Unsynchronized Duty-cycle Control for Sensor Based Home Automation Networks

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Abstract

Home automation networks are good environments for merging sensor networks and consumer electronics technologies. It is very important to reduce the energy consumption of each sensor node because sensor nodes operate with limited power based on a battery that cannot be easily replaced. One of the primary mechanisms for achieving low energy operation in energy-constrained wireless sensor networks is the duty-cycle operation, but this operation has several problems. For example, unnecessary energy consumption occurs during synchronization between transmission schedules and sleep schedules. In addition, a low duty-cycle usually causes more performance degradation, if the network becomes congested. Therefore, an appropriate control scheme is required to solve these problems. In this paper, we propose UDC (Unsynchronized Duty-cycle Control), which prevents energy waste caused by unnecessary preamble transmission and avoids congestion using duty-cycle adjustment. In addition, the scheme adjusts the starting point of the duty-cycle in order to reduce sleep delay. Our simulation results show that UDC improves the reliability and energy efficiency while reducing the end-to-end delay of the unsynchronized duty-cycled MAC (Media Access Control) protocol in sensor-based home automation networks.

Keywords: Home automation networks, sensor networks, unsynchronized duty-cycle, congestion control, resource control

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1. Introduction

Wireless sensor networks are expected to be used in a wide range of applications that are hard to wire, require portability, and unable to accommodate traditional wired sensors. There has also been a growing interest in the wireless sensor network technology for the home domain. Numerous applications have been proposed for the home, such as health monitoring, home surveillance, and home automation. Home automation networks are good environments for merging sensor networks and consumer electronics technologies. In home automation networks, many sensors distributed in homes collect various bits of physical data such as temperature, humidity, motion, and light, to provide information to the home control system [1][2].

To realize these home automation networks, many sensor devices should detect events in the home and send them directly to the base station through the wireless channel. As sensor nodes do not have sufficient computational ability and battery power, it is very important to reduce the energy consumption of each sensor node. One of the primary mechanisms for achieving low energy operation in energy-constrained wireless sensor networks is the duty-cycle operation. In this approach, each sensor node periodically cycles between awake and sleep states. During sleep state, nodes turn off their radios to conserve energy. During the awake state, nodes turn on their radio to transmit and receive packets [3].

Duty-cycled MAC (Media Access Control) protocols developed for wireless sensor networks can be categorized into synchronized and unsynchronized approaches. Synchronized approaches, such as SMAC [4], use periodic synchronization messages to schedule duty-cycling and packet transmissions. Such message exchanges consume significant amounts of energy even when no traffic is present. Unsynchronized approaches, such as XMAC [3], use preamble sampling techniques that periodically wake up for a very short period of time and sample the medium for activities with a long preamble. Unsynchronized approaches are widely used because of the high overhead introduced by the synchronized awake and sleep schedules. Although the unsynchronized approaches are simple and energy-efficient, their preamble sampling exhibits several problems. For example, the sending node typically has to transmit a preamble for a long time until the receiving node awakes because the sending node is not aware of the wakeup time of the receiving node. This wastes energy and leads to latency problems. In addition, if the incoming traffic of the receiving node is high, then the transmission requirements of the sending nodes are not satisfied properly. This makes network congestion problems worse.

In this paper, we propose the UDC (Unsynchronized Duty-cycle Control) scheme. The proposed scheme prevents energy waste caused by unnecessary preamble transmission through inference with the wakeup time of the receiving node. In addition, the scheme provides congestion control using duty-cycle adjustments. These duty-cycle adjustments are a resource control technique in which the check interval of the receiving node is adjusted on the basis of traffic conditions. Finally, the scheme adjusts the starting point of the duty-cycle in order to reduce sleep delay caused by periodic sleep. Consequently, the UDC scheme improves reliability and energy efficiency as well as reduces sleep delay of unsynchronized duty-cycled MAC protocol in sensor-based home automation networks.

The rest of this paper is organized as follows. In Section II, we present research works related to duty-cycle adjustment schemes and congestion avoidance schemes for wireless sensor networks. The details of UDC are then presented in Section III. In Section IV, the simulation results are described. Finally, Section V presents the conclusion and discusses our future work.

2. Related Work

In this section, low duty-cycle operation and control schemes in wireless sensor networks are described. In addition, existing research work on congestion avoidance in wireless sensor networks is discussed.

2.1 Duty-cycle Adjustment Schemes

Duty-cycled MAC protocols developed for wireless sensor networks can be categorized into synchronized and unsynchronized approaches. Synchronized approaches, such as SMAC [4] and DMAC [5], negotiate a schedule that specifies when the nodes should be awake and when they should be asleep within a frame. These approaches use periodic synchronization messages to schedule duty-cycling and packet transmissions. Such message exchanges consume significant energy even when no traffic is present. They also incur high overhead introduced by the synchronized awake and sleep schedules.

Unsynchronized approaches, on the other hand, such as BMAC [6] and WiseMAC (Wireless Sensor MAC) [7], use preamble sampling techniques where nodes periodically wake up for a very short duration and sample the medium for activities through a long preamble. Although unsynchronized approaches are simple and energy efficient, the long preamble exhibits several disadvantages. First, the receiver typically has to wait for the full period until the preamble is finished before the data exchange can begin. This wastes energy of both the receiver and sender. Second, an unsynchronized approach suffers from overhearing problems, where non-targeted receivers also wake up during the long preamble and stay awake until the end of the preamble to find out if the packet is destined for them. This leads to energy waste and latency problem [3].

There have been several studies on reducing sleep latency and adjusting the duty-cycle to the traffic load. BMAC [6] provides an interface where the application can adjust the duty-cycle to adapt to changing traffic loads. In wireless sensor networks, nodes may join and leave the network, or the size of the neighborhood will change due to changes in the physical environment. BMAC can adjust for these changes and optimize its power consumption, latency, and throughput to support the services relying on it. However, there is no specific adaptation scheme on BMAC. Accordingly, the method of adaptation is left to the application developer.

In the adaptive listening scheme proposed in SMAC [4], a node that overhears its neighbor's transmission wakes up for a short period of time at the end of the transmission, so that if it is the next hop of its neighbor, it can receive the message without waiting for its scheduled active time. However, nodes on the path to the sink that are more than one or two hops away from the receiver cannot be notified of the ongoing traffic, and therefore packet forwarding will stop after a few hops.

XMAC [3] also uses an adaptive algorithm for automatically adjusting the duty-cycle of receivers to the offered traffic load, which further reduces per-hop latency. In a tree-topology network, where the nodes periodically sense and transmit data over multiple hops to a base station, the nodes closer to the base station will receive and transmit more data than those further towards the leaves. As such, the nodes in the network must have different sleep schedules to effectively accommodate the different traffic loads.

ADCA (Asynchronous Duty-cycle Adjustment) [8] is a duty-cycle based protocol to reduce power consumption without lowering network throughput or lengthening transmission delay. It allows each node in a sensor network to independently set its own awake and sleep schedule. Media access is thus staggered and collisions are reduced. According to the statuses of previous transmissions, ADCA adjusts the duty-cycle length to shorten the transmission delay and increase throughput.

In the QPS (Quorum-based Power Saving) protocol [9], the time axis on each node is evenly divided into beacon intervals. A node may stay awake or sleep during each beacon interval. Given an integer n, a quorum system defines a cycle pattern, which specifies the awake/sleep schedule during n continuous beacon intervals, for each node. Since the pattern repeats every n beacon intervals, we call n the cycle length. The merit of QPS protocols is that a station is required to remain awake only $O(\sqrt{n})$ beacon intervals every cycle, and that at least one of these awake beacon intervals is guaranteed to overlap with that of another node.

2.2 Congestion Avoidance Schemes

Most prior works on congestion control for wireless sensor networks focused on traffic control approaches. ESRT (Event-to-Sink Reliable Transport Protocol) [10] is a transport solution developed to achieve reliable event detection and congestion control. In ESRT, the sink is required to periodically configure its source sending rate to avoid congestion. All data flows are throttled to a lower rate when congestion is detected. Woo and Culler [11] proposed an adaptive traffic control scheme, in which the locally generated traffic and route-through traffic are proportionally assigned bandwidths to provide fairness among flows with different path lengths, which also prevents congestion.

Resource control approaches have received little attention. TARA (Topology Aware Resource Adaptation) [12] increases network resources to alleviate congestion and improve throughput. It incipiently checks the influence of multiple paths on the end-to-end channel capacity and provides some guidelines for designing the resource control approach. The TADR (Traffic-Aware Dynamic Routing) [13] algorithm was proposed to route the packets around the congested areas and scatter excessive packets along multiple paths of idle and under-loaded nodes. The TADR algorithm is designed by constructing a mixed potential field using depth and normalized queue length to force the packets to steer clear of obstacles created by congestion and eventually move towards the sink.

3. Unsynchronized Duty-cycle Control

We propose the UDC (Unsynchronized Duty-cycle Control) scheme in order to improve the reliability and energy efficiency, while reducing sleep delay in sensor-based home automation networks. The UDC scheme is composed of two main components: transmission scheduling and duty-cycle adjustment. In the transmission scheduling, a sending node adjusts its transmission time based on the wakeup time of a receiver node in order to reduce unnecessary preamble transmission. In the duty-cycle adjustment, the check interval of the receiving node is adjusted based on traffic condition. When congestion is detected, the receiving node alleviates congestion by increasing reception capacity through reducing the check interval. The starting point of the check time is also adjusted in order to reduce sleep delay caused by periodic sleep during multihop transmissions.

3.1 Transmission Scheduling

The proposed UDC scheme is designed on the basis of unsynchronized duty-cycled MAC protocols. In the unsynchronized duty-cycle, the nodes periodically wake and check the channel for a short period of time. If there is incoming traffic, then they try to receive those packets from the sending nodes. **Fig. 1** shows the unsynchronized duty-cycle parameters defined in this paper. D_{check} is the duration of the check time, and T_{start} is the starting point of one duty-cycle. The check interval is the interval between the two starting points of the duty-cycle. A long check interval means low energy consumption and a low packet transmission rate. In contrast, a short check interval means high energy consumption and a high packet transmission rate. Therefore, we set $D_{MIN\_CHECK\_INTERVAL}$ and $D_{MAX\_CHECK\_INTERVAL}$ to the minimum and maximum thresholds of the check interval, respectively, to guarantee the upper bound of packet delivery and lower bound of energy consumption.

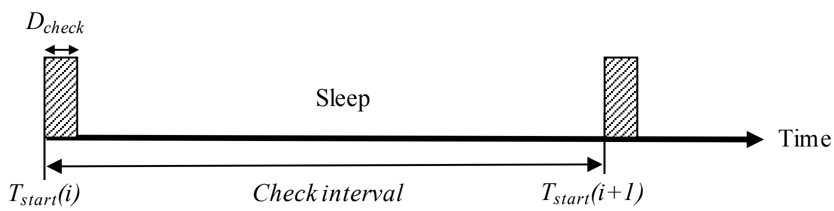


Fig. 1. Duty-cycle parameters

The proposed scheme uses a short preamble that is similar to XMAC to reduce unnecessary transmission delay and energy consumption caused by a long preamble. **Fig. 2** shows the channel access mechanism of the proposed scheme. When a sender node has a packet to send, it waits for a random backoff time and then monitors the channel for T_{listen}. If no activity on the channel is sensed during this interval, then the node transmits a preamble packet and waits for the ACK (Acknowledgment) packet during $T_{waitACK}$. If the ACK packet is received correctly, the sender node starts data transmission. Otherwise, it retransmits the preamble packet and waits for the ACK packet for the duration of the check interval. $D_{PREAMBLE}$ and D_{ACK} are the duration of the preamble packet and ACK packet, respectively.

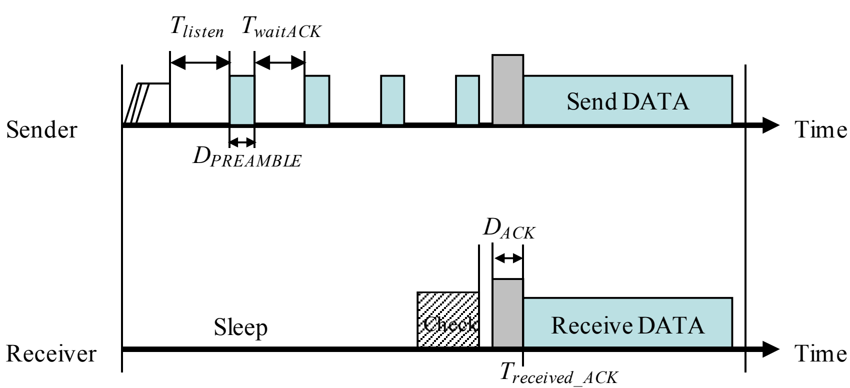


Fig. 2. Channel access mechanism of the UDC scheme

In an unsynchronized duty-cycle, the sending node is not aware of the wakeup time of the receiving node. This has caused a lot of overhead from the series of short preamble transmission. We try to reduce this overhead from preamble transmission through the inference of wakeup times of the receiving nodes as in (1). $T_{next\_TX}(i)$ is the next transmission time of the sending node to node i. $T_{recv\_ACK}(i)$ is the receiving time of an ACK packet from node i acquired by overhearing, and I_{check} is the check interval of the current duty-cycle. D_{ACK} is the duration of the ACK packet, and SIFS (Short Interframe Space) is the small time interval between the check time and transmission time of the ACK packet [14].

$$T_{next\_TX}(i) = T_{recv\_ACK}(i) + I_{check} - D_{ACK} - SIFS - D_{check} \quad (1)$$

After calculating the next wakeup time, a sending node adjusts the transmission time of its preamble packet in order to reduce unnecessary preamble transmission. In addition, the sending node can turn off its radio and go to sleep to save energy until the next wakeup time. Fig. 3 shows the transmission time adjustment of preamble packet.

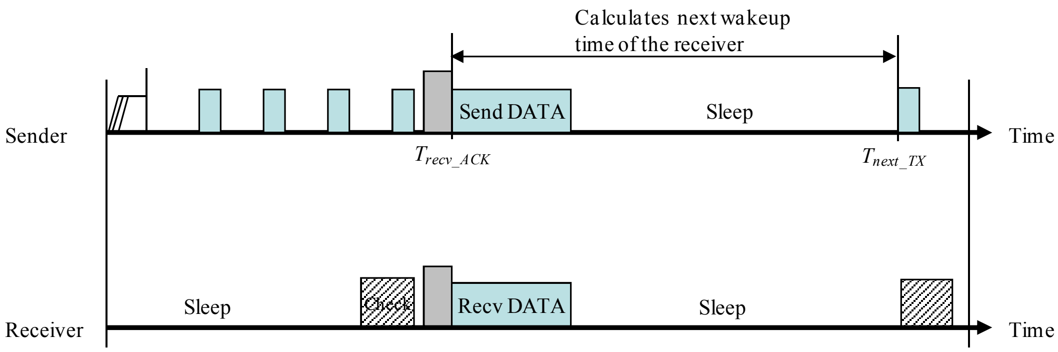


Fig. 3. Transmission time adjustment of preamble packet

However, if multiple nodes that want to transmit preamble packets to the same receiving node and they set their sending time to be the same, a collision occurs at the receiving node. We define the inverse backoff mechanism in order to avoid these collisions. The backoff time is uniformly distributed in ($D_{PREAMBLE}$, $2D_{PREAMBLE}$). In the inverse backoff mechanism, the sending nodes start to transmit the preamble packets at the backoff time before the predicted wakeup time. The node that sets the shortest backoff time enables the ACK packet to be received. Fig. 4 shows the inverse backoff mechanism. Two senders try to transmit a packet to the same receiver. The backoff time of sender 2 is lower than sender 1 and thus, sender 2 receives the ACK packet from the receiver.

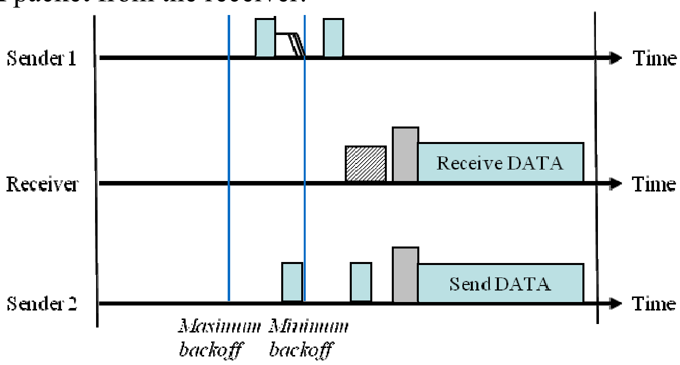


Fig. 4. The inverse backoff mechanism

3.2 Duty-cycle Adjustment

Congestion control schemes for wireless sensor networks can be categorized into traffic control and resource control approaches. The traffic control approach can alleviate network congestion by reducing transmission demand. When congestion is detected, the traffic control approach notifies the source node of the congestion and triggers it to adjust the traffic according to its available resources. The resource control approach can alleviate network congestion by increasing reception capacity [12].

The proposed duty-cycle adjustment is a resource control technique where the check interval of the receiving node is adjusted based on traffic conditions. When congestion is detected, the receiving node alleviates congestion by increasing reception capacity through reducing its check interval. The proposed congestion control is similar to ADCC (Adaptive Duty-cycle Based Congestion Control) [2]; however, it does not adjust the active time, but the instead adjusts check interval of the duty-cycle because the proposed scheme is based on an unsynchronized duty-cycle. The proposed scheme periodically calculates the required check interval using incoming packet information of the sending nodes. Equation (2) shows *check(x)*, the required check interval at the node *x*. N_x is the set of child nodes of node *x*. $t_{INTER\text{-}ARRIVAL}(i)$ is the packet inter-arrival times of node *i*.

$$check(x) = \frac{1}{\sum_{i}^{N_x} \frac{1}{t_{INTER-ARRIVAL}(i)}} \tag{2}$$

If the required check interval is within a certain threshold as in (3), then the scheme adjusts its own check interval to reduce congestion. On the other hand, if the check interval is below the minimum threshold, then the scheme notifies the child nodes of the congestion so that the transmission rate of these child nodes can be adjusted.

$$D_{MIN\_CHECK\_INTERVAL} \le check(x) \le D_{MAX\_CHECK\_INTERVAL} \tag{3}$$

The proposed scheme uses an explicit congestion notification method by broadcasting the congestion message including *change_inter_arrival* value to the child nodes. Equation (4) shows the *change_inter_arrival* value that is utilized in changing the transmission rate of the child nodes. The node that receives the congestion message sets the new transmission rate by multiplying its transmission rate by this value.

$$change\_inter\_arrival = \frac{D_{MIN\_CHECK}}{check(x)} \tag{4}$$

The duty-cycle adjustments of UDC, which consist of congestion detection, resource control, and traffic control, are repeated. When congestion occurs, UDC not only increases the packet reception rate of a receiving node but also decreases the packet transmission rate of the sending nodes.

The second duty-cycle adjustment scheme resets the starting point of the check time in order to reduce sleep delays caused by periodic sleeps during multihop transmission. In duty-cycled MAC protocols, an intermediate node may have to wait until the receiver wakes up before it can forward a packet. This is called sleep delay. Sleep delay increases proportional to the number of hops, with the constant of proportionality being the duration of a single cycle. In the

UDC scheme, sleep delay is minimized by adjusting the starting point of the check time at intermediate nodes. **Fig. 5** shows an example of starting point adjustment in a multihop topology. Packets that were generated by source nodes *s1* and *s2* are transmitted to intermediate nodes *i1* and *i2*. When the check time is started, intermediate nodes receive these packets and route to the node *i3*. At this time, node *i3* acquires duty-cycle information of nodes *i1*, *i2* and adjusts its starting point of the check time in consideration of the intermediate nodes' starting points.

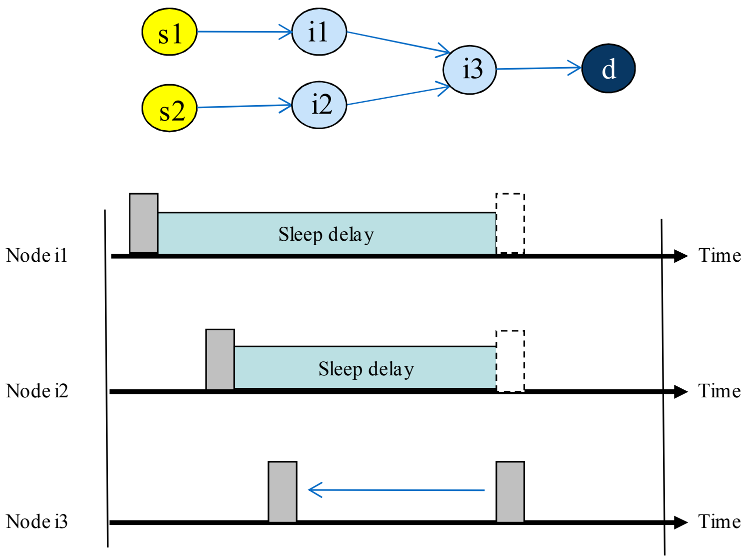
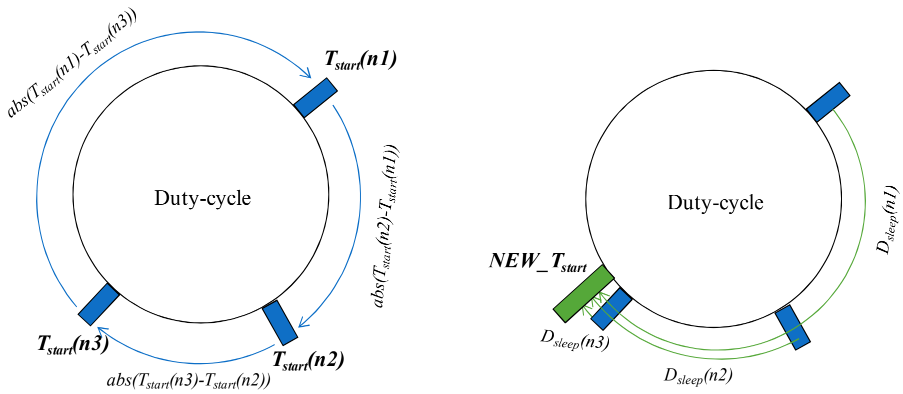


Fig. 5. An example of resetting the starting point of the check time

Fig. 6 shows the process of starting point resetting. First, when an intermediate node receives packets from subordinate nodes, the starting point of the check time contained in that packet is extracted and inserted into the neighbor list. Then, the neighbor list is sorted by those starting points. In order to find the optimal point to minimize sleep delay, the time difference between two adjacent starting points in the neighbor list is calculated. The later point among the pair that is confirmed as the largest time difference is selected as the new starting point of the check time.



(a) Calculate the time difference (b) Select new starting point

Fig. 6. The process of starting point resetting

4. Performance Evaluation

In order to evaluate the proposed UDC scheme, we use the ns-2 network simulator. The network topology for the simulation is shown in **Fig. 7**. In the simulation environment, nodes *s1*, *s2*, and *s3* transmit packets toward node *i* and node *i* forwards these packet to node *d*. Sending nodes perform transmission scheduling that adjusts their transmission time based on the wakeup time of node *i*. Node *i* performs duty-cycle adjustments in which the check interval is adjusted on the basis of traffic condition. When congestion is detected, node *i* increases reception capacity by reducing the check interval.

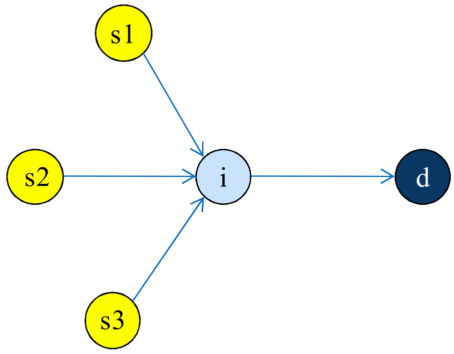


Fig. 7. Simulation topology

Each node has the same duty-cycle period. The duration of the check time is set to 15 ms and the check interval is set to 500 ms. The total preamble packet transmission time is also set to 500 ms. The minimum and maximum check intervals are set to 300 ms and 700 ms, respectively. Other parameters are summarized in **Table 1**. When the simulation is initiated, nodes *s1*, *s2*, and *s3* start packet transmission at 300 s, 500 s, and 900 s, respectively. We compare UDC with the channel access mechanism of X-MAC.

Table 1. Summary of simulation parameters

Parameter	Value
Area size	2000 m x 2000 m
Radio range	100 m
Interface queue	5
Packet size	50 B
Check interval	500 ms
$D_{MIN\ CHECK\ INTERVAL}$	300 ms
$D_{MAX\ CHECK\ INTERVAL}$	700 ms
D_{CHECK}	15 ms
Tlisten	15 ms
$T_{waitACK}$	14.1 ms
$D_{PREAMBLE}$	0.9 ms
Packet interval	1 s
Simulation time	1000 s

Fig. 8 compares the average number of short preamble packets of the UDC scheme and XMAC for each sending node. Through transmission scheduling, the UDC scheme reduces the amount of preamble packet transmission. The proposed scheme improves energy

efficiency by preventing energy waste caused by unnecessary preamble transmissions.

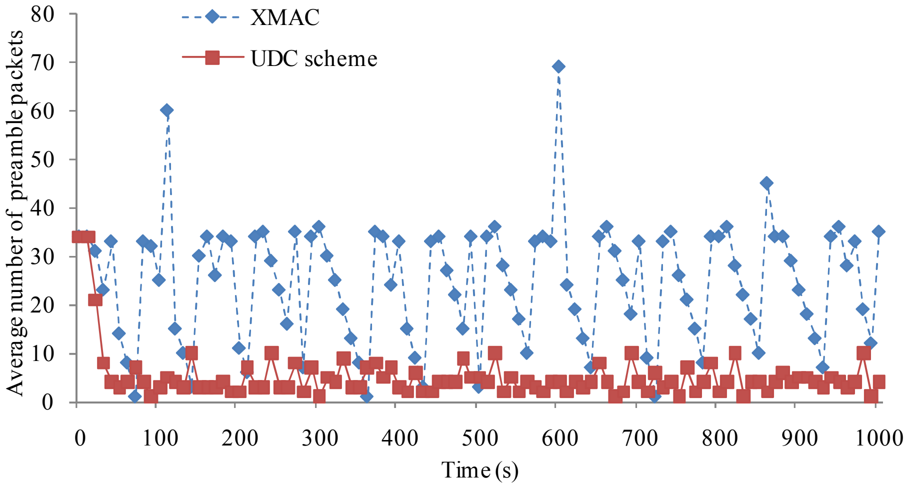


Fig. 8. The average number of short preamble packets using packet interval of 1 s

The average number of short preamble packets under different packet intervals is shown in **Fig. 9**. We vary the packet interval of the sending nodes from 200 ms to 1000 ms and measure the average number of short preamble packets. **Fig. 9** shows that the UDC scheme significantly reduces the amount of preamble packets transmitted.

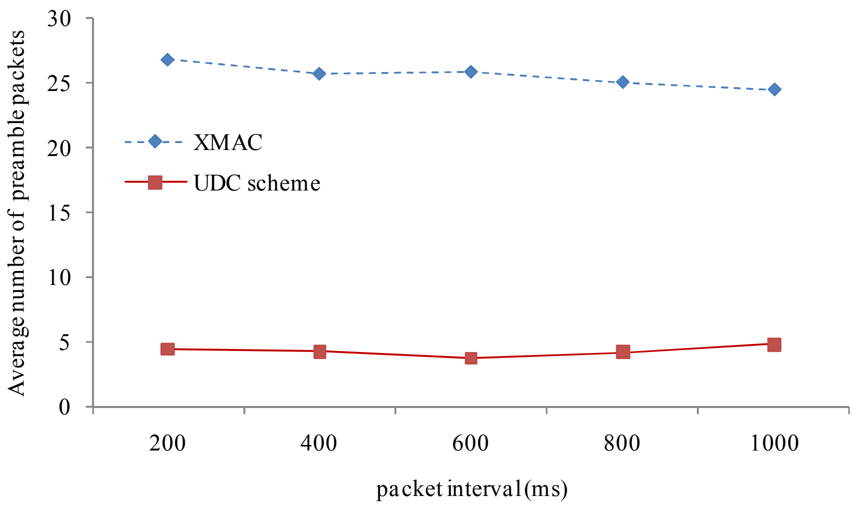


Fig. 9. The average number of short preamble packets under different packet intervals

Fig. 10 compares the average packet reception rate of the UDC scheme and XMAC. When nodes *s2* and *s3* start transmission, the network becomes congested, and consequently, the packet reception rate of XMAC is decreased to 600 s. The UDC scheme increases the resources of node *i* by decreasing the duration of the check interval so that node *i* can receive more packets. The packet reception rate of the UDC scheme is no longer increased after 700 s, because the duration of the active time has exceeded the maximum threshold. At this time, the UDC scheme uses traffic control by decreasing the packet transmission rate of the sending nodes. The results show that the UDC scheme achieves higher throughput compared to the XMAC.

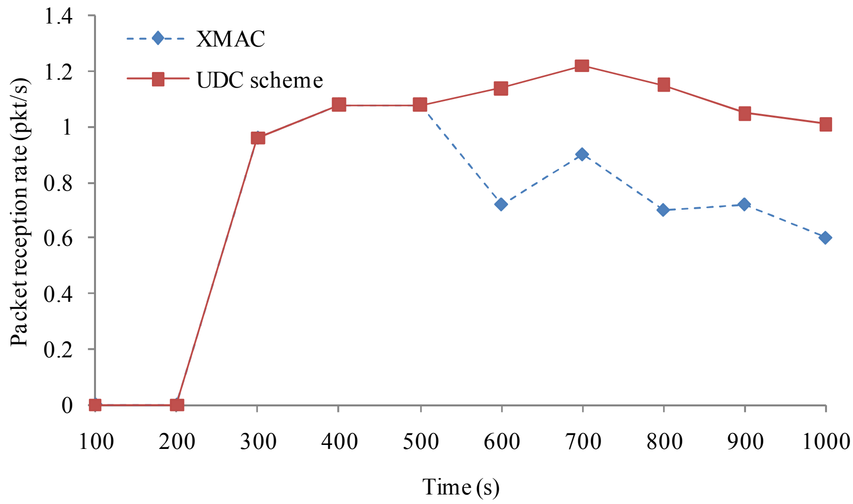


Fig. 10. Average packet reception rate at node d

Fig. 11 compares the loss rates of the UDC scheme and XMAC for each sending node. XMAC shows a high loss rate because many packets collide or are dropped when the network is congested. The UDC scheme, on the other hand, has a low loss rates due to its duty-cycle adjustments. In UDC the scheme, when congestion is detected, the receiving node alleviates congestion by increasing reception capacity through reducing the check interval.

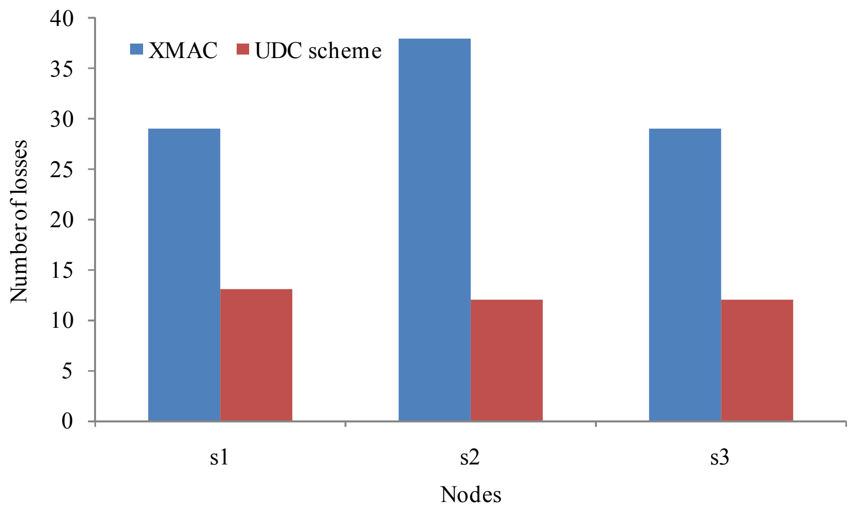


Fig. 11. Total number of losses

In order to evaluate the starting point resetting algorithm, we simulate this algorithm in the multihop topology shown in **Fig. 5**. **Fig. 12** compares average sleep delay at each hop of the UDC scheme and XMAC. The UDC scheme has a low average sleep delay due to the starting point resetting algorithm. The average sleep delay of the UDC scheme is reduced by about 56% compared to of XMAC.

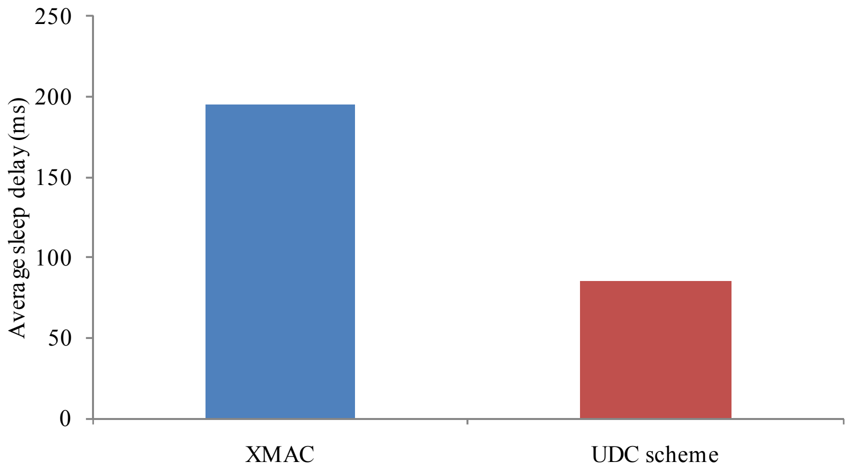


Fig. 12. Average sleep delay

5. Conclusion

Home automation networks are good environments for merging sensor networks and consumer electronics technologies. In home automation networks, many sensors distributed in the house collect various physical data such as temperature, humidity, motion, and light to provide information to the home control system. As sensor nodes operate with limited power based on a battery that cannot be easily replaced, it is very important to reduce the energy consumption of each sensor node. Therefore, energy efficiency is a fundamental issue in the design of communication protocols developed for wireless sensor networks. One of the primary mechanisms for achieving low energy operation in energy-constrained wireless sensor networks is the duty-cycle operation. In this approach, each sensor node periodically cycles between awake states and sleep states. However, the low duty-cycle usually causes performance degradation.

This paper proposes the UDC, an unsynchronized duty-cycle control scheme for home automation networks. The UDC scheme is composed of two main components: transmission scheduling and duty-cycle adjustment. In the transmission scheduling, a sending node adjusts its transmission time based on the wakeup time of a receiver node in order to reduce unnecessary preamble transmission. In the duty-cycle adjustment, the check interval of the receiving node is adjusted based on traffic conditions. When congestion is detected, the receiving node alleviates congestion by increasing its reception capacity through reducing the check interval. The starting point of the check time is also adjusted in order to reduce sleep delay caused by periodic sleep during multihop transmissions. The proposed scheme not only provides energy efficiency but also achieves reliability and reduces delay compared with previous MAC protocols.

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