Adaptive Active Period Control for Low Power Consumption and Low Latency in Multi-hop Wireless Sensor Networks

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Abstract: IEEE 802.15.4 beacon-enabled mode can use the superframe structure for data transmission. In using the superframe structure, the duty cycle of the wireless personal area network defined by the values of the beacon order (BO) and superframe order (SO) can be adjusted in order to achieve high channel utilization and low power consumption. The optimum values of BO and SO vary according to the network condition. The present paper proposes a novel method that achieves low power consumption and low latency in a multi-hop wireless sensor network. In the proposed method, active periods in the superframe structure are appropriately assigned to routing nodes according to the network topology prior to data transmission, and the values of SO are adaptively adjusted depending on the traffic load. Simulation results demonstrate the effectiveness of the proposed method.

1 INTRODUCTION

With the rapid growth of wireless technologies and the downsizing of devices, a number of investigations regarding wireless sensor networks (WSNs) have been conducted in recent years. Environmental monitoring, crime prevention, disaster prevention, home automation, and smart metering are considered to be major applications of sensor networks.

The IEEE 802.15.4 standard defines the medium access control (MAC) and physical layer specifications for low-rate and low-power WSNs (IEEE 802 Working Group, 2006). Zigbee (Zigbee Aliance, 2006), which is a representative WSN, adopts the IEEE 802.15.4 standard. In IEEE 802.15.4, there are two modes of operation: non-beacon-enabled and beacon-enabled modes.

In the non-beacon-enabled mode, communication is not synchronized, even if the parent-child relation between neighboring nodes is established. In addition, the child node can start the transmission at any time when data is to be transmitted, because the parent node is always active. This, however, causes a significant increase in power consumption.

In the beacon-enabled mode, after the parent-child relation between neighboring nodes is established, these nodes communicate while synchronizing with a beacon. A child node transmits data toward a parent node when the parent node is active. Power consumption can be reduced because the parent node can sleep in the beacon-enabled mode.

The present paper deals with IEEE 802.15.4 beacon-enabled WSNs while considering these characteristics. The active period in the superframe consists only of a contention access period (CAP). For the sake of simplicity in validating the proposed method, every contention free access period (CFP) is neglected.

In the beacon-enabled mode, the duty cycle is determined by two parameters, the beacon order (BO) and superframe order (SO), both of which are integers and 0 SO BO 14. When the duty cycle is small, the power consumption is low for a low traffic load. The end-to-end transmission delay and power consumption, however, increase when the traffic is heavy, because collisions frequently occur. On the other hand, when the duty cycle is large, collisions can be reduced in the case of heavy traffic. Power consumption, however, increases even when the traffic load is low.

Determination of the appropriate BO and SO is difficult because a wide variety of applications and network topologies are assumed in WSNs. Although a number of methods that adaptively control the active period by adjusting BO and SO have been proposed, few of these methods deal with a multi-hop network in which the congestion in the vicinity of the sink node poses a serious problem.

The present paper proposes a novel method that

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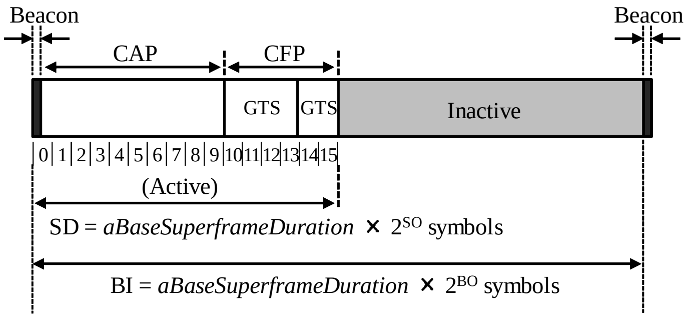

Figure 1: IEEE 802.15.4 superframe structure.

achieves low power consumption while maintaining low end-to end transmission delay for an IEEE 802.15.4 beacon-enabled multi-hop WSN. In the proposed method, active periods in the superframe structure are appropriately assigned to routing nodes according to the network topology prior to data transmission in order to reduce the congestion in the vicinity of the sink node. After transmission starts, the values of SO are adaptively adjusted depending on the traffic load. Simulation results demonstrate the effectiveness of the proposed method.

The rest of this paper is organized as follows. Section 2 introduces an overview of IEEE 802.15.4 beacon-enabled mode. Section 3 describes related works. Section 4 explains our proposed method in detail. Section 5 gives an evaluation of our proposed method by showing simulation results. Finally, Section 6 concludes the paper.

2 OVERVIEW OF IEEE 802.15.4 BEACON-ENABLED MODE

2.1 Characteristics of IEEE 802.15.4 Beacon-enabled Mode

The superframe structure in the beacon-enabled mode is shown in Figure 1 . The beacon Interval (BI) and superframe Duration (SD) are determined by Eqs. (1) and (2).

$$\begin{aligned} BI &= aBaseSuperframeDuration \times 2^{BO} \quad (1) \\ SD &= aBaseSuperframeDuration \times 2^{SO} \quad (2) \\ & \quad (0 \leq SO \leq BO \leq 14) \end{aligned}$$

The value of $aBasesuperframeDuration$ is fixed to 960 [symbols] (= 15.36 [msec]). The smaller the BI, the more significantly the delay can be reduced, because the frequency of active periods becomes large per unit time. The larger the SD, the greater the number of frames that can be transmitted in a superframe. However, it is necessary to appropriately set BO and SO depending on the number of full function devices (FFDs), because a multi-hop network cannot be configured if BO = SO. Here, the node, which has the routing function and can have multiple child nodes in its communication range, is configured as the FFD. The sink node and routing nodes are referred to as the coordinator and the routers, respectively, in ZigBee. In the present paper, these nodes are assumed to be configured as FFDs, and sensor nodes corresponding to end devices in Zigbee are configured as reduced function devices (RFDs). The duty cycle in the IEEE 802.15.4 beacon-enabled mode is expressed in Eq. (3).

$$\begin{aligned} DutyCycle &= \frac{ActivePeriod}{ActivePeriod + SleepPeriod} \\ &= \frac{SuperframeDuration}{BeaconInterval} \\ &= \frac{2^{SO}}{2^{BO}} \end{aligned} \quad (3)$$

The smaller the difference between BO and SO, the larger the duty cycle.

2.2 Parameters BO and SO and Number of FFDs

If multiple FFDs in the IEEE 802.15.4 beacon-enabled mode have SDs at the same time, collisions among beacons are likely to occur. When such collisions occur, communication is unavailable because synchronization for the communication is not achieved. Therefore, it is necessary for each FFD to use each SD exclusively in order to avoid collisions among beacons. Eq. (4) holds for the case in which each FFD uses each SD exclusively.

$$2^{BO-SO} \geq FFDnum = \sum_{k=0}^{hop-1} n^k \quad (4)$$

Here, the network is assumed to configure an n-ary tree by the FFDs. An n-ary tree is a tree in which,

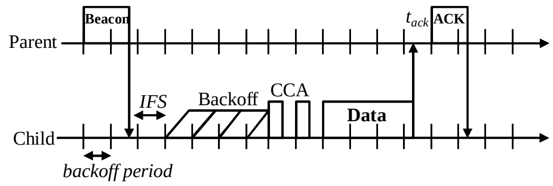

Figure 2: Slotted CSMA/CA.

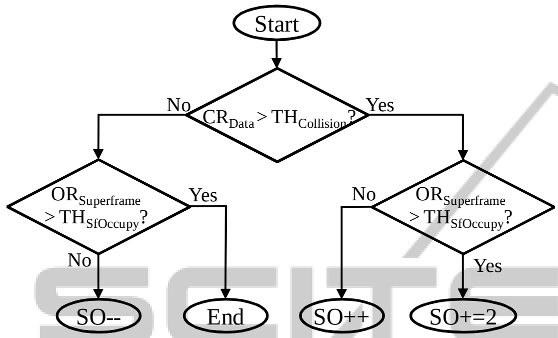

Figure 3: Flowchart of sink node in DSAA.

with the exception of edge routers, every FFD has n child nodes. An edge router is a routing node that is the farthest from the sink node. In an n-ary tree, all hopcounts between the sink node and each sensor node are the same. The hopcount is denoted as hop in Eq. (4).

3 RELATED WORK

In order to control the active period, adjusting the values of BO and SO adaptively is considered to be effective. A number of methods have been proposed that adaptively increase or decrease the values of BO and SO, with the goal of reducing power consumption and transmission delay (Joen et al., 2007), (J. Lee et al., 2007), and (Paz et al., 2010). The dynamic superframe adjustment algorithm (DSAA), in which SO is adaptively adjusted while fixing BO (B. H. Lee et al., 2010), is one such method. In the DSAA, the collision ratio and the superframe occupation ratio, which are metrics of the traffic load, are calculated, and SO is adjusted according to the calculated traffic load. However, these methods, including the DSAA, are intended for use with a single-hop network.

3.1 Calculation of Collision Ratio and Superframe Occupation Ratio in DSAA

Slotted carrier sense multiple access with collision

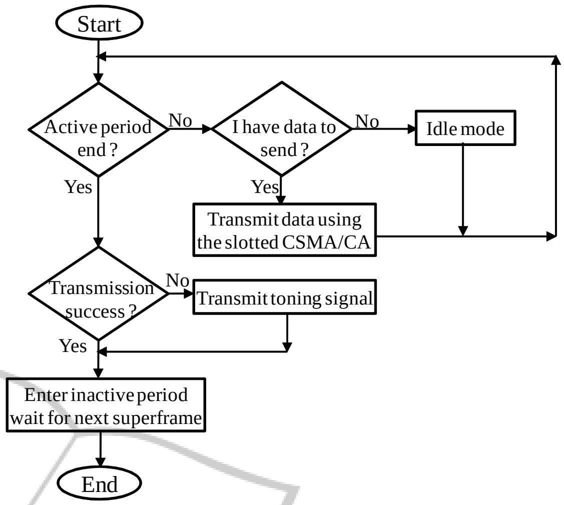

Figure 4: Flowchart of sensor nodes in DSAA.

avoidance (CSMA/CA) is used in the CAP of IEEE 802.15.4 in the DSAA. In slotted CSMA/CA, clear channel assessment (CCA) and back-off are conducted based on the smallest unit of time expressed in unit backoff periods (UBPs) = 20 [symbols]. Figure 2 shows an overview of the slotted CSMA/CA mechanism.

The collision ratio and the occupation ratio of the superframe are represented by Eqs. (5) and (6), respectively.

$$OR_{Superframe} = \frac{Packet_{Rx} \times Node_{UBPs\_Total}}{S_{UBPs\_SO} - S_{UBPs\_Beacon}} \times 100\% \quad (5)$$

$$CR_{Data} = \frac{Node_{Data\_Failure}}{Node_{Data\_Success} + Node_{Data\_Failure}} \times 100\% \quad (6)$$

Here, $Packet_{Rx}$ is the number of packets received in the CAP, $Node_{UBPs\_Total}$ is the number of UBPs needed to complete the data transmission, S_{UBPs_SO} is the number of UBPs in the active period, and S_{UBPs_Beacon} is the length of the beacon frame in UBP. $Node_{Data\_Success}$ is the number of nodes that have successfully transmitted data, and $Node_{Data\_Failure}$ is the number of nodes that have unsuccessfully transmitted data. Unsuccessful transmission is detected by means of a toning signal (Koubaa et al., 2006).

3.2 Overview of DSAA

The sink node will start to adjust the duty cycle of the next superframe when the values of $ORsuperframe$ and $CRData$ are calculated. Based on the relation among $ORsuperframe$, $CRData$, $THsuperframeOccupy$, and $THCollision$, there are four possible situations. Depending on the situation, the sink node adjusts the value of SO, as shown in Figure 3.

If a child node needs to send data in the CAP, the child node will try to transmit the data using the slotted CSMA/CA algorithm. Otherwise, if there is no data to send, the node will switch to the idle mode. At the end of the CAP, if the node has no data to send, the node will do nothing and will enter the inactive period or the CFP. However, if the node cannot transmit its data successfully in the current superframe, the node will send a toning signal to notify the sink node of the failure. The flowchart is shown in Figure 4.

New active periods of some other FFDs may start after an active period of an FFD ends n a multi-hop network. Therefore, there is a possibility that the toning signal will collide with subsequent beacons or data packets. This indicates that the DSAA is not applicable to the multi-hop networks. In addition, the toning mechanism imposes some changes on both the hardware and the protocol itself (Koubaa et al., 2006).

4 PROPOSED METHOD

The present paper proposes a novel method that achieves low power consumption while maintaining a low end-to-end transmission delay for an IEEE 802.15.4 beacon-enabled multi-hop WSN. In the proposed method, active periods in the superframe structure are appropriately assigned to routing nodes according to the number of edge routers, prior to data transmission in order to reduce the congestion in the vicinity of the sink node. After the data transmission starts, the values of SO are adaptively adjusted depending on the traffic load.

Each sensor node can directly communicate with only one edge router. The traffic load is calculated in a manner similar to the DSAA. The toning signal is not used in the calculation of the collision ratio. Instead of the toning signal, the number of retransmissions is used as the metric of the traffic load. The number of retransmissions is appended to data packets in the sending node, and the number is counted in each receiving node.

4.1 Active Period Assignment Depending on Number of Edge Routers

In a multi-hop WSN, when the traffic load corresponding to the sensing frequency at each sensor nodes is high, congestion occurs in the vicinity of the sink node. In order to mitigate such congestion, the

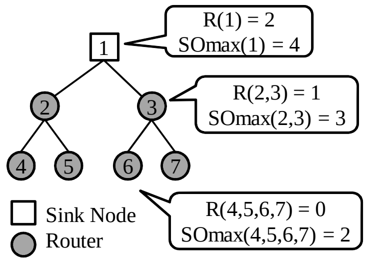

Figure 5: Example of active period assignment.

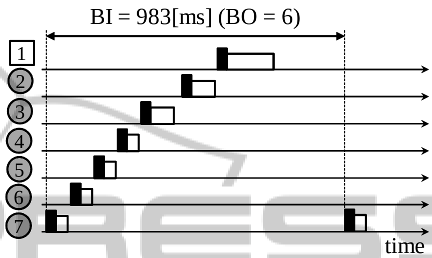

Figure 6: Beacon scheduling.

active period of the FFD is assigned to be long, because the number of hops to the sink node is small and the number of sensors placed beneath the FFD is large. Here, SO of each FFD is decided based on the number of edge routers beneath the FFD.

The node number of each FFD is denoted as i [1, 2, c, n]. $n_{ER}(i)$ is defined as the number of edge routers beneath the $FFD(i)$. Integer $R(i)$ is defined as the smallest R that satisfies Eq. (7).

$$n_{ER}(i) \leq 2^R \tag{7}$$

BOmin is defined as the smallest *BO* that satisfies Eq. (8).

$$\sum_{i=1}^{n} 2^{R(i)} \leq 2^{BO} \tag{8}$$

In the network that constructs an n-ary tree, as mentioned in Section 2.2, *BOmin* can be expressed as Eq. (9).

$$2^{BO_{min}} \geq hop \times n^{hop-1} \tag{9}$$

$SOmax(i)$, or the maximum value of SO for each $FFD(i)$, is determined by Eq. (10).

$$SO_{max}(i) = R(i) + (BO - BO_{min}) \tag{10}$$

For example, if the network topology is a 3-hop binary tree, $R(i)$ is determined as shown in Figure 5, and $BOmin = 4$. When $BO = 6$, $SOmax(i)$ is determined as shown in Figure 5.

In the proposed method, beacons are scheduled as shown in Figure 6 so that no collisions occur, and low latency can be achieved when the active period of each FFD is $2^{SOmax(i)}$ (Eq. (2)). This active period assignment prior to the data transmission can achieve low power consumption and low latency, even when the traffic load is high.

4.2 Adaptive Active Period Control Method based on Traffic Load

The active period of each FFD is adaptively controlled using the metric of the traffic load in a manner similar to the DSAA. The occupation ratio of the superframe denoted as ORsuperframe is determined by Eq. (5). The number of retransmissions as the metric of the traffic load is evaluated using RTData. RTData of each parent node is the number of retransmissions per frame received from its child nodes. Each node counts the number of retransmissions when transmitting data. In the sensor node, the number of retransmissions is added to the data frame when the sensing data is transmitted to the parent node. In the routing node, the number of retransmissions of the routing node is added to the number of retransmissions included in the data frame. Based on this information, the parent nodes detect the occurrence of collisions at their child nodes and increases the active period immediately.

In the proposed method, four thresholds are defined, whereas two are defined in the DSAA. These thresholds are denoted as $THSfOccupy(1)$, $THSfOccupy(2)$, $THSfOccupy(3)$, and $THRetry$ and are set for $ORsuperframe$ and $RTData$, where $THSfOccupy(1)$ $THSfOccupy(2)$ $THSfOccupy(3)$. In each FFD, the occupation ratio of the superframe and the number of retransmissions are calculated at the end of the active period. As shown in Figure 7, SO of the next active period is adjusted according to the traffic load, comparing ORsuperframe and RTData with four thresholds. The traffic load is represented using four stages in the same manner as the DSAA. These four thresholds enable finer adjustment of SO than the DSAA.

5 PERFORMANCE EVALUATION

5.1 Simulation Scenarios

The performance improvement achieved by the proposed method is evaluated via simulation. The IEEE 802.15.4 beacon-enabled mode, the DSAA and the proposed method are compared using the QualNet simulator. The value of BO is fixed to 6 in both methods. The value of SO can be adjusted from 0 to the maximum value that is possible in the network topology. Simulation is conducted for five tree topologies, 2-, 3-, and 4-hop binary trees, and 2- and 3-hop quad trees. Each edge router is assumed to be able to directly communicate with 1 to 20 sensor nodes. In each topology, the number of sensor nodes and routing nodes are determined as shown in Table 1. As an example, Figure 8 shows the topologies of 2-, 3-, and 4-hop binary trees when each edge router has five sensor nodes as child nodes.

Table 2 shows the simulation parameters. The four thresholds used in the proposed method are constant values, as shown in Table 2. Evaluation is conducted in terms of the total energy consumed by all of the nodes and the average end-to-end transmission delay with respect to the number of sensor nodes and the offered load. The offered load represents the number of frames to be sent by one sensor node per sec. In

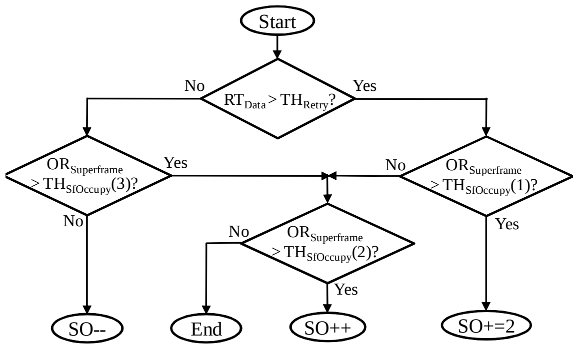

Figure 7: Flowchart of FFDs in proposed method.

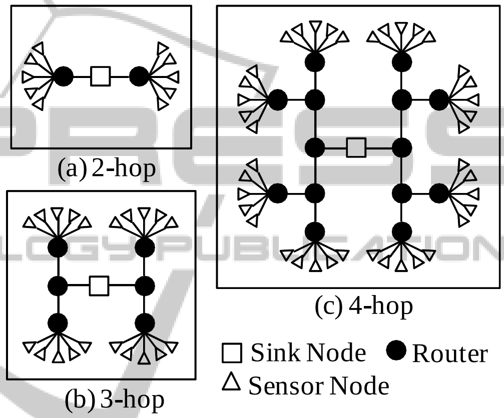

Figure 8: Network topology of binary tree.

Table 1: Topology and number of nodes.

Topology(n,h)	(2,2)	(2,3)	(2,4)	(4,2)	(4,3)
Relay Node	2	6	14	4	20
Sensor Node(5)	10	20	40	20	80
Sensor Node(10)	20	40	80	40	160
Sensor Node(15)	30	60	120	60	240
Sensor Node(20)	40	80	160	80	320

N-ary tree is denoted as n and hopcount is denoted as h.

Table 2: Simulation parameters.

Parameter	Value
Physical Layer	IEEE 802.15.4 250[Kbps]
Data Frame Size	30[bytes]
Offerd Load	0.0167[pps]
$TH_{SfOccupy}(1)$	60[%]
$TH_{SfOccupy}(2)$	40[%]
$TH_{SfOccupy}(3)$	20[%]
TH_{Retry}	0

addition, the sensing frequency is assumed to be the same at each sensor node. The carrier sensing range is assumed to be twice the transmission range, which means that no hidden terminals are considered.

5.2 Simulation Results

5.2.1 Comparison with the IEEE 802.15.4

The proposed method ($BO = 6$) and the IEEE802.15.4 beacon-enabled mode ($BO = 6$, SO =0, 1, 2, and 3) are compared for a 3-hop binary tree. The simulation results are compared in terms of the average total power consumption and the end-to-end transmission delay with respect to the number of nodes in Figures 9 and 10, respectively.

As shown in Figure 9, the power consumption is the lowest for the case of IEEE 802.15.4 $SO = 0$ when the number of sensor nodes is small. The power consumption, however, increases significantly as the number of sensor nodes increases. Figure 10 shows that the delay increases due to collisions as the traffic load increases. Even for the case of IEEE 802.15.4 $SO = 1$, the delay starts to increase from the point at which each edge router has approximately 16 sensor nodes, and the power consumption also increases. On the other hand, for the case of IEEE 802.15.4 $SO = 2$ or $SO = 3$, the power consumption is much higher than for case of $SO = 0$ or $SO = 1$. This is because power wastage occurs due to the increase in active periods.

The power consumption of the proposed method is approximately equal to that of IEEE 802.15.4 $SO = 0$, when each edge router has one to five sensor nodes, and is equal to that of IEEE 802.15.4 $SO = 1$, when each edge router has more than five sensor nodes. When each edge router has more than 17 sensor nodes, the delay in IEEE 802.15.4 $SO = 1$ increases due to collisions. On the other hand, the delay is at most approximately 1.5 [s] in the proposed method. It can be shown that the proposed method appropriately adjusts the value of SO according to the traffic load. Similar characteristics are shown in other topologies.

Figure 11 shows the variation of SO of the sink

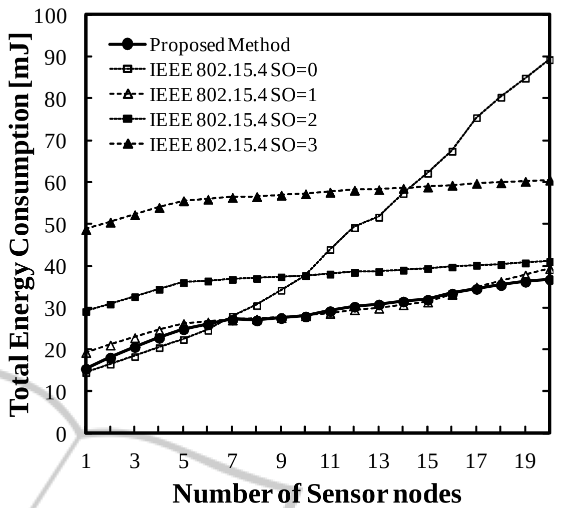

Figure 9: Energy consumption with respect to number of nodes (3-hop binary tree).

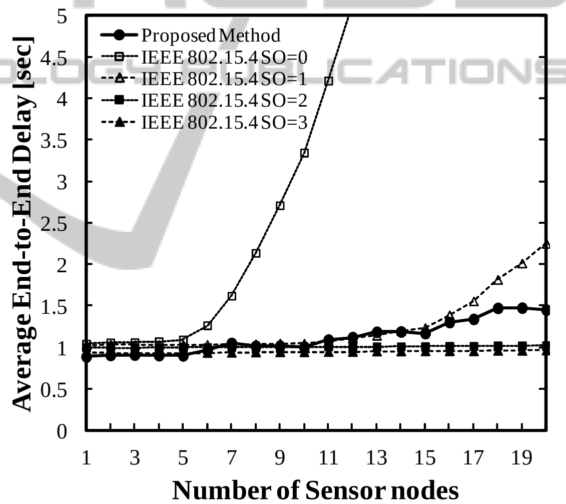

Figure 10: Delay with respect to number of nodes (3-hop binary tree).

node with respect to the simulation time in a 3-hop binary tree topology for the proposed method. In Figure 12, the proposed method and IEEE 802.15.4 $SO = 0, 1, 2,$and 3 are compared in terms of the delay and power consumption in this topology. Figures 11 and 12 show that the proposed method reduces the power consumption and delay by appropriately adjusting the value of SO depending on the traffic load.

Figures 13 and 14 show the characteristics in the case of a high traffic load. In these figures, the proposed method ($BO = 6$) and IEEE802.15.4 beacon-enabled mode ($BO = 6, SO = 0, 1,$ and 2) are compared for a 4-hop binary tree. The results in terms of the average total power consumption and the end-to-end transmission delay with respect to the offered

Table 3: Variation of number of sensor nodes.

Simulation time[sec]	0 - 700	700 - 1200	1200 - 1700	1700 - 2200	2200 - 2700	2700 - 3600
Number of sensor nodes	5	10	15	20	10	5

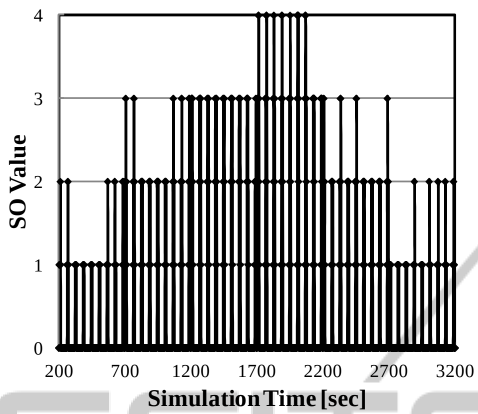

Figure 11: Value of SO with respect to simulation time.

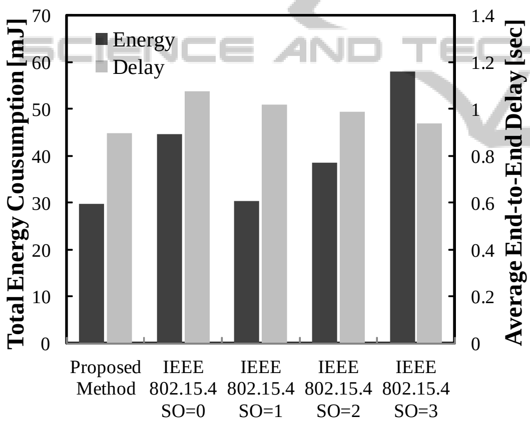

Figure 12: Energy consumption and delay.

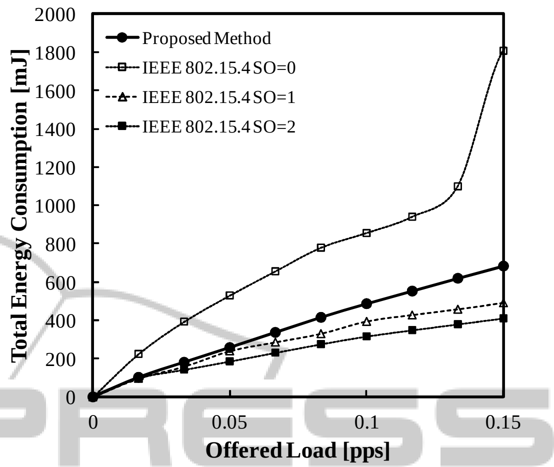

Figure 13: Energy consumption with respect to offered load (4-hop binary tree).

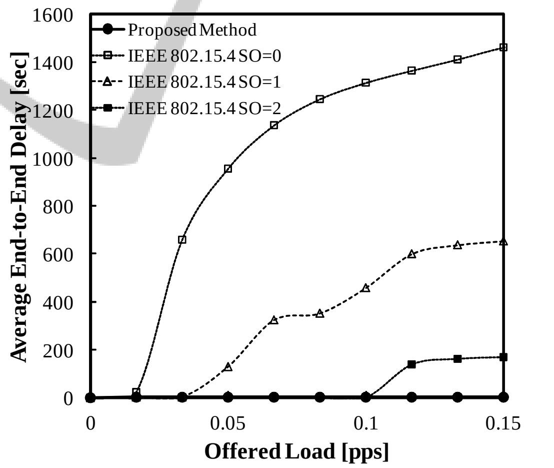

Figure 14: Delay with respect to offered load (4-hop binary tree).

load are compared inFigures 13 and 14, respectively. As shown in Figure 15, even for the case of IEEE 802.15.4 SO = 2, the delay increases significantly due to collisions in the vicinity of the sink node. The proposed method, however, reduces the delay by suppressing such collisions. This is achieved by appropriately setting the value of SO according to the number of edge routers in the topology, prior to the data transmission.

5.2.2 Effect of thresholds in Adaptive Active Period Control

The SO adjustment mechanism of the proposed method (Figure 7) and that of the DSAA (Figure 3) are compared for a 3-hop binary tree. In this comparison, the proposed method and the DSAA use the same active period assignment. When the thresholds of the superframe occupation ratio and the number of retransmissions are expressed as $THSfOccupy$ and $THRetry$, respectively, the SO adjustment mechanism of the DSAA is represented as the DSAA ($THSfOccupy$, $THRetry$). The simulation results in terms of the average total power consumption and the end-to-end transmission delay are compared in Figures 15 and 16, respectively. As can be seen, the power consumption of the proposed method is lower than that of the DSAA, while maintaining the low delay. This effect is mainly achieved by the thresholds defined in the proposed method.

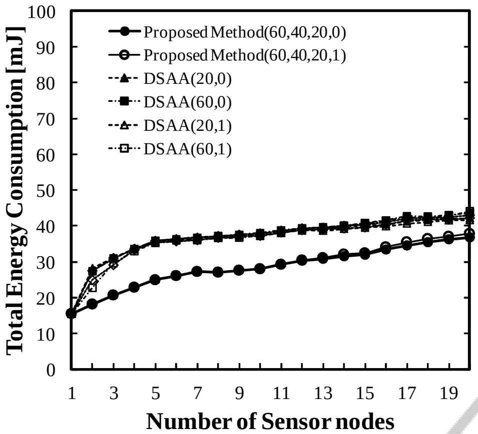

Figure 15: Energy consumption with respect to number of nodes (3-hop binary tree).

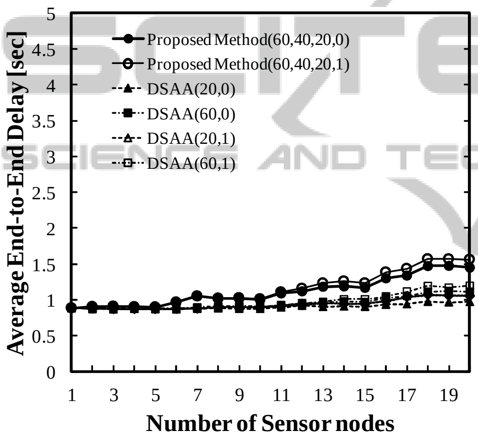

Figure 16: Delay with respect to number of nodes (3-hop binary tree).

6 CONCLUSIONS

The present paper proposed a novel method that reduces the power consumption while keeping the latency low in an IEEE 802.15.4 beacon-enabled multi-hop WSN. In the proposed method, active periods in the superframe structure are appropriately assigned to routing nodes depending on the number of edge routers, prior to data transmission. After the data transmission starts, the values of SO are adjusted appropriately depending on the traffic load. A simulation evaluation has demonstrated that the proposed method maintains lower power consumption and lower end-to-end transmission delay regardless of the traffic load, as compared to the IEEE 802.15.4 beacon-enabled mode.

The setting of appropriate thresholds and the evaluation of various BO values for various network topologies are areas for future research.

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