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Delay and Reliability Analysis of p-persistent Carrier Sense Multiple Access for Multi-event Industrial Wireless Sensor Networks

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***Abstract*— In industrial environments various events can concurrently occur and may require different quality of service (QoS) provision based on different priority levels. To reduce the chances of collision and to improve efficiency in multi-event occurrence, Carrier Sense Multiple Access (CSMA) is a preferable choice for Medium Access Control (MAC) protocols. However, it also increases the overall delay. In this paper, a Priority MAC protocol for Multi-Event industrial wireless sensor networks (PMME) is proposed. In PMME, use of different p values/sequences is proposed to enable multi-priority operation, which can be optimized to suit different operational classes within industrial applications including emergency, regulatory control, supervisory control, open-loop control, alerting and monitoring systems. In this work, novel mathematical model as well as simulations are presented to validate the accuracy and performance of the proposed protocol. Mathematical analysis shows that the proposed PMME can prioritize data packets effectively while ensuring ultra-reliable and low latency communications for high priority nodes. Simulations in Castalia verify that PMME with different p values/sequences notably reduces packet delay for all four priority classes. The PMME also returns a high packet success rate compared to other two well-known priority enabled MAC protocols, QoS aware energy-efficient (QAEE) and multi-priority based QoS (MPQ), in multi-event industrial wireless sensor networks.**

***Index Terms*— priority MAC, CSMA p-persistent, QoS, industrial wireless sensor network, Industry 4.0**

I. INTRODUCTION

INDUSTRIAL wireless sensor network (IWSN) can be defined as a network of sensors which gathers information from monitored areas using wireless links. The ease of deployment and the potential for scalability/flexibility of IWSNs have resulted in its wider adaptation [1-4] such as automation, process control, health industry and environmental monitoring [5-9].

In IWSNs, in accordance with the emergency levels or criticality of applications, various priority levels can be established [10]. In healthcare, higher priority levels are mostly assigned to emergency events such as first aid for stroke patients [9], or accidents [11]. In other industries, events such as fire hazards, leakages, sensory readings exceeding critical thresholds, poisonous gas or liquid detection in chemical industry [7] can be classified as emergency. Lower priority levels are mainly used for less critical events such as periodic measurement of temperature, humidity, or light intensity. Higher priority events generally require higher quality of service (QoS) (i.e., lower delays or near real-time communications and higher reliability) compared to the less critical events. In addition, low energy consumption is also desired, especially in IWSNs installed in rotary elements of industrial machinery [12].

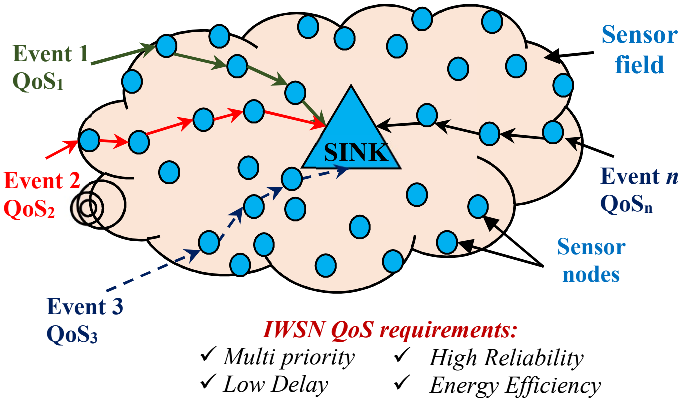

Fig. 1. IWSN QoS requirements

In even more serious situations (see Fig. 1), many events would occur simultaneously requiring more stringent response of the network in a highly competitive fashion [13-15]. For instance, in industrial systems, there are four types of information: safety/emergency information which requires highest reliability and lowest delay of few milliseconds; regulatory/supervisory control information demands high

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reliability and delay of tens of milliseconds; open loop control or alerting information needs medium reliability and delay of seconds to minutes while monitoring information does not require any specific criteria [16]. In the event of an emergency, which links various parts of the factory, multiple emergency messages should be delivered instantly. Another similar scenario develops in forest fire alarm system, where five danger levels of forest fire are established. Level 5 signifies highest level of urgency where the fires can start at any time, therefore, the sensory data must be transmitted quickly to the management center. If a Level 4 (high) or Level 3 (considerable) are reported, the sensor data should reach the center with high reliability because it could indicate a possibility of forest fire. Level 2 (moderate) and Level 1 (low or none) concern with the data which is not too serious and thus can be transmitted without imposing specific requirements of latency or reliability [17]. If wildfire breaks out, the monitoring system must report it immediately. Sometimes, after long periods of dry weather or during summer heat waves, there could be several wildfires, leading to multiple alarms originating within the network. Another similar scenario appears in environmental monitoring systems such as sensory system in a smart house or smart building which operates different priority levels based on the criticality of the sensory information. Gas leakage, smoke, fire sensors fall in as level 1 sensors (highest priority); window breaking, door tampering sensors as level 2 (high); temperature, video, infrared sensors for outdoor area intrusion as level 3 (medium); air quality, house temperature sensors for simple monitoring as level 4 (low) [5-7]. Gas leakage/fire incidents can cause a chain of indoor alarms leading to a communication dispute. To support multiple simultaneous requests with different priority levels, it is necessary for traditional and industrial sensor networks to have an emergency priority mechanism.

In past few years, many QoS based Medium Access Control (MAC) protocols are proposed for Wireless Sensor Networks (WSNs)/IWSNs based on [1, 11, 18-29]. However, only few targeted priority as a primary focus. These works can be categorized as reservation based protocols [1, 11], contention based protocols [22, 23], or hybrid protocols [24, 25]. Contention based protocols are based on Carrier Sense Multiple Access (CSMA) scheme which can be split into synchronous and asynchronous protocols. In asynchronous protocols, CSMA p-persistent is used to reduce the chances of collision and improve efficiency [26-29]. In addition, there are two protocols which support different levels of priority, namely QoS aware energy-efficient (QAEE) [22] and multi-priority based QoS (MPQ) [23]. The two protocols considered different packet priorities, however, the packets still had to wait until the end of the disputed window before they can be transmitted. In multiple access events, the situation becomes even worse, where multiple conflicting packets would even reduce the packets' success rate as well as increase delay for retransmission after the collision.

In order to solve the problem of priority transmission of concurrent important packet types, ensuring small delay and satisfactory packet success rate, we propose a Priority MAC protocol for Multi-Event wireless sensor network (PMME) which combines Beacon and priority MAC mechanisms [30]. The contributions of this paper are as follows:

1) A novel CSMA p-persistent mechanism is proposed in which multiple p values can be used for different data priority levels.
2) An extensive mathematical analysis for delay and reliability of received data frames in PMME protocol is presented.
3) PMME is implemented along with QAEE and MPQ protocols to enable comparative analysis in multi-event IWSN.

The rest of the paper is organized as follows: Section II describes the QAEE and MPQ MAC protocols which are based on p-persistent CSMA and considers the priority of data. Section III introduces the proposed PMME MAC protocol with two enhancements. The evaluation of PMME performance based on mathematical analysis and simulations is presented in Section IV and Section V. Finally, the conclusion and future works are covered in section VI.

II. RELATED WORK

Several research works have proposed MAC protocols for multi-priority sensor networks [2, 22, 23, 25, 31] and analyzed the effectiveness of CSMA p-persistent scheme in terms of network delay and reliability [27-29]. In particular, Bhandari and Wang [2] proposed a priority-based deterministic channel access mechanism to reduce the access delay by assigning different MAC layer attributes and used an emergency indication slot to prioritize critical traffic over normal traffic. Although the research enhanced the reliability of the sensor networks, it only considered two levels of priority. Argoubi et al. [25] presented a QoS based MAC protocol for wireless sensor network (WSN) which ensured service differentiation. It was based on a duty-cycle approach which combined TDMA and CSMA/CA schemes. The protocol also introduced an earliest deadline first queue scheduling policy which aimed to prioritize urgent traffic while taking into consideration the packet deadline. This protocol also considers only two priority levels, i.e., urgent and ordinary traffic.

Kim *et al.* [22] presented the QAEE protocol which considered two priority levels of packets and allowed high priority packets to be transmitted faster than low priority ones. In this protocol, receiver node wakes up periodically and listens to the environment for a guaranteed period of time, T_g. Upon success, it sends WakeupBeacon to notify senders. The receiver node waits for a time, T_w, to receive all TxBeacons. The senders insert packet priority bits and the Network Allocation Vector (NAV) field in their TxBeacons. Afterwards, they wait for the RxBeacon with NAV field from the receiver. Since the receiver receives multiple TxBeacons with different priority values, it will select one with highest priority. It then propagates the RxBeacon, carrying the address of the selected sender. Based on the received RxBeacon, the selected sender will be allowed to send data while other senders will not be active during NAV time. QAEE has two disadvantages. First, it considers only two priority levels. Second, the receiver must wait until it receives all TxBeacons from all senders and then sends out RxBeacon. Therefore, many senders still have to wait and consume energy during idle listening time for RxBeacon.

Sarang *et al.* [23] proposed MPQ which improved QAEE by considering four priority levels and significantly reducing the delay of highest priority packets by accepting first TxBeacon with the highest priority and then sending RxBeacon to the selected sender without waiting until T_w runs out. The MPQ protocol uses CSMA p-persistent mechanism with p inversely proportional to the number of senders, n_s. This mechanism spreads TxBeacon frames from n_s senders evenly to reduce collision. However, the MPQ protocol still has two limitations. First, only the highest priority packets will be processed earlier, while the lower priority packets need to wait until T_w expires. Secondly, assigning p values is quite rigid and unrealistic.

The authors in [31] presented a Priority MAC protocol which considered four priority levels for data transmission, enabling timely access for the highest priority data by hijacking the dedicated transmission bandwidth of the lower priority one. However, this work did not address the case of multiple sensor nodes simultaneously sending the time-critical data to the controller with different deadline bounds.

In [27-29], p-persistent CSMA models were used to analyze the network delay, but it did not consider different priority requirements.

With the existing shortcomings of the above multi-priority MAC protocols and the limitation of non–priority mathematical p-persistent analyses, further improvements to the MAC protocols should be introduced to improve multi-event IWSN performance. In addition, the new proposal should also take into account the QoS requirements for different WSN/IWSN applications as summarized in Table I.

TABLE I

QOS REQUIREMENTS FOR DIFFERENT PRIORITY APPLICATIONS

Applications	Information Category	Priority QoS Requirements	
		Reliability	*Delay/Time constraint*
Industry systems [1,11]	Safety/Emergency information	Very high	Few milliseconds
	Regulatory/supervisory control information	High	Tens of milliseconds
	Open loop control or alerting information	Medium	Seconds to minutes
	Monitoring information	Low	Minutes to hours
Forest fire alarm system [17, 32]	Level 5: Fires can start at any time (Emergency)	Highest	Immediately
	Level 4, 3: High possibility of forest fire	High	As soon as possible
	Level 2: Low possibility of forest fire	Medium	Normal (4-12 mins depends on the time in a day)
	Level 1: Low/non possibility of forest fire	Low	Not required
Environmental monitoring system in smart house [5-8]	Gas leakage, smoke and fire sensors	Highest	Immediately
	Window breaking, door tampering sensors	High	As soon as possible
	Temperature, video, infrared sensors for outdoor area intrusion	Medium	Realtime
	Air quality, house temperature sensors for simple monitoring	Low	Not required (within 1 minute)

TABLE II

MATHEMATICAL VARIABLES

Variables	Description	Value used in simulation
a	Distinguishing base	2,3
N	Number of priority levels	4
i	Priority level	[1..N]
p_{rand}	Random value	[0,1]
p_i	Access probability with priority level i	[0,1]
$p_{i,N}$	Linear access probability with priority level i	$i \big/ \sum_{j=1}^{N} j$
$p_{i,a,N}$	Non-linear access probability with priority level i and distingushing base a	$a^{i-1} \big/ \sum_{j=1}^{N} a^{j-1}$
txRetries	Number of TxBeacon retry	[0..*maxTxRetries*]

III. PROPOSED SOLUTION

In order to achieve the multi-level priority, a PMME protocol with two variations is proposed and compared to QAEE and MPQ. The authenticity and performance superiority of the proposed work is ensured with the comparative analysis of the proposed work with MPQ protocol. To prioritize packets as per the requirements of the data, PMME allows the sender to transmit a TxBeacon following CSMA p-persistent mechanism with the p value proportional to the priority level of data (see Fig. 2). The receiver shortens the waiting time for sending RxBeacon, when it receives first TxBeacon from any sender. After waiting for a Short Inter-Frame Space (SIFS) (the required interval for processing a packet and switching the radio state of the sensor node), it sends the RxBeacon accepting the first sender. This RxBeacon also informs other senders to sleep during the data transmission of the selected sender. Frequently used variables are listed in Table II.

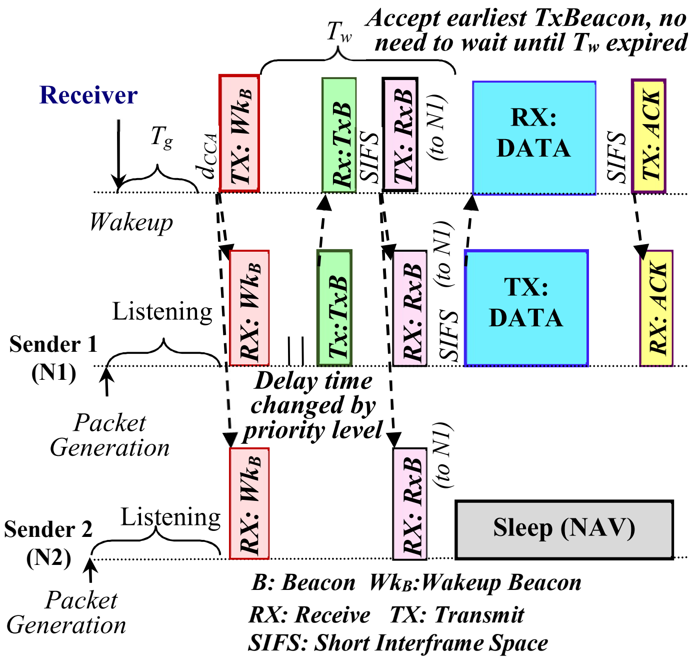


Fig. 2. Description of PMME operation

A. CSMA p-Persistent Mechanism with p Varied by Priority Level

To prioritize packets, in PMME, a new CSMA p -persistent mechanism is applied in which TxBeacon is sent from sender which has data frame to send with p_i varied by priority level (see Fig. 3), higher the priority level, larger the p_i value. In the proposed work, two different types of p_i value are used, linear and nonlinear (see details in Table II*)* to support different QoS requirements of data packet based on the important/ emergency levels [9-11]. In this mechanism, if a sender has data to send, it kickoffs the process by setting its *txRetries* value to *maxTxRetries*. Then, it listens to the medium for a certain time, d_{CCA}, to check if the medium is clear. If the sender finds the medium busy, it will sense the medium again. Otherwise, the sender sows to get a random value p_{rand} (uniform distribution) in the interval [0,1] and follows these next steps:

1) If $p_{rand} \leq p_i$, the sender sends its TxBeacon and countdown its *txRetries* value by one.
2) If $p_{rand} > p_i$, the sender defers to the next time slot and checks the state of the medium again, before sowing to get another p_{rand} value.

As indicated in Fig. 3, the process repeats until the sender receives its RxBeacon (which means there is no collision), at which it starts sending its data frame. In case of collision, the sender checks *txRetries* value. If it reaches zero, the sender will delete the TxBeacon and drop the data frame. Otherwise, it will go back to the medium sensing step. It is clear from this proposed protocol that any data packet with higher priority (i.e., higher p_i value) will have a better chance of early channel access than the ones with lower priority.

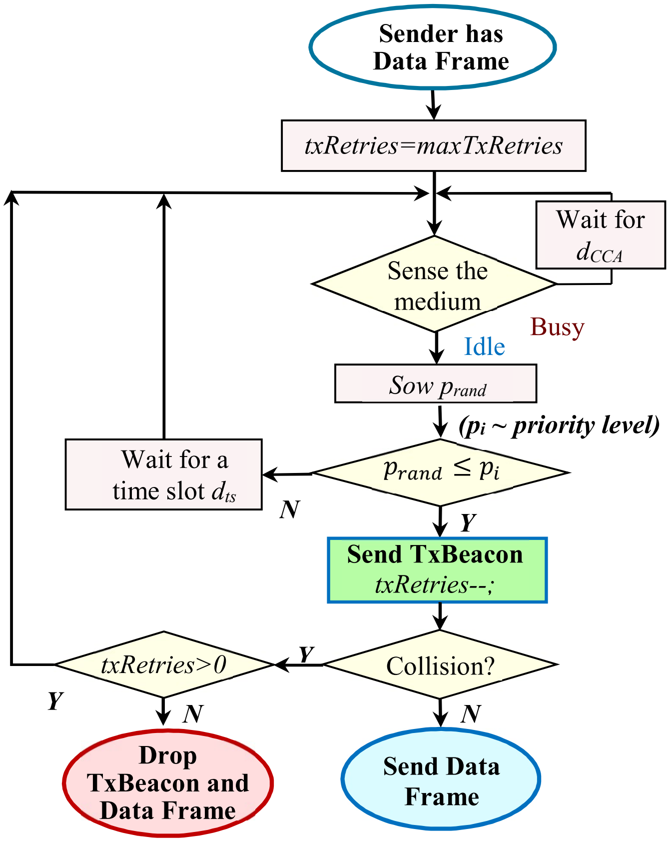


Fig. 3. CSMA *p*-persistent PMME for multievent IWSN

B. *The Earliest TxBeacon Acceptance Mechanism*

To reduce the waiting time in the colliding window after a sender sends WakeupBeacon, PMME protocol uses the earliest TxBeacon acceptance mechanism by sending RxBeacon right after receiving the first TxBeacon. This RxBeacon also announces to all other senders not sending their frames during the NAV time. By doing so, the proposed protocol reduces the waiting time compared to T_w in QAEE and MPQ protocols. The quick response to RxBeacon, also helps other senders in avoiding transmission of their frames, and save energy by sleeping during NAV time.

IV. MATHEMATICAL ANALYSIS OF PMME PERFORMANCE

A. *Assumptions and Notations*

In this paper, a collocated network with limited number of senders is considered, which implies that each sender can hear the transmission of every other sender in the network, therefore, no hidden or exposed terminals exist. As the selected scenario points to the IWSN applications which do not encounter the hidden and exposed terminal problems, therefore, the discussion will be limited to small independent networks, with larger networks covered using multi-channel hierarchical architecture with sub-clustering to facilitate communications and avoid hidden and exposed terminal problems. It is assumed that all terminals exist at a single-hop distance and form a collocated network/cluster irrespective of the infrastructure or ad hoc mode. In addition, the following assumptions and notation are used:

a. A *p*-persistent CSMA for TxBeacon access is used. Hence, each sender accesses the channel in the idle state with probability p_i of sending its TxBeacon frame, where p_i takes value from Table II given $\sum_{i=1}^{N} p_i = 1$.
b. The number of contending senders is M.
c. N priority levels are used, where, probability of a frame which has priority level i is p_{i*}. For simplicity, we assume that all types of priority frames have equal probability, that means $p_{i*} = 1/N \, with \, i = 1,2,\dots,N$
d. The propagation delay is assumed to be significantly smaller than the slot time, so, it is neglected [33].
e. Ideal channel conditions are assumed with symmetric channel, so a transmission failure is only caused by access collision [27].
f. It is assumed that sender can detect collision after their timer is expired or when it receives RxBeacon to another sender.
g. The maximum TxBeacon retransmission value is denoted by *maxTxRetries*.

B. *Reliabilily Analysis using PMME*

The reliability, R, is calculated as $R = N_r/N_s$, where N_s is the packets sent by the sources and N_r is the number of received packets at the receiver. In PMME, TxBeacon is the request frame of a sender which has data to send. However, the immediate sending of TxBeacon is only possible when the sender senses that the environment is idle and when its random number p_{rand} is smaller than the value p_i. After the sender sends its TxBeacon, it waits to receive its corresponded RxBeacon (with the accepted address of its own) and this frame also alerts other senders to sleep during the following data transmission.

a) Probability Approximation for M Senders Accessing Single Channel

Assume that $t_{occupied}$ is the total time a sender occupies the channel to send its data (from sender sending TxBeacon, receiving RxBeacon from the receiver, sending DATA, and receiving ACK from the receiver as detailed in Fig. 2), and each sender has a data frame to send in a cycle of time t_{cycle}.

Figure 4 shows the scenario where a receiver receives data from M senders. If there is only one sender which has to send a data frame, it successfully occupies the channel where the probability p_o is calculated as:

$$p_o = \frac{t_{occupied}}{t_{cycle} - \left(T_g + d_{CCA}\right)}. \tag{1}$$

Suppose there are M senders that request to transmit their data frames. During a cycle of time when each of M senders has one data frame to send, there are three situations:

- The channel is free because no sender accesses the channel, the probability of this situation, p_f, is:

$$p_f = \left(1 - p_o\right)^M. \tag{2}$$

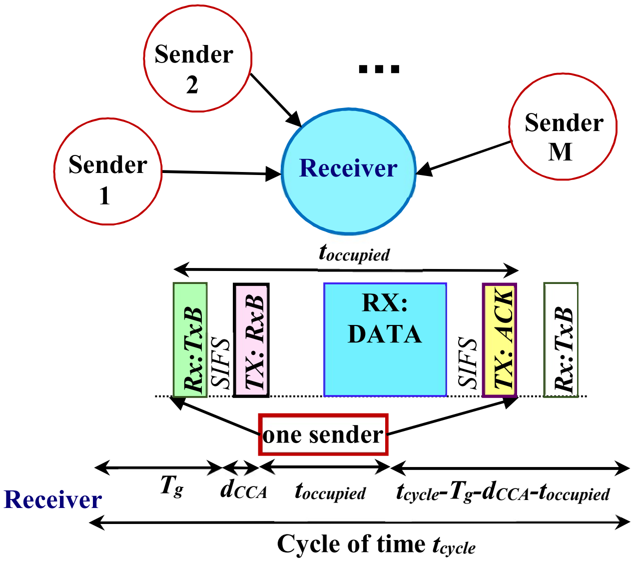


Fig. 4. Senario of p-persistent PMME with one receiver and M senders

- The channel is accessed by one sender while others have not, the probability of this situation, p_s, is:

$$p_s = C_M^1 \times p_o \times \left(1 - p_o\right)^{M-1}. \tag{3}$$

- There is collision in the channel because two or more senders access the channel at the same time [28, 29, 31], the collision probability in the channel p_c is the complement of the two above probabilities and can be expressed as :

$$p_c = 1 - p_s - p_f. \tag{4}$$

So, the probability that one sender successfully accesses the channel when one or more senders access the channel $p_{s,M}$ is given by

$$p_{s,M} = \frac{p_s}{p_s + p_c} = \frac{p_s}{1 - p_f}. \tag{5}$$

The probability that the collision happens when one or more senders access the channel $p_{c,M}$ is expressed as:

$$p_{c,M} = \frac{p_c}{1 - p_f}. \tag{6}$$

b) Approximate Loss Probability of M Senders with Maximum Retransmission maxTxRetries

In the case of multiple concurrent senders, there can be collisions between TxBeacons, then TxBeacons will be lost and be resent again. When the number of retransmissions of TxBeacon reaches over *maxTxRetries*, it will be deleted. So the loss probability would be calculated as

$$p_{loss,M,maxTxRetries} = p_{c,M}{}^{maxTxRetries} = \left(\frac{p_c}{1 - p_f}\right)^{maxTxRetries}. \tag{7}$$

From Eq. (7), it is clear that the higher the *maxTxRetries* value, the lower the loss probability of TxBeacon.

c) Approximate Probability of Successful Transmission with M Senders

At the first sow, a sender with i priority data frame will successfully send TxBeacon with the probability, $R_{TxB,i,M,1}$ where

$$R_{TxB,i,\mathrm{M},1} = p_i \times p_{s,M}. \tag{8}$$

So, the probability of TxBeacons of all priority data frames, successfully sent after the first sow is given by

$$R_{TxB,N,M,1} = \sum_{i=1}^{N}\left(p_{i*} \times R_{TxB,i,M,1}\right) = p_{s,M} \times \sum_{i=1}^{N}\left(p_{i*} \times p_i\right). \tag{9}$$

At the second sow, for simplification, assuming that collision frame would be resent right in the next sow, the ratio of TxBeacon of i priority data frame, successfully sent after the second sow is given by

$$\begin{aligned} R_{TxB,i,\mathrm{M},2} &= R_{TxB,i,\mathrm{M},1} + \left(1 - R_{TxB,i,\mathrm{M},1}\right) p_i \times p_{s,M} \\ &= 1 - \left(1 - p_i \times p_{s,M}\right)^2. \end{aligned} \tag{10}$$

Therefore, the total probability of TxBeacons of all priority data frames, successfully sent after the second sow can be expressed as

$$\begin{aligned} R_{TxB,N,M,2} &= \sum_{i=1}^{N} p_{i*} \times R_{TxB,i,M,2} \\ &= \sum_{i=1}^{N}\left(p_{i*} \times \left(1 - \left(1 - p_i \times p_{s,M}\right)^2\right)\right). \end{aligned} \tag{11}$$

If the number of sows is set to k, the ratio TxBeacon of the i^{th} priority data frame will be successfully sent after the k^{th} sow is given by

$$\begin{aligned} R_{TxB,i,M,k} &= R_{TxB,i,M,\mathrm{k}-1} + \left(1 - R_{TxB,i,M,\mathrm{k}-1}\right) \times p_i \times p_{s,M} \\ &= 1 - \left(1 - p_i \times p_{s,M}\right)^k. \end{aligned} \tag{12}$$

The total ratio of TxBeacons of all priority data frames could be successfully sent after the k^{th} sow is

$$\begin{aligned} R_{TxB,N,M,\mathrm{k}} &= \sum_{i=1}^{N}\left(p_{i*} \times R_{TxB,i,M,\mathrm{k}}\right) \\ &= \sum_{i=1}^{N}\left(p_{i*} \times \left(1 - \left(1 - p_i \times p_{s,M}\right)^k\right)\right). \end{aligned} \tag{13}$$

C. Delay Analysis using PMME

In PMME, as seen in Fig. 2, frame delay in the MAC layer (d_{MAC}) has eight components: (1) the listening delay from packet generation to reception of WakeupBeacon (including the random start time to get sensor data, the guaranteed period of time and clear channel assessment time); (2) time to receive WakeupBeacon from receiverd_{WkB}; (3) access time of TxBeacon d_{access}; (4) time to send TxBeacon d_{TxB}; (5) time for receiving corresponding RxBeacon d_{RxB}; (6) time for sending the data packet d_{DATA}; (7) time to receive acknowledgement d_{ACK}; and (8) other times for status transition as well as time for sensing the environment each time sender need to send a frame (with assumption that propagation delay is so small to be neglected). Thus, the frame delay is obtained by:

$$\begin{aligned} d_{MAC} &= \left(T_{start} + T_g + d_{CCA}\right) + d_{WkB} + d_{access} \\ &\quad + d_{TxB} + d_{RxB} + d_{DATA} + d_{ACK} + 4d_{SIFS}. \end{aligned} \tag{14}$$

where T_{start} presents the average startup time of all sensors.

From Eq. (14), it is clear that the difference in delay of different priority packets at the MAC layer depends mostly on the access time to send the TxBeacon and the random start time of sensors. This access delay will be impacted by p_i, data packet size, and the number of competing senders at a time.

The access delay greatly impacts delay of data frames and therefore, PMME protocol is primarily focused. Here, access delay is defined as the time taken to transmit TxBeacon since the data packet has been generated [27]. The numerical expression of average access delay can be expressed as [27]

$$d_{access,k} = \sum_{j=1}^{k} T_j \times R_j \Big/ \sum_{j=1}^{k} R_j \tag{15}$$

where T_j denotes the time taken until the TxBeacon is sent at the j^{th} sow, k is the number of sowing, and R_j is the success transmission rate of TxBeacon at the j^{th} sow where $\sum_{j=1}^{k} R_j = R_{TxB,j}$. As PMME considers N priority levels with $i = 1..N$ and M senders at a time, average time to successfully transmit TxBeacon of a data frame of priority i and all priority data frame at j^{th} sow are denoted as $d_{TxB,i,M,j}$ and $d_{TxB,N,M,j}$, respectively.

At the first sow, $d_{TxB,i,M,1}$ and $d_{TxB,N,M,1}$ are the time for sensing the state of the medium (see Fig.3), then

$$d_{access,i,M,1} = d_{TxB,N,M,1} = d_{CCA}. \tag{16}$$

After one sow, the unsent TxBeacon left behind from the previous sow has to wait for a duration of d_{ts} and then wait for another d_{CCA} period to sense the medium before sowing again (see Fig. 3). Then, at the second sow, the average time to successfully transmit TxBeacon of a data frame of priority i after two sows is calculated based on Eq. (10) and Eq. (15) as

$$d_{access,i,M,2} = \frac{d_{CCA} \times p_i \times p_{s,M} + (2d_{CCA} + d_{ts}) \times \left(1 - p_i \times p_{s,M}\right) \times p_i \times p_{s,M}}{p_i \times p_{s,M} + \left(1 - p_i \times p_{s,M}\right) \times p_i \times p_{s,M}}. \tag{17}$$

Thus, the average time to successfully transmit TxBeacons of all priority data frames after two sows is calculated as

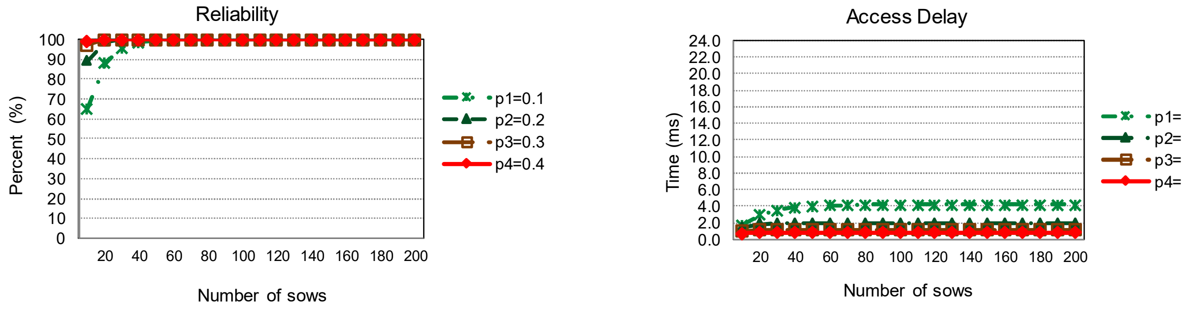
$$d_{access,N,M,2} = \frac{\sum_{i=1}^{N} \left(p_{i*} \times \begin{pmatrix} d_{CCA} \times p_i \times p_{s,M} + \left(2d_{CCA} + d_{ts}\right) \\ \times \left(1 - p_i \times p_{s,M}\right) \times p_i \times p_{s,M} \end{pmatrix} \right)}{\sum_{i=1}^{N} \left(p_{i*} \times \left(p_i \times p_{s,M} + \left(1 - p_i \times p_{s,M}\right) \times p_i \times p_{s,M} \right) \right)}. \tag{18}$$

If the number of sows is set to k, then the average time to successfully transmit TxBeacon of an i priority data frame at the k^{th} sow is approximately calculated as

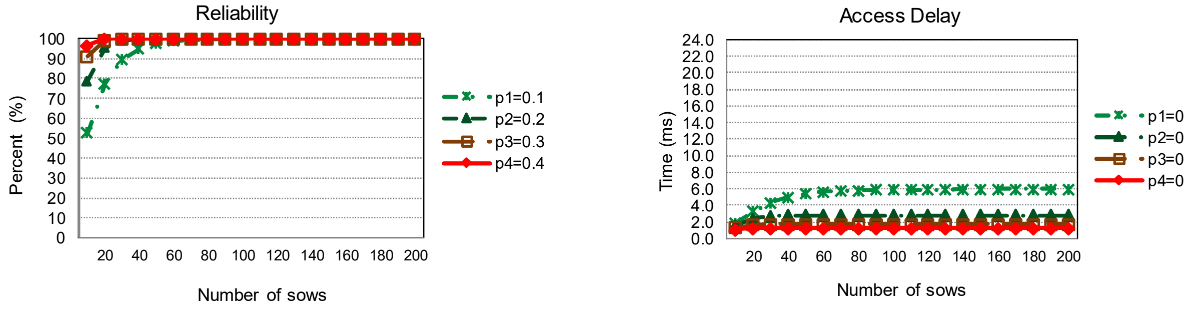
$$\begin{aligned} d_{access,i,M,k} &= \frac{\begin{pmatrix} d_{access,i,M,k-1} \times R_{access,i,M,k-1} + \left(kd_{CCA} + (k-1)d_{ts}\right) \\ \times \left(1 - p_i \times p_{s,M}\right)^{k-1} \times p_i \times p_{s,M} \end{pmatrix}}{R_{TxB,i,M,k}} \\ &= \frac{\begin{pmatrix} d_{CCA} \times p_i + \left(2d_{CCA} + d_{ts}\right) \times \left(1 - p_i \times p_{s,M}\right) \times p_i \times p_{s,M} + \ldots \\ + \left(kd_{CCA} + (k-1)d_{ts}\right) \times \left(1 - p_i \times p_{s,M}\right)^{k-1} \times p_i \times p_{s,M} \end{pmatrix}}{1 - \left(1 - p_i \times p_{s,M}\right)^{k}}. \end{aligned} \tag{19}$$

The average time to successfully transmit TxBeacons of all priority data frames at the k^{th} sow is calculated as

$$d_{access,N,M,k} = \frac{\sum_{i=1}^{N} p_{i*} \times \begin{pmatrix} d_{CCA} \times p_i \times p_{s,M} + \left(2d_{CCA} + d_{ts}\right) \times \left(1 - p_i \times p_{s,M}\right) \\ \times p_i \times p_{s,M} + \ldots + \left(kd_{CCA} + (k-1)d_{ts}\right) \\ \times \left(1 - p_i \times p_{s,M}\right)^{k-1} \times p_i \times p_{s,M} \end{pmatrix}}{\sum_{i=1}^{N} p_{i*} \times \begin{pmatrix} p_i \times p_{s,M} + \left(1 - p_i \times p_{s,M}\right) \times p_i \times p_{s,M} \\ + \ldots + \left(1 - p_i \times p_{s,M}\right)^{k-1} \times p_i \times p_{s,M} \end{pmatrix}}. \tag{20}$$



a) linear p_i, $M = 1$



b) linear p_i, $M = 10$

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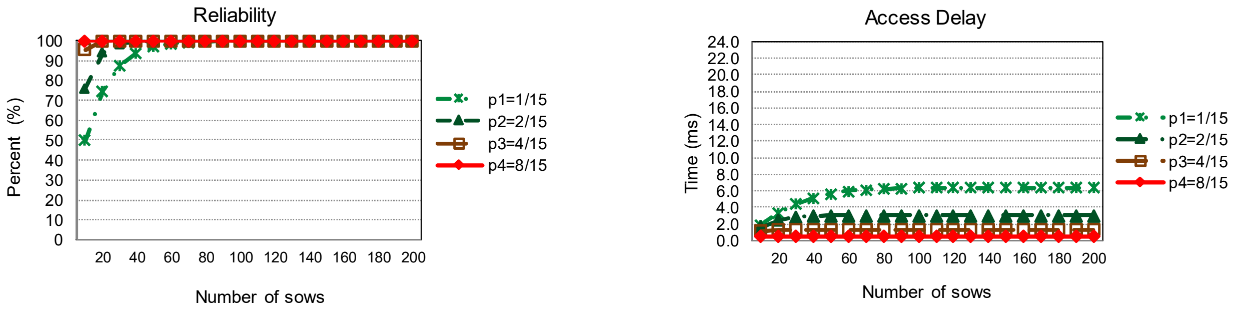
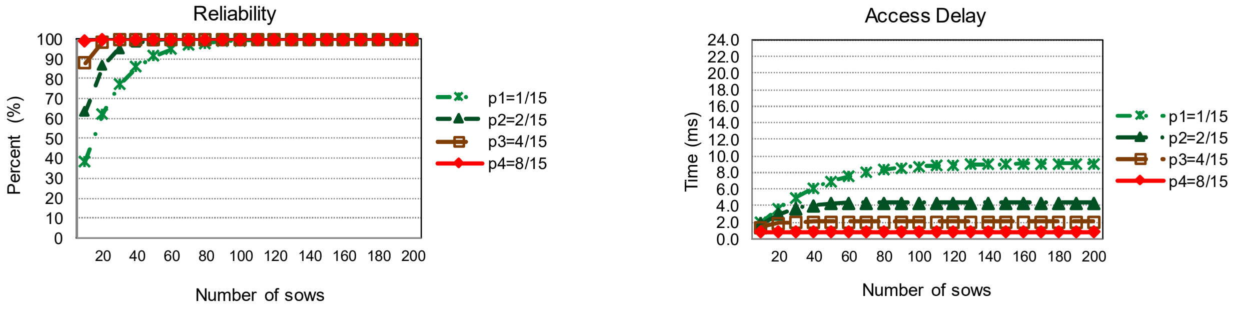
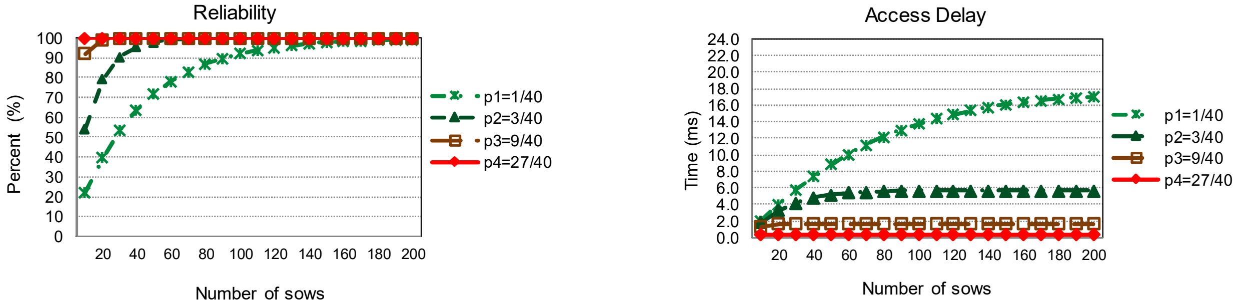


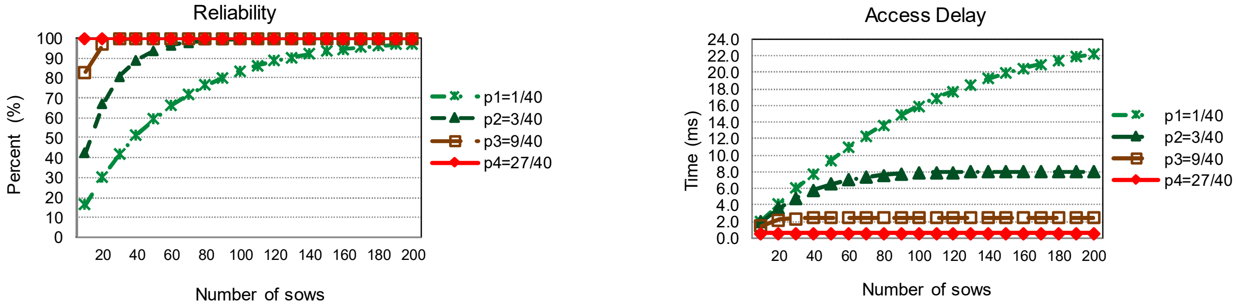
c) nonlinear p_i *with* $a = 2, M = 1$



d) nonlinear p_i *with* $a = 2, M = 10$



e) nonlinear p_i *with* $a = 3, M = 1$



f) nonlinear p_i *with* $a = 3, M = 10$

Fig. 5. Analysis of reliability and access delay of transmitting TxBeacon with different value k, number of senders M, and p_i

D. Evaluation and Discussion

This section provides analysis of TxBeacon access delays and the success rate of PMME. The parameters used for evaluation purposes are summarized in Table II and III. Different $\mathrm{p_i}$ values and sequences (linear/non-linear) are used. In addition, four priority levels ($N = 4$) are defined with equal priority frames rate ($p_{i*} = 1/N$).

Figure 5 shows transmission success rate and the average access delay of TxBeacon at the MAC layer as expressed in Eq. (13) and Eq. (20) with number of senders (M) varying from 1 to 10 for different sowing times.

As can be seen from Fig. 5, the higher the number of sowing times, the higher the delay and success rate of TxBeacon transmission. Besides, when M increases, the delay is also increased, and the success rate reduced. For linear p_i sequences with $M = 1$ (Fig. 5a) and $M = 10$ senders (Fig. 5b), delay and reliability values would be nearly saturated (over 99.99%) since the number of sows reach 18, 26, 42, 87 and 28, 40, 60, 124 for priorities p_4, p_3, p_2 and p_1. The average access delay was recorded to be 0.80, 1.17, 1.92, 4.16, and 1.24, 1.77, 2.81, 5.94 milliseconds respectively.

For nonlinear p_i sequence, with number of sows of 200, only p_4, p_3, p_2 get near 100% reliability reliability, while p_1 is not given enough priority to achieve near 100% reception rate which not required in most of the industrial applications and acceptable for most of the process control and automation applications. With non-linear p_i sequence, value of p_1 is relatively small of the range 1/15 or 1/40, for $a = 2$ and $a = 3$ respectively. Even with the higher number of sows say 200, the sensor does still not receive the chance to send TxBeacon. On the positive note, the access delay for highest priority, p_4, lies below 1 millisecond even with high number of colliding senders, which offer suitable solution for highly mobile and time constraint applications, for instance robotics, high-speed assembly etc. However, in case of lower p_i value, the access delay would vary from 5 to more than 22 miliseconds. Thus, according to mathematical analysis, by varying p_i by the priority levels, we can change both delay and reliability of transmitted frames.

Using Eq. (14) and replacing its parameters/variables with the values summarized in Table II and III (T_{start} is chosen to be 2.5ms), the average MAC delay (in ms) of a data packet when running simulations in the next section can be calculated as

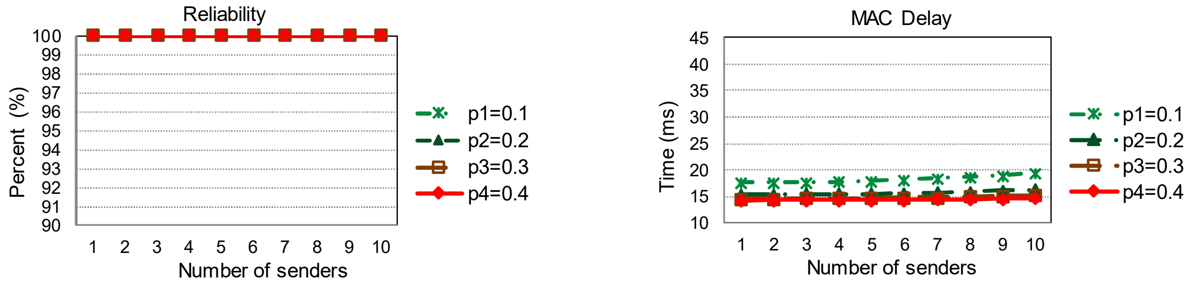
$$d_{avrMAC} = d_{access} + 12.964 \tag{21}$$

Fig. 6 shows successful transmission rate and the average MAC delay as expressed in Eq. (13), (20) and (21) where the number of sows is fixed to 200, and the number of senders vary from 1 to 10.

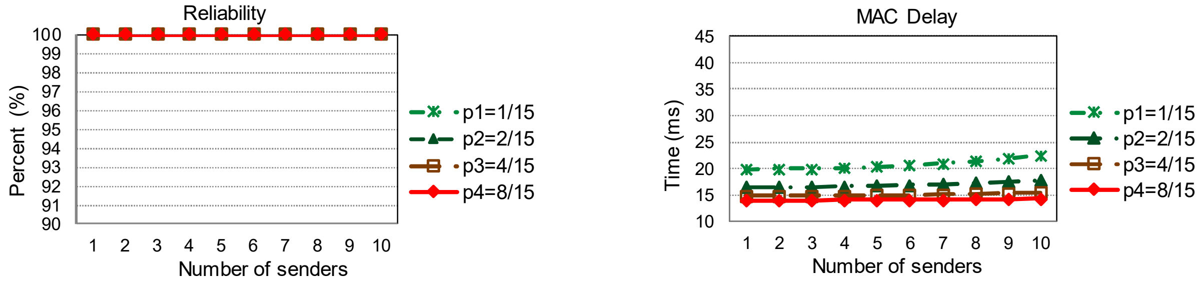
As shown in Fig. 6, when the number of senders increases, the overall reliability will be degraded and the delay will be higher due to the higher number of collisions and added delays. For higher priority frames, the increase in delay is insignificant while for lower priority frames, the increase in delay is greater. This is because the higher the priority, the higher the p_i value of a frame, and the PMME scheme will support higher priority frames before other lower priority ones.

It can be seen that the difference in delay between traffic with different priority levels is small when the difference in values of p_i is small (Fig. 6a) and vice versa (Fig. 6c). Therefore, changing p_i value of a frame can adjust the frame delay according to a certain threshold as per the application requirements. The priority frames will then be processed more quickly and reliably, but the downside of solution is that the frames with the lowest priority will be treated with lower quality.

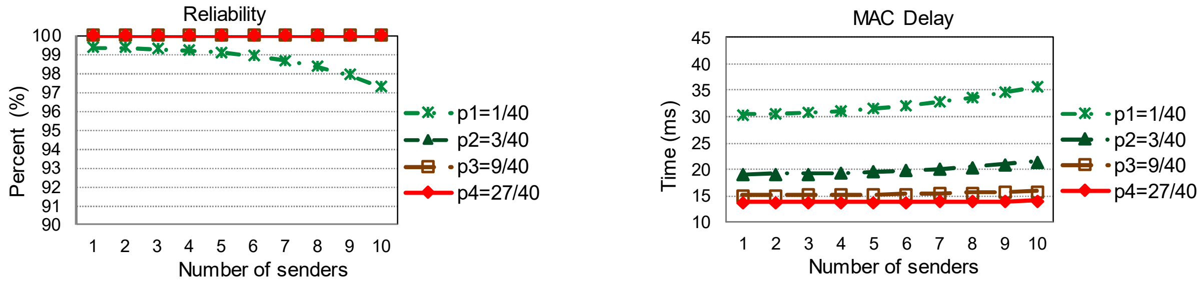
Fortunately, there are data frames that do not require high real-time or reliability, like monitoring systems within industry so this tradeoff is well suited for industrial applications.



a. *linear* p_i



b. *nonlinear* p_i *with* $a = 2$



c. *nonlinear* p_i *with* $a = 3$

Fig. 6. Analysis of reliability and MAC delay with k=200, different number of senders *M*, and p_i

V. SIMULATION ANALYSIS OF PMME PERFORMANCE

This part introduces the simulation results for evaluating, comparing multievent IWSN performance using our proposed PMME to QAEE and MPQ MAC protocols based on Castalia 3.3 simulation [35] and OMNeT ++ 4.6 [36] using the CC2420 transceiver standard [37].

A. Simulation Parameters

Table III shows main parameters in simulation. Sensor nodes are randomly distributed in the sensor field. At a single time there are 1 to 10 senders sending data where only one sink serves as a receiver which is placed in the center. Each sender sends data packets of events at a rate of 1 event per second with equal packets of different priority levels.

Performance parameters evaluated in our simulation are as follows:

- *Average packet delay:* It is a ratio of the total packet delays of received packets to the total number of packets received at the receiver. The packet delay is an expression of how much time it takes on average for a data packet to get from the source to the destination.
- *Packet success rate (PSR):* It is a ratio of the total number of packets received at the receiver to the total packets sent from all senders.

B. Result and Analysis

In this section, simulation results show that our PMME could adapt to the different QoS requirements of multiple packet types especially with lower delay for all types of packets.

1) *Average packet delay*

Fig. 7 shows average packet delay comparisons for QAEE, MPQ and three different p_i type PMME under different number of concurrent senders. It can be observed that the increased number of senders results in increased packet delays due to the increase in collisions. The QAEE and MPQ schemes use T_w to receive multiple TxBeacon requests and then accepts the highest priority sender, so it takes longer to receive all the requests. Since many senders compete to send packets, there will be collision resulting in the retransmission of TxBeacon. MPQ improves delay in comparison to QAEE by using high priority data packets along with incorporation of early termination of contention window (at the time receiver receive TxBeacon with highest priority, not by T_w). Although the three MAC protocols use p-persistent collision avoidance mechanism to disperse the TxBeacon, PMME has the lowest average packet delay as it accepts the first sending request, then the first sending sender does not has to wait any longer, until T_w expires like in QAEE and MPQ (except for p_4) schemes. Furthermore, when the number of competing senders increases, the PMME delay increases at a lower rate compared to that of the QAEE and MPQ schemes.

TABLE III

SIMULATION PARAMETERS

Parameter	Value
Network size	10m x 10m
Number of concurrent sender nodes	1-10
Senders' positions	Random
Bandwidth	250kb/s
Radio	CC2420
WakeupBeacon size	6 bytes
TxBeacon size	14 bytes
RxBeacon size	13 bytes
MAC overhead	11 bytes
Retry limit *maxTxRetries*	10
Application header	5 bytes
DATA packet size	28 bytes
ACK packet size	11 bytes
d_{CCA}	0.128ms
t_s	0.32ms
SISF (CC2420)	0.01ms
Physical frame overhead	6 bytes
T_w	5ms
T_g	6.7ms
listenTimeout	15ms
waitTimeout	5ms
Random start time of sensors	0-5ms
Event rate or Packet rate	1 event/s or 1 packet/s
Number of packets/ sensor	1000

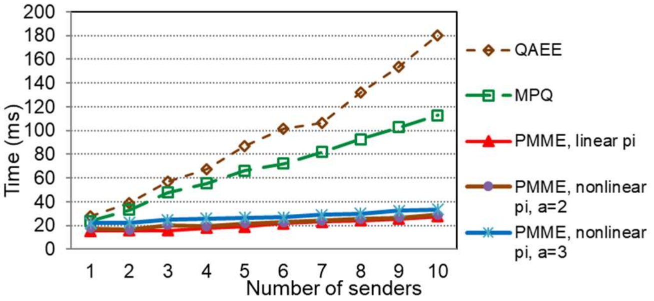


Fig. 7. Analysis of general average packet delay

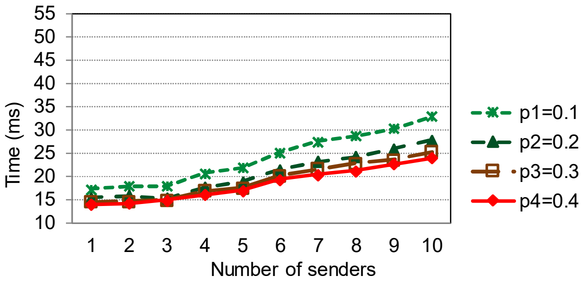
The QAEE and MPQ MAC protocols assume that p is the inversion of the number of sender nodes while PMME distinguishes priority levels with p_i values. In fact, it is impossible to know exactly the number of nodes that send data simultaneously at a time in a sensor network so the approach of PMME is more reasonable. With three types of p_i values in PMME, the average packet delay is nearly the same as each other, in such, nonlinear p_i value with $a = 3$ provides a slightly higher delay. This is consistent with the results of mathematical analysis, presented in Fig. 5, in that the larger the range of p_i values, the higher the difference of the access delays, thus leading to an increase in the average delay.

2) *Packet delay of different priority levels*

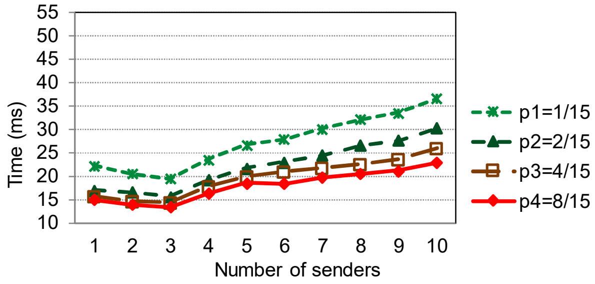
Packet delay according to PMME packet priority is shown in Fig. 8. In order to perform a different priority mechanism, in simulation, we select three p_i sequences: linear p_i sequences with $p_1 = 0.1, p_2 = 0.2, p_3 = 0.3$ and $p_4 = 0.4$; nonlinear p_i sequence with $a = 2$, and $p_1 = 1/15, p_2 = 2/15, p_3 = 4/15$ and $p_4 = 8/15$; and nonlinear p_i sequence with $a = 3$, and $p_1 = 1/40, p_2 = 3/40, p_3 = 9/40$ and $p_4 = 27/40$.

As shown in Fig. 8, higher the priority level of a packet, smaller the packet delay. This effect is due to the p-persistent mechanism with p_i varied by the priority levels. It is worth mentioning that the larger difference in p_i values, the greater equivalent delay deviation, which corresponds to the choice of a value. Higher p_i leads to lower packet delay and vice versa.

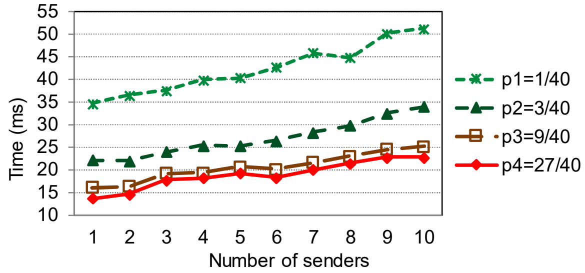
The trend in the packet delay given the same number of senders is comparable to theoretical analysis as presented in Fig. 6, however, the simulation results have more fluctuations



a) *linear* p



b) *nonlinear* p*,* $a = 2$



c) *nonlinear* p*,* $a = 3$

Fig. 8. Average packet delay using PMME protocol with 4 priority levels with different p types

and delays are higher in value. The reasons for the increased delay include: 1) random start times, 2) TxBeacon collision detection delay; and 3) randomness introduced in number of sows using p_{rand}. Elaborating these further, as nodes (sink and senders) have random start times, which means T_{start} in Eq. (14) is not a fixed value, it might be in the range of 0-5ms. In addition, in simulation, senders cannot detect TxBeacon collision right after it happens to immediately retry to send TxBeacon in the next slot as is the case in theoretical analysis. On the contrary, the resending TxBeacon has to wait for NAV time (if the sender receives RxBeacon to other sender) or wait for a duration of waitTimeout (5ms) to make sure that TxBeacon has not successfully been received by the receiver before resending. Finally, in theory, the delay is only evaluated with the 200 sows for which it takes approximately 100ms to the 200^{th} sow, but in a specific simulation, the number of sows may be less or more depending on the random value of p_{rand}, and when p_1 is relatively small, the number of sows should be increased until TxBeacon has the opportunity to be sent, then the packet delay must be higher.

3) *Packet success rate*

Figure 9 shows the packet success rate in multi-event IWSN using QAEE, MPQ, and PMME protocols. The three MAC protocols' use of p-persistent approach helps the network avoid unnecessary collision by using the probable delay mechanism. As the number of concurrent senders increases, the collision frequency increases, resulting in lower packet success rate. As can be seen in the figure, PMME helps the network to operate more efficiently with higher packet success rate than the QAEE and MPQ schemes. The reason is that due to the immediate delivery of the RxBeacon in PMME, other nodes are aware of the activity even during the NAV time and therefore stay idle, leading to a further decrease of collision frequency and helping the packets to be successfully delivered to the destination with lower latency compared to the QAEE and MPQ. Besides, in case of multiple senders, many QAEE and MPQ TxBeacon frames continued to be sent during the remaining T_w period but only one can be confirmed, thus others would be resent. As the number of TxBeacon retransmissions is limited, many QAEE and MPQ data packets will not reach the receiver.

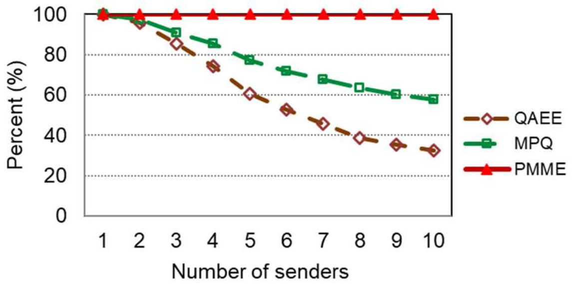


Fig. 9. Packet success rate with QAEE, MPQ, and PMME protocols with *maxTxRetries = 10,* linear p

VI. CONCLUSION AND FUTURE WORK

In this paper, a novel solution is proposed to support concurrent events in IWSNs which define different QoS needs for different priority levels of data packets. The proposed priority MAC protocol named PMME introduces two enhancements to two previous priority MAC protocols QAEE and MPQ: 1) In CSMA p-persistent mechanism, value of p adapts to the priority levels of the data, and 2) the earliest possible TxBeacon acceptance mechanism is implemented. Mathematical analysis along with system simulations are performed using different scenarios by varying number of nodes, p values/sequences and the maximum number of retransmissions, *maxTxRetries*. The results have shown that the proposed PMME has significantly improved the average packet delay for all packet types. In addition, it differentiates packets by priority levels, i.e. higher the priority level, lower the packet delay and vice versa. Besides, PMME achieves high packet success rate in comparison to QAEE and MPQ. In addition, the investigation reveales that by changing the value of p, latency and reliability of the priority packets can be adjusted to fit the requirements of the diverse IWSN applications with many different priority levels.

In future, we will introduce further improvements on multi-priority industrial sensor network performance by combining packet priority awareness in the MAC layer and energy awareness routing to improve IWSN suitability in industrial application.

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