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A Novel Metric for Opportunistic Routing in Heterogenous Duty-cycled Wireless Sensor Networks

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***Abstract*—This paper investigates the suboptimal problem of existing state-of-the-art routing protocols when they are applied to heterogeneous duty-cycled wireless sensor networks (WSNs). In particular, we discover that the selected optimal routes with the least cost based their routing metric may not always lead to the least transmission cost. The key reason is that the existing routing metrics used do not sufficiently capture packet transmission cost in heterogeneous duty-cycled WSNs. To address this issue, we propose a novel routing metric, namely expected transmission cost (ETC), which efficiently captures packet transmission cost in heterogeneous duty-cycled WSNs by estimating both expected rendezvous cost and communication cost. Based on ETC, we design an opportunistic routing protocol (EoR) which is proved to select optimal routes with the least packet transmission cost. Our experimental results show that EoR outperforms the state-of-the-art protocols in terms of energy efficiency, latency, and packet delivery ratio.**

I. Introduction

Low duty cycle operation has been widely deployed for energy saving in traditional wireless sensor networks [1], [2] 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 [3] (e.g., Everlast nodes with 50% duty cycle [3], [4], and Trior nodes with 20-40% [5]). The duty cycle of an energy harvesting sensor is usually designed to be proportional to its energy availability, harvesting capability, and energy storage capability [3], [6]. 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 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 [3]. 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 [7]–[9].

We argue that existing routing protocols for duty-cycled WSNs (e.g., CTP [10] and ORW [11]) may not work efficiently when applying to heterogeneous duty-cycled WSNs, especially when duty cycles of nodes are significantly 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 a 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 by a sender until its receiver wakes up). [1]. Generally, rendezvous cost can also be the time cost of listening by a sender in case of the receiver-initiated MAC approach [12]. For simplicity, we illustrate the basic concept of rendezvous cost using a sender-initiated asynchronous MAC (i.e., X-MAC [2]). The communication cost of a node usually depends on the quality of the link with its receiver. For rendezvous cost, since no link exists between the sender and its receivers (i.e., the receiver is sleeping), the rendezvous cost of a node is independent with link-related parameters. The rendezvous cost of a sender node depends on how its packet sending time aligns with its receivers' wakeup time. In heterogeneous duty-cylced WSNs, the rendezvous cost of a sender node with its neighbor node may be different from its other neighbour nodes since nodes operate at different duty cycles. Moreover, in many cases, rendezvous cost can be a dominant factor in packet transmission cost [1]. Illustration examples are discussed in section II.

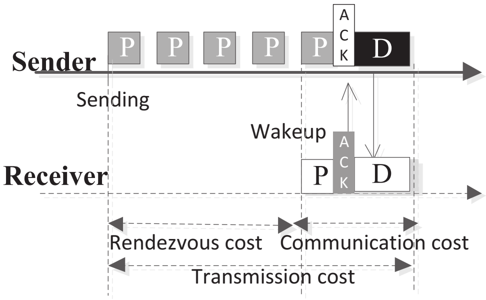

Fig. 1. The transmission cost in asynchronous duty-cycled WSNs

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[1] Note that packet transmission cost we mention in this paper is also known as packet transmission delay and radio-on time of the sender

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However, the routing metrics used in the existing duty-cycled routing protocols fail to capture rendezvous cost. In particular, ETX [13] used in CTP [10] bascially considers only link reliability of possbile routes, and selects the most reliable route. This implies that only communication cost is captured. In the most recent opportunistic routing protocol (ORW) [11], although the expected duty cycled wakeups (EDC) metric the authors proposed attemps to capture the expected duration (i.e., number of wakeups) to transmit a packet, only reliability of multiple links to the forwarding candidates is considered. As a result, EDC can be viewed as an adaptation of ETX to opportunistic routing, and rendezvous cost is not captured properly in EDC. Both ETX and EDC fail to capture rendezvous cost properly in heterogeneous duty-cycled WSNs. Consequently, both CTP and ORW may experience suboptimal problems in routing and forwarding priority assignment. For example, selecting a forwarding candidate set with the least value of EDC may not lead to the least actual transmission cost (the detailed analysis can be found in section II).

To address the limitation of existing routing metrics, we first propose a novel routing metric for opportunistic routing in heterogeneous duty-cycled WSNs, named expected transmission cost (ETC). ETC considers both rendezvous cost and communication cost. We introduce an efficient method to compute expected rendezvous cost of a node, which is then used to construct ETC. We then design an ETC-based opportunistic routing protocol (EoR). In EoR, a node selects an optimal number of forwarding candidates so that its total transmission cost is minimized. Our aim is to select the best path based on ETC, which also leads to an actual path with the least cost. We implement EoR in TinyOS-2.1.2 using a cross-layer approach which exploits preamble transmissions in the MAC layer to carry necessary information used for the opportunistic forwarder selection. Data packets are then deterministically forwarded to the selected forwarder. In this way, EoR solves both suboptimal and duplicate problems which exist in ORW [11].

We conduct comprehensive TOSSIM simulations and experiments with Telosb motes to evaluate the performance of EoR, and also compare with the state-of-the-art routing protocols (i.e., CTP and ORW) under various network conditions. The results show that EoR achieves 100% in selecting the routes with the least packet transmission cost, while both CTP and ORW only achieve less than 77.6%. As a result, EoR achieves over 40% improvement in both energy efficiency and packet transmission delay, and over 20% improvement in packet delivery ratio compared with both CTP and ORW. Our experiments also demonstrate that EoR outpperforms ORW in terms of scalability.

In summary, this paper makes the following contributions.

- We discover the limitations of existing routing metrics and protocols when they are applied in heterogeneous duty-cycled WSNs. (section II)
- We propose a novel routing metric – ETC to capture packet transmission cost including both rendezvous cost and communication cost. We also design an ETC-based opportunistic routing protocol (EoR) to demonstrate its impact on network performance. (secion III and IV)
- We apply diagnostic tracing to evaluate the optimality of EoR, and conduct comprehensive TOSSIM simulation and experimental studies with Telosb motes under different network conditions. The results demonstrate that EoR achieves better energy efficiency, packet transmission delay, and packet delivery ratio compared to both CTP and ORW. (section V)

II. MOTIVATION

A. Revisiting ORW

In this section, we revisit ORW [11], the state-of-the-art opportunistic routing protocol for duty-cycled WSNs. The core of ORW is a new metric EDC. The EDC of a node i is calculated as follows.

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

where $p(i,j)$ is single hop EDC which considers the link reliability between node i and node j in the forwarding candidate set F_i. EDC can be viewed as an adaptation of ETX to opportunistic routing, however, instead of considering a single link as ETX, it considers links to a number of forwarding candidates. The second term reflects the subsequent delay from candidates to the sink. w is a constant value as forwarding cost. Based on EDC metric, each node in ORW selects its forwarding candidate set. The first wake-up node in the forwarding candidate set becomes the next hop. EDC has been proved to work efficiently in traditional duty-cycled WSNs. However, when applied in heterogeneous duty-cycled WSNs, it has many limitations which we will discuss in the next section.

B. Motivation

In this section, we discover limitations of ORW and motivate our work through examples. First, we present some definitions used in our work.

Cycle (L): The period from the time when a node goes to sleep to the next time when the node goes to sleep.

Forwarder candidates' active ratio per cycle (FAR) of a node (i.e., projected duty cycle): The ratio of periodic wakeup period of all forwarding candidates of a node in a cycle, excluding overlapping wakeup periods among candidates.

Periodic duty cycle of a node (P%): The ratio of periodic wakeup period of a node in a cycle. Note that the total duty cycle of a node can be larger than P as a node may extend its wakeup period up on receiving or transmitting packets.

In duty-cycled WSNs, rendezvous cost can be a dominant factor in packet transmission cost of a node. For example, a sender i selects a low duty-cycled node j as a forwarder which requies only one transmission (i.e., ETX =1), the expected communication cost is then equal to the cost of transmitting one packet (e.g., 20ms). However, the expected rendezvous cost of node i is about half of a cycle length L on average, i.e., $L = 1s$, and the worst case can be L [1]. As a result, transmission cost can be high even though communication cost is very low.

We use the following examples to show how ORW fails in selecting optimal forwarders. We assume that all nodes operate at the same cycle length of L (L = 1s) and links have perfect quality ($p = 1$) unless otherwise specified.

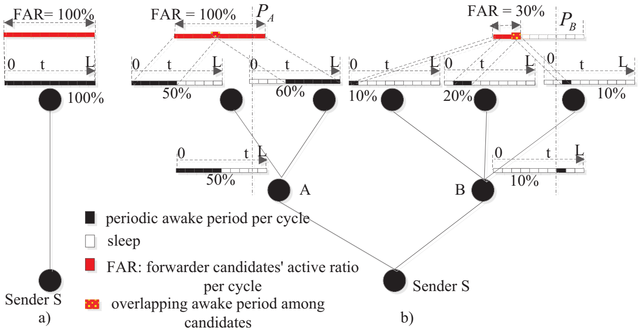

Fig. 2. An illustration for heterogeneous duty cycled WSNs

In the first example, we assume a very simple case where a node S has only one forwarding candidate F which operates at 100% duty cycle, as illustrated in Fig. 2a. According to ORW, with perfect reliability of link $S-F$, the expected transmission duration of S is equal to $1/1 = 1$ wakeup cycle (i.e., 1s) while the actual transmission cost of node S is only equal to the cost of transmitting a packet (i.e., 20 ms). With the link reliability of 0.5, the calculated value by ORW is 2 wakeup cycles (i.e., 2s), while the actual transmission cost is equal to the cost of transmitting 2 packets (i.e., 40 ms) within a cycle. The reason is that its forwarder is always active to receive packets.

In the second example, we assume A and B are two neighbors of node S, node A has a periodic duty cycle of 50% and node B has 10%, as shown in Fig. 2b. The link to A and B, respectively, has the same reliability of 1. In ORW, node S considers A and B equally in selecting forwarders. By definition, the communication cost of S to A and B are equal. However, the actual transmission cost to A and B is totally different because the rendezvous cost to A is up to 50% of L (i.e., 500 ms), while the rendezvous cost to B is up to 90% of L (i.e., 900 ms).

Assume A has two forwarding candidates, one with a periodic duty cycle of 60%, another with 50%; FAR of A is 100% (overlapping wakeup period of the two forwaders is 10% of a cycle). This means that A always has at least one wakeup forwarder. Whenever A has packets to send, A can forward the packets immediately without incurring a rendezvous cost. B has three forwarding candidates, two nodes with a periodic duty cycle of 10% and one node with a periodic duty cycle of 20%; the active period of the second node overlaps with that of the third node so that FAR of B is 30%. This means that over a period of 70% of L, B has no wakeup forwarder. When B has packets to send, it may have to wait for a period up to 70% of L (i.e., 0.7s) until a candidate wakes up. As all links have the same reliability of 1, it is obvious that the transmission cost of A is actually much lower than that of B. However, according to ORW, one-hop EDC of A is $1/(1+1) = 0.5$ wakeup cycle while EDC of B is $1/(1+1+1) = 1/3$ wakeup cycle. This does mean that based on EDC, the cost to forward packets through B is lower than that of A while the actual result should be opposite. As a result, in ORW, node S prefers to select B as its forwarder instead of A, which leads to suboptimal performance. Through the above examples, it is obvious that without considering rendezvous cost properly, ORW exposes many drawbacks in heterogeneous duty-cycled WSNs.

III. EXPECTED PACKET TRANSMISSION COST METRIC

Based on observations in the previous section, we first present a method to estimate the expected rendezvous cost of a node. We then introduce a new metric, ETC, which considers both rendezvous cost and communication cost.

We assume that each node i has a forwarding candidate set F_i, and for simplicity, every node has the same cycle length L. Each node (i.e., node j) operates at duty cycle D_j. The assumption about duty cycle is reasonable for both stable duty cycling and adaptive duty cycling approaches as explained in Section VI. In each cycle, a node j periodically wakes up and remains active for a periodic wakeup period of $T_a^j = D_j * L$ to listen for incoming packets. We use $T_a^{over}(j,k)$ to denote the overlapping wakeup period between nodes j and k.

The rendezvous cost of a node (i.e., node i) depends on the probability of its packet transmission time aligning with the wakeup period of at least one forwarding candidate, i.e., rendezvous probability. As an event which triggers a node to generate and send a packet can occur at any time within a cycle, the rendezvous probability (in other words, expected rendezvous cost) of a node with its neighbor node is proportional to the wakeup ratio of its neighbor. This means that expected rendezvous cost is proportional to neighbor's duty cycle. With multiple forwarding candidates used in opportunistic routing, expected rendezvous cost is proportional with the wakeup ratio of all forwarding candidates (FAR). We calculate FAR of a node (i.e., node i) as follows.

$$FAR_i = \frac{\sum_{j \in F_i} T_a^j - \sum_{j,k \in F_i} T_a^{over}(j,k)}{L} \tag{2}$$

FAR of a node indicates the ratio of time period in a cycle the node has at least one wakeup forwarding candidates. During this fraction of time period, if the node has packets to send, the packets can be forwarded immediately because the packet sending time is overlapped with one or several forwarding candidates' wakeup period. If a packet is transmitted by node i at any time t, the probability, that the packet is delayed for a waiting period (i.e., rendezvous cost) until there is at least one forwarding candidate wakes up, is computed as follows.

$$P_{waiting}^i = 1 - FAR_i \tag{3}$$

$P_{waiting}^i$ of a node also indicates the ratio of time period in a cycle the node has no wakeup forwarding candidates. $P_{waiting}^i$ is assigned to 0 if FAR_i is greater or equal to 1 (may be due to variations in measuring). The rendezvous cost of node i is up to $T^i_{wp-max} = P^i_{waiting}L$, and expected rendezvous cost T^i_{rc} is calculated as follows.

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

where N_i is the number of candidates in F_i. In case $FAR_i = 1$ and $P^i_{waiting} = 0$, the expected rendezvous cost of i is zero, as illustrated in node S in Fig. 2a and node A in Fig. 2b. 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 $L/2$. This result matches with the average sleep latency which is used porpularly in existing low power listening MAC protocols [1].

To compute communication cost, we denote γ as the average time period required to transmit a data packet and receive an acknowledgment message through a link with perfect link quality. Note that with the same power transmission, values γ of nodes are similar and there is not much difference between energy used for transmission and reception because the distance covered by sensor nodes is very short [2].

Let ETX_{ij} denote the expected transmission count of the link between nodes i and j. While node i transmits a packet, node j wakes up and may not receive the packet if the wakeup period of node j (T^j_a) is smaller than the time required for node i to transmit and retransmit a packet for ETX_{ij} times ($T^j_a < \gamma ETX_{ij}$) (because after being active for T^j_a, node j goes to sleep if it does not receive any packet). We use the ratio $\mu_{ij} = \gamma ETX_{ij}/T^j_a$ to express the possibility that a node i may need more than one cycle to transmit a packet successfully to a forwarding candidate j.

However, in opportunistic routing, a decision to determine the forwarder is delayed until after the packet transmission and a forwarding opportunity is shared among forwarding candidates. When a sender transmits a packet, it is only required at least one of forwarding candidates successfully receives the packet. If no forwarding candidate receives the packet within the first cycle, the sender may have to spend more than one cycle to transmit the packet. This case may occur if the lowest value μ^{min}_i among values $\mu_{ij} (\forall j \in F_i)$ is greater than 1. We then estimate the number of cycles with failed packet transmissions of node i (i.e., $C_i = \lfloor \mu^{min}_i \rfloor$).

We now estimate expected communication cost of node i spending in the cycle with successful transmission. In opportunistic routing, because a forwarding opportunity is shared among forwarding candidates, we introduce average ETX value of forwarding candidates calculated using the equation below, instead of considering individual values.

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

The expected communication cost of a node i is then computed as follows.

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

The expected transmission cost (ETC) for a single hop is calculated in Eq. (7). We use the number of cycles to indicate expected transmission cost.

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

As forwarding opportunities are shared among forwarding candidates, the transmission cost of node i in long term will converge to a value based on the average transmission cost by forwarding candidates. Therefore, we calculate the expected multi-hop transmission cost of node i based on the one-hop cost and the average ETC value of forwarding candidates using Eq. (8). We denote $f(F_i)$ as a function to calculate ETC_i based on forwarding candidate set F_i.

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

IV. ETC-BASED ROUTING PROTOCOL

In this section, we present the design of EoR, an ETC-based opportunistic routing protocol, aiming to address the limitations of ORW. EoR leverages on some existing methods used in ORW such as forwarding candidate set selection, cost of forwarding, and link estimation. In summary, EoR works on the top of low power listening protocols where nodes periodically wake up to listen for incoming packets. When a sender has data packets to send, it transmits preambles until its forwarder wakes up (rendezvous cost). EoR is designed to minimize this rendezvous cost as well as the communication cost of senders by operating based on ETC metric which is able to capture both the expected rendezvous cost and the expected communication cost of a node. Based on ETC, a node running EoR selects a number of forwarding candidates which provide the lowest forwarding cost.

A. Forwarding Candidate Set Selection and The Forwarding Value

We adopt the forwarding candidate set selection method in ORW. Instead of only requiring the neighbor to provide a routing progress in ORW, a node adds a neighbor node to its forwarding candidate set if adding the neighbor node helps lower its ETC value, as illustrated in Algorithm 1. The forwarding candidate set selection mechanism computes a forwarding candidate set F_i through adding neighbor nodes sorted in an increasing order by their ETC values to the forwarding candidate set and determining the set with the minimum ETC. In other words, after sorting potential forwarders by their ETC values, a node i uses a greedy algorithm to determine the optimal forwarding candidate set, resulting in the minimum ETC metric of node i (ETC_i). After selecting the forwarding candidate set, a node i can determine a single value which describes the ETC that a forwarding candidate must provide at least, named the forwarding decision threshold of node i (FDT_i). This value is used later in our mechanism to select the unique forwarder. We present briefly the algorithm below.

Given a network topology as a directed graph $G = N, L$ which consists of a set of nodes N and a set of links LS. Each node i in the network has a set of neighbor nodes N_i.

Each neighbor table entry of node i contains the information of a neighbor node j (i.e., node id, periodic wakeup period, overlapping active period pattern, ETC_j, and ETX_{ij}). The algorithm is described in Algorithm 1. The detailed description and proofs to demonstrate for the optimal selected set which leads to a loop free topology can be found in [11]. The cost of forwarding parameter w in ORW is also used in our algorithm.

Algorithm 1 EoR routing algorithm

```
INPUT: $G = N, LS$, $N_i$ ($\forall i \in N$) 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($n_1, n_2, ..., n_{k_i}$) with ($ETC_1 \leq ETC_2 \leq ... \leq ETC_{k_i}$)
    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
```

B. Forwarding Strategy and Unique Forwarder Selection

This section indicates the limitations in ORW, and proposes an efficient mechanism for unique forwarder selection. In ORW, long data packets can be received by multiple forwarding candidates as a sender sends data packets directly before a unique forwarder is selected. As a result, a sender may have to spend cost to receive multiple acknowledgments and this design may lead to high collision probability at the sender. Moreover, a sender cannot control surely how many forwarders have already forwarded its packets as ORW coordination is based on overhearing only. This leads to a heavy duplicate problem, especially in high traffic load [14].

We propose an efficient and lightweight scheme for unique forwarder selection. EoR uses a cross-layer design for the forwarding strategy, and exploits transmissions of preamble of the under layer (i.e., X-MAC) to carry information and involves in selecting the unique and best forwarder in real time. In particular, when the MAC layer of a node i receives a packet to send from the upper layer, it firstly sends preambles containing two 8-bit values including the FDT_i value and the ETC_i value of node i, instead of the 16-bit destination address as in existing schemes [2]. As preamble carries information instead of the destination address, we name them information-centric preambles (i-preamble) to distinguish with normal preambles. When an i-preamble is received, receiver j first checks the attached FDT_i value. If the ETC value of receiver j is smaller than or equal to FDT_i, node j then selects itself as a forwarding candidate. The candidate then executes a back-off before it sends out an ACK message. The back-off period of a candidate j, B_j, is inversely proportional to its providing 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 a predefined maximum back-off time. RT_i is a given routing progress threshold of node i, currently we use $RT_i = 2(ETC_i - FDT_i)$. B_j is a non-negative number, thus it is assigned to 0 if the calculated value is negative. Following the back-off mechanism, the forwarding candidate which provides the lowest cost and is available at the packet sending time, is given the highest priority to send an acknowledgment first because its back-off time fires the earliest. The first node which acknowledges the preamble transmission is selected as the unique forwarder. Upon receiving the first preamble acknowledgment, the sender stops its preamble transmission, ignores other acknowledgments (if have), and sends data packets deterministically to the selected forwarder by inserting the source address in the acknowledgment message as the destination address of data packets. After receiving data messages, the forwarder responses back with an acknowledgment and then continuously forwards data packets to the next hop. After receiving the acknowledge, the sender goes to sleep if its sending packet queue is empty. Other wakeup forwarding candidates, which hear the preamble acknowledgment or the data packet transmission, cancel their acknowledgment transmission. In this way, EoR only anycasts preambles while the data packet is transmitted deterministically to the unique forwarder which is the best available forwarder at the packet sending time.

C. The setting-up phase

Similar to ORW and CTP [10], the setting-up phase of EoR starts from the sink node to leave nodes. A node stays awake during its setting-up phase. In addition, at the end of this phase, each node will sleep a full interval of L before it wakes up to start its regular duty cycle.

The sink node first broadcasts an advertisement message. An advertisement message of a node containing its periodic duty cycle (i.e.,D) and ETC value (for the sink node, $ETC_{sink} = 0$ and $Dsink = 100\%$). As the sink node is always active and the expected transmission cost is zero, sink neighbor nodes select the sink as their next hop after receiving its advertisement message. Each sink neighbor node then calculates its routing metric and executes a random back-off time before it broadcasts its advertisement message. To distribute the wakeup time of nodes and reduce a chance of collision, we intentionally use a large contention window for the setting-up phase. After broadcasting, the node listens for a timeout T_O^1 to check whether its packet transmission is successful or not. After timeout, if no problem is detected, the node then sleeps for a full interval. A retransmission may be required in other cases.

The neighbor nodes in a node's listening vicinity receive its advertisement message and possibly advertisements from other neighbor nodes. When receiving an advertisement message from a neighbor node, a receiver stores information of the sender in the neighbor table. It also records the receiving time which enables it to calculate the next wakeup time of the sender (e.g., $t_{sender}^{wakeup} = t_{currenttime} + T_O^1 + L$) and the relative periodic wakeup period of the sender within its cycle (e.g., from t_{sender}^{wakeup} to $t_{sender}^{wakeup} + D_{sender} * L$) based on its own clock. Note that the receiver may have such information from other neighbor nodes too, which enables the receiver to detect overlapping wakeup periods of its forwarding candidates. A receiver keeps listening for advertisement messages from neighbor nodes and uses the greedy algorithm to select the first forwarding candidates as described in Section V.A. By selecting the first forwarding candidates, the receiver can calculate its current ETC value. A node stops listening and completes its setting-up phase if the node does not receive any advertisement from a neighbor node which has a smaller ETC value compared to its current ETC metric, within a timeout T_O^2 ($T_O^2 > T_O^1$) calculated from the receiving time of previous advertisement (as the node may already receive all advertisements from potential neighbors). The node then executes a random back-off, broadcasts an advertisement, waits for a timeout T_O^1, and finally sleeps to finish its setting-up phase, as same as the processes of neighbor sink nodes. Similarly, other nodes execute the same operations as described above in their setting-up phase. At the end of this phase, a directed acyclic graph (DAG) topology of the network is established, which has been proved in [11].

D. Update

Similar to ORW, EoR employs a pool of forwarding candidates, where each packet may be forwarded through a different path. As a result, changes of individual forwarding candidates (wakeup time drift, link quality change, ...) have limited impact on the overall quality of the forwarding candidate set. In EoR, as long as aggregation of forwarding candidates performs stably, the dynamics of individual forwarding candidates will be hidden to guarantee stability. EoR reuses light-weight link estimation in ORW. For ETC routing metric update, we reuse 16-bit destination address to attach ETC value of a sender in i-preambles (i-preamble type 1), as described in section IV.B. This enables neighbor nodes to update ETC metric of the sender each time the sender sends a packet. In this way, the routing update of EoR does not incur any extra communication overhead.

When the ETC value of sender i does not change and the node wakes up at its periodic duty cycle to send packets (i.e., periodic timer fires), sender i, instead of sending preambles with ETC value, sends preambles with its elapsed wakeup period (T_{elapse}) which is used for detecting changes in overlapping wakeup patterns of nodes (i-preamble type 2). The overlapping wakeup period of forwarding candidates may change over time because of clock drift. We later show that changes of overlapping wakeup period has only little impact on the EDC value of a node.

When a receiver wakes up and overhears a preamble from a neighbor node (i.e., node A) with the elapsed wakeup period information, the receiver can calculate the relative periodic wakeup period of the sender within a cycle (e.g., from $t_{current} - T_{elapse}$ to $t_{current} - T_{elapse} + D_{sender} * L$) based on its own clock. The receiver may update the record for this neighbor if there is any change. Based on relative periodic wakeup periods of neighbors, the receiver can compute the overlapping wakeup period among forwarding candidates. However, a node updates its routing metric only if changes are significant (i.e., the change > 0.1). The reason is that changes in wakeup patterns of individual nodes have a small impact on its EDC value, thus it does not require an absolute measurement. The purpose of updating based on significance is to minimize overhead. We also note that in real implementation, low duty cycle nodes are not required to update their overlapping wakeup period as their wakeup periods are small and have little impact on the ETC value of a node.

V. PERFORMANCE EVALUATION

We now move to evaluate our proposed ETC based procotol EoR (named EoR-ETC) by simulations and experiments with Telosb motes, and compare it with the two state-of-the-art routing protocols–EDC based ORW (named ORW-EDC) and ETX based CTP (named CTP-ETX).

A. Implementation

To make EoR comparable with ORW, we implement EoR as replacement for the unicast forwarding logic in the data collection protocol. We implement EoR based on the baseline of ORW implementation [11] in TinyOS-2.1.2, and reuse several components in [11] as described in Section IV. Since there is no practical implementation of MAC protocols for energy harvesting nodes available to the research community, for a fair comparison, we use the BoX-MAC-2 protocol [15] and the CC2420 Telosb platform used in both ORW and CTP. To create heterogeneous duty-cycled scenarios and enable nodes to operate at high duty cycles, we configure the periodic wakeup period of a node i to D_iL, instead of using the default value of $t_{backoff} + t_{ack}$ as in the original BoX-MAC-2 [15]. Note that the energy harvesting process of an energy harvesting node is usually hidden from the routing layer. Therefore, the above setting for high duty-cycled nodes, instead of using energy harvesting nodes, is reasonable for evaluating the performance of routing protocols. Low duty-cycled nodes use the same receive check duration as in the original BoX-MAC-2. For simplicity, we assume that all nodes use the same cycle length of L.

For EoR, we enable BoX-MAC to send 802.15.4 header as preamble, instead of sending data packet directly. We use packet transmission cost as an indicator for both energy consumption and packet delivery delay. To measure these costs, we record changes in the radio's states and use counters to accumulate the time period used in each state. The end-to-end delay is the packet delivery delay from the source node to the sink node. We use the sequential difference recovery approach [16] to measure the end-to-end delay. To ensure realistic TOSSIM simulation evaluation, our radio noise model is based on closest-fit pattern matching (CPM) and an experimental noise trace (i.e., meyer-heavy.txt) from Meyer Library at Standford University [17]. Table 1 gives the detailed parameters used in our simulation. Other parameters are set to the default values as in ORW [11].

TABLE I
PARAMETERS

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

To create heterogeneous duty cycled scenarios, we use three types of nodes including highly energy constraint nodes (traditional sensor) which operate at low duty cycle (type 1), and higher energy capacity nodes with a periodic duty cycle of 20 $\%$ (type 2) or 40 $\%$ (type 3). We use (N-X%-Y%) to denote simulations or experiments with network density of N, consisting of $X\%$ of type 3 nodes, $Y\%$ of type 2 nodes, and the rest are type 1 nodes. Each result is calculated from an average of over 50 random topologies.

B. Evaluation Methodology

We generate 50 different random topologies with various network densities and number of nodes with high duty cycle in a fixed area. For each topology, we run different simulations based on the obtained topology, including 1) packet forwarding of a leave node to the sink through the selected routes by a protocol; 2) diagnostic tracing for packet forwarding of the leave node to the sink through different paths (up to 100 paths depending on the network density). Note that the leave node generates 50 packets randomly. In each test case, we record the routing metric value of each protocol, and measure the actual transmission cost. We obtain an average value after 50 packet transmissions as the average packet transmission cost of the leave 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. We finally compare routing metric values together and actual transmission cost values together to find the case with the least routing metric value and that with the least actual transmission cost. Because a routing protocol normally selects its default route with the least value of its routing metric, if the route also leads to the least actual transmission cost, we state that the routing protocol produces an optimal routing; if not, we refer it as a sub-optimal routing. We report the average suboptimal ratio of each routing protocol.

C. Impact of Network Density

We select to report the simulation results of seven topologies, as shown in Table 2.

The results show that ORW-EDC and CTP-ETX make a high ratio of sub-optimal routing. The suboptimal ratios of the two protocols increases when the network density increases. The reason is that without considering rendezvous cost properly, selecting routes with the least value of EDC or ETX may not lead to the least actual transmission cost. This can be explained clearly using both Fig. 3 and Fig. 4 which indicate that rendezvous cost is a dominant factor in packet transmission cost. The optimal routes selected by ORW and CTP may be the results of random effects when routes with the highest link quality also offer the lowest rendezvous cost. When the network density and the number of high duty-cycled nodes increase, the probability of such a selection decreases. By considering both rendezvous and communication cost together, we see that EoR-ETC produces 100% optimal routing.

Now we run full simulations for tests T1-T7. Each leave node generates a packet every four cycles at a random time within a cycle. Fig. 3 shows the average end-to-end packet delay of each protocol. While the delay of CTP-ETX decreases slowly when the network density increases, graphs of ORW-EDC and EoR-ETC decrease significantly. This is due to the fact that when the network density increases, the two opportunistic routing protocols exploit a higher number of candidates to forward packets quickly. The result of EoR is better than that of ORW because EoR exploits high duty cycled forwarders to reduce the rendezvous cost and good links to reduce the communication while ORW focuses only on link quality. Fig. 4 helps explain the above result. EoR-ETC achieves the least rendezvous cost which is significant lower than ORW-EDC and much lower compared to CTP-ETX. The gap between graphs of EoR with ORW and CTP increases when the number of high duty-cycled nodes increases. In tests T5, T6, and T7, the network density remains the same but the number of high duty-cycled nodes increases. We can observe another point from results which is that ORW does not benefit much from the increase of high duty cycled nodes. On the contrary, the delay and rendezvous cost of EoR continue decreasing significantly. The reason is that with more high duty-cycled nodes, a node in EoR-ETC can achieve a higher FAR. As a result, its rendezvous cost can be reduced considerably.

Fig. 5 illustrates the average one-hop communication cost among various tests. CTP achieves the lowest communication cost as the protocol selects only one forwarder which offers the least number of transmissions (i.e. ETX). Its communication cost decreases over the tests as a node has more options of good links when the density increases. In case of ORW and EoR, the communication cost increases when the network density increases. Figure 6 explains for this phenomenon. In higher density network, ORW and EoR tends to add more forwarding candidates, thus average link quality may be reduced. The graph of EoR is slightly higher than that of ORW because EoR considers in balance both rendezvous cost and communication cost, instead of only considering link parameters as occurs with ORW. Comparing the trend

TABLE II

SUBOPTIMAL RATIO OF ROUTING PROTOCOLS

Test case	Test ID	ORW-EDC	CTP-ETX	EoR-ETC
$200 - 20\% - 10\%$	T1	38%	22.4%	0%
$300 - 20\% - 10\%$	T2	41.7%	24.5%	0%
$400 - 20\% - 10\%$	T3	46.2%	27.2%	0%
$500 - 20\% - 10\%$	T4	48.9%	30.06%	0%
$600 - 20\% - 10\%$	T5	54.25%	31.89%	0%
$600 - 25\% - 15\%$	T6	58.62%	35.25%	0%
$600 - 30\% - 20\%$	T7	63.46%	37.41%	0%

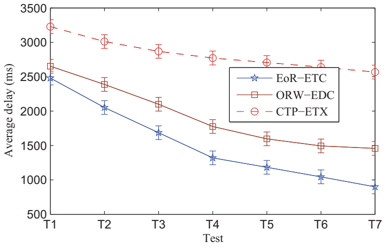

Fig. 3. Average end-to-end packet delay

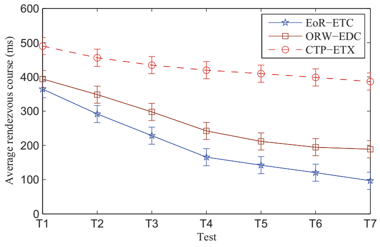

Fig. 4. Average one-hop rendezvous cost

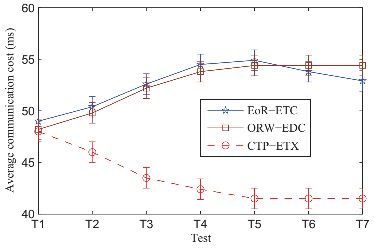

Fig. 5. Average per-hop communication cost

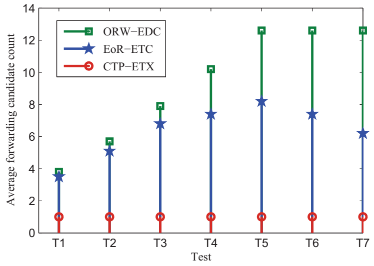

Fig. 6. Average forwarding candidate count

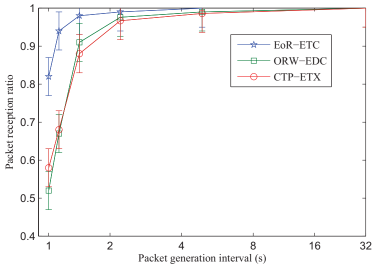

Fig. 7. Packet reception ratio under various traffic loads

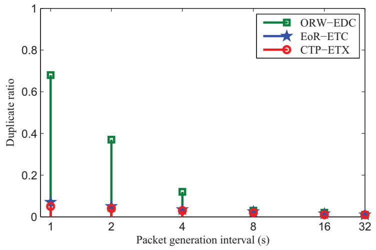

Fig. 8. Duplicate ratio under various traffic loads

of graphs in Figures 3, 4, and 5, we can see that rendezvous cost is the dominant factor in transmission cost. Results of the tests T5, T6, and T7 in Figures 5 and 6 shows an interesting characteristic of EoR is that with a higher number of high duty cycled nodes and having great enough FAR value, a node in EoR tends to select a smaller number of forwarding candidates and the communication cost of EoR also decreases. The reason is that with more choices of high duty-cycled neighbors, a node can achieve a low rendezvous cost with a smaller number of forwarding candidates. When a node achieves a low rendezvous cost, it has a tendency to select nodes with higher link quality to reduce the communication cost and total transmission cost. Communication costs of ORW in the last three tests are similar. Compare to EoR, ORW is more greedy as the number of forwarding candidates in ORW increases quickly and at a much higher rate than EoR, as shown in Fig. 6. This leads to a scalability problem as sensors are resource constraint devices. In EoR, because a node is aware of its expected rendezvous cost, it may not add more forwarding candidates when its expected rendezvous cost is low enough.

D. Impact of Traffic Load

We now evaluate the performance of EoR under various traffic loads. We conduct experiments with 40 Telosb nodes $(40 - 20\% - 20\%)$ in an indoor environment. Each node generates a packet every 1 to 32 cycles. Fig. 7 presents the result of packet reception ratio. The ratio of all protocols decreases when traffic load is heavier due to a higher collision probability. However, ORW and CTP show lower performance due to their inefficient channel utilization. In CTP, a sender occupies the channel during its long waiting period until its designated forwarder wakes up. This suppresses transmissions of other neighbor nodes and incurs high collision in high traffic load. Figure 8 presents the result of duplicate ratio under various traffic loads. The duplicate ratio of ORW increases quickly when the traffic load increases. This is because ORW anycasts data packets directly to neighbor nodes while its duplicate suppression is based on overhearing only. As a result, in high traffic loads, a sender cannot control which forwarders have forwarded its packets. The detailed arguments for this phenomenon can be found in Section IV.B. The duplicate problem degrades the channel utilization and causes packet loss. This experiment reveals the scalability limitation of ORW. In all cases, EoR achieves the highest packet reception ratio. The reasons are 1) EoR solves the duplicate problem of ORW, 2) EoR forwards packets quickly by selecting routes with the least transmission cost, thus improving channel utilization and reducing packet collision. For this reason, the duplicate ratio of EoR is as similar as the deterministic routing protocol (i.e., CTP).

Figure 9 reports the result of the packet transmission cost, indicating both packet transmission latency and radio-on time of sender (energy consumption). We also conduct an experiment which all Telosb nodes operate at a low duty cycle (i.e., $40 - 0\% - 0\%$). In high data rate scenarios, ORW witnesses a bad duplicate problem which introduces a higher packet transmission cost due to a high number of retransmissions, duplicate transmissions, and collisions. The packet transmission cost of CTP is high in all traffic loads due to a high rendezvous cost. EoR achieves the least cost even in high traffic loads. The packet transmission cost of all protocols in the test of $40-20\%-20\%$ is lower than that in the test of $40-0\%-0\%$ because packets can be forwarded faster when there are high duty-cycled nodes. However, the gap between the two graphs of EoR is greater than others as EoR actively exploits high duty-cycled nodes to reduce its rendezvous cost. In case of $40-0\%-0\%$, EoR achieves better energy efficiency and packet transmission latency compared to ORW in high data rates. This reflects the efficiency of EoR's deterministic forwarding and coordination mechanisms. When the packet generation interval is greater than 8s, the performance of EoR is slightly lower than ORW. The reason is that EoR employs the preamble acknowledgment which is more expensive than the direct data packet transmission of ORW. The gap between the graphs of EoR and other protocols in high data rates is larger than in low data rates. We conclude that EoR achieves a higher improvement in high data rate scenarios.

Figure 10 presents the cost breakdown in the experiment of $40 - 20\% - 20\%$ with a packet generation interval of 32 s. The rendezvous cost of ORW and EoR is reduced remarkably compared to that of CTP, with a tradeoff of a slight increase in communication cost. The figure shows clearly that rendezvous cost is the dominant factor. Therefore, to achieve high energy efficiency and low packet latency, a routing protocol should essentially consider rendezvous cost. As a result, EoR achieves the lowest rendezvous cost.

The distribution of the average one-hop packet transmission delay is given in Fig. 11. EoR and ORW have a higher number of nodes with a low packet delay compared to CTP. The explainations are given in the discussion for Fig. 9. An interesting point is that the three protocols have the similar number of nodes with the delay lower than 80 ms. Those nodes are sink neighbor nodes which may have only one parent node, the sink node. This is due to good paths towards the sink and the sink is always active.

E. Routing Update

Following the design of EoR, a node advertises its routing metric each time it has packets to send without incurring extra communication overhead. We now evaluate the average interval of the overlapping wakeup pattern update. Our calculation is based the worst case of the clock drift of sensors (i.e., 40 ppm). The wakeup pattern of a node may change up to 2.4 ms per minute. Compared to our update policy (i.e., updating the metric only if changes are significant), EoR may require to update the wakeup pattern of a neighbor node only after an interval of more than an hour. We run the above tests with a packet generation of 1 minute for 3 days in indoor environment and report the average update interval of nodes. The results show that the average interval of the 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. Note that in EoR, a small change in an individual node has a low impact to the overall performance.

VI. RELATED WORKS

We discuss related work in this section. Existing routing metrics in WSNs vary from distance-based to link-based, and energy-based (i.e., residual energy, energy balancing [18]). Among those metrics, link-based metric (i.e., ETX [13]) is one of the most popular metrics, and it has been widely used in many routing protocols such as CTP [10]. Besides traditional deterministic routing, opportunistic routing (i.e., ExOR and MORE [19]) was originally proposed to improve throughput in dynamic wireless mesh networks. GeRaF [19] and CMAC [20] proposed to use geographic information, however, geographic information may not be always feasible for resource-constrained WSNs. EAX and EATT [19] are adaptations of single-path link-based metrics (i.e., ETX) for opportunistic routing. Dynamic Switch-based Forwarding (DSF) [21] selects forwarders based on the wakeup schedule and different metrics such as reliability and energy consumption. However, DSF is designed for synchronized networks which may incur high control overhead. Several theoretical studies on time-independent protocols [22], [23] have been investigated, but there is no practical solution with real implementation. Recently, Ghadimi et al. [11] proposed ORW, a practical routing protocol for duty-cycled WSNs, and they proposed a new metric – EDC which basically adapts ETX to opportunistic routing in duty-cycled WSNs. Although ORW has been proved to work efficiently in low duty-cycled WSNs, this paper shows that without considering rendezvous cost properly, ORW will suffer from many drawbacks when applied to heterogeneous duty-cycled WSNs.

With the ability of energy harvesting, sensor nodes may have different wakeup patterns compared to traditional battery-powered sensor nodes. In energy harvesting WSNs, nodes with high effective energy may wake up periodically and

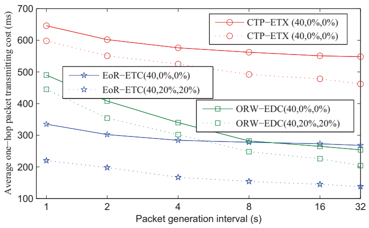

Fig. 9. Average packet transmission cost under various traffic load

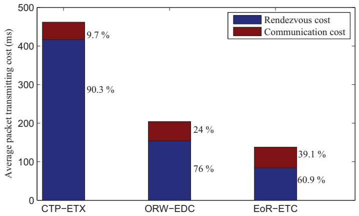

Fig. 10. Ratio between rendezvous cost and communication cost

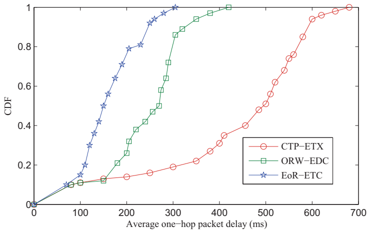

Fig. 11. The distribution of average one-hop packet delay

remain awake fully to listen for a significant time period which depends on their duty cycle [3]. In traditional WSNs, a node wakes up fully only if it detects energy on the channel by clear channel accessment (CCA) [2]. There are two main trends in computing the optimal duty cycle for a single energy harvesting node based on its energy availability. The first one [6] proposes to adapt duty cycle over time between thresholds of the minimum and maximum values. The second trend proposes to enable a node to operate at a stable duty cycle over time such that the variance of duty cycle of a single node is minimized [24], [25]. In this paper, we do not investigate in power management, instead we focus on routing, thus for simplicity, we assume a node operates at a stable periodic duty cycle (i.e., D %). While our assumption falls into the later trend, it is also reasonable for the former as D can be computed as the average value between the maximum and minimum values.

VII. CONCLUSION

This paper investigates the limitations of the state-of-the-art routing protocols by analyzeing packet transmission cost in heterogenous duty-cycled WSNs. We then introduce a novel routing metric, Expected Transmission Cost (ETC), and design an ETC-based EoR routing protocol. 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 a fair comparison with CTP and ORW, this paper implements EoR for multipoint-to-point traffic only. For our future work, we will implement EoR for point-to-multipoint and point-to-point cases by adding extra header fields, and further evaluate its performance.

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