Residual Time Aware Forwarding for Randomly 
Duty-Cycled Wireless Sensor Networks

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Abstract—This paper studies data forwarding in wireless sensor networks (WSNs) where sensor nodes are randomly duty-cycled to save energy. The duty-cycling operation requires the data delivery strategy to be more adaptive for the dynamics caused by the uncertainty of node working schedules. However, the existing maximum-advance routing scheme, at each step the forwarding node selects the node closest to the destination as its next hop forwarder among neighbors, performs poorly in randomly duty-cycled WSNs.

In this paper, we propose a new residual time aware (RTA) routing metric for randomly duty-cycled WSNs. RTA is designed to be responsive to the dynamics caused by duty-cycling operation. We also present a residual time aware forwarding (RTAF) strategy using this metric for randomly duty-cycled WSNs. Simulation results demonstrate that our proposed RTAF strategy reduces the retransmissions and delivery delay introduced by the duty-cycling operation. Therefore, it is shown that RTAF increases the data delivery ratio and average advance per hop, and significantly reduces the end-to-end delivery latency.

Keywords—geographic routing; contention-based forwarding; duty-cycled wireless sensor network;

I. INTRODUCTION

Wireless sensor networks (WSNs) used for monitoring and surveillance purposes are always composed of a large number of tiny sensors that are capable of sensing, computation and wireless communication. These sensors usually rely on limited non-rechargeable battery power, and are expected to last over several months or years. Therefore, extending network lifetime becomes one of the primary design goals in WSNs [1].

To conserve sensors’ energy and consequently extend the WSNs lifetime, one common approach is to dynamically schedule each sensor’s wake/sleep cycle (or duty cycle) [2]. The radio will be turned off when it is not actively sending and receiving, and it will be turned on when communication is expected [3].

The duty-cycling operation in WSNs can be loosely categorized into two main types: 1) random duty-cycling, where sensors are turned on and off in a random fashion independent of each other; and 2) coordinated duty-cycling, where sensors coordinate via communication and information exchange to collectively achieve an on/off (or wake/sleep) schedule followed by multiple sensors. For random duty-cycling, its advantage lies in its simplicity and without any additional communication overhead for coordination among neighbors. However, randomly turning off the wireless radio inevitably results in uncertain connectivity of the network. The price randomly duty-cycled WSNs pay is the potential routing performance degradation, which is caused by the duty-cycle-related uncertainty. One way to alleviate this negative effect is to deploy sensors in large quantities [4].

Geographic routing is considered to be an efficient and scalable data delivery scheme and is quite commonly adopted for information delivery in large scale WSNs. The basic idea for geographic routing is greedily forwarding data packets to the neighbor geographically closest to the destination [5]. Early studies [6] [7] assume all nodes maintain neighbor tables which store information (such as location, link quality) of all radio-hop neighbors. The next-hop forwarder is determined as a priori by the forwarding node.

However, several recent studies [8] [9] have stressed that the realistic link conditions in wireless networks are highly unreliable and change with time due to many factors such as interference, attenuation, and fading. In this case, these priori forwarding methods will perform poorly in realistic conditions as it may forward packets on lossy links. The unreliable links may cause the drastic reduction of packet delivery rate and increase energy consumption of sensor nodes if retransmission mechanism is adopted. Thus, in order to adapt the lossy links, on demand contention-based forwarding algorithms are proposed, e.g., GeRaF [10], IGF [11], BLR [12], CBF [13] and BOSS [14], where neither topological knowledge nor routing tables are needed at each node and the selection of the next hop forwarder is done
as a *posteriori*. In these algorithms, the next hop forwarder is chosen based on the contention among neighbors. The contention process is always achieved by calculating a routing metric for assigning different time slots to coordinate between neighbors (timer-based contention) and the routing metric is critical important to contention-based forwarding, since it determines the relay priority assignment and the next hop forwarder selection.

In this work, we address the problem of geographic routing in randomly duty-cycled WSNs over unreliable wireless links. Specifically, the contributions of our work can be summarized as follows: 1) We show that the existing routing metrics are not appropriate for randomly duty-cycled WSNs through analysis and simulation. 2) We propose a new *residual time* aware (RTA) routing metric for randomly duty-cycled WSNs which is more responsive to the dynamics resulting from the uncertainty of node working schedules. 3) We present a *residual time aware forwarding* (RTAF) strategy using this metric for randomly duty-cycled WSNs, which reduces the retransmissions and delay introduced by the duty-cycling operation.

The remainder of this paper is organized as following. In Section II, we briefly review related work. The model and assumptions are introduced in Section III. In Section IV, we present the detailed design description of the proposed RTA routing metric and the RTAF strategy using this metric. In Section V, we conduct detailed simulations to evaluate the performance of RTAF. Finally, Section VI concludes this paper.

II. Related Works

**Routing metric**: Greedy geographic routing is mainly characterized by the routing metrics applied to each forwarding step, which plays a key role in the routing decision. There has been intense research [15] [16] [17] on choosing routing metrics for different applications and network assumptions, e.g., considering the energy balancing [6] and link quality [7]. The authors in [18] propose a general framework for efficient geographic routing, called normalized advance (NADV). NADV framework can meet different performance objectives, such as packet error rate, link delay, and energy consumption. Different from the earlier works, we propose a new metric for randomly duty-cycled WSNs to mitigate the impact of duty-cycling operation.

**Randomly duty-cycled WSNs**: There have been numerous studies and results on optimal sleep scheduling for coordinated duty-cycled WSNs, e.g., [19] [20] [21]. However, to the best of our knowledge, there are few works addressing the data delivery in randomly duty-cycled WSNs, where sensors turn themselves on and off randomly. The authors in [22] provide a solid analysis of bounds of the delay for sending data from a node to a sink in randomly duty-cycled WSNs, prove that any message generated by a sensor will reach the sink in a time proportional to the distance between the sensor and the sink, which depends on the network parameters (node density, connectivity range, duration of active and sleeping periods). Different from the assumption in this paper, they assume the forwarding node will remain active until all their neighbors have received the data packet. While we adopt the contention-based forwarding, as long as one neighbor who can provide positive advance successfully receives the data packet, the forwarding node finishes its task. In [4], the authors propose the coverage intensity, and analyze its properties over time as functions of individual sensor on/off schedules in randomly duty-cycled WSNs. The author in [23] shows that the randomly duty-cycled network is asymptotically connected with probability one when satisfying certain conditions based on the result presented in [24]. Both centralized and distributed stochastic routing algorithms for low duty-cycled networks are presented. However, these methods require nodes periodically exchanging HELLO (or beacon message) packet when they are awake. Like ExOR [25], every node maintains a list of potential forwarders, which is attached in the data packet. Only the neighbors included in the list will contend for taking the forwarding task. Different from this approach, we adopt a beacon-less and simple scheme, which does not require exchanging HELLO packet periodically.

III. Model and Assumptions

A. System Model

We assume sensor nodes are homogeneous, energy-constraint, and static once deployed. Each sensor knows its own geographical location; the source node knows where the destination is. Sensors follow an independent random wake/sleep schedule, where each sensor dynamically turns on and off the radio in turn independent of other sensors. We assume that in each cycle the sleep (off) duration $t_s$ is uniformly distributed within $[M_s - V_s, M_s + V_s]$ and the wake (on) duration $t_a$ is uniformly distributed within $[M_a - V_a, M_a + V_a]$, where $M_s$ and $M_a$ are the mean of each. Each node only knows the current wake/sleep schedule, e.g., the residual time when in awake state. We assume that the duty-cycling operation is completely independent of the data transmission for the following reasons: 1) simplicity; 2) connectivity, avoiding sensor nodes being “synchronized” by data transmission; 3) energy efficiency, avoiding sensor nodes always keeping awake for data transmission (contending for taking the forwarding task). We assume the wireless link is unreliable and the packet reception ratio (PRR) of a link is dependent of distance within the physical radio range. We also assume the node density is sufficiently high so that geographic routing is possible for end-to-end data delivery.
B. Packet Delivery Scheme

In this paper, the basic data delivery strategy we adopt is the forwarding scheme described in BOSS [14], a three way handshake protocol. The Data packet being forwarded is sent first and waits for responses for a maximum time of $T_{max}$ seconds, only the neighbor who successfully receives it and provides positive advance\(^2\) contends for becoming the next hop forwarder. Each contender will start a timer whose value depends on a metric. When the timer expires, it sends a Response message to the forwarding node. This Response message will suppress other neighbors’ contention. The forwarding node then broadcasts a Selection message to announce the contention result. Each neighbor receiving the Selection message will immediately cancel its timer and delete the stored Data except for the one selected by the forwarding node. Finally, the new forwarding node starts again the protocol by broadcasting a new Data packet.

IV. RESIDUAL TIME AWARE FORWARDING DESCRIPTION

In this section, we first show that existing routing metrics are not suitable for randomly duty-cycled WSNs and based on the observation, we present a new RTA routing metric for randomly duty-cycled WSNs which is more adaptive to the dynamics resulting from the uncertainty of node working schedules. We then present the design description of RTAF strategy using this metric.

A. Limitation of Existing Routing Metric

![Figure 1](image)

Figure 1. An example scenario for data delivery in randomly duty-cycled WSNs, among A’s neighbors that have received the Data packet sent from A, node B provides maximum advance. However, B has limited residual time, which causes the failure of the three way handshake transmissions in contention-based forwarding between B and D.

Consider an example scenario as shown in Figure 1, where forwarding node A broadcasts a Data packet to neighbors. Node B and C successfully receive the Data packet and provide positive advances for the packet, thus they store the Data and start timers to contend for taking the forwarding responsibility. In this case, since the contenders are those who hold the Data, the routing metric in BOSS [14] only considers the advance provided by each contender (maximum-advance metric). In Figure 1, B wins the contention because it can provide more advance than C.

\(^2\)Advance in geographic routing refers to the decreased geographical distance between the data packet and its destination.

![Figure 2](image)

Figure 2. An example of the random node working schedules corresponding to Fig. 1, sensors follow an independent random sleep (on/off) schedule.

However, the maximum-advance metric may incur performance degradation in randomly duty-cycled WSNs, such as end-to-end delivery delay and energy efficiency degradation. Figure 2 illustrates an example of the random node working schedules corresponding to Figure 1. As a winner in the next hop forwarder contention, B broadcasts the Data to discover its neighborhood. Unfortunately, B has to turn off the radio to conserve energy before getting a Response message, for its residual time is limited. Both B and C drop the Data packet since neither of them receives a Selection message. Finally, B has to retransmit the Data packet when in the next awake state. In fact, it would be better if C takes the forwarding responsibility instead of B since its residual time is longer.

We observe that the maximum-advance routing metric is not suitable for randomly duty-cycled WSNs and the next hop selection of a forwarding node will significantly influence its subsequent forwarding process. Other routing metrics in [15], [16], [17] etc. are also not suitable for the random duty-cycling operation is not taken into consideration. Thus, an appropriate routing metric is needed in the contention phase to help the forwarding node make a foresighted selection. To avoid the potential transmission failures, the new metric should be aware of the residual time of both the forwarding node and the contender itself, where the contention timer’s value as well as its maximum value should be set dynamically.

B. Residual Time Aware Routing Metric

In this subsection, we present the design description of the proposed RTA routing metric for randomly duty-cycled WSNs. RTA metric design includes two key issues: 1) dynamically setting the maximum value of a timer; and 2) assigning the relay priority for each contender.

For node $i$, let $T_{r(i)}$ denote its current residual time keeping awake state, $T_{max}$ denote the maximum value of its timer when contending to take the forwarding task; $T_{set}$ denote the initial value of this timer; $R$ denote the radio range of a node. $T_{max}$, a predefined value, is the upper bound for setting the maximum value of a contention timer.
After the forwarding node broadcasting a Data packet, it waits for responses for an upper bound time of $T_{\text{max}}$. Let $ADV(i,j)$, defined as (1), denote the advance provided by node $j$ when forwarding a Data packet sent from node $i$.

$$ADV(i,j) = \text{Dist}(i, \text{dest}) - \text{Dist}(j, \text{dest}) \quad (1)$$

where $\text{dest}$ is the destination’s position, $\text{Dist}(a,b)$ represents the Euclidean distance between the positions of $a$ and $b$.

![Figure 3. An example of the random node working schedules, the forwarding node $i$ and its next hop candidate $j$](image)

1) **The maximum value of a timer**: Instead of setting the maximum value of a timer a predefined fixed value, in randomly duty-cycled WSNs, we take the forwarding node’s residual time into consideration. To avoid the three way handshake transmission failures, the Response message should be replied before the forwarding node turning off its radio. As shown in Figure 3, when forwarding node $i$ broadcasts a Data packet to discover the next hop forwarder, its current residual time $T_r(i)$ is also piggybacked on the Data packet. Suppose node $j$ successfully receives the Data and provides positive advance for the packet toward the destination, it will check whether $T_r(i)$ is shorter than $T_{\text{max}}$. If it is, its timer’s maximum value is set $T_{\text{max}}^{(j)}$, otherwise, $T_{\text{max}}^{(j)}$ is set $T_{\text{max}}^r$ defined as (2).

$$T_{\text{max}}^{(j)} = \min\{T_{\text{max}}^r, T_r(i)\} \quad (2)$$

However, the smaller the maximum value of a timer, the higher the collisions produced by the neighbors sending Response messages because timers expire almost concurrently.

2) **Priority assignment**: In contention-based forwarding, the assigned initial value for a contention timer reflects the priority of the contender. The earlier time slot a timer assigns, the higher its priority. For the WSNs in which all nodes are awake during routing, the node which has maximum advance assigning the earliest time slot becomes the next hop contender. However, in randomly duty-cycled WSNs, the residual time of a contender should be taken into account, which will significantly influence its subsequent forwarding process.

For a contender $j$, the timer’s value $T_{\text{set}}^{(j)}$ is defined as (3),

$$T_{\text{set}}^{(j)} = [1 - \lambda \cdot \frac{ADV(i,j)}{R}] \cdot T_{\text{max}} + \text{random}(0, \tau) \quad (3)$$

where $\tau$ is a small parameter, $\text{random}(0, \tau)$ is a function obtaining a random value between 0 and $\tau$. $\lambda$ is a modification coefficient by taking the residual time into consideration and defined as (4),

$$\lambda = \min\left\{ \frac{T_r^{(j)}}{(1 - \frac{ADV(i,j)}{R})T_{\text{max}}^{(j)} + T_{\text{max}}}, 1 \right\} \quad (4)$$

$(1 - \frac{ADV(i,j)}{R}) \cdot T_{\text{max}}^{(j)}$ is the roughly estimated contention time needed by this contender and $T_{\text{max}}^r$ is the reserved time in advance for its subsequent forwarding process. From (3) and (4), we can see that the contender providing more advance at the same time having longer residual time will be assigned higher priority. If two contenders have the same $\lambda$, the contender which provides more advance will be assigned higher priority.

C. Residual Time Aware Forwarding

In this subsection, we present the RTAF strategy using the routing metric introduced above for randomly duty-cycled WSNs. Nodes involved in RTAF mainly play two roles: 1) as a forwarding node; and 2) as a contender.

For a forwarding node $i$, it first broadcasts the Data packet and waits for Responses for a maximum time of $\min\{T_{\text{max}}, T_r(i)\}$ seconds. If receiving no Response, it will rebroadcast the Data packet and its neighbors start again the contention process. The Data retransmission process can be tried up to $K_1$ times. If receiving a Response or more, it will send a Selection message to announce the contention result. This message contains the identifier of the contender selected by the forwarding node. Then, it waits for the confirmation of the Selection message. If failed to receive an ACK (the Data broadcasted by its next hop forwarder serves as an implicit ACK), it will resend the Selection message up to a maximum number of $K_2$ times. If overhearing the ACK, it will go back to the monitoring state and wait to receive a Data packet.

For a contender, once receiving a Data packet, it starts a contention timer whose value depends on our proposed RTA routing metric. When the timer expires, it sends a Response message to the forwarding node and waits for a Selection message sent from the forwarding node. The contender that wins the competition will take the forwarding task as a new forwarder. The Response or Selection message will suppress other neighbors’ contention, i.e., for contenders except for the one selected by the forwarding node, if overhearing a Response or Selection, they will immediately cancel contention timers, delete the stored Data and go back to the monitoring state.

It is worth noting that due to the duty-cycling operation, the node in any state could enter into the sleep mode. Data delivery in RTAF is best-effort; the end-to-end delivery is not guaranteed. The retransmission process is tried limited times at each step. In the worst situation (block situation, e.g., all neighbors are asleep), if exceeding the retransmission...
limit, the Data packet will be dropped (or recovery routing mechanism to circumvent the “hole” is applied; although the bypassing “hole” mechanism is not the focus in this paper, RTAF can adopt the similar recovery mechanism presented in [14]).

V. SIMULATION

In this section, we conduct simulations to evaluate the performance of RTAF using ns-2 [26] by comparing it with MAF\textsuperscript{3}. All the results have been averaged over 100 Monte-Carlo runs.

A. Simulation settings

In the implementation of our simulation, sensor nodes are deployed in a 200m x 200m field. A sink node is positioned at the bottom left (0m, 0m) of the field, and the source node is located at the top right (200m, 200m) of the field. A Data packet generated by the source node is forwarded toward the sink over multiple hops. The key communication parameters of nodes generally applies to IEEE 802.15.4. The sensor transmission range r is taken 40m. The length of a Data packet is 50 bytes. The average wake/sleep schedule period is set 5s, node duty cycle setting (the average fraction of time that a sensor is in an awake state in one wake/sleep schedule) is listed in Table I. We set \( K_1 = 5 \) and \( K_2 = 0 \). The retransmission process can be tried up to 5 times at each step. If exceeding the retransmission limit, the Data packet will be dropped and the end-to-end transmission was marked as a failed round. Only the successful end-to-end transmissions are included in the statistical results.

For simplicity and without loss of generalization for wireless lossy link, we use a simplified link quality model with respect to distance defined as (5).

\[
P_{\text{RR}}(d) = \begin{cases} 
1 & d < L_{T_s} \\
\frac{L_{T_s} - d}{L_{T_s} - L_{T_s}} & L_{T_s} \leq d \leq L_{T_s} \\
0 & d > L_{T_s}
\end{cases} \tag{5}
\]

\( L_{T_s} \) is the initial position of the transitional region, \( L_{T_e} \) is the end position of the transitional region, and \( d \) is the distance between the sender and receiver. According to [28], \( L_{T_s} \) and \( L_{T_e} \) are set 10m and 40m, respectively.

B. Evaluation metrics

We select six evaluation metrics as follows:

* **Advance Per Hop:** This metric measures the effectiveness of a geographic routing algorithm. It is the ratio of the sum of one-hop advances to the number of hops.

* **End-to-End Hops:** This metric measures the number of hops needed for an end-to-end transmission, i.e., data transmission times. The cost of a transmission consists of the sending cost of the sender, and the receiving cost of one-hop neighbors. Given fixed number of neighbors, the transmission cost is proportional to the sending cost. And the cost of sending a data packet is much larger than that sending a control message. Thus, this metric actually reflects the end-to-end energy efficiency of a routing algorithm.

* **End-to-End Delivery Delay:** This metric measures how long it takes for a data packet to arrive at the sink from the source node.

* **Duty-Cycling Introduced Delay Ratio:** This metric measures the delayed time caused by the duty-cycling operation for an end-to-end transmission.

* **Duty-Cycling Introduced Delay Ratio:** This is the ratio of the Duty-Cycling Introduced Delay to the End-to-End Delivery Delay. It represents the influence degree of the duty-cycling operation on the end-to-end delivery delay.

* **Data Delivery Ratio:** This is the ratio of the successful end-to-end transmissions to the total number of tests.

C. Impact of node duty cycle

In this comparison, 400 sensor nodes are uniformly placed in the field, forming a two dimensional grid. We examine the performance difference between RTAF and MAF under different node duty cycles. In Figure 4, two groups of comparison results are provided by setting \( T'_{\text{max}} \) (the upper bound of the contention timer) 0.5s and 1s, respectively. We do not provide the results when node duty cycle is set 10% and \( T''_{\text{max}} \) is set 1s because there is no successful end-to-end transmission for MAF, i.e., the data delivery ratio is zero.

Figure 4(a) illustrates the changes of the average advance per hop of RTAF and MAF while increasing the node duty cycle. The figure clearly shows that the average advance per hop increases with increasing the node duty cycle from 10% to 35% for both strategies. The reason is that the larger the node duty cycle, the more the neighbors can provide positive advances and consequently the larger the average advance per hop. However, we can see that on average RTAF provides about 10% and 22% improvements over MAF when \( T'_{\text{max}} = 0.5s \) and \( T''_{\text{max}} = 1.0s \), respectively. We also observe that

<table>
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<th>( M_s ) (s)</th>
<th>( M_a ) (s)</th>
<th>( V_s ) (s)</th>
<th>( V_a ) (s)</th>
<th>Duty Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>0.5</td>
<td>2.25</td>
<td>0.25</td>
<td>10%</td>
</tr>
<tr>
<td>4.25</td>
<td>0.75</td>
<td>2.125</td>
<td>0.375</td>
<td>15%</td>
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<tr>
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<td>1</td>
<td>2</td>
<td>0.5</td>
<td>20%</td>
</tr>
<tr>
<td>3.75</td>
<td>1.25</td>
<td>1.875</td>
<td>0.625</td>
<td>25%</td>
</tr>
<tr>
<td>3.5</td>
<td>1.5</td>
<td>1.75</td>
<td>0.75</td>
<td>30%</td>
</tr>
<tr>
<td>3.25</td>
<td>1.75</td>
<td>1.625</td>
<td>0.875</td>
<td>35%</td>
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</tbody>
</table>

\textsuperscript{3}In this paper, we refer to the routing strategy that adopts the same packet delivery scheme as RTAF but using the maximum-advance metric as maximum-advance forwarding (MAF). Since the contenders in our packet delivery scheme are those who have successfully received the Data and provide positive advances for the packet, in this case, the maximum-advance metric is adopted in the WSNs without duty-cycling operation [14]. In fact, the maximum-advance metric is also essential for many geographic routing algorithms, e.g., GPSR [5], TPGF [27].
the advantages of RTAF are more obvious when $T'_{max} = 1.0s$. This is because in our test $M_a$ is ranged from 0.5s to 1.75s, the possibility of failure of the three way handshake transmissions is larger than that when $T'_{max} = 0.5s$.

Figure 4(b) shows the average end-to-end hops for RTAF and MAF as the node duty cycle changes. In this test, it is seen that RTAF behaves a little better than MAF. This is partly because that we only consider the successful end-to-end transmissions of MAF. If transmission failures are accounted, it can be predicted that RTAF will show more obvious advantages over MAF. From this figure, we can see that the duty-cycling operation dramatically affects the end-to-end hops, the average end-to-end hops could be ranged from 30 to 12 with the increase of the node duty cycle.

Figure 4(c) reports the end-to-end delivery delay under different node duty cycles. Although transmission failures of both strategies are not accounted, RTAF shows obvious superiority to MAF. Averagely, RTAF can provide up to 40% and 48% improvements over MAF when $T'_{max} = 0.5s$ and $T'_{max} = 1.0s$, respectively.

Figure 4(d) and Figure 4(e) show the duty-cycling introduced delay and its proportion to the end-to-end delay for both forwarding strategies. From Figure 4(d), we observe that the duty-cycling operation has significant impact on the delivery delay as the node duty cycle increasing. Compared with MAF, RTAF is less influenced by the duty-cycling operation, especially at higher node duty cycles. For example, when node duty cycle is 30%, there is no duty-cycling introduced delay at all. As shown in Figure 4(e), the duty-cycling introduced delay ratio of RTAF decreases more rapidly, dropped from 83% to 0% with the increase of the node duty cycle. While for MAF, the ratio does not change much. This confirms that RTAF has lowered the effect of the performance degradation caused by the duty-cycling operation. When the node duty cycle is higher, the improvement is larger.

Figure 4(f) plots the data delivery ratio for both strategies under different node duty cycles. As the node duty cycle increases, the data delivery ratio for both strategies increases as well. At lower node duty cycles, RTAF has higher delivery ratio than MAF. For instance, when node duty cycle is 10%, RTAF can provide up to 50% improvements over MAF.

D. Impact of node density

In this test, we evaluate the performance of RTAF and MAF under different node densities by varying the the number of nodes placed in the field from 200 to 400. The node duty cycle is set 15% and $T'_{max}$ is set 0.5s. The random topologies are all generated by the setdest tool in ns-2. Figure 5 shows the performance improvement when we vary the node densities.

Figure 5(a) is the result of the average advance per hop of RTAF and MAF at increasing node densities. Similar to Figure 4(a), with the increase of the node density, more contenders participate in contention for the next hop forwarder, thus the average advance per hop increases. RTAF provides up to 13% improvement over MAF on average. Due to the random topologies, the improvement ranges from 5%
to 20%.

Figure 5(b) compares the end-to-end hops performance improvement of RTAF against MAF. It is shown that RTAF has better performance than MAF, although only the successful end-to-end transmissions of both strategies are accounted.

Figure 5(c) depicts the effects of node density on the end-to-end delivery delay. We can see that RTAF yields a satisfactory performance compared with MAF, can provide 34% less delivery latency on average. One of the main advantages of RTAF over MAF lies in the decreased end-to-end delivery delay.

Figure 5(d) and Figure 5(e) show the duty-cycling introduced delay and its proportion to the end-to-end delay under different node densities. It shows the reduction of the effect of duty-cycling operation on delivery delay is quite obvious.

Figure 5(f) depicts the data delivery ratio for both strategies under different node densities. It is shown that 23% or more improvement on average in the data delivery ratio is obtained by adopting the RTAF.

From Figure 4 and Figure 5, we can see that all the performances are improved with increasing the node duty cycle or node density for both strategies. Anyway, RTAF shows more or less advantages over MAF. In randomly duty-cycled WSNs, the data delivery is inevitably influenced by the duty-cycling operation. RTAF is designed to reduce the effects of the performance degradation caused by the duty-cycling operation, such as retransmissions, delay introduced by duty-cycling. These results above suggest that RTAF is superior to MAF in the presence of all evaluation metrics by lowering such negative effects.

VI. CONCLUSION

In this paper, we proposed a new residual time aware (RTA) routing metric for randomly duty-cycled WSNs, which is more responsive to the dynamics resulting from the uncertainty of nodes’ sleep scheduling. RTA metric dynamically sets the maximum value of a contention timer, assigns the relay priority for each contender based on an overall consideration including the advance and its residual time. We also presented a residual time aware forwarding (RTAF) strategy using this metric for randomly duty-cycled WSNs. RTAF is designed to reduce the effects of the performance degradation caused by the duty-cycling operation. We evaluated the performance of RTAF by comparing it with MAF using ns-2. The results demonstrate that RTAF achieves increasing the average advance per hop, data delivery ratio and consequently end-to-end energy efficiency. More remarkably, on average RTAF provides 40% and 34% less end-to-end delivery latency under different node duty cycles and different node densities, respectively.

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