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Efficient Backoff Priority-based Medium Access Control Mechanism for IoT Sensor Networks

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***Abstract*—Recent rapid penetration of Internet of Things (IoT) in various fields such as smart homes, healthcare, and industrial applications has raised new challenges on the QoS requirements including data prioritization and energy saving. In IoT networks, data is heterogeneous and varies in a wide range of categories and urgency. More critical data must be served more quickly and reliably than regular data. In order to deal with crucial issues effectively and improve the performance of wireless sensor networks in IoT, we propose an efficient Backoff Priority-based Medium Access Control (BoP-MAC) scheme that supports multiple priority data and exploits the use of backoff mechanism. In our proposed solution, data priority is utilized to properly resize the backoff window at the MAC layer to ensure that high-priority data are transferred earlier and more reliably. Numerical simulations are used on OMNeT++ to verify the efficiency of our proposed BoP-MAC protocol in comparison with that of a notably conventional MAC protocol called Timeout Multi-priority-based MAC (TMPQ-MAC) protocol. The attained experimental results demonstrate that our developed BoP-MAC protocol outperforms the comparable conventional one and becomes more efficient for large-scale wireless sensor networks. It can effectively cope with various data priorities and enhance significantly the overall performance, in terms of latency, energy consumption, and packet success ratio, of the network.**

***Index Terms*—Backoff window, Internet of things, MAC protocol, Wireless sensor networks.**

I. Introduction

Nowadays, Internet of Things (IoT) has been emerging as one of the key digital transformation technologies and predicted to influence the global economy with an estimated $4 trillion to $11 trillion and 75.4 billion connected devices by 2025 [1]. IoT has been one of hot research topics in a wide variety of academic and industrial disciplines [2-6]. Many researches have been introduced in order to cope with IoT challenges and issues including QoS flexibility [2, 3], energy efficiency [4-6] and particularly various priority data provision [7-9]. In general, conventional works consider separately or simultaneously the requirements of data priority and energy usage, and their methods can be divided into three main categories that are MAC layer, routing and queue priority in network layer, or application layer [6]. However, each method category has its own limitations. The application layer and priority-queue or routing approaches could theoretically prioritize a wide variety of traffic and data types, but they have a high complexity that is not suitable for the fact that, in IoT, sensors normally have restricted memory and energy [8, 9]. Conversely, the MAC layer approach capable of reducing energy consumption while ensuring a sufficient communication quality is more widely used [10-15]. The reason is that MAC protocol directly controls transceivers, which are the most energy consumed elements. Hence, the development of energy-efficient, QoS-guaranteed and data priority-based MAC protocols is essential.

Up-to-date MAC protocols developed, to the best of our knowledge, hardly fulfill the critical issues of modern IoTs, particularly for provisioning concurrently multiple-priority-level data services [11-15]. In the work of [11], a MAC protocol has been introduced to deal with two priority levels (high or low) of the data packet and high priority data packet is preferentially handled. However, using a fixed timeout timer causes the latency to increase significantly. To improve on this, an advanced MAC protocol which is Timeout Multi-Priority-Based MAC (denoted as TMPQ-MAC) [12] is a receiver-initiated protocol that is able to provide a synchronous way and take into account four separate packet priority levels, where the timeout timer stops early on receiving the highest priority data transmission request in order to decrease the end-to-end delay and extend the lifetime of network. Moreover, in [13], the authors assigned the packet priority by considering the residual energy, rather than using the data emergency and the work did not guarantee the small average latency of packets. In addition, [14] only considered very few levels of data priority. On the other hand, different scheduling algorithms were developed to enhance the media access control protocol performance, specially by dynamically adapting the size of contention windows [14, 15]. It is showed that adaptively controlling the contention window size plays a major role in improving the network efficiency. Indeed, in order to enhance the network performance, the authors in [15] also introduced an adaptive contention back-window scheme by calibrating the waiting time but unfortunately, it was only applied for un-narrow band and not restricted powered WLAN. On the other hand, several MAC protocols that consider the backoff mechanism have been introduced [16, 17], however, they did not consider the data priority and have not been designed for low-speed IoT environments.

In this paper, to overcome the shortcomings of the above studies, we target an efficient media access control protocol by taking the advantages of a data priority-based collision avoidance approach. Our developed MAC scheme is able to exploit the use of duty cycle and active/sleep periods by applying RTS/CTS handshaking mechanism like traditional MAC protocols while provisioning multi-priority data services and controlling the backoff contention window of data transmission considering the data priority for IoT wireless sensor networks and so, called backoff priority-based

MAC protocol (BoP-MAC). Numerical simulations using OMNeT++ are employed to evaluate the performance of the proposed BoP-MAC solution. We also compare our developed solution to the notable traditional WSN MAC protocol, that is TMPQ MAC protocol, under various network conditions. The obtained results prove that our proposed BoP-MAC solution remarkably gains better performance than the TMPQ-MAC. It offers significantly lower average delay, consumes dramatically less energy while guaranteeing a sufficiently greater packet success rate, especially with large scale networks.

The rest of the paper is organized as follows. The proposed BoP-MAC mechanism is presented in Section II. Section III presents performance evaluation of BoP-MAC and TMPQ-MAC protocols based on numerical experiments, and our conclusion is given in Section IV.

II. Proposed Backoff Priority-based Media Access Control Mechanism

A. *Media Access Control Mechanism*

Fig. 1 describes the main principles of SMAC [18] and TMPQ-MAC [12] protocols which have two schemes that can solve the delay reduction and priority handling at the MAC layer. SMAC works synchronously and uses RTS/CTS/DATA/ACK (Request-To-Send/Clear-To-Send) where the contention window is applied to RTSs. The RTS/CTS mechanism helps to avoid hidden terminals and also helps to reduce the level of conflicts due to the small size of RTS/CTS compared to DATA packets. In this mechanism, the contention window is determined by a random value in the range 0-CW. SMAC does not handle data prioritization, all data sent from sensor nodes are treated equally. TMPQ-MAC is improved from SMAC and MPQ by using the same operating mechanism as SMAC but adding four priority levels (p_4, p_3, p_2, p_1) for data like MPQ and using this priority to prioritize data. Sending RTS in TMPQ-MAC follows p-persistent CSMA-CA principle, in addition to distinguish sending priority of data TMPQ-MAC treats RTS receiving with highest priority (p_4) as SMAC while with RTS of lower priority (p_3, p_2, p_1) will be sorted in priority order at the end of fixed window T_w (equivalent to CW of SMAC). This ensures that priority data is received in priority order and the highest priority data is sent at the earliest. However, using the p-persistent CSMA-CA mechanism in combination with Tw increases the average packet sending delay and also causes RTS loss by allowing many RTSs to be sent before only at most one RTS is received in a cycle.

B. *Backoff Behavior*

The backoff behavior is described in [19], with backoff time counter is decremented as long as the sender senses the idle state of the channel, stopped when the sender detects transmission on it (channel busy), and revived as it senses the channel and finds the idle state again for greater than a distributed interframe space (DIFS). The sender transfers a frame as the backoff time gets to zero. At every transmission period, the backoff time is assigned uniformly in the range

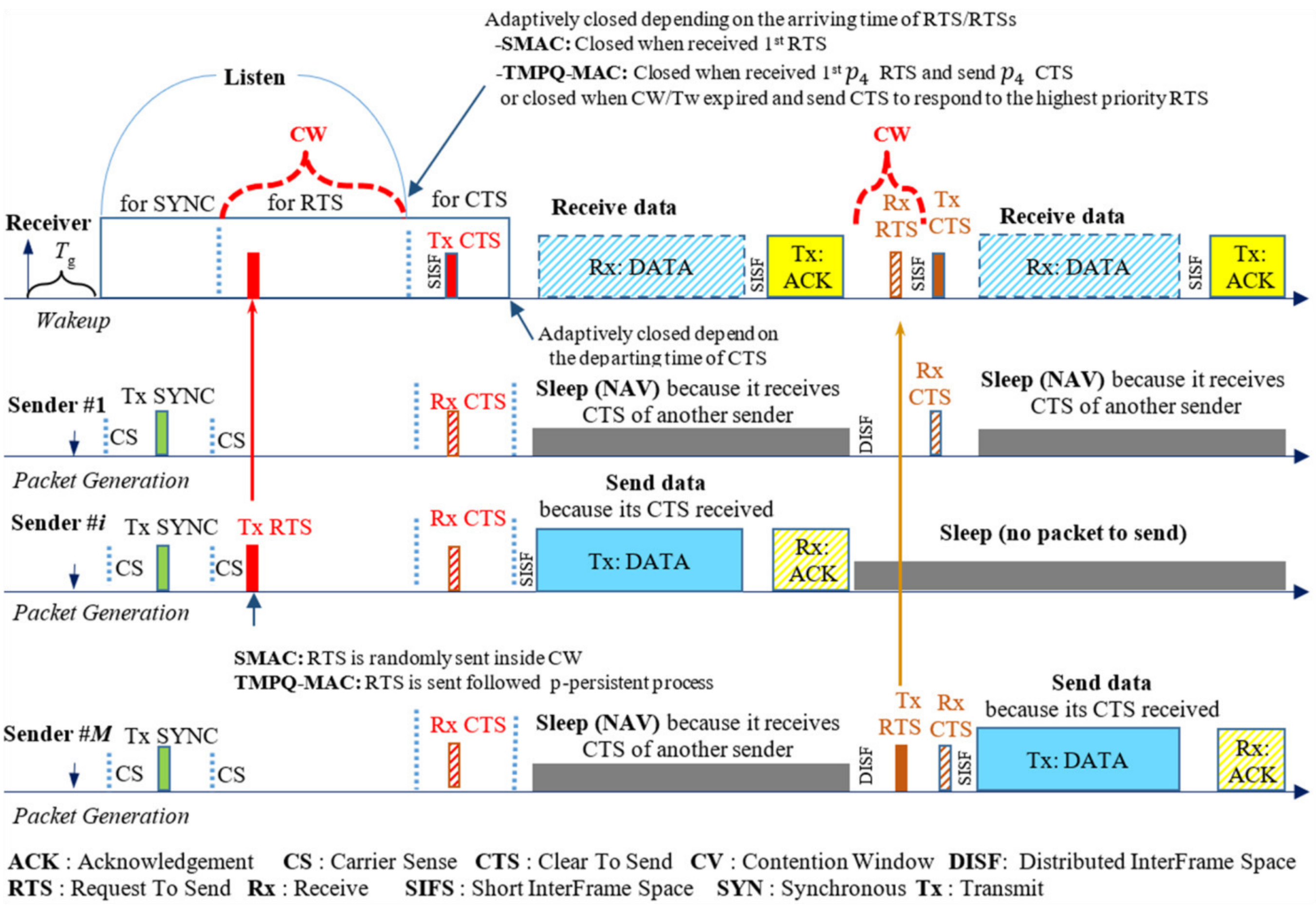


Fig. 1. Principles of S-MAC and TMPQ-MAC protocols

between 0 and (w-1). At the first attempt of transmission, w is fixed at the minimal value of backoff window. When the transmission is failed, the value of w is twofold until it reaches the pre-determined maximum value.

C. *Proposed Approach*

Our proposed BoP-MAC protocol employs a SMAC duty cycle and duration of active and sleep periods that are fixed, depending on the application requirements. It also inherits the data prioritization approach introduced in the work of [12] (TMPQ-MAC). We divide levels of priority into four types of data that are urgent, most important, important, and normal consecutively. The contention window is adaptively split into separate sections based on the data priority levels and the number of consecutive collisions.

Fig. 2 illustrates the contention window sizes used in our proposed BoP-MAC mechanism. An RTS is transmitted from a sender with its collision window adaptable to the data priority level and the busy condition of the channel. If a sender has data, it senses the channel to determine whether the medium is idle or not and randomly transfers its RTS frame within its priority window. In case of a busy medium found, the sender will double its priority contention window. Here, to prevent the collision of the same priority level RTSs from different senders, RTS sending will be started randomly within its contention window duration. Consequently, our MAC protocol is able to lessen the waiting time of receiving the not-selected-senders' CTSs, which can compare to T_w of TMPQ-MAC protocol or CW in SMAC, the earlier sending CTS (like Rx-Beacon in TMPQ-MAC) mechanism also enables other senders to ward off sending frames, and reduce the energy consumption by sleeping in the time of NAV.

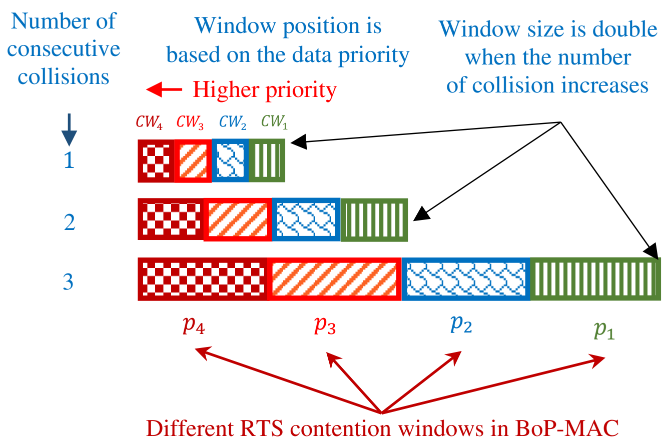


Fig. 2. Priority contention window control of BoP-MAC

III. Performance Evaluation and Discussions

In this section, we have simulated and evaluated the performance of IoT sensor networks that utilize our developed BoP-MAC protocol exploiting the adaptive contention window and backoff mechanism. Numerical simulations are conducted on Castalia 3.3 [20] with CC2420 transceivers [21]. The key experimental parameters and values applied are summarized in Table I. To assess the overall network performance, the three performance indicators taken into account is listed as follows:

- *Average packet delay:* is defined as the duration for senders from the data generated time to the time their data arrive the sink.
- *Average energy consumption:* is determined as the mean consumed energy per bit.
- *Average packet success rate:* is calculated as a ratio of the entire number of different packets (not count for duplicate packets) that are received to the sent packet total.

TABLE I. Main Experimental Parameters

Parameter	Value
Size of sensor network area	10m x 10m
Number of sender nodes	1 to 10
Link bandwidth	250kb/s
Radio	CC2420
Size of SYN	6 bytes
Sizes of RTS/Tx-Beacon	13/14 bytes
Sizes of CTS/Rx-Beacon	13 bytes
MAC overhead size	11 bytes
Listen interval	17ms
RTS/Tx Beacon retransmission number	10
Packet arrival rate	1 packet/s
Application header length	5 bytes
Sensor Startup Randomization	1ms
DATA packet size	28 bytes
ACK packet size	11 bytes
CCA Check Delay	0.128ms
Physical frame overhead	6 bytes
T_g	6.7ms
CW for SMAC and T_w for TMPQ-MAC	10ms
CW_{min} - CW_{max} for BoP-MAC	4-16

1) *Average end-to-end delay of different packet priorities*

Fig. 3 demonstrates the average end-to-end latency of various packet priorities of TMPQ-MAC and BoP-MAC. The end-to-end packet delay in the network with TMPQ-MAC is greater than in that of BoP-MAC for all four packet priority levels.

A T_w timer used at the receiver for TMPQ-MAC to collect TxBeacons from all senders. If p_4 TxBeacon is received by the receiver, the receiver sends back RxBeacon to p_4 sender, other senders knows and wait until the next frame (for NAV duration shown in the RxBeacon). If receiver does not receive p_4 TxBeacon but other lower priority ones, it will have to wait till the end of T_w timer, and then select the greatest and earliest priority TxBeacon to determine. Therefore, the average delay of p_4 packets is lowest ranging from 13.4 to 69.7ms while the average delay of p_3, p_2, and p_1 packet is higher, in the ranged from 30.7, 30.7 and 30.6 to 152.8, 153.5, and 138.0ms, accordingly. The results seem to show different trend in the delay of p_3, p_2, and p_1 packet because with the limited number of RTS retransmission, RTS of higher priority level will reach the receiver more with higher number of retransmission compared to the RTS of lower priority level.

BoP-MAC uses the scheme of accepting first RTS, the contention window is close and receiver immediately send CTS, that bring about a less packet delay compared to TMPQ-MAV. Furthermore, with the adaptive window size based on priority, the average delay of p_4 packets is lowest ranging from 12.3 to 16.9ms while the average delay of

p_3, p_2, and p_1 packet is ranged from 12.9, 13.8 and 14.8 to 20.8, 23.7 and 25.8ms, accordingly.

Actually, the graphs present a gradual growth in the average end-to-end packet delay of each priority level as the number of sending nodes increases because as the number of senders increases, the probability of contention is higher.

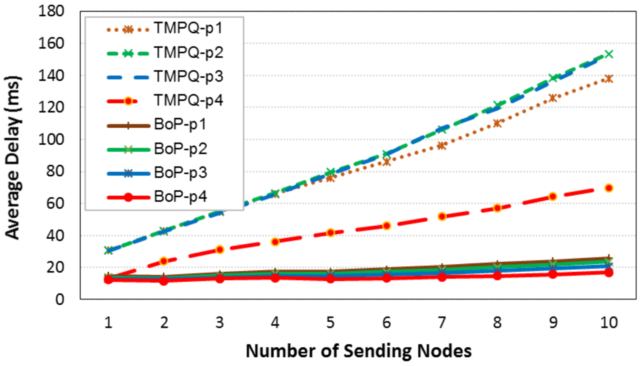


Fig. 3. Average multi-priority packet delay comparison between TMPQ-MAC and BoP-MAC

2) *Average end-to-end delay*

Fig. 4 describes the average end-to-end delay of all priority packets obtained by the proposed BoP-MAC protocol in comparison with that of the comparable TMPQ-MAC protocol. It is showed that the average delay attained in the proposed BoP-MAC-based network is greatly cut down compared to that of the TMPQ-MAC one. The reason for the cut down is that BoP-MAC soon adopted RTS scheme for all RTSs, not just p_4 one. The average delay of the entire packet using BoP-MAC when the number of nodes increases from 1 to 10 steadily increases from 13.5ms to 21.8ms while the corresponding delay with TMPQ-MAC increases rapidly from 26.3ms to 114.4ms.

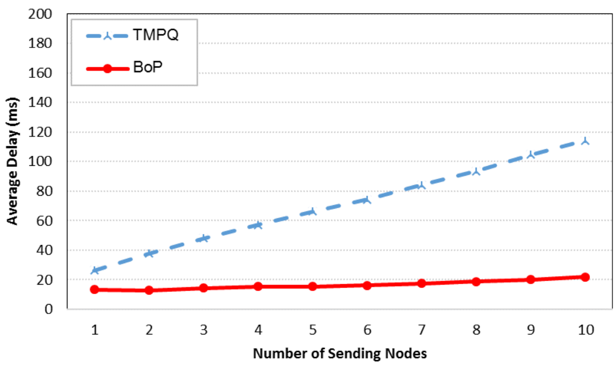


Fig. 4. Average packet delays of TMPQ-MAC and BoP-MAC

3) *Average energy consumption per successful delivered bit*

The simulated results in Fig. 5 illustrate that the average consumed energy (calculated in *mJ per bit*) of the proposed BoP-MAC-based network is much less than that of the network with TMPQ-MAC, and as the number of nodes increases the difference in energy consumption turn into more observable. Specifically, the average power consumption with BoP-MAC when the number of simultaneous sending nodes increases from 1 to 10 is 0.23*mJ/bit* to 0.25*mJ/bit* while with TMPQ-MAC the corresponding power consumption is 0.22 *mJ/bit* to 0.59*mJ/bit*.

The BoP-MAC makes the use of adaptive contention window, so the earliest RTS sender could transmit its packets while other nodes will sleep until the next period. Meanwhile, in TMPQ-MAC, using p-persistent mechanism, all senders have to seed and wait until they can send their TxBeacons. In that case, if p_4 TxBeacon reaches the receivers, the TxBeacon contention window is closed and p_4 RxBeacon is sent from the receiver to confirm the p_4 sender, if not, all senders must stay awake until T_w is expired. Hence, the average senders' wake-up time is much more than that of BoP-MAC, this explains the expanded consuming energy in TMPQ-MAC for wakeup state.

Moreover, as the sender number is enlarged, the competition level becomes greater and more energy is consumed, too. In this circumstance, BoP-MAC offers many advantages over TMPQ-MAC with an adaptive closing window when receiving the earliest incoming RTS, the node number becomes greater, the total congestion window time of each node and the power consumption become less than that of TMPQ-MAC.

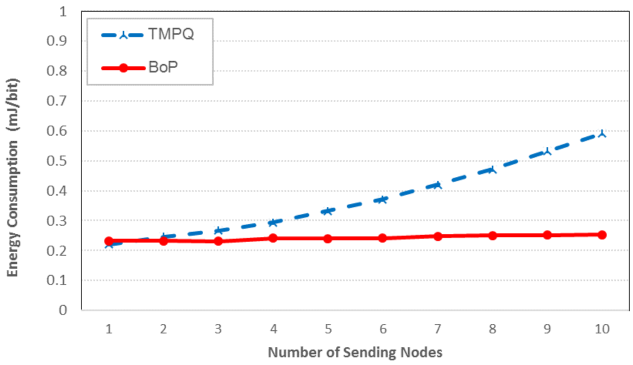
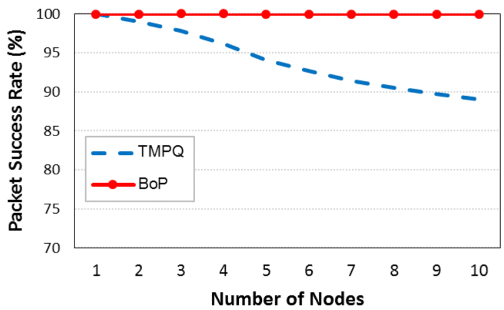
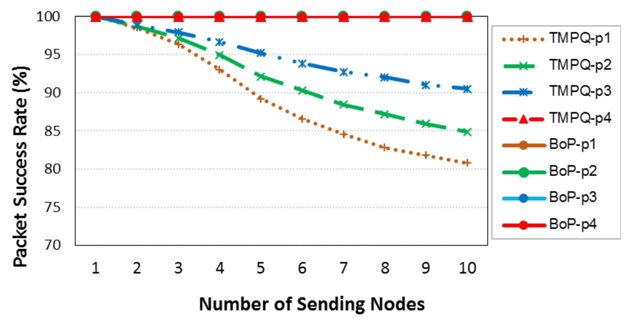


Fig. 5. Energy consumption comparison

4) *Average packet success rate*



a) Average packet success rate



b) Different priotity packet success rate

Fig. 6. Packet success rate analysis

Fig. 6 describes the average packet success rate (PSR) comparison between TMPQ-MAC and BoP-MAC protocols. Fig. 6a describes the total average for all packet priority levels. We can see that TMPQ-MAC has 88% PSR when the number of senders reaches 10 while BoP-MAC gets 100% PSR. Fig. 6b demonstrates the separate priority packet PSR of the two MAC protocols. For BoP-MAC, the PSR is 100% with all four priority level packets, but for TMPQ-MAC the PSRs are nearly 100% for p_4 packets, while for p_3, p_2, p_1 are lower with the corresponding value of 90.5, 84.8, 80.8 % PSR when the number of senders reaches 10.

This result also shows that TMPQ-MAC has a higher packet loss rate despite having the same retransmission number as BoP-MAC. And if the transmission rate has not reached 100%, the number of retransmissions needs to be increased to get better PSR, and so the packet transmission delay will also increase. If the number of retransmissions is restricted, the higher priority packets will be sent more than the lower priority packets, which will reduce the delay between non-highest priority in TMPQ-MAC because the end-to-end delay only counts for successfully transmitted packets. This further explains the results in Fig. 3, the simulation delay of TMPQ-MAC with the three lower priority categories is almost not much different.

IV. Conclusions

In this paper, we have investigated media access control mechanisms for modern IoT wireless sensor networks that are able to provision multi-priority data and effectively deal with critical challenges on the QoS requirement. To enhance the overall performance, in terms of end-to-end delay, power consumption and packet loss rate, of multi-event IoT sensor networks, we have successfully proposed a backoff priority-based media access control scheme that exploits the duty cycle of traditional MAC protocols like SMAC and fully take the advantages of active/sleep durations with the RTS/CTS handshaking method while being capable of serving multi-priority data effectively and adjusting the backoff contention window for the data transmission with the order of data priority. We have also simulated and evaluated the performance of the proposed BoP-MAC solution in comparison with TMPQ-MAC protocol, one of the notable conventional WSN MAC protocols under various network conditions. Numerical simulations demonstrate that, under the same network and traffic conditions, our proposed BoP-MAC solution offers significantly higher performance than the TMPQ-MAC. The developed BoP-MAC scheme is able to lower the average delay remarkably and consume dramatically less energy while ensuring a greater network packet success rate.

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