A Scheduling Method for Reducing Latency in Wi-SUN FAN Networks

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***Abstract*—** The Wireless Smart Utility Network Field Area Network (Wi-SUN FAN) is a standard wireless communication technology for building large-scale outdoor multi-hop networks. Nodes in a Wi-SUN FAN network can communicate stably by performing channel hopping based on unicast and broadcast schedules. However, transmission of unicast or broadcast may be restricted according to the broadcast schedule, resulting in additional latency depending on the timing of frame generation. This paper presents a scheduling method to reduce the latency while preserving the unicast and broadcast throughput ratio. By keeping the ratio of Broadcast Interval (BI) and Broadcast Dwell Interval (BDI) unchanged, but making BDI more frequent, the time from frame creation to transmission is reduced. The method was evaluated using Wi-SUN FAN hardware, and the results showed that in one-hop communication, the latency of unicast frames decreased by up to 36% and the latency of broadcast frames decreased by up to 58%. Additionally, in a mesh network consisting of 21 devices, the round-trip latency decreased by up to 20%.

Keywords*— *Wi-SUN FAN; Wireless Sensor Network; IoT Network; Latency; Channel Scheduling

I. INTRODUCTION

Many devices are connected wirelessly in the Internet of Things (IoT) network [1], and are deployed and used in a wide range of applications such as smart cities, health care, smart homes, industrial monitoring, smart grids, agriculture, etc. For many resource-constrained smart devices, low-power wireless communication technologies are important for receiving or transmitting information or commands.

The Low Power Wide Area (LPWA) network provides wide area connectivity for low power and low data devices [2]. Wireless Smart Utility Network (Wi-SUN) is an LPWA wireless communication technology based on IEEE 802.15.4-2015 [3]. One of the Wi-SUN profiles, Wi-SUN Field Area Network (Wi-SUN FAN) [4], was standardized in 2021 as IEEE 2857, enabling the construction of large-scale outdoor multi-hop IoT networks. Wi-SUN FAN can provide reliable communication through CSMA/CA and frequency channel hopping. In addition, it supports IPv6 over Low Power Wireless Personal Area Networks (6LoWPAN) [5] and IPv6 routing protocol for LLNs (RPL) [6], enabling the formation of a stable IPv6 wireless mesh network. The Wi-SUN Alliance which maintains and manages Wi-SUN is conducting a Wi-SUN FAN certification program related to device interoperability and standard compliance [7][8].

The nodes in Wi-SUN FAN communicate wirelessly by channel hopping according to two schedules: unicast schedule and broadcast schedule. A node in a Wi-SUN FAN network transmits and receives broadcast frames, such as RPL control messages and IP multicast packets, only during the Broadcast Dwell Interval (BDI) of each Broadcast Interval (BI) period. At other times, the node transmits and receives unicast frames. Unicast frames in a node's queue must wait to be transmitted during the BDI, and broadcast frames must wait outside the BDI.

To reduce this communication latency, the BDI can be adjusted. Decreasing the BDI while maintaining the BI reduces both the communication latency of the unicast frame and the throughput of the broadcast frame. Increasing the BDI reduces both the communication latency of broadcast frames and the throughput of unicast frames. In networks that require high throughput for both unicast and broadcast transmissions, such as applications that use IP multicast to propagate requests and collect responses through unicast [9], it is difficult to reduce the throughput of either the unicast or broadcast schedule. Therefore, it is necessary to reduce the communication latency caused by the schedule while maintaining the ratio between the two throughputs.

In this paper, we investigate the effect of unicast and broadcast scheduling on communication latency and propose a scheduling method that reduces latency while preserving the throughput ratio of both schedules. The performance of the method is then evaluated using actual Wi-SUN FAN devices.

The structure of the rest of the paper is as follows: Section 2 provides an explanation of the operation of Wi-SUN FAN and related research. In Section 3, the unicast and broadcast schedules are analyzed to reduce latency. The performance evaluation using Wi-SUN FAN devices is presented in Section 4. Finally, the paper concludes in Section 5.

II. BACKGROUND

A. Wi-SUN FAN Protocol Stack

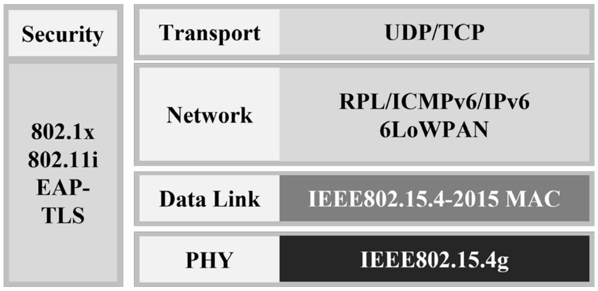

Fig. 1. Wi-SUN FAN protocol stack

Wi-SUN FAN [4] enables the construction of large-scale mesh networks by connecting smart devices deployed in applications such as smart cities and smart utilities. Fig. 1 shows the network stack of the Wi-SUN FAN protocol. In the data link layer, Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) based on IEEE 802.15.4 [3] and multiple access through frequency channel hopping are used. At the network layer, 6LoWPAN [5], IPv6 [10], ICMPv6 [11], and RPL [6] technologies are supported to form a stable multi-hop network. In addition, Wi-SUN FAN supports Multicast Protocol for Low-Power and Lossy Networks (MPL) [12] for multicast transmission of data. MPL delivers multicast messages to all nodes that have subscribed to target addresses within the MPL domain and uses a retransmission mechanism based on a trickle timer [13].

B. RPL

RPL is a routing protocol for Low-Power and Lossy Networks (LLNs) and supports point-to-point, point-to-multipoint, and multipoint-to-point traffic flows [6]. The node that starts the network or acts as a border router becomes the root node. A Destination Oriented Directed Acyclic Graph (DODAG) is formed from the root node to create routes. The RPL control messages used for forming and maintaining the DODAG are as follows.

- DODAG Information Object (DIO)
- DODAG Information Solicitation (DIS)
- Destination Advertisement Object (DAO)
- Destination Advertisement Object Acknowledgement (DAO-ACK)

The nodes participating in DODAG, including the root node, broadcast DIO messages using the trickle timer [13]. Nodes that have not yet joined the DODAG receive DIO messages, select a preferred parent node, and then send a unicast DAO message to the root node. Upon receiving the DAO message, the root node sends a DAO-ACK message back to the source of the DAO, completing the node's joining of the DODAG. Nodes can also request DIO messages from neighboring nodes by broadcasting DIS messages.

C. Unicast and Broadcast Schedules of Wi-SUN FAN

Nodes in Wi-SUN FAN transmit and receive frames according to two channel schedules, unicast and broadcast.

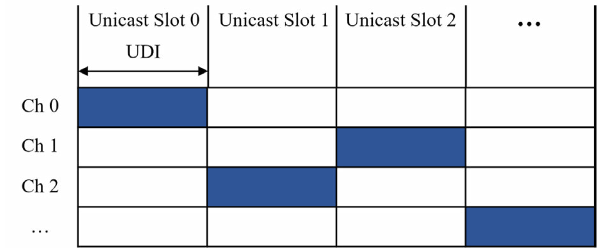

Fig. 2. Channel hopping on a unicast schedule

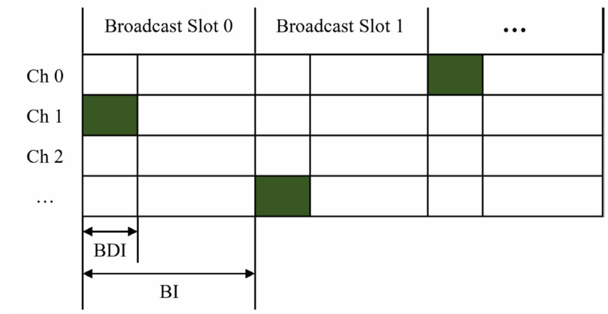

Fig. 3. Channel hopping on a broadcast schedule

In the unicast schedule, as shown in Fig. 2, the unicast slots are repeated and frequency channel hopping is performed by transmitting and receiving using different frequency channels for each slot. The duration of a single unicast slot is referred to as the Unicast Dwell Interval (UDI) and can range from 15ms to 255ms. Since each node in the network maintains its own unicast schedule, to transmit a frame to a neighboring node, it must calculate the frequency channel that the node is currently listening on and transmit the frame on that channel.

In the broadcast schedule, as depicted in Fig. 3, broadcast slots with a Broadcast Interval (BI) size are repeated, and a different frequency channel is used for each slot. Only during the Broadcast Dwell Interval (BDI) time, which starts from the beginning of each broadcast slot, broadcast frames such as RPL DIO, DIS, and MPL messages are transmitted and received using the channel of the broadcast slot. The BDI ranges from 100ms to 255ms, and the BI, the interval between two BDI starts, is calculated using (1).

$$BI = \alpha \times \max(UDI, BDI) \qquad (1)$$

BI is calculated by multiplying the higher value of UDI and BDI by the BI coefficient α. According to the Wi-SUN FAN standard [4], a value of 4 is recommended for α. Unlike unicast schedules, which are unique to each node, broadcast schedules are synchronized across the entire network and shared between all nodes.

Fig. 4 illustrates the broadcast schedule and the unicast schedules of three nodes participating in the network. Each color depicts a different frequency channel. The BDI has a higher priority than the unicast schedules. Therefore, during the BI time, broadcast frames are processed during the BDI time, while unicast frames are processed during non-BDI times.

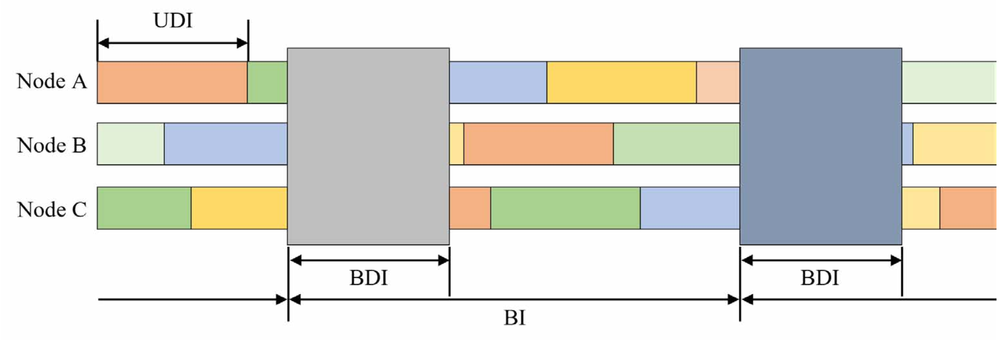

Fig. 4. Unicast and Broadcast schedules of three nodes of Wi-SUN FAN

D. Related Work

Recently, several studies have been conducted to evaluate and improve the communication performance of Wi-SUN FAN networks.

The authors in [14] studied the issue of packet loss due to the failure of mobile devices to select appropriate routing nodes in the Wi-SUN FAN system and presented an ETX transition-based algorithm for smooth handover.

In [15], the authors found the optimal control message setting value for node participation in the Wi-SUN FAN network and proposed an instant response configuration scheme of the control message to enhance the speed of network configuration in multi-hop scenarios.

In [16], the authors reduced unnecessary RPL preferred parent changes with optimized RSL threshold scheme and MAC address filtering scheme to stabilize the multi-hop routing configuration of the Wi-SUN FAN system.

In [17], the authors evaluated the data packet forwarding speed from the mobile node to the gateway in the Wi-SUN FAN system and proposed a routing algorithm to ensure stable communication for mobile nodes.

The authors in [18] proposed a load balancing routing method to address RPL load imbalance, which occurs when multiple nodes select the same node as their preferred parent node, by using a threshold based on the number of child nodes.

In [19], the authors developed an evaluation board that integrates multiple wireless devices and evaluated the performance of the Wi-SUN FAN multi-hop network transmission in both tree-type and star-type topologies.

The channel schedule of Wi-SUN FAN has an impact on both unicast and broadcast transmission performance. In [20], the authors conducted computer simulations to analyze the effects of channel scheduling and channel hopping on network performance, and proposed an optimal value for the BI coefficient to maximize unicast transmission throughput while ensuring stability of the RPL DIO message transmission interval. However, it should be noted that in addition to RPL DIO, broadcast traffic also includes other types of traffic, such as IP multicast packets, and the optimal setting value may vary depending on the desired broadcast throughput and the specific application.

III. Unicast and Broadcast Schedules Analysis to Reduce Latency

The nodes in a Wi-SUN FAN network communicate broadcast frames only during BDI time, which is a portion of the BI time. The rest of the BI time is used for communicating unicast frames. The ratio of BI to BDI, denoted by γ with a value of (2).

$$\gamma = BI / BDI \tag{2}$$

If γ decreases, broadcast throughput increases and unicast throughput decreases. Conversely, if γ increases, broadcast throughput decreases and unicast throughput increases. In this paper, the focus is on communication latency, and the ratio of BI to BDI, γ, is fixed, as the required broadcast throughput varies depending on the application.

The time to communicate a unicast frame within one BI time is defined as UTI and it is given by (3).

$$UTI = BI - BDI \tag{3}$$

It is assumed that a node has no other packets to transmit and can send a packet as soon as it is created. If the node generates a unicast frame during BDI, it cannot be transmitted immediately and must be transmitted after waiting for the end of the maximum BDI duration. That is, the generated unicast frame has a latency of the maximum BDI time with a probability of $(1/\gamma)$. Conversely, a broadcast frame has a latency to the maximum UTI time with probability $((\gamma - 1) / \gamma)$.

Fig. 5 represents the latency that occurs depending on the time of creation of the frame. The blue representation depicts the latency of unicast frames, while the yellow representation depicts the latency of broadcast frames. As an example, if a broadcast frame is created at time x, its latency would be (UTI / 2). Instead of using the expected value of the frame's latency, the area of the blue or yellow shape is utilized. The area of the blue shape for the unicast frame is (4) and the area of the yellow shape for the broadcast frame is (5).

$$AREA\_UC = (BDI * BDI) / 2 \tag{4}$$

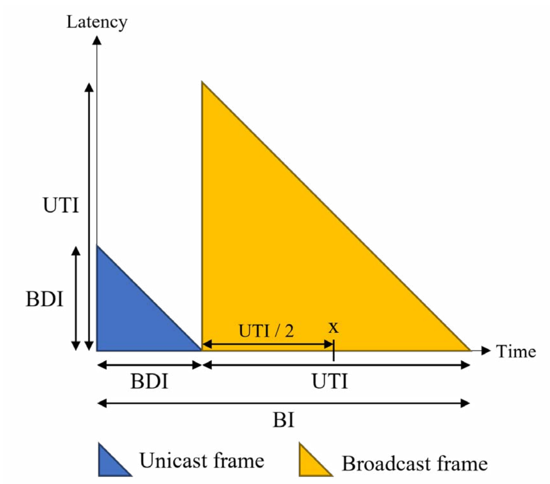

Fig. 5. Latency at the time a unicast or broadcast frame is created

$$AREA\_BC = (UTI * UTI) / 2 \quad (5)$$

In order to reduce the latency from frame creation to transmission, it is necessary to reduce the area of the blue and yellow shapes shown in Fig. 5. If both BI and BDI are reduced while maintaining the value of γ, the communication latency can be decreased while still maintaining the unicast and broadcast frame throughput for a specific period of time. As demonstrated in Fig. 6, if both BI and BDI are halved, the areas of the unicast and broadcast frames (AREA_UC and AREA_BC) are also halved. The probability of the latency occurring remains unchanged, but the latency value of the frames is reduced, leading to a decrease in the overall communication latency.

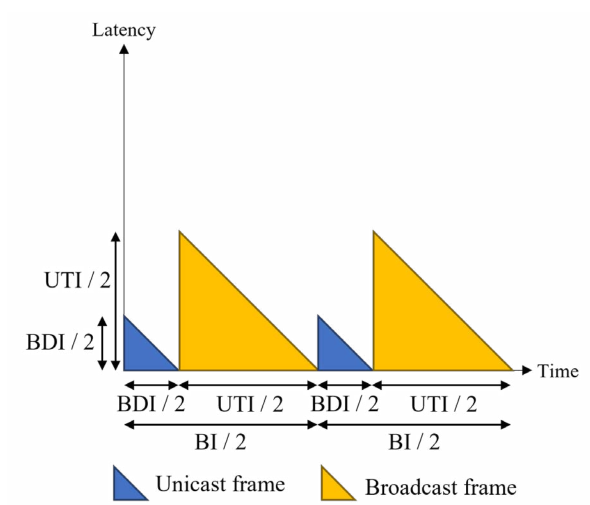

Fig. 6. Latency at the time a unicast or broadcast frame is created when BI and BDI are half

Fig. 7. Wi-SUN FAN devices used in the experiment

IV. Performance Evaluation Using Wi-SUN FAN Communication Devices

In this section, the performance of the Wi-SUN FAN system is evaluated by adjusting BI and BDI while maintaining the unicast and broadcast throughput and reducing communication latency. For performance evaluation, wireless communication devices developed by Dong-Nam Grand ICT R&D Center and certified by the Wi-SUN Alliance FAN certification program [8] are utilized. Fig. 7 shows an image of the wireless communication devices. The parameters used in the experiments are listed in TABLE 1. To create a network environment for both unicast and broadcast transmission, an experiment was conducted where one border router multicasts

TABLE 1. Parameters of the experiment

Features	Values
Number of nodes	2/21
CCA energy detection duration	960us
Maximum backoff exponent	5
Minimum backoff exponent	3
Maximum number of backoff	4
Maximum number of retransmissions	0/3
Number of frequency channels	16
Unicast Dwell Interval	200ms
Broadcast Dwell Interval	100~250ms
Broadcast Interval	400~1000ms
γ = BI / BDI	4
Maximum sending interval of DAO	60s
Trickle Imin for DIO	3.2768s
Trickle Imax for DIO	2
Trickle Imin for MPL	2000ms
Trickle K for MPL	1
Number of timer expiration for MPL	0/1
Packet queue length	8
Application data packet size	110bytes

a request using MPL, and other devices unicast responses to the border router. γ is fixed at 4.

A. *Latency From Packet Creation To Transmission*

To confirm that the analyzed scheduling method reduces latency, the average latency from the time data is created in the application layer at the top of the device's network stack to successful radio transmission is measured. One-hop wireless communication is performed using two devices. The MAC retransmission and MPL retransmission parameters are set to 0, and a unicast frame and a broadcast frame are generated every 5 seconds for 30 minutes.

Fig. 8 and Fig. 9 show the measurement of time from creation to transmission of unicast and broadcast frames based on changes in BDI and BI. For each 20% decrease in BI and BDI, the latency of unicast frames decreases by about 10-18%, and the latency of broadcast frames decreases by about 18-33%. This is because decreasing BI and BDI results in more frequent opportunities for unicast and broadcast transmission. Frequent BDI leads to faster delivery of both unicast and broadcast frames.

B. *Round-Trip Latency In A Mesh Network*

To measure the impact of the analyzed scheduling method on end-to-end latency, a mesh network was built with 21 devices as shown in Fig. 10. The Border Router (BR) generates a request message which is broadcasted to all devices through MPL. The device that receives the request message then transmits a response message to the BR via unicast. The generation interval for request messages is set to 10 seconds, with a MAC retransmission setting of 3 and an MPL retransmission setting of 1. Each experiment was conducted for

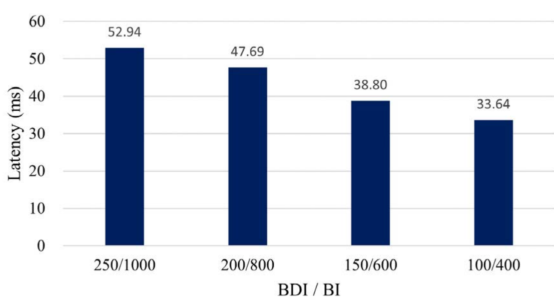

Fig. 8. Latency from unicast frame creation to transmission

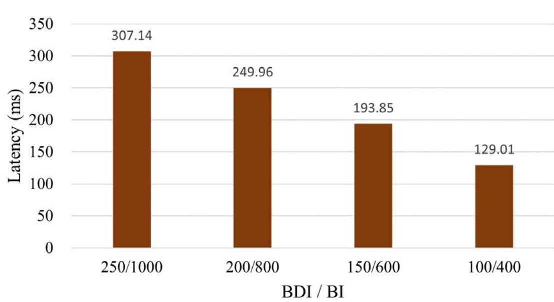

Fig. 9. Latency from broadcast frame creation to transmission

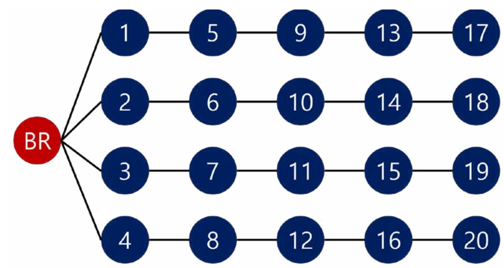

Fig. 10. Node placement and topology in mesh networks

1 hour for each BDI and BI.

Fig. 11 shows the average packet delivery ratio (PDR) and round-trip latency for different values of BDI and BI. PDR refers to the success rate of receiving a response to a request sent by the BR. Even though the values of BDI and BI are changed, the PDR remains constant because γ has a fixed value. This results in similar throughput and transmission success rates for both unicast and broadcast frames. However, the average round-trip latency decreases as BDI and BI decrease. The best performance is achieved when the BDI is 100ms and the BI is 400ms. Reducing the BDI by 60% results in a reduction in latency by approximately 20%. There is a lack of improvement in performance compared to the results from the one-hop experiment, due to several factors such as wireless collisions, delay in multi-hop forwarding, and increased control messages in mesh networks. However, there is still a significant improvement in latency performance while

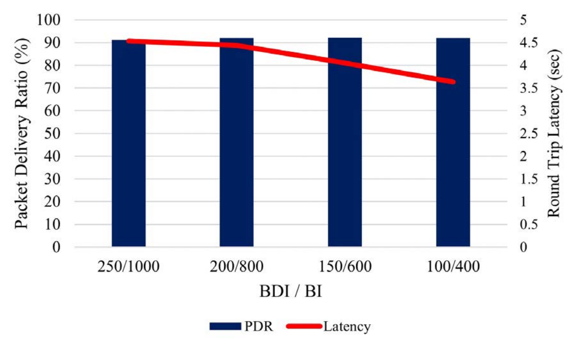

Fig. 11. PDR and average round-trip latency for a request period of 10 seconds in a mesh network

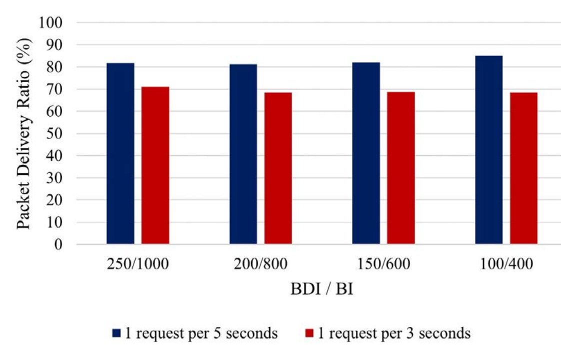

Fig. 12. PDR with request period of 5 and 3 seconds in mesh network

maintaining a high packet delivery success rate.

Fig. 12 illustrates the PDR under high network traffic, generated by sending requests once every 5 seconds and 3 seconds for 30 minutes. Despite changes in the BDI, the PDR does not vary significantly, indicating that the network's peak traffic throughput remains unaffected, regardless of the unicast or broadcast schedule.

V. Conclusion

In this paper, the unicast and broadcast schedules are adjusted in Wi-SUN FAN networks to reduce communication latency while keeping traffic throughput unchanged. The method considers both unicast and broadcast frames, including multicast packets, and reduces round-trip latency while maintaining the balance of BI and BDI. The one-hop communication experiment showed a reduction in the latency of unicast frames by up to 36% and a reduction in the latency of broadcast frames by up to 58%. In the mesh network experiment, the round-trip latency decreased by up to 20%.

However, due to timing synchronization issues in actual devices, there is a limit to the reduction of BI values. Therefore, additional research is required to increase traffic throughput and reduce latency. this is left for future research.

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