Data Fragmentation Scheme in IEEE 802.15.4 Wireless Sensor Networks

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***Abstract*— The IEEE 802.15.4 Medium Access Control (MAC) protocol is designed for low data rate, short distance and low power communication applications such as Wireless Sensor Networks (WSN). However, in the standard 802.15.4 MAC, if the remaining number of backoff periods in the current superframe are not enough to complete data transmission procedure, the sensor nodes hold the transmission until the next superframe. When two or more sensor nodes hold data transmission and restart the transmission procedure simultaneously in the next superframe, it causes a collision of data packets and waste of the channel utilization. Therefore, the MAC design is inadequate to deal with high contention environments such as densely deployed sensor networks. In this paper, we propose a data fragmentation scheme to increase channel utilization and avoid inevitable collision. Our proposed scheme outperforms the standard IEEE 802.15.4 MAC in terms of collision probability and aggregate throughput. The proposed scheme is easily adapted to the standard IEEE 802.15.4 MAC without any additional message types.**

I. Introduction

The IEEE 802.15.4 low-rate wireless personal area network (LR-WPAN) [1] is one of the candidates for standard wireless sensor networks (WSNs). Previous works on the 802.15.4 MAC are mostly centered around the performance studies on the original 802.15.4 MAC [2]–[4]. In Misic *et al* [5] the problem of the small backoff range is discussed and analyzed. We note that WSNs are ideal for applications such as security systems, environmental monitoring, industrial automation, and consumer electronics that operate periodically [6]. For example, the IEEE 802.15.4 is widely used in applications of consumer electronics, vital monitoring applications and security systems, such as smoke detectors operate with a small beacon interval. In this paper, we deal with such applications that operate in small beacon intervals. Previous works, such as [7], [8] were related to the modification of BO value itself to increase performance. However, our proposed scheme deals with small beacon interval situations, and we do not require modification to the BO.

The IEEE 802.15.4 MAC standard wastes the number of backoff periods at the end of a superframe. This is because typical data frame is too large to be transmitted during the small number of remaining backoff periods. This causes inevitable collision and waste of channel utilization. Therefore, we propose to fragment large data frames into smaller frames to transmit in small number of backoff periods that are not being used in the IEEE 802.15.4 standard. Previous works [9], [10] use the data fragmentation scheme to increase the performance in the legacy of 802.11, however we adapt the fragmentation scheme to 802.15.4 MAC to solve these problems. Using the fragmentation scheme, we intend to avoid the inevitable collision and achieve high channel utilization compare to the MAC of the IEEE 802.15.4 legacy.

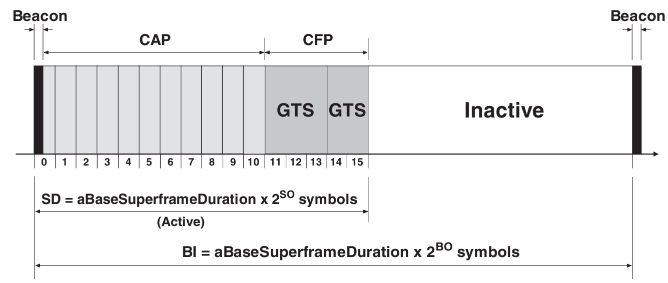

Fig. 1. An example of the superframe structure

II. IEEE 802.15.4 MAC

The IEEE 802.15.4 WSNs consist of sensor device nodes and a controlling coordinator. The coordinator manages all device nodes and handles the superframe structure. The superframe is bounded by the transmission of a beacon frames and have active and inactive portions. The coordinator interacts with its devices only during the active portion and enters sleep mode during the inactive portion to save the power consumption. Fig. 1 shows the superframe structure which consists of active and optional inactive portions. The beacon frame is used for time synchronization and system configuration between the coordinator and sensor nodes. The active portion consists of a contention access period (CAP), where the sensor nodes equally access the channel using contention, and an optional contention free period (CFP). The length of a superframe is controlled by the value of beacon order (BO) and the length of CAP is represented by superframe order (SO). The values of BO and SO are determined by the coordinator [1].

The standard of 802.15.4 states that, channel detection in 802.15.4 MAC is based on the CSMA-CA procedure [1]. The CSMA-CA algorithm is used before the transmission of data or MAC command frames transmitted within the CAP. The backoff in IEEE 802.15.4 MAC is processed within the CSMA-CA algorithm. The initial value is given as $macMinBE$ and the system randomly selects a backoff time from a number between [0::$2^{BE}-1$] [1]. After the random backoff, the remaining CSMA-CA operations can be undertaken and the data transmission can be performed until the end of the CAP. In cases where the randomly selected backoff period is smaller

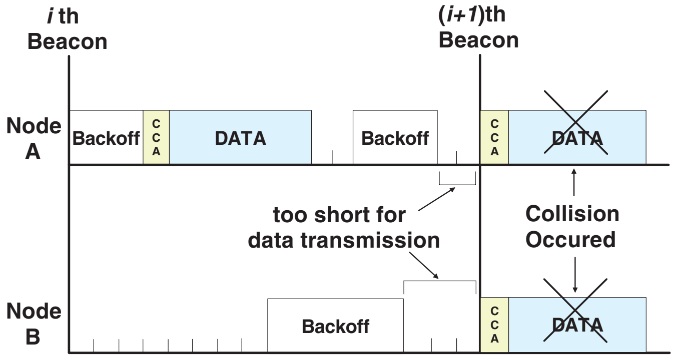

Fig. 2. IEEE 802.15.4 Standard

than the remaining number of backoff periods in the CAP, the sensor nodes complete CCA and the data transmission procedures. However, where in cases the remaining number of backoff periods in the CAP are not enough to transmit a data frame, the sensor nodes ignore the remaining backoff periods in the current superframe and waits for the next superframe to complete CCA and the data transmission procedures [1]. This is very inefficient in applications where the beacon interval is given as a small value.

Inevitable Collision: In WSNs, in some cases two or more sensor nodes proceed CCA procedure simultaneously at the start of a new superframe, due to the shortage of remaining backoff periods in the CAP from the previous superframe. These nodes perform CCA at the same time, therefore all nodes detect the channel is idle. This causes the nodes to transmit data at the same time, leading to an inevitable collision. From this property, there always exists inevitable collision in 802.15.4 MAC. We represent this drawback of 802.15.4 MAC in Fig. 2. In Fig. 2, although node A and B finish random backoff within the ith superframe, they wait for the $(i+1)$th superframe to perform CCA and data transmission. When they begin CCA, they both detect that the channel is idle. Therefore they transmit data at the same time after the CCA procedure, this causes a collision. Situations like this are easily seen when the beacon interval is set as a low value. In the applications of consumer electronics where a short interval is set, this inevitable collision becomes a significant problem. This problem causes the transmission delay due to the frequent collisions.

Waste of Channel Utilization: Moreover, when the remaining number of backoff periods in the CAP are not enough to proceed CCA and the transmission of data frames, the channel remains idle because the sensor nodes wait for the next superframe. These remaining number of backoff periods are short, however when the length of superframe is also short, *i.e. when* $BO \leq 6$ [6], these remaining number of backoff periods can not be neglected. These remaining backoff periods, in frequent beacon interval based applications, take up a large portion of the total time.

To solve the problems stated above, *i.e.,* inevitable collision and waste of channel utilization, we propose to adapt the fragmentation scheme in IEEE 802.11 [11] for IEEE 802.15.4 MAC. The fragmentation scheme divides the data to fit into the remaining number of backoff periods in the CAP of a superframe. By fitting the data into the remaining number of backoff periods in the CAP, we can avoid the inevitable collision and increase the channel utilization. As a result, we can reduce the collision probability per transmission and increase the aggregate throughput of the WSN. When the contention of the system is high, we expect the performance improvement to be significant.

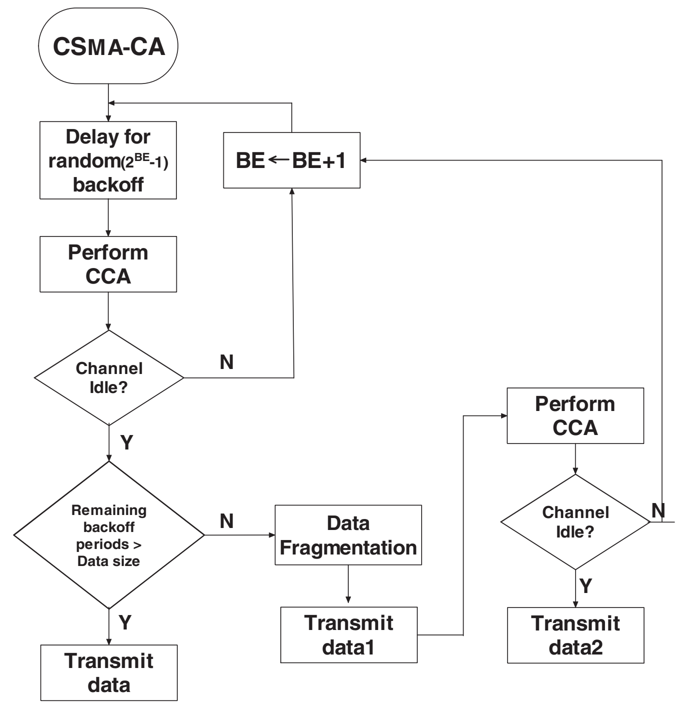

Fig. 3. Data fragmentation algorithm

III. Data Fragmentation Scheme

Fig. 3 shows the data fragmentation algorithm, including the fragmentation procedure. The proposed fragmentation algorithm is based on the IEEE 802.11 MAC [11]. We modify the transmission procedure of the IEEE 802.15.4 CSMA-CA algorithm to adapt this scheme. We add the fragmentation procedure before transmitting a data frame, when the remaining number of backoff periods in the CAP are not enough to transmit the original data frame. Also, to let the sensor node which transmitted the fragmented data frame continue its transmission at the next superframe, we allow the sensor node to perform CCA, without additional backoff, at the beginning of the new superframe. After the CCA the sensor node transmits the remaining fragment of the data frame without a backoff procedure.

In the fragmentation procedure, the data payload is fragmented depending on the remaining number of backoff periods in the CAP. For example, when there are 8 remaining backoff periods in the CAP of the current superframe, the sensor node can transmit data for only 5 backoff periods. Therefore, the data frame is fragmented to this size. This is because the MAC and PHY overhead takes up 1 backoff period and 2 backoff

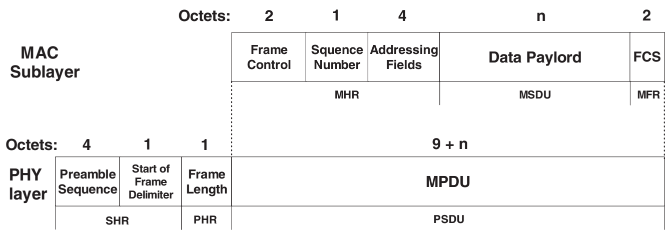

Fig. 4. Schematic view of the data frame

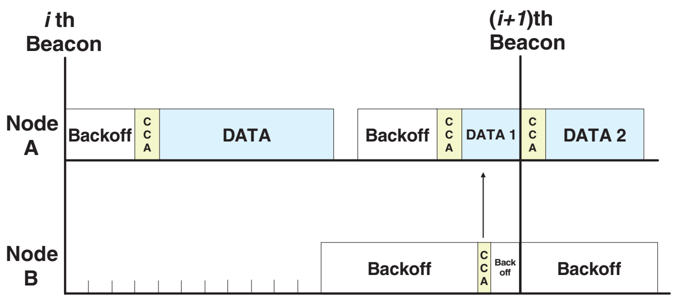

Fig. 5. Data transmission using data fragmentation scheme

periods are reserved for the receipt of the ACK packet. The structure of the data frame is represented in Fig. 4.

We show the data transmission using data fragmentation scheme in Fig. 5. In Fig. 5 node A finishes its backoff before node B, therefore the channel remains idle at this point. If this were the situation in legacy 802.15.4, because the data cannot be transmitted within the remaining number of backoff periods in the CAP, node A ignores the remaining backoff periods. However when using the data fragmentation scheme, node A starts CCA and transmits the fragmented data. In this way, when node B performs CCA after its backoff time the channel is occupied, therefore node B starts an additional backoff. In the $(i+1)$th superframe, while node B still performs its given backoff, node A performs CCA again and transmits the left-over data. With the data fragmentation scheme we can reduce the collision probability per transmission by avoiding inevitable collisions, and increase the aggregate throughput by using the remaining number of backoff periods. When using the data fragmentation scheme, MAC and PHY overhead are added to the fragmented data frame. Compared to the utilization of the remaining number of backoff periods, this overhead is small. Moreover, there is an additional channel utilization by avoiding the collision in the start of the next superframe. When the length of the superframe is short, the proportion of additional channel utilization to the length of the superframe increases. Applying our scheme in the application of consumer electronics, vital monitoring applications and security systems where the BO is less than 6 [6], the performance improvement of the system is significant. The proposed scheme is compatible with the standard IEEE 802.15.4 MAC.

IV. Simulation Experiments

In this section, we evaluate the performance of our data fragmentation scheme compared to the legacy of IEEE 802.15.4. We present the simulation results for the collision probability and the aggregate throughput under the two different *aMaxBE* values (5 and 7), to eliminate the problem stated in [5]. We also vary the number of sensor nodes to evaluate the performance under high contention, and different lengths of the superframe by modifying the BO value. Other IEEE 802.15.4 parameters are based on the default values specified in [1]. For simulations, we made a JAVA event-based 802.15.4 simulator. All simulations run for 1,000 seconds and we iterate each simulation 10 times to increase the confidence. We made following several assumptions for the simulations.

- We assume a saturated network where all sensor nodes always have a data frame to transmit.
- There is no inactive portion in the superframe. We set the same value for BO and SO.
- We assume contention-based access method of the beacon enabled 802.15.4 MAC. There is only CAP in the superframe, and no CFP.

We simulate the sensor network configured in the star topology, where there is a single coordinator to which a large number of sensor node attempting to transmit. We show the parameters for the simulations in Table I.

TABLE I
SIMULATION PARAMETERS

Parameters	Values
Number of sensor nodes	$1 \sim 20$
Beacon Order	$0 \sim 6$
Superframe Order	$0 \sim 6$
Transmission rate of data frame	250 Kbps
Data payload	90 bytes
Data frame overhead	15 bytes
Ack frame	11 bytes
macMinBE	3
aMaxBE	5, 7

A. Collision probability

To evaluate the performance of the data fragmentation scheme, we evaluate the collision probability under different number of sensor nodes and different lengths of superframe. In the IEEE 802.15.4 MAC, there exists an unavoidable collision when more than two sensor nodes wait for the next superframe to transmit data frames. With the data fragmentation scheme, we can avoid such collision. As a result the reduction of collision probability per transmission can be observed. We expect to see dramatic decrease in collision probability as the length of the superframe decreases.

Fig. 6 and Fig. 7 show the collision probability with respect to the number of sensor nodes when BO=1 and BO=3, respectively. We simulate two scenarios with different backoff ranges by modifying the *aMaxBE* value to rule out the problem of small backoff ranges [5]. From Fig. 6 we can see that there are almost 30% reduction in collision probability with the data

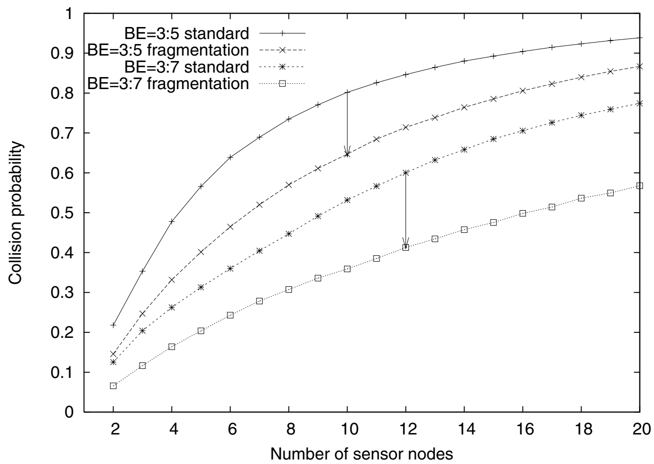

Fig. 6. Collision probability vs Number of sensor nodes, when BO=1.

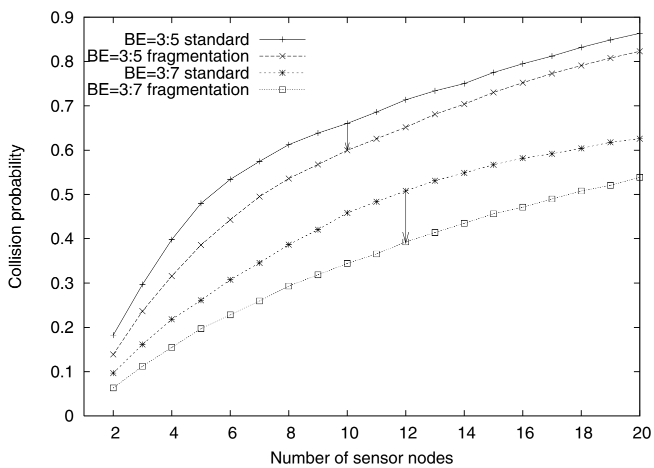

Fig. 7. Collision probability vs Number of sensor nodes, when BO=3.

fragmentation scheme compared to the 802.15.4 standard. We can also see that the impact of the data fragmentation scheme is greater as the backoff range becomes wider.

Here we evaluate the collision probability by varying the length of the superframe, via modifying the BO value. To evaluate the collision probability with respect to the BO values, we simulate 10 sensor nodes. From Fig. 8 as the length of the superframe decreases, the collision probability of the data fragmentation scheme dramatically decreases. For example, when the BO is 0, the collision probability is reduced by 50%. This is because of the collision avoidance at the start of the superframe. However, when the length of superframe reaches some point (BO=6), the improvement of our scheme is insignificant. This is because, the collision avoidance is minor compared to the long length of superframe. However as mentioned above, we consider the application of consumer electronics whose BO is less than 6 only [6], therefore the performance improvement of our scheme is still valid. As we said in previous sections, one of the two problems with the legacy of 802.15.4 MAC is that it has inevitable collision. We corroborate through our simulations that when using the data fragmentation scheme we can avoid the collision, as a result we reduce the collision probability per transmission.

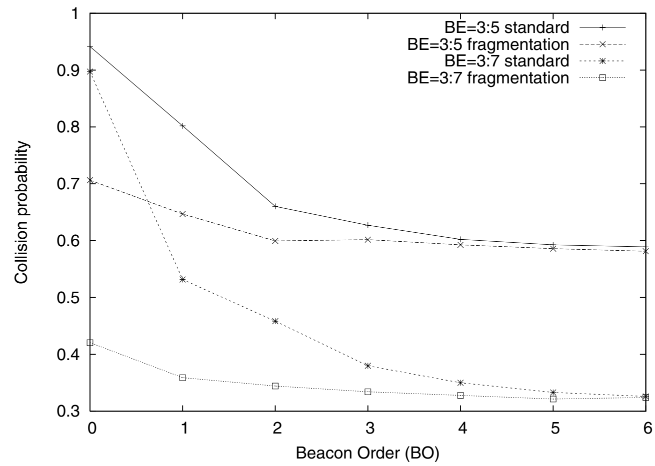

Fig. 8. Collision probability vs BO, when 10 sensor nodes deployed.

B. Throughput

In this section, we show the aggregate throughput performance of the data fragmentation scheme. The throughput performance of the 802.15.4 MAC quickly degrades as the number of contending sensor nodes increase. Generally, it takes an average of 7.68 ms to send one data frame over a 802.15.4 link, with 250 Kbps nominal bit-rate. This is because a transmission goes through the following sequences: contention (1.28ms on average = 4 backoff periods) + CCA (0.64ms) + data frame transmission (4.16ms) + ACK (1.6ms). Here, the original data frame is 120 bytes. The achievable average transport throughput is thus 125 Kbps. Any higher throughput is obtainable only through the reduction of the idle time. In this paper, we do not deal with the throughput increment under the modification of the idle time, therefore the achievable aggregate throughput is up to 125 Kbps.

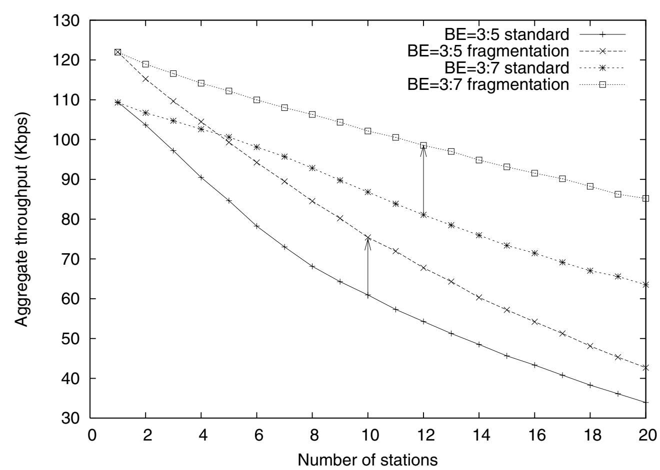

Fig. 9. Aggregate throughput, when BO=1.

We evaluate the aggregate throughput once again under different number of sensor nodes and different lengths of superframes. Using the data fragmentation scheme, we increase the channel utilization. This is done through using the wasted idle backoff periods due to shortage of remaining bakcoff periods in the CAP. Compared to the length of a

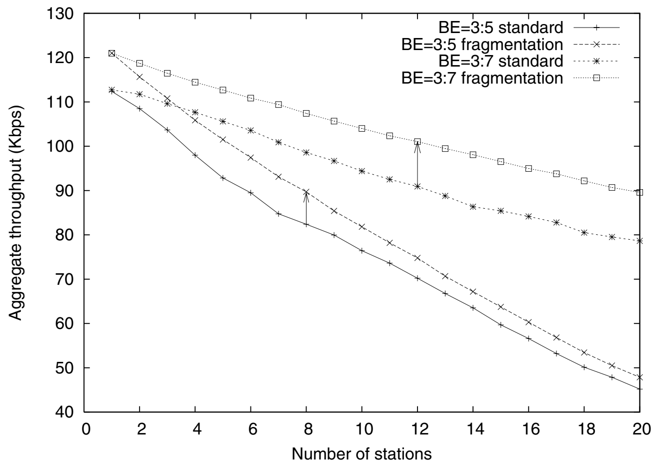

Fig. 10. Aggregate throughput, when BO=3.

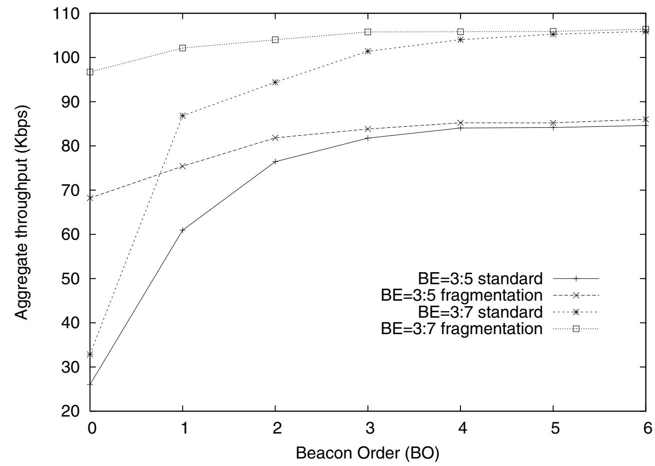

Fig. 11. Aggregate throughput vs BO, when 10 sensor nodes deployed.

superframe this channel utilization increment is small, but with the increased chance of transmitting the data from avoiding the inevitable collision, it becomes significant. Fig. 9 and Fig. 10 represent the aggregate throughput with and without the data fragmentation scheme under various number of contending sensor nodes. In Fig. 9, we see up to 35% throughput increase and the gap grows larger as the sensor node population increases. With a wider backoff range, the improvement of aggregate throughput becomes more significant.

We also evaluate the aggregate throughput performance under different lengths of superframes. To evaluate the impact of superframe length on our scheme, we deploy 10 sensor nodes and evaluate the aggregate throughput while varying the BO value from 0 to 6. From Fig. 11 as the length of superframe decreases, the aggregate throughput improvement of data fragmentation scheme increases. This result is caused from the increment in channel utilization. However, as we mentioned when the length of superframe reaches some point (BO=6), the improvement of our scheme is minimized. The performance improvement of the data fragmentation scheme on the WSN lies on the short length of superframe, meaning that the BO value should be less than 6.

Applications such as security systems should alarm the status of current situation very frequently to the users as fast as possible. In other words, the data transmission is expected to be guaranteed with a small delay bound. By using the data fragmentation scheme in 802.15.4 WSNs we were able to reduce the collision probability and therefore we can expect a smaller delay bound. Through this we can see that the effectiveness of adapting the data fragmentation scheme to the IEEE 802.15.4 MAC is significant.

V. Conclusion

In this paper, we point out problems of the IEEE 802.15.4 MAC standard when considering WSN with frequent beacon intervals. The IEEE 802.15.4 results inevitable collision and waste channel utilization. To solve these problems, we propose a data fragmentation scheme for 802.15.4 based WSN. The data fragmentation process is simple to adapt and there is only little overhead. However, the performance improvement outweighs this overhead. With this scheme we can reduce the collision probability per transmission and increase the aggregate throughput. The performance improvement is significant when the length of a superframe is shorter. Applying the data fragmentation scheme in applications such as vital monitoring and security systems, the total network performance improve significantly.

VI. Acknowledgement

This research is supported by the Ubiquitous Autonomic Computing and Network Project, the Ministry of Information and Communication (MIC) 21st Century Frontier R&D Program in Korea.

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