MPT-MAC: A Multiple Packets Transmission MAC Protocol for Wireless Sensor Networks

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***Abstract*—Event detection is a major application in wireless sensor networks (WSNs). Current Medium Access Control (MAC) protocols for WSNs are mainly optimized for the situation that an event generates only one data packet on a single node and the event occurrence rate is low. When an event generates multiple data packets or the event occurrence rate is relatively high, packet delivery latency and delivery ratio are degraded rapidly. In this paper, we present a new MAC protocol called Multiple Packets Transmission MAC (MPT-MAC) for event-based WSNs. MPT-MAC schedules multiple data packets generated by an event on a single node to be forwarded over multiple hops in an operational cycle. By this means, MPT-MAC can achieve low delivery latency and high delivery ratio under heavy traffic loads. We use event delivery latency (EDL) and event delivery ratio (EDR) to measure the event detection capability of MPT-MAC protocol. We show the performance of MPT-MAC through detailed ns-2 simulation. Compared to S-MAC-AL, R-MAC and DW-MAC, MPT-MAC can achieve lower EDL and higher EDR without more energy consumption. Furthermore, MPT-MAC can obtain lower duty cycle than DW-MAC when satisfying the latency requirement of the applications.**

***Index Terms*—wireless sensor networks, medium control access, event detection, duty cycle, event delivery latency, event delivery ratio**

I. Introduction

With the development of wireless communication, embedded computation and sensor technology, WSNs are used widely in applications including military, industry, agriculture and environmental monitoring, and have been an active research area in the past few years.

Medium Access Control (MAC) protocols control how the wireless devices access the sharing wireless channel, being fundamental protocols and key techniques in wireless sensor networks. In the wireless MAC protocol used by wireless ad hoc networks, such as IEEE 802.11[1], the wireless devices must listen to the wireless channel in order not to miss incoming packets, even when no packets are transmitted or received. Idle listening consumes significant energy[2]. Therefore, traditional MAC protocols are not suitable for WSNs in which sensor nodes are generally battery-powered.

To reduce energy consumption of idle listening, duty cycling mechanism[3][4] has been introduced in wireless sensor network MAC protocols. In duty cycling, each sensor node follows a periodic active/sleeping schedule and the percentage of time in the active state is called duty cycle. When a node is active, it turns on its radio to transmit or receive data packets. However, when sleeping, it turns off its radio to save energy. Most of existing MAC protocols for WSNs adopt duty cycling mechanism, such as S-MAC[4][5], T-MAC[6], R-MAC[7], DW-MAC[8], B-MAC[3], X-MAC[9], RI-MAC[10] and so on.

Event detection is among the major applications in wireless sensor networks. Sometimes we need the long message to describe the event. However, the cost of re-transmitting the long message is very high. So when a node detects an event, more than one small data packet may be generated to describe the event. In addition, with more and more sensor nodes deployed, multiple nodes may detect the events and transmit data packets simultaneously. Current MAC protocols for WSNs are mainly optimized for the situation that an event generates only one data packets on a single node and the event occurrence rate is low. Under such heavy traffic loads, the performance of existing MAC protocols degrades obviously.

In this paper, we present a new MAC protocol for event-based WSNs, called MPT-MAC. MPT-MAC is a synchronous duty cycle MAC protocol. It allows nodes to wake up to communicate in sleep period and to continuously transmit multiple data packets generated by an event. MPT-MAC can achieve low delivery latency and high delivery ratio under heavy traffic loads. Furthermore, with the requirement of the applications satisfied, MPT-MAC can obtain low duty cycle to save energy and prolong the network lifetime. The contributions of this work are as follows:

- Presenting a new MAC protocol MPT-MAC, that schedules sensor nodes to continuously transmit multiple data packets generated by an event.
- Analyzing the possibility of low duty cycle in MPT-MAC when satisfying the requirements of applications.
- Using event delivery latency and event delivery ratio to measure MPT-MAC.
- Evaluating MPT-MAC protocol using NS2 simulator and comparing it with existing MAC protocols.

The rest of the paper is organized as follows. In Section II, we discuss related work and analyze some synchronous MAC protocols. Section III details the design of MPT-MAC. In Section IV, we show results from our simulation-based evaluation of MPT-MAC, including a comparison with existing

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MAC protocols. Finally, Section V presents the conclusions.

II. RELATED WORK

Duty cycle MAC protocols can be classified into two categories: synchronous and asynchronous. In synchronous MAC protocols, all nodes need to be synchronized and wake up simultaneously to transmit data packets, for example, S-MAC, T-MAC, R-MAC, DW-MAC, and so on.

However, in asynchronous MAC protocols, all nodes decide wake-up time according to their own schedules and need not to be synchronized. Asynchronous protocols mainly include B-MAC, X-MAC, RI-MAC, and so on. MPT-MAC presented in this work is a synchronous duty cycle MAC protocol, so we only discuss synchronous MAC protocols in this section.

S-MAC[4] was one of original synchronous duty cycle MAC protocols for WSNs. Figure 1 shows an overview of S-MAC. A cycle of S-MAC is composed of three periods: SYNC, DATA and SLEEP. At the beginning of SYNC period, the node wakes up to broadcast a SYNC packet to synchronize neighbor nodes. In DATA period, if node A wants to send a data packet to node B, they use RTS/CTS/DATA/ACK to complete data transmission. After transmitting the packet, node A and B turn to sleep. Node C without data communication will turn off its radio to sleep at the beginning of SLEEP period.

In S-MAC, nodes periodically alternate between being active and sleeping to reduce energy consumption of idle listening. But in one operational cycle, a data packet can be forwarded only one hop, so multi-hop transmission latency will be greatly increased. Wei Ye et al. proposed S-MAC with adaptive listening(S-MAC-AL)[5] to reduce data transmission latency. As shown in Figure 1, if node C overhears CTS packet from B to A, it will adaptively wake up after the transmission between A and B is done. After node B received a data packet, it will send an RTS to C. If C is the next hop of the data packet, node B can immediately forward the data packet to C and needs not to wait the next cycle. By adaptive listening, a data packet can be delivered up to two hops in one operational cycle.

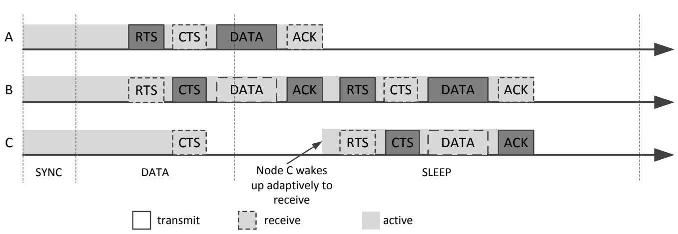

Fig. 1: Schedule of S-MAC and S-MAC-AL

The duration time of DATA period in S-MAC and S-MAC-AL is fixed. Even though nodes have no data packets to communicate in the current cycle, they wait to sleep until DATA period is ended. Nodes in WSNs have no data communications in most of time, so idle listening of DATA period will waste significant energy. The fixed DATA period is not suitable for light traffic load. T-MAC[6] is primarily designed to shorten the DATA period when no traffic is around the nodes, so that nodes can preserve more energy. Its principle is that nodes go to sleep if they cannot detect any specified events in TA. TA is the minimum idle listening time of nodes in a cycle. Although T-MAC can preserve more energy than S-MAC when there is no traffic, it also only delivers a packet up to two hops within one operational cycle and cannot reduce multi-hop delivery latency of data packets.

Some approaches are proposed to reduce deliver latency. However, they make some specific assumptions on the communication pattern. For example, D-MAC[11] reduces data delivery latency only for data gathering tree. The streamlined wakeup optimization proposed by Cao et al.[12] addresses only the case in which each sensor node sends data to a sink node. Lu et al.[13] discusses how to minimize end-to-end delivery latency for a tree or a ring network.

R-MAC[7] introduces a new cross-layer approach to reduce packet delivery latency in multi-hop forwarding. Figure 2 shows the schedule of R-MAC. RTS/CTS in S-MAC are replaced by the pioneer frame (PION) of R-MAC. In an operational cycle, PION is forwarded over multiple hops during DATA period to inform nodes B and C when to wake up to receive or transit the data packets during SLEEP period. According to the number of hops carried in PION, nodes that are on the data forwarding path calculate their wake-up time during the SLEEP period using the equation (1).

$$T_{wakeup}(i) = (i-1) \cdot (durDATA + SIFS + durACK + SIFS) \quad (1)$$

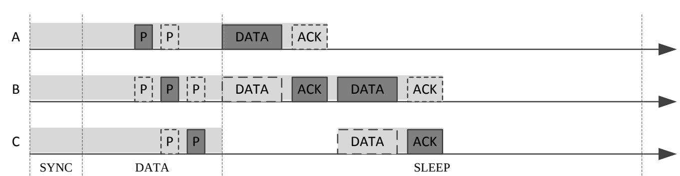

Fig. 2: Multi-hop forwarding of R-MAC

The process of PION forwarding goes on till the DATA period is over, so the number of hops over which R-MAC can forward a data packet in a cycle is limited by the duration of the DATA period. However, a source node (e.g., node A in Figure 2) always starts transmitting a data packet at the beginning of the SLEEP period, two hidden terminal nodes that have succeeded in contending the channel in the DATA period will cause collision at the following SLEEP period.

In order to resolve the collision between the hidden source nodes at the SLEEP period, DW-MAC[8] uses one-to-one mapping to schedule nodes to wake up. Figure 3 gives the overview of the scheduling approach in DW-MAC. In this example, node A wants to transmit a data packet to node B. A firstly contends the channel and then transmits a SCH control frame during the DATA period. Supposed that transmission of SCH starts at T_1 units after the beginning of the DATA period and the duration of transmission is T_3. Based on T_1, T_3, the ratio between T_{Sleep} and T_{Data} and the equation (2), we can calculate the wake-up time T_2 from the beginning of the

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SLEEP period of node A and B, and the maximum wake-up duration T_4. By one-to-one mapping function, data transmission during the SLEEP period will not collide. Furthermore, DW-MAC uses cross-layer approach like R-MAC to reduce multi-hop delivery latency.

$$\frac{T_2}{T_1} = \frac{T_4}{T_3} = \frac{T_{Sleep}}{T_{Data}} \tag{2}$$

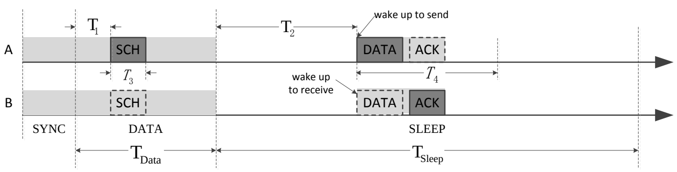

Fig. 3: Overview of the schedule in DW-MAC

Although DW-MAC resolves the problem that the hidden source nodes collide at the beginning of the SLEEP period, it only schedules one data packet to forward during the SLEEP period. If multiple data packets are generated by an event on a single node, DW-MAC has to schedule nodes to transmit data packets to the sink node in multiple operational cycles. This increases the data packets delivery latency. In addition, DW-MAC transmits SCH control frame for each data packet and multiple SCHs waste more energy.

These MAC protocols propose several approaches to reduce packet delivery latency. However, they are optimized for one data packet of an event and low event occurrence rate. MPT-MAC proposed in this paper can schedule multiple data packets generated by an event on a single node to be forwarded over multiple hops in an operational cycle, so it can work well under heavy traffic loads, such as when an event generates multiple data packets on a single node and the event occurrence rate is very high.

III. MPT-MAC DESIGN

A. Overview

MPT-MAC is a synchronous duty-cycle MAC protocol. Each operational cycle of MPT-MAC is also divided into three periods: SYNC, DATA and SLEEP period. We denote the duration of each period by T_{Sync}, T_{Data} and T_{Sleep} respectively. Similar to prior works, MPT-MAC must use synchronizing mechanisms[14][15] to resolve the clock drift and ensure to synchronize the clock in sensor nodes.

The principle of MPT-MAC is that nodes are scheduled to wake up during SLEEP period and to deliver multiple data packets over multiple hops in an operational cycle. In order to deliver multiple data packets, the receiver node that is scheduled to wake up in the SLEEP period waits for a little duration T_{wait} after receiving a data packet. If the node does not receive any data packet during T_{wait}, it will go to sleep.

Figure 4 shows the example of multiple data packets transmission in MPT-MAC. In this example, node A detects an event and generates two data packets for this event. These two packets need to be transmitted to node B. According to

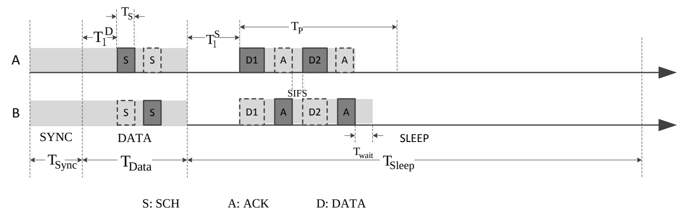

Fig. 4: Multiple packets scheduling of MPT-MAC

the scheduling algorithm of MPT-MAC, node A and B wake up to transmit the data packet at T_1. Unlike DW-MAC, node B will keep listening to the channel. If there are other data packets in the A's queue, Node A can transmit the data packet D2 to B SIFS delay after receiving ACK for D1 from B. Once A receives ACK for D2, A goes to sleep. However, node B will wait for a little duration T_{wait} after receiving D2. If B doesn't receive anything during T_{wait}, it will go to sleep. As described in the example, node A only needs one operational cycle and one SCH frame to transmit two data packets to B in MPT-MAC, but DW-MAC needs two operational cycles and two SCH frames. With the number of the data packets generated by an event on a node increasing, the number of the operational cycles and the SCH frames needed by DW-MAC will increase accordingly.

B. Wakeup Scheduling

MPT-MAC uses one-to-one mapping function to schedule nodes to wake up intelligently, just like DW-MAC. Node A that wants to transmit a data packet to node B contends the wireless channel using CSMA/CA protocol in IEEE 802.11. Once succeeding in contending the channel, node A will transmit a special SCH frame (SCH includes all fields of RTS/CTS and has the same function with RTS/CTS) that replaces RTS control frame. Node B replies with a SCH frame as CTS. Node A and B calculate their wake-up time T_i in the SLEEP period using the equation (3) respectively.

$$T_i^S = SDTR \cdot T_i^D \tag{3}$$

In the equation (3), we denote by $SDTR = \frac{T_{Sleep}}{T_{Data}}$ the ratio between the duration of the SLEEP period and the DATA period and by T_i^D the time difference between nodes transmitting/receiving SCH frame and the beginning of the DATA period.

As shown in Figure 5, in order to reduce multi-hop delivery latency of data packets transmission, MPT-MAC uses cross-layer approach to schedule multiple data packets to forward over multiple hops in a cycle. In the example, node B will send its own SCH frame after receiving a SCH frame from the up hop node A. The SCH frame transmitted by node B plays two roles: firstly, it is the ACK of node A's SCH frame, secondly, the next hop node C receiving B's SCH frame uses the mapping function in the equation (3) to calculate wake-up time to receive data packets, so that multiple data packets can be forwarded over multiple hops in an operational cycle.

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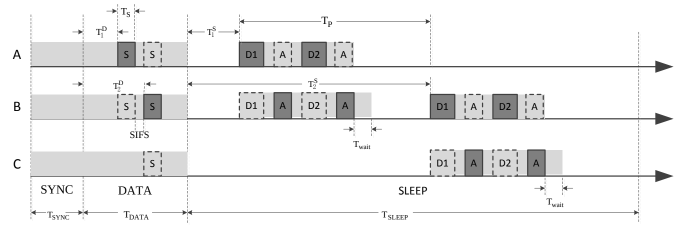

Fig. 5: Multiple hops optimization in MPT-MAC

C. Multiple Packets Transmission

We denote by T_P the maximum time of a node occupying the channel during the SLEEP period, if it succeeds transmitting the SCH frame during the DATA period. According to the equation (3) and Figure 5, the time of node A using the channel without collision in the SLEEP period can be calculated by the following equation:

$$\begin{aligned} T_P &= T_2^S - T_1^S \\ &= SDTR \cdot T_2^D - SDTR \cdot T_1^D \\ &= SDTR \cdot (T_2^D - T_1^D) \\ &= SDTR \cdot (T_S + SIFS) \end{aligned} \tag{4}$$

In DW-MAC, node A will go to sleep immediately after transmitting data packet D1 in the time interval T_P. However, the communication latency u between two nodes is less than T_P in common. We denote u as the following equation (5):

$$u = durDATA + SIFS + durACK + SIFS \tag{5}$$

Therefore, MPT-MAC can transmit multiple data packets in the time T_P. In order to avoid collision between A's transmission and B's, according to the equations (4) and (5), the maximum number of data packets transmitted by node A is $N_{max} = [\frac{SDTR \cdot (T_S + SIFS)}{u}]$. Each node must maintain a transmitting/receiving counter. The counter is added by 1 when the node transmits or receives a data packet.

When one of the following three situations happens, the node does not transmit the data packets in the queue or receive data packets any more, and goes to sleep:

1. The value of counter is equal with N_{max};
2. Nodes find that the remain time of T_P is less than u;
3. The receiver node cannot receive any data packet in T_{wait}, it turn to sleep. Because the sender node transmits the next data packet SIFS delay after receiving ACK of the previous data packet, we denote $T_{wait} = SIFS + T_{MAX\_PRO\_DLY}$, where $T_{MAX\_PRO\_DLY}$ presents the maximum propagation delay.

D. Low Duty Cycle

Duty cycle is denoted by the ratio between the active time of a node and the cycle:

$$duty\_cycle = \frac{T_{Sync} + T_{Data}}{T_{Sync} + T_{Data} + T_{Sleep}}$$

If a node has lower duty cycle, it will consume less energy and the lifetime of the node is longer. However, low duty cycle increases the sleep latency during the data packets forwarded. The major challenge of MAC protocol design for WSNs is how to tradeoff between low latency and energy consumption.

Compared with DW-MAC, MPT-MAC can schedule multiple data packets to deliver multiple hops without collision in an operational cycle, so it is possible for MPT-MAC to achieve lower duty cycle than DW-MAC. We analyze the relationship between the duty cycle and the data packets delivery latency, when a node transmits two data packets in one hop in DW-MAC and MPT-MAC. We give some following assumptions in DW-MAC and MPT-MAC to simplify the analysis:

1. Nodes always generate data packets when waking up.
2. Nodes always succeed in contending the channel at the same time T_D.
3. Nodes have the same T_{Sync} and T_{Data}, so $T_{Listen} = T_{Sync} + T_{Data}$.
4. The duration of one RTS/CTS handshake is $t = 2 \cdot durCtrl + SIFS$. We use $durCtrl$ to present the duration of control packet transmission.
5. DW-MAC's duty cycle is d, and MPT-MAC's duty cycle is $k \cdot d$, where k is a constant.

According to the wake-up scheduling mechanism described in subsection III-B, we can calculate the two data packets deliver latency in one hop in DW-MAC and MPT-MAC respectively:

$$\begin{aligned} Delay_{DW} &= T_{Cycle}^{DW} + SDTR_{DW} \cdot T^D + u \\ &= T_{Cycle}^{DW} + \frac{T_{Listen} \cdot (1-d)}{T_{Data} \cdot d} \cdot T^D + u \\ &= T_{Cycle}^{DW} + T_{Cycle}^{DW} \cdot \frac{T^D}{T_{Data}} \cdot (1-d) + u \end{aligned} \tag{6}$$

$$\begin{aligned} Delay_{MPT} &= SDTR_{MPT} \cdot T^D + 2 \cdot u \\ &= \frac{T_{Listen} \cdot (1-kd)}{T_{Data} \cdot kd} \cdot T^D + 2 \cdot u \\ &= T_{Cycle}^{DW} \cdot \frac{T^D}{T_{Data}} \cdot \frac{1-kd}{k} + 2 \cdot u \end{aligned} \tag{7}$$

The difference between $Delay_{DW}$ and $Delay_{MPT}$ is given by the following equation (8) according to the equations (6) and (7):

$$\begin{aligned} Delay_{MPT} - Delay_{DW} &= T_{Cycle}^{DW} - u + T_{Cycle}^{DW} \cdot \frac{T^D}{T_{Data}} \\ &\quad - \frac{1}{k} \cdot T_{Cycle}^{DW} \cdot \frac{T^D}{T_{Data}} \end{aligned} \tag{8}$$

From the equation (8), as long as k satisfies the condition of $k \geq \frac{T_{Cycle}^{DW} \cdot T^D}{(T_{Cycle}^{DW} - u) \cdot T_{Data} + T_{Cycle}^{DW} \cdot T^D}$, the delivery latency of DW-MAC will be greater than that of MPT-MAC, $Delay_{DW} \geq Delay_{MPT}$. Obviously, T_{Cycle}^{DW} is much greater than u, so we can draw a conclusion $\frac{T_{Cycle}^{DW} \cdot T^D}{(T_{Cycle}^{DW} - u) \cdot T_{Data} + T_{Cycle}^{DW} \cdot T^D} < 1$. Therefore, when k is greater than a number less than 1, which means the duty cycle of MPT-MAC is less than that of DW-MAC, MPT-MAC will achieve lower data packets delivery latency than DW-MAC.

IV. SIMULATION AND EVALUATION

A. Measure Metrics

For the event detection applications, packet delivery latency (PDL) and packet delivery ratio (PDR) cannot reflect well the capability of event detection in WSNs. Therefore we introduce event delivery latency (EDL) and event delivery ratio (EDR)[16].

- Event Delivery Latency. Supposed that Node S detects an event at T_0 and generates N data packets to describe the event. The sink node R receives all data packets of the event at T_1, we denote $EDL = T_1 - T_0$.
- Event Delivery Ratio. EDR is the ratio between the events succeeded in receiving by the sink node and the number of the events detected by source nodes. Only if the sink node receives all data packets of an event, we call that the sink node succeeds in detecting this event.

To some extent, EDL and EDR can also reflect the network's PDL and PDR. EDL and EDR are more suitable for event-based WSNs, because they reflect well the capability of event detection.

B. Simulation Environment

We evaluate MPT-MAC using version 2.29 of the NS2 simulator and compare it with S-MAC-AL, R-MAC and DW-MAC.

Table I lists the key network parameters used in our simulations. These parameters are the default values in the S-MAC-AL module distributed with NS-2 package. They are used also in the simulations of R-MAC and DW-MAC. We ignore the state transition power and energy consumed by other modules such as CPU and memory[17].

TABLE I: Network parameters

Bandwidth	20Kbps	Tx Range	250m
Tx Power	0.5 W	Carrier Sensing Range	550 m
Rx Power	0.5 W	Contention Window	64 ms
Idle Power	0.45 W	Size of RTS/CTS/ACK	10 B
Sleep Power	0.05 W	Size of SCH	14 B
SIFS	5 ms	Size of Data	50 B
DIFS	10 ms	Channel Encoding Ratio	2
		Slot Time	1 m

Traffic loads are generated by constant bit rate (CBR) flows. CBR can generate variable size data packets (50 bytes in common). So we can simulate the situation that an event detected by a node generates multiple packets by setting UDP's packet size to 50 bytes. For example, if the data generated by CBR is 100 bytes, UDP will send two data packets, which presents a node generates two data packets when detecting an event. Intermediate replying nodes do not aggregate or compress data. We also assume that data processing at any node can be finished within a SIFS duration, so data processing will not introduce extra latency. The transmission latency of all types of packets can be calculated by the equation (9), where we choose 5 bytes for the preamble size p and 2 for channel encoding ratio Encode_Ratio in our simulations.

$$durPkt = \frac{Size_{Pkt} \cdot Encode\_Ratio + p}{Bandwidth} + 1ms \quad (9)$$

Table II lists the transmission latency of all types of packets.

TABLE II: Transmission latency of packets

Type of Packet	Size of Packet(B)	Latency(ms)
RTS/CTS/ACK	10	11
SCH	14	14.2
DATA	50	43

In order to evaluate the MPT-MAC's performance under lower duty cycle, we adopt variable duty cycle in MPT-MAC. However, we keep the same duty cycle of 5% for other MAC protocols. The duration of SYNC, DATA, SLEEP and duty cycle are shown in Table III.

We use two types of scenarios for our simulations: chain and grid network.

Figure 6 give an example of a chain scenario. All nodes are equally spaced in a straight line and neighbor nodes are placed 200 m apart to compose a chain. A CBR that generates the event periodically is connected with node 0 as the source node, and node n is the sink node. In our simulations, we use 21 nodes to compose the chain, so from the source node to the sink node is 20 hops.

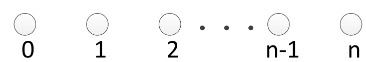

Fig. 6: n-1 hops chain

In the grid network scenario, the 7x7 grid network is composed of 49 nodes. As shown in Figure 7, the x coordinate and the y coordinate of each node are 200m apart. The sink node locates the center of the grid network, and its coordinate is (600, 600).

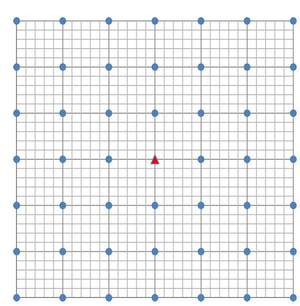

Fig. 7: 7x7 grid network

Based on a correlated-event workload[18], we use a Random Correlated-Event (RCE)[8] to simulate random events. RCE randomly selects a coordinate (x, y) and generate an event there. If the sensing radius of a node is R, only the nodes can detect the event within the circle centered at (x, y) with radius R. With R increasing, more nodes will detect the event and the traffic loads become heavier. Table IV shows the average

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TABLE III: Duty cycle configuration

MAC	T_{Sync}(ms)	T_{Data}(ms)	T_{Sleep}(ms)	T_{Cycle}(ms)	Duty Cycle
S-MAC-AL	55.2	104.0	3025.8	3185.0	5%
R-MAC	55.2	168.0	4241.8	4465.0	5%
DW-MAC	55.2	168.0	4241.8	4465.0	5%
MPT-MAC	55.2	168.0	variable	variable	variable

number of nodes detecting the event with different R. In our simulations, we can adjust the sensing radius of nodes and the number of data packets generated by a node detecting an event to simulate the different types of scenario. In the chain and grid network scenarios, we simulate that a node generates multiple data packets when it detects an event by adjusting the size of data packet in UDP, so that we can evaluate the event detection capability of MPT-MAC.

TABLE IV: Number of nodes detecting the event with different sensing radius

Range	100	150	200	250	300	350	400	450	500
Nodes	0.8	1.8	3.1	4.7	6.5	8.6	10.9	13.3	15.8

C. Event Delivery Latency Evaluation

In this subsection, we evaluate the EDL of MPT-MAC. A node can generate N data packets when detecting an event. EDL is the interval from the source node detecting the event to the sink node receiving all data packets of the event. The average EDL is the average value of EDL of all events.

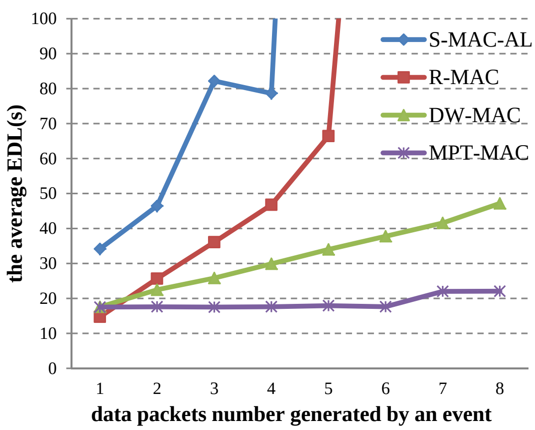

Fig. 8: Average EDL in the 20-hops chain

For the 20-hops chain scenario, we evaluate the average EDL when the number of data packets generated by an event is from 1 to 8. In our simulations, the source node generates an event per 50s. From Figure 8, we find that the average EDL of S-MAC-AL increases to 82.19197s when $N = 4$, and the average EDL of R-MAC increases to 66.42565s when $N = 5$. However, MPT-MAC's average EDL doesn't increase nearly when $N \leq 6$, and it only increases 20% when $N \geq 7$. Because MPT-MAC can schedule multiple data packets to deliver over multi-hop in one operational cycle, when $N \geq 2$, the average EDL of MPT-MAC outperforms DW-MAC. Furthermore, in the case of $N = 8$, the average EDL of MPT-MAC is 22.1s, but the average of EDL of DW-MAC is 47.2s. MPT-MAC reduces the average EDL over DW-MAC by 46.8%.

Figure 9 shows the results of our EDL evaluation for grid network. In our simulations, we keep the sensing radius of nodes 200m, RCE generates an event per 200s and the number of data packets generated by the event is 1 to 8.

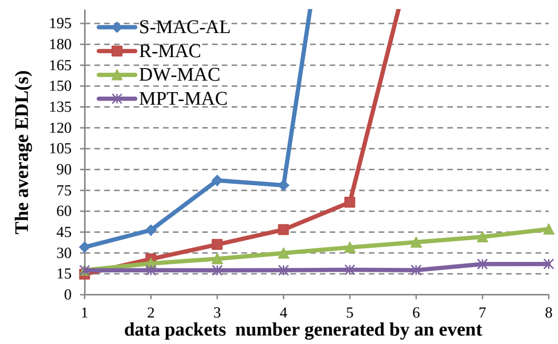

Fig. 9: Average EDL in the 7x7 grid network

From Figure 9 we can see that the average EDLs of S-MAC-AL, R-MAC and DW-MAC all increase with the number of data packets increasing. However, MPT-MAC's average EDL is about 7.9s when $N \leq 6$. When $N = 8$, the average EDL of MPT-MAC is 16.13227s, and DW-MAC is 73.59882s. The average EDL of MPT-MAC is only 22% of DW-MAC.

D. Event Delivery Ratio Evaluation

In this subsection, we evaluate the event delivery ratio of MPT-MAC. The number of data packets generated by an event is 6 in the event deliver ratio evaluation.

In the chain scenario, only node 0 can generate events. Consequently, in order to evaluate the EDR of MPT-MAC, we adjust the event generating rate from an event per 50s to an event per 15s.

Figure 10 shows the EDR of MAC protocols under the different event generating rate. We can find the EDRs of S-MAC-AL and R-MAC are always less than 1, and when the event generating rate reaches an event per 15s, the EDR of R-MAC and S-MAC-AL significantly reduces to 0.13 and 0.0945 respectively. The EDR of DW-MAC keeps 1 until the event generating rate increases to an event per 25s. When the event generating rate increases to an event per 20s, the EDR of DW-MAC reduces to 0.8. And the EDR of DW-MAC is only 0.236 when generating an event per 15s. However, the EDR of MPT-MAC always remains 1 until an event per 15s.

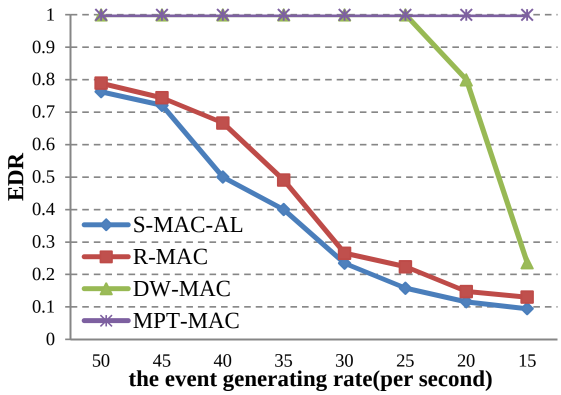

Fig. 10: EDR in the 20-hops chain

For the grid network, there are more nodes that detect the event with the increase of the node's sensing radius, so the traffic loads of the network is increased. Figure 11 shows the results of the EDR evaluation for 7x7 grid network under the different sensing range when RCE generates an event per 200s. We find that the EDR of S-MAC-AL and R-MAC is 0.083 and 0.156 respectively when the node's sensing radius increases to 500m. When the node's sensing radius is 500m, the EDR of DW-MAC is 0.711, and the EDR of MPT-MAC still is about 0.9, which is 25% higher than that of DW-MAC.

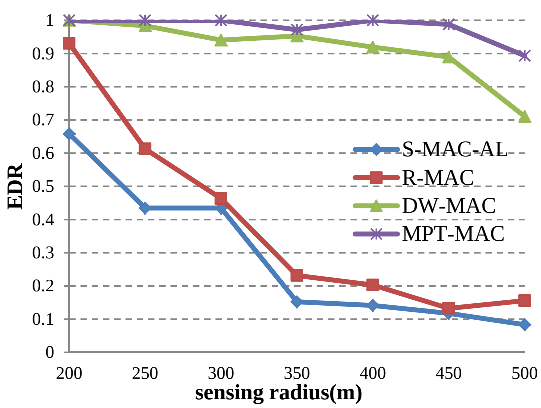

Fig. 11: EDR in the 7x7 grid network

E. Energy Consumption Evaluation

In this subsection, we evaluate the energy efficiency of MPT-MAC. We vary the number of data packets generated by an event on a single node from 1 to 8 in the chain and grid network scenarios, and observe the average energy consumption during the entire simulation.

Figure 12 shows the average energy consumption in the chain scenario. When the number of data packets is increased, the average energy consumption of S-MAC-AL and R-MAC both increase. However, the average energy consumption of DW-MAC and MPT-MAC increase slowly. Because less SCH frames are transmitted in MPT-MAC than in DW-MAC, the average energy consumption of MPT-MAC is always little lower than DW-MAC. When an event generates 8 data packets in a single node, the average energy consumption of MPT-MAC is 5% less than DW-MAC.

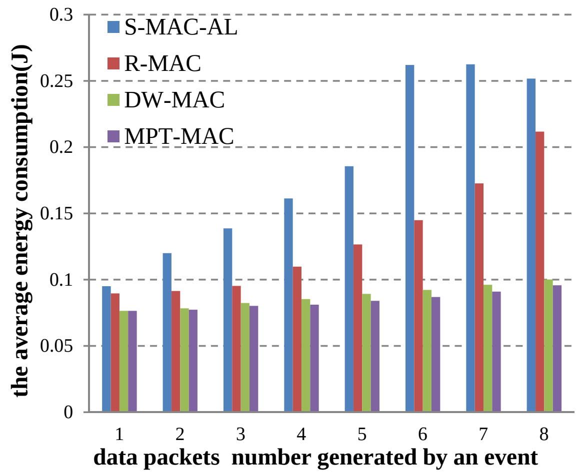

Fig. 12: Average energy consumption in the 20-hops chain

Figure 13 shows the average energy consumption for 7x7 grid network. In this simulation, we set the sensing radius as 200m and RCE generates an event per 200s. We find that the energy efficient of MPT-MAC is as much as that of DM-MAC. However, Figure 9 shows the average EDL of MPT-MAC is much less than that of DW-MAC under this condition.

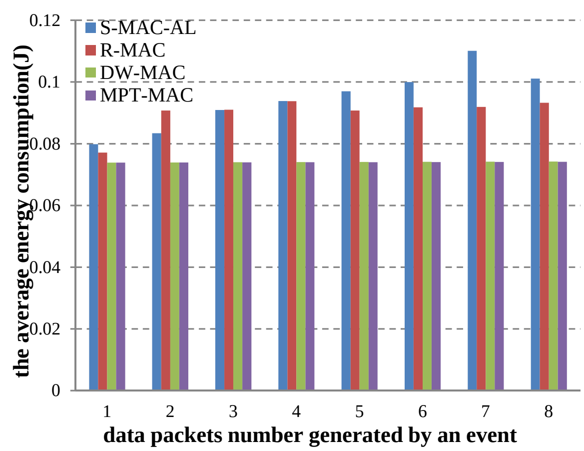

Fig. 13: Average energy consumption in the 7x7 grid network

F. Duty Cycle Evaluation

According to the analysis in the subsection III-D, MPT-MAC can achieve comparable or better EDL than DW-MAC with 5% duty cycle. In this subsection, we evaluate the EDL and the average energy consumption of MPT-MAC when it adopts variable duty cycle from 2% to 5%, but the duty cycle of DW-MAC keeps 5%. We only use 7x7 grid network to evaluate the duty cycle of MPT-MAC. In our simulation, we keep the sensing radius of 200m for MPT-MAC and DW-MAC. RCE generates an event per 200s and each event generates 6 data packets.

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The average EDL of MPT-MAC with different duty cycle is shown in Figure 14. We find that the average EDL of MPT-MAC remains about 10s when the duty cycle is less than 3.5%, and the average EDL of MPT-MAC increase obviously when the duty cycle is less than 3%. The average EDL of DW-MAC is about 51.04s. Even though the duty cycle of MPT-MAC reduces to 2%, the average EDL of MPT-MAC is 22.3s, that is still about 50

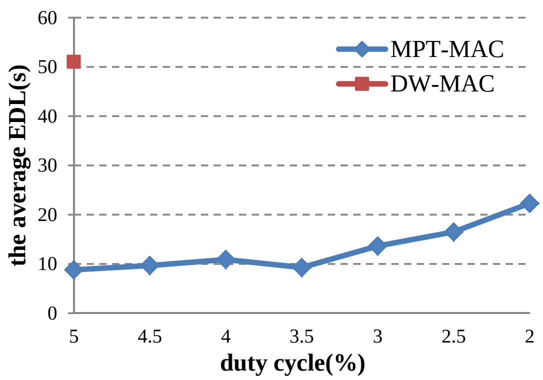

Fig. 14: Average EDL of MPT-MAC with different duty cycle

From the results shown by Figure 14, we draw a conclusion that the average EDL of MPT-MAC is much lower than that of DW-MAC even when the duty cycle of MPT-MAC is only 2%. So it is possible for MPT-MAC to achieve higher energy efficient. Figure 15 shows that the average energy consumption of MPT-MAC with 2% duty cycle is 8% less than that of DW-MAC with 5% duty cycle. During the entire simulation, in most of time nodes have data communications. When the traffic loads are ultra-light or even zero, lower duty cycle gains higher energy efficient.

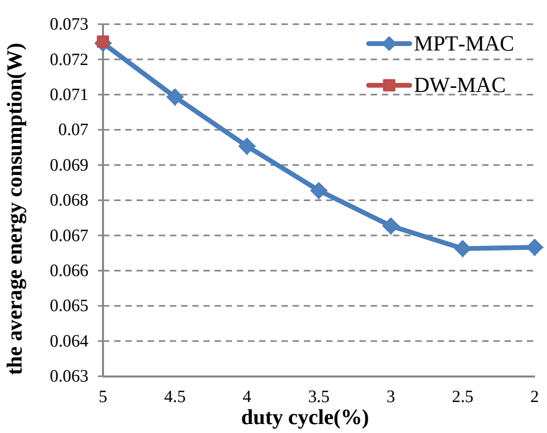

Fig. 15: Average EDL of MPT-MAC with different duty cycle

V. Conclusion

In this paper, we presented MPT-MAC, a new synchronous duty cycle MAC protocol for event-based WSNs to reduce event delivery latency and to increase event delivery ratio under heavy traffic loads. With the number of data packets generated by an event on a single node and the event generation ratio increasing, MPT-MAC achieved lower EDL and higher EDR than the existing MAC protocols without more energy consumption. Furthermore, MPT-MAC with 2% duty cycle achieved lower EDL than DW-MAC with 5% duty cycle, which means that MPT-MAC can preserve more energy and prolong the lifetime of the WSNs.

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