

Performance Evaluations for IEEE 802.15.4-based IoT Smart Home Solutions

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Abstract

The Internet of Things (IoT) is going to be a market-changing force for a variety of real-time applications such as e-healthcare, home automation, environmental monitoring, and industrial automation. Low power wireless communication protocols offering long lifetime and high reliability such as the IEEE 802.15.4 standard have been a key enabling technology for IoT deployments and are deployed for home automation recently. The issues of the IEEE 802.15.4 networks have moved from theory to real world deployments. The work presented herein intends to demonstrate the use of the IEEE 802.15.4 standard in recent IoT commercial products for smart home applications: the Smart Home Starter Kit. The contributions of the paper are twofold. First, the paper presents how the IEEE 802.15.4 standard is employed in Smart Home Starter Kit. In particular, network topology, network operations, and data transfer mode are investigated. Second, network performance metrics such as end-to-end (E2E) delay and frame reception ratio (FRR) are evaluated by experiments. In addition, the paper discusses several directions for future improvements of home automation commercial products.

Keywords: IoT, home automation, 802.15.4, smart home, e-healthcare

1. Introduction

The Internet of Things (IoT) is an innovation in the field of communication where a number of people and intelligent devices are connected so that anyone at any time and any place can efficiently access information about other objects and services [1], [2]. The vision of IoT relies on the networking of embedded and ubiquitous devices; for example, actuators and sensors. The IEEE 802.15.4 standard, characterized by low power, low cost, high reliability, and simplicity at industrial, scientific and medical (ISM) frequency band, has recently received a lot of attention as it is one of the key enabling technologies for IoT deployments. In addition, the IEEE 802.15.4 standard supports IPv6 which provides an unimaginable number of IP addresses for IoT connected devices. Furthermore, it supports multi-hop communications which helps to extend network coverage efficiently. The IEEE 802.15.4 standard, therefore, has been widely deployed in many industrial applications such as home automation, e-healthcare, environmental monitoring, and industrial automation. The work presented in this paper focuses on applications of the IEEE 802.15.4 standard for home automation.

Home automation is an extremely appealing application for IoT. It involves the controlling and monitoring of home appliances in a unified system - the integration of embedded devices such as lighting, heating, and air conditioning to realize

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smart applications for home control. Home automation systems allow users to easily control and monitor their homes via smartphones, pads, laptops, and desktops connected with the Internet. Conservative home automation solutions are mostly based on power line or wired-bus communication; however, power line carrier is a toxic technology and shows serious reliability to provide real-time environmental sensor information. Furthermore, power line needs a mandatory gateway to communicate with mobile devices. Therefore, they are complex, expensive, inflexible, and involved with time-consuming installations and, thus, the use of technology is limited [3]. Wireless sensor networks (WSN) are fundamental in wireless home automation whose main requirements are quality-of-service (QoS) and real-time constraints satisfaction [4]. Several wireless technologies such as ZigBee (based on IEEE 802.15.4 standard), Z-Wave, Bluetooth, 6LoWPAN, Wi-Fi, UWB are studied in literature for home automation [5] and among those technologies; Zigbee, Bluetooth and Wi-Fi are employed for commercial products. However, Bluetooth consumes much energy than ZigBee and cannot support flexible multi-hop communications. In addition, Wi-Fi may not be very feasible for battery powered sensors due to its high power consumption [3]. On the other hand, the IEEE 802.15.4 has shown to be a very reliable and easy-to-implement wireless technology in real home scenarios [6, 7].

There has been a considerable amount of research on the IEEE 802.15.4 standard (see [8-12], and references therein). Performance evaluation of the IEEE 802.15.4 medium access control (MAC) protocol has been carried out by simulations for small and low load networks in [8] and dense networks in [9]. In addition, power consumption, delay, throughput, and packet reception ratio are numerically analyzed in [10-12]. This paper also evaluates the performance of the IEEE 802.15.4 but based on real IoT commercial products. Home automation applications using IEEE 802.15.4 standard for connectivity has been widely studied in literature [4-7, 13-19]. A priority-based CSMA/CA algorithm to support deadline-aware scheduling in home automation using IEEE 802.15.4 is proposed in [4] in which the authors efficiently allocate the guaranteed time slots (GTS) in the super frame, the duration between two consecutive beacon frames, for periodic traffic flows transmission. Nonetheless, the authors in [13] proposed a scheduling scheme to obtain optimal parameters for home automation networks. In [14], the deployment of wireless sensor networks and wireless systems applied to home and building automation systems is analyzed. The authors propose an in-house 3D ray launching code to illustrate influences of topology and morphology to the operation of wireless links in realistic scenarios. The potential deployment of Zigbee/IEEE 802.15.4 standard with multi-hop in smart home environment is described in [15]. Here, the authors show that sensors and communication devices used for the deployment in smart home are not required to have a high speed in communication capacities and that IEEE 802.15.4 is possible to satisfy home automation network requirements. In [16], comprehensive summary of home area communications and networking technologies for energy management is provided. Energy management has been also examined in [17]. The authors here propose a home energy control systems design that provides intelligent services for users and demonstrate its implementation. In addition, several aspects of the IEEE 802.15.4 MAC in contention access period (CAP), contention free period (CFP) of a superframe, and the overall cross period, respectively, were analyzed in [18] to meet home automation requirements. Furthermore, the authors in [19] present home automation network architecture for energy management inside smart grid environments. In order to achieve smart grid potential, they solve the problem of interoperability among different communication technologies deployed in the grid. All of these works are in theory; however, the issues and deployments of the IEEE 802.15.4 networks have to move real world employments.

This paper explores how the IEEE 802.15.4 is applied in the recent IoT commercial products for smart home applications. In particular, the Smart Home Starter Kit [20], which was released at the beginning of 2015, was analyzed. We investigate its operating channel, network topology, network operations, and data transfer mode. In addition, important performance metrics such as end-to-end delay (E2E Delay) and frame reception ratio (FRR) are evaluated by experiments. To the best of our knowledge, this paper is the first work to analyze the performance of the IEEE 802.15.4-based IoT commercial products.

The rest of the paper is structured as follows. Section II describes several important features of the IEEE 802.15.4 standard which are used in IoT Smart Home Starter Kit. Section III explains our experiment setup. Performance evaluations, important findings, and discussions are presented in Section IV. Finally, Section V concludes this paper.

2. IEEE 802.15.4 standard

The IEEE 802.15.4 standard defines specifications for physical (PHY) and medium access control (MAC) layers, targeted for wireless personal area networks (WPAN). A PAN consists of one PAN coordinator and multiple sensors which transmits data to the coordinator. The IEEE 802.15.4 standard supports two PHY options based on direct sequence spread spectrum (DSSS). The 2.4 GHz PHY uses QPSK modulation, whereas 780/868/915 MHz uses BPSK modulation. The IEEE 802.15.4 PHY layer offers 31 channels out of which 4 are in 780 MHz for China, 1 is in 868 MHz band for Europe, 10 are in 915 MHz for North America, and 16 are in the 2.4 GHz bands throughout of the world. The 868/915 MHz PHYs support data rates of 20 kbps, 40 kbps, and optionally 100 kbps and 250 kbps. The 2.4 GHz PHY supports the data rate of 250 kbps [21].

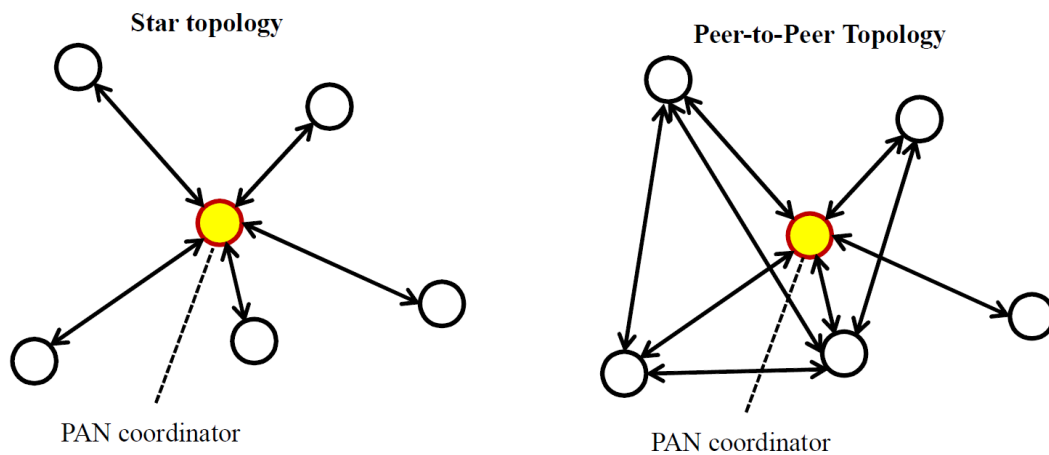


Fig. 1 Topology in the IEEE 802.15.4 networks

2.1. Network Topology

Depending on application requirements, an IEEE 802.15.4 PAN can operate in either of two topologies: star topology and peer-to-peer topology. In star topology, the communication is established between end devices and the PAN coordinator. In peer-to-peer topology, each device is capable of communicating with any other device within its radio sphere of influence, as shown in Fig. 1 [21].

2.2. Channel Access

According to [21], carrier sense multiple access algorithms with collision avoidance (CSMA/CA) algorithm is used for radio channel access. The IEEE 802.15.4 standard supports two channel access algorithms. A beacon-enabled PAN uses a slotted (CSMA/CA), the slot boundaries of each sensor are aligned with the slot boundaries of the PAN coordinator. On the other hand, if beacons are not available (non-beacon-enabled PAN), a simple unslotted CSMA/CA is used. Each device maintains three variables for transmission attempt: Number of Backoffs (NB), Contention Window (CW), and Backoff Exponent (BE). NB is the number of times CSMA/CA algorithm was required to back off while attempting the current transmission. CW is the number of backoff slots that need to be clear of channel activity before transmission. BE is the backoff exponent related to how many slots a sensor shall wait before attempting to access channel. Fig. 2 explains slotted CSMA/CA algorithm in beacon-enabled mode. First, NB, CW, and BE are initialized to 0, 2, and BE_{min} respectively, and device locates the boundary of next backoff period (Step 1). Upon reception of the beacon frame, sent by the PAN coordinator, device delays for a random number of backoff slots in the

range from 0 to $2^{BE}-1$ (Step 2). Then, the PHY layer performs clear channel assessment (CCA) (Step 3). The carrier sensing starts on a backoff period boundary. The MAC layer then proceeds, provided that the remaining CSMA/CA algorithm steps including frame transmission and any acknowledgment are completed before the end of a CAP slot. If the MAC layer cannot proceed, it must wait until the start of CAP in next superframe and then repeat again. If the channel is assessed busy (Step 4), the MAC layer increases both NB and BE by one, ensuring that BE is not more than aMAXBE, and CW is set to 2. If NB is less than or equal to macMaxCSMABackoffs, the CSMA/CA algorithm returns Step 2, else it terminates with Transmission Failure status. If the channel is assessed to be free (Step 5), the MAC layer must ensure that the contention window is expired before data transmission. For this, the MAC layer decreases CW by 1. If CW is greater than 0, it must go to Step 3, else it starts to transmit on the boundary of the next slot period. The unslotted CSMA/CA used in non-beacon-enabled mode is almost the same as slotted CSMA/CA, except Step 1.

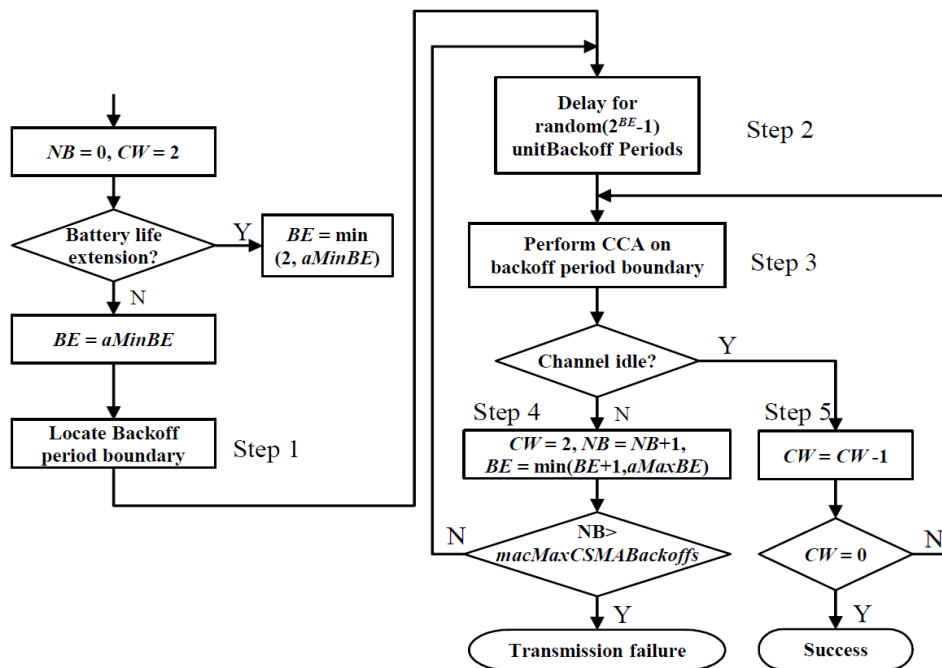


Fig. 2 Slotted CSMA/CA algorithm, unslotted CSMA/CA algorithm is almost the same as except Step 1

2.3. Data Transfer Mode

Direct data transmission: This is data transfer from a sensor to the PAN coordinator. In beacon-enabled PAN, if a network device wants to transmit data to the coordinator, it first listens for the beacon frame. Upon receipt of the beacon frame, the device synchronizes to the superframe structure. Then, the device transmits its data frame to the coordinator using slotted CSMA/CA mechanism. After receiving the data frame, the coordinator may optionally send back an acknowledgment to confirm the successful reception of the data frame, as explained in Fig. 3 (a). In non-beacon-enabled PAN, on the other hand, the device simply transmits its data frame to the coordinator by using unslotted CSMA-CA. The coordinator optionally acknowledges the successful reception of the data frame by transmitting acknowledgment frame as illustrated in Fig. 3 (b) [21]

Indirect data transmission: This transmission refers to data transfer from the PAN coordinator to the sensor. In beacon-enabled PAN, when the PAN coordinator wants to transmit data frame to a network device, it sets frame pending field in beacon frame to 1. The device regularly listens to the network beacon and then transmits a MAC command to request the data by using slotted CSMA/CA. The coordinator acknowledges the successful reception of the data by transmitting back an acknowledge frame. The data frame is then immediately transmitted. Upon receiving the data frame, the sensor optionally sends back the acknowledgement to confirm data reception. This operation is shown in Fig. 4 (a). In non-beacon-enabled PAN, on the

other hand, a device transmits a MAC command to request data using unslotted CSMA/CA to the PAN coordinator at an application-defined rate. The coordinator acknowledges the reception of the data request by transmitting an acknowledge frame. If there is pending data frame, the coordinator transmits the frame using unslotted CSMA/CA. Otherwise, the coordinator indicates this fact either in the acknowledgment frame following the data request or in a data frame with a zero-length payload [21]. This operation is shown in Fig. 4 (b).

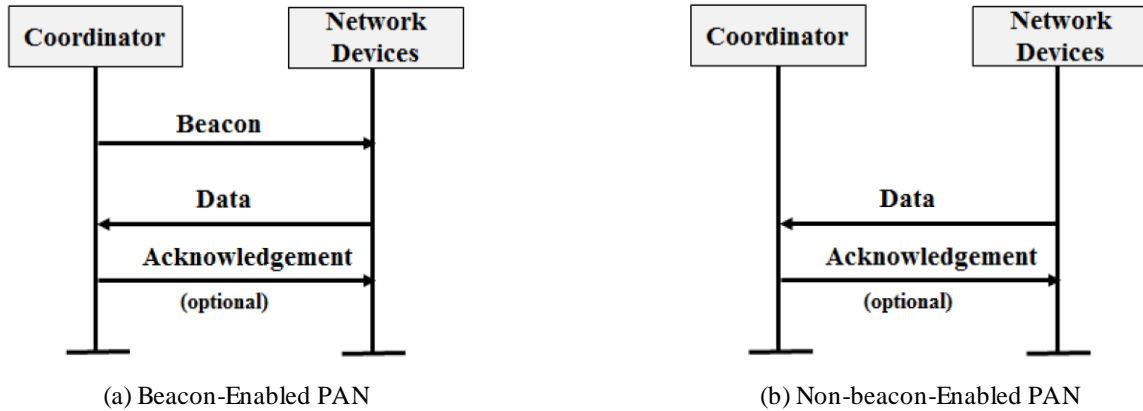


Fig. 3 Direct data transmission from sensor to PAN coordinator

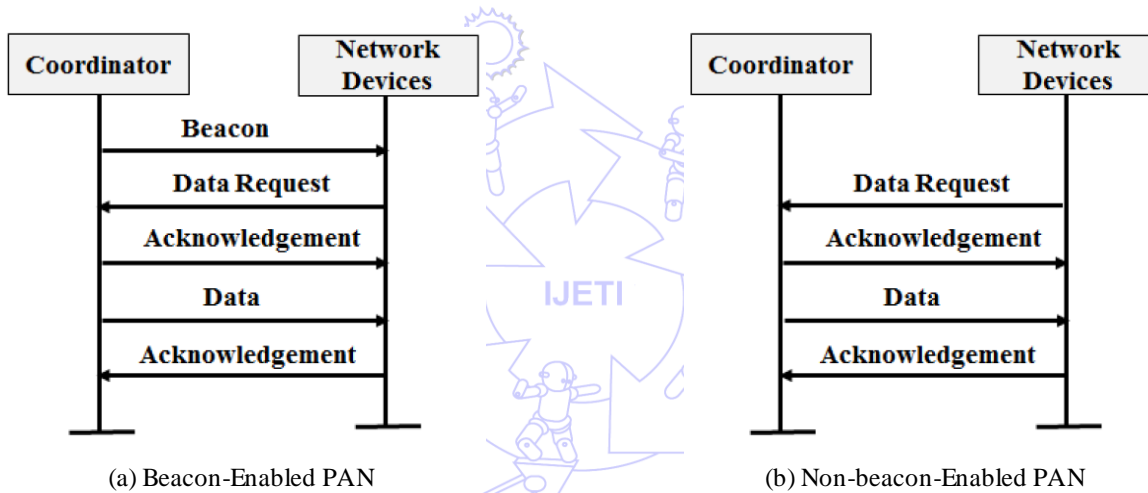


Fig. 4 Indirect data transmission from PAN coordinator to sensor

3. Experiment Setups

We analyze the Smart Home Starter Kit which includes a central SmartThings Hub, acting as the PAN coordinator, and several home appliances sensors such as a door lock, motion detectors, light, and moisture sensors as shown in Fig. 5. The SmartThings Hub is connected to the Internet through an Ethernet cable plugged into a router. It wirelessly connects other sensors using IEEE 802.15.4 for connectivity so that users can receive messages about what is going on and use their smartphones to remotely control different things in their homes or offices.

To understand the behavior and traffic pattern of the network, a sniffing tool is used to analyze how frames are exchanged in the network. The sniffing tool is capable of real-time capture for all frames supported by Zigbee protocol and the IEEE 802.15.4 standard. In our analysis, Wireshark is used as a network protocol analyzer to capture all frames on an IEEE 802.15.4 channel. For this, a sniffer hardware tool running a sniffer firmware plugged into a PC is needed. In this work, we use an Atmel RZUSBSTICK platform to sniff IEEE 802.15.4 frames. A channel from 11 to 26 in 2.4 GHz ISM band can be selected from sniffer capture interface to collect all frames operating on that channel, as can be seen in Fig. 6.

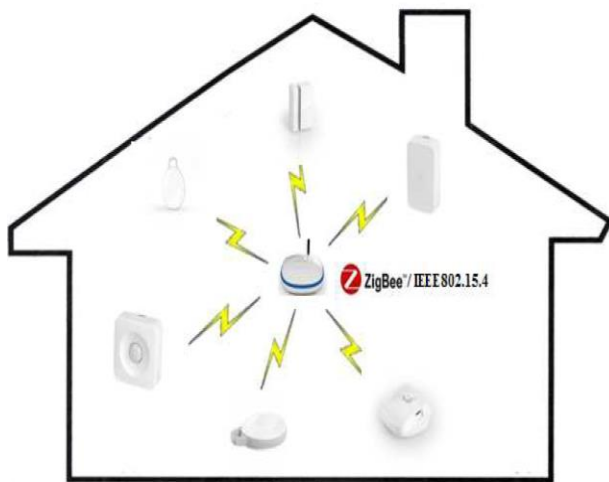
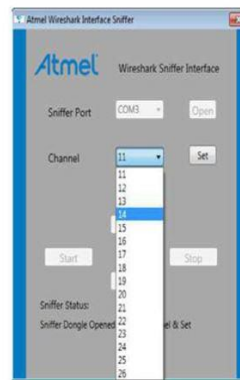


Fig. 5 Smart Home Starter Kit - the SmartThings Hub is connected to several home appliances sensors using IEEE 802.15.4 standard



IEEE 802.15.4 Operating Channels in the 2.4GHz ISM Band



RZUSBSTICK plugged into a PC



Wireshark to Capture Real-time Packets

Fig. 6 Atmel Wireshark Interface Sniffer, Sniffer hardware platform, and Wireshark used to capture frames operating on IEEE 802.15.4 channels in 2.4GHz ISM band

In our experiment, the distance from the SmartThings Hub and connected sensors are adjusted at 4m, 8m, and 13m. In addition, traffic generation rate of each sensor is varied. Data was collected from several experiments at different times. Each experiment lasted for several hours to get stable results as we did not observe any qualitative differences in our results. All experiments were conducted in an industrial institution. From the database captured by Wireshark, we investigate the network topology, the operating channel, and the network operation of current Smart Home Starter Kit. Moreover, the performance of IEEE 802.15.4-based IoT commercial products in terms of E2E delay and FRR are also investigated.

4. Performance Evaluations and Discussions

4.1. Important Findings

First, 16 channels in 2.4GHz ISM band are scanned to find the operating channel of Smart Home Starter Kit. The result shows that the Smart Home Starter Kit operates on channel 14, i.e., 2.42 GHz with data rate of 250kbps. Fig. 7 shows the 16 IEEE 802.15.4 operating channels in 2.4 GHz ISM band and channel 14 at which the Smart Home Starter Kit works. We then analyze packet capturing in channel 14. We found that each sensor just communicates with the SmartThings Hub. Two sensors do not directly talk with each other. Therefore, it can be inferred that the Smart Home Starter Kit uses star topology. In addition, there is no beacon frame sent regularly from the SmartThings Hub to other sensors, meaning that non-beacon-enabled mode is employed. Although the non-beacon-enabled mode consumes much energy than the beacon-enabled mode, it can reduce the entire latency. For this reason, delay-sensitive sensors of the Smart Home Starter Kit employ the non-beacon-enabled mode. Whenever a frame is successfully received either by the SmartThing Hub or by sensor, a 5-byte acknowledgement frame is sent to confirm the reception. We focus on the transmission between the SmartThing Hub and the door sensor. The communication between the two accurately follows the IEEE 802.15.4 standard. In particular, in direct data transmission, when the SmartThings Hub receives a 54-byte data frame from sensor, it immediately sends an acknowledgment frame to notify the transmission status. In indirect data transmission, the sensor first sends 12-byte request frame to the SmartThings Hub to ask for downlink data frame. Upon receiving the request frame, the SmartThings Hub replies with acknowledgement frame. Then, it transmits 45-byte data frame to the sensor. After receiving data frame, the sensor transmits another acknowledgement to the SmartThings Hub. Fig. 8 and Fig. 9 show how operation of the Smart Home Starter Kit in both direct and indirect data transmission respectively matches with the operation of non-beacon-enabled mode defined in the IEEE 802.15.4 standard.

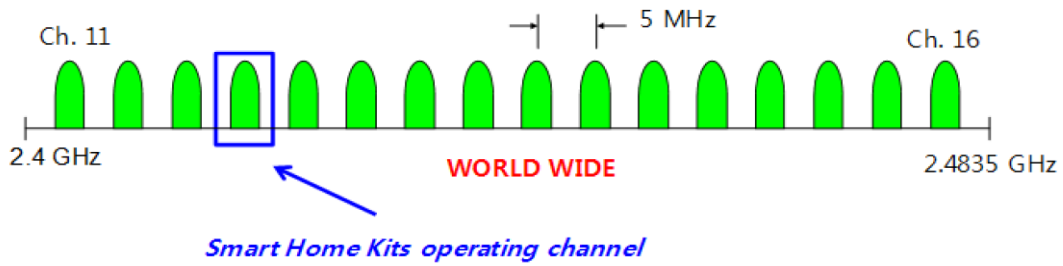


Fig. 7 The 2.4GHz ISM IEEE 802.15.4 operating channels in which the Smart Home Starter Kit operates on channel 14

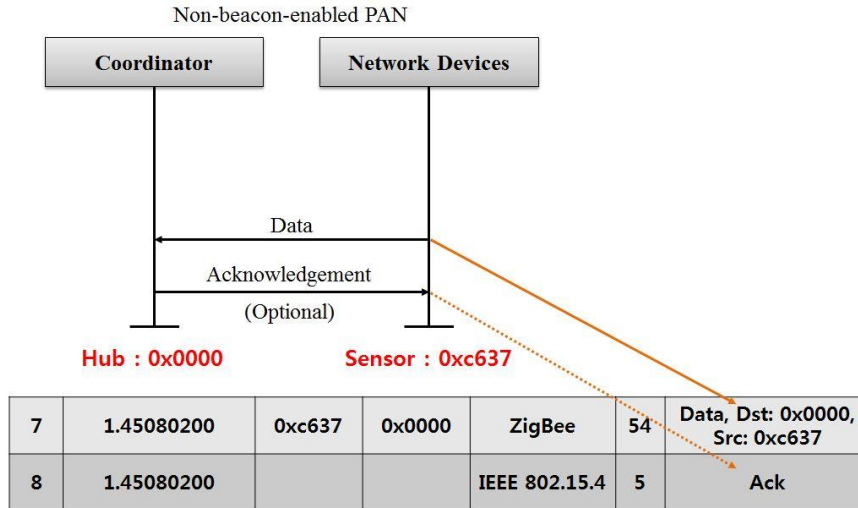


Fig. 8 Matching between operation of Smart Home Starter Kit and that of IEEE 802.15.4 standard - Direct data transmission

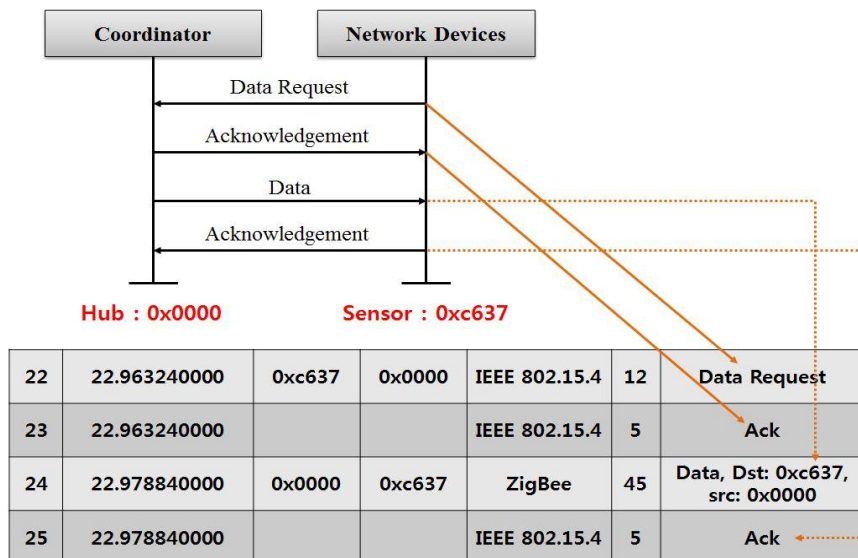


Fig. 9 Matching between operation of Smart Home Starter Kit and that of IEEE 802.15.4 standard - Indirect data transmission

4.2. Performance Evaluations

Our work investigates end-to-end delay (E2E Delay) and frame reception ratio (FRR) for the Smart Home Starter Kit in both an office and a home environment. We selected the door sensor for the evaluation because its frame generation can be controlled. We divide our experiments into two cases. In one case, there is no closing door action. SmartThings Hub was configured to send data to the sensors in 20 seconds and 6 seconds intervals. However, this interval may be slightly varied due to the collision with other sensors in the network. In the second case, closing door action is generated. Whenever the closing action is detected, the

door sensor sends data to the SmartThings Hub. In addition, the sensor regularly sends data request to the Hub almost every 1s if there is no closing door action. The sending interval is reduced from 6s to 1s due to closing door actions and interference with other sensors. The result is the mean value obtained from several experiments in which each experiment lasts for several hours. Frame Reception Ratio (FRR): We focus on direct data transmission from the sensor to the SmartThings Hub because this uplink traffic is more important than downlink traffic. Therefore, the FRR is calculated only for data frame sent by the door sensor to the SmartThings Hub but not successfully received by the SmartThings Hub. According to the operation of CSMA/CA algorithm explained in II-B, if the sensor fails to attempt the channel three times, the frame will be dropped. This frame is considered as lost frame. In our evaluations, the retransmitted frames are not considered as new frames. In the collected database, we see that if the sensor does not receive acknowledgement frame from the SmartThings Hub, it retransmits data frame but no more than three times. Lost frames are kept through 'sequence number' field of each data frame. The FRR is calculated as the following:

$$FRR = \left(1 - \frac{\text{Total number of frames lost}}{\text{Total number of frames sent}} \right) \times 100 \quad (\%) \quad (1)$$

Fig. 10 illustrates how FRR depends on distance from SmartThings Hub to the door sensor in our office environment. This can be inferred from the figure that the FRR decreases as the distance increases. This is understandable because long distance affects radio signal strength i.e., signal attenuation increases as distance increases. In fact, FRR also depends on the number of sensors in the network. In our experiment with distance 4m from the SmartThings Hub to the door sensor and no closing door action, the FRR is 99.46% with 3 sensors in the network. However, if the number of sensors operating in the same frequency is 300, the FRR drops to 98%. This is reasonable because more sensors in the network results in more collision. It also can be seen from the figure that the FRR without closing door action is higher than that of no closing door action. This is because closing door actions results in more traffic in the networks. Consequently, more collision and more frames lost will occur. It is also worth noting that if generated closing door actions exceed the buffer limitation, the door sensor cannot capture all data frames and thus many data frames cannot be seen from Wireshark. The reason is that sensor fails to detect all closing door action and that data frames are dropped by limited queue size of the sensor. The frames lost by the latter case can be simply estimated by frame generation rate and memory of the sensor. End-to-End Delay (E2E Delay): Only delay for successfully transmitted data frames is considered, i.e., delay caused by dropped frames is ignored. E2E delay is calculated from the point sensor sends data frame to the SmartThings Hub until the point the frame is received by the Hub.

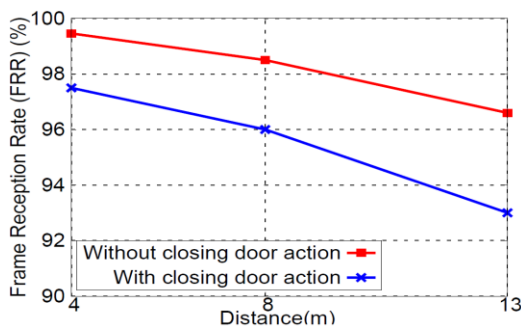


Fig. 10 Frame Reception Rate with respect to distance from SmartThings Hub to door sensor in the office environment

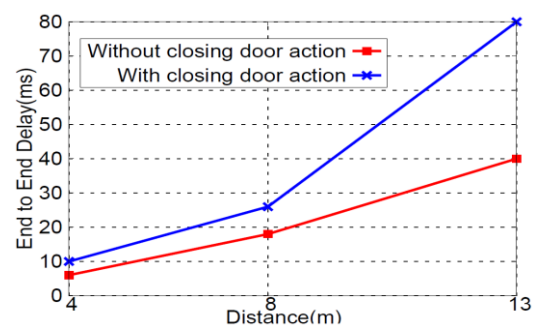


Fig. 11 E2E Delay with respect to distance from SmartThings Hub to door sensor in the office environment

Fig. 11 shows how E2E delay varies with the distance from the door sensor to the SmartThings Hub in our office environment. As can be observed from the figure, as distance increases, E2E delay increases as well because data frame has to travel for a longer distance. However, distance does not have strong impact on the E2E delay. This is shown in the packet capture that when a data frame is transmitted after only one channel attempt. In this case, we observe almost no delay for the sensor to receive acknowledgment from the SmartThings Hub. Thus, the main reason for delay is the time to implement CSMA/CA algorithm, i.e., the time to attempt radio channel. In each time, once the sensor senses that the channel is busy, it backs off and

performs carrier sensing again. This activity indeed contributes a significant part to the E2E delay. We observe from the figure that when there are closing door actions, the E2E delay dramatically increases with the distance. This is due to the fact that closing door actions create more traffic and more collisions in the network. As the result, the door has to do more channel attempts, and these results in higher E2E delay. In addition, in our experiments, bad wireless channel conditions caused by wireless interferences aggravate the overall E2E delay.

Fig. 12 illustrates FRRs in our home environment with various distance settings. The overall FRRs are lower than the office environment. The main differences of the environments between home and office are the number of Wi-Fi and Bluetooth devices within the coverage of SmartThings Hub. The Smart Home Starter Kit shares the 2.4GHz ISM band with other wireless technologies such as Wi-Fi, Bluetooth and so on. In our office, there are lots of commercial Wi-Fi and Bluetooth devices that operate on the same frequency band with the SmartThings hub. Those wireless technologies can interfere with the SmartThings hub. Thus, the hub suffers from severe wireless interferences. Those interferences cause critical packet corruptions. Fig. 13 depicts E2E delays in our home environment. Those interferences from other technologies significantly degrade E2E delay performance of the hub. Since diverse devices occupy the operating channel of the hub, the idle time of channel is reduced. So, it directly affects the delay performance of the hub.

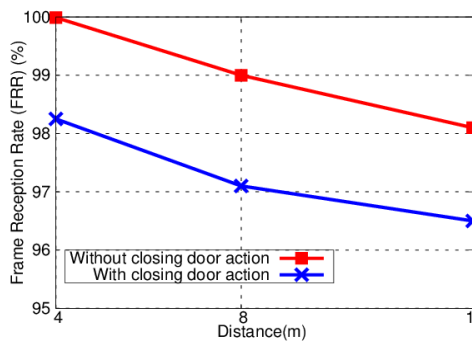


Fig. 12. Frame Reception Rate with respect to distance from SmartThings Hub to door sensor in the home environment

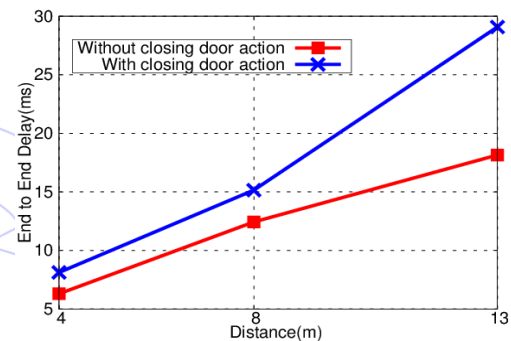


Fig. 13. E2E Delay with respect to distance from SmartThings Hub to door sensor in the home environment

4.3. Discussions

We pointed out from the experiment that non-beacon-enabled PAN with star topology is currently used for connectivity between the SmartThings Hub and other home appliances sensors. However, since the non-beacon-enabled PANs do not allow radio duty cycle (RDC) in which network devices can enter low power states to reduce their power consumptions, the current Smart Home Starter Kit is not power efficiency. In addition, as the smart home automation products are still in a very early state, they are implemented with simple solutions. It may be possible that in their next versions, other topologies and RDC can be applied to improve power efficiency and network coverage. In addition, the interference impacts of other wireless technologies are severe in the office environment. To avoid the problem, the hub needs to learn the interference intensity of various wireless technologies and hop to preferable channel in a specific environment.

5. Conclusion

This paper demonstrates how IEEE 802.15.4 is used and how it performs in the commercial SmartThings Kit products. We investigate the network topology, the operating frequency, the network operation mode and how data is transferred in the products. Besides, we analyzed its performance in terms of frame reception rate ratio, end to end delay, and network throughput. To the best of our knowledge, this is the first work to analyze commercial IEEE 802.15.4 based IoT products. In addition,

limitations and possible improvements of future products are also discussed. The results of this paper therefore can be used to guide the developments of future IoT home automation products.

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