Smart Control for Energy Efficient Networking of IEEE 802.11ah-based IoT

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Abstract

Since Internet of Things (IoT) is configured to support up to 8000 various IoT devices scattered within 1 Km range, smart controls of transmission power and wireless channel according to the communication environment and channel status are essential feature for energy-efficient IoT networking. Also smart channel selection and cognitive switching are necessary in order to mitigate the channel interferences and environmental noises. In this paper, we propose a smart control for energy efficient networking of IEEE 802.11ah-based IoT with hybrid slotted CSMA/CA-TDMA (HSCT) MAC protocol. The proposed HSCT MAC protocol enhances the performance of IEEE 802.11ah on sub-1GHz RF channel with limited transmission rate. In the HSCT, the contention among IoT devices IoT devices is minimized by employing scheduled TDMA slot (T-slot), while T-slot requests are handled by CSMA/CA contention-based MAC scheme. The proposed smart RF control scheme has been implemented on TI CC1312R high-performance Sub-1GHz wireless launch pad. This paper also provides the performance analysis of the proposed scheme based on measured results.

Ⅰ. Introduction

In Internet of Things (IoT) network, up to 8000 IoT devices are scattered at various positions within 1 Km with different surrounding environment. As a result, the wireless communication channels may experience diverse interferences and various distances, and the AP (access point) of IoT network must be able to provide cognitive and efficient channel managements [1-3]. Especially, since the IoT devices are remotely operated by limited battery capacity without frequent manual maintenances, the IoT communication must be energy efficient.

The IEEE 802.11ah (WiFi-HaLow) operating in sub-1GHz frequency range can provide only 50Kbps ~ 4Mbps transmission rates [4, 5]; thus the medium access control (MAC) protocol with these low transmission rates must be very efficient.

In this paper we propose a smart control for energy efficient operations of IEEE 802.11ah IoT networks with hybrid CSMA/CA-TDMA MAC protocol. In the proposed scheme, the contention among IoT devices is minimized by using scheduled TDMA slot allocations with CSMA/CA-based request handling [6-8]. The communication channel is cognitively selected considering frequency interferences on the path between AP and IoT device, and transmission rate and transmission power are adaptively adjusted for energy efficient IoT networking. The proposed scheme has been implemented on Texas Instrument (TI) CC1312R high-performance sub-1GHz wireless Launchpad [18, 19]. This paper provides measured results and performance analysis.

The rest part of this paper is organized as follows. In section II, related works are briefly explained, including hybrid CSMA/CA-TDMA MAC protocol. In section III the proposed scheme of smart control for IEEE 802.11ah IoT Networking is explained in detail. Section IV explained the implementation and performance analysis. The performance analysis on the smart channel selections, energy-efficient adjustment of the transmission rates and transmission powers are explained in detail. Finally, section V concludes this paper with brief explanation of future research plan.

Ⅱ. Related Work

2.1 IEEE 802.11ah (WiFi-HaLow) / Sub-1GHz

Wi-Fi Alliance standardized IEEE 802.11ah (WiFi-Halow) using sub-1GHz range for IoT networking [4]. Current IEEE 802.11ah standard is using MAC protocol based on CSMA/CA scheme, and most countries allocate 900MHz frequency range for IEEE 802.11ah IoT networking. In Korea, 917.5 ~ 923.5MHz frequency range has been allocated for IoT networks [5], while Japan 916.5 ~ 927.5 MHz range. In the IoT networking regulation in Korea, total 32 channels are specified with 200KHz bandwidth in 917.5 ~ 923.5 MHz range. Channels 2, 5, 8, 11, 14, and 17 can transmit with maximum 4W, while channels 20 ~ 32 can transmit with maximum 200mW transmission power [5].

2.2 Hybrid Slotted CSMA/CA-TDMA MAC for IEEE 802.11ah

Recently many research works pointed the pure performance of the CSMA/CA-based MAC of IEEE 802.11ah, especially for a large number of IoT terminals up to 8000 [6]. As a solution for IoT networking with massive IoT terminals, the hybrid slotted CSMA/CA-TDMA was proposed , as depicted in Fig. 1 [6].

In the hybrid CSMA/CA-TDMA MAC, the AP configures a super frame of beacon period (BP) (e.g., 100 ms ~ 1sec duration) that is composed of C-slot (CSMA/CA slot) and T-slot (TDMA slot). The AP periodically broadcast the configuration of the super frame using

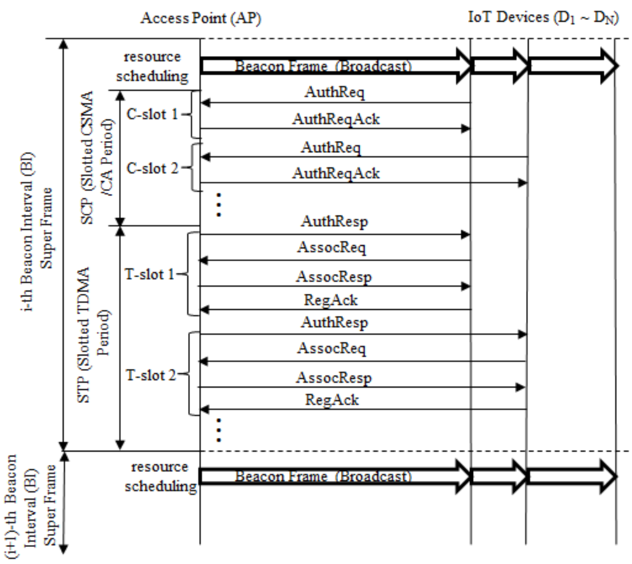

Fig. 1 Hybrid CSMA/CA-TDMA Super Frame

beacon message that contains the duration, position, and number of C-slots and T-slots. The beacon message informs the start of a super frame, and each IoT device synchronizes according to the beacon frame. The positions of T-slots are numbered for mini-slot (0.5ms) duration from the beacon frame.

In order to register to AP, each IoT device sends Authentication Request (AuthReq) messages using the C-slot with contention. When the AuthReq message is successfully delivered to the AP, the AP assigns T-slot for the IoT device, and Authentication Response (AuthResp) is replied to the IoT device. In the same T-slot association request (AssocReq) and association response (AssocResp) messages are exchanged.

The number of C-slots and T-slots are adjusted according to the number of registered IoT devices and the number of T-slot requests.

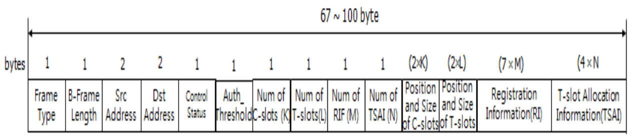

Fig. 2. Beacon Frame

2.3 Sub-1GHz Wireless Communication Module

For low power long range IoT networking few sub-1GHz communication modules are commercially available: LoRaWAN module [7-13] and TI CC1312R high-performance Sub-1GHz wireless module [14-17].

LoRa (long range) is using frequency shift chirp spread spectrum modulation technology to enable long-range transfer of information with a low transfer rate [12, 13]. The LoRaWAN is a MAC layer long range network protocol which is used for low power wide area network (LPWAN). The limitations of LoRa are low data rate (up to 27 Kbps) and limitations with duty cycles that effectively limits the number of messages during a specific time frame. The LoRa is evaluated not to be suitable for real time applications that require lower latency [9].

TI CC1312R SimpleLink High-Performance Sub-1GHz Wireless MCU [14] combines a flexible, very low-power RF transceiver with a powerful Cortex-M4F CPU in a platform supporting multiple physical layers and RF standards. The IT CC1312R supports a proprietary long-range mode (LRM) that supports 2.5 Kbps and 5 Kbps. It also provides transmission rate of 100 Kbps ~ 4Mbps using GFSK modulation. TI CC1312R LaunchPad is a development kit with sub-1GHz RF based on CC1312R MCU [15].

Ⅲ. Smart Control for IEEE 802.11ah IoT Networking

3.1 Hybrid Slotted CSMA/CA - TDMA MAC

All IoT devices in the hybrid slotted CSMA/CA-TDMA (HSCT) synchronize the beacon interval (BI) when they receive the beacon frame as shown in Fig. 2 [18, 19]. Within the super-frame the C-slots and T-slots are configured and numbered for mini-slot interval (0.5 ms). The beacon frame includes the detailed information of (i) the number total C-slots in the slotted CSMA/CA period (SCP), and the duration of each C-slot, (ii) the number of total T-slots, and their individual durations, (iii) the authentication control threshold value, and (iv) the MAC address and AIDs (association IDs) of the individual IoT devices which sent authentication requests in order to associate with the AP. The length of the beacon frame is 67 ~ 100 bytes [6].

Unregistered IoT device can send registration request using one of the C-slots, and registered IoT device can send T-slot request using the C-slot. The number of C-slots is adjusted according to the amount of registration requests and data T-slot requests.

3.2 Registration of IoT Devices with Authentication Control Threshold (ACT)

As shown in Fig. 1, unregistered IoT device selects one of the C-slots based on authentication control threshold (ACT) algorithm [6], and sends AuthReq frame that contains the information of the IoT device such as MAC address and authentication algorithm number (AAN).

If the AuthReq frame is successfully delivered, the AP replies with AuthReqAck that confirms the successful delivery of the AuthReq and prohibits retransmission of the AuthReq. The AP also checks the availability of T-slot for the IoT device which sent the AuthReq. If T-slot is available in this BI, the T-slot index is included in the AuthReqAck frame; if T-slot is not available in this BI, the AP sends “no free T-slot” flag in the AuthReqAck frame asking the IoT device to wait for a T-slot in next BI.

Each beacon frame contains registration information (RI) block that consists of several RI fields indicating the allocations of T-slots for specific IoT devices, as shown in Fig. 3 [6]. The beacon frame also contains T-slot allocation information (TSAI) block that indicates T-slot allocation for specified IoT device defined by association ID (AID). Fig. 4 depicts TSAI block. The total number of RI fields and TSAI fields in each the beacon frame is less than or equal to the total number of T-slots in the BI.

If T-slot is available for the IoT device in authentication procedure, the AP sends AuthResp frame and the AssocReq and AssocResp are exchanged in the assigned T-slot for the IoT device without contention. If the IoT device is successfully associated, the AP assigns 2-byte association identifier (AID) for the newly registered IoT device. The AuthResp message contains the AID assigned for the device.

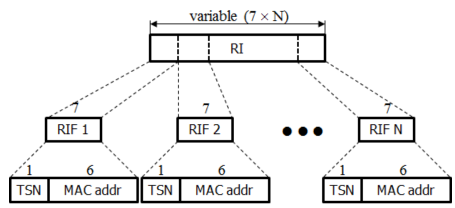

Fig. 3. Registration Information (RI) block

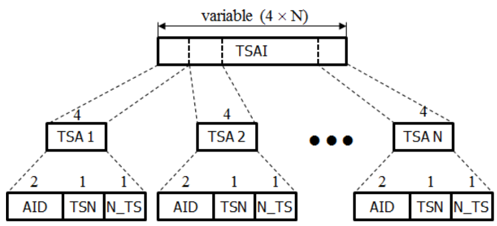

Fig. 4. T-Slot Allocation Information (TSAI) block

3.3 Smart Channel Selections based on Continuous Measurements of Attenuation and Channel Interferences

The IEEE 802.11ah IoT network configures a star topology where a centralized AP (access point) communicates with a large number of IoT devices scattered in wide area of up to 1 Km transmission range. Because of the long distance between the AP and IoT device, various interferences may affect both sender side and receiver side. As explained in section 2.1, IEEE 802.11ah IoT networks are using sub-1GHz frequency range (e.g., 917.5 ~ 923.5 MHz in Korea, 916.5 ~ 927.5 MHz in Japan, and 863 ~ 868 MHz in Europe), and 6 ~ 11 channels of 1MHz bandwidths are configured. The number of available channels is different according to the channel bandwidth. For example, if the channel bandwidth is 200 KHz total 32 channels can be configured in 917.5 ~ 923.5 MHz range.

In order to obtain the best performance with energy efficiency, the AP and IoT devices must continuously monitor the average attenuation and the frame/bit error ratio in their frame exchanges. If the measured frame/bit error ratio is high while the received signal strength (measured as RSSI (received signal strength indicator) is in good range, there may be interference in the channel frequency, and the AP and IoT device must try other channel in order to mitigate frame error ratio because of the channel interferences.

The change of channel for individual IoT device is determined after negotiations between the AP and the IoT device. After measurements of the received signal strength and frame/bit error rate, the IoT device can ask channel switching to the AP. The AP can also ask channel switching based on following conditions: (i) high frame/bit error rates while the received signal strength (e.g., RSSI) is in good level, and (ii) no acknowledgements after multiple transmissions of data/control frames.

When there is continuous communication failure between the AP and the IoT device, both AP and IoT device reset to the initially configured default communication channel that is usually the lowest frequency band.

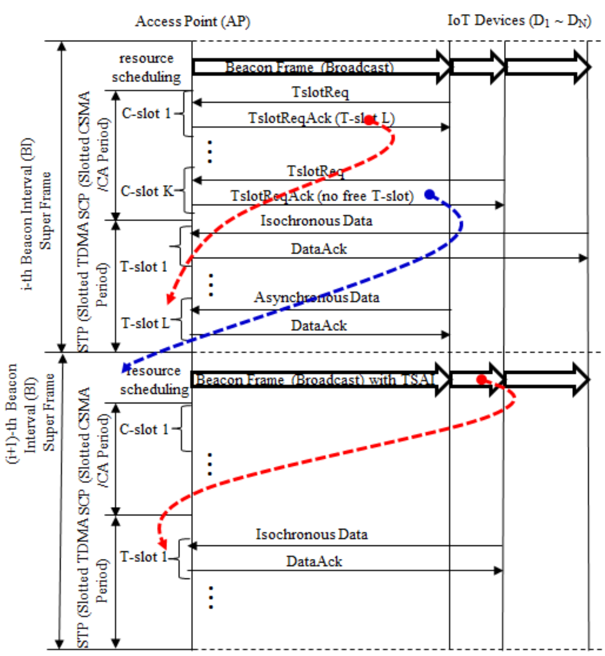

Fig. 5 C-slot Accesses for T-slot Allocations

3.4 Contention-based C-Slot Access to Request T-Slot

Besides the AuthReq frame for registration, the IoT device must send T-slot request (TslotReq) frame to the AP for T-slot allocation to deliver data frame, as depicted in Fig. 5. The TslotReq frame includes data traffic type (e.g., isochronous traffic for periodic data transmission, asynchronous traffic for sporadic data report, real-time urgent message), and the size of data block. In order to minimize the possible contention in C-slots by massive number of IoT device, the access group is partitioned into the randomly selected C-slots, where the IoT device can select only one C-slot uniformly from the provided C-slots in the BI [6].

The contentions in the access of C-slot can be mitigated by using a slotted fixed-window CSMA protocol, called Sift, where the selection of backoff slot is controlled by Sift geometric probability distribution [6], instead of uniform distribution used in usual CSMA/CA-based WiFi.

Once the TslotReq frame is successfully delivered, the AP checks the available T-slot in the same BI, and replies TslotReqAck frame. If T-slot is available in the same BI, the position and the size of the T-slot are informed by the TslotReqAck frame. If there is no available T-slot in the same BI, "no free T-slot flag" is used to notify that the IoT device must wait for T-slot in next BI.

3.5 T-Slot Allocations and Data Frame Exchanges

The data traffics are classified as three categories as shown in Table 1: urgent real-time data, asynchronous data, and isochronous data. In the case of urgent real-time data, the IoT device accesses the C-slot and sends urgent short data (UrgData) frame immediately, instead of requesting T-slot. By this mechanism, the urgent short data block can be handled without additional delay in T-slot allocation. The length of the urgent short message, however, is limited to few bytes in order to avoid increased contentions by long frame transmission in C-slot.

The asynchronous data transmission is used to deliver sporadic occasional data. For asynchronous data transmission, the standard frame exchange procedure of TslotReq and TslotReqAck is performed, and each asynchronous sporadic data transmission is handled individually.

If the IoT device must periodically report measured data to the IoT server, then the AP can periodically schedule T-slot for the isochronous data from specific IoT device without individual TslotReq/TslotReqAck frame exchange. The configuration of isochronous data transmission is determined at the registration of the IoT device. By periodic scheduling of the isochronous data traffic, the contention at the C-slot can be mitigated.

TABLE 1. Traffic Type and T-slot Allocations

Traffic type	Application	Data delivery
Urgent real-time	urgent data	direct use C-slot
Asynchronous	sporadic data	T-slot Request/ T-slot Allocation
Isochronous	periodic data or urgent data	pre-scheduled periodic T-slot

3.6 Smart Selection of Transmission Rate and Tx Power according to Channel Status

In order to provide high performance and energy efficient operations of IoT network, the transmission rate and transmission (Tx) power must be optimally selected considering the channel condition between the AP and the IoT device. For example, the TI CC1312R sub-1GHz wireless MCU supports 2.5 or 5 Kbps in long range mode (LRM), and 100 ~ 500 Kbps in normal mode using GFSK modulation.

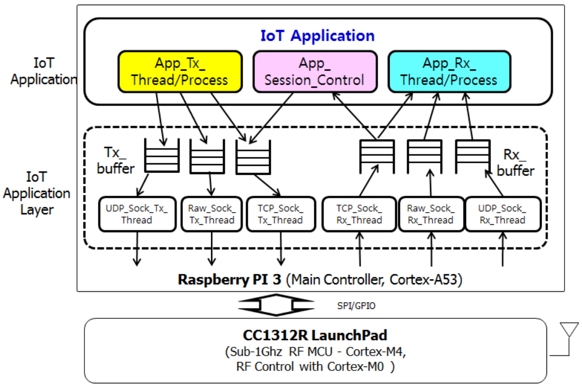

Fig. 6 Functional Block Diagram of IEEE 802.11ah / Sub-1GHz IoT Module based on TI CC1312R LaunchPad

Considering the limited transmission rate of the sub-1GHz RF channel, the transmission rate must be configured as high as possible in order to increase the overall capacity. If the AP and the IoT device are located in short distance and the maximum transmission rate between the AP and the IoT device is possible at good receive signal strength, then the transmission power can be adjusted to lower Tx power in order to save energy. If the distance between the AP and the IoT device is long and the frame/bit error rate is high at high transmission rate with highest Tx power, the transmission rate must be adjusted to lower rate.

The selection of channel, transmission rate and Tx power are dependent to the channel status between the AP and the IoT device. In the configuration of super frame for each BI, the AP determines the channel, Tx rate and Tx power for each IoT device, and performs scheduling that minimizes the overhead of channel switching, Tx rate and Tx power changes.

The AP and the IoT devices must continuously monitor the received signal strength of each frame and frame/bit error rate in order to provide optimal selection of channel, Tx rate and Tx power.

IV. Implementation and Performance Analysis of IEEE802.11ah/Sub-1GHz Module

4.1 Implementation of IEEE 802.11ah/Sub-1GHz IoT Communication Module based on TI CC1312R LaunchPad

The proposed smart control for energy efficient networking of IEEE 802.11ah-based IoT has been implemented on TI CC1312R high-performance sub-1GHz wireless LaunchPad [14, 18, 19]. Fig. 6 depicts the functional block diagram. The IoT application are programmed with C and Python programming language on Linux operating system (OS) environment with Raspberry Pi 3 single board computer. CC1312R LaunchPad is connected to the Raspberry Pi by SPI (serial peripheral interface) / GPIO (general peripheral input / output).

Currently, the IoT application contains application message transmission (Tx) and reception (Rx) threads and application session control module. IoT application layer provides socket interfaces for the IoT applications. Three kinds of sockets are provided: TCP socket, UDP datagram socket, and row socket. For the CC1312R RF module, Ubuntu Linux network device driver has been developed to provide software MAC functions for IEEE 802.11ah. The detailed controls of CC1312R RF module are implemented as a Linux kernel driver module for IEEE 802.11ah on CC1312R.

4.2 Performance Measurement and Analysis of IEEE 802.11ah/Sub-1GHz Communications

(1) Frame Loss and Throughput vs. Tx Rate

Table 2 shows the measured performance of frame loss, CRC error, and average RSSI according to different Tx rate at line-of-sight 700 meter distance in open area with 20dBm Tx power. While the Tx rate is less than or equal to 200Kbps, there was no frame loss; but, when the Tx rate is increased beyond 300Kbps, the frame loss increases while the average RSSI is at the same level.

TABLE 2. Performance according to Tx rate at line-of-sight 700m distance in open area (Tx power 20dBm)

Tx Rate	Frame Loss	CRC Error	Average RSSI [dBm]
50Kbps	0	0	-64.25
100Kbps	0	0	-64.53
200Kbps	0	0	-64.55
300Kbps	7	0	-62.89
400Kbps	7	0	-63.52
500Kbps	37	0	-63.16

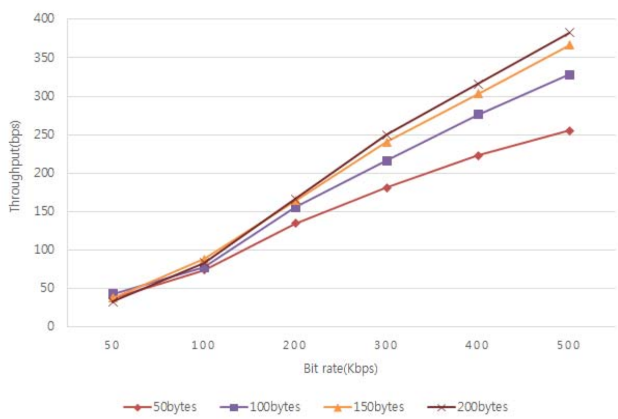

Fig. 7. Throughput vs. Payload Size

Fig. 7 shows the measured throughputs according to the frame size, when the transmission rates are 50 ~ 500Kbps. Because of the overhead of the hybrid CSMA/CA-TDMA MAC and the frame header in physical/MAC layer, the end-to-end throughput is less than the transmission rate. If the frame size is smaller, the overhead becomes more severe, while the overhead becomes lesser if the frame size becomes larger. At 500 Kbps Tx rate, the achieved throughput with 200 byte payload size is 380Kbps which is much higher than LoRaWAN that is limited less than 27Kbps [9]

(2) Frame Error Ratio vs. Tx Power

The Tx power of CC1312R LaunchPad can be adjusted between 6 ~ 14dBm, while Tx power can be adjusted up to 14dBm. Fig. 8 depicts the frame error ratio (FER) vs. Tx power on CC1312R high gain mode. As the Tx power is increased up to 14 dBm, the FER is reduced from 100% to less than 40%. Thus the Tx power must be adjusted according to the channel condition (e.g., distance or obstacle) between the AP and IoT devices. In order to obtain the energy efficient IoT networking, continuous monitoring and adjustment of the optimal configuration of channel frequency, Tx rate, and Tx power must be performed for each IoT device.

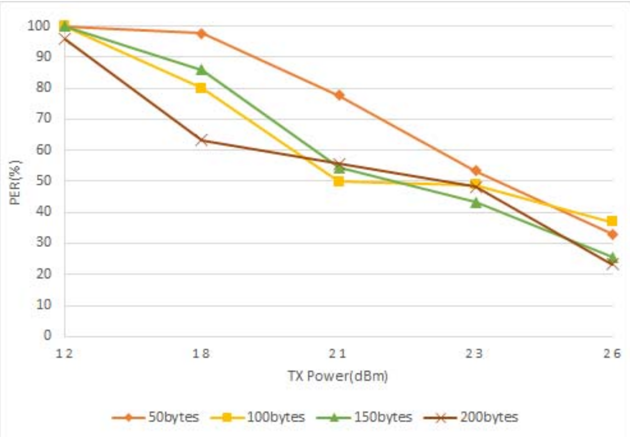

Fig. 8. Frame Error Rate (FER) vs. Tx Power on CC1312R (Tx Rate: 100Kbps)

4.3 Monitoring Channel Attenuations and Interferences for Smart Channel Selections

(1) Continuous Monitoring of RSSI and FER

Even though the AP and IoT device are statically positioned without movement and the Tx rate and Tx power are same, the RSSI values are measured differently according to the channel center frequency, as shown in Fig. 9. Since the lower RSSI value means higher frame error ratio (FER) possibility, the communication channel must be selected considering the measured RSSI values for each channel.

Another significant issue is the channel interference. If there is strong channel interference at the receiver side (both AP and IoT device), the frame error ratio increases even though the measured RSSI is high, because of the higher bit errors at the receiver side. In order to avoid the increased FER because of the channel interferences, the AP and IoT devices must continuously monitor the RSSI values and FERs at each frame exchanges including beacon frame.

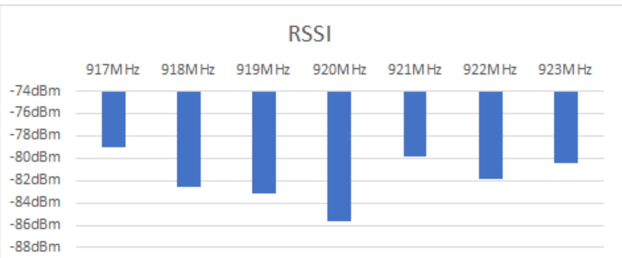

Fig. 9. RSSI vs. Channel Center Frequency

In the proposed smart control for energy efficient IoT networking, smart channel selections based on continuous measurements of attenuation and channel interferences are supported. When the receiver side determines high channel interference from the measured RSSI and FER values, it can recommend channel switching to the sender side. The channel switching is finally determined by the AP which collects all channel switching requests from IoT devices.

(2) Smart Channel Selection and Channel Switching

The smart channel selection and channel switching to avoid channel interferences are processed dynamically according to the measured values of RSSI and FER at the receiver side. Since each IoT device may experience different channel interference, the IEEE 802.11ah-based IoT network that covers 1 Km range cannot select just one channel frequency for all IoT devices.

Since the dynamic channel switching within a BI for individual C-slot or T-slot requires additional delay for channel re-configuration and inter-frame gap for RF settle down, the smart channel selection and dynamic channel switching must be carefully scheduled. With the dynamic channel switching, each T-slot may be configured at different Tx rate and Tx power for individual IoT device.

In order to minimize the overhead of channel switching and re-adjustment of Tx rate and Tx power, the re-configuration of channel selections and Tx rate/power may be scheduled for each BI interval instead of C-slot/T-slot interval. Currently the smart channel selection and channel switching with dynamic Tx rate/power adjustment are under developments

(3) Smart Selection of TxPower and TxRate

In the proposed scheme, the AP continuously monitors the RSSI and error rate of the frame exchanges between AP and IoT devices. Based on the accumulated monitoring data, the AP selects most appropriate TxPower and TxRate for the IoT device. The configuration update of TxPower and TxRate is handled by control frames using 100Kbps for reliable delivery.

TABLE 3. Adjustment of TxPower and TxRate

IoT Node	RSSI (dBm)	TxPower (dBm)	TxRate (kbps)
S1	-73	14	300
S2	-57	12	500
S3	-59	14	400
S4	-76	14	200
S5	-74	14	300

Table 3 depicts the results of smart adjustments of TxPower and TxRate for 5 IoT devices which are distributed in the wide area (distances of 100 ~ 700 meter from the AP). When the RSSI is more than -60 dBm and error rate is 0, the TxPower is adjusted to lower level. But, if the RSSI is less than -60 dBm and frame error rate is more than 0, the TxPower is maximized and the TxRate is adjusted to lower level.

V. Conclusion

In this paper, we proposed a smart control for energy efficient networking of IEEE 802.11ah-based IoT with hybrid slotted CSMA/CA-TDMA (HSCT) MAC protocol. The proposed HSCT MAC protocol enhances the performance of IEEE 802.11ah on sub-1GHz RF channel with limited transmission rate. In the proposed scheme, the contention among IoT devices is minimized by using scheduled TDMA slot (T-slot) as much as possible, with CSMA/CA contention based request handling. For isochronous traffic, pre-scheduled T-slots are provided without additional T-slot request procedure. The cognitive communication channel is used to minimize the channel interferences, and Tx rate and Tx power are adjusted to maximize energy efficiency and overall IoT network throughput.

The proposed scheme has been implemented on TI CC1312R high-performance sub-1GHz wireless LaunchPad. Performances were measured and analyzed in real environment. As the result of the proof-of-concept implementation, the performance of the proposed scheme was confirmed that can be utilized in realistic IoT networking for devices within 1 Km range.

The smart channel selection and dynamic channels switching with Tx rate/power adjustment are under development. Also as future work, optimized design of RF analog circuit with antenna impedance-matching is required for specific IoT applications in various installation environments.

Acknowledgement

This research was supported by the MSIT(Ministry of Science and ICT), Korea, under the ITRC(Information Technology Research Center) support program(IITP-2019-2016-0-00313) supervised by the IITP(Institute for Information & communications Technology Planning & Evaluation).

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