Unicast Subslot Scheduling for Wi-SUN FAN System with Packet Collision Reduction

Hee-Jun Lee, Sang-Hwa Chung
Department of Information Convergence Engineering
Pusan National University
Busan, Republic of Korea
heejun@pusan.ac.kr, shchung@pusan.ac.kr

***Abstract*—** Wi-SUN FAN, a global standard wireless communication technology for building large-scale multi-hop networks, enables robust network operation through CSMA/CA-based MAC protocol and neighbor synchronized channel hopping. However, packet collision due to the Hidden Node Problem between child nodes with the same RPL preferred parent is a problem to be resolved. We propose a unicast subslot scheduling scheme to solve this problem and secure a high packet transmission success rate. The proposed method showed up to 27% higher packet transmission success rate in a simulation environment with high traffic, and the tradeoff with latency can be adjusted by modifying parameters.

Keywords—WI-SUN FAN; Hidden node; CSMA; RPL; scheduling

I. Introduction

IoT, which utilizes various data by connecting a large number of devices, has developed rapidly and is being used in various infrastructures such as smart cities, smart factories, and smart grids. In addition, wireless communication technology for effectively collecting a lot of data is very important in IoT.

Wireless Smart Utility Network (Wi-SUN) is a global standard wireless communication technology based on IEEE 802.15.4-2015 [1] for building IoT networks [2] and maintained by Wi-SUN Alliance [3]. Wi-SUN Field Area Network (FAN) [4] is one of several technical specifications of Wi-SUN and is a profile for building large-scale multi-hop networks that supports Internet Protocol version 6 (IPv6) [5]. Wi-SUN FAN supports IPv6 routing protocol for LLNs (RPL) [6] to configure a stable network, and transmits data using Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA) based protocols.

The CSMA/CA-based approach uses Clear Channel Assessment (CCA) and backoff techniques to detect the transmission of other devices and prevent wireless communication collisions. However, the stability of the network deteriorates due to the well-known Hidden Node Problem (HNP) [7]. When two different transmitters attempt to transmit a packet at the same time and fail to detect each other, a wireless communication collision occurs at the receiver listening to both signals.

In the Wi-SUN FAN system, each node performs frequency hopping according to its own unicast schedule. The sender calculates the receiver's unicast schedule and transmits the packet by changing it to the appropriate frequency. Through this neighbor synchronized channel hopping technique, packets with different destinations are less likely to collide. However, HNP is still a problem to be solved between packets transmitted to the same destination. In particular, in the path created in the tree structure through RPL, most of the network data is gathered at the same point as the border router, so it is necessary to prevent wireless communication collision between nodes having the same RPL-preferred parent node to increase network stability.

In this paper, we propose a unicast subslot scheduling scheme using RPL information to solve the problem of reliability degradation due to HNP between nodes with the same RPL preferred parent node and to secure a high traffic transmission success rate.

The remainder of this paper is organized as follows. In Section 2, Media Access Control (MAC) layer and RPL of Wi-SUN FAN system, and related research are described. In Section 3, the proposed technique is introduced. Section 4 evaluates the proposed technique, and finally Section 5 concludes this paper.

II. Background

A. RPL

RPL [6] is a routing protocol for low-power lossy networks and has been standardized by the IETF ROLL Working Group. In Wi-SUN FAN, a node uses RPL to deliver data to a desired destination.

Wi-SUN FAN forms a Destination Oriented Directed Acyclic Graph (DODAG), and the border router connected to the external network becomes the root node. Unicast traffic in DODAG can be divided into upward traffic toward the root node and downward traffic toward the opposite direction of the root node. In RPL, the following control messages are used by nodes to create and maintain routing.

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

- Destination Advertisement Object Acknowledgement (DAO-ACK)

Nodes participating in DODAG broadcast DIO, and the node receiving the DIO selects one of the nodes that transmitted the DIO as a preferred parent node and forms an upward path. The node that selects the preferred parent node becomes a child node of the selected node and sends DAO towards the root node. The node that received the DAO forms a downward path toward the node that sent the DAO. In addition, it is possible to request DIO from another node through the DIS message, and success of DAO transmission can be guaranteed through the DAO-ACK message of the root node.

DODAG is generally formed in the form of a tree as in the example in Fig. 1. All nodes except the root node transmit their own generated packets and upward packets to their preferred parent node. And the sending node transmits the packet in competition with nodes having the same preferred parent node.

B. MAC layer of Wi-SUN FAN

All nodes of Wi-SUN FAN maintain their own unicast schedule [4]. The unicast sequence consists of slots of the size of Unicast Dwell Interval (UDI), and the node performs frequency hopping by listening to a different channel for each slot. In addition, the node maintains a broadcast schedule consisting of broadcast slots having a size of a Broadcast Interval (BI) and transmits and receives broadcast packets within a Broadcast Dwell Interval (BDI). Broadcast schedule timing is synchronized between nodes.

Fig. 2 shows an example of Unicast/Broadcast Sequence, topology, and communication range of four nodes. A node listens to the frequency channel of its unicast slot and changes the reception channel to the frequency channel of the broadcast slot when the BDI time comes. If Node B wants to transmit a unicast packet to Node A, Node B must change the channel to a frequency suitable for Node A's Unicast Slot. In this way, the Wi-SUN FAN node can prevent collision between packets with different destinations through neighbor synchronized channel hopping of the unicast schedule. On the other hand, if nodes B, C, and D attempt to transmit to node A at the same time, node C can detect the transmission of node B and node D through CCA and defer the transmission. But because node B and node D do not detect each other, packet collision occurs and node A receives no packets.

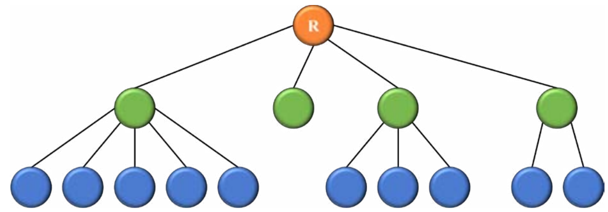

Fig. 1. DODAG Formation Example

C. Related work

Several studies have been conducted for stabilization and performance improvement of Wi-SUN FAN.

In [8], the authors proposed a routing method to solve the frequent RPL preference parent change problem in Wi-SUN FAN. Received Signal Level (RSL) threshold scheme and MAC address filtering scheme reduce the number of unnecessary parent changes.

In [9], the authors proposed a routing algorithm for mobile nodes in Wi-SUN FAN. The proposed method using RSL metric shortens the routing process interval of mobile nodes and implements stable mobile communication.

In [10], the authors proposed a channel scheduling method to improve the unicast throughput of the Wi-SUN FAN system. A coefficient used in BI calculation were optimized to handle high unicast traffic by controlling the proportions of unicast channel usage and broadcast channel usage.

If many nodes select the same node as the parent node, load imbalance will occur, reducing the benefit of frequency hopping. In [11], the authors proposed a load balancing algorithm that prevents load concentration on a specific node by limiting the number of child nodes.

In [12], the authors compare the reliability and throughput of CSMA and IEEE 802.15.4 TSCH of IETF 6TiSCH [13], and

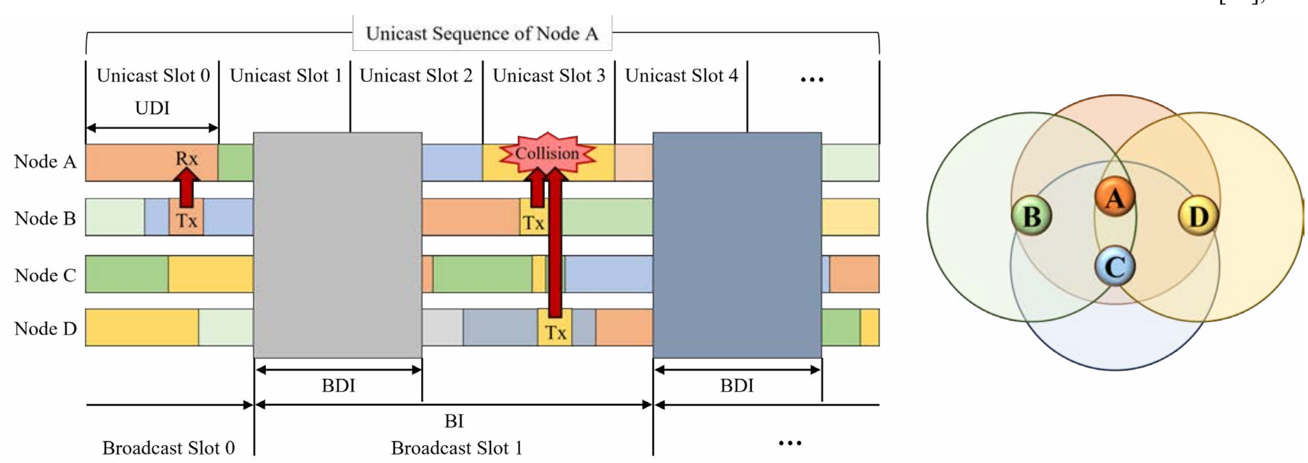

Fig. 2. Channel hopping sequence and topology of nodes A, B, C, and D

propose a Self-Configurable Grouping (SCG) method that improves network stability while maintaining a high throughput upper bound. CSMA shows high traffic throughput when there are no hidden nodes in the network, but as the ratio of hidden nodes increases, the performance is very poor due to the packet collision problem caused by HNP. In SCG, the coordinator collects neighbor information of all nodes in the network and groups them according to the hidden node probability, so that TSCH or CSMA can be used according to the group. However, there is an overhead that the neighbor information of all nodes in the network must be gathered to the coordinator, and the channel hopping mechanism of Wi-SUN FAN is not considered. A mechanism is needed to resolve HNP between nodes with the same RPL preferred parent.

III. Proposed Approach

In Wi-SUN FAN, there will be fewer collisions between packets to different destinations due to channel hopping of nodes. Therefore, communication between RPL parent-child that sends and receives unicast packets needs to be improved. When it is possible to detect each other even between nodes having the same preferred parent, packet collision can be prevented through CCA. However, if each other is not detected, packet collision due to HNP may occur. If unicast transmission of child nodes that are not detected from each other is scheduled, packet collision due to HNP can be reduced.

Therefore, we propose a unicast subslot scheduling scheme using RPL information to solve the decrease in communication reliability due to HNP and increase the packet transmission success rate in the Wi-SUN FAN system with high traffic. The algorithm of the proposed method is shown in Algorithm. 1.

A. *Create RplConnectedNodesTable*

A node can identify its child nodes by receiving a DAO packet or receiving a data packet rather than a control message. The node stores the identified child nodes and parent node IDs in RplConnectedNodesTable. ID can be determined in size of 1 byte or more according to the size of the network by using the address of the node. The nodes stored in RplConnectedNodesTable are nodes that have a parent or child relationship with the node.

B. *RplConnectedNodes advertising*

The node whose RplConnectedNodesTable has been updated advertises the ID sequence made by the contents of RplConnectedNodesTable into a packet to the child or parent node. ID sequence can be included in DIO option or IEEE 802.15.4 Information Element (IE) [1].

C. *Calculating unicast subsequence size*

The node r receiving the ID sequence creates a unicast subsequence for the node s if the node s transmitting the ID sequence is one of its RplConnectedNodes. A unicast subsequence is a sequence composed by dividing one unicast slot into several subslots. Node r calculates size_subseq(s), which is the size of unicast subsequence for node s, using (1).

Algorithm. 1 Unicast Subslot scheduling algorithm

```
If received a packet from node n Then
   add ID(n) to neighbor_table
End if
If identify a new RPL child or RPL parent node n Then
   add ID(n) to RplConnectedNodesTable
   create ID_sequence with RplConnectedNodesTable
   broadcast DIO with ID_sequence
End if
If received ID_sequence from node s Then
   If Node s is in RplConnectedNodesTable Then
      sizeIDseq(s) = number of IDs in ID_sequence
      size_subseq(s) = min(sizeIDseq(s), MAX_SIZE_SUBSEQ)
      save size_subseq(s)
      For each i = 0 → (size_subseq(s) – 1) do
         If ID_sequence[i] is not in neighbor_table AND
ID_sequence[i] is not myID AND subslot(s)[i mod
size_subseq(s)] is not set Then
            subslot(s)[i mod size_subseq(s)] = FALSE
         Else
            subslot(s)[i mod size_subseq(s)] = TRUE
         End if
      End for
      save subslot(s)
   End if
End if
If to send a unicast packet to node s Then
   subslot_index = (current_time – start_time_unicast_slot(s)) /
(UDI / size_subseq(s))
   If subslot(s)[subslot_index] == TRUE Then
      send a unicast packet to node s
   Else
      defer transmission
   End if
End if
```

$$\text{size\_subseq}(s) = \min(\text{sizeIDseq}(s), \text{MAX\_SIZE\_SUBSEQ}) \quad (1)$$

sizeIDseq(s) is the number of IDs contained in the ID sequence received from node s, and MAX_SIZE_SUBSEQ is the maximum size of unicast subsequence. size_subseq(s) is set to the smaller of sizeIDseq(s) and MAX_SIZE_SUBSEQ, and is the number of subslots in the unicast subsequence for node s. MAX_SIZE_SUBSEQ should be set in advance in consideration of UDI so that a node can have a sufficient transmission opportunity within one Subslot.

D. *Unicast subslot allocation*

As shown in Fig. 3, node r needs to determine the subslot that cannot be transmitted in the unicast subsequence for node s. Node r checks whether a node in each item of the ID sequence received from s is a hidden node. If the node in the i-th item of the ID sequence is a hidden node, the i-th subslot of the unicast subsequence for node s is a subslot in which node r cannot transmit a unicast packet to node s. However, if the size of the subsequence is limited by MAX_SIZE_SUBSEQ and is smaller than the size of the ID sequence, the index of the subsequence is calculated by modulo operation of MAX_SIZE_SUBSEQ on the index of the ID sequence. Only when all nodes of the ID sequence corresponding to the subsequence index are hidden nodes, the corresponding subslot is determined as a subslot that cannot be transmitted. For example, if MAX_SIZE_SUBSEQ is 2 and the ID sequence contains 5 IDs, both the 1st and 3rd nodes of the ID sequence must be hidden nodes, so that the 1st subslot becomes an

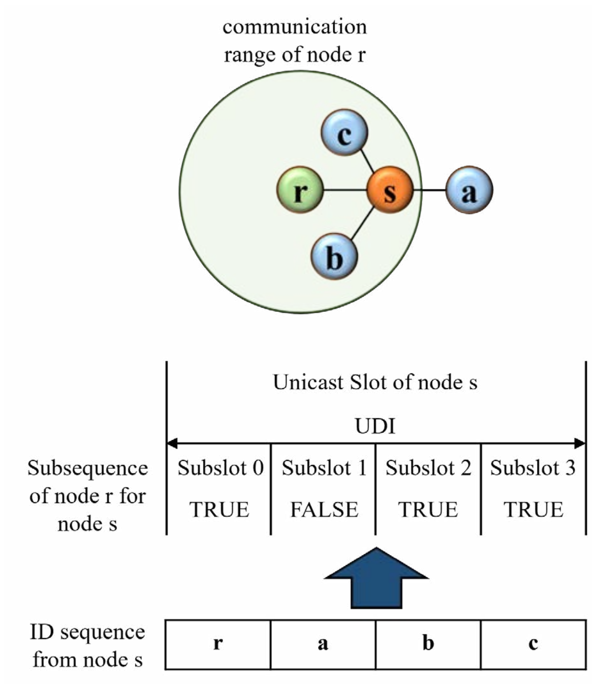

Fig. 3 unicast subslot scheduling for node s in node r

unavailable subslot. This is to prevent the node's transmission opportunity from being lost too much.

E. Unicast packet transmission

When node r transmits a unicast packet to node s, it determines whether or not to transmit the packet by calculating the current subslot number.

Through the proposed method, the node can avoid transmitting simultaneously with the hidden node, and packet collision caused by HNP can be prevented.

IV. EVALUATION

In this section, we evaluate the performance of the proposed method in this paper. For performance measurement, the channel hopping sequence operation of Wi-SUN FAN and timing sharing of each node through IEEE 802.15.4 IE in the packet are implemented in Contiki OS [14]. Simulations were also performed using Cooja [15], a simulation tool for Contiki OS. The experiment compares the network performance when the proposed method is applied and when it is not applied. To

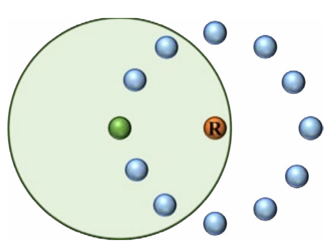

Fig. 4. Nodes placement and communication range of green node in the simulation

check the collision problem between child nodes having the same preferred parent, one root node and 12 non-root nodes are arranged in a star topology as shown in Fig. 4. The number of MAC retransmissions is set to 3, and UDI is set to 250ms. All non-root nodes send data packets to the root node at regular intervals. The measurement metrics are PAR, which is the probability of successful packet transmission at the link level, and end-to-end latency.

A. Comparison of performance according to traffic load

Fig. 5 and Fig. 6 show the average PAR and average latency of the proposed method and the original method according to the data generation period of each node. When the data generation rate is low and the traffic load is low, both methods show a PAR close to 100%, but as the traffic load increases, the PAR of the original method sharply decreases, showing a difference of up to 27%. As the traffic load increases, packet collisions due to HNP increase. The proposed method reduced this problem.

However, the latency of the proposed method is about 2 times higher. In the proposed method, the number of hidden nodes reduces the transmission opportunity, so packet collisions are reduced, but latency is high.

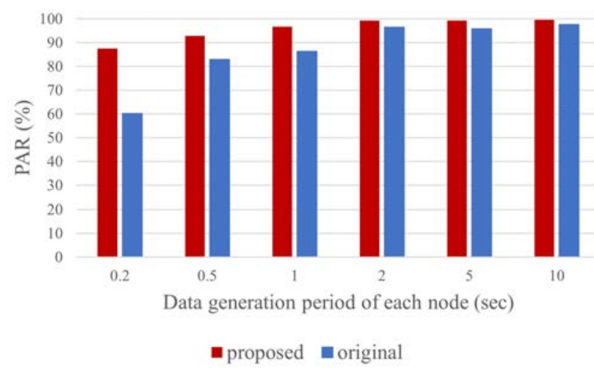

Fig. 5. Average PAR according to traffic load

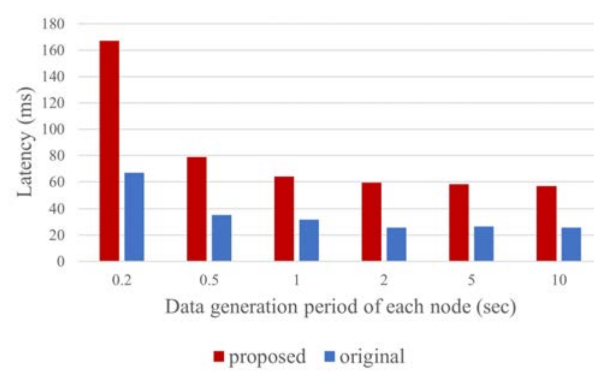

Fig. 6. Average End-To-End Latency according to traffic load

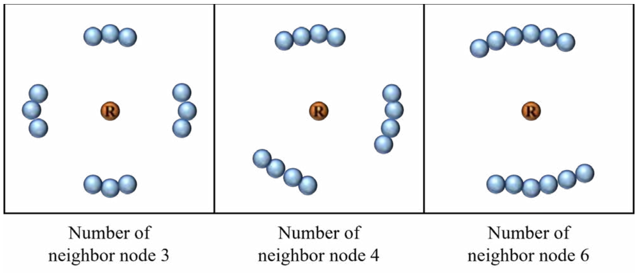

Fig. 7. Nodes placement according to the number of neighboring nodes of non-root node in the simulation

B. Comparison of performance according to number of neighbors

In order to measure the performance according to the number of neighbors of a node or the number of hidden nodes of a node, as shown in Fig. 7, nodes were arranged according to the number of neighboring nodes of a non-root node, and the packet generation period was fixed to 1 second.

Fig. 8 and Fig. 9 show the average PAR and average latency according to the number of neighboring nodes. In the proposed method and the original method, PAR does not change even if the number of neighboring nodes is changed. However, in the proposed method, the average latency increases as the number of neighboring nodes decreases. This is because the transmission opportunity decreases as the number of hidden nodes of a node increases.

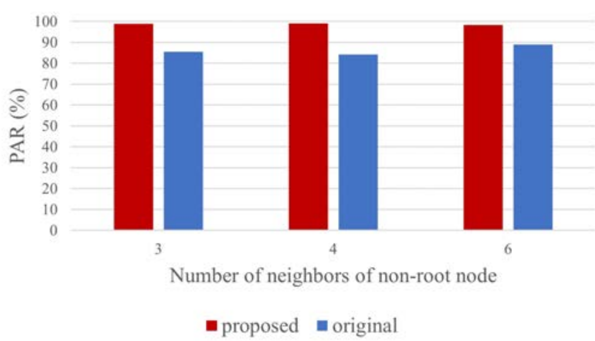

Fig. 8. Average PAR according to the number of neighboring nodes

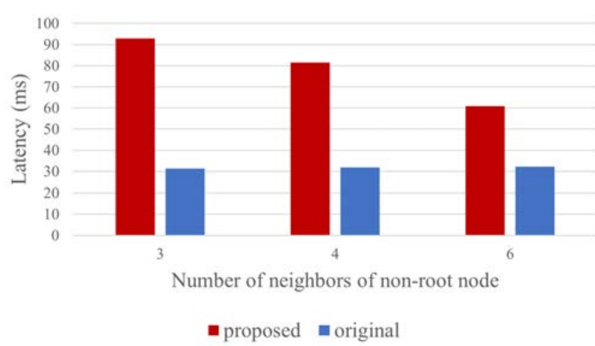

Fig. 9. Average latency according to the number of neighboring nodes

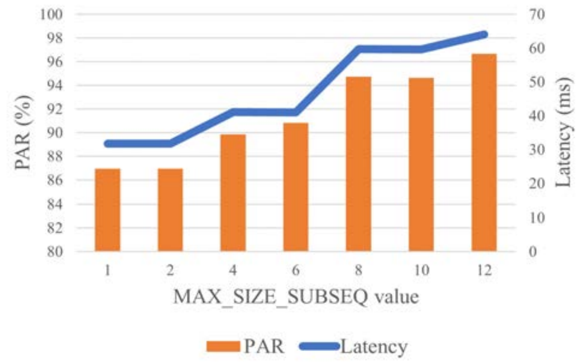

Fig. 10. Average PAR and latency according to the subsequence size limit

C. Comparison of performance according to the limited number of subslots

The maximum size of the unicast subsequence of the proposed scheme is limited to the MAX_SIZE_SUBSEQ value. Reducing this value increases the probability of considering a detectable neighbor for each subslot and increases the node's transmission opportunity.

Fig. 10 shows the average PAR and latency of the proposed method according to the MAX_SIZE_SUBSEQ parameter value. As the parameter value decreases, the average PAR decreases, but the average latency also decreases. When the parameter value is 1, the performance is similar to the original method. Therefore, in the proposed method, PAR and latency can be adjusted using this parameter value. Optimal performance can be found by adjusting parameters according to traffic load and node density.

V. CONCLUSION

Wi-SUN FAN is a global standard wireless communication technology suitable for building large-scale multi-hop networks in various infrastructures. Robust network operation is possible using CSMA/CA based MAC protocol and neighbor synchronized channel hopping sequence. However, packet collisions due to HNP between nodes with the same RPL-preferred parent in high-traffic networks are still a problem to be resolved. We propose a unicast subslot scheduling scheme to solve this problem and secure a high traffic transmission success rate. The proposed method shows high PAR even in a high traffic environment, but there is a trade-off in that latency increases. In the future, it will be possible to conduct research on finding the optimal performance by adjusting parameters according to node density and traffic load.

ACKNOWLEDGMENT

This research was supported by the MSIT(Ministry of Science and ICT), Korea, under the Grand Information Technology Research Center support program(IITP-2022-2016-0-00318) supervised by the IITP(Institute for Information & communications Technology Planning & Evaluation)

This work was supported by Institute of Information & communications Technology Planning & Evaluation(IITP) grant funded by the Korea government(MSIT) (No. 2020-0-01450, Artificial Intelligence Convergence Research Center [Pusan National University])

REFERENCES

[1] "IEEE Standard for Low-Rate Wireless Networks," in IEEE Std 802.15.4-2015 (Revision of IEEE Std 802.15.4-2011) , vol., no., pp.1-709, 22 April 2016, doi: 10.1109/IEEESTD.2016.7460875.

[2] H. Harada, K. Mizutani, J. Fujiwara, K. Mochizuki, K. Obata and R. Okumura, "IEEE 802.15.4g Based Wi-SUN Communication Systems," IEICE Trans. Commun, vol. E100-B, no. 7, pp. 1032-1043, July 2017.

[3] Wi-SUN Alliance, [online] Available: https://www.wi-sun.org

[4] "Field Area Network (FAN) Technical Overview," Wi-SUN Alliance FAN 1.0 Overview, [online] Available: https://wi-sun.org/download/fan-1-0-overview/

[5] S. Deering and R. Hinden, "Internet Protocol Version 6 (IPv6) Specification," IETF RFC 2460, Dec. 1998.

[6] T. Winter et al., "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks," IETF RFC 6550, Mar. 2012.

[7] A. Rahman and P. Gburzynski, "Hidden Problems with the Hidden Node Problem," 23rd Biennial Symposium on Communications, 2006, 2006, pp. 270-273, doi: 10.1109/BSC.2006.1644620.

[8] D. Hotta, R. Okumura, K. Mizutani and H. Harada, "Stabilization of Multi-Hop Routing Construction in Wi-SUN FAN Systems," 2020 IEEE 17th Annual Consumer Communications & Networking Conference (CCNC), 2020, pp. 1-6, doi: 10.1109/CCNC46108.2020.9045471.

[9] R. Wayong, R. Okumura, K. Mizutani and H. Harada, "A Routing Protocol toward Reliable Mobile Communication in Wi-SUN FAN," 2021 IEEE 18th Annual Consumer Communications & Networking Conference (CCNC), 2021, pp. 1-6, doi: 10.1109/CCNC49032.2021.9369584.

[10] R. Wayong, R. Okumura, K. Mizutani and H. Harada, "A Scheduling Scheme For Channel Hopping In Wi-Sun Fan Systems Toward Data Throughput Enhancement," 2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring), 2020, pp. 1-5, doi: 10.1109/VTC2020-Spring48590.2020.9128591.

[11] R. Hirakawa, R. Okumura, K. Mizutani and H. Harada, "A Novel Routing Method with Load-Balancing in Wi-SUN FAN Network," 2021 IEEE 7th World Forum on Internet of Things (WF-IoT), 2021, pp. 362-367, doi: 10.1109/WF-IoT51360.2021.9595050.

[12] X. Ni, M. Baddeley, N. Jiang and Y. Jin, "A Self-Configurable Grouping Method for Integrated Wi-SUN FAN and TSCH-based Networks," 2021 IEEE 32nd Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), 2021, pp. 1079-1084, doi: 10.1109/PIMRC50174.2021.9569431.

[13] P. Thubert, "An Architecture for IPv6 over the TSCH mode of IEEE 802.15.4", Internet Engineering Task Force Internet-Draft draft-ietf-6tisch-architecture-30, May. 2021, [online] Available: https://datatracker.ietf.org/doc/html/draft-ietf-6tisch-architecture-30.

[14] A. Dunkels, B. Gronvall and T. Voigt, "Contiki - a lightweight and flexible operating system for tiny networked sensors," 29th Annual IEEE International Conference on Local Computer Networks, 2004, pp. 455-462, doi: 10.1109/LCN.2004.38.

[15] F. Osterlind, A. Dunkels, J. Eriksson, N. Finne and T. Voigt, "Cross-Level Sensor Network Simulation with COOJA," Proceedings. 2006 31st IEEE Conference on Local Computer Networks, 2006, pp. 641-648, doi: 10.1109/LCN.2006.322172.