwarding issue of ORW. The observations above also indicate that the rendezvous cost is an important factor which should be considered in routing in heterogeneous duty-cycled WSNs.

B. EXPECTED PACKET TRANSMISSION COST METRIC

Based on the observations presented above, this section describes our estimation method to calculate the expected rendezvous for a node in opportunistic routing scenarios. We then propose ETC (expected transmission cost) routing metric that takes into account both communication and rendezvous cost for forwarding candidate selection.

We denote F_i as the forwarding candidate set having N_i candidates of node i. All nodes have the same cycle length of L (i.e., $L_i = L$). D_j is the periodic duty cycle of node j. It means that in every cycle, node j wakes up periodically and is active in a periodic wakeup period of T_a^j, where $T_a^j = D_j{*}L$, to listen on channels for incoming packets. We denote $T_a^o(j,k)$ as the overlapping wakeup period between nodes j and k.

1) EXPECTED RENDEZVOUS COST

As discussed in the previous sections, the rendezvous cost of a node i depends on the probability of its packet transmission time aligning with the wakeup period of at least one forwarding candidate. As a node may send packets at a random time within a cycle, the expected rendezvous cost of node i is proportional to the wakeup ratio of its forwarding candidates [18], [45], [45], [46]. In other words, the rendezvous cost of i is proportional to its forwarders' duty cycle. As a node i in opportunistic routing has multiple forwarding candidates, its rendezvous cost is proportional to its forwarder candidates' active ratio per cycle (FAR). We estimate FAR of a node i as follows.

$$FAR_i = \frac{\sum_{j\in F_i} T_a^j - \sum_{j,k\in F_i} T_a^o(j,k) + \sum_{f_i^*\in F_i} T_a^o(f_i^*)}{L_i} \tag{2}$$

where f^* consists of subsets of F_i having more than 3 forwarding candidates whose wakeup periods overlap each other. FAR of node i is used to estimate the ratio of time period per a cycle that i has at least one forwarding candidate which is awake and can forward its packets. If a node sends a packet when one of its forward is available, its packet can be forwarded immediately.

If a packet is sent by i at a random t, the probability that the packet is suspended for a waiting time period (i.e., rendezvous cost) [4], [45], [45], [46] until i has at one wakeup forwarder, is calculated as follows.

$$P^i_{waiting} = 1 - FAR_i \tag{3}$$

$P^i_{waiting}$ of i implicitly reflects the ratio of time per a cycle that i has no awake forwarders. $P^i_{waiting}$ is 0 when FAR_i is 1. In figure 2, node A has two forwarding candidates with the total FAR of 100%. As a result, the probability $P^A_{waiting}$ a

TABLE 1. Validation Test Results.

FAR_i	T^i_{rc}	**Average Actual Rendezvous Cost**
0.182	0.2045	0.2108
0.29	0.1775	0.1732
0.365	0.15875	0.1602
0.58	0.105	0.1032
0.86	0.035	0.041

packet sent by A is delayed by a waiting period (i.e., rendezvous cost) is equal to 0 because A always has at least one wakeup forwarder. Similarly, node B has three forwarding candidates with the total FAR of 30% only. This means that over 70% period of a cycle, node B has no wakeup forwarder, when packets sent by B will experience a waiting period (i.e., rendezvous cost). The probability $P^B_{waiting}$ is then equal to 0.7 ($P^B_{waiting} = 1 - 0.3$).

Based on $P^i_{waiting}$, the rendezvous cost of i is generally up to $T^i_{wp-max} = P^i_{waiting}L$, and the expected rendezvous cost T^i_{rc} is estimated following the formulation below.

$$T^i_{rc} = P^i_{waiting}L_i/(1 + NG_i) \tag{4}$$

where NG_i is the number of candidate groups in F_i, which have no overlapping wakeup period with each other.

In section IV.A, we present our implementation of a **simple and lightweight algorithm to estimate** FAR_i **and calculate** NG_i. We now validate the estimation of FAR_i and T^i_{rc}.

Validating FAR_i and T^i_{rc}: In case $FAR_i = 1$ and $P^i_{waiting} = 0$, the expected rendezvous cost of i is zero. In case node i has only one forwarding candidate (i.e., deterministic routing) and the candidate operates at low duty cycle (i.e., 1%); as a result, FAR_i is approximately equal to 0, and $P^i_{waiting}$ is toward 1; then the expected rendezvous cost of i is $L_i/2$. This result matches with the average sleep latency which is used popularly in existing low power listening MAC protocols [4].

We now conduct simulation experiments to validate the calculation of FAR_i and T^i_{rc}. We run simulations consisting of a sender node i, 3 forwarding candidates of i and a sink node. In each simulation, each forwarding candidate randomly selects its periodic duty cycle and wakeup time. The sender generates 100 packet transmissions, one packet per a transmission at a random time, to the sink node through the forwarding candidates. Based on the wakeup schedules of the forwarding candidates, we calculate FAR_i and T^i_{rc}. We also record the actual rendezvous cost in each transmission and calculate the average actual rendezvous cost of the sender i after 100 packet transmissions. Results are reported in Table I. The results show that the expected rendezvous cost T^i_{rc} calculated following the equation (4) is quite closed to the average actual rendezvous cost. Small deviations may be due to various reasons such as the measurement error, the calculation error, the estimation rounding, or the small number of tests. The validation test proves that the estimation of FAR_i and T^i_{rc} is accurate enough.

2) EXPECTED COMMUNICATION COST

To calculate the communication cost, we use γ to indicate the average period needed for a packet transmission and an acknowledgment reception through a perfect quality link. By using same power transmission configuration, nodes have a similar value of γ. In addition, the energy used for reception an transmission is almost the same as the transmission range of sensor nodes is short [5].

We denote ETX_{ij} as the expected transmission count for the link from node i to node j. When i sends a packet, its forwarder, node j, may be awake but may not receive the packet successfully if its wakeup period T^j_a is shorter than the period needed for i to transmit as well as retransmit the packet ETX_{ij} times ($\gamma ETX_{ij} > T^j_a$). The reason is that after waking up and remaining awake for a period of T^j_a, j will sleep again if j doesn't hear any incoming packet. We denote μ_{ij}, with $\mu_{ij} = \gamma ETX_{ij}/T^j_a$, as the possibility that i may require more than one cycle for a successful packet transmission to j.

In opportunistic routing, the forwarder determination is postponed until after packet transmission time. The packet forwarding chance is shared among nodes in the forwarding candidate set. When a node sends a packet, the node needs at least one forwarder receiving its packet successfully. If its packet is not transmitted successfully within the first cycle, the node has to take more than one cycle for the packet transmission. This situation may happen if μ^{min}_i, the lowest value among values $\mu_{ij}(\forall j \in F_i)$ is higher than 1. We then estimate the number of cycles of node i, when packet transmissions are failed (i.e., $C_i = \lfloor \mu^{min}_i \rfloor$).

We now compute the expected communication cost of i in the cycle when its packet is transmitted successfully. For opportunistic routing, we use the average value of ETX of forwarding candidates since the forwarding chance is shared among them. The average ETX value of forwarding candidates is calculated as follows.

$$\overline{ETX_i} = \frac{\sum_{j \in F_i} ETX_{ij}}{size(F_i)} \tag{5}$$

We then calculate the expected communication cost of i as follows.

$$T^i_{comm} = \lfloor \mu^{min}_i \rfloor L_i + \gamma \overline{ETX_i} \tag{6}$$

3) EXPECTED TRANSMISSION COST

Based on the expected rendezvous and communication cost calculation above, we calculate expected transmission cost (ETC) for the single hop case as shown in Eq. (7). The number of cycles is used for estimating the expected transmission cost.

$$ETC^{singlehop}_i = (T^i_{rc} + T^i_{comm})/L_i \tag{7}$$

Because the chance to become the forwarder is shared by forwarding candidates, the packet transmission cost of i in the long run converges to a value based on average transmission cost of its forwarding candidates. Similar to ORW, we compute the expected packet transmission cost (ETC) of node i

for the multi-hop case based on the one-hop value and average ETC value of its forwarding candidates, as shown in Eq. (8). We denote $f(F_i)$ as the function for computing ETC_i of i with the set F_i of forwarding candidates.

$$f(F_i) = ETC_i = ETC_i^{singlehop} + \sum_{j \in F_i} ETC_j/size(F_i) \tag{8}$$

C. EOR ROUTING PROTOCOL

This section describes EoR, our proposed opportunistic routing protocol based on ETC. EoR is designed for addressing the mentioned limitations of ORW. EoR is implemented to run with duty-cycled WSNs where sensors periodically wake up for receiving packets.

1) OPTIMAL FORWARDING CANDIDATE SET SELECTION

So far, we have described the method to compute the expected packet transmission cost for a given node i using the function f. In this subsection, we discuss how EoR selects an optimal forwarding candidate set for a given node i in a simple way so that constrained sensor nodes can calculate by itself.

Consider a network with the topology as a directed graph $G =< N, L >$ consisting of a set N of nodes and set L of links. $N_i = \{n_1, n_2, \ldots, n_{|N_i|}\}$ is neighbor node set of node i. Sorting nodes in N_i in increasing order of their expected transmission cost, we obtain a sorted set $N_i^* = \{m_1, m_2, \ldots, m_{|N_i|}\}$ ($ETC_{m_{j+1}} > ETC_{m_j} \forall j < 0$ and $j <| N_i | -1$). We define a former subset of a sorted set N_i^* that is a subset consisting of first k items of N_i^* in the same order.

Definition 1: An optimal forwarding candidate set of a node i is a set with the lowest cost.

For a given node i, we now study distinctive characteristics of the optimal forwarding candidate set F_i^{opt} in the neighbor set of the node. Based on findings, we then define a rule on how to select F_i^{opt}.

Lemma 1: A subset X of N_i^* is is an optimal forwarding candidate set only if X is a former subset of N_i^*.

Proof: We use contradictions to prove this lemma.

Assume the optimal forwarding candidate set F_i^{opt} is not a former subset of N_i^*. We have at least two nodes m_j and $m_{j+1} \in N_i^*$ such that $m_j \notin F_i^{opt}$ and $m_{j+1} \in F_i^{opt}$. Denote $F_i^{opt'} = F_i^{opt} \cup \{m_j\}$. Now we compare the cost in cases of F_i^{opt} and $F_i^{opt'}$ by considering transmission cost to forward a packet by each forwarding candidate in the sets. The cost in case of F_i^{opt} and that in case of $F_i^{opt'}$ is different only in the case when m_j (in the case with $F_i^{opt'}$) and m_{j+1} (in the case with F_i^{opt}) receive and forward the packet and no other nodes in the sets receive or forward the packet.

In the calculation for $F_i^{opt'}$, the cost is ETC_{m_j}. In the calculation for F_i^{opt}, the cost is $ETC_{m_{j+1}}$. According to the sorted set, $ETC_{m_j} < ETC_{m_{j+1}}$, so $f(F_i^{opt'}) < f(F_i^{opt})$. Based on the definition of the optimal set, it is obvious that F_i^{opt} cannot be the optimal forwarding candidate set if it is not a former subset of N_i^*.

Lemma 2: Given a former subset F, ($F = \{m_1, m_2, \ldots, m_{j-1}\}$), of N_i^* and a node $m_j \in N_i^* \setminus F$. If $ETC_{m_j} < f(F_i)$, *then* $f(F_i \cup \{m_j\}) < f(F_i)$.

Proof: See proofs 3.2 and 3.3 in appendix of ORW [18].

This lemma shows that given a node m_j with expected cost which is smaller than current expected cost of node i ($f(F_i)$), if m_j is inserted to the subset F, the expected cost of node i with the newly subset will be lower. As a result, according to lemma 1 and definition 1, if $F \in F_i^{opt}$, then $\{F \cup m_j\} \in F_i^{opt}$.

Lemma 3: Given a former subset F of N_i^* and a node $m_j \in N_i^* \setminus F$. If $ETC_{m_j} > f(F_i)$, *then* $f(F_i \cup \{m_j\}) > f(F_i)$.

Proof: Similar to the proof for lemma 2.

Lemma 3 indicates that if a node m_j with expected cost which is higher than current expected cost of node i ($f(F_i)$), if m_j is inserted to the subset F, the expected cost of node i with the newly subset will be higher. As a result, according to definition 1, $m_j \notin F_i^{opt}$.

Theorem 1: For a given node i, a former subset F_i^{opt} of N_i^* ($F_i^{opt} = \{m_1, m_2, \ldots, m_k\}, k <| N_i |$) is the optimal forwarding candidate set of the node if $f(F_i^{opt} \setminus m_k) > f(F_i^{opt})$ and $f(F_i^{opt} \cup m_{k+1}) > f(F_i^{opt})$

Proof:

We have $f(F_i^{opt} \setminus m_k) > f(F_i^{opt})$ (1). In addition, with $ETC_{m_{k-2}} < ETC_{m_{k-1}}$ and both m_{k-1} and $m_k \in F_i^{opt}$, according to lemma 2, we then have $f(F_i^{opt} \setminus m_k) < f(F_i^{opt} \setminus \{m_k \cup m_{k-1}\})$ (2).

From (1) and (2), we obtain: $f(F_i^{opt}) < f(F_i^{opt} \setminus \{m_k \cup m_{k-1}\})$ (3).

Similarly, we have $f(F_i^{opt}) \leq f(F')(\forall F' \in F_i^{opt})$ (*).

Now we consider $F_i^{opt} = \{m_1, m_2, \ldots, m_k\}$ and a next node in the neighbor list m_{k+1}. We have $ETC_{m_k} < ETC_{m_{k+1}}$ and $f(F_i^{opt} \cup m_{k+1}) > f(F_i^{opt})$. According to lemma 3, m_{k+1} is not an element of the optimal forwarding candidate set. Therefore, $\forall F = \{F_i^{opt} \cup m_h\}(\forall k + 1 < h \leq| N* |)$ is not a former subset of $N*$ and, according to lemma 1, is not an optimal forwarding candidate set (as node m_{k+1} is also not) (**).

From (*) and (**), F_i^{opt} is the valid former subset with the lowest cost of $N*$. As a result, we conclude that F_i^{opt} is the optimal forwarding candidate set of node i.

Through above studied characteristics of the optimal forwarding candidate set, a node i just needs to add each neighbor node sequentially, in the direction from the beginning of the sorted neighbor list N_i^* to the end, to its set of forwarding candidates if adding the node reduces its ETC value. This finding enables us to use a greedy approach in routing. Based on the theorem we justified above, we propose Algorithm 1 as a greedy algorithm for the optimal forwarding candidate set selection. Note that the cost of forwarding parameter w to create a loop-free topology [18] is also used in our algorithm.

One important aspect the algorithm achieved is that it is very simple, lightweight, and practical to enable each constrained node to select the optimal forwarding candidate set by itself.

Algorithm 1 Greedy Algorithm for Optimal Forwarding Candidate Set Selection (Node i, N_i, F)

INPUT: a neighbor list N_i of node i with neighbor information
OUTPUT: ETC_i and optimal forwarding candidate set F_i^{opt}
Initialize: $ETC_i = \infty$, $F = \emptyset$
  Sort N_i based on its expected packet transmission cost $\rightarrow N_i^*$;
  for $j = 1; j \leq | N_i |; j++$ **do**
    if $ETC_j \leq ETC_i - w$ and $f(F \cup j) < f(F_i)$ **then**
      Set: $F = F \cup \{j\})$ and update: $ETC_i = f(F)$;
    else
      return F
    end if
  end for

Algorithm 2 EoR Routing and Update Algorithm

INPUT: $G = N, L, N_i$ $(\forall i \in N)$ with size k_i
Initialize: $ETC_{sink} \leftarrow 0$, $ETC_i \leftarrow \infty$, $FDT_i \leftarrow 0$, $F_i = \emptyset$
Repeat
  for all $i \in N$ **do**
    sort $N_i(n_1, n_2, \ldots, n_{k_i})$ with $(ETC_1 \leq ETC_2 \leq \ldots \leq ETC_{k_i})$
    for $j = 1; j \leq k_i; j++$ **do**
      if $(f(F_i \cup j) < f(F_i) \&\& ETC_j \leq ETC_i - w$ **then**
        update: $ETC_i = f(F_i \cup j)$;
        update: $F_i = F_i \cup j$;
        $FDT_i = ETC_j$
      else
        return FDT_i
      end if
    end for
  end for
  UNTIL ETC of all nodes remain unchanged

2) FORWARDING STRATEGY AND UNIQUE FORWARDER SELECTION

This section indicates the limitations in ORW, and proposes an efficient mechanism for unique forwarder selection.

In the design of ORW, several forwarding candidates may receive long data messages from the sender. The reason is that the sender transmits its messages directly. Therefore, the sender may receive multiple acknowledgments from forwarding candidates. This results in an inefficient issue due to a high collision probability incurring at the sender. In addition, the sender may not know how many forwarding candidates forward its messages because the coordination in ORW is implemented using overhearing only. This may result in a heavy duplicate problem, especially in high traffic load.

We design a lightweight and efficient mechanism for selecting an unique forwarder based on unique value, named the forwarding decision threshold (FDT). The value of FDT_i of each node i in the network is determined and updated using Algorithm 2. In particular, FDT of a node is a single value which describes the ETC value that a forwarding candidate must provide at least. This value is used in our mechanism to select the unique forwarder.

We implement EoR's forwarding strategy using a cross-layer method. EoR exploits preamble transmissions at the MAC layer for carrying necessary information and involving in the unique best forwarder selection in a real time manner. The particular procedures are as follows. When MAC layer of node i gets a message to be sent from its upper layer, MAC layer then transmits preambles piggyback with two 8-bit values of FDT_i and ETC_i values, instead of containing the 16-bit destination address a state-of-the-art work [5]. We call such a preamble as an information-centric preamble (i-preamble) to make a difference with a normal preamble because the preamble contains information, not the destination address. When a receiver node j receives an i-preamble, it first looks at the FDT_i value. If its ETC is equal or smaller than FDT_i, j is then selected as a forwarder by itself. j then performs a back-off before transmitting back an ACK packet. The back-off timer of j, B_j, is inversely proportional to its offered routing progress gap compared to FDT_i as follows.

$$B_j = B_{max}(RT_i - [FDT_i - ETC_j])/RT_i \tag{9}$$

where B_{max} is the predefined value for the maximum back-off time. RT_i is the routing progress threshold given for node i and is configured with $RT_i = 2(ETC_i - FDT_i)$. B_j should be non-negative, so its minimum value is 0. The back-off mechanism gives the highest priority to a forwarding candidate that offers the lowest cost and is available at the time of packet sending. It means that the back-off timer of such a forwarding candidate fires the earliest. The mechanism selects the first candidate that acknowledges the preamble transmission as the unique forwarder. Once the sender receives the first preamble acknowledgment, it stops the preamble transmission, rejects later acknowledgments, and starts transmitting its data deterministically to the unique forwarder. It is done by using the source address of the acknowledgment packet as the destination address of the data packet. Upon receiving data packets, the unique forwarder responds an acknowledgment packet and continuously forwards the packets to next hops. The sender then sleeps if it has no more packet to send. Other forwarding candidates abort its acknowledgment to the sender's preamble transmission if they overhear an acknowledgment from another candidate or a data packet from the sender. Following the above procedures, the preamble transmission in EoR is designed like anycast while data messages are delivered deterministically to a selected forwarder.

3) RETRANSMISSION POLICY FOR FAULT TOLERANCE

Due to the link dynamic, temporary failures (i.e., by congestion, queue overflow, or unreliable wireless links,...) may happen on the link which may result in failure in data transmissions. For fault tolerance, after acknowledging i-preamble of the sender, the forwarder waits for receiving data packets.

After a timeout t_0, if the forwarder does not receive data packets, it will go to sleep to save energy. In the case of the sender, after receiving the first acknowledge for its i-preamble, the sender sends out data packets toward the selected forwarder. Without receiving any acknowledgment, the sender will retransmit data packets within a timeout t_0. If the timeout fires without any successful transmission, the sender stops trying retransmission to that forwarder. The reason is that if the sender keeps retransmitting data packets to a deterministic forwarder which may have been failed or slept, it may waste a huge resource to wait until the forwarder returns. In EoR, after the timeout t_0, the sender triggers preamble transmission again to exploit for other potential forwarders, as backup nodes, to forward data packets. This policy allows a node to overcome failures and save energy.

4) THE SETTING-UP PHASE

Similar to CTP [17] and ORW, EoR's setting-up phase is executed from the sink to leave nodes. Nodes remain awake in the setting-up phase. At the end of the setting-up phase, every node sleeps in a full cycle L before the node wakes up and starts its regular duty cycle.

At first, the sink sends a broadcast advertisement packet containing the following information: 1) its periodic duty cycle (i.e.,D) and its ETC value. Note that the sink node has ETC value of 0 and $Dsink$ of 100 %. Because the sink is always awake and its expected zero cost is 0, the neighbor nodes of the sink select it as the next hop upon receiving its advertisement. Each node then computes its ETC value and performs a random back-off before broadcasting its advertisement packet. To achieve a good distribution of wakeup time for nodes and to lower the collision occurring, we set a large contention window for this phase. After sending the advertisement packet, each node listens for a timeout T_O^1 for checking if its transmission is successful. The node goes to sleep for a full cycle after the timeout if it doesn't detect any problem with the advertisement transmission. A transmission for the advertisement may be needed in other cases.

Nodes may receive advertisement packets from their neighbor nodes. Upon receiving an advertisement packet from a neighbor, the receiver gets information of the sender and stores in its neighbor table. The receiver records its packet receipt time that will be used to compute the sender's next wakeup time (e.g., $t_{sender}^{wakeup} = t_{currenttime} + T_O^1 + L$) as well as the sender's relative periodic wakeup period within its cycle (e.g., from t_{sender}^{wakeup} to $t_{sender}^{wakeup} + D_{sender} * L$) using its own clock. Similarly, the receiver also has information of other neighbors, that enables it to detect overlapping wakeup periods of its forwarding candidates. The node listens to advertisement packets and runs the greedy mechanism to select its first forwarding candidates as presented in Section III.C.1. By having the first forwarding candidates, the node then computes its ETC value. The node finishes the setting-up phase if it doesn't hear any advertisement from neighbors that offer a smaller ETC value in comparison to its current ETC value, within a timeout T_O^2 ($T_O^2 > T_O^1$). Before completing its setting-up phase, the node performs a random back-off, broadcasting its advertisement, and listening for a timeout T_O^1. The node then goes to sleep to complete its setting-up phase, as same as the procedures of sink neighbor nodes. The procedures are executed similarly for other nodes. At the end of the setting-up phase, the network is built as a directed acyclic graph (DAG) topology, which was proved in citeORW2014.

5) UPDATE

Similar to ORW, EoR also utilizes a set of forwarding candidates, and each packet may be transmitted through a different route. Therefore, changes in individual candidates result in a limited impact on overall quality of the set. In EoR, as long as the aggregation of candidates performs stably, changes in individual candidates can be hidden to achieve stability. In implementation, EoR reuses the light-weight link estimation implemented in ORW. For updating the ETC metric, we exploit the 16-bit destination address in i-preambles (i-preamble type 1) to carry out the ETC value of the sender, as described in section III.C.2. In this way, neighbors of the sender can get updates of the ETC value of the sender each time it transmits a packet. As a result, the routing metric update of EoR doesn't require extra communication overhead.

If a sender i has no change of its ETC value, when it wakes up at a periodic duty cycle to transmit messages, the sender transmits preambles with its elapsed wakeup period (T_{elapse}), instead of ETC values. T_{elapse} information is utilized to detect updates in the overlapping wakeup patterns of nodes. We call this as the i-preamble type 2. We later show that updates of overlapping wakeup period normally has a small impact on ETC value of a node.

When a node wakes up and overhears a type 2 i-preamble from a neighbor containing its elapsed wakeup period information, the node then computes the relative periodic wakeup period of the neighbor within a cycle (e.g., from $t_{current} - T_{elapse}$ to $t_{current} - T_{elapse} + D_{sender} * L$) using its own clock. If there is a change, the node updates its neighbor information. Based on the relative periodic wakeup period of neighbor nodes, the node can calculate the overlapping wakeup period of its forwarding candidates. For stability, the node updates its ETC value only if it detects a significant change (i.e., ETC value change > 0.1), similar to ORW [18]. The reason is that changes happening in wakeup patterns of individual forwarding candidates of a node, especially candidates operating in low duty cycle, have a little impact on the ETC metric of the node. Therefore, it doesn't require absolute measurement. Updating based on the significant changes is to maintain the stability of the network and to reduce energy consumption of nodes.

IV. PERFORMANCE EVALUATION

This section presents the performance evaluation of EoR by test-bed and simulation experiments with Telosb

Algorithm 3 FAR Calculation Algorithm (Node i, Cycle Length L)

INPUT: a forwarding candidate list F_i of node i with N_i candidates. Each candidate j wakes up periodically for a period from $j.start$ to $j.end$ within a cycle.
OUTPUT: FAR_i and NG_i
Initialize: $FAR_i = 0$
$NG = 0$
$D_{max} = 0$ //the longest period when there is no wakeup forwarding candidate
$LE = 0$ //the node id which has the most recent wakeup ending time

```
Sort candidates in F_i by wakeup starting time;
if N_i > 0 then
  Set: FAR_i = F_i[0].end − F_i[0].start, and NG = 1
end if
for j = 0; j < N_i; j++ do
  if F[j+1].end > F[LE].end then
    // wakeup period overlapping
    if F[j+1].start < F[LE].end then
      Set: FAR_i = FAR_i + (F_i[j+1].end − F_i[LE].end)
    else
      Set: FAR_i = FAR_i+(F_i[j+1].end−F_i[j+1].start; )

      Set: NG++; // a new group is found
      if D_max < (F_i[j+1].start − F_i[LE].end) then
        D_max = (F_i[j+1].start − F_i[LE].end);
      end if
    end if
    Set: LE = j + 1
  end if
end for
Return FAR_i = FAR_i/L
```

sensor nodes. We compare EoR with state-of-the-art protocols including ORW, CTP, DOF [21] and COF [22].

A. IMPLEMENTATION

For a fair comparison with ORW, we implemented EoR replacing the unicast forwarding logic in CTP, the data collection protocol and by modifying the baseline implementation of ORW [18] using TinyOS-2.1.2. The implementation of EoR reuses several elements of ORW, as discussed in Section III.B. For the MAC protocol, we implement EoR on the top of BoX-MAC-2 protocol [47] and the CC2420 Telosb platform. For creating scenarios with heterogeneous duty-cycled nodes, we reconfigure the setting of periodic wakeup period of node i with the value D_iL, instead of applying the default value with $t_{backoff} + t_{ack}$ as in BoX-MAC-2 [47]. The above setting for nodes with a high duty cycle is reanable, instead of deploying real energy harvesting sensors, because actually harvesting processes of an energy harvesting-enable sensors are normally hidden from routing in the network layer. Nodes with a low duty cycle utilize the

TABLE 2. Parameters.

parameter	value	parameter	value
Data packet length	32 bytes	Nodes	100-600
Preamble length	6-9 bytes	w	0.1
B_{max} window size	15	ACK pkt	9 bytes
Maximum clock drift	40 ppm	(T_O^1, T_O^2)	(20, 25)ms
Time TX/RX a byte	0.032 ms	L	1s
Inter-frame space	192 μs	Hardware	CC2420

default receive check duration configured in original BoX-MAC-2. To keep the evaluation tractable, we set all nodes using the same cycle length L.

In EoR implementation, BoX-MAC is set to transmitting preambles with 802.15.4 header, instead of data messages. The measured packet transmission cost is used as the indicator for both packet latency and energy consumption [48]. For measuring the cost, we record changes occurring in radio's states and add counters for accumulating time duration of each state. We use the latency of packet delivery from a source to the sink node as the end-to-end latency, which is measured using the sequential difference recovery approach [49].

For simulations, to create realistic TOSSIM simulations, we use the radio noise model with closest-fit pattern matching (CPM) associating with an experimental noise trace (i.e., meyer-heavy.txt) from Meyer Library by Standford University [50]. The detailed parameters of experiments are presented in Table 2. For other parameters, we use the default setting as in ORW [18].

For FAR estimation and NG calculation of a node i, we implement a simple algorithm as illustrated in Algorithm 3. The general idea of the algorithm is that we first sort forwarding candidates by their wakeup starting time. In this order, only wakeup period of a node which is not overlapped with previous candidates is counted in FAR. The algorithm returns FAR_i value, NG, as well as D_{max}, the longest period when there is no wakeup forwarding candidate. Note that D_{max} is also the actual worst case $T^i_{rc-worst}$ of rendezvous cost of node i. When two forwarders have the same FAR value, we use D_{max} to select the better candidate. The lower the value of D_{max} the shorter the actual rendezvous cost is expected.

For creating scenarios with heterogeneous duty-cycled sensors, we configure three types of sensors including energy resource-constrained nodes (traditional sensors) which operate at low duty cycle (Type 1), and nodes having higher energy capacity with the periodic duty cycle of 20 % (type 2) or 40 % (type 3). We denote [N-X%-Y%] to indicate experiments with the network density of N with $X\%$ nodes of Type 3, $Y\%$ of Type 2, and the rest are nodes of Type 1. Each simulation result is reported based on the average value with 50 random topologies. For testbed, in default we conduct experiments with 40 Telosb nodes $(40 - 20\% - 20\%)$ in an indoor environment if other configurations are not specified.

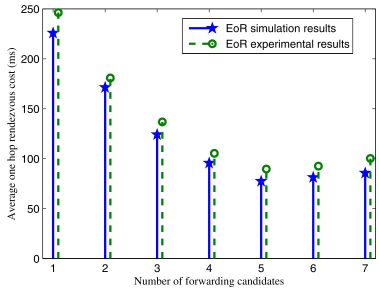

FIGURE 3. Average end-to-end rendezvous cost.

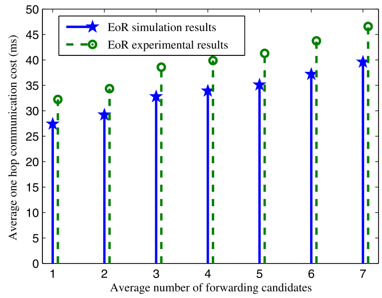

FIGURE 4. Average end-to-end communication cost.

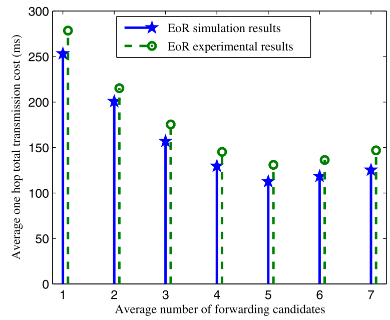

FIGURE 5. Average total end-to-end transmission cost.

B. ANALYSIS OF THE TRADE-OFF BETWEEN RENDEZVOUS COST AND COMMUNICATION COST

In this subsection, we analyze the trade-off between rendezvous cost and communication cost based on simulation results within the test T7 and experimental results with a controlled number of forwarding candidates from one to seven, and their contribution to the total transmission cost. The purposes of our analysis are to (1) show the trade-off between rendezvous cost and communication; (2) how EoR makes the best trade-off between the two types of cost to achieve the least total transmission cost.

Fig. 3 presents the main trend of rendezvous cost when the number of forwarding candidates increases. Within one forwarding candidate (i.e., similar to CTP), the rendezvous cost is very expensive because a sender has to wait for a long period until its deterministic forwarder waking up. When the number of forwarding candidates increases, the average one hop rendezvous cost is reduced quickly from over 230 *ms* in case of one candidate to only over 85 *ms* in case of five candidates based simulations, and from 248 *ms* to 100 *ms* based on experiments, respectively. With more forwarding candidates, the higher chance packets can be forwarded earlier; thus the rendezvous cost is lower. The least rendezvous cost is witnessed within five candidates. We observe slightly higher results in testbed than simulation due to hardware delay and differences between simulation and real deployment. However, the relative performance remains the same.

The rendezvous cost starts increasing when the number of candidates increases from five to seven. This phenomenon is explained in section III.B. When the cost of the later two forwarding candidates is higher than the cost of the sender within the first five candidates, adding the later two candidates leads to a higher overall cost for the sender. In addition, the higher the number of forwarding candidates the higher the collision probability may happen.

Fig. 4 presents the main trend of communication cost. As neighbors are sorted in an increasing order of transmission cost they offer, later candidates offer higher transmission cost. This results in a higher average ETX of all links to forwarding candidates. Average communication cost hence increases gradually when the number of candidates increases.

Comparing Fig. 3 with Fig. 4, it is obvious that rendezvous cost has a different tendency compared to communication cost. Adding more forwarding candidates helps reduce rendezvous cost, but increases communication cost. This is a trade-off. The figures show clearly that average rendezvous cost is the dominant factor and much higher than average communication cost. Therefore, the trend of average total end-to-end transmission cost as shown in Fig. 5 is the same with that of average rendezvous cost. By trading off rendezvous cost and communication cost, an EoR node exploits an optimal forwarding candidate set to minimize the total transmission cost.

C. DIAGNOSTIC TRACING TEST

In this diagnostic tracing test, we do simulation tests to compare the actual transmission cost of routes selected by the routing protocols with the measured transmission costs of other routes. The purpose is to evaluate that the route selection made by the routing protocols is efficient or inefficient. We define that a route selection made by a routing protocol is called efficient if its selected route incurs the least actual transmission cost. Otherwise, the route selection is inefficient.

We do simulations with 200 nodes consisting of 20% of type 3 nodes and 10% of type 2 nodes, for the diagnostic tracing test as follows. We run different simulations for the routing protocols with random topologies. For each topology, we select a leaf node. For each test case, the leaf node generates 50 packets randomly. In each test case, we record the routing metric value and the selected route for the leaf node in each protocol, and measure its actual transmission cost. We calculate the average value of 50 message transmissions

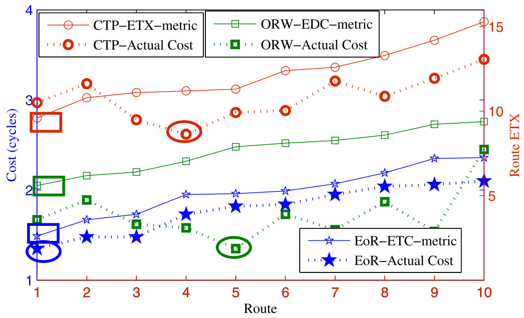

FIGURE 6. An illustration for diagnostic tracing tests. Note that the left y-axis is used for EoR and ORW (unit: Cycles) while the right one is for CTP (unit: Route ETX or in other word, transmission count).

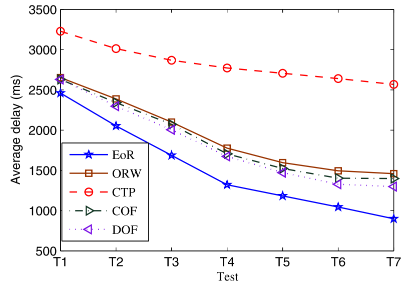

FIGURE 7. Average end-to-end packet delay.

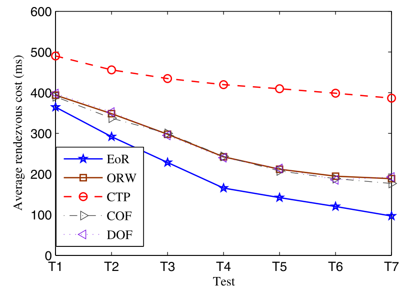

FIGURE 8. Average one-hop rendezvous cost.

as the average packet transmission cost of the leaf node. The reason for obtaining the average value is that in the long run, the actual transmission cost of a node converges to the average value. For diagnostic tracing, we run similar simulations and obtain the cost for packet forwarding of the leaf node to the sink, but through different routes. We use a greedy approach to tests almost every possible route from the leaf node to the sink.

We then compare routing metric values and obtained actual transmission cost values of the selected routes by the routing protocols with other routes of diagnostic tracing, to verify the efficiency of the route selection by the routing protocols.

An illustration of diagnostic tracing test results with EoR, ORW, and CTP is given in Fig. 6. Results of DOF and COF are similar to ORW. Note that actual tracing tests are performed with a great number of different routes. In Fig. 6, results of only 10 routes are given for illustrations. The figure presents routing metric values (solid line graphs) and measured actual packet transmitting costs (dashed line graphs) of 10 different routes in each routing protocol. The left Y-axis is used for EoR and ORW (unit: cycles) while the right one is for CTP (unit: transmission count or route ETX). The route selected by each routing protocol is the 1^{st} route which is the route with the least routing metric value, while other routes are tested randomly. In the figure, for each routing protocol, the route with the least routing metric value is highlighted with a rectangle while a circle is used for the one with the least actual cost.

Obtained results presented in Fig. 6 show that the selected routes of ORW and CTP are not the routes with the least actual transmission cost from the leaf node to the sink. It does mean that ORW and CTP make an inefficient route selection in this case. In the case of EoR, the route selected by EoR is also the route with the least actual transmission cost. It does mean that EoR makes an efficient route selection. We run the same test for different 50 random topologies. Statistical results indicate that more than 20% of route selections made by ORW, CTP, DOF, and COF are inefficient while that of EoR is almost zero. This proves that addressing the limitations of ORW and CTP enables EoR to make efficient route selections.

D. IMPACT OF NETWORK DENSITY

Now we run full simulations for 7 tests with various node densities (test T1 with $200 - 20\% - 10\%$, test T2 with $300 - 20\% - 10\%$, test T3 with $400 - 20\% - 10\%$, test T4 with $500-20\%-10\%$, test T5 with $600-20\%-10\%$, test T5 with $600-25\%-15\%$, test T7 with $600-30\%-20\%$). Each leaf node produces and forwards a message every four cycles at a random time in a cycle. Fig. 7 presents the average values of end-to-end packet latency of each protocol. While the latency in the graph of CTP decreases slightly when we increase the network density, ORW, DOF, COF, and EoR witness a significant decrease. This is because the opportunistic routing protocols exploit more forwarding candidates to forward packets quickly. The EoR results are better than ORW, DOF, and COF because EoR tends to exploit forwarders with a high duty cycle for lowering the rendezvous cost and selecting good enough links for lowering the communication cost. On the other hand, ORW, DOF, and COF consider link quality parameters only. Fig. 8 can also help find reasons for the above result. EoR witnesses the least rendezvous cost that is much lower than DOF, COF, as well as ORW and CTP. The gap between EoR and other protocols increases when we increase the number of nodes with a high duty cycle. ORW, DOF and COF witness similar rendezvous cost because DOF and COF mainly tend to improve the communication cost of ORW as shown in Fig. 9.

For the T5, T6, T7 tests, we keep the network density, but we increase the number nodes with a high duty cycle. We find that ORW, DOF, and COF don't have a significant benefit from increasing the number of nodes with a high duty cycle. On the other hand, we find that EoR performance is improved significantly. In particular, the rendezvous cost and latency of

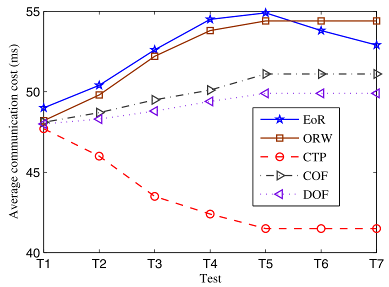

FIGURE 9. Average per-hop communication cost.

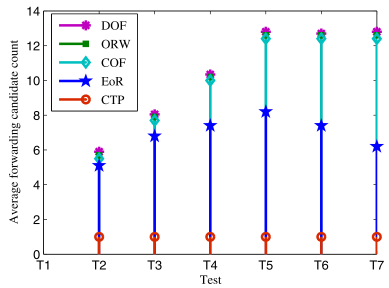

FIGURE 10. Average forwarding candidate count.

EoR is reduced significantly. That is due to the fact that with a higher number of nodes with a high duty cycle, an EoR node achieves a higher FAR value. Therefore, the rendezvous cost of EoR nodes is decreased considerably.

Figure 9 shows the average values of one-hop communication cost in different tests. CTP witnesses the lowest communication cost because CTP forwards a packet deterministically to one forwarder which has the least ETX value (transmission count). The communication cost of CTP nodes decreases over the tests because nodes have better options for good link selection. On the contrary, that of ORW, EoR, DOF, and COF increases when we increase the network density. Results in figure 10 help explain reasons behind the phenomenon. In networks with a higher density, the opportunistic routing protocols like ORW, EoR, DOF, and COF, normally select more forwarding candidates, so the average link quality decreases. EoR witnesses a slighlty higher communication cost in comparison with ORW, DOF, and COF because EoR prefers the balance of both communication cost and rendezvous cost, instead of taking into account the link parameters only. Although DOF and COF improve communication cost noticeably compared to ORW, their overall improvement of end-to-end delay is small compared to EoR in heterogeneous duty cycled WSNs.

Figures 7, 8, and 9 show that rendezvous cost exposes as the dominant factor in the total packet transmission cost. Values of EoR in tests T5, T6, and T7 presented in figures 9 and 10 imply an interesting phenomenon that with an increase in the number of nodes with a high duty cycle and a great enough FAR value, an EoR node tends to have a smaller set of forwarding candidates and its communication cost is lowered. This is due to the reason that with more choices of neighbors operating with a high duty cycle, an EoR node can lower its rendezvous cost even with a small set of forwarding candidates. In that case, an EoR node tends to select neighbors with a better link quality to lower its total transmission cost. The communication cost of ORW, DOF, and COF in the last three test cases are quite similar. ORW, DOF, and COF seem to be more greedy because the size of their set of forwarding candidates expands quickly. This may result in a scalability issue for resource-constrained sensors. In EoR, an EoR node is aware of its expected rendezvous cost, so the node may not add more candidates if its expected rendezvous cost is low enough (i.e., adding more candidates doesn't help lower its total transmission cost).

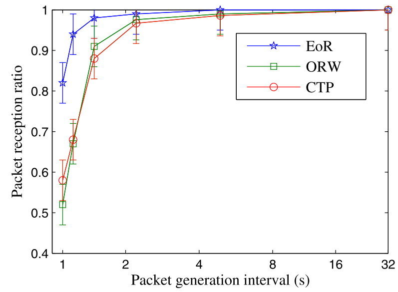

FIGURE 11. Packet reception ratio vs traffic loads.

E. IMPACT OF TRAFFIC LOAD

We now evaluate the performance of EoR under various traffic loads based on testbeds. Because the performance of ORW, DOF, and COF are quite similar, from now on, we present only results of ORW as the representative of the three opportunistic routing protocols. In testbeds, every node is configured to generate at least a message every 1 to 32 cycles. We measure the packet reception ratio, which is presented in figure 11. The ratio of EoR, ORW, and CTP decreases when we decrease the packet generation interval, in other words, we increase the traffic load. This is due to increasing the collision probability. However, CTP and ORW witness a lower ratio because of their inefficient channel utilization. A sender in CTP occupies the channel for the whole waiting period until its receiver is available for receiving. This blocks other nodes from transmission and results in a high collision in scenarios with high traffic load.

Figure 12 shows the duplicate ratio results under different traffic load settings. ORW witnesses the duplicate ratio increasing quickly when we increase the traffic load. The reason is that ORW transmits data messages directly to neighbors while ORW implements duplicate suppression using overhearing only. Therefore, in scenarios with a high traffic load, a sender couldn't control how many candidates forward its messages. The detailed arguments explaining this issue is presented in Section III.B. Duplication transmissions degrade the channel utilization and causes packet loss. The experiment indicates the scalability issue of ORW. In all scenarios, EoR witnesses the highest ratio of packet reception.

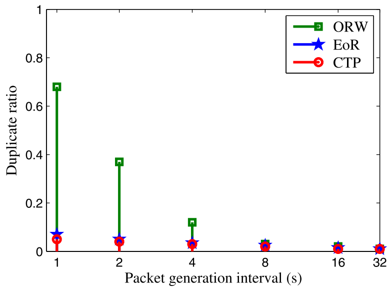

FIGURE 12. Duplicate ratio vs traffic loads.

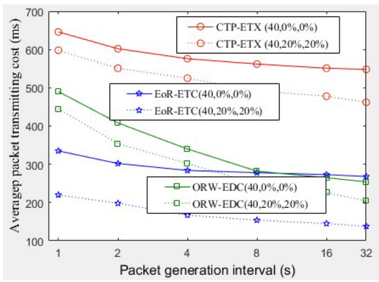

FIGURE 13. Packet transmission cost vs traffic load.

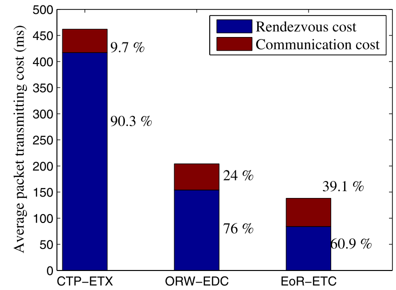

FIGURE 14. Rendezvous and communication cost Ratio.

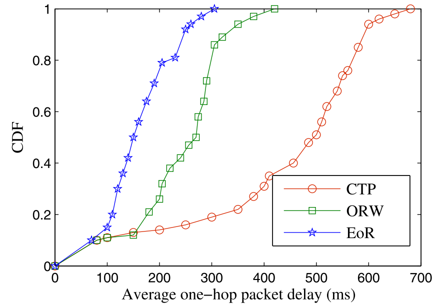

FIGURE 15. Packet delay distribution.

The results are achieved because 1) EoR addresses the duplicate issue of ORW, 2) EoR nodes can forward their messages quickly based on routes with low packet transmission cost, thus reducing collision and increasing the channel utilization. As a result, the results of EoR is similar to CTP.

Figure 13 presents average packet transmission cost results which imply both radio-on time (energy consumption) of the sender and packet forwarding delay. We conduct experiments using all nodes with a low duty cycle (the case with $40-0\%-0\%$) in comparison with the case with $(40-20\%-20\%)$. In tests with a high data rate, ORW suffers from packet duplication issues which result in greater number of packet transmissions, collisions, and duplicate packet transmissions. As a result, ORW shows a higher packet transmission cost. For CTP, its packet transmission cost is high in all cases because of a high rendezvous cost. This indicates the advantages of the opportunistic routing in comparison with the deterministic routing. EoR witnesses the least total transmission cost in all cases. In general, the results with the $40-20\%-20\%$ test are lower than those with the $40-0\%-0\%$ test because packets are transmitted faster when there are nodes with a high duty cycle. However, EoR achieves the greatest benefit when nodes with a high duty cycle are deployed. The reason is that EoR actively selects and exploits nodes with a high duty cycle to lower its rendezvous cost.

In the $40-0\%-0\%$ tests, EoR also shows a higher energy efficiency and shorter packet transmission delay in comparison with ORW. This indicates the efficiency of the deterministic packet forwarding mechanism in EoR. The results of EoR are slightly lower compared to ORW when we increase the packet generation interval to over 8s. This is due to the reason that EoR uses preamble acknowledgment that can be expensive in the environment with low duty cycled nodes only. ORW transmits packets directly instead. We find that the gap between results of EoR and other protocols in scenarios with a high data rate is bigger than those in scenarios with a low data rate. Therefore, we conclude that EoR shows better improvement in scenarios with a high data rate.

Figure 14 shows the cost breakdown in tests with $40-20\%-20\%$ and the generation interval of 32 s. The figure indicates that opportunistic routing protocols like ORW and EoR achieve a lower rendezvous cost in comparison to CTP. Their tradeoff is that their communication cost is slightly higher than CTP. The results present clearly that the rendezvous cost is dominant in comparison with the communication cost. As a result, for optimizing the packet delay and energy consumption, a routing protocol should take into account the rendezvous cost. For that reason, EoR shows the lowest overall cost.

Figure 15 presents the distribution of one hop packet transmission latency for CTP, ORW, and EoR. The graphs of ORW and EoR show a greater number of nodes experiencing a low packet latency (i.e., < 250 ms) in comparison with CTP. The same reasons discussed in figure 13 are applied to this case. An interesting point here is that ORW, EoR, and CTP have a similar number of nodes experiencing a packet latency lower than 80 ms. Analyzing the logs, we find that those nodes are located nearby the sink and the sink is their parent node.

F. SETTING UP, CONVERGENCE, AND ROUTING UPDATE COST

This section presents measurement results of EoR and ORW in terms of setting up cost, convergent time, and routing update cost. We measure the cost of over 100 experiments and report average results. Obtained results show that the setting up cost, the convergent time, and the routing update cost of EoR is only slightly higher than those of ORW. Statistically, each node in EoR takes approximately a period of time equal to 3.24 cycles to complete its setting up phase while that of ORW is 2.86 cycles.

Because both EoR and ORW use the light-weight link estimation which is mainly based on overhearing without the need of expensive probing for link measurement and neighbor discovery, their convergent time is quite similar. The routing metric ETC and EDC of nodes reach an initial stable point within the first 2.8 and 2.4 minutes, respectively. The two metrics are optimized slightly over time since a node running EoR and ORW may add new neighbors, however, improvements in the routing metrics witnessed are small. The results indicate that both EoR and ORW achieve stability quickly after network deployment or topology changes. In addition, due to the significance based routing update policy of EoR, changes of individual forwarding candidates have a limited impact on the routing metric. The dynamics of individual forwarding candidates may be hidden as long as aggregation of the pool of candidates performs stably. This helps EoR maintain the stability even in presence of changes in some neighbor nodes.

As described in the previous section, EoR forwards packets based on FDT and the destination field of the typical preamble message is released, which is exploited for routing update in EoR. For that reason, EoR routing update does not incur any extra communication overhead. Moreover, EoR utilizes the significance based routing update policy which reduces the frequency of routing updates to maintain the stability of the system. We witness that routing update cost of EoR and ORW is acceptable and significantly lower than CTP to maintain similar stability [18].

Regarding to the EoR's routing update policy, we also observe that changes in overlapping wakeup pattern of individual forwarding candidates have only little impact on the ETC value, thus EoR does not require to update FAR frequently in order to maintain its optimality. For efficiency, an absolute measurement of FAR is not necessary. Our obtained results show that average interval of wakeup pattern update of a node is much lower than the one required. In particular, although a node receives wakeup pattern updates of neighbors every 5.45 minutes on average, a node updates its metric due to a significant change of the overlapping wakeup patterns only after 3.62 hours on average. Therefore, the update scheme of EoR works properly to maintain the routing metric update and its optimality. Note that in EoR, a small change in an individual node has a low impact on the overall performance.

V. CONCLUSION

This paper investigates the limitations of the state-of-the-art routing protocols by analyzing packet transmission cost in heterogenous duty-cycled WSNs. We then introduce a novel routing metric, Expected Transmission Cost (ETC), and design an ETC-based routing protocol (EoR). By directly capturing both duty cycle and communication cost, ETC enables EoR to select routes which lead to the minimum transmission cost. Through our analysis and evaluation, we show that EoR significantly improves the network performance in terms of energy efficiency, packet delivery latency, and delivery rate. For future works, we plan to explore the packet transmission cost with the rendezvous cost-aware in independent duty-cycled WSNs as well as adapting ETC for deterministic routing in dynamic WSN environments.

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