Accurate Analysis of IEEE 802.15.4 Slotted CSMA/CA over a Real-Time Wireless Sensor Network

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Abstract. Here, we present the collision probability of the IEEE 802.15.4 slotted Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) mechanism over a real-time wireless sensor network (RT-WSN), also called a synchronous network system. The "backoff," the random delay of CSMA/CA, can be used to create a probability model and to determine the average packet delay over RT-WSN. The proposed theoretical analysis model was nearly consistent with the simulation and with experimental results. This suggests that the slotted CSMA/CA mechanism cannot be applied effectively to RT-WSN because it cannot avoid a high collision rate with RT-WSN application requirements and, therefore, may waste a great deal of system bandwidth. We found that the packet collision rate increased up to 731% compared to an ideal model with more than 10 users within an RT-WSN. Without improvements in methodology, the high collision rate makes this slotted CSMA/CA mechanism unsuitable for RT-WSN applications.

Keywords: Real-time, wireless sensor network, collision, IEEE 802.15.4, CSMA/CA.

1 Introduction

The numerous advantages of wireless networking technology, including portability, no requirements for cables, flexibility, and low cost of constructing a network topology, have allowed it to be applied successfully in industry, medicine, transportation,

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telemedicine, and home applications. Technological progress and the integration of wireless communication, batteries, and embedded processors have driven the development of Wireless Sensor Networks (WSN) [1]. In contrast with other types of wireless networks, the WSN data transmission method uses many sensing sources, called sensor nodes, routed to a single destination, called the sink node. The sensor nodes can detect various environmental parameters within their effective sensing distance, such as temperature, humidity, luminosity, wind speed, and pressure. The sensed information is gathered by the sink node, and then may be analyzed by network administrators and users. Recently, WSN has become increasingly widespread and its applications have expanded to sensor networks [2], industrial communication [3], home applications, and medical treatment [4]. This has produced ever-increasing demands for WSN. Real-time performance is sometimes required, especially in multimedia applications, and, to guarantee real-time execution, the access time of wireless media applications must occur within a maximum delay time. In many networks, packet faults can be revised by the acknowledge/retransmit mechanism of the protocol used. Such systems will become paralyzed by the uncertain delays experienced in real-time applications [5].

Medium access control (MAC) performance analysis of the IEEE 802.15.4 low-rate wireless personal area network (LR-WPAN) [6] is discussed in this study. The beacon mode with slotted Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) applied to real-time WSN (RT-WSN) was evaluated under real-time conditions in a star network topology. Singh et al. [7] analyses the performance under the IEEE 802.15.4 star topology. They found that the saturation throughput of n nodes can be calculated by an embedded Markov renewal process, and also the relation between the size of backoff and throughput. Therefore, they obtain an analytical model for the finite arrival rate case from the relation. This finite load model captures very well the qualitative behavior of the system. Finally, they used ns2 simulator to verify their model and simulation results. Kim et al. [8] studied the focus of the IEEE 802.15.4 unslotted CSMA/CA and proposed a simple mathematics model that utilized the wireless channel in the busy state to got the M/G/1 queueing system to make analysis. They can calculate the throughput, delay, and energy consumption in the bust state. Park et al. [9] proposed a new analysis model, which utilized the discrete time Markov chain to analyse the throughput and energy consumption of the slotted CSMA/CA. Timmons et al. [10] analysed the performance of the medical sensor body area networking context, which works in long-time operation. Hence, they focus on the power consumption issue.

The network performance parameters, time delay, throughput, and power consumption were also measured in these studies, and shown to affect the CSMA/CA RT-WSN. In this study, we evaluated the MAC performance required in real-time applications and then analyzed the effects of CSMA/CA RT-WSN when users need to use as much bandwidth as possible.

Sections 2 and 3 of this paper describe the IEEE 802.15.4 standard and the construction of the network model, respectively. Section 4 shows the mathematical analysis of our proposed network model. The performance results of the simulation and experiment are verified in Section 5. Section 6 presents our conclusions.

2 Overview of the IEEE 802.15.4 Standard

The new standard of 802.15.4 was used to develop two-layer protocol stacks, the physical layer (PHY) and MAC, for LP-WPAN applications [6]. This standard has a number of characteristics, as follows:

- The data transmission rate can be 250, 40, or 20 kbps through the air.
- Star or peer-to-peer operation.
- Allocated 16-bit short address, with a maximum of 65535 connections.
- CSMA-CA channel access.
- Acknowledged protocol for transfer reliability.
- Low power consumption.
- Energy detection.
- Link quality indication.
- 16 channels in the 2450 MHz band; 10 channels in the 915 MHz band; and 1 channel in the 868 MHz band.

Figure 1 shows the two-layer structure of a star topology sensor network consisting of one personal area network (PAN) coordinator and several sensor nodes. The data flow path is from leaf nodes, called sensor nodes, to the PAN coordinator.

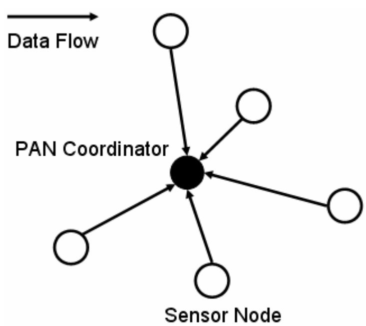


Fig. 1. The structure of a Star topology sensor network

There are two working modes, beacon and non-beacon, in the IEEE 802.15.4 standard. The beacon mode uses broadcast communication to synchronize the network. The coordinator periodically broadcasts the beacon frame to all of the sensor nodes. The superframe structure, which is largely designed to allocate the time distribution mechanism, is defined in the beacon mode, as shown in Figure 2 [6]. This causes all of the sensor nodes in the network to synchronize two functions, sleep and wake-up. As the network works only in the active state, the time in this state can be divided into 16 equal segments, called time slots. Any action involves the use of one time slot as the basic working unit. For example, the transmission operation costs three time slots, and the waiting operation costs five time slots.

The two-part active state consists of the contention access period (CAP) and the contention-free period (CFP). During the CAP, the system will allow the sensor nodes to compete freely to obtain channel access rights in the slotted CSMA/CA mechanism. Then, during the CFP, the system gives the sensor node exclusive access to the channel within its allocated time slot(s). Under these conditions, one node does not need to compete with other nodes to obtain access rights, guaranteeing the specificity of the sent data. The sensor node can also enter the power-saving mode to reduce power consumption during the inactive period. The lengths of the active and inactive periods can be adjusted by the superframe Order (SO) and Beacon Order (BO), respectively. According to the definition of the IEEE 802.15.4 standard, these can be set as follows: 0≦SO≦BO≦14, *aBaseSuperframeDuration* (which is a constant) = 960 as the default value, and one symbol (which is also a constant) = 16 μs in 2.4 GHz bandwidth operation. Therefore, the duration of the superframe is from 15.36 ms to 215.7 s. It does not use the superframe structure as SO = 15.

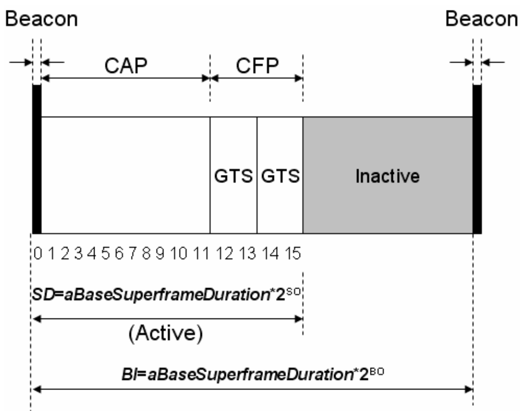


Fig. 2. The superframe structure of IEEE 802.15.4

During CAP, the sensor node competes with others to obtain channel access rights using the slotted CSMA/CA mechanism, as shown in Figure 3 [6]. The backoff period represents one unit of the time slots in CSMA/CA. In the slotted CSMA/CA, the backoff period boundaries of the sensor devices cannot be aligned with the time slot boundaries of the coordinator. Each sensor device maintains three variables, *NB*, *CW*, and *BE*. *NB,* which is used to determine when the channel is in the busy state, has an initial value of 0. *CW* indicates when the channel is empty and when it begins to transmit the data. PHY performing clear channel assessment (CCA) is used to detect whether the channel is idle or not. According to the range, $2^{BE}-1$, CSMA/CA allows the sensor node to delay one random backoff period. As this allows sensor nodes to transmit without overlapping with each other, their collision probability can be effectively reduced. When the channel is in the busy state, it can reattempt access within the number of *macMaxCSMAbackoffs*, which is a constant. Then, *BE* will be incremented by 1 such that it can increase the random range. The competition fails when the retry number is greater than *macMaxCSMAbackoffs*. After ensuring that the channel is empty twice ($CW=2$), the node begins to access the channel for successful competition.

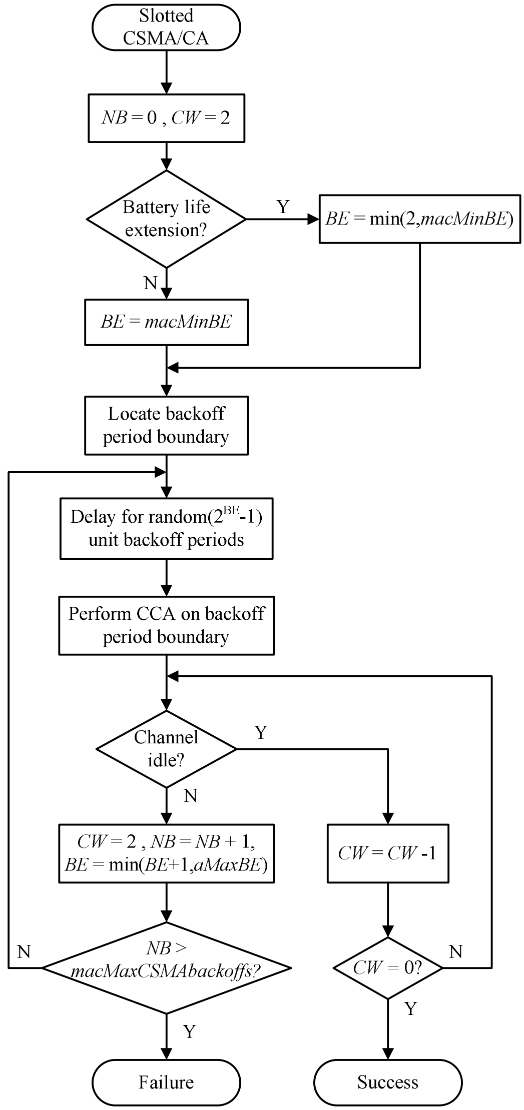


Fig. 3. The slotted CSMA/CA mechanism

Table 1. Default values of the CSMA/CA parameters

Parameters	Default Value
aMaxBE	5
macMaxCSMABackoffs	4
macMinBE	3
macBattLifeExt	FALSE

CSMA/CA contains one other parameter, the binary constant *macBattLifeExt*. If the system needs to reduce the duty cycle of the network, *macBattLifeExt* can be set as "TRUE," which can reduce the delay of the backoff period and conserve battery energy. The default values of the CSMA/CA parameters are shown in Table 1.

3 Our Network Module

Our proposed network system is constructed as a star network consisting of one master node and many slave devices for monitoring. This protocol includes two classic tasks, a synchronous and an asynchronous task [11, 12]. The synchronous task involves periodic polling of each slave node for received data (*e.g.*, temperature, luminosity, humidity, pressure, rotation, and angle) from monitoring sensor devices. The asynchronous task does not involve periodic transmission and its transmission time is therefore fixed (event-driven). In comparison with previous systems, this type of system generally requires the ability to take the bounded time to be finished within the critical path.

In the synchronous task, data from the sensor nodes will be periodically and continuously sent to the coordinator. Generally, the system is capable of maintaining the sampling rate so that it can be implemented within the limitations of the memory buffer. For real-time requirements, the synchronous task of the sensor network is defined by RT-WSN.

The star topology sensor network of the IEEE 802.15.4 standard was employed in this study. Our system used the beacon-enabled configuration, which allows the coordinator to periodically broadcast beacons to all of the sensor nodes. After receiving the beacon, the sensor node performs the slotted CSMA/CA mechanism to obtain the access rights of the channel. Then, the successful node sends its packet to the coordinator. This is just one way to transmit the packet from the sensing node to the coordinator. Although the CSMA/CA mechanism can decrease the probability of collision, too many sensors and too heavy a traffic load within the network will cause a high collision rate. This results in the loss of the packet, increased delays and decreased the bandwidth, and the gradual degradation of network performance. To analyze, in detail, collision performance under the CSMA/CA mechanism, some terms of the network model are defined as follows:

- Maximize traffic load: The traffic load is equal to the maximum throughput of the system. Under the IEEE 802.15.4 standard at 2.4 GHz, the maximum bandwidth is 250 kbps. Throughput is possible in the saturate case, although the network simultaneously uses many sensor nodes.
- Fixed packet length: The length of all packets is set to a fixed value with a maximum of 128 bytes, according to the IEEE 802.15.4 standard.
- Without re-transmit/acknowledgment: Because of the requirements for real-time operation, the re-transmit mechanism settings do not provide redundant time for re-transmission by the network's sensor nodes [5]. When data are missing or the transmission is in error, the sensor node waits until the next beacon cycle to re-send the packet.
- Without inactive/sleep mode: When the system is operating at a high utilization rate or in a high duty cycle, it disables the sleep mode.

- Without packet loss rate: The packet cannot be lost in the normal case. Although some packets will be lost because of factors related to environment, distance, interference, and signal intensity, this study does not consider the effects of these factors.

When the sensor nodes are sent their packets passively according to the requirements of the coordinator, the maximum sampling rate of the system corresponds to the set

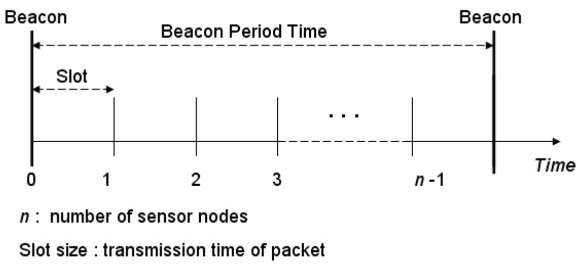


Fig. 4. Our network module

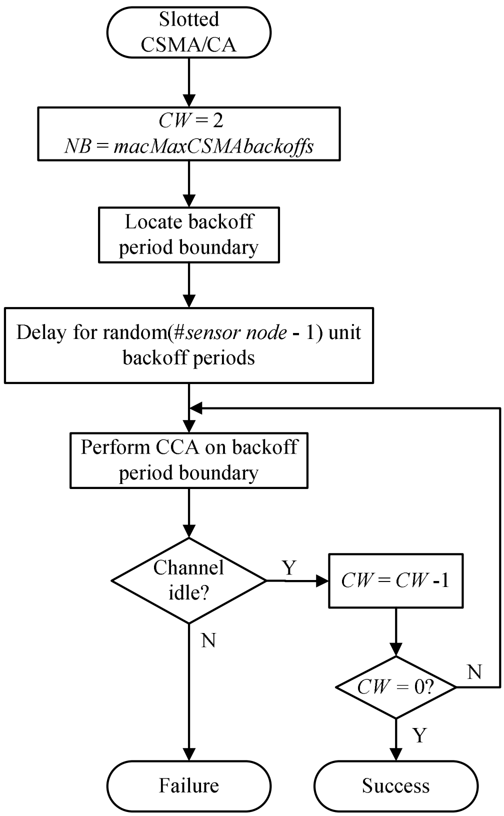


Fig. 5. The slotted CSMA/CA mechanism after adjusting

beacon period. To obtain real-time data in our model, we set the beacon period time equal to the sum of the packet transmission times of all of the sensor nodes. For example, when five sensor nodes are in the network, each with a packet transmission time of 4 ms, the beacon period is set to a minimum of $5 \times 4 = 20$ ms. In the beacon enabled mode, the superframe structure can be adjusted by our proposed method to reduce the redundant action. Hence, the length of one time slot equals the transmission time of one packet, and the number of time slots equals the number of sensor nodes, as shown in Figure 4.

In our module without collision, the packets of all of the sensor nodes can only be sent once during the beacon period. The system waits until the next beacon cycle to transmit, because collisions may cause the loss of the packet. In this case, this time slot cannot be used by any node, which wastes bandwidth. Although the backoff period is one random time slot length, it cannot run over the beacon period time. The maximum of the random variable is $(n - 1)$, where n is the number of sensor nodes. For example, the maximum length of the backoff period is four when the number of sensor nodes is five. With clear channel assessment (CCA), there is no time to compete again if the channel is in the busy state.

4 Mathematical Analysis

In this study, we propose a network analysis model to analyze the behavior of the slotted CSMA/CA over RT-WSN. Too many collisions cause time delays, which waste bandwidth and prevent the requirements of real-time operation. An analysis of the degree of network collisions therefore allows an evaluation system performance.

From the protocol of one packet, it will be allocated one random length of the backoff period during the competition case. Here, one unit of the backoff period is equal to the unit length of one time slot. There are n time slots during the beacon period, where n is the number of sensor nodes. The packet can randomly choose one of n time slots to access, as shown in Figure 6. Two sensor nodes will choose the random variables in the system. A collision will occur if more than two nodes choose the same random variable. In this case, both of the packets may be lost. This is one of the major causes of network performance degradation.

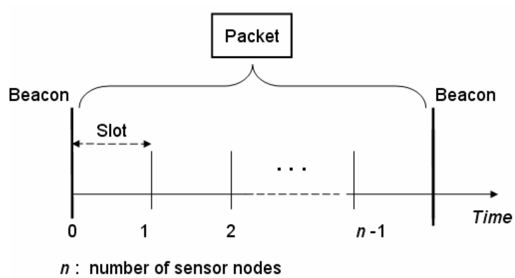


Fig. 6. Packets to be transmitted during any time slot

The following important parameters are defined for our model:

- n : Number of sensor nodes.
- *Network*(i) : There are i sensor nodes inour network model.
- *slot* : The time slot is equal to the packet transmission time.
- *#slot* : Number of time slot.
- $D_{Avg}(n)$: Average of packet delay of the sensor node in n sensor nodes.
- *Collision*(i) : The number of sensor nodes that simultaneously choose the same random variable is "i," which will generate "i" collisions and lose "i" packets during the same "backoff" period.
- $P(e)$: Outcome probability of the event e.
- $S(e)$: One set contains the amount of all possible outcome samples during event e, also called "sample space" of the event e.

To analyze the collision probability within n sensor nodes over RT-WSN, or $P(Collision(n))$, the statistics of the sample space are be gathered first. We assume that one slot can be chosen as the candidate element among n sensor nodes. One candidate element among n time slots with n packets can be chosen, and all candidate elements can be counted by the statistics method as shown in (1).

$$S(Network(n)) = \#slot^{n} = n^{n} \tag{1}$$

Let $S(Network)$ be the total sample space over RT-WSN, containing a combination of collision and non-collision incidents. Let "*#slot*" be the number of slots, and *Collision*(0), …, *Collision*(n) be the collision probability of the nodes 0, 1, …, n, respectively. Therefore, the sample $S(Network)$ of the network is the union of all incidents as shown in (2).

$$S(Network) = S(Collision(0)) \cup S(Collision(1)) \cup S(Collision(2)) \cdots \cup S(Collision(n)) \tag{2}$$

Let $Set(Collision(i))$ be the set number of *Collision*(i). Hence, the collision probability within i sensor nodes, $P(Sollision(i))$, under $S(Network)$ is shown in Eq. (3).

$$P(Collision(i)) = \frac{S(Collision(i))}{S(Network(n))} \tag{3}$$

Therefore, *Collision*(i) means that there are i time slots to be wasted. Then, it will take more cost of $i \times slot$ time delays. Hence, The average packet time delays under n sensor nodes, $D_{Avg}(n)$, is the summation of the wasted time delays of all possible collision probability as shown in Eq. (4).

$$\begin{aligned} D_{Avg}(n) &= \left(P(Collision(0)) \cdot 0 + P(Collision(1)) \cdot 1 + \cdots + P(Collision(n)) \cdot n\right) \cdot slot \\ &= \left(\frac{S(Collision(0))}{S(Network(n))} \cdot 0 + \frac{S(Collision(1))}{S(Network(n))} \cdot 1 + \cdots + \frac{S(Collision(n))}{S(Network(n))} \cdot n \right) \cdot slot \end{aligned} \tag{4}$$

First, to get $(n - i)$ elements without collision from n sensor node samples, let the amount of them be shown in Eq. (5).

$$C^{n}_{n-i} = \frac{n!}{(n-i)!(n-(n-i))!} \tag{5}$$

Second, let the permutation of $(n - i)$ elements within n time slots be shown in Eq. (6).

$$P^{n}_{n-i} = \frac{n!}{(n-(n-i))!} \tag{6}$$

Finally, let $D_{Avg}(n)$ be the average package delay with the collision case in n sensor nodes, and it can be derived from above equations and shown in Eq. (7), where $Set(G(i\ , i))$ will be shown in Eq. (8).

$$D_{Avg}(n) = \frac{slot}{n^n}\sum_{i=0}^{n} C^{n}_{n-i} \cdot P^{n}_{n-i} \cdot S(G(i,i)) \cdot i \tag{7}$$

Then, the recursion relation $S(G(i\ , k))$ can be defined as Eq. (8). There are 2 initial conditions are as follows. One, $S(G(0\ , 0)) = 1$, is non-collision and the other, $S(G(1\ , 1)) = 0$, is one sensor node with the collision case.

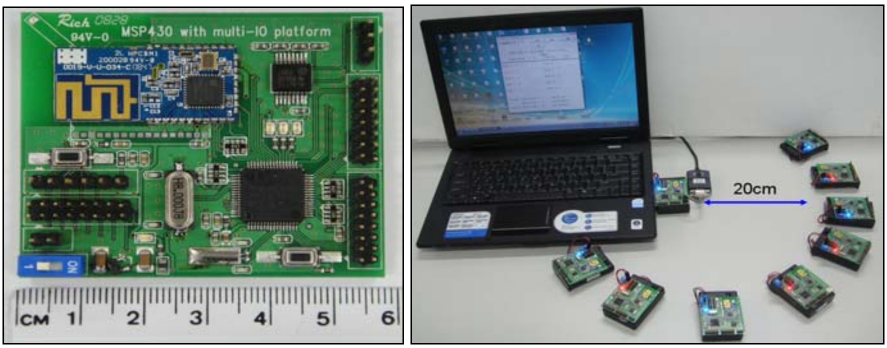
$$S(G(i\,,k)) = \left\{ \begin{array}{ll} 1 & ,\text{if i} = 0, \\ 0 & ,\text{if i} = 1, \\ k^i - \sum_{d=0}^{k-1} C^{k}_{k-d} \cdot P^{k}_{k-d} \cdot S(G(d\,,d)) & ,\text{if i} > 1. \end{array} \right|_{i=k} \tag{8}$$

5 Simulation and Experiment Results

To confirm our methodology, we verified our proposed theoretical analysis with simulation and experimental results. We found that the slotted CSMA/CA mechanism cannot be applied effectively to RT-WSN because it cannot avoid a high collision rate with real-time application requirements, and wastes a great deal of system bandwidth. We used the simulation tool Matlab to create the network model to be simulated. Figure 7(a) shows our implementation hardware [13] with the ZigBee RF module [14] and the MPS430 microcontroller [15]. The real experiments over RT-WSN within one office are shown in Figure 7(b). In our experiment, the transmission packet time was 8.706 ms and the number of sensor nodes ranged from 1 to 10.

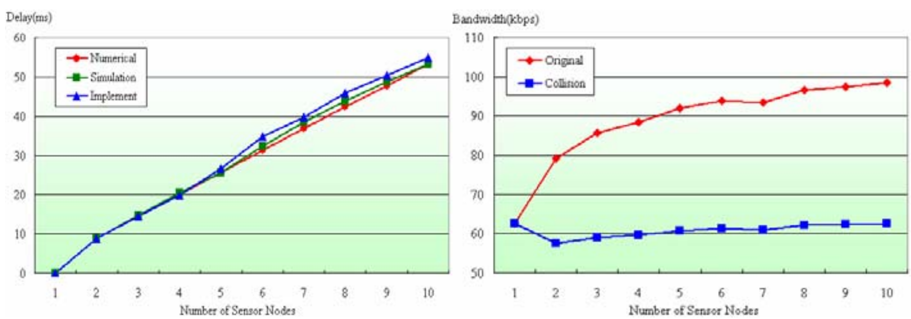
A comparison among the numerical, simulation, and experimental results is shown in Figure 8(a); the number of sensor nodes is on the horizontal axis and the average transmission delay within one packet on the vertical axis. We found few differences among all three sets of results. The average delay per packet was 55 ms in the 10 sensor nodes. Therefore, the packet load was (8.7 + 55) / 8.7 × 100% = 731% that of the standard mode.

The real bandwidth effect of the measurement collision is shown in Figure 8. In this experimental platform, the access critical time of one packet was about 14.712 ms, and the length of one packet without the header was 115 bytes (IEEE 802.15.4 standard). Hence, the system bandwidth within one sensor node was 62 kbps.



(a) (b)

Fig. 7. (a) Our experiment platform. (b) The experiment of the RT-WSN environment with eight sensor nodes.



(a) (b)

Fig. 8. (a) The average packet delay on 10 nodes. (b) The bandwidth effect of collision on 10 nodes.

6 Conclusions

In this study, we proposed an effective mathematical analysis methodology to be applied to real-time WSN under the IEEE 802.15.4 standard. Our theoretical analysis model was consistent with the simulation and experimental results indicating that this slotted CSMA/CA mechanism cannot be effectively applied to RT-WSN because it cannot avoid the high collision rate with real-time application requirements and wastes a great deal of system bandwidth. We found that the packet collision rate increased up to 731% compared to an ideal model with 10 users within RT-WSN.

Generally, most synchronous network systems possess real-time characteristics because they need to use as much network bandwidth as possible. We found that the slotted CSMA/CA mechanism is not a good choice for real-time applications, when the user wants to increase sensor nodes in the system to consider that there is the side effect of the high packet collision rate. The IEEE 802.15.4 standard is suitable for asynchronous system applications in distributed networks in the home, industry, and medical settings.

Acknowledgment

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