Article

Duty Cycle Control Method Considering Buffer Occupancy for IEEE 802.15.4-Compliant Heterogeneous Wireless Sensor Network

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Abstract: This paper proposes a Duty-Cycle (DC) control method in order to improve the Packet Delivery Ratio (PDR) for IEEE 802.15.4-compliant heterogeneous Wireless Sensor Networks (WSNs). The proposed method controls the DC so that the buffer occupancy of sensor nodes is less than 1 and assigns DC to each sub-network (sub-network means a network consisting of a router node and its subordinate nodes). In order to use the appropriate DC of each sub-network to obtain the high PDR, this paper gives analytical expressions of the buffer occupancy. The simulation results show that the proposed method achieves a reasonable delay and energy consumption while maintaining high PDR.

Keywords: IEEE 802.15.4; duty-cycle; active period control; heterogeneous sensor network; tree topology

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1. Introduction

Ad-hoc sensor networks have been paid attention in various applications, such as environment monitoring and smart home [1–16]. Today, heterogeneous Wireless Sensor Networks (WSNs) also gain enormous attention due to the diversification of applications, such as medical applications and environmental monitoring systems [17,18]. In heterogeneous WSNs, various components are heterogeneous, such as sensor nodes' traffic sources (low/middle/high) and network topology (star/tree). Therefore, it is difficult to control heterogeneous WSNs nodes' operations because of their complexities.

The IEEE 802.15.4 is the standard of WSN. The devices communicate with superframe structure in the IEEE 802.15.4 standard [19]. In the superframe structure, the communication of each node is managed by the active and sleep cycles (Duty-Cycle). The energy consumption of WSN nodes are saved by controlling DC. The Quality of Service (QoS), such as Packet Delivery Ratio (PDR) and delay, is controlled by tuning the MAC (Medium Access Control) parameters [18,20–22].

Z. Xiao et al. proposed a scheduling protocol for star topology WSNs [20]. The protocol proposed in Reference [20] controls active and sleep periods taking into account the buffer occupancy of sensor nodes. However, the protocol proposed in Reference [20] is not suitable for controlling heterogeneous WSNs nodes' operations since it is proposed under the assumption of the homogeneous networks.

A. Karalis et al. proposed a beacon signal avoidance protocol for homogeneous tree topology WSNs in order to achieve high PDR and low energy consumption [22]. Although the collision avoidance protocol proposed in Reference [22] can avoid beacon signal collisions, it does not guarantee collision avoidance of outgoing packets of sensor nodes.

The Tele-Medicine Protocol (TMP) [18] is an IEEE 802.15.4-based MAC protocol for heterogeneous WSNs. The TMP tunes DC and MAC layer parameters to meet the QoS requirements in the medical field. The TMP controls the active-period length of a superframe

to be shorter in order to reduce energy consumption. However, for high data rate nodes, the shorter the active period, the more packets are lost, and the lower the PDR [23–26].

This paper proposes a duty-cycle control method in order to improve the PDR for IEEE 802.15.4-compliant heterogeneous WSNs. The proposed method tunes the DC so that the buffer occupancy of sensor nodes is less than one and assigns DC to each sub-network (sub-network means a network consisting of a router node and its subordinate nodes). The appropriate DC of each sub-network can be used to obtain the high PDR; thus, this paper gives analytical expressions of the buffer occupancy. The proposed method can control DC heterogeneous star and/or tree-topology wireless sensor networks. Simulation results show the effectiveness of the proposed method.

2. Related Works

2.1. IEEE 802.15.4

In the IEEE 802.15.4 beacon enable mode, the devices communicate using the superframe structure. The superframe consists of three parts: the beacon frame, active period, and inactive period, as shown in Figure 1. Nodes send and receive packets during only the active period. The active period is divided into CAP (Contention Access Period) and CFP (Contention Free Period). The devices communicate using CSMA/CA in the CAP. The proposed method assumes to use only CAP.

Figure 1. The superframe structure of IEEE 802.15.4.

Figure 2 shows the flow chart of IEEE 802.15.4 Clear Channel Access (CCA). MacCSMABackoffs is the number of retransmissions. Contention windows (CW) are used to communicate fairly. Each node checks whether the channel is idle before sending packets.

Beacon Interval (BI) means the time interval between two superframes. The length of BI is determined by the parameter BO (Beacon Order), which is expressed by

$$BI = aBaseSuperframeDuration \times 2^{BO} (ms), \quad (1)$$

where $aBaseSuperframeDuration$ is the basic length of the superframe and consists of 16 time slots, and one time slot length is 0.96 ms. So, the $aBaseSuperframeDuration$ is 15.36 ms. Superframe Duration (SD) means the length of the active period. The length of SD is determined by SO (Superframe Order), which is expressed by

$$SD = aBaseSuperframeDuration \times 2^{SO} (ms). \quad (2)$$

From Figure 1, BO and SO satisfy $SO \leq BO$. The ratio of the length of the active period to that of the superframe is called DC. DC is expressed by

$$DC = \frac{2^{SO}}{2^{BO}}. \quad (3)$$

Figure 2. Flow chart of IEEE 802.15.4 packet transmission.

2.2. TMP (Tele-Medicine Protocol)

The TMP tunes DC for heterogeneous WSNs. In the TMP, DC is controlled to reduce energy consumption while meeting the allowable delay. The energy consumption increases as the active period become longer. Therefore, the TMP sets DC as small as possible to minimize energy consumption while guaranteeing QoS.

3. Proposed Method

This paper proposes a DC control method to achieve high PDR for IEEE 802.15.4-compliant heterogeneous star and/or tree topology WSNs. Figure 3 shows the example of a tree topology heterogeneous WSNs. In homogeneous WSN, communication qualities, such as PDR and energy consumption, can be improved by setting the same DC for all sensor nodes. On the other hand, in heterogeneous WSNs where data rates of sensor nodes are different, even if the same DC control is applied to all sensor nodes, the high communication quality may not be achieved because of the different characteristics of

the network nodes. In order to solve this problem, the proposed method allocates an appropriate DC for each sub-network (sub-network means a network consisting of a router node and its subordinate nodes). DC is controlled in consideration of the buffer occupancy of nodes.

Figure 3. Example of a tree topology heterogeneous Wireless Sensor Networks (WSNs).

This paper assumes that each router node does not generate its own packet. In this section, we also assume that there are no transmission failures. Each router node generates a packet when relaying packets from the end devices. We assume that the number of generating packets of router node i in one superframe duration λ_i is given by

$$\lambda_i = \frac{DataRate_i}{8 \times P} \times BI, \quad (4)$$

where $DataRate_i$ is the total data rate of end devices which belong to router node i , and P is a packet payload size (byte).

Assuming that there are no transmission failures, the data rate of router node i is given by

$$DataRate_i = \sum_{j=1}^{N_i} DataRate_j, \quad (5)$$

where N_i is the number of end devices which belong to router node i . Assuming that router node i transmits n_i packets during $aBaseSuperframeDuration$, the total number of transmitted packets during one active period, which indicates the service rate of node i , μ_i , is

$$\mu_i = n_i \times 2^{SO}. \quad (6)$$

Assuming no contention, n_i is given by

$$n_i = \frac{aBaseSuperframeDuration - Beaconframe}{maxDelay}, \quad (7)$$

where $maxDelay$ is given by Equation (8), and expressed as

$$maxDelay = macCSMABackoff * (T_{Backoff} + T_{CCA}) + T_{PktTx} + T_{ACK} + T_{SIFS} + T_{TA}, \quad (8)$$

where $macCSMABackoff$ is the maximum number of carrier sensing trials, $T_{Backoff}$ and T_{CCA} are time to backoff and carrier sense, respectively. T_{PktTx} expresses the time to transmit a packet. When the data transfer speed is 250 (Kbps),

$$T_{PktTX} = \frac{PacketSize(byte)}{250(Kbps)}. \quad (9)$$

In Equation (8), T_{ACK} is the time to transmit an ACK frame, T_{SIFS} is short inter frame space, and T_{TA} is the waiting time for the next transmission.

From Equations (4) and (6), the buffer occupancy of router node i ρ_i is expressed as the ratio of the number of generating packets of router node i in one superframe duration, λ_i , to the service rate of node i , μ_i . ρ_i is given by

$$\begin{aligned}\rho_i &= \frac{\lambda_i}{\mu_i} \\ &= \frac{\frac{DataRate_i}{8 \times P} \times aBaseSuperframeDuration \times 2^{BO}}{n_i \times 2^{SO}}.\end{aligned}\quad (10)$$

For avoiding buffer overflow, DC should be controlled so that ρ_i is less than 1, as shown in Figure 4. From Equations (4)–(10), DC should satisfy:

$$DC > \frac{DataRate_i}{8 \times P} \times \frac{aBaseSuperframeDuration}{n_i}.\quad (11)$$

Figure 4. Buffer model in the proposed method.

4. Simulation Results

The proposed method is evaluated by Network Simulator 2 (NS2) [27]. Table 1 shows the simulation parameters. Simulation is conducted by using a frequency band of 2.4 GHz. In this simulation, the energy consumption parameters of CC2420 [28] are used; Tx energy is 31.25 mW, Rx energy is 35.28 mW, Idle energy is 0.712 mW, and Sleep energy is 0.144 mW. In addition, this paper uses IEEE 802.15.4 default MAC parameters [19].

This study assumes that the packet transmissions are failed due to collisions caused by concurrent transmissions.

This study does not assume transmission failures due to physical layer conditions.

Table 1. Simulation parameters.

Parameters	Value
Frequency band	2.4 (GHz)
Packet length	100 (byte)
Simulation time	10–1000 (s)
Tx energy	31.25 (mW)
Rx energy	35.28 (mW)
Idle energy	0.712 (mW)
Sleep energy	0.144 (mW)
macMaxBE	5
macMinBE	3
macCSMABackoff	4
macMaxFrameRetries	3

4.1. Star Topology WSN

Figures 5 and 6 show the PDRs of the TMP method [18] and the proposed method in the star topology WSN, respectively. The data rate of each node is shown in Table 2. In the TMP method, the PDR of end devices decrease as the number of nodes increases. This is because the TMP method does not adequately control DC for high data rate nodes. On the other hand, in the proposed method, the PDR of end devices do not decrease so much. It is seen from this result that the proposed method can cope with the increase in the data rate.

Table 2. Data rate of each node (bps).

NodeID	N1	N2	N3	N4	N5	N6	N7	N8
DataRate	444	500	570	667	800	1K	1.3K	2K

Figure 5. Packet Delivery Ratio (PDR) of each node in Tele-Medicine Protocol (TMP) method.

Figure 6. PDR of each node in the proposed method.

4.2. Tree Topology WSNs

Figure 7 shows the tree topology WSNs used in this simulation. Nodes 1 and 2 are route nodes. Networks 1 and 2 are composed of router node 1 and its end devices and router node 2 and its end devices, respectively. Each router node does not generate its own packet. Each router node generates a packet when relaying packets from the end devices. This study compares the proposed method, the DC control method considering buffer occupancy for 802.15.4-compliant homogeneous WSN, and the TMP method. We evaluate the proposed method under three scenarios. Table 3 shows the DC for each method. The proposed method uses three DC patterns since the proposed method tunes the DC according to the data rate of the subordinate nodes. Table 4 shows data rate of each node. In these tables, DC_i and $DataRate_i$ are DC and data rate of router node i , respectively.

Figure 7. Network topology in the simulation.

Table 3. Duty-Cycle (DC) for each method.

Scenario	DC1	DC2
802.15.4	1.0	1.0
TMP	0.125	0.125
Prop-scenario1	0.125	1.0
Prop-scenario2	0.125	0.5
Prop-scenario3	0.5	1.0

Table 4. Data rate of each node (bps).

Scenario	N3	N4	N5	N6	N7	N8	N9	N10
Scenario-1	200	200	400	800	1.6K	2K	2.7K	4K
Scenario-2	200	200	400	800	200	400	800	2K
Scenario-3	200	400	800	2K	1.6K	2K	2.7K	4K

4.2.1. PDR Evaluation

Figures 8 and 9 show the number of packets in the buffer of a sensor node with and without appropriate DC control, respectively. In Figure 9, the number of packets in the buffer increases in time. On the other hand, in Figure 8, the number of packets in the buffer does not increase because the generated packets are processed in the active period. It is seen from Figures 8 and 9 that the appropriate DC control can avoid packet accumulation in buffer.

Figure 8. Number of packets in buffer with appropriate DC control.

Figure 9. Number of packets in buffer without appropriate DC control.

Figures 10–12 show the PDRs of the IEEE 802.15.4, TMP, and proposed method in scenario 3. The IEEE 802.15.4 and proposed method achieve high PDR. On the other hand, as the data rate of the node increases, the PDR of the TMP decreases. The TMP method has a lower PDR, although it achieves low energy consumption.

Figure 10. PDR of IEEE 802.15.4 in scenario 3.

Figure 11. PDR of TMP in scenario 3.

Figure 12. PDR of proposed method in scenario 3.

4.2.2. Delay Evaluation

Figure 13 shows the average delay of each scenario and each method. In this study, the delay is defined as the time from the focused packet transmission to arrival at the coordinator. The lower the delivery ratio becomes, the more packet retransmission occurs. If the focused packet is not successfully transmitted within the active period, the packet is

newly transmitted at the next superframe, which causes extreme delay. In Scenarios 1 and 3, the delay of TMP increases due to the decrease in PDR.

Figure 13. Delay of each scenario.

4.2.3. Energy Consumption Evaluation

Figure 14 shows the energy consumption of whole network nodes. The TMP uses low DC, so energy consumption is low. Since IEEE 802.15.4 sets DC regardless of the data rate of the nodes, it wastes the energy by idle listening. The proposed method reduces idle listening by setting appropriate DC for each sub-network while guaranteeing PDR.

Figure 14. Energy consumption of each scenario.

4.2.4. Sensitivity Analysis

Figures 15–17 shows the sensitivity analysis of the PDR, delay, and energy consumption in scenario 3. The horizontal axis of each graph is the variation of the data rate in the range of -20% to $+20\%$. From Figures 15–17, the TMP is sensitive to data rate variations regarding PDR and delay, and proposed method is sensitive to data rate variations regarding delay. In addition, these figures illustrate that the variations in data rate do not affect the order of performances.

Figure 15. Sensitivity analysis of PDR.

Figure 16. Sensitivity analysis of delay.

Figure 17. Sensitivity analysis of energy consumption.

4.3. Summary of Results

Table 5 summarizes the simulation results of the PDR, delay, and energy consumption of each method. Tables 6–8 show the evaluation criteria for each of Good, Average, and Bad in Table 5. Table 5 illustrates that the proposed method achieves a reasonable delay and energy consumption while maintaining high PDR.

Table 5. Summary of results.

	PDR	Delay	Energy
IEEE 802.15.4	Good	Good	Bad
TMP	Average	Bad	Good
Proposal	Good	Good	Average

Table 6. Evaluation criteria of PDR.

PDR Range	Grade
$90\% < \text{PDR}$	Good
$70\% < \text{PDR} \leq 90\%$	Average
$\text{PDR} \leq 70\%$	Bad

Table 7. Evaluation criteria of delay.

Delay Range	Grade
$\text{delay} < 15.36 \text{ (ms)}$	Good
$15.36 \text{ (ms)} \leq \text{delay} < 30.72 \text{ (ms)}$	Average
$30.72 \text{ (ms)} \leq \text{delay}$	Bad

Table 8. Evaluation criteria of energy consumption.

Energy Consumption Range	Grade
energy consumption < 17.5 (J)	Good
$17.5 \text{ (J)} \leq \text{energy consumption} < 35 \text{ (J)}$	Average
$35 \text{ (J)} \leq \text{energy consumption}$	Bad

5. Conclusions

This study proposed a DC control method for improving the PDR for IEEE 802.15.4-compliant heterogeneous WSNs. The proposed method controls active and sleep periods taking into account the buffer occupancy of nodes with the high data rate. The proposed method tunes the DC so that the buffer occupancy of sensor nodes is less than one. The appropriate DC of each sub-network was used to obtain the high PDR. The simulation results showed that the proposed method achieved a high PDR and low delay not only in the star topology WSN but also in tree topology WSNs.

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