JCSE Journal of Computing Science and Engineering

Regular Paper

Journal of Computing Science and Engineering,
Vol. 14, No. 2, June 2020, pp. 76-87

A Local Channel Blacklisting Method Using Adaptive Channel-Quality Estimation in TSCH-Based Wireless Sensor Networks

Kihoon Jeon, Sanghwa Chung*, and Donghwa Yoo
Department of Electrical, Electronic and Computer Engineering, Pusan National University, Busan, Korea
gnsjkr@gmail.com, shchung@pusan.ac.kr, donghwayoo@pusan.ac.kr

Abstract

Owing to the development of the Internet of Things (IoT) paradigm, the energy consumption of devices and the reliability of communication have become important issues. Enhanced TSCH technology introduces a technique to select high-quality channels by using energy detection in the TSCH protocol to improve the reliability of communication in a dynamic environment where interference changes. However, it is difficult to apply ETSCH technology to a multi-hop network because the node that performs energy detection consumes more energy than the node that does not. In this article, we propose an adaptive channel-quality estimation (ACE), which flexibly adjusts the duty cycle of energy detection according to whether interference dynamically changes or not. ACEs are generally applicable regardless of the degree of change of interference, which improves energy efficiency. Also, we present ACE-blacklisting based TSCH (ACEB-TSCH) that uses ACE and local channel blacklisting to blacklist the wireless channel based on energy detection in a multi-hop network. Experimental results show that ACEB-TSCH has a performance improvement of 15.94% over TSCH and 8.59% over PDR-blacklisting based TSCH.

Category: Network and Communications

Keywords: IEEE 802.15.4; IEEE 802.15.4e TSCH; Internet of Things; ETSCH; Wireless channel blacklisting

I. INTRODUCTION

A. Background

In a wireless sensor network (WSN), wireless sensor modules communicate with each other and exchange data. Each sensor node gauges some conditions, such as humidity and temperature, and transmits measured data to the sink node through wireless communication. Wireless communication is a core technology of Internet of Things (IoT) as it is less expensive to set it up, more portable, and convenient than wired communication.

IEEE 802.15.4 [1] defines the MAC layer and the PHY layer in low rate wireless personal area networks (LR-WPAN). This standard is designed for reliable, low power, and low-speed wireless communications. For use in wireless embedded Internet, such as WSNs, this standard has the advantage of being energy efficient and lightweight. Based on IEEE 802.15.4, IEEE 802.15.4e TSCH (i.e., Time Slotted Channel Hopping) mode [2], which is a MAC layer that further improves performance in IEEE 802.15.4, has been proposed.

In TSCH, the nodes synchronized in the network communicate with each other in a timeslot and hop multiple channels. It is aimed at low power communication, improvement of network throughput and reliability of

Open Access http://dx.doi.org/10.5626/JCSE.2020.14.2.76 http://jcse.kiise.org

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Received 16 February 2020 ; **Revised** 14 June 2020; **Accepted** 19 June 2020

*Corresponding Author

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pISSN: 1976-4677 eISSN: 2093-8020

communication, and a noise-resistant wireless sensor network. The TSCH discretizes time into timeslots, hopping several radio channels. By performing frequency hopping, a WSN that is robust against wireless interference such as multipath fading can be configured, thereby leading to improvement in the reliability of communication. The IEEE 802.15.4 Standard defines 16 channels in the 2.4 GHz non-license ISM band. To communicate with the desired channel at the desired time, the node must be synchronized with the other node and aware of its schedule.

The 2.4-GHz band does not require a license; thus, many wireless technologies can use it. Cross-technology interference can be raised by technologies using 2.4 GHz. Many things use the 2.4 GHz ISM band, such as Wi-Fi, Bluetooth, and microwave ovens, and because of the license-free property, many wireless technologies to be devised can use the 2.4 GHz band. The IEEE 802.15.4e TSCH mode can improve the reliability of communication by intentionally excluding channels with heavy radio interference. The technology that implements this is enhanced TSCH (ETSCH) [3] protocol. ETSCH estimates the quality of each channel through energy detection (ED) that can be performed by the transceiver, such that it can communicate with some nodes through the channels which are of good quality and improve the reliability of communication.

In addition to TSCH, ETSCH implements two techniques, a non-intrusive channel-quality estimation (NICE) technique and an enhanced beacon sequence list (EBSL). NICE estimates the channel-quality by performing EDs during the silent period in the timeslot and reduces the hopping sequence list (HSL) update period by solving the channel sampling period problem that is affected by the slot-frame size. At this point, ED is performed for every timeslot. Based on the channel-quality, a good channel is extracted. Whitelisted channels that are included in the updated HSL are the channel hopping resources used for communications. NICE enables high-reliability communication in a dynamic environment without interfering with network throughput because it can be performed separately from communication by performing ED in the idle period. Fig. 1 is a timeslot structure defined in the standard. The idle periods (macTsTxOffset, macTsRxOffset) can be checked requiring acknowledgement [2].

Enhanced beacon (EB) is a packet that transmits information about a network to nodes by broadcast and enables participation in it. In ETSCH, EB delivers a list of high-quality channels generated by the PAN Coordinator (or sink node). If an EB loss occurs owing to external interference and the channel list is not properly transmitted to other nodes, HSL mismatch happens and the reliability of communication can be reduced. EBSL is a technique that uses a dedicated channel list for EB to reduce EB loss.

In this article, we propose an adaptive channel-quality estimation (ACE) that adjusts the duty cycle of EDs, and an ACEB-TSCH (ACE-blacklisting based TSCH) that includes local channel blacklisting. Through the ACEB-TSCH, the NICE scheme of ETSCH can be extended to multi-hop network scenarios such as industrial IoT networks.

The rest of the article is organized as follows. In Section II, TSMP, which is the underlying mechanism of the TSCH protocol, the general concept of TSCH, and ATSCH and ETSCH, which introduced ED-based blacklisting, are described. In Section III, interference dynamicity, ACE, local channel blacklisting techniques, and ACEB-TSCH are proposed. Section IV describes the experimental setup for verifying the ACE and ACEB-TSCH. In Section V, we analyze the performance of the results of the two experiments. Section VI concludes the article.

B. Objectives

The main concepts and goals of the ACEB-TSCH are as follows:

- Hardware-based channel-quality estimation such as ETSCH: Blacklists can be made through channel-quality estimation using EDs.

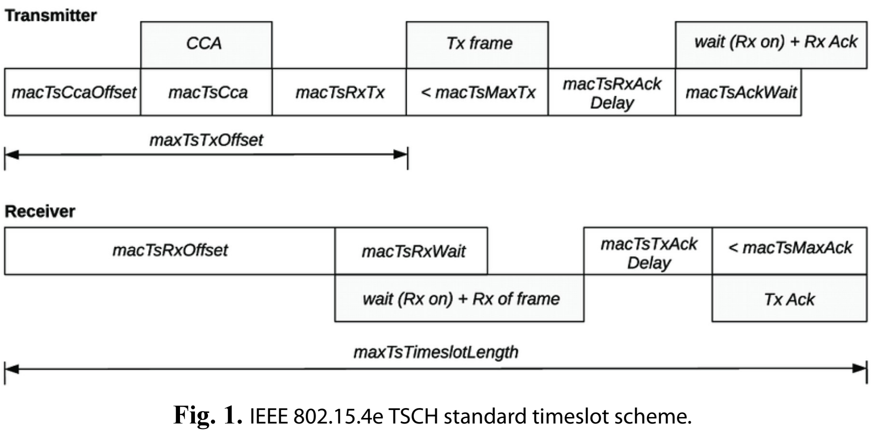


Fig. 1. IEEE 802.15.4e TSCH standard timeslot scheme.

- Channel selection technique: To decide how to express blacklist of communication links formed by two nodes, a channel should be selected considering the local blacklist of two nodes. Before that, it is necessary to devise a way to exchange blacklists between the nodes.
- Expansion of NICE to multi-hop network: Ultimately, it is aimed at expanding and applying the NICE technique of ETSCH to multi-hop network.
- Adjustment of the duty cycle of EDs based on interference dynamicity: This prevents unwanted energy consumption.

II. RELATED WORK

A. TSMP

Time synchronized mesh protocol (TSMP) [4] is the source of the IEEE 802.15.4e TSCH protocol and is characterized by high reliability and low power. The concept of synchronized communication, timeslot, and channel hopping of TSCH was derived from TSMP. The IEEE 802.15.4e TSCH mode is based on TSMP and defines more specifically the MAC layer protocol. Other examples of the concept of TSMP include WirelessHART [5], ISA100.11a [6], and Bluetooth [7].

B. IEEE 802.15.4e TSCH

Figs. 2 and 3 show the 15.4e TSCH protocol communication mechanism. In TSCH, two nodes communicate with each other in a predetermined band and in a predetermined time zone. That is, the time axis is divided into timeslots, and two nodes communicate at a timeslot offset and a channel offset. After the TSCH network is created, a number indicating a specific time point is assigned to the timeslot. This number is the ASN (absolute sequence number) and is defined as 5 bytes in the standard. The ASN is assigned to a timeslot by increasing by 1. A slotframe, which is a unit of a group for timeslots, is repeated. The schedule of the link may be determined by the channel offset and the slot offset and may also be referred to as a cell. The link consists of a Tx node sending a packet and an Rx node receiving that packet. At a point in time, a node either sends a packet, receives it, or sleeps. The 16 wireless channels, 11 to 26 channels of the 2.4 GHz band defined in the IEEE 802.15.4 standard, can be used. In TSCH protocol, a dedicated slot between nodes can be allocated by timeslot scheduling. For example, in Fig. 3, at timeslot offset 0 and channel offset 0, B has a schedule to send packets to A, and A has a schedule to receive packets from B. This is also shown in the network graph in Fig. 2. That is, a cell of the scheduling table corresponds to an edge of the network graph. In the general TSCH protocol, the physical channel is selected by the blind hopping method. Blind hopping is theoretically chosen arbitrarily with all the frequencies being uniformly distributed during communication. This may reduce the decrease in reliability of communication due to the effects of external interference or multipath fading. A typical channel selection technique used in the TSCH protocol is shown in Eq. (1).

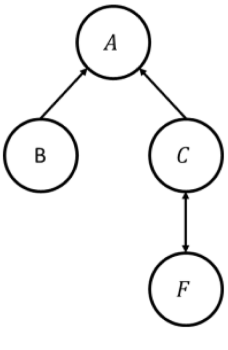
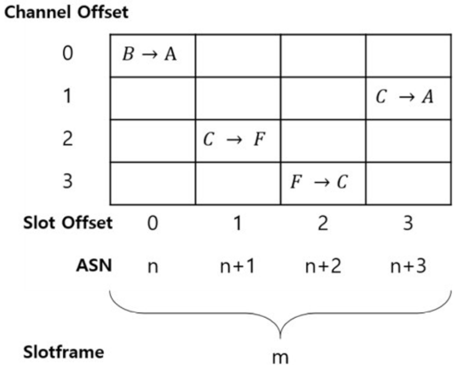


Fig. 2. Example of IEEE 802.15.4e TSCH network topology.



Channel Offset				
0	$B \rightarrow A$			
1				$C \rightarrow A$
2		$C \rightarrow F$		
3			$F \rightarrow C$	
Slot Offset	0	1	2	3
ASN	n	n+1	n+2	n+3

Fig. 3. Example of IEEE 802.15.4e TSCH schedule table.

$$Channel = HSL[(ASN + ChannelOffset)\%16] \quad (1)$$

Eq. (1) plays a role in mapping the channel offset appearing in the schedule to a physical channel to be used for actual communication. The ASN is shared by all the synchronized nodes and increases by 1 with each timeslot increase as the network has already started. Channel offset can be selected from 0 to 15. HSL is a table that holds the available channels, 11 to 26. This means that the ASN has a unique value at a specific timeslot, thus communication can be performed simultaneously using up to 16 channels in the timeslot.

C. Adaptive TSCH

Adaptive TSCH (ATSCH) [8] utilizes the received signal strength indicator (RSSI) value through ED in the radio transceiver to estimate the quality of the radio channel. Based on this, ATSCH excludes low-quality wireless channels and secures the reliability of wireless communication by communicating with high-quality channels.

D. Enhanced TSCH

ETSCH [3] proposed the NICE and EBSL to solve the problems of ATSCH.

ATSCH defines a timeslot for performing ED and performs ED only in that timeslot. However, because this reduces the available timeslots, which is the network resources, ETSCH can devise a NICE to perform ED in an idle period of a timeslot, thereby not reducing the network throughput.

In the present work, two experiments were conducted. One compared the performance of the energy efficiency of TSCH, ETSCH, and ETSCH with ACE, and the other was the reliability of communication of general TSCH, PDR-blacklisting based TSCH, which implements Multi-Arm Bandit link estimation and distributed blacklist negotiation of MABO-TSCH and ACEB-TSCH.

III. ACEB-TSCH

The ACEB-TSCH communicates by blacklisting bad-quality channels, based on ED in addition to general TSCH protocol in multi-hop network environments. ACEB-TSCH uses a NICE technique of ETSCH to perform ED. Because ETSCH has a 100% duty cycle of ED, that is, ED is performed in every timeslot, a technique capable of controlling the duty cycle according to a specific policy is required to prevent unnecessary energy consumption due to ED. To solve this problem, ACE was proposed as a preliminary work [9]. ACEB-TSCH advances is based on the NICE technique of ETSCH and ACE in terms of expanding those to multi-hop networks. If the change in the channel-qualities is dynamic, the frequency of ED is increased for a quick update of the channel-qualities, and if the change in the channel-qualities is not dynamic, the frequency of ED is reduced to prevent unnecessary energy consumption by ED. Fig. 4 simply expresses these concepts.

First, we describe interference dynamicity, which is a measure to determine whether the change in the interference is dynamic or not. We then present ACE that the duty cycle of EDs is adjusted based on interference dynamicity.

Thereafter, the local channel blacklisting technique for exchanging the blacklists between some nodes and selecting a physical channel to be used for communication, employing the exchanged blacklists, will be described. Finally, we propose ACEB-TSCH, which manages ACE and local channel blacklisting technique.

A. Interference Dynamicity

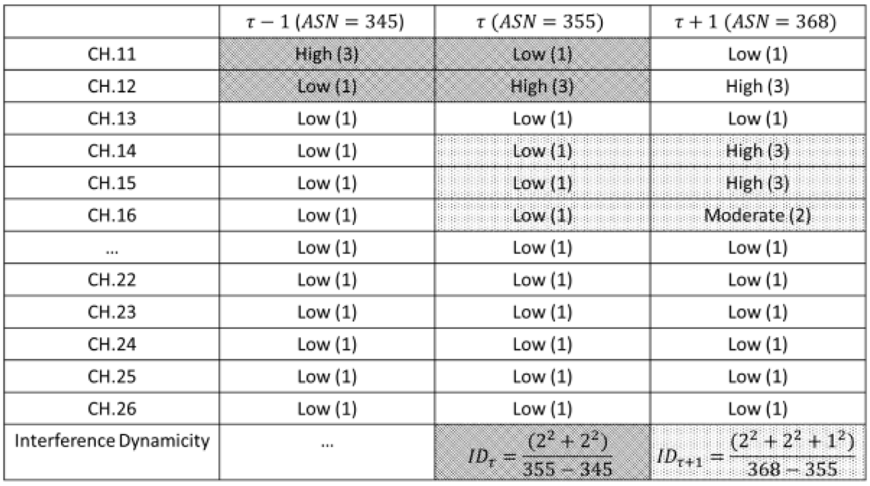
Channel quality estimation (CQE) presented by ATSCH [8] is a measuring technique that employs a simple exponential smoothing technique [10] to average RSSI values. Energy detection can be performed to measure the RSSI value and the equation of CQE is as follows:

$$CQE_\tau(ch) = \alpha ED_\tau(ch) + (1 - \alpha) CQE_{\tau-1}(ch) \qquad (2)$$

$ED_\tau(ch)$ is the RSSI value of the channel that is measured by energy detection at time τ. $CQE_\tau(ch)$ denotes the calculated CQE value of the channel *ch* at the time τ and the exponential smoothing coefficient α can be used to control the degree of reflection of the measured RSSI value in the CQE.

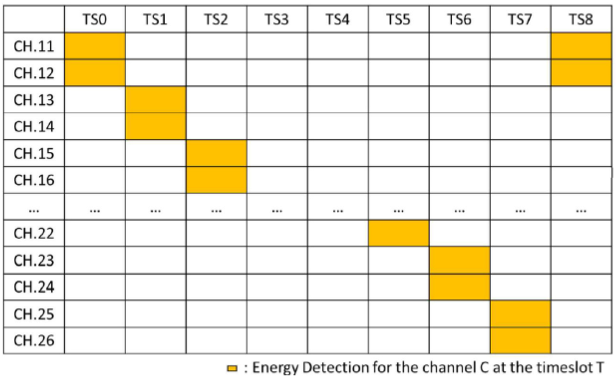
Interference dynamicity can be used to determine whether the change in interference is dynamic or less dynamic based on the CQE value. The equation is as follows:

$$ID_\tau = \Sigma_{i=11}^{26} \frac{\{CQE_\tau(ch_i) - CQE_{\tau-1}(ch_i)\}^2}{ASN_\tau - ASN_{\tau-1}} \qquad (3)$$



	$\tau - 1\ (ASN = 345)$	$\tau\ (ASN = 355)$	$\tau + 1\ (ASN = 368)$
CH.11	High (3)	Low (1)	Low (1)
CH.12	Low (1)	High (3)	High (3)
CH.13	Low (1)	Low (1)	Low (1)
CH.14	Low (1)	Low (1)	High (3)
CH.15	Low (1)	Low (1)	High (3)
CH.16	Low (1)	Low (1)	Moderate (2)
...	Low (1)	Low (1)	Low (1)
CH.22	Low (1)	Low (1)	Low (1)
CH.23	Low (1)	Low (1)	Low (1)
CH.24	Low (1)	Low (1)	Low (1)
CH.25	Low (1)	Low (1)	Low (1)
CH.26	Low (1)	Low (1)	Low (1)
Interference Dynamicity	...	$ID_\tau = \frac{(2^2 + 2^2)}{355 - 345}$	$ID_{\tau+1} = \frac{(2^2 + 2^2 + 1^2)}{368 - 355}$

Fig. 4. Example of calculating interference dynamicity.



	TS0	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8
CH.11	🟨								🟨
CH.12	🟨								🟨
CH.13		🟨							
CH.14		🟨							
CH.15			🟨						
CH.16			🟨						
...	...	...	...	...	...	...	...	...	...
CH.22						🟨			
CH.23							🟨		
CH.24							🟨		
CH.25								🟨	
CH.26								🟨	

🟨 : Energy Detection for the channel C at the timeslot T

Fig. 5. Performance of energy detection for 16 IEEE 802.15.4 channels.

Fig. 4 shows a simplified example of the calculation of interference dynamicity. In Fig. 4, the CQE value is shown as three values, high (3), moderate (2), and low (1) to simplify the example and CQE value is increased in the high intensity of the interference. At time τ, the CQE value of the channel 11 changed from high to low, and the CQE value of channel 12 changed from low to high. The degree of change is $(3 - 1)^2 = 2^2$ for both the channels and that of other channels is 0. The sum of these values can be used to calculate the total variation in the CQE values. ID_τ can be calculated by dividing the total change amount by the ASN difference between the time τ and the time $\tau - 1$, i.e., the time taken for the CQE value to change. At the time $\tau + 1$, the CQE values of channels 14 and 15 changed from low to high, and the CQE value of channel 16 changed from low to moderate. The degree of change is 2^2, 2^2, and 2^1 for channels 14, 15, and 16, respectively, and the change amount for the remaining channels is 0. The total change in the CQE value can be obtained by summing all of them, and $ID_{\tau+1}$ can be calculated by dividing the total change amount by the ASN difference between the time $\tau + 1$ and the time τ.

The time required to perform ED on one channel is 128 μs [1]. ETSCH shows that it is theoretically possible to perform ED 3 times in the Tx timeslot and twice in the Rx timeslot. Our experiments on energy efficiency for ACE is conducted twice regardless of the type of the timeslot. Fig. 5 shows how to perform energy detection for each channel in each timeslot. The time taken to scan all the channels is 8 timeslots. In the experiment, the length of one timeslot is defined as 15 ms, and the ACE scans the total channel for every ED period (the ED period will be explained later).

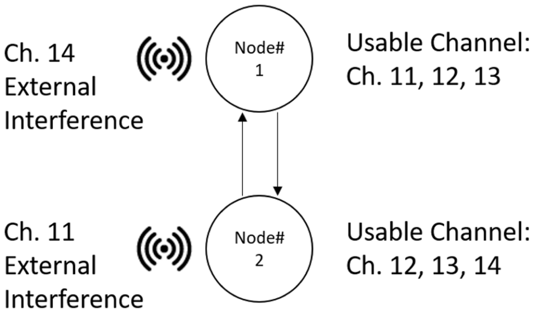


Fig. 6. Example with different blacklist between nodes.

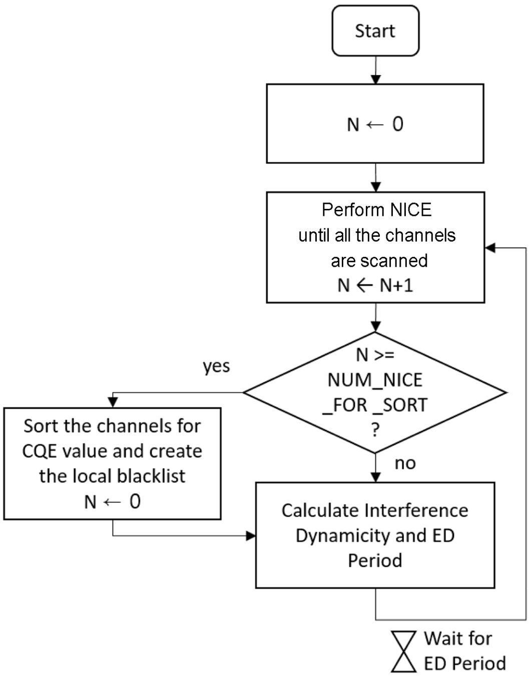


Fig. 7. Flowchart of ACE.

B. Adaptive Channel-Quality Estimation

ACE reduces the ED period if the interference dynamicity value is large and increases the ED period when the interference dynamicity value is small. Fig. 6 shows the working of ACE. First, NICE is performed to measure the channel-qualities of 16 channels and it takes 8 timeslots. Based on the measured CQE values, interference dynamicity is calculated for the entire channels and the ED period is produced. After that, it waits without performing ED during the calculated interval. N and NUM_NICE_FOR_SORT shown in Fig. 7 are related to the number of performing NICE for all channels. Each time 16 channels are energy detected, N increases by 1. When the N value reaches NUM_NICE_FOR_SORT, the channels are sorted based on the CQE value to generate a blacklist that excludes low-quality channels. This implies that blacklisting occurs periodically.

C. Local Channel Blacklisting

As the quality of a wireless channel depends on space, blacklist management associated with a link is required in accordance with an area where a pair of nodes to be communicated is located. Considerations for implementing local channel blacklisting are as follows:

- How to express Blacklist Information.
- How can blacklist be generated in association with the links?
- How to choose the physical channel to be used for communication considering the blacklists?
- How can a blacklist be managed in a distributed manner?

First, we describe how to express blacklist information. Second, we illustrate how to create a blacklist between nodes and select the physical channel to be used for communication. Last, we explain how to exchange blacklists between the nodes.

1) Blacklist Information

There can be several ways of representing blacklist information. In this article, we have used 2-byte blacklist information using one bit per wireless channel [11]. Fig. 7 shows how data is represented by blacklist information. Each bit of the 2-byte blacklist information indicates whether the channel is blacklisted or not. It has a value of 1 if the channel is blacklisted, and a value of 0 if it is not. Each node communicates by excluding the n low-quality channels (blacklisting) and by sorting the measured CQE values using channel-quality estimation through ED.

2) Link-Associated Blacklist and Channel Selection

Link-Associated Blacklist introduces the link-mask concept proposed by ATSCH [8]. Link-mask is a concept that starts from the fact that there is no guarantee that the measured CQE value at the node will have the same CQE value at the other nodes to communicate with. Fig. 8 is an example showing that a pair of communicating nodes can generate different blacklists. For easy understanding, if blacklist length is 1, and channels are 11, 12, 13, and 14, a total of four node 1 will be subject to external interference of channel 14 nearby, thus the blacklist contains channel 14, and channels 11, 12, and 13 are usable. Because node 2 is subject to external interference of channel 11 in the vicinity, 11 is included in the blacklist and the available channels are 12, 13, and 14. Like this, the two nodes communicate with each other; however, the blacklists generated by each node may be different.

When each node has its local blacklist generated by ED, the link-mask is the intersection of the two blacklists [8] or a union. The physical channel to be used when communicating should be a channel that does not belong to the blacklist of the two nodes. Specifically, a channel in which the corresponding bit of the link-mask is 0 is used as a physical channel. However, as the link-mask, which is the union of the blacklists of two nodes, may cause exhaustion of channel resources, the size of the blacklist should be limited to less than 8. In the present work, we have set the blacklist length to 10 and implemented the link-mask with the intersection of a blacklist of two nodes.

Next, the channel can be selected using the generated link-mask. The channel selection algorithm is shown in Algorithm 1.

Algorithm 1 Channel selection

```
$ch \leftarrow HSL[(ASN + ChannelOffset)\%16]$
**if** Current timeslot is dedicated slot of n1, n2 **then**
    **while** $(ch \in \mathrm{n1}.BL_{using})\&(ch \in \mathrm{n2}.BL_{using})$ **do**
        $ch \leftarrow (ch+1)\%16$
    **end while**
    **return** 11 + $ch$
**else**
    **return** 11 + $ch$
**end if**
```

First, a channel is selected in a manner of selecting from a general TSCH protocol, and then it is confirmed whether the current timeslot is a dedicated slot of the node itself. In the case of a dedicated slot, the channel is incremented by 1 and a channel having a corresponding bit of 0 in the link-mask, explicitly, a channel of good quality, is selected, and communication is performed. If it is not a dedicated slot, the channel selection method of the general TSCH protocol is followed.

3) Blacklist Exchange

The blacklist exchange algorithm allows a pair of nodes to exchange their local blacklists. Here, in order to minimize the additional overhead for exchanging blacklists, we have included the blacklist in the unicast packet, which occurs in existing UDP data packets or control packets sent to improve or maintain routes in a routing protocol, such as RPL. In the case of a unicast message, when a transmitting node sends a data frame, the receiving node receives a data frame and sends an Ack frame. The blacklist exchange algorithm works by sending the local blacklist of the sender together with the data frame and sending the local blacklist of the receiver together with the Ack frame. Algorithms 2 and 3 show the blacklist

Channel bit	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Blacklisted?	0	0	1	1	1	1	1	0	0	0	0	0	1	1	1	1

Blacklist Information: 0x3E0F (0b0011111000001111)

Fig. 8. Example of blacklist information on how to exchange blacklists between the nodes.

exchange algorithm for the transmitter and the receiver, respectively.

Algorithms 2 Blacklist Exchange (Tx)

```
When timeslot starts, consider the local blacklist of Tx, Rx node
$BL_{local}$←the most recent local blacklist information of the transmitter
Transmit the data frame which includes $BL_{local}$
if the ack frame is received successfully then
    $BL_{neighbor}$←the local blacklist information included in the ack frame
    $neighborRow_{RxNode}.BL_{local}$←$BL_{local}$
    $neighborRow_{RxNode}.BL_{neighbor}$←$BL_{neighbor}$
end if
```

Algorithms 3 Blacklist Exchange (Rx)

```
When timeslot starts, consider the local blacklist of Tx, Rx node
if the data frame is received successfully then
    $BL_{local}$←the most recent local blacklist information of the receiver
    $BL_{neighbor}$←the local blacklist information included in the data frame
    Transmit the ack frame which includes $BL_{local}$
    $neighborRow_{TxNode}.BL_{local}$←$BL_{local}$
    $neighborRow_{TxNode}.BL_{neighbor}$←$BL_{neighbor}$
end if
```

D. Implementation

ACEB-TSCH is implemented using the ACE and the local channel blacklisting technique. Fig. 9 shows the flow of ACEB-TSCH. Fig. 6 shows the mechanism by which a local blacklist is generated. In a state in which the local blacklist is periodically updated, ACEB-TSCH confirms whether the timeslot is a dedicated slot. Unicast packets are transmitted unconditionally in dedicated slots.

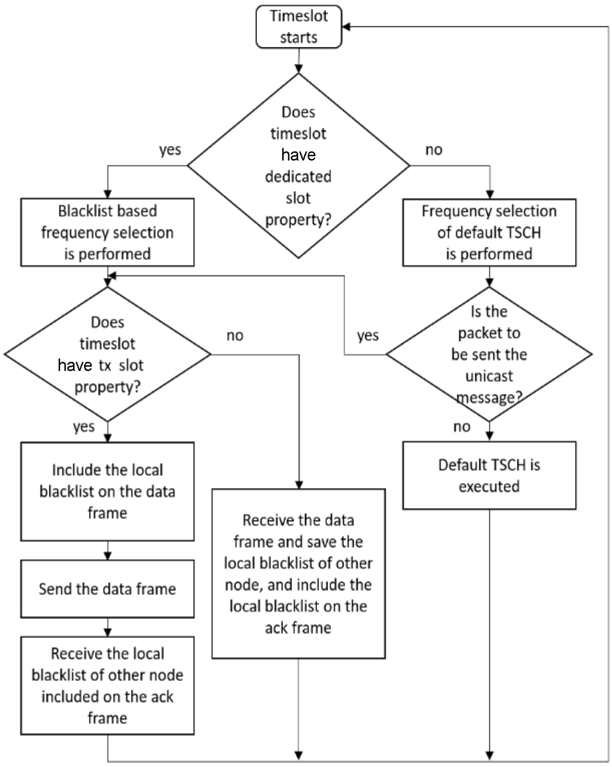


Fig. 9. Flowchart of ACEB-TSCH.

If it is a dedicated slot, perform channel selection referring to link-mask. In the case of a dedicated Tx slot of the node itself, the data frame is carried with 2-byte blacklist information. The local blacklist of the correspondent node contained in the Ack frame is then stored, and the link-mask can be generated based on the local blacklist. When the node itself is a dedicated Rx slot, it listens to receive the data frame. When receiving the data frame, it stores the local blacklist of the Tx node and sends its local blacklist to the Ack frame.

IV. PERFORMANCE ANALYSIS

A. Adaptive Channel-Quality Estimation

The experiments were performed to compare ETSCH with ACE with general TSCH and ETSCH. For this experiment, we implemented the ACE using the OpenWSN [12] project. OpenWSN stack consists of IEEE 802.15.4 [1], IEEE 802.15.4e [2], RPL [13], 6LoWPAN [14], and CoAP [15]. It was implemented using the OpenMote-CC2538 board. These motes were placed in a 9 m × 6 m workspace randomly. The transmission power was 0 dBm and the timeslot duration was 15 ms. In this experiment, ED was set to be performed twice, regardless of the type of timeslot. In the experiment, a sink node communicates with a sensor node. The sink node acts as an IPv6 gateway. One EB timeslot was allocated to transmit the enhanced beacon between the sink node and the sensor node, and one dedicated slot from the sensor to the sink was allocated to carry the packets. The sink node transmits the enhanced beacon in the EB timeslot every time. With parameter settings, the exponential smoothing coefficient was set to 1 to better reflect the latest CQE value. For ETSCH, HSL whitelisting was done every 20 EDs per channel. The noise generators were implemented to generate external interferences. In the implementation, we used an OpenMote-CC2538 and set the transmission power to 7 dBm. The hopping period of the channel was 1s. While the number of noise generators increased and the change of interference was made dynamic, the network reliability was measured accordingly.

In the ACE experiment, the reliability of communication was measured using PDR. The PDR was calculated by dividing the total number of packets sent from the sending node by the number of packets received at the receiving node.

Specifically, the implementation of ACE estimates the quality of 16 channels before computing the Interference Dynamicity. At this point, whitelisting (or blacklisting) was done and EBSL was updated.

Fig. 10 shows the reliability of the communication of

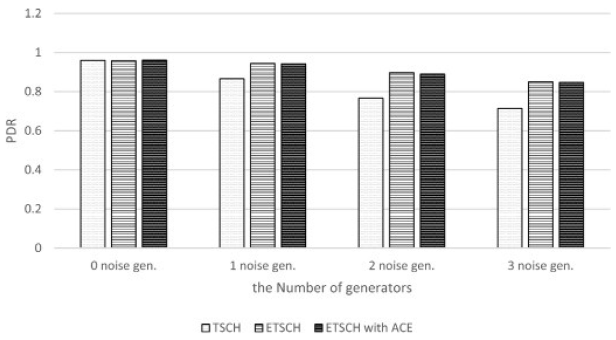


Fig. 10. Reliabilities of TSCH, ETSCH, and ETSCH with ACE under four external interference scenarios.

each technique under four interference scenarios. Generally, the more the number of noise generators is, the more dynamically the external interferences change and the less is the reliability of communication. TSCH shows that the greater the interference changes, the more the reliability of communication is degraded as compared to the other two techniques. Under four interference scenarios, ETSCH and ETSCH with ACE showed a similar PDR. This result implies that ETSCH consumes unnecessary energy to perform energy detection as compared with securing reliability of communication through ED.

Fig. 11 shows the duty cycle of EDs for ETSCH with the ACE technique. The more dynamic the change in interference, the greater is the duty cycle of EDs. The trend may be different depending on Eq. (5). Building on this duty cycle of EDs and the previously measured reliability, the energy consumed by the sink node can be measured. It is supposed that the sink node has one EB timeslot and seven RX timeslots and the seven sensor nodes have one EB timeslot to receive EB from the sink, and one TX timeslot to send to the sink, respectively. The nodes connect with star topology. The nodes always send packets to the sink node in the dedicated Tx timeslot of themselves. Herein, the energy consumption of the sink node in ETSCH is calculated as follows [3].

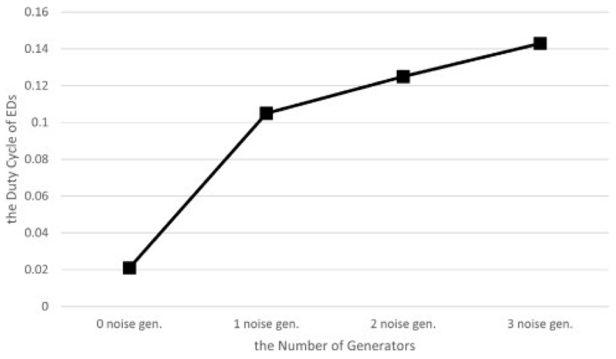


Fig. 11. ED duty-cycle of ETSCH with ACE under four interference environments.

Table 1. Symbols, meanings, and values of Eq. (4)

Symbol	Meaning	Value
ETX	Expected transmission count	1/PDR [16]
I_{ED}	Current of ED	20 mA [17]
N_{ED}	The number of ED	16
T_{ED}	Time of ED	128 us
I_{Rx}	Current of Rx	20 mA [17]
N_{Rx}	The number of Rx	7
I_{Tx}	Current of Tx	24 mA [17]
N_{Tx}	The number of Tx	1
T_{Tx}	Time of Tx per 1 byte	1.76 ms
V_{cc}	Voltage	3.3 V

$$E = [I_{ED}N_{ED}T_{ED} + ETX(I_{Rx}N_{Rx}T_{Tx}) + (I_{Tx}R_{Tx}T_{Tx})] \times V_{cc} \quad (4)$$

The meaning and value of each symbol are shown in Table 1. In Eq. (4), it is possible to calculate the energy consumption for the general TSCH by not considering the first term, related to energy consumption for performing ED. The energy consumption for ETSCH with ACE can be obtained by applying the duty cycle of EDs to Eq. (4).

Fig. 12 shows the energy consumption for each technique with increasing interference dynamicity. If the interference change is not severe, TSCH and ETSCH with ACE consume energy similarly because ETSCH with ACE perceives the degree of interference change and reduces the duty cycle of EDs. By controlling the frequency of EDs, it prevents unnecessary energy consumption. ETSCH, however, has much energy consumption because it always performs EDs in all the time slots. In the case of TSCH, if the change in interference is dynamic, the reliability is

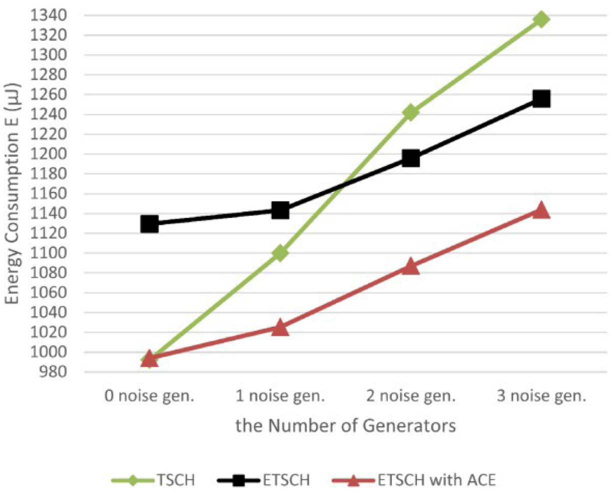


Fig. 12. Energy consumption of TSCH, ETSCH, and ETSCH with ACE under four interference scenarios.

lowered and the energy consumption is rapidly increased owing to packet retransmission. When the number of noise generators is 2, the interference dynamicity increases more and TSCH consumes more energy than ETSCH. ETSCH starts to gain an effect on EDs and the reliability of communication is higher. ETSCH reduces energy consumption than TSCH. This becomes more marked when the number of noise generators is 3. In Fig. 12, ETSCH with ACE shows that there is performance improvement in terms of energy consumption compared to ETSCH because it controls the duty cycle of EDs depending on the degree of interference change.

Fig. 13 shows the improvement in performance in terms of energy consumption for ETSCH with ACE versus other techniques when interference dynamicity changes. The performance is improved by 10.1% compared with ETSCH and 8.4% compared with TSCH on an average. ETSCH with ACE reduces the duty cycle of EDs when the change in interference is not dynamic. This is the reason why ETSCH with ACE improves the performance by 12% in terms of energy efficiency, compared to ETSCH when the noise generator is zero. Compared with TSCH, ETSCH with ACE degraded the performance by approximately 0.2% as it performs EDs at a small frequency. As interference dynamicity increases, the performance of the ETSCH with ACE becomes better than that of TSCH because the frequency of packet retransmission increases and the energy consumption becomes worse as the reliability of TSCH decreases. On the contrary, compared with the ETSCH, as the interference changes more dynamically, the improvement in the performance is less because ETSCH performs EDs at every time slot. In the case of ETSCH, as interference dynamicity increases, the performance of reliability and energy consumption are secured. However, in the experiment, ETSCH showed that the frequency of ED is excessively high compared to securing the reliability of communication. Also, the ETSCH demonstrated improvement in performance in the environment where the external interference change was severe. Thus, the energy consumption is increased in the place where the interference is not changed. This result is not important for the sink node. However, it is a problem when the ETSCH is applied to a multi-hop wireless sensor network, which is generally set up in a wide area other than the IVN. ACE provides a basis for extending the black-listing technique based on energy detection to wireless multi-hop networks.

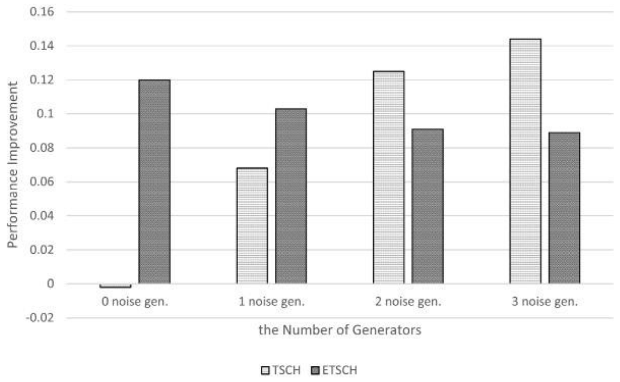


Fig. 13. Performance improvements of ETSCH with ACE compared to TSCH and ETSCH in terms of energy consumption.

B. ACEB-TSCH

Table 2 shows the parameter settings for the ACEB-TSCH experiments. In this experiment, OpenMote- CC2538 was used as in the ACE experiment. The implementation of PDR-blacklisting based TSCH refers to blacklist negotiation and Multi-Armed Bandit link estimation of MABO-TSCH [11]. The noise generators were implemented to hop to arbitrary channel once every 10 seconds. Figs. 14 and 15 are the RPL [13] routing tree and TSCH schedule table used in the ACEB-TSCH experiment, respectively. The schedule tables were created regarding the DeTAS [18] technique. Routing tree and schedule table apply to both general TSCH, PDR-blacklisting based TSCH, and ACEB-TSCH. The routing and scheduling were implemented with the static method.

Table 2. Parameter setting of the ACEB-TSCH experiments

Parameter	Value
Default TSCH	
Slotframe size	17
The number of SERIALRX	3
The number of shared slots	2
Timeslot duration (ms)	15
Packet queue size	10
Maximum retries	1
RPL DIO period (sec)	3
RPL DAO period (sec)	6
PDR-blacklisting based TSCH	
Blacklist size	10
Reward	10000
ACEB-TSCH	
Exponential smoothing coefficient	1
The number of ED per slot	1
Blacklist size	10
Etc.	
UDP packet period (sec)	1
Tx power of the noise generators (dBm)	7
Tx power of the nodes (dBm)	0

	0~1	2~4	5	6	7	8	9	10	11	12	13	14~16
0	SHARED	SERIAL RX	1	2	1	2	1	2	1	2	1	
1				3	5	3	5	3	6	4		
2			7		8	9						

Fig. 14. TSCH schedule used in ACEB-TSCH reliability of communication experiment.

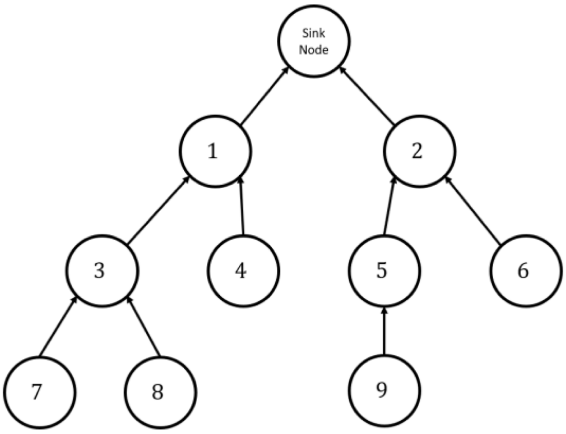


Fig. 15. RPL routing tree used in ACEB-TSCH reliability of communication experiment.

The experiment assumed a data collection application. All sensor nodes transmit UDP packets once per second toward the sink node, and the gateway with the sink node receives UDP packets to measure the reliability of communication.

Fig. 16 shows the reliabilities of TSCH, PDR-black listing based TSCH and ACEB-TSCH while increasing the number of noise generators causing external interference. The noise generators hop channels every 10 seconds. The reliability is measured using the ratio of the number of packets received at the sink node when the noise generator is N, and the number of packets received at the sink node when the noise generator is zero. Overall, the reliability of communication decreases as the number of noise generators increases. Especially in the case of TSCH, the reliability decrease is much larger compared to other techniques as the noise generator increases. For ACEB-TSCH, because the blacklist size is set to 10, high reliability of 96% is measured until the number of noise generators is 8. When the number of noise generators is 12, the number of low-quality channels exceeds the size of the blacklist, 10. Therefore, those low-quality channels are not blacklisted properly and the reliability decreases greatly. When the number of noise generators is 16, the reliability decreases more than that of 12 noise generators. In addition, PDR-blacklisting based TSCH is generally more reliable than TSCH; however, they are less reliable than ACEB-TSCH. Fig. 16 shows why the PDR-blacklisting TSCH is less reliable than the ACEB-TSCH.

Fig. 17 shows that the reliability of PDR-black listing based TSCH increases when there is an increase in the hopping period of 10 noise generators. This implies that the PDR-blacklisting based TSCH requires sufficient packet transmission samples to measure the correct PDR. As the hopping period increases, more samples are collected for measuring the PDR, such that a more accurate PDR is calculated and a more accurate blacklist is generated based on the calculated PDR, thereby naturally improving the reliability of communication. In Fig. 17, the reliability of the PDR-blacklisted TSCH is lowered compared to ACEB-TSCH because there are not enough samples of packet transmission to measure the correct PDR value. In addition, because the noise generator aims at a random channel every 10 seconds, it is difficult to generate a reliable blacklist as the number of samples is not sufficiently

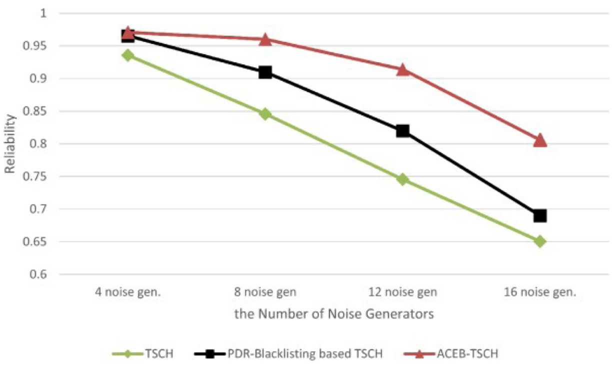


Fig. 16. Reliabilities of TSCH, PDR-blacklisting interference scenarios.

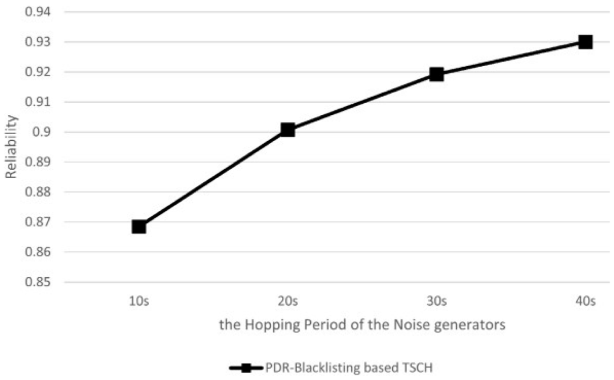


Fig. 17. Changes in reliabilities for PDR-blacklisting based TSCH depending on changes in the hopping period of 10 noise generators.

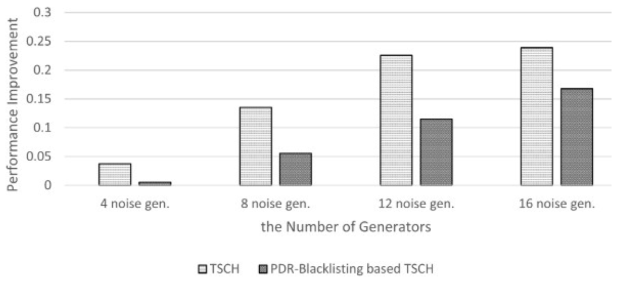


Fig. 18. Performance improvement of ACEB-TSCH compared to TSCH, PDR-blacklisting based TSCH in terms of reliability of communication.

collected, and the condition of external interferences changes before the accurate PDR is calculated. The ACEB-TSCH is superior to the PDR-blacklisting TSCH, as it can instantly determine whether the channel-quality is good or bad. It can also accurately generate blacklists in response to external interferences.

Fig. 18 shows the performance improvement of ACEB-TSCH compared to the rest of the techniques in terms of reliability of communication. The ACEB-TSCH shows an average improvement of 8.59% compared to the PDR-blacklisted TSCH, and 15.94% compared to TSCH.

V. CONCLUSION

ETSCH is difficult to apply to general wireless multi-hop networks. First, the entire area covered by the network is too wide for a sink node to perform the CQE. Based on the locality of the channel-quality, channel-quality mismatches occur depending on the region, which reduces the reliability of communication because of an inaccurate blacklist. Generating inaccurate blacklists can be prevented by measuring channel-quality in sensor nodes as well as the sink node. However, the energy detection policy of ETSCH is based on the assumption that only sink nodes perform ED. Since sensor nodes are energy-limited hardware, it is always unnecessary to consume energy for EDs. To modify the existing ETSCH 100% duty cycle of EDs policy, we propose interference dynamicity which determines whether external interference changes dynamically or not and propose ACE to control the duty cycle of EDs. In this way, it is possible to secure the reliability of communication and reduce unnecessary energy consumption in an environment where the changes in interferences are so severe to the extent that ED can be performed in the sensor node with limited energy. ACE reduces the duty cycle of EDs even under environments with low interference dynamicity, thereby reducing energy consumption. In other words, ACE is required to extend the ETSCH to a general wireless multi-hop network. The experiments with ACE show that the reliability of the communication is secured even if the duty cycle of ED is not maintained as much as that of ETSCH. Because of the ACE technique, the energy efficiency was improved by 8.4%, compared to general TSCH, and by 10.1% compared to ETSCH on an average.

Also, the experiments of ACEB-TSCH showed that the NICE technique of ETSCH is applied to a wireless multi-hop network. The reliability of communication using ACEB-TSCH can be obtained in an environment where external interference changes rapidly. The experimental results showed that the reliability of communication was improved by 8.59% compared to that of PDR-black listing based-TSCH, and by 15.94% compared with that of general TSCH.

In future work, research should be conducted for resolving the collision of communication between links within a communication range by considering both neighbor-aware communication scheduling and the blacklisting techniques.

ACKNOWLEDGMENTS

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20182020109660).

This work was also supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. NRF-2018R1D1A1B07049355).

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Kihoon Jeon

Kihoon Jeon received the B.E. and M.E. degrees in computer engineering from Pusan National University, Busan, Korea, in 2016 and 2018, respectively. He is currently a Senior Researcher with the SK Hynix, Icheon, Korea. His research interests include active industrial wireless sensor network, IoT, and future Internet.

Sanghwa Chung

Sanghwa Chung received the B.S. degree in electrical engineering from Seoul National University, Seoul, Korea, in 1985, the M.S. degree in computer engineering from Iowa State University, Ames, in 1988, and the Ph.D. degree in computer engineering from the University of Southern California, Los Angeles, in 1993. He was an Assistant Professor with the Department of Electrical and Computer Engineering, University of Central Florida, Orlando, from 1993 to 1994. He is currently a Professor with the Computer Engineering Department, Pusan National University, Busan, Korea. He is currently the head of Dong-Nam Grand ICT R&D Center in Busan, Korea. His research interests are in the areas of industrial wireless sensor networks, IoT, Future Internet, and SDN.

Donghwa Yoo

Donghwa Yoo received the B.E. and M.E. degrees in computer engineering from Pusan National University, Busan, Korea, in 2018 and 2020, respectively. He is currently a Senior Researcher with the KT, Seoul, Korea. His research interests include active industrial wireless sensor network, IoT, and future Internet.