Firmware Distribution with Erasure Code for IoT applications on IEEE 802.15.4g Mesh Network

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Abstract

Sub-1 GHz (920 MHz) frequency bands for LPWAN (Low Power Wide Area Network) wireless communications systems are attracting attention from various IoT applications. Environmental and infrastructure monitoring systems, such as smart meter, ground inclinometer, and bridge sensor, are widely deployed. With LPWAN wireless communication systems on 920 MHz bands having the features of long distance, low rate and low power consumption, a huge number of IoT devices distributed in wide area can be connected to communication networks. Although these networks can be configured in a star configuration for a relatively small area, the mesh configuration has been emerging recently. IEEE 802.15.4g-FSK PHY/OFDM PHY is a typical PHY technology in mesh networks for the purpose of transferring IoT application data over a wider area. When distributing the same data such as firmware to IoT devices during network operation, improving the efficiency of distribution method becomes critical. On the one hand, using broadcast transmission, the delivery confirmation cannot be performed. On the other hand, unicast transmission is very time consuming if the number of IoT devices is large. Therefore, we proposed a new firmware distribution method with erasure code for large number of IoT devices. Our computer simulation result shows that the proposed method improves the efficiency of distribution by 1.48 times compared with conventional method and achieves higher spectrum efficiency for IEEE 802.15.4g-OFDM PHY.

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Takenori Sumi[1,3], *Senior Member*, Yukimasa Nagai[1], *Senior Member*, Jianlin Guo[2], *Senior Member* and Hiroshi Mineno[3], *Senior Member*

[1]*Information Technology R&D Center,* Mitsubishi Electric Corporation
Kamakura, Japan
Sumi.Takenori@dc.MitsubishiElectric.co.jp
[2]*Mitsubishi Electric Research Laboratories*
Cambridge, USA
[3]*Graduate School of Science and Technology*, Shizuoka University
Shizuoka, Japan

***Abstract*— Sub-1 GHz (920 MHz) frequency bands for LPWAN (Low Power Wide Area Network) wireless communications systems are attracting attention from various IoT applications. Environmental and infrastructure monitoring systems, such as smart meter, ground inclinometer, and bridge sensor, are widely deployed. With LPWAN wireless communication systems on 920 MHz bands having the features of long distance, low rate and low power consumption, a huge number of IoT devices distributed in wide area can be connected to communication networks. Although these networks can be configured in a star configuration for a relatively small area, the mesh configuration has been emerging recently. IEEE 802.15.4g-FSK PHY/OFDM PHY is a typical PHY technology in mesh networks for the purpose of transferring IoT application data over a wider area. When distributing the same data such as firmware to IoT devices during network operation, improving the efficiency of distribution method becomes critical. On the one hand, using broadcast transmission, the delivery confirmation cannot be performed. On the other hand, unicast transmission is very time consuming if the number of IoT devices is large. Therefore, we proposed a new firmware distribution method with erasure code for large number of IoT devices. Our computer simulation result shows that the proposed method improves the efficiency of distribution by 1.48 times compared with conventional method and achieves higher spectrum efficiency for IEEE 802.15.4g-OFDM PHY.**

Keywords*— *IoT, Sub-1GHz OFDM PHY, wireless mesh networks, firmware distribution, IEEE 802.15.4g-OFDM PHY.

I. Introduction

920 MHz frequency bands for wireless communication systems are attracting attention from various IoT applications, e.g., environmental monitoring and infrastructure monitoring application for location, temperature, humidity and water level, smart metering, and ground inclinometer application. Wireless communication systems on 920 MHz (Sub-1 GHz) bands have the features of long distance, low rate and low power consumption for conventional standards, e.g., IEEE 802.15.4g [1], SigFox, Wi-SUN, IEEE 802.11ah/HaLow, and LoRaWAN. These standards have been deployed widely in the market. For long life IoT devices, the firmware update for a large number of IoT devices is also considered as new IoT application. Since 920 MHz bands have the features of long distance up to 1 km and several km extension in mesh networks, a large number of IoT devices are deployed in the area. When distributing the same data such as firmware to IoT devices during network operation, improving the efficiency of distribution method becomes an issue. For example, using broadcast transmission, the delivery confirmation cannot be performed, and unicast transmission takes a very long time if the number of IoT devices is large. Furthermore, power consumption is an issue for IoT devices that run on battery power when transmitted by unicast. Thus, firmware distribution for IoT devices using 920 MHz narrow bands is a challenge. Therefore, efficient firmware distribution method for large scale IoT networks needs to be investigated. We have studied firmware distribution method for low rate IEEE 802.15.4g FSK PHY [2]. However, IoT applications of higher data rates with OFDM PHY also need to be studied since the existing IoT systems operating with FSK PHY are expected to be replaced with OFDM PHY to support larger data. In this paper, we propose a firmware distribution method and evaluate the performance of our proposed firmware distribution method for IEEE 802.15.4g Mesh Network using OFDM PHY.

The rest of this paper is organized as follows. Section II presents related work. Section III describes the proposed firmware distribution method with erasure code. Section IV provides the simulation architecture and results for various conditions. Finally, we conclude our paper in Section V.

II. Related Work

There are existing researches for wireless communications using 920 MHz bands and firmware distribution. Since 920 MHz bands are narrow bands compared to 2.4 GHz and 5 GHz for ISM band, special regulation for "10 % transmission duty cycle" and "longer backoff mechanisms" are applied in specific regions.

Throughput performance has been demonstrated in [3] and [4], which focus on the PHY and MAC protocol enhancement for higher-throughput, protocol efficiency and delay via simulation and measurement result using prototypes. Japanese standard ARIB STA-T108 (20 mW, unlicensed) defines the use of IEEE 802.15.4g system from 920.5 – 928.1MHz (7.6 MHz bandwidth), but the ARIB STA-T107 (250 mW, passive system) and the ARIB STD-T108 (250mW, licensed/registered) also define operation from 920.5 – 923.5 MHz (3.0 MHz). Therefore, 923.5 – 928.1 MHz (4.6 MHz bandwidth) is the only reasonable frequency band for IEEE 802.15.4g applications in the unlicensed spectrum. It indicates that transmission efficiency is critical since multiple wireless systems may coexist in same area. IEEE 802.15.4g is regulated to operate over 200 kHz bandwidth channel in the Sub-1 GHz band. Even low duty cycle constraint applied in the Sub-1 GHz band, e.g., Japanese and European standard allow up to 10% transmission duty cycle for the number of IoT Devices increased with various standards. Therefore, ensuring higher efficiency for spectrum use in the Sub-1 GHz is clearly important. Furthermore, firmware distribution for IoT devices using 920 MHz with narrow band is a challenge. T. Fukuda, et al. propose effective firmware distribution methods for IoT using blockchain based technology [5]. Especially, a firmware distribution method that provides incentives for distributors to help with distribution to reduce the gas costs, using a smart contract and access control based on update records. However, issues specific to narrow bandwidth wireless networks and network configuration have not been considered. F. Ebbers, et al. described a large-scale analysis of IoT firmware version distribution [6]. The difficulties in updating firmware for IoT devices and the results of the analysis were described, but specific network solutions were not mentioned.

From the related work, the results of previous studies have not mentioned highly efficient firmware updates for IoT devices in the Sub-1 GHz band. Therefore, high efficiency firmware method is considered an important issue to consider for further proliferation of IoT devices in the futures.

III. Proposed Method

Firmware distribution to IoT devices requires sending the same firmware data to a large number of IoT devices via wireless communication networks. Firmware distribution using unicast transmission is inefficient because the same firmware data is sent to each device individually. Delivery confirmation is not performed when broadcast transmission is applied. As a result, both unicast and broadcast are unsuitable for firmware distribution, especially in large scale multi-hop networks. Therefore, it is considered more efficient to distribute to a large number of IoT devices using multicast. However, the delivery confirmation is an issue for multicast as well. It is difficult to deliver all firmware data to all IoT devices in a single transmission because wireless communication suffers from packet errors due to the dynamically varying received signal power and/or interference from other wireless systems. Even if multicast is used, individual retransmissions are required for error packets, and in an environment where many errors occur, there is no difference from unicast transmission with huge retransmission for error packets. Therefore, we propose a firmware packet transmission method that applies erasure code to firmware data to reduce the number of packet retransmissions and improve communication efficiency [2].

A. *Firmware Packet Transmission*

We consider a multi-hop IoT mesh network consisting of a network manager and a large number of IoT devices. The network manager is the source of the firmware data and the IoT devices are the destinations of the firmware data.

The proposed firmware transmission method involves two phases of operations, i.e., the neighbor discovery and the firmware distribution.

The neighbor discovery is performed so that each device including the network manager in the network knows its neighbors. Is to reduce the redundant packet transmission. The neighbor discovery can be done in different ways, e.g., using a specific neighbor discovery method such as a route discovery process or using the conventional request and response mechanism. An IoT network can be an ad hoc network. To ensure the latest neighbor information, network manager can initiate the neighbor discovery process before the firmware distribution.

Once the neighbor discovery is completed, the network is ready for firmware distribution. Initially, the network manager sets its firmware reception status as ‘yes’ and sets its neighbor’s firmware reception status as ‘no’, all IoT devices set their firmware reception status and their neighbor’s firmware reception status as ‘no’. This status will be dynamically updated as the firmware distribution process progresses. The network manager initiates the firmware distribution process by broadcasting the encoded firmware packets. The broadcasted firmware packets will be received by the neighbors of the network manager, i.e., the first hop IoT devices. When a first hop IoT device has received the minimum number of the firmware packets required for decoding, it starts the decoding process. Upon successfully decoding the firmware data, the first hop IoT device changes its firmware reception status to ‘yes’ and is ready to relay firmware data to the second hop IoT devices. To do so, it first checks if all its neighbors have successfully received the firmware data. If yes, the first hop IoT device will not transmit any firmware packet to avoid the redundant packet transmission, instead it broadcasts an ACK packet to let its neighbors know its reception of the firmware data. When neighbors receive the ACK packet, they update their neighbor firmware reception status. Accordingly, this ACK packet serves as an active acknowledgement of firmware reception. If no, the first hop IoT device relays the firmware by broadcasting the encoded firmware packets. In other words, an IoT device transmits the firmware packet only if it has at least one neighbor that has not acknowledged the reception of firmware data. In our proposed transmission method, the reception of a firmware packet from a neighbor is considered as a passive acknowledgement of the firmware data reception. All network devices including the network manager monitor either active or passive acknowledgement from their neighbors and update their neighbor’s firmware reception status dynamically. Upon successfully decoding the firmware data, the second hop IoT devices also perform the firmware relay operation similarly as the first hop IoT devices do. This relay process continues until all IoT devices in the network have successfully received the firmware data. In other words, each IoT device including the network manager receives either active or passive acknowledgement from all its neighbors. To reduce the redundant packet transmission, even an IoT device has started the firmware relay, it stops relay when all its neighbors have received the firmware data. This is because in mesh networks, an IoT device can receive firmware packets from multiple neighbors.

Fig. 1 illustrates the efficiency of the proposed firmware distribution method. While IoT device 4 is receiving firmware packets from IoT device 2, IoT device 3 is also receiving firmware packets from IoT device 1. IoT device 3 finishes the reception before IoT device 4 does. IoT device 3 then performs firmware relay since its neighbors IoT devices 4 and 7 have not acknowledged the firmware reception. Meanwhile, IoT device 4 overhears the firmware packet transmission from IoT device 3. As a result, IoT device 4 will not relay firmware since its neighbors, IoT devices 2 and 3, have acknowledged the firmware reception. In another case, IoT device 5 finishes firmware reception before IoT device 8 that receives firmware from IoT device 6. Therefore, IoT device 5 starts firmware packet transmission since its neighbor IoT device 8 has not acknowledged the firmware reception. When IoT device 8 finishes firmware reception, it starts firmware relay as well since its neighbor IoT device 9 has not acknowledged the firmware reception. When IoT device 5 overhears firmware packet transmission from IoT device 8, it stops firmware relay since its all neighbors have acknowledged the firmware reception.

B. Firmware Distribution Method Implementation

In the proposed firmware distribution method, as shown in Fig. 2, the transmitter first erasure codes the firmware data (K information packets in the figure) to generate M redundant packets ((1) in the figure). If firmware data is large, the transmitter performs erasure coding multiple times.

Then, the Transmitter sends up to a total of K information packets and redundant packets ((2) in the figure). The Information packet and the redundant packet contain packet type indicating whether it is an information packet or redundant packet, sequence number, packet index, and payload. The sequence number is incremented each time the transmitting station encodes firmware data and is used to identify which data the response is to. The packet index indicates the index of information packets or redundant packets. After K packets have been sent, depending on the number of packet errors in the IoT device, additional information packets and redundant packets are sent until the IoT device can decode the firmware data ((3) in the figure). Here, the additional packets to be sent are those not sent in (2) in the figure. The IoT device uses the received K or more packets to decode and recover the firmware data ((4) in the figure). The IoT device sends an ACK (Acknowledgement) packet to the transmitter if decoding succeeds, and a NACK (Negative Acknowledgment) packet to the transmitter if decoding fails.

In a mesh network, relaying by flooding is inefficient for delivery. The proposed method reduces the number of relaying devices by using ACK or NACK packets used to confirm the delivery of firmware distribution. Devices send an ACK or NACK packet to the same device to which the ACK or NACK packet sent by a neighboring device is destined. Only devices that receive ACK or NACK packets will perform relaying, thereby reducing the number of relaying devices.

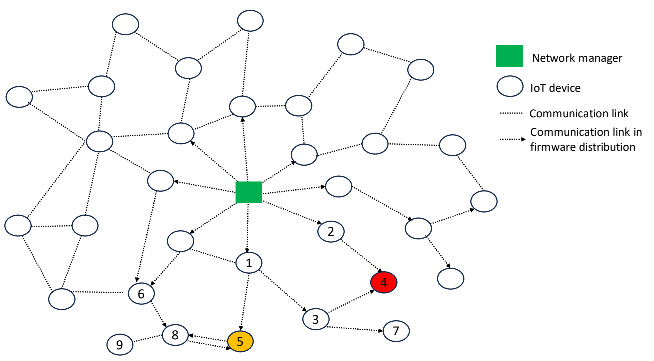

Fig. 1. Efficient firmware distribution diagram

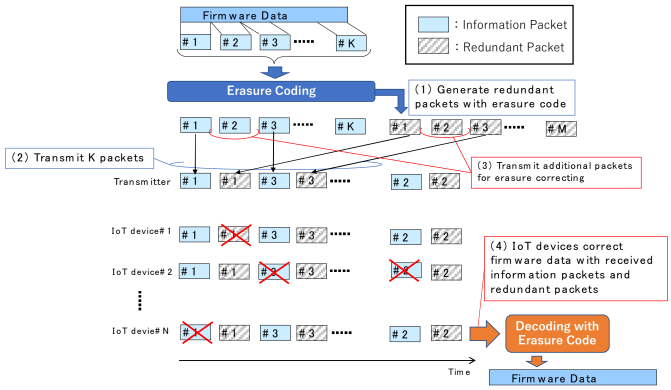

Fig. 2. Proposed firmware distribution method

IV. Simulation Evaluation

We evaluated the proposed firmware distribution method using computer simulation. A discrete-event network simulator, named ns-3, is modified to support IEEE 802.15.4, mesh network and firmware distribution [7].

TABLE I. shows simulation parameters. In the computer simulation using ns-3, IEEE 802.15.4g, which is used in IoT devices in the 920 MHz band, was used as the wireless communication method and evaluated in an environment where IoT devices are connected in mesh network from a transmitter. Firmware data transmitter and IoT devices use either FSK PHY or OFDM PHY for wireless communication. In our simulations, SEAMCAT Extended hata Model (Suburban) for propagation between terminals from below rooftop height to near street level is applied as Fig. 3. SEAMCAT Extended Hata Model (Suburban) is represented by combination of Non-Line-Of-Sight (NLOS) and Line-Of-Sight (LOS).

Fig. 4 shows an example of device placement. A network manager is placed at the center of a circle with a radius of 500 m, and 100 to 1000 IoT devices are randomly placed within the circle.

Fig. 5 shows effective throughput for the proposed method with erasure code and conventional method using flooding with or without erasure code. The figure shows that the proposed method improves effective throughput, and the improvement rate is higher when the number of devices in the network is small. The improvement rate is higher when the proposed method of relay device selection is used than when the erasure code is applied to flooding. Compared to simply using flooding, the proposed method improves the effective throughput by 1.87 times from 1.96 kbps to 3.66 kbps for FSK and by 1.8 times from 4.4 kbps to 7.92 kbps for OFDM when the number of terminals is 100. When the number of terminals is 1000, the effective throughput increases 1.57 times from 1.1 kbps to 1.74 kbps for FSK and 1.48 times from 2.33 kbps to 3.45 kbps for OFDM compared to flooding. The proposed scheme improves the effective throughput when using OFDM PHY as much as when using FSK PHY.

V. Conclusion

We proposed the firmware distribution method using erasure code to achieve higher efficiency for limited radio frequency and evaluated the proposed method for large scale mesh network of IEEE 802.15.4g OFDM PHY with computer simulation. The performance of the proposed method is compared to the effective throughput of conventional firmware distribution methods. In the best case, the effective throughput of the proposed method was 1.8 times higher when the number of IoT devices was 100. It was also 1.48 times higher when the number of IoT devices was as large as 1000.

Future work is evaluation in mixed environments with devices supporting both IEEE 802.15.4g-FSK PHY and IEEE 802.15.4g-OFDM PHY, and performance evaluation using IoT testbeds.

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TABLE I. SIMULATION PARAMETERS

Firmware distribution parameters	Value
The number of devices	100 - 1000
Erasure code	Rate-Compatible QC-LDPC
K, the number of information packets	360
M, the number of redundant packets	360
Firmware distribution packet length	248 Byte
PHY/MAC	IEEE 802.15.4g
MAC parameters	**Value**
macMinBE	5
macMaxBE	8
PHY parameters	**Value**
Modulation	FSK, OFDM MCS4 (QPSK 3/4)
Data rate	100 kbps (FSK), 300 kbps (OFDM MCS4)
Frequency	923.7 MHz
Channel spacing	400 kHz
Propagation Model	SEAMCAT extended Hata model (Suburban)
Antenna height	1.5 m

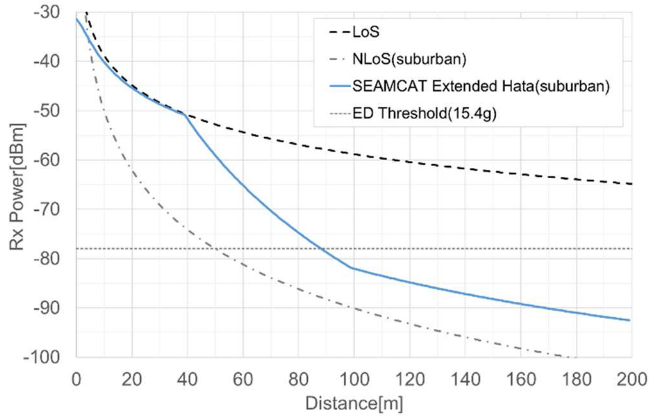

Fig. 3. SEAMCAT extended Hata model (suburban)

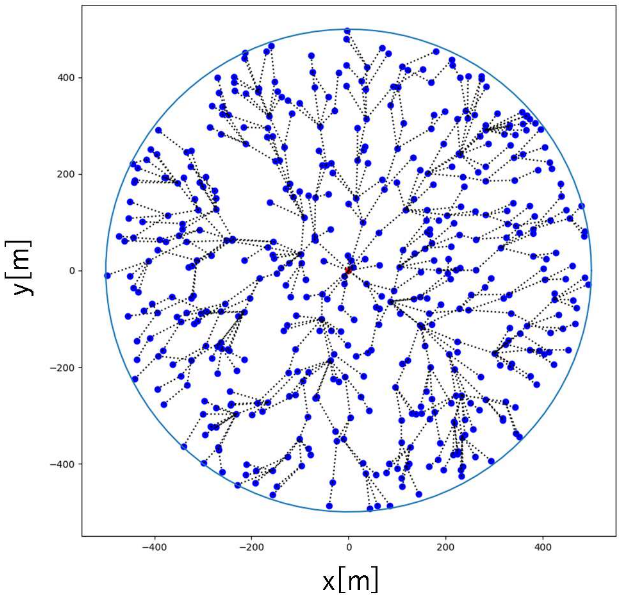

Fig. 4. An example of device placement (500 devices)

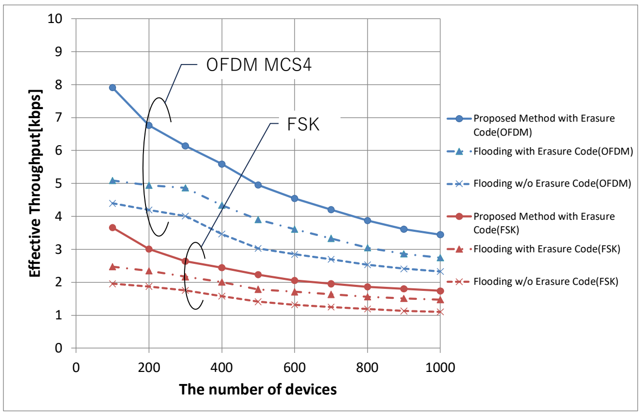

Fig. 5. Effective throughput