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Analysis and Evaluation of Channel-Hopping-Based MAC in Industrial IoT Environment

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Abstract
Owing to the development of the Internet-of-Things (IoT) paradigm, channel hopping is the most widely used method for solving multipath fading problem caused by various structures in industrial environments or by external interference of communication devices using the same frequency band. To meet these demands, IPv6 over the time slotted channel hopping (TSCH) mode of IEEE 802.15.4e (6TiSCH) has emerged as the standard for low power lossy networks in industrial IoT environments. TSCH supports slot-based channel hopping with the IEEE 802.15.4e standard and ensures reliable connection from external interference through strong time synchronization. Wireless Smart Utility Network (Wi-SUN), which constructs a Field Area Network (FAN), proposes non-slotted channel hopping and specifies only minimum constraints. However, there is limited existing research on these networks. Therefore, in this study, we analyze and evaluate the performance of channel-hopping-based medium access control (MAC) in an industrial environment. Simulation results in various environments show that non-competitive MAC provides reliable and efficient transmission.

Category: Network and Communications

Keywords: Wireless technologies; Embedded software; Embedded control and communication

I. INTRODUCTION

With the advent of Industry 4.0, there has been increased research on industrial Internet-of-Things (IIoT) and machine-to-machine (M2M) networks, especially in the manufacturing area, for industrial networking applications, such as monitoring of production efficiency, intelligence, and manufacturing environment, through the integration of information and communications technology (ICT). Advances in devices that are always connected to low-cost modules have created opportunities for a wide range of applications. Accurate data collection and monitoring techniques using structured and accessible IIoT networks help companies create smart strategies for commercialization, distribution management, and inventory management [1]. Smart metering (e.g., water, gas, and electricity), smart grids, and facility monitoring systems are good examples of such IIoT networks. The IIoT network was developed from the wireless sensor network (WSN) and various standard technologies such as 6TiSCH [2], WirelessHART [3], ISA100.11a [4], Zigbee [5], and Wi-SUN [6] have emerged. Table 1 compares the characteristics of standard networks for IIoT environments. These network technologies can be divided into two criteria.

First, technologies such as 6TiSCH, WirelessHART, and ISA100.11a use the IEEE 802.15.4 physical layer and provide high reliability to industrial devices based on the IEEE 802.15.4e [7] time slotted channel hopping

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Table 1. Comparison of IIoT standard networks

	IP support	MAC	Scheduling	Routing	Transport
IETF 6TiSCH	○	TSCH	Distributed	RPL	UDP
ISA 101.11a	○	TSCH	Centric	Mesh under	UDP
Wireless HART	×	TSCH	Centric	Mesh under	UDP
Zigbee	○	CSMA/CA	None	RPL	UDP
Wi-SUN	○	CSMA/CA	None	RPL	UDP/TCP

(TSCH) medium access control (MAC) layer. TSCH uses a time-division multiple access (TDMA) scheme instead of the competition-based carrier sensing multiple access/collision avoidance (CSMA/CA) scheme used in IEEE 802.15.4. TDMA avoids collisions and improves power consumption, and channel hopping, and blacklisting schemes can be used to solve interference and fading problems. In addition, by using the IEEE 802.15.4g [8] PHY layer, the sub-1-GHz band can have a longer transmission distance than the existing 2.4 GHz one.

Second, Zigbee and Wi-SUN configuration use the CSMA-based competitive MAC layer. Zigbee uses the same IEEE 802.15.4 or IEEE 802.15.4g PHY layer as TSCH and communicates over a single channel. It is often used in the intelligent home appliance domain rather than the IIoT domain since frequent collisions and interference occur in competition-based transmission. Wi-SUN uses the IEEE 802.15.4g PHY layer and the MAC layer further defined by the Wi-SUN Alliance. Wi-SUN is developed as an intelligent metering system for electricity, gas, and water. This technology is mainly used in the application domain, such as automatic meter reading (AMR) and advanced metering infrastructure (AMI) [9]. It includes a FAN specification to cover a wide range. Unlike Zigbee, Wi-SUN introduced the un-slotted channel hopping (USCH) technique to solve the problem of interference or collisions caused by a single channel.

TSCH and Wi-SUN, which use channel hopping for reliable network configuration, have many features in common. 6TiSCH is actively being used and researched in the industrial IoT device domain, and Wi-SUN is actively researched on building smart cities domain. The routing protocol for LLN (RPL) [10], a de facto standard for low-power and lossy network (LLN) environments, is used as the IPv6 routing protocol. In addition, IPv6 over low-power wireless personal area networks (6LoWPAN) [11] is applied as an adaptation layer to support IPv6 addressing. 6LoWPAN enables the construction of a mesh network where numerous nodes can be connected and communicate through multi-hop paths. With the application of the IEEE 802.15.4g PHY layer, the sub-1-GHz frequency band is used to provide a longer transmission distance through higher diffraction compared to the 2.4 GHz frequency band, which is mainly used in WSNs. However, a clear difference between these two techniques is related to the function of the MAC protocol. 6TiSCH uses a non-competitive scheme using TDMA-based slots, and Wi-SUN is based on a CSMA-based slotless competition scheme. As a result, these two protocols can show different performances even with the same network adaptation and PHY layers. However, limited research data is comparing these two protocols in terms of their MAC performance. This study, therefore, analyzes the MAC operation of the 6TiSCH and Wi-SUN protocols and evaluates the differences between these two methods through various experiments. Both protocols were implemented through Contiki-OS and simulated using a Cooja simulator.

II. BACKGROUND

A. IEEE 802.15.4e TSCH

IEEE 802.15.4e TSCH [7] is an amended extension of 802.15.4. The existing 802.15.4 standard did not guarantee deterministic transmission due to distributed and random operation using CSMA/CA-based MAC protocol. In addition, it was vulnerable to collision due to an increase in the number of nodes using a single channel. Based on these challenges, 802.15.4e was proposed with more stringent restrictions on reliability and deterministic transmission.

The core of TSCH is channel hopping for high reliability and time synchronization for low power operation. The accuracy of time synchronization affects the power usage of the nodes and can range from a few microseconds to a few milliseconds. Based on this operability, TSCH ensures high reliability, availability, and security under harsh operating conditions and industrial environments containing massive steel structures that interfere with multipath fading. The 802.15.4e amendment describes only the techniques by which TSCH nodes communicate and does not define detailed network configuration, maintenance, or schedule. In this regard, there has been active research on scheduling techniques for discovering and connecting neighboring nodes using 6LoWPAN [11] and RPL [10] and for allocating resources adaptively according to traffic volume between neighboring nodes for multipath transmission.

1) TSCH Protocol Structure

In TSCH, time is divided into slots. Each slot is an opportunity for a node to send or receive packets. This slot may or may not be used according to the schedule, and the radio is turned off to save energy when the slot is not in use. The presence or absence of an Acknowledgement (ACK) packet in the MAC layer in the slot is determined according to the type of packets sent and received. Broadcast packets do not receive an ACK. In general, unicast packets, which use ACKs, seek accuracy of data transfer. This group of slots is called a slot frame, and is repeatedly used during node operation. One slot in a slot frame is identified by a slot offset, an absolute slot number (ASN), and a channel offset. The slot offset represents the relative position of the slot within the entire slot frame. The ASN is a value that increases by one every time a slot passes after the network starts at the root node, and all nodes maintain the same value, i.e., the time since the network started. The channel offset is an integer used to generate the channel hopping pattern, which is calculated through Eq. (1).

$$f_{ch} = \mathrm{F}\cdot\{(\mathrm{ASN}+\mathrm{ch}_{\mathrm{offset}})\mathrm{mod}\ N_{\mathrm{ch}}\} \quad (1)$$

N_{ch} represents the number of available channels in the network. In this case, the calculated f_{ch} does not represent a physical channel number defined in an actual ISM frequency band but a logical position in a predefined channel hopping sequence. The combination of channel offset and slot offset is represented by the matrix shown in Fig. 1 and is repeated in each cycle of the slot frame.

Slots can be shared or used as dedicated single nodes. Shared slots follow the CSMA/CA method, and two nodes designate a dedicated slot through negotiations and make a schedule for one-way communication. For example, the MAC layer broadcast packets are sent using shared slots, while unicast packets are sent through dedicated slots.

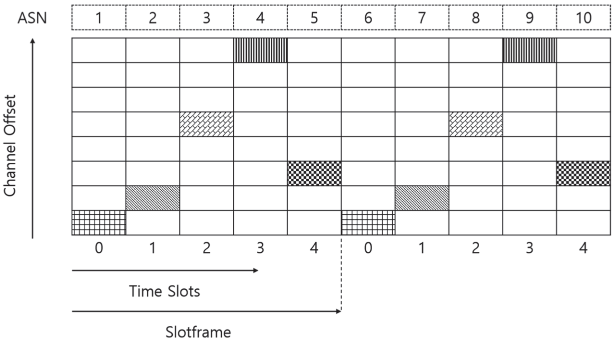

Fig. 1. Example of TSCH schedule matrix.

2) TSCH Synchronization and Scheduling

Although the IEEE 802.15.4 standard specifies how to handle TSCH schedules, it does not specify how to configure the scheduling schemes. Therefore, many scheduling algorithms have been proposed. The most basic scheduling algorithm is Scheduling Function 0 (SF0) [12]. However, SF0 only has the most basic functionality on LLN. Orchestra scheduling [13] voluntarily creates and maintains schedules using RPL information. Since the slot offset of the dedicated cell is determined using a hash function based on its MAC address, the scheduling cell can be allocated quickly. However, if a dedicated slot cannot be allocated, there is a disadvantage a broadcast slot is used to transmit. The minimal scheduling function (MSF) allocates a scheduling cell, as shown in Fig. 2, following 6TiSCH's 6top protocol [14] of the Internet Engineering Task Force (IETF) WG standard. At least one dedicated slot is allocated to one preferred parent node for transmitting traffic. It is also possible to add, remove, and rearrange the cell through the ADD, DELETE, and RELOCATE commands, as needed. Fig. 2 shows an operation example of the 6top protocol. Node A, a child node, sends an ADD request to node B, which is a parent node. At this time, the number of cells required by the user and a list of candidate capable of allocating cells is transmitted together. Accordingly, the parent node determines whether the received cell list can be allocated by comparison with its schedule, and it finally selects a cell that can be allocated and transmits it to the child node in response to the request. It determines the collision of traffic and schedule by itself and adjusts the number of scheduled cells to show the most stable data transmission. Therefore, in this study, we perform data transmission using MSF in TSCH and evaluate this technique.

B. Wi-SUN

Wi-SUN is an international standard for M2M wireless communications provision based on smart IoT systems. Wi-SUN's physical layer and link layer were developed based on the IEEE 802.15.4 standard. Wi-SUN FAN is one of the technical specifications for interworking with cloud systems through automation, such as smart city

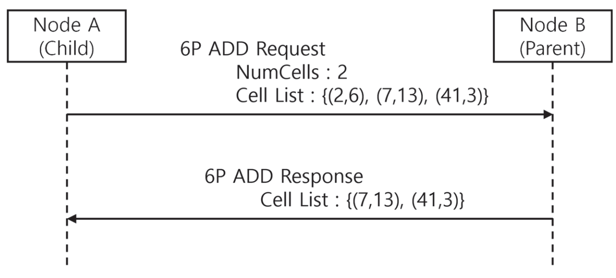

Fig. 2. Schedule allocation using 6top protocol.

applications, AMR, and AMI. With IPv6 compatibility, Internet Control Message Protocol for IPv6 (ICMPv6), and RPL, it is possible to sustain stable communication with millions of terminals in multiple hops on LLN.

Wi-SUN FAN is mainly used for outdoor network configuration. An important requirement for Wi-SUN, which prefers to fast transfer speeds and large memory capacities, is a high transfer success rate. It is compatible with other Wi-SUN FANs and handles multiple services and meets the requirements of various applications through secure IPv6 communication. When power is applied, and nodes operate, the nodes form a mesh network that cooperates with other nodes. In addition, the data is transmitted using another node as a relay node, and the radio transmission range is thus increased through this multi-hop communication [15].

1) Wi-SUN Protocol Structure

The Wi-SUN FAN protocol [6] uses a PHY layer that conforms to the IEEE 802.15.4g-2012 standard [8]. It uses 2-FSK modulation with channel spacing from 100 to 600 kHz, which results in data rates from 50 to 300 kbps. Wi-SUN FAN is operated with non-slot-based CSMA/CA. Channel hopping is introduced to avoid signal interference or collisions between transmitted frames. Fig. 3 shows an example of channel hopping of Wi-SUN. In addition, the 6LoWPAN adaptation layer enables IPv6, ICMPv6, and RPL to be used at the network layer to efficiently communicate with numerous devices located in the FAN.

Wi-SUN's MAC layer supports unicast and broadcast frame transmissions synchronized with neighbor nodes. Each node propagates its channel schedule. This allows neighboring nodes to know which channel the node operates on at any given time. The node listens for unicast channel schedule information that is propagated when it is not transmitting data or not receiving broadcast packets. As such, broadcast and unicast channel information is exchanged between nodes, but overall time synchronization in the PAN does not occur. It also supports communication using fixed channels without using channel hopping.

Unicast channel hopping is receiver-oriented. The channel hopping order is derived from the node's EUI-64 address and the set of available channels. A node knows a schedule by receiving the unicast schedule information of its neighbor node. Therefore, when node A receives data from node B, as shown in Fig. 4, it first sends a data request to node B's receiving channel and then changes its receiving channel to node B's transmitting channel to receive data. When the reception of data is completed, it finally transmits an ACK and returns to the channel in the channel hopping order in which it should wait for the reception.

The unicast receive schedule shows when the node can receive packets on each channel. As shown in Fig. 5, during the dwell interval, the node maintains the channel in order and waits for the reception. This is like a virtual slot, and this channel hopping sequence is generated and distinguished according to the virtual slot. The broadcast reception schedule is also similar to the unicast.

As shown in Fig. 6, the dwell interval is the same, but

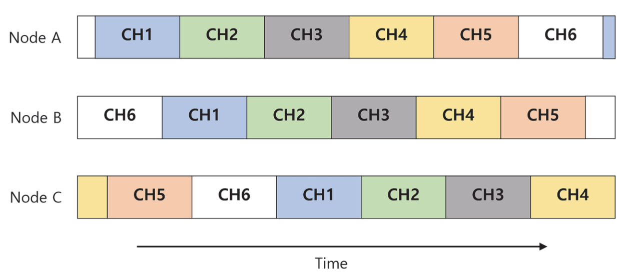

Fig. 3. An example of Wi-SUN channel hopping.

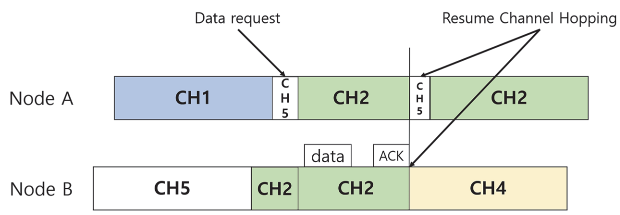

Fig. 4. Example of receiver-oriented transmission.

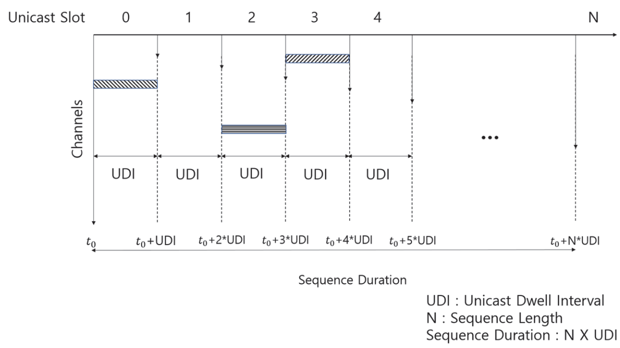

Fig. 5. Wi-SUN unicast dwell interval and slot structure.

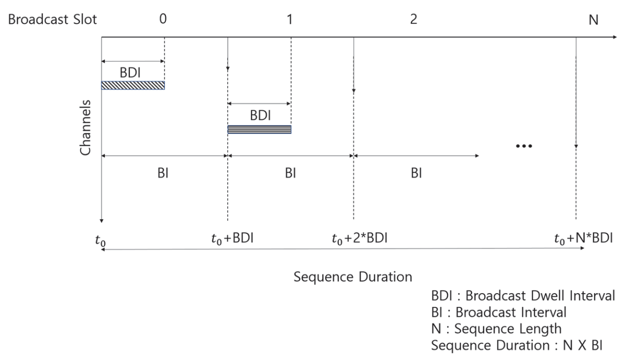

Fig. 6. Wi-SUN broadcast dwell interval and slot structure.

the broadcast also has a broadcast interval (BI) to determine the period of broadcast reception.

The node of Wi-SUN receives the broadcast schedule information element (BS IE) during the network participation process. The BS IE includes a broadcast schedule identifier (BSI), a use channel and channel hopping function, a BI, and a broadcast dwell interval (BDI). Each node includes its broadcast schedule timing information in the broadcast timing information element (BT IE) and transmits it in every data frame. In addition, the BS IE and the BT IE transmitted from the root node are propagated to lower nodes having higher ranks so that all nodes can have a synchronized broadcast transmission time.

2) Wi-SUN Network Configuration

Wi-SUN nodes perform multiple frame exchanges at the MAC and network layers for communication and network participation between neighboring nodes. The neighbor node discovery and network participation process consist of four frames exchanged by a trickle timer: PAN Advertisement (PA), PAN Advertisement Solicit (PAS), PAN Configuration (PC), and PAN Configuration Solicit (PCS). First, the PA frame provides the minimum information for a node to join the network, discover other nodes, or select one of several PANs. Second, PAS is used for accelerating the transmission rate of PA frames to nodes that newly participate in the network. At this time, the PAS is transmitted as plain text without encryption because the node has not yet joined. Third, the PC propagates to neighboring nodes, including nodes participating in the network, and it contains their channel hopping schedule, group key information, current time, and details for secure operation of the various PANs. Finally, PCS is used to accelerate the PC frame transmission period of the neighbor nodes.

The trickle timer is used to adjust the transmission intervals between frames. The interval I of the trickle timer is set to a value between [$I_{\min}$, $2^{I_{\min}}$]. In order to avoid collision during transmission, the time T during transmission is randomly selected to a value between [$I/2$, I]. When the system remains stable, I doubles and increases exponentially until the maximum value $2^{I_{\min}}$ is reached to minimize repetitive transmissions. In contrast, when the system is unstable, the trickle timer is initialized to $I_{\min}$ and repeats the incrementing operation. A trickle timer reduces the amount of control packets wasted on the network.

III. PREVIOUS RESEARCH ON CHANNEL-HOPPING MAC

Some studies have evaluated the performance of 6TiSCH using TSCH MAC and MSF, and several studies have been conducted to evaluate the overall performance of Wi-SUN.

One study measured the overall performance of the 6TiSCH network through OpenWSN [16], an open-source project designed to comply with the 6TiSCH specification. In [17], 37 motes were tested in the IoT-LAB testbed to evaluate the performance of the OpenWSN project. The firmware used in the evaluation was OpenWSN Release 1.14.0. Packet delivery ratio (PDR) and end-to-end reliability were measured as the ratio of received packets to received packets within the experimental period. A total of 3,544 packets were sent from each node to the root node using multi-hop transmission. The end-to-end reliability of a total of 36 data generation nodes was 99.8% on average, and all nodes showed more than 99% reliability. Although retransmission occurs in the MAC layer, when it is transmitted using another channel, the end-to-end reliability is not affected unless the maximum number of retransmissions is reached. The latency represents the time between the sender creating the packet and the receiver receiving the packet finally. Therefore, the latency is affected by various network parameters, such as the number of hops between the sender and the receiver, the length of the slot frame, the relative position of the transmitting and receiving cells, and the PDR at each hop. In a five-top linear topology, experiments were conducted for various situations with a slot length of 10 ms and slot frame lengths of 31, 67, and 101, with PDRs of 100%, 80%, 60%, and 40%. Based on the slot frame length of 101 defined in the standard, the minimum slot time was 10.050 seconds, and the maximum was 17.625 seconds.

A previous study used orchestra scheduling of 6TiSCH and Contiki-OS and Cooja simulator [18]. The length of a one-time slot was 15 ms, and the number of nodes was arranged in a grid formed up to 100 nodes. They experimented with two cases where only nodes that do not have child nodes, that is, leaf nodes, generate traffic in the topology, and all nodes generate data except the root node. When the number of nodes was 100 for the two scenarios with a transmission period of 30 seconds, the packet transmission rate was about 100% and 97%, respectively. The delay time was observed to be a maximum of 1 second and 3.6 seconds. This means that orchestra scheduling also shows high PDR in a situation with a relaxed data rate.

Based on 6TiSCH networks, a new distributed SF called the channel ranking scheduling function (CRSF) has been suggested [19]. They performed a detailed performance evaluation of three different scheduling functions for 6TiSCH networks: the CRSF, Orchestra, and MSF. The research shows that the CRSF effectively builds schedules based on the current characteristics of the network, achieving up to a 0.998 PDR in scenarios with 4×4 deployments, periodic traffic patterns, and a slot frame length of 29 and up to a 1.0 PDR in scenarios with 4×4 deployments, burst traffic patterns, and a slot frame length of 29. The MSF, on the other hand, achieves the best RDC performance with values ranging from 5.5% in scenarios with periodic traffic, slot frame lengths of 47 timeslots, and a 4×4 topology and up to 70.0% in scenarios with periodic traffic, slot frame lengths of 47 timeslots, and an 8×8 topology.

Another paper investigated the joining time in 6TiSCH networks since fast network formation is expected in industrial environments [20]. Since 6TiSCH networks are expected to offer high performance and fast bootstrapping, the network formation time could be impacted by the network size and the rate of control packets. Therefore, to study the impact of the misbehaviors on the joining time, the researchers implemented the node's misbehaving attack, denying the neighbor's request, at the 6top sublayer, then integrated it in the 6TiSCH simulator, a reliable tool for 6TiSCH networks. The obtained results demonstrated that the increase in the joining time could reach 174% when considering high misbehaving rates. The proposed attack is ineffective in small networks, unlike large-scale networks, where the joining time is proportional to the number of misbehaving nodes.

Another experiment analyzed the performance of Wi-SUN's F-RIT MAC [21]. They simulated the difference in packet rate based on whether pre-carrier sense (Pre-CS) was performed. A total of 20 nodes were used, and the experiment was conducted by adjusting the transmission period from 1,000 seconds to 10 seconds. In the case of Pre-CS, there was a slight difference according to the length of the data frame, but when the data period was 1,000 seconds, the transmission success rate was over 99%. In the case of 10 seconds, the transmission success rate was about 70%. To guarantee a 90% of transmission success rate when using Pre-CS, the data period should be longer than 100 seconds.

A previous study evaluated Wi-SUN's performance in various topologies [9]. The performance of channel-hopping-based Wi-SUN using Texas Instruments' SimpleLink TI 15.4 stack was evaluated. End-to-end reliability was measured as the ratio of the response times to the request times measured at the gateway. The average packet transfer rate over six hops using seven nodes was 99.7%, and the lowest was 99.4%. Round trip time (RTT) is measured differently depending on the hop count of each node, and the farthest node shows the largest RTT. The RTT was measured from a minimum of 0.19 seconds to 1.17 seconds. To test the scalability, 20 and 100 data-generating nodes were placed and tested to give PDRs of 99.7% and 97.14%, respectively.

Another previous study evaluated that the hidden node problem (HNP) limits the throughput and PDR of CSMA/CA due to collisions. In contrast, the complexity of control signaling in 6TiSCH limits its upper bound of throughput [22]. Therefore, the researchers suggested the self-configurable grouping (SCG) method for integrated Wi-SUN FAN and TSCH-based networks. Eliminating around 99% HNP in CSMA/CA, the SCG method dramatically improved its reliability by maintaining the relatively high upper bound of throughput. Finally, the SCG method almost doubled the network throughput compared with both 6TiSCH and Wi-SUN FAN in heavy traffic scenarios while providing extremely high reliability of more than 99.999%.

In each study, both 6TiSCH based on TSCH MAC and Wi-SUN based on CSMA/CA MAC showed good performance in terms of reliability or latency. Furthermore, Follow-up studies have been conducted to improve shortcomings while taking advantage of the advantages of TSCH MAC-based 6TiSCH and CSMA/CA MAC-based Wi-SUN. However, the parameters vary as a result of various applications: different packet transmission cycles, node placements, network topologies, and PHY layers. Therefore, in this work, we evaluate the MAC performance of channel-hopping-based mesh networks using the same packet transmission period, network topology, and nodes. Latency is measured through RTT, and the energy consumption is evaluated through the duty cycle of the radio module.

IV. ANALYSIS OF CHANNEL HOPPING MAC FEATURES

As mentioned earlier, the two protocols have a lot in common, including IEEE 802.15.4g, 6LoWPAN, and RPL. However, due to the structure of MAC, there is a big difference in the operation method. 6TiSCH based on TDMA supports slot-based transmission. CSMA/CA-based Wi-SUN considers channel intervals as virtual slots but does not use slots for transmission. Therefore, before the experiment, the characteristics of the two protocols are analyzed according to the presence or absence of slots.

A. Application Perspective

6TiSCH aims to communicate wirelessly with management systems and the data produced by equipment and sensors in industrial environments. Therefore, it aims at deterministic transmission to cope with various industrial environments and to provide reliable communication. Wi-SUN aims to control the interworking of data collected from various applications in smart cities, such as smart grids, AMIs, and EV charging stations. Both 6TiSCH and Wi-SUN protocols can be used for applications that perform remote data collection and control functions such as SCADA, Smart Grid, and Smart Farm. Based on the long transmission range use of the sub-1-GHz frequency, these protocols have advantages in outdoor network configuration, support high reliability and low delay packet transmission, and are suitable for stable and accurate operation. Assuming that both protocols are used for the same application, there are pros and cons in performance, depending on the data cycle and network size and on the characteristics of the MAC. In the case of 6TiSCH, precise synchronization is performed, which allows advantages in relatively large network configurations and accuracy in short data cycle communications. In contrast, Wi-SUN has a short delay time and efficient communication when the data period is longer in a small network.

B. Collision Perspective

Accurate transmission of data in the IIoT environment is one of the important factors regardless of the type of application. Loss of data due to collisions causes major problems in the control or monitoring of industrial machines. Therefore, accurate transmission of packets is essential regardless of the frequency of data generation or node density. The presence or absence of a slot is closely related to the possibility of a collision occurring during transmission.

If slots are allocated to each node in advance, there is no situation where multiple nodes within the interference range transmit simultaneously. However, this is the case when scheduling is centralized. If the scheduling is randomly generated at each node in a distributed manner, such as 6TiSCH, collision is likely to occur in the remaining slots, except for shared slots for sending and receiving broadcast packets. For example, all synchronized nodes A, B, C, and D communicate with the 6th channel offset at the 40th slot offset, i.e., cells (40, 6), such as A→B and C→D. The collision is repeated in every slot frame if the period of traffic A→B and C→D is less than the product of the slot frame length and the time of one slot, or if the difference in the occurrence time of two traffics is within one slot frame. 6TiSCH has the RELOCATE command of the 6top protocol to improve this repetitive collision. If each node's packet rate decreases below a certain threshold owing to the influence of external interference or collision at each node, another random cell is allocated through the RELOCATE command to continue communication. However, there is a disadvantage in that conflicts between the cell relocation and the time when a certain threshold is reached through the RELOCATE command are neglected.

Since the CSMA/CA scheme used in Wi-SUN is a non-slot structure, and there is no scheduling, collisions occur due to multiple nodes requesting transmission at the same time. Request-to-send (RTS) and clear-to-send (CTS) and waiting for a random time are used to cope with the problem of collision. The node requesting transmission sends the RTS to the receiving node. If the receiving node is not currently performing the transmission or is not waiting for reception from another node, the receiving node responds to the CTS to start the transmission. However, since the reception and transmission cannot be performed at the same time, the conflict due to the transmission requests of multiple adjacent nodes is a disadvantage of the non-slot method. Therefore, if the CSMA/CA detects a collision, it performs the back-off technique. However, if node density is high and data traffic is high, there is still a possibility of conflict even after performing the back-off, and there is a disadvantage in terms of latency due to the back-off.

C. Latency Perspective

The location of cells in slots according to scheduling in the MAC is an important factor determining latency. In the worst case, owing to the relative position in the slot, there is a case of waiting for a time that is less than the length of the slot frame. For example, assume that nodes A–B–C form a multi-hop and transmit packets from A to C, the slot frame length is 101, and the number of cells in the schedule is one. If the schedule of A→B is located at slot offset 3 and the schedule of B→C is located at slot offset 2, this data will wait for 100 nodes for node B. In addition, when a retransmission occurs, it is necessary to wait for as much as the time of the slot offset to transmit the data again through the corresponding schedule. If a large number of cells are allocated according to the amount of traffic, the problem of maximum latency is alleviated to some extent, and any attempt to reduce the number of slot frames can reduce the latency due to the above problems. However, if the slot frame is reduced in a state where the number of nodes is large, the probability of collisions is increased by selecting the same cell, and in some cases, the schedules of all nodes cannot be accommodated. The ideal cell layout is not easy to configure with distributed scheduling, and it is not always possible to maintain an ideal state due to interference. Therefore, the slot frame length 101 and MSF defined in the standard are used.

In the case of Wi-SUN, the data are created and transmitted at the same time, so there is no delay time due to the scheduling. Therefore, it can be said that the delay time is less than 6TiSCH with a fixed schedule when there is a low density of nodes with a low probability of collisions. However, the main cause of the latency of the CSMA/CA technique is the back-off. If a collision is detected after the frame is transmitted, back-off is performed. At this time, the delay in the packet queue becomes longer according to the maximum back-off time, which leads to an increase in latency. Reducing the back-off time to reduce latency has trade-offs that increase the probability of collision. Wi-SUN introduced channel hopping to prevent collisions on the same channel. Collisions due to channel problems are expected to be resolved if the conflicting nodes attempt to transmit using different channels. In addition, to prevent collisions by retransmitting through another channel in case of retransmission, in this work, the duration of back-off is less than 250 ms, which is the dwell time of at most one channel.

Based on the parameters defined above, the formula for the delay time is defined as follows. The delay time in the multi-hop of the 6TiSCH network is shown in Eq. (2). H_{num} is the number of hops, and $offset_{rxtx}$ is the product of the slot time and the difference in relative position on the schedule of the cell where reception and transmission take place. PDR represents the packet delivery ratio between hops. It means the product of the ratio of the successful packet transmission of the node within one slot frame to the delay caused by the change of the positions of the receiving and transmitting cells according to each hop movement. Wi-SUN performs the transmission using the back-off timer when a packet is generated. The formula is shown in Eq. (3). $backoff_t$ refers to the time when the random back-off timer expires. T_{CCA} denotes a period for performing CCA, and L, H_{num}, and PDR refers to the mean latency, number of hops, and packet delivery ratio, respectively. In other words, the latency of Wi-SUN may be expressed as the sum of the CCA period and the expiration time for the execution of the back-off timer in each hop.

$$L = \Sigma_{n=1}^{H_{num}} \left(offset_{rxtx} \times \frac{1}{\text{PDR}} \right) \tag{2}$$

$$L = \Sigma_{n=1}^{H_{num}} \left(backoff_t \times \frac{1}{\text{PDR}} + T_{CCA} \right) \tag{3}$$

Fig. 7 is the result of deriving the delay time according to the change in PDR for the case of schedule difference of 100, 50, and 10 slots based on Eq. (2). The length of one slot is 15 ms, and the calculation result is 150 ms minimum and 1,500 ms maximum when the PDR is 100%. Assuming PDR of 80% or more, the average delay on one hop is 1,000 ms. This result assumes that there is only one transmission opportunity in one slot frame. If the transmission opportunity increases, the scheduling difference of the slots is reduced so that the latency can be reduced. Fig. 8 shows the result of deriving the delay time according to the change in the PDR for the back-off time of 250 ms, 125 ms, and 50 ms based on Eq. (3). Unlike 6TiSCH, there is no restriction on the schedule, so this is dependent on the delay caused by the back-off based on the transmission probability. If the back-off time is 125 ms, the minimum and maximum delay times are 140.625 ms and 1265.625 ms, respectively.

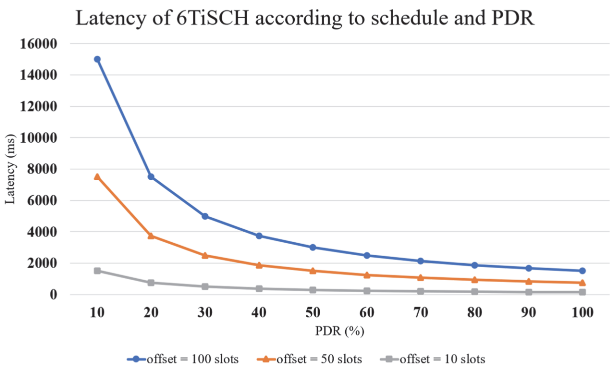

Fig. 7. Latency of the 6TiSCH according to change of schedule and PDR.

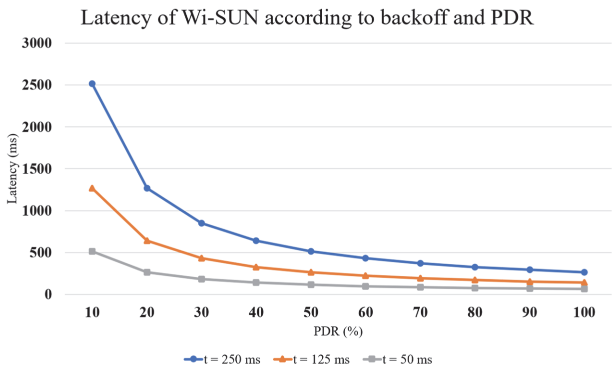

Fig. 8. Latency of the Wi-SUN according to change of the back-off and PDR.

D. Network Scalability Perspective

6TiSCH and Wi-SUN show performance differences owing to the increase in the number of nodes due to the characteristics of the slot and non-slot-based structure. First, in the case of 6TiSCH, synchronization and scheduling are essential for network configuration and operation. Therefore, there is a disadvantage that the latency increases according to the position of the schedule and the length of the slot frame. In addition, when the size of the network grows, there is an overhead for flexible scheduling, but after stabilization, stable transmission is performed regardless of the period or interference of data. In contrast, Wi-SUN has an advantage when the number of nodes is small. The smaller the number of nodes configured in the entire network, the lower the probability of collision during contention-based transmissions, which leads to lower latency transmissions. However, if the number of nodes participating in the network increases, the probability of collision at each hop increases, which affects the end-to-end packet transmission rate and latency in multi-hop transmission. Therefore, for stable transmission with Wi-SUN, it may be more rational to configure several small networks in which a few nodes participate in a large number of root nodes rather than one large network with a large number of nodes dependent on a single root node.

As discussed above, the two MAC protocols have different advantages and disadvantages in terms of packet rate and latency. Therefore, in this work, we compare the performance through experiments with various parameters.

Simulation with different numbers of nodes, traffic cycles, and traffic types is carried out to reflect various aspects such as the number of schedules generated, the relative location of schedules, and transmission through other channels in case of a collision. The simulation also analyzes aspects of efficient transmission.

V. METHODS AND EXPERIMENTAL

A. Simulation Methods

The simulation for evaluating the performance of the MAC involves PDR, latency, bandwidth, and energy consumption through duty-cycle measurements. The simulation is performed through a UDP application. The operation of the UDP application is as follows. In the topology, the sensor nodes perform bottom-up transmission that generates 50 bytes of data according to the transmission period and transmits it to the root node. Accordingly, the root node checks the data of the sensor node, records the reception, and transmits the same content back to the sensor node. The sensor node finally confirms receipt of the data it sent and records the reception. The operation of this UDP application depicts the data flow in a typical IIoT. Sensor nodes generate data through sensing and send the data to the root node for sending to the server. In addition, it generates downlink traffic from the server to the sensor node.

To measure the performance according to the difference in MAC, various simulations were performed according to two traffic patterns, two packet transmission cycles, and four-node numbers. Traffic patterns are divided into burst and random patterns. Burst traffic starts with all sensor nodes with a short time difference and starts transmission with the same packet transmission period. In other words, a large number of sensor nodes generate data in a short unit of time to put a heavy load on the network. Random traffic starts with every sensor node at a random time and transmits data with a constant packet transmission period from that time. As a result, the total load on the network is less than that in the previous case. For the experiment, the packet transmission period was kept as 10 seconds and 100 seconds. The IIoT has a short data transmission cycle for continuous acquisition and immediate control of sensor data. In this regard, the simulation was performed based on 10 seconds, which is a data collection cycle, and the transmission cycle of 100 seconds was also performed in consideration of the frequent retransmission and the environment where AMI is applied. The number of nodes is divided into seven types. All consist of 5, 10, 15, 25, 50, 75, and 100 nodes, including the root node. We observe the decrease in packet transmission rate and the increase in latency as the size of the network and the number of hops increase. End-to-end latency is measured between two application layers based on the record at the node where the packet is generated and at the node that received the packet.

B. Simulation Environments

The simulation was carried out using the Cooja simulator included in Contiki-OS. 6TiSCH and Wi-SUN MAC were implemented using Contiki-OS. 6TiSCH can actively respond to traffic by allocating a schedule according to the traffic demand using the MSF. In addition, the length of one slot is 15 ms, and a total of 101 slots constitute a slot frame. Channel hopping is performed using Eq. (1) given above. Initially, the radio is turned on and waits for synchronization, and when synchronized, slots without a schedule turn off the radio and perform a sleep operation. Wi-SUN minimizes collisions by using a back-off timer that waits a random time before transmission based on CSMA/CA and then performs transmission. The current Wi-SUN specification does not specify sleep behavior. Therefore, all Wi-SUN nodes do not transmit or receive packets. The behavior of the Wi-SUN nodes may vary depending on the application's requirements. We perform the Clear Channel Assessment (CCA) mode 1, defined in the Wi-SUN specification, twice to detect the transmission of data, and the sleep operation is performed for the rest of the time to save energy. The period of the CCA was set to 15.625 ms, similar to 6TiSCH's slot duration.

Commonly, RPL and ICMPv6 are used as the network layer, and 6LoWPAN is used as the adaptation layer. It communicates with IPv6 addresses. Also, link layer security (LLSEC) was not applied to measure the performance of MAC. Transmission of control messages, such as DIO, DIS, and DAO by RPL is prevented from

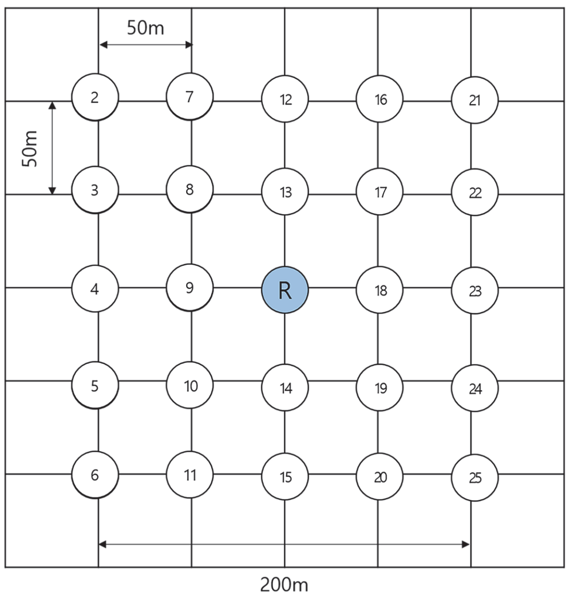

Fig. 9. Example of 5×5 grid topology.

Table 2. Simulation configuration

	6TiSCH	Wi-SUN
Number of nodes	5, 10, 15, 25, 50, 75, 100	
Devices	Cooja mote	
Number of radio channels	16	
MAC protocol	TSCH+MSF	CSMA/CA
MAC retransmission	Maximum 3 times	
Duration (hr)	1	
Packet interval (s)	10, 100	
Packet size (byte)	50	

being duplicated by using the trickle timer. As shown in Fig. 9, all nodes are arranged using a grid format. The distance between the nodes is 50 m, the transmittable distance is 60 m, and the interference influence distance is 70 m. Therefore, diagonal nodes are affected by interference with each other. Table 2 shows the overall settings for the simulation.

VI. SIMULATION RESULTS AND EVALUATION

A. Packet Delivery Ration

First, the PDR is analyzed. Fig. 10 shows the situation where each sensor node generates traffic with a period of 10 seconds starting at a random time. In this situation, as the number of nodes increases, the packet transmission rate decreases. However, both protocols show high reliability, with more than 96% PDR, even in simulations with 100 nodes. Both protocols show 100% PDR for 10 nodes and over 99% PDR for up to 50 nodes. In the case of 6TiSCH, when the number of nodes is 75 and 100, the PDR decreases linearly, whereas in the case of Wi-SUN, when the number of nodes is 25, 50, and 100, the PDR decreases more rapidly, i.e., 99.285%, 98.513%, and 96.489%. It can be determined that the hop increases as the number of nodes increases and the collision increases due to contention-based transmission.

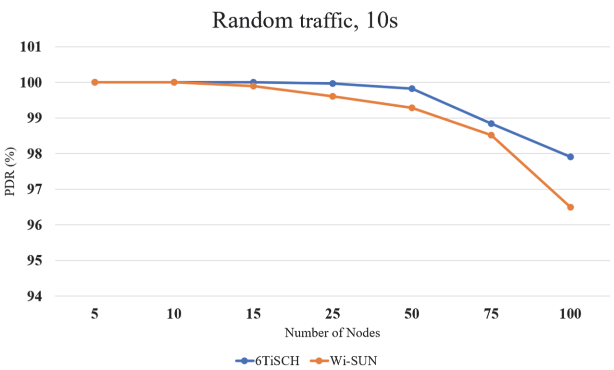

Fig. 10. The average packet rate changes as the number of nodes increases when traffic is generated at random with a period of 10 seconds.

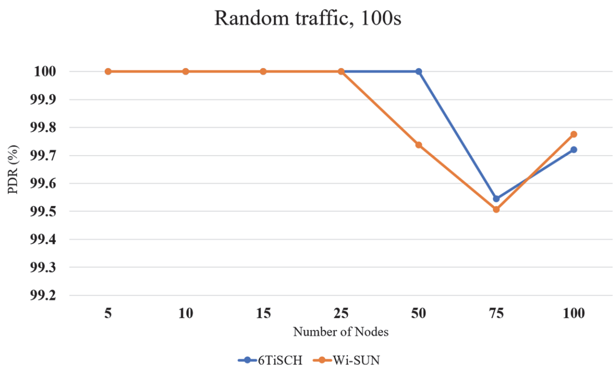

Fig. 11. The average packet rate changes as the number of nodes increases when traffic is generated at random with a period of 100 seconds.

Fig. 11 shows the results of traffic with the same condition as that in Fig. 10 but with a period of 100 seconds. Both protocols showed more than 99.5% PDR with excellent stability. In the case of 6TiSCH, PDR improved by about 0.8% for 75 and 100 nodes compared to the case with a period of 10 seconds. In contrast, Wi-SUN shows a performance increase of about 0.5%, 1%, and 3% for 25, 50, 100 nodes when compared to the case with a 10-second period. The difference in reliability due to the packet transmission period shows that the load of the network when a retransmission occurs is more as the number of hops increases in a multi-hop environment. In the case of 6TiSCH, cells are allocated to each node through MSF scheduling, and retransmission is also processed through this to enable deterministic transmission. In contrast, if Wi-SUN has many nodes and frequent retransmissions, it is likely to be exposed to collisions even if the transmission is performed after the random time the back-off timer expires.

Next, we present the results for a situation where all nodes start with short time differences and generate burst traffic transmitting packets with the same period. Fig. 12 shows a performance drop of up to 4.6% as the number of nodes increases in the case of 6TiSCH when the transmission period is 10 seconds. In the case of 5 and 100 nodes, 100% of PDR and about 95% of PDR is obtained. It shows deterministic transmission that minimizes collisions owing to the flexible scheduling response and TDMA-based characteristics even under heavy network load. In contrast, Wi-SUN shows the weakness of CSMA/CA contention-based transmission. A maximum of 99.642% PDR is obtained. When the number of nodes is the highest, only a 40% PDR is obtained, which is a decrease of 48%. The difference, in this case, is up to 54% compared to the competing scheme. The use of

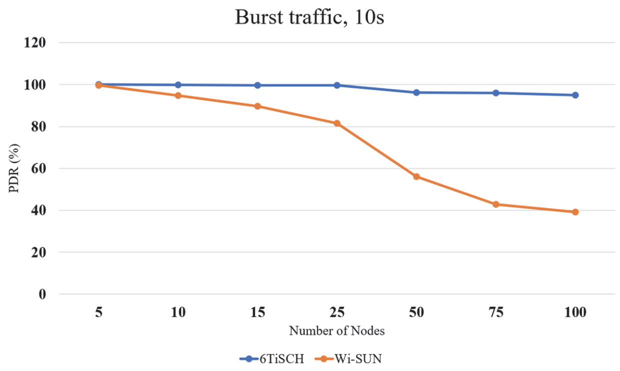

Fig. 12. The average packet rate changes as the number of nodes increases when traffic is generated at burst with a period of 10 seconds.

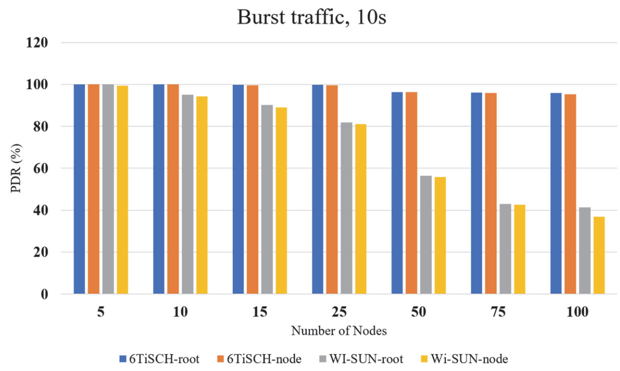

Fig. 14. Change in packet rates as the number of nodes increases at the root node and sensor nodes in each protocol.

channel hopping can maintain 80% performance for 25 nodes, but this can be the result of the radical difference from the non-competitive method of TDMA. This result can be attributed to the fact that a large number of nodes is included in the communication interference range of neighboring nodes. Except for the farthest node from the central root node in the grid topology, the remaining nodes have four nodes in their transmission range apart from themselves and eight nodes in the interference range. Therefore, a surge of traffic in a short time caused many collisions.

When the period of traffic generation increased to 100 seconds, the result is slightly improved. Fig. 13 shows Wi-SUN improved PDR by up to about 6%. This results in a difference of at least 45% of PDR. In the case of 6TiSCH, the maximum performance was improved by about 1%. As a result, the difference is up to 50%, and the performance drop is less than the previous result. This can be considered as the difference between the results shown in Figs. 10 and 11. The results shown in Figs. 12 and 13 indicate that 6TiSCH supports a 95% packet rate and stable transmission even under various conditions of burst traffic.

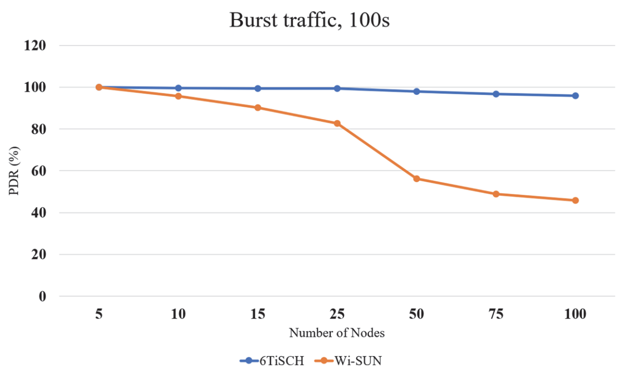

Fig. 13. The average packet rate changes as the number of nodes increases when traffic is generated at burst with a period of 100 seconds.

The results in Fig. 12 were analyzed in more detail to derive Fig. 14. In the situation where burst traffic occurs every 10 seconds, both protocols observed the PDR of upstream traffic from the sensor node to the root node and downlink traffic from the root node to the sensor node. In the case of 6TiSCH, in which cell arrangement of nodes for upstream and downstream traffic has already been completed through scheduling, generation of downstream traffic does not affect the transmission of upstream. However, in the case of Wi-SUN, there is a loss of data in both upstream and downstream traffic due to collision with upstream traffic coming to the root node owing to the occurrence of downstream traffic. It can be considered that the root node generates downward traffic for the data that arrived earlier, creating a conflict with upward traffic that arrives consecutively from nodes that are one-hop neighbors. For both protocols using RPL, DODAG is configured, and the closer the node is to the root node, the more traffic it relays.

B. Latency

The latency in simulations with the most difference in PDRs has been analyzed, with a traffic cycle of 10 seconds. In all situations, nodes have grid-based topology, as shown in Fig. 9. Thus, if 25 nodes are deployed, they form a multi-hop topology from 1 to 4 hops, and if 75 nodes are deployed, they have a distance of up to 8 hops. This will also be larger than the number of nodes with small hops of distance compared to long distances. Fig. 15 shows the end-to-end latency measured with 100% PDR in the burst traffic of 6TiSCH and Wi-SUN. If the number of nodes is less than 15, Wi-SUN shows less delay. There is a relatively small difference between about 5 ms and 33 ms. Crossover occurs when there are more than 25 nodes. From this point on, 6TiSCH shows a faster transfer delay. When the number of nodes is 75, the largest difference is approximately a second. As a result, we can observe the pros and cons of both networks from a latency perspective depending on the size of the

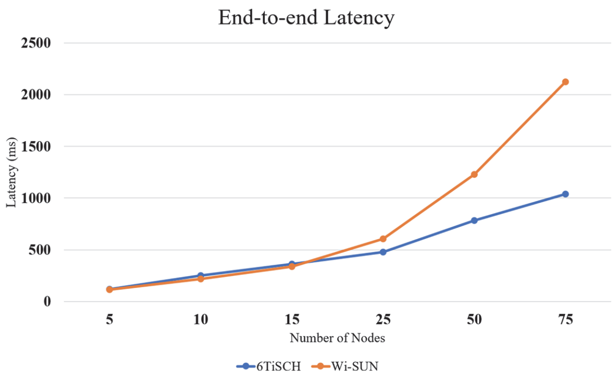

Fig. 15. Change in end-to-end latency with 100% PDR depending on the number of nodes.

network. If the network is small, it is sent quickly without the overhead of the schedule. Also, From Eqs. (2)–(3) and Figs. 7–8, 6TiSCH has a lot of schedules created to handle the traffic, resulting in a delay less than the expected maximum one. In contrast, Wi-SUNs can be seen approaching the maximum delay time, which could be attributed to the maximum back-off owing to repeated collisions.

C. Bandwidth

Fig. 16 shows the results of calculating the bandwidth based on the latency at 100% PDR. Both protocols transmit 50 bytes of data in one transmission. As a result of changes in the distance of the hop and the size of the network, 6TiSCH has a bandwidth of up to 3.4 kbps from a minimum of 385 bps, and Wi-SUN has a bandwidth of up to 3.5 kbps from 190 bps. As with crossover in terms of latency, performance ranks change between 15 nodes and 25 nodes in bandwidth. In relatively small networks, Wi-SUNs can also perform fast transfers based on sufficiently small conflicts. If there are multiple small networks with small sensor nodes on one root node, stable data processing can be performed without the burden of scheduling or synchronizing the entire nodes. However, if numerous sensor nodes are placed on one board router node, 6TiSCH is better for stable and fast transmission. Therefore, the two protocols differ based on the environment and requirements of the application in which they are deployed and on the size of the network.

D. Radio Duty Cycle

Finally, the average energy consumption in each network is analyzed through the measurement of the average radio duty cycle on each node. The largest portion of the WSN's power consumption is attributable to the radio portion that sends and receives packets. Therefore, if the duty cycle is high when compared with the operating time of the radio over the same time, the node consumes more energy.

Fig. 17 shows the change in the duty cycle of 6TiSCH and Wi-SUN as the number of nodes increases. First, in the case of 6TiSCH, we see a linear increase in duty cycle at about 2.7%, 3%, 3.6%, 5.5%, and 7.4% as the number of nodes increases. This indicates that the amount of traffic increased as the number of nodes and cells increased gradually to handle traffic generated by the behavior of MSF. In addition, on multiple hop topology, the number of packets delivered by nodes that are close to the root node increases, and the increase in the schedule results in a higher average duty cycle. In contrast, Wi-SUN shows a slight increase of 8.3%, 8.6%, 8.8%, 9%, and 9.4%. By using CCA on a competitive method instead of syncing and controlling the radio by schedule, a high duty cycle can be observed. In addition, the increase in duty cycle according to the number of nodes indicates an increase in the number of retransmissions.

Fig. 18 shows the average duty cycles of Tx and Rx as the number of nodes in Wi-SUN increases. While the duty cycle of Tx is around 0.7% to 1.34%, the Rx is 0.14% to 0.25%. This means many retransmissions occurred for one packet reception. If CCA cycles are increased further,

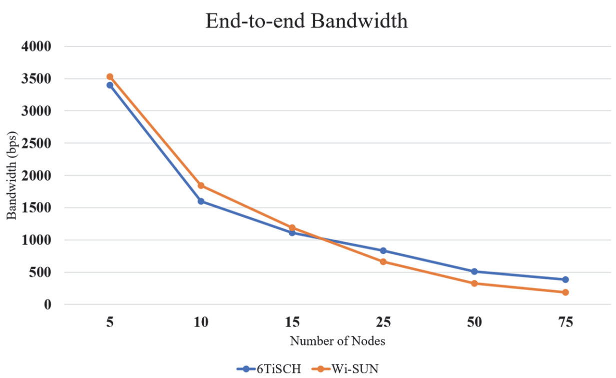

Fig. 16. Change in end-to-end bandwidth with 100% PDR depending on the number of nodes.

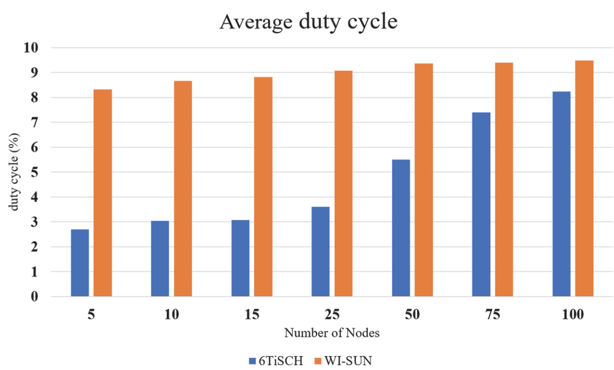

Fig. 17. Radio duty cycle changes with the increasing number of nodes.

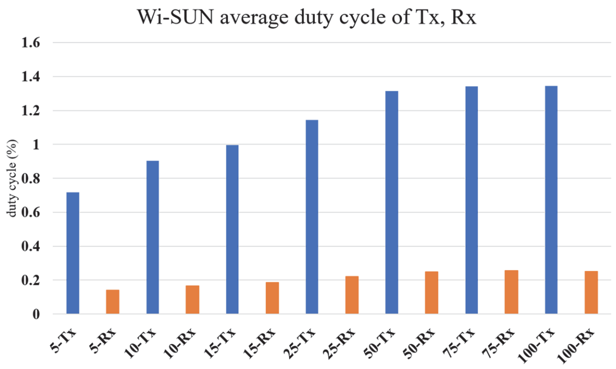

Fig. 18. Average duty cycle in Tx, Rx, depending on the number of nodes in Wi-SUN.

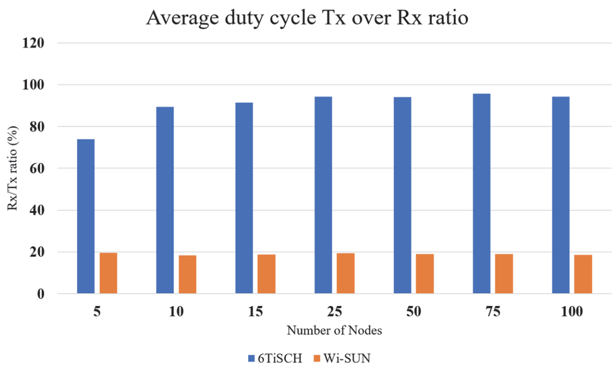

Fig. 20. Average duty cycle comparison of Rx to Tx Of 6TiSCH and Wi-SUN.

the difference in duty cycle between Tx and Rx would be greater, and the energy consumption for transmission would be greater in Wi-SUN than in 6TiSCH.

Fig. 19 shows the average duty cycle of Tx and Rx as the number of nodes in 6TiSCH increases. The part that is significantly different from Wi-SUN is that the ratio of duty cycle in Rx increases close to Tx. The duty cycle ratio of Tx was 0.1% to 0.54%, and that of Rx was 0.07% to 0.51%. This means, in addition to the smaller number of retransmissions compared to Wi-SUN, minimum radio activity was required to send packets to the receiving node. In other words, it is possible to operate with the time being synchronized based on TDMA so that the correct transmission is performed at the specified time. The duty cycle of Tx is higher than Rx because 6TiSCH also may be included in collisions or retransmissions of EB or RPL controlled packets sent to the broadcast.

Fig. 20 shows the ratio of radio duty cycle to Tx, Rx to determine the transmission efficiency. 6TiSCH had a higher Rx for the ratio of Tx, from at least 74% to a maximum of 95.61%. In comparison, Wi-SUN ranged from at least 18.36% to up to 19.33%, which is a difference of about 77% compared to 6TiSCH. This illustrates the energy efficiency aspects of MAC in both competitive and non-competitive ways. Thus, 6TiSCH performs efficient transmission using less energy through precise synchronization and slot-based transmission compared to Wi-SUN.

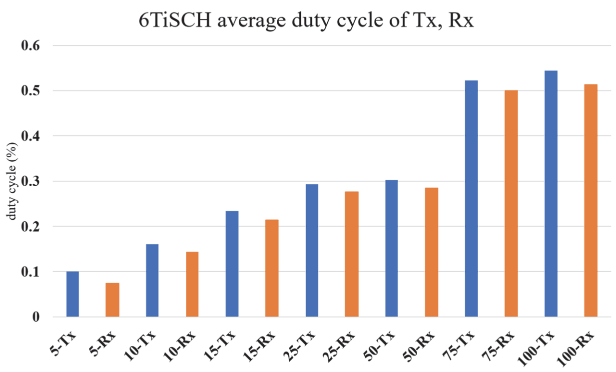

Fig. 19. Average duty cycle in Tx, Rx, depending on the number of nodes in 6TiSCH.

VII. CONCLUSION

In this study, we analyzed the characteristics of channel-hopping-based MAC in an IIoT environment and conducted an evaluation based on simulations from various perspectives. 6TiSCH uses TSCH MAC based on the TDMA scheme with slot structure, and Wi-SUN performs USCH using CSMA/CA-based MAC with a non-slot method. Both techniques have common features that make up the network, such as channel hopping, 6LoWPAN, and RPL, but the basis of the MAC protocol is different. Based on the Contiki-OS and COOJA simulator, various simulations were conducted for comparison of the performance of both protocols. 6TiSCH showed higher PDR for burst and random traffic compared to the USCH MAC protocol. Even in environments where the number of nodes increases, the performance drop of 6TiSCH was relatively small compared to Wi-SUN. However, Wi-SUN showed a significant performance drop owing to the limitations of the competition-based protocol when burst traffic occurred, despite the channel hopping on a large network scale. Moreover, observations of the radio duty cycle indicate that the ratio of Rx to Tx is lower because of CCA and retransmission, which results in a higher amount of energy used to transmit the packets. However, in the absence of burst traffic, channel hopping confirmed that even when multiple nodes participated in the network, the packet delivery ratio remained 96% or higher, and the communication performance remained reliable, even if no precise time synchronization was performed. In addition, even in situations with burst traffic, small networks have a PDR of more than 90% and take advantage of communicating with less than 6TiSCH. Therefore, depending on the size of the network to be configured, it was confirmed that the TDMA-based scheduling of 6TiSCH might work as an overhead.

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