Contention-based geographic forwarding in asynchronous duty-cycled wireless sensor networks

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SUMMARY

In asynchronous duty-cycled wireless sensor networks, it is desirable that the data forwarding scheme is adaptive to the dynamics caused by the uncertainty of sensor nodes’ working schedules. Contention-based forwarding is designed to adapt to the dynamic environments. In this work, we are interested in the contention-based geographic forwarding (CGF) for two asynchronous duty-cycling (ADC) models, which we refer to as uninterruptible ADC (U-ADC) and interruptible ADC (I-ADC). We propose a new residual time-aware routing metric for CGF in the I-ADC model and present a residual time-aware forwarding scheme using this metric. We evaluate the performance of CGF in both asynchronous duty-cycling models. Simulation results show that CGF in the U-ADC model provides a shorter delivery delay while suffering from a high sender effective duty cycle problem. CGF in the I-ADC model incurs a very long data delivery delay, but it can achieve a good load balancing among nodes. It is also demonstrated that the proposed residual time-aware forwarding scheme lowers the effects of the performance degradation caused by the pure asynchronous duty-cycling operation. Copyright © 2011 John Wiley & Sons, Ltd.

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1. 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].

For the conservation of sensors’ energy and consequently the extension of the network lifetime, scheduling each sensor’s wake/sleep cycle (or duty cycle) [2] has been widely employed in WSNs (usually implemented in the MAC layer). In this approach, when a sensor node is in the sleep mode, the sensor’s processor will be turned off, but a low-power timer or some other triggering mechanism may be running to wake up the sensor at a later time. Therefore, it consumes only a tiny fraction of the energy, compared with that consumed in the active mode. More specifically, a radio will be turned off when it is not actively sending and receiving, and it will be turned on when communication is expected [3].

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The duty-cycling operation in WSNs can be loosely categorized into two main types: (1) synchronous (or 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, and (2) asynchronous (or random) duty cycling, where sensors are turned on and off in a random fashion independent of each other. As to the asynchronous duty cycling, its advantage lies in its simplicity and good scalability, without involving 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 asynchronous duty-cycled WSNs pay is the potential routing performance degradation, which is caused by the duty-cycle-related uncertainty. One straightforward way to alleviate this negative effect is to deploy sensors in large quantities [4].

For asynchronous duty-cycling protocols in the literature, when a sender has data, the sender transmits a long preamble that is at least as long as the sleep period of the receiver [5] or transmits several short preambles constantly before the receiver wakes up [6] because of the lack of duty cycle scheduling knowledge of the receiver. A node without holding data periodically wakes up for a short period to sample the medium, detecting whether there is a packet to receive or not, and goes to sleep if not. If it is the intended receiver, it will stay awake to receive the data and then forward it to the downstream receiver. However, a sender usually waits for a long period before the receiver wakes up. For example, if the duty cycle length is 1 s, that is, nodes wake up every 1 s, a sender needs to wait for 0.5 s to detect the receiver on average [7]. In this case, the sender’s effective duty cycle is about 50%, which is defined as the percentage of time a node has its radio on. Because the power consumption in the listening mode is of the same order of magnitude as in the transmitting mode, the sender’s idle listening incurs much more energy than transmitting the data packet itself. In this work, we refer to this kind of asynchronous duty-cycling operation, where the sender keeps active until finishing the data forwarding, as the uninterrupted asynchronous duty cycling (U-ADC). Correspondingly, if the sender follows its own duty cycle, regardless of whether having data to send or not, we call it as the interruptible asynchronous duty cycling (I-ADC).

In WSNs, the information obtained from sensors will be meaningless without the location information. Therefore, geographical location information of sensors is usually assumed to be available in the literature. 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 [8]. Early studies [9, 10] assumed that all nodes maintain neighbor tables that 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 [11–13] have stressed that the realistic link conditions in wireless networks are highly unreliable and change with time because of many factors such as interference, attenuation, and fading. In this case, these a priori forwarding methods will perform poorly in realistic conditions as it may forward packets on lossy links. The unreliable links may cause drastic reduction of packet delivery rate and increase energy consumption of sensor nodes if retransmission mechanism is adopted.

For adaptation to the lossy links, on demand contention-based geographic forwarding (CGF) algorithms are proposed [14–18], where neither topological knowledge nor routing tables are needed at each node and the selection of the next-hop forwarder is done a posteriori. In these algorithms, the next-hop forwarder is chosen on the basis of the contention among neighbors. The contention process is always achieved by calculating a routing metric for assigning different time slots to coordinate between neighbors, that is, the timer-based contention. Therefore, in contention-based forwarding, the routing metric is critically important because it determines the relay priority assignment and the next-hop forwarder selection. The contention mechanism releases the need to keep neighborhood location information updated, thus avoiding sending beacons periodically. Nodes employing CGF only need to know their own locations and that of the destination. So, CGF has been considered to be robust to frequent topology changes, scalable to large-scale node deployment, and applicable to data-centric applications and resource-constrained networks.

In this work, we focus on CGF in asynchronous duty-cycled WSNs, where the duty-cycling operation is completely independent of each sensor node. We present CGF schemes for two asynchronous duty-cycling models, that is, uninterrupted asynchronous duty cycling (U-ADC) and interruptible
asynchronous duty cycling (I-ADC). We show that the sender suffers from a high effective duty cycle in the U-ADC model. Then, we study CGF in the I-ADC model. We propose a new residual time-aware routing metric, which is more responsive to the dynamics because of the sender’s interruptible duty cycle. The residual time refers to the remaining time of a node keeping awake state in current wake/sleep schedule. Finally, we present a residual time-aware forwarding (RTAF) scheme using this metric for the interruptible asynchronous duty-cycled WSNs. To the best of our knowledge, this is one of the first works on the interruptible asynchronous duty-cycled WSNs.

The remainder of this work is organized as follows. In Section 2, we survey related work. Section 3 presents the network model. Section 4 discusses the CGF for asynchronous duty-cycled WSNs in detail. Simulation results are presented in Section 5. Finally, Section 6 concludes this paper.

2. RELATED WORK

Routing metric:
Greedy geographic forwarding 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 [19–23] on choosing routing metrics for different application scenarios and network assumptions, for example, considering the energy balancing [9] or link quality [10]. The authors in [24] proposed a general framework for efficient geographic routing, called normalized advance. Normalized advance framework can meet different performance objectives, such as packet error rate, link delay, and energy consumption. Advance (or progress, advancement) in geographic routing refers to the decreased geographical distance between the current location of the data packet and its destination. As a new addition to the geographic routing metric design space, a new metric for asynchronous duty-cycled WSNs is proposed to mitigate the impact of interruptible duty-cycling operation.

Synchronous duty-cycled WSNs:
There have been many studies and results on optimal sleep scheduling for synchronous (coordinated) duty-cycled WSNs, in which many duty-cycling MAC protocols have been proposed [25–30]. In synchronized duty-cycled WSNs, neighboring nodes periodically exchange synchronization information with each other to negotiate their wake/sleep schedules, so that data transmission can take place during their common awake time slots. For example, S-MAC [29] presents a synchronous periodic sleeping MAC with fixed duty cycles to reduce the time and energy wasted on idle listening. In S-MAC, nodes periodically wake up and then return to sleep. At the beginning of each awake period, nodes align their wake/sleep schedules by exchanging synchronization and schedule information with its neighbors.

Asynchronous duty-cycled WSNs:
Asynchronous duty-cycling protocols in the MAC layer, for example, B-MAC [5], X-MAC [6], P-MAC [31], and RI-MAC [32], are then proposed to avoid the high overhead of periodic clock synchronization in synchronous duty-cycled WSNs. OC-MAC is proposed in [7] to explore opportunistic cooperation among senders in order to decrease the waiting time and energy consumption of senders. In [33] and [34], the authors provided solutions for end-to-end delivery delay guarantee in low-duty-cycled WSNs, either by increasing duty cycle at individual node or increasing the number and optimizing the placement of sink nodes. The above studies are of the static sleep scheduling protocols. Recently, for adaptation to the network condition changes such as interference at runtime, dynamic duty cycle control scheme is proposed, for example, [35]. Wang et al. presented the DutyCon in [36], a dynamic duty cycle control scheme that provides an end-to-end communication delay guarantee while achieving energy conservation. The authors in [37] provided a solid analysis of bounds of the delay for sending data from a node to a sink in asynchronous duty-cycled WSNs, where sensors turn themselves on and off randomly. They proved 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 many network parameters (node density, connectivity range, duration of active
and sleeping periods). Their analysis is based on the U-ADC model, and the forwarding node will remain active until all their neighbors have received the data packet. In [4], the authors proposed the coverage intensity and analyzed its properties over time as functions of individual sensor on/off schedules in randomly duty-cycled WSNs. The author in [38] showed that the randomly duty-cycled network is asymptotically connected with a probability of 1 when satisfying certain conditions on the basis of the result presented in [39].

Data forwarding in duty cycled WSNs:
In [40], the authors introduced a dynamic switch-based forwarding to minimize the impact of sleep latency in low-duty-cycled networks. Su et al. proposed both on-demand and proactive routing algorithms to find minimum latency routes for intermittently connected sensor networks because of duty cycling [41]. The authors in [42] and [43] studied the geographic routing in duty-cycled WSNs. Several flooding schemes for duty-cycled WSNs also have been investigated [44–48]. Different from the existing work, we focus on the geographic routing in asynchronous duty-cycled WSNs. To avoid the high overhead for periodical exchanging duty cycling settings as well as to better support scalability and mobility, we adopt the state-free CGF scheme.

3. NETWORK MODEL

3.1. Assumptions
We assume sensor nodes are homogeneous and energy-constrained. The locations of sensor nodes are static or change slowly. Each sensor node knows its own geographical location; the source node knows where the destination is. Sensor nodes follow a completely 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 is $t_{\text{off}}$ and the wake (on) duration is $t_{\text{on}}$. The duty cycle length is $t_{\text{off}} + t_{\text{on}}$. Each node only knows its current wake/sleep schedule, for example, the residual time when in the awake state. We also assume that the node density is sufficiently high so that geographic routing is possible for end-to-end data delivery. In geographic routing, the sender may not have any neighbor that can provide a positive advance toward the destination. In this case, a certain recovery mechanism should be applied to circumvent the hole (also called ‘void’ or local minimum in the literature).

3.2. Duty-cycling model
We investigate geographic routing in two asynchronous duty-cycling models, that is, U-ADC and I-ADC.

Most existing asynchronous duty-cycling protocols in the literature are based on the U-ADC model. Take the low-power listening [49] implementation in CC2420 stack for example, the transmitter will not sleep while it is attempting to wake up a duty cycling receiver (thus being called uninterruptible). However, a sender usually has to wait for a long period before the intended receiver wakes up; thus, the effective duty cycle of the sender will be much higher than the default duty cycle, which incurs much more energy cost. Therefore, the overloaded senders will die much earlier than other nodes, consequently degrading the network performance.

The I-ADC will not sacrifice energy for the latency, which preserves the original node activities that are specified by the duty-cycling operation. The I-ADC may suffer from longer receiver discovery latency than U-ADC. Therefore, the I-ADC model is not suitable for time-critical applications. However, it can achieve a good load balance among sensor nodes.

An example of the comparison between the U-ADC model (X-MAC [6]) and the I-ADC model is shown in Figure 1. In X-MAC, a sender keeps awake and waits for the receiver to wake up; it continuously broadcasts a series of short preamble packets, which contain the ID of the intended receiver. When a node wakes up and receives a short preamble packet, it checks the intended receiver ID that is piggybacked on the preamble packet. If the node is the intended recipient, it sends an early ACK to inform the sender and remains awake for the subsequent data transmission. Otherwise, the
node returns to sleep immediately and continues its duty cycling. For example in Figure 4(a), when node A tries to forward the data toward the destination, it experiences a long receiver discovery delay until the intended receiver wakes up and detects the preamble. In effect, although individual nodes are not synchronized to wake up at the same time within a time frame, a node does synchronize with its neighbors locally in learning the wake-up schedules of intended receivers. However, the I-ADC is of the pure asynchronous duty cycling; nodes will not be synchronized by any data transmission. As shown in Figure 4(b), when node A takes the forwarding responsibility, because it has not enough residual time to forward the data to its downstream neighbors, it will follow the default duty-cycling schedule. When waking up in the next duty cycle, it sends out short preambles to discover the intended receiver.

3.3. Link model

Recent studies [11, 12] have shown that realistic link conditions in wireless networks can be highly unreliable and identified the existence of the three distinct reception regions: fully connected, transitional, and disconnected regions. In the fully connected region, nodes transmit packets reliably, approaching 100% delivery probability in the absence of congestion. In the transitional region, link quality varies considerably: some links may exhibit perfect quality whereas others the opposite. In the disconnected region, no links or only weak links exist. In this work, we assume that the wireless link is unreliable and that the packet reception ratio (PRR) of a link is dependent of distance within the physical radio range.

We use the Nakagami distribution defined in Equation 1 to describe the power $x$ of a received signal:

$$f(x, m, \Omega) = \frac{m^m x^{m-1}}{\Gamma(m)\Omega^m} \exp\left(-\frac{mx}{\Omega}\right),$$  \hspace{1cm} (1)$$

where $\Gamma$ is the Gamma function, $m$ denotes the Nakagami fading parameter, and $\Omega$ is the average received power. Assuming TwoRayGround signal propagation, $\Omega$ can be expressed in Equation 2 as a function of $d$, the distance between the sender and the receiver.
where $P_t$ is the transmission power, $G_t$ and $G_r$ are the antenna gains, $h_t$ and $h_r$ are the antenna heights, $L$ is the loss factor, and $n$ is the path-loss exponent. We assume that a packet is received successfully if the received signal power is greater than the receiving power threshold. Then, by using Equations 1 and 2, we can derive the PRR at a certain distance $d$.

4. CGF IN ASYNCHRONOUS DUTY-CYCLED WSNs

In this section, we present CGF schemes for two asynchronous duty cycling models, that is, U-ADC and I-ADC.

4.1. CGF in U-ADC model

Because the CGF protocol is usually based on a request-to-send/clear-to-send exchange, it can be easily embedded in asynchronous duty-cycling MAC protocols, for example, X-MAC [6]. The CGF procedure in the U-ADC model is described as follows. The short preamble packet broadcasted by the sender contains its own location, the destination location, and the identifier of the DATA packet. The contention window size is also specified in the short preamble. Each sender’s neighbor who receives the preamble and has a positive packet advance toward the destination will contend to serve as the next-hop receiver. Specifically, it starts a back-off timer where the value depends on a certain metric.

When the back-off timer expires, the neighbor broadcasts an early ACK message, which contains its own position and the identifier of the DATA packet. Note that the contention window size of the next-hop selection is less than the interval between two preambles. The neighbor that responds to the early ACK firstly wins the selection to be the next-hop receiver. Then, the sender and the intended receiver begin to exchange DATA and ACK messages. Other neighbors who overhear the early ACK will stop back-off timers and go to sleep immediately to conserve energy. After receiving an ACK from the intended receiver, the sender goes back to sleep. As mentioned earlier, the sender will remain active until the data are forwarded to the downstream receiver in the U-ADC model.

4.2. CGF in I-ADC model

The routing procedure in the I-ADC model is different from that in the U-ADC model because the sender will strictly preserve the default duty-cycling schedule. In this subsection, we first show that existing routing metrics are not suitable for CGF in the I-ADC model from the observation. We propose a new RTAF routing metric for interruptible asynchronous duty-cycled WSNs. We then present the design description of the RTAF scheme using this metric.

4.2.1. Observation. Consider an example as shown in Figure 2, where node S has data to send. After the first short preamble is sent, there are two available neighbors B and C in active state, which provide positive advances for the packet. Both of them detect the preamble; thus, they will contend to serve as the next-hop receiver. From the maximum-advance metric [8] or the EXT metric [24], node A may possibly be selected as the next-hop receiver because it provides a larger advance toward the destination. As a winner in the next-hop receiver contention, node A broadcasts short preambles to discover its next-hop forwarder. Unfortunately, A has to turn off the radio to conserve energy before getting an early ACK message because its residual time is limited. Finally, A retransmits the data in the next awake cycle. In fact, it would be better if B takes the forwarding responsibility instead of A if it has a longer residual time, as shown in Figure 2(b).

We observe that the next-hop selection of the next-hop receiver will significantly influence its subsequent forwarding process. The maximum-advance or EXT routing metrics may not be applied for interruptible asynchronous duty-cycled WSNs directly. Other routing metrics in the literature such as those in [19–21] are also not suitable because the random duty-cycling operation is not
4.2.2. Residual time-aware routing metric. Assuming node $i$ is the sender and node $j$ is one of $i$’s neighbors that have a positive advance toward the destination, let $EADV(i, j)$, defined in Equation (3), denote the expected advance provided by node $j$ when forwarding a data packet sent from node $i$.

$$EADV(i, j) = \{Dist(i, dest) - Dist(j, dest)\} \cdot PRR$$  \hspace{1cm} (3)$$

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

In contention-based forwarding, the assigned initial value for a contention timer reflects the priority of the contender. The earlier the time slot a timer assigns, the higher its priority will be. If all sensor nodes are always awake, the neighbor that has maximum advance and good link will be assigned the earliest time slot to contend to be the next-hop forwarder. However, in interruptible asynchronous duty-cycled WSNs, the residual time of a contender should be taken into account, which will significantly influence its subsequent forwarding process.

For node $j$, let $T_{r}^{(j)}$ denote its current residual time keeping the awake state; $T_{cw}$ denote the contention window size, that is, the maximum value of a contention timer; and $R$ denote the radio range...
of a node. The back-off timer’s initial value \( T_{\text{backoff}}^{(j)} \) is defined in Equation (4),

\[
T_{\text{backoff}}^{(j)} = \left[ 1 - \lambda \cdot \frac{\text{EADV}(i, j)}{R} \right] \cdot T_{cw} + \text{random}(0, \tau),
\]

where \( \tau \) is a small parameter; \( \text{random}(0, \tau) \) is a function obtaining a random value between 0 and \( \tau \), which is used to mitigate the potential simultaneous transmissions; and \( \lambda \) is a modification coefficient by taking the residual time into consideration and defined in Equation (5),

\[
\lambda = \min\left\{ \frac{T_p^{(j)}}{T_{cm} + T_{rm}}, 1 \right\},
\]

where \( T_{cm} \) is the current medium time needed for ensuring node \( j \) to finish the DATA/ACK exchange with sender \( i \) and \( T_{rm} \) is the reserved medium time for its subsequent forwarding process from node \( j \) to its downstream link.

\[
T_{cm} = T_{cw} + T_d + T_a
\]

\[
T_{rm} = \{T_p + T_{cw}\} \cdot k + T_d + T_a
\]

where \( T_p \), \( T_d \), and \( T_a \) denote the transmission delay and propagation delay of preamble, DATA, and ACK messages, respectively, and \( k \) is a system parameter specifying the number of preambles to be transmitted in the reserved medium time. From Equation (4), we can see that the contender with a larger EADV value at the same time having a longer residual time will be assigned a higher priority.

4.3. Residual time-aware forwarding

In the I-ADC model, a sender or a contender will enter into the sleep mode regardless of whether having finished the data forwarding task or not, which may degrade the routing performance. To reduce the negative effect of the interruptible asynchronous duty-cycling operation, we present the RTAF scheme using the routing metric introduced above.

Figure 3 illustrates two possible data-forwarding failures that RTAF tends to avoid. As shown in Figure 3(a), the sender goes to sleep before the DATA/ACK exchange is finished. In this case, packet duplication would occur. The receiver tries to forward the DATA immediately after receiving DATA from the sender and returning an ACK, while the sender will also retransmit DATA in the

![Figure 3](image-url)

Figure 3. Two possible data-forwarding failures that RTAF tends to avoid.
next duty cycle because it has not got the ACK before turning off the radio. From Figure 3(b), we see that data transmission failure occurs when a node with limited residual time contends to be the next-hop receiver. Thus, a node with limited residual time should not be considered as the intended receiver. Let $T_{\text{min}}$ denote the minimum medium time needed for data forwarding as in Equation (8).

$$T_{\text{min}} = T_p + T_{cw} + T_d + T_a$$

(8)

RTAF has the following three rules to avoid potential data-forwarding failures: (1) if the sender does not have enough residual time to finish a data-forwarding process, that is, its residual time is less than $T_{\text{min}}$, it will go to sleep before its default duty-cycling schedule; (2) if a node’s residual time is shorter than $T_{\text{min}}$, it will not attend the next-hop receiver contention and can go to sleep in advance; and (3) once a node gets involved in the DATA/ACK exchange, it should not go to sleep until the DATA/ACK exchange is finished because this process does not cost much medium time. This may happen when the channel is busy because of the channel access delay, where the required medium time to finish the data forwarding is larger than $T_{\text{min}}$.

The detailed RTAF design is given as follows. When a sensor node has data to send or relay, it first checks whether it has enough residual time. If yes, it broadcasts a series of short preambles, which includes its own location, the destination location, the identifier of the DATA packet, and the contention window size. Each node periodically turns on the radio to detect forwarding requests. If a node overhears a preamble and it has a positive advance toward the destination and enough residual time, it starts a back-off timer to contend to be the next-hop receiver, where the back-off time is calculated as in Equation 4. When the timer expires, it broadcasts an early ACK message within the contention window. It is possible that the sender receives multiple responses. In this case, the contender that has the earliest timeout wins the contention. Other contenders that overhear the early ACK will cancel their back-off timers and go to sleep immediately. Once the next-hop receiver is determined, the unicast of DATA/ACK exchange between the sender and the specific next-hop receiver follows. During this process, neighbors that are not involved in the data forwarding can go to sleep to save energy. The state transition graphs of the sender and the contender are shown in Figure 4.

4.4. Bypassing holes

Because of the purely random duty-cycling operation, there exists a temporary block situation, that is, the sender may not have any neighbor that provides a positive advance toward the destination. In this case, the recovery mechanism should be applied to circumvent the hole. In our design, the current forwarding node will retransmit the DATA message within certain times before entering into the perimeter routing mode.
In the case of perimeter routing, the preamble packet includes some extra information. Specifically, the perimeter routing indicator is enabled, and the contention window setting is also specified. The presented recovery mechanism has some similarity as in [18], although the difference lies in the routing metric. Half of $T_{cw}$ will be assigned to neighbors with a positive advance toward the destination and the second half to other neighbors for perimeter routing. When the sender broadcasts preambles, the neighbors that have positive advance will contend to become the next-hop receiver in the first half of $T_{cw}$, which is the same process as in a greedy routing mode. If no neighbor responds during the first half of $T_{cw}$, it will enter the perimeter routing mode. After this, if the next-hop receiver has any neighbor with a positive advance when it broadcasts the preambles, it will resume to a greedy routing mode.

Let $\angle sjd$ be the directed angle between the sender S, its arbitrary neighbor $j$, and the destination D. As shown in Figure 5, $\angle sjd$ denotes the directed angle from $sj$ to $jd$, which is the signed angle through which $sj$ must be rotated about $j$ to coincide with $jd$. Because only the neighbors with negative advances calculate directed angles, $|\angle sjd|$ can range from 0 to $\pi/2$ degrees. The contention-based forwarding in perimeter routing mode follows two rules: (1) the neighbor with a larger directed angle and at the same time with a longer residual time will be given higher priority and (2) the perimeter routing tends to follow a single direction to circumvent the temporary hole. That is, the direction depends on the first forwarder’s directed angle in the perimeter routing mode. Take Figure 5 for example; suppose node B is selected as the next-hop receiver in the perimeter routing mode, and the directed angle is counter-clockwise. Then, if node B still faces a temporary block situation, the directed angle is calculated according to the counter-clockwise direction. Therefore, node C has a higher priority to take the forwarding task than node A if they have the same residual time.

We define the directed angle following the first forwarder’s direction in perimeter routing mode as the positive value; the opposite direction takes the negative value. Thus, $\angle sjd$ ranges from $-(\pi/2)$ to $\pi/2$ degrees. Given the directed angle $\theta$, each neighbor computes its delay time according to Equation (9).

$$T_{\text{backoff}}^{(j)} = (1 - \lambda \cdot \frac{\theta + \frac{\pi}{2}}{\pi}) \cdot \frac{T_{cw}}{2} + \frac{T_{cw}}{2} + \text{random}(0, \tau),$$

where $\lambda$ is defined as in Equation (5). Although nodes may enter into the sleep mode because of the duty-cycling operation, if the recovery mechanism is enabled, CGF in asynchronous duty-cycled WSNs guarantees that the data packets can reach their destination even when holes exist in greedy forwarding.

Figure 5. Bypassing holes according to the directed angle. The sender S forwards a data packet to the neighbor with a larger angle and a longer residual time in the perimeter routing mode. In this example, node B is selected as the next-hop receiver.
5. SIMULATION

In this section, we conduct simulations to evaluate the performance of CGF in asynchronous duty-cycled WSNs using ns-2 [50]. We first show that senders may suffer from a high effective duty cycle in the U-ADC model, which incurs an unbalanced load among nodes. We then report the simulation results of RTAF for the I-ADC model. All the results have been averaged over 100 runs, and the related standard deviations are provided as error bars.

5.1. Simulation settings

In the implementation of our simulation, sensor nodes are deployed in a 200 m × 200 m field, forming a two-dimensional grid. A sink node is positioned at the bottom left (0 m, 0 m) of the field, and the source node is located at the top right (200 m, 200 m) 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 apply to IEEE 802.15.4. The sensor transmission range \( r \) is taken as 30 m. The length of a data packet is 50 bytes. The wake/sleep schedule period (default duty cycle length) is set to 1 s. We vary the default duty cycle (the average fraction of time that a sensor node is in the awake state in one wake/sleep schedule). For the RTAF scheme, the delivery deadline is set to 20 s; once exceeding the deadline, the data packet is dropped, and the current simulation round will be marked as a failed round. Only the successful end-to-end transmissions are included in the statistical results. We define node density as the number of nodes deployed in the field.

5.2. Evaluation metrics

We consider the following metrics. The last two metrics measure not only the communication overhead but also the energy efficiency of a routing protocol.

* Effective duty cycle, the fraction of time that a sensor is in awake state during one wake/sleep schedule
* End-to-end delay, how long it takes for a data packet to arrive at the sink from the source node in a simulation run
* Data delivery ratio, the ratio of the amount of packets received by the sink to the total amount of packets sent by the source
* Number of data transmission, the number of hops that a data packet traverses from the source to the sink in a simulation run
* Control message overhead, the total number of control messages in a simulation run

5.3. CGF in the U-ADC model

In this test, we vary the node default duty cycle from 1% to 30% to evaluate the CGF in the U-ADC model, the node density is set to 26 × 26. Figures 6 and 7 show the simulation results of the maximum sender effective duty cycle. Figure 8 shows the performance of CGF in the U-ADC model under different node duty cycles in terms of the end-to-end delivery delay, number of data transmission, and control message overhead.

Figure 6 shows 100 samples of the maximum sender effective duty cycle for CGF in the U-ADC model when the node duty cycle is set to 1% and 10%. The maximum sender effective duty cycle is selected from all forwarders involved in the data forwarding in each simulation run. We see that both of them have wide variation ranges. When the node duty cycle is set to 1%, the maximum effective duty cycle variation ranges from 15% to 98%. The average maximum effective duty cycle is about 53%, which confirms that when nodes wake up every 1 s, a sender needs to wait for 0.5 s on average to detect the receiver [7]. In Figure 6(b), where the node duty cycle is set to 10%, the average time of that sender having its radio on is 0.47 s.

Figure 7(a) illustrates the maximum sender effective duty cycle for CGF in the U-ADC model under different duty cycles. It shows that the average maximum effective duty cycle almost remains constant regardless of the default duty cycle settings, and its value remains around 0.5 s. Figure 7(b) plots the ratio of the maximum effective duty cycle to the default duty cycle. When nodes employ
Figure 6. Samples of maximum sender effective duty cycle for CGF in the U-ADC model.

(a) Default duty cycle: 1%

(b) Default duty cycle: 10%

Figure 7. Maximum sender effective duty cycle for CGF in the U-ADC model under different node duty cycles.

(a) Maximum sender effective duty cycle

(b) Ratio of the maximum effective duty cycle to the default duty cycle

A very low duty cycle, the ratio would be very high. This indicates that the sensor nodes that are always involved in data forwarding would die quickly compared with other nodes.

Figure 8 shows the results of the delay and communication costs of CGF in the U-ADC model as a function of the node duty cycles. As shown in Figure 8(a), the end-to-end delivery delay decreases as the node duty cycle increases. The reason is that the average next-hop receiver discovery latency decreases with an increase of the node duty cycle. In other words, the average sender effective duty cycle will decrease as the node duty cycle increases. However, from Figure 7(a), we know that the maximum sender effective duty cycle still remains constant, around 50%. Figure 8(b,c) illustrates the changes of communication costs at increasing node duty cycles. We can see that the number of data transmission decreases gradually as the node duty cycle increases, and the control message overhead increases gradually as the node duty cycle increases. In the U-ADC model, CGF achieves almost a 100% data delivery ratio.

5.4. CGF in the I-ADC model

To evaluate the proposed RTAF scheme for CGF in the I-ADC model, we compared it with the CGF using the EXT [24] routing metric. First, we evaluated the impact of node duty cycle on the performance of the different protocols. Then, we evaluated the impact of the node density.

5.4.1. Impact of node duty cycle. In this test, 26 × 26 nodes are uniformly placed in a 200 m × 200 m square area; we vary the node duty cycle from 10% to 50%. Figure 9 shows the simulation results. Note that only the successful end-to-end transmissions are reported.
Figure 8. Performance of CGF in U-ADC model under different node duty cycles.

Figure 9(a) plots the end-to-end delivery delay as the node duty cycle increases. The figure shows that RTAF significantly decreases the end-to-end delivery delay when the node duty cycle is small, for example, 10%. However, as the node duty cycle increases, there is not much difference between RTAF and CGF-EXT. This is because, when the node duty cycle is large (e.g., larger than 30%), the next-hop receiver discovery latency will be short, and the residual time is always larger than the required medium time to finish the data forwarding.

Figure 9(b) illustrates the changes of the data delivery ratio at increasing the node duty cycles. It is seen that RTAF achieves a little better result in terms of the data delivery ratio metric when node duty cycle is set to 10%. However, both schemes incur low data delivery ratio under low node duty cycles. The reason is that, in our simulations, the delivery deadline is set to 20 s. It could be expected that if we relax the limit of the delivery deadline, their delivery ratios will also approach 100% when the node duty cycle is low. Figure 9(a,b) indicates that CGF in the I-ADC model suffers from a very long data delivery delay; thus, it is not suitable for time-critical applications.

Figure 9(c,d) reports the number of data transmission and control message overhead, respectively. It is seen that RTAF improves the energy efficiency. It can save about 30% of data transmission cost and 40% of control message overhead when the node duty cycle is 10%. However, when the node duty cycle increases, RTAF does not show much advantage over CGF-EXT.

5.5. Impact of node density

In this test, we vary the node density from $22 \times 22$ to $30 \times 30$. The node duty cycle is set to 10%. Evaluation results are shown in Figure 10.

Figure 10(a) depicts the performance comparison on the end-to-end delivery delay under different node densities. As seen in the figures, RTAF more or less outperforms CGF-EXT with respect to this metric. Figure 10(b) reports the data delivery ratio as the node density increases. It clearly
Figure 9. Impact of node duty cycle for CGF in the I-ADC model

Figure 10. Impact of node density for CGF in the I-ADC model.
shows that data delivery ratio increases with the increase of node density, from 5% to 50%. RTAF shows little advantage over CGF-EXT in this metric.

Figure 10(c,d) show the results of data transmission and control message overhead, respectively. RTAF only shows an obvious advantage over CGF-EXT when node density is set to 26 × 26. This is because, when the node density is high, the possibility that the residual time is shorter than the required medium time to finish the data forwarding decreases. Therefore, RTAF degrades to CGF-EXT as the node density increases.

5.6. Discussion

From the simulation results, we can see that CGF in the U-ADC model can provide much shorter delivery delay than that in the I-ADC model. However, the sender may suffer from a high effective duty cycle in the U-ADC model. Consequently, the overloaded senders will die much earlier than other nodes. Different from prior work in asynchronous duty-cycled WSNs, our work focuses on the CGF in the I-ADC model, where nodes will not be synchronized by any data transmission. Each node in the I-ADC model guarantees that the effective duty cycle is less than the default duty cycle. However, CGF in the I-ADC model incurs a very long data delivery delay; thus, it is not suitable for delay-sensitive applications. Our proposed RTAF does lower the effects of the performance degradation caused by the asynchronous duty-cycling operation, compared with the alternative approach CGF-EXT, especially in low duty cycle and node density. However, this is the first attempt to address data forwarding in the I-ADC model. We believe further gain is possible to improve the routing performance in the I-ADC model, for example, improving the end-to-end delivery latency and energy efficiency, which will be our future work.

6. CONCLUSION

In this work, we study the CGF for two asynchronous duty cycling models, that is, the U-ADC and the I-ADC. To the best of our knowledge, this is one of the first works on data forwarding for the interruptible asynchronous duty-cycled WSNs. We propose a new residual time-aware routing metric, which is more responsive to the dynamics resulting from the uncertainty of nodes’ sleep scheduling. We present the RTAF scheme using this metric. We evaluate the performance of CGF in the U-ADC model and the I-ADC model. Simulation results demonstrate that CGF in the U-ADC model provides a shorter delivery delay while suffering from a high sender effective duty cycle problem. CGF in the I-ADC model incurs a very long data delivery delay, but it can achieve a good load balance among nodes. It is also shown that RTAF more or less improves the routing performance for CGF in the I-ADC model.

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REFERENCES


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