Traffic-aware GTS Allocation Interval Determination for IEEE 802.15.4 DSME Networks

Inhyeok Kang
Division of Software
Hallym University
Chuncheon, Republic of Korea
M23522@hallym.ac.kr

Sol-Bee Lee
Smart Computing Laboratory
Hallym University
Chuncheon, Republic of Korea
thfqla3535@hallym.ac.kr

Jung-Hyok Kwon
Smart Computing Laboratory
Hallym University
Chuncheon, Republic of Korea
jhkwon@hallym.ac.kr

Eui-Jik Kim†
Division of Software
Hallym University
Chuncheon, Republic of Korea
ejkim32@hallym.ac.kr

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***Abstract*— In this paper, we propose a traffic-aware guaranteed time slot (GTS) allocation interval determination (TaAID) for IEEE 802.15.4 deterministic synchronous multichannel extension (DSME) networks. TaAID aims to allow each coordinator to determine its GTS allocation interval. TaAID allocates allocation order to each coordinator based on its traffic load, which depends on the hop count and the number of child devices within the cluster. The simulation results demonstrated that TaAID outperformed the legacy DSME in terms of aggregate throughput and average end-to-end delay.**

Keywords—allocation order, DSME, GTS allocation interval, IEEE 802.15.4, traffic awareness

I. Introduction

The widespread use of the Internet of Things (IoT) in various industries has increased the need for timely and reliable communication among devices in the network [1]. The deterministic and synchronous multichannel extension (DSME) was standardized in IEEE 802.15.4-2015 as a medium access control (MAC) protocol to meet these requirements [2]. DSME ensures efficient and reliable communication through multi-channel access and guaranteed time slot (GTS).

However, DSME is constrained in effectively managing the diverse traffic loads of each cluster in a cluster-tree network. Due to its fixed GTS allocation interval, GTS allocation may not be appropriately conducted for each cluster with varying traffic loads. This leads to unnecessary end-to-end delays and a waste of channel utilization, ultimately degrading network performance.

In this paper, we propose a traffic-aware GTS allocation interval determination (TaAID) for IEEE 802.15.4 DSME networks. TaAID focuses on determining the appropriate GTS allocation interval for each coordinator by considering the traffic load of each cluster within the cluster tree network. The traffic load of each cluster depends on the hop count and the number of child devices for the coordinator, which serves as the cluster head. Each coordinator determines the allocation order for its GTS allocation interval based on its traffic load. Consequently, coordinators with higher traffic loads are assigned a higher allocation order, resulting in GTSs being allocated at shorter intervals. We conducted an experimental simulation to verify the superiority of TaAID. The results showed that TaAID achieved 44.32% higher aggregate throughput and 53.94% lower average end-to-end delay compared to the legacy DSME.

II. Overview of IEEE 802.15.4 DSME

A. DSME Multi-superframe Structure

DSME employs a multi-superframe structure composed of multiple superframes. Fig. 1 shows the DSME multi-superframe structure. Each superframe consists of a beacon frame for broadcasting enhanced beacon (EB), a contention access period (CAP) for exchanging control packets using carrier sense multiple access with collision avoidance (CSMA/CA), and a contention-free period (CFP) for transmitting data via GTSs. At the beginning of the network, the personal area network (PAN) coordinator configures the multi-superframe structure by setting the beacon order (*BO*) to determine the beacon interval (*BI*), the multi-superframe order (*MO*) to determine the multi-superframe duration (*MD*), and the superframe order (*SO*) to determine the superframe duration (*SD*).

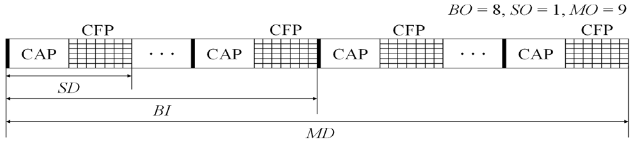

Fig. 1. DSME multi-superframe structure.

B. Allocation Order

The allocation order is an integer value that determines the DSME GTS allocation interval assigned to each coordinator. When GTS allocation is required, the coordinator transmits a GTS request message including the *AO* to the parent coordinator. If $MO \leq BO$, *AO* is set to 0 by default. On the other hand, if $MO > BO$, it can be set within the range of 1 to 8. The DSME GTS allocation interval, determined by the *AO*, is calculated as:

$$\begin{cases} BI \times 2^{MO-BO} / 2^{AO} & \text{for } MO > BO \\ MD & \text{for } MO \leq BO \end{cases} \quad (1)$$

III. Design of TaAID

TaAID is designed to allow the coordinator to determine its GTS allocation interval by considering its traffic load. In TaAID, the traffic load of the coordinator depends on its hop count and the number of child devices. We consider a static DSME-enabled cluster-tree network, which consists of coordinators and end devices. In particular, a PAN coordinator acts as the root of the network. The coordinator can act as a cluster head and cluster member, and periodically broadcast EB to ensure synchronization with the joined network and its neighbors. The end device only acts as a cluster member (i.e., leaf device) and periodically generates data packets. We assume that each coordinator and end device transmits data to its parent device (i.e., cluster head) towards the root. We also assume that $MO > BO$, and it is shared across the network through the EB broadcast by the PAN coordinator. Accordingly, each coordinator can set its *AO* within the range of 1 to 8. A higher *AO* results in a shorter GTS allocation interval, leading to more GTSs are allocated within the multi-superframe. To determine the *AO*, it is assumed that each coordinator knows the maximum hop count and the total number of devices in the network. In TaAID, *AO* of the *i*-th coordinator is calculated as:

$$AO_i = tl_i \times AO_{max} \,/\, tl_{max} \quad (2)$$

where tl_i refers to the traffic load of the i-th coordinator. tl_{max} refers to the maximum value of traffic load among all coordinators. AO_{max} refers to the maximum value of valid AOs. Specifically, tl_i is calculated as:

$$tl_i = hc_i \times n_{child,i} \,/\, n_{dev} \quad (3)$$

where hc_i and $n_{child,i}$ refer to the hop count and the number of child devices of the i-th coordinator. n_{dev} refers to the number of devices (i.e., coordinator and end device) in the network.

Upon determining the *AO*, each coordinator calculates the GTS allocation interval using (1). Subsequently, during the CAP period, it sends a GTS request message to its parent device, including its *AO*. Upon receiving the GTS request message, the parent device compares its GTS allocation status with the information contained in the received GTS request message. Afterward, the parent device allocates GTSs based on the GTS allocation interval determined by the *AO* and sends a GTS response message back to the requesting coordinator. Upon receiving the GTS response message, the coordinator updates its GTS allocation status and broadcasts a GTS notify message to announce the newly allocated GTSs to its neighbors. By executing this procedure on each device as needed, the GTS scheduling among the devices is completed.

IV. Performance Evaluation

We performed the experimental simulation to verify the performance of TaAID in IEEE 802.15.4 DSME using the MATLAB simulator. The simulation results of TaAID were compared with legacy DSME in terms of aggregate throughput and average end-to-end delay. In legacy DSME, the *AO* values of all devices were initially set to 0 by default. In the simulation, we considered a cluster-tree network comprised of 25 coordinators and multiple end devices. The number of end devices varies from 4 to 40. The coordinators were arranged in a 5x5 grid structure, and the end devices were randomly deployed within an area of 120x120 m^2, generating data packets with a specific packet generation rate at the beginning of each multi-superframe. The packet generation rate of the end device is defined as the number of data packets generated during a multi-superframe duration and was set to 8 and 16, respectively. *SO*, *MO*, and *BO*, which define the multi-superframe structure, were set to 5, 13, and 7, respectively. The data packet size and data rate were set to 100 bytes and 250 kbps, respectively.

Fig. 2 illustrates the aggregate throughput for varying the number of end devices when the packet generation rate is 8 and 16, respectively. The aggregate throughput of TaAID is higher than that of legacy DSME, regardless of the number of end devices and the packet generation rates. In TaAID, each coordinator uses the GTS allocation interval determined by the allocation order, which considers its own traffic load. Consequently, coordinators with high traffic loads can obtain more opportunities for data transmission by being assigned GTSs more frequently within the multi-superframe duration, leading to higher aggregate throughput on average. Quantitatively, TaAID achieves a higher aggregate throughput of 18.23% and 70.40% compared to the legacy DSME when the packet generation rate is 8 and 16, respectively.

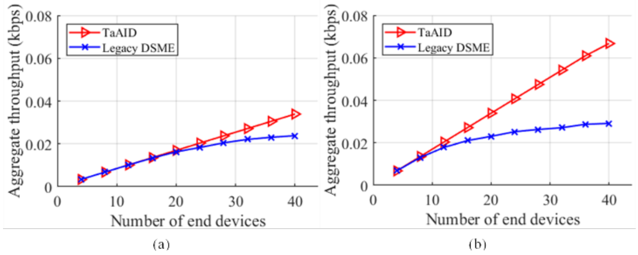

Fig. 2. Aggregate throughput: (a) 8 packets/*MD* and (b) 16 packets/*MD*.

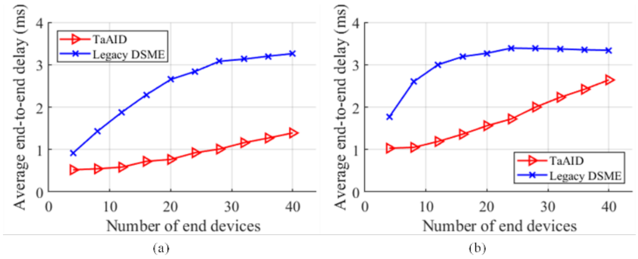

Fig. 3. Average end-to-end delay: (a) 8 packets/*MD* and (b) 16 packets/*MD*.

Fig. 3 illustrates the average end-to-end delay for varying the number of end devices when the packet generation rate is 8 and 16, respectively. The average end-to-end delay of TaAID is lower than that of legacy DSME, regardless of the number of end devices and the packet generation rates. In TaAID, each coordinator has a GTS allocation interval determined by considering its traffic load. Consequently, the coordinator with a high traffic load allocates GTSs more frequently within a multi-superframe duration, thereby decreasing latency at each hop compared to legacy DSME. Quantitatively, TaAID achieves a lower average end-to-end delay of 63.94% and 43.93% compared to legacy DSME when the packet generation rate is 8 and 16, respectively.

V. Conclusion

This paper presents TaAID for IEEE 802.15.4 DSME networks. TaAID aims to allocate GTSs at the appropriate intervals for each coordinator within a DSME-enabled cluster-tree network, considering the traffic load of its cluster. Each coordinator determines the allocation order for its GTS allocation interval with traffic awareness, considering its hop count and the number of child devices. The simulation was conducted in the environment of varying network sizes. The simulation results showed that TaAID achieved 44.32% higher aggregate throughput and 53.94% lower average end-to-end delay compared to the legacy DSME, respectively.

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References

[1] I. Behnke and H. Austad, “Real-Time Performance of Industrial IoT Communication Technologies: A Review,” *IEEE Internet Things J.*, vol. 11, no. 5, pp. 7399–7410, 1 Mar. 2024.

[2] *IEEE Standard for Low-Rate Wireless Networks*, IEEE Std 802.15.4-2015, Apr. 2016.