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PREDICTIVE CHANNEL SCANNING AND SWITCHING ALGORITHM FOR THE COEXISTENCE OF IEEE 802.15.4 AND WIFI

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Abstract. *Among the coexistence problems for the 2.4-GHz industrial, scientific, and medical (ISM) band, interference between WiFi and IEEE 802.15.4/ZigBee networks in particular has become a dominant problem because of the wide installation of WiFi access points (APs). This paper proposes a predictive channel scanning and switching (PCSS) algorithm that efficiently avoids WiFi interference. In this PCSS algorithm that is based on an IEEE 802.15.4e-2012 multi-channel communication network, each device rapidly senses the interference and switches the channel. This paper evaluates the performance of PCSS by comparing it with existing methods and shows that PCSS is superior.*

Keywords: Channel adaptation, IEEE 802.15.4, Interference, Multi-channel, WiFi

1. **Introduction.** An IEEE 802.15.4 low-rate wireless personal area network (LR-WPAN) is a physical/media access control (MAC) layer protocol for a ZigBee network. It is used at 868 MHz, 915 MHz, and 2.4 GHz. Among these, 2.4 GHz is an industrial, scientific, and medical (ISM) band used by both WiFi and Bluetooth.

The transmission power of WiFi is about 30 times that of IEEE 802.15.4 [1]. It is known that WiFi usually has a radio range of about 100 m, whereas IEEE 802.15.4 has a range of about 10 m [2]. Therefore, there are many possibilities for an IEEE 802.15.4/ZigBee network to be influenced by WiFi, and it is susceptible to interference from WiFi. Because WiFi is now being used in many mobile devices following the explosive popularity of smart phones, laptop computers, and tablet PCs, it might exist everywhere. In addition, IEEE 802.15.4/ZigBee networks are used in various places for applications such as home automation, consumer electronics, healthcare monitoring, surveillance, and sensor networks. Thus, there is an increasing possibility that IEEE 802.15.4/ZigBee and WiFi might exist in the same region. An environment in which numerous WiFi access points (APs) are established independently without planning also yields interference problems because of the coexistence of IEEE 802.15.4 and WiFi.

ZigBee communication can be used for mobility and serviceability of patients and patient's condition is efficiently monitored and cared by remote patient monitoring (RPM) in hospitals [3]. However, if many patients use ZigBee channels at the same time, channel overlapping may result. In addition, if there is interference from WiFi as a result of using the same frequency band, continuous and reliable communication of important data such as vital signs may not be expected.

Radio frequency (RF) remotes are faster, more reliable, and have a greater range than infrared (IR) remotes. Furthermore, they do not require line-of-sight operation like IR remotes. As a result, RF remotes have been progressively replacing IR remotes in homes. They need to consider interference of microwave ovens, cordless phones, and home appliances using WiFi and Bluetooth because these all commonly use the 2.4 GHz band. The dynamic multi-channel agility (DMCA) method proposed in [4] uses the channels chosen within a subset of available channels the target and control devices construct. However, because the method uses a subset of channels, it wastes channel resources.

A prompt multi-channel scanning and switching algorithm that predicts the effect of interference in advance is necessary. A channel adaptation mode applied to the predictive channel scanning and switching (PCSS) algorithm enables ZigBee devices to avoid interference by comparing the energy detection (ED) value in the current channel with a proper threshold before the channel becomes unavailable. Even though PCSS selects an available channel among 16 channels, the channel selection and switching process is prompt and quickly predicts interference.

Studies have examined channel switching for multiple channels as a method that can be used in an IEEE 802.15.4/ZigBee network to avoid interference from WiFi with relatively strong transmission power and wide coverage. There have been several studies on switching channels using a table, in which channel state information is saved [5,6] to avoid interference in an IEEE 802.15.4/ZigBee network. In one study [5], the nodes of a network included in the interference domain switch to another available channel and then switch back to the previous channel once there is no more interference. The method proposed in [6] is to switch to the channel whose state is judged to be the best by using a channel_info table in which the energy level of each channel is saved when the interference occurs. However, it switches channels using the channel information obtained before the interference occurs. Thus, repeated attempts to switch to a channel that cannot be used can occur.

In addition, one study proposed an algorithm that switches channels by reflecting the current state [7]. It selects and changes to the new channel through a pseudo random sequence generator using a PAN ID, a cluster ID, the current channel, and counter parameters. A channel switching algorithm based on random channel selection considering the current state cannot guarantee the channel quality after switching, and this method cannot be used to select good channels stochastically. Another random channel selection method, random prime double hash (RPDH), was proposed in [8]. In the worst case scenario, selecting a new channel may lead to worse results than scanning and switching all channels.

In addition, the CSMA-RTS-DATA protocol, which can be applied to a multi-channel system, was proposed in [9]. It designates one control channel among 16 channels and adjusts receivers to this control channel. The sender transmits a request to send (RTS) packet when the control channel is unused. The availability of the channel is determined using a clear channel assessment (CCA) process before the sender transmits the packet. If the channel is used, the sender goes through the random backoff process and then attempts to transmit again. The receiver changes the control channel until it receives an RTS without error, at which point the sender forwards data packets through the control channel where this RTS packet was received. However, this method requires a CCA process, a random backoff process, and a process in which the receiver changes the control channel until the receiver obtains an RTS. These processes incur overhead, real-time performance is affected by delay, and multi-channel efficiency decreases.

This paper proposes an algorithm that solves the problems that can occur in the aforementioned existing channel switching processes. The proposed algorithm efficiently uses the 16 channels in an IEEE 802.15.4/ZigBee network and has the potential to minimize the overhead, delay, and redundant procedures that can occur when switching channels.

The remaining parts of this paper are as follows. Section 2 explains the multi-superframe structure of IEEE 802.15.4. Section 3 describes the PCSS algorithm proposed by this paper and the channel diversity modes to which the algorithm is applied. In Section 4, the performance of a network using the PCSS algorithm is evaluated. Section 5 draws the final conclusion of this paper.

2. **Multi-Superframe Structure of IEEE 802.15.4.**

The superframe structure used in IEEE 802.15.4/ZigBee is shown in Figure 1.

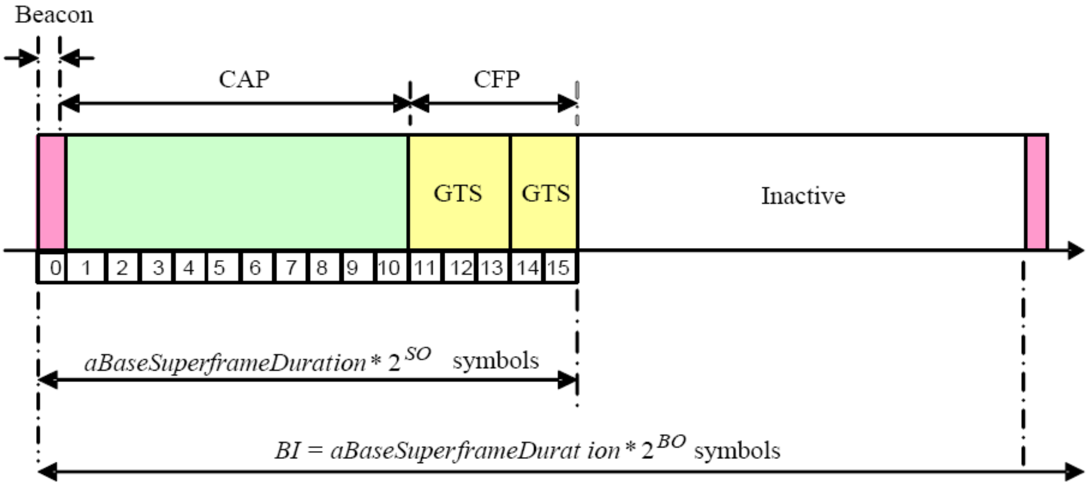

Figure 1. Superframe structure

The active portion of each superframe is divided into 16 slots and is composed of three parts: a beacon, contention access period (CAP), and contention free period (CFP). The CFP follows immediately after the CAP and extends to the end of the active portion of the superframe. If guaranteed time slots (GTSs) have been allocated by the PAN coordinator, they are located within the CFP and occupy contiguous slots. The CFP therefore grows or shrinks depending on the total length of all combined GTSs [10]. The structural characteristics of the GTSs and the superframe are such that a maximum of seven nodes can be allocated as GTSs, and GTS slots are to be used in a single channel. In order to solve these limitations, a new multi-superframe structure was proposed in the IEEE 802.15.4e-2012 standard [11].

The multi-superframe structure is described by the values of beacon order (BO), superframe order (SO), and multi-superframe order (MO). BO describes the interval at which the coordinator transmits its beacon frame. The values of BO and the beacon interval (BI) are related as follows:

$$BI = BSD \times 2^{BO}\ symbols,\ 0 \leq BO \leq 14 \tag{1}$$

where BSD is the number of symbols within a superframe when the superframe order (SO) is equal to 0. If BO = 15, the coordinator does not transmit beacon frames except when requested to do so, such as on receipt of a beacon request command. The values of SO and MO are ignored if BO = 15. SO describes the length of a superframe. The values of SO and the superframe duration (SD) are related as follows:

$$SD = BSD \times 2^{SO}\ symbols,\ 0 \leq SO \leq 14. \tag{2}$$

MO also describes the length of a multi-superframe, which is a cycle of repeated superframes. The values of MO and the multi-superframe duration (MD) are related as follows:

$$MD = BSD \times 2^{MO} \; symbols, \; 0 \leq SO \leq MO \leq BO \leq 14. \tag{3}$$

For example, the multi-superframe structure in the case of BO = 6, SO = 3, and MO = 5 is shown in Figure 2. A multi-superframe structure is composed of three parts, the beacon, CAP, and CFP, like the superframe structure of the legacy IEEE 802.15.4, but the superframe can be repeatedly used within the beacon interval. In the CFP of the superframe, one of the 16 channels can be chosen and used in each GTS slot and, for this channel selection, an energy detection (ED) scan should be conducted for each channel.

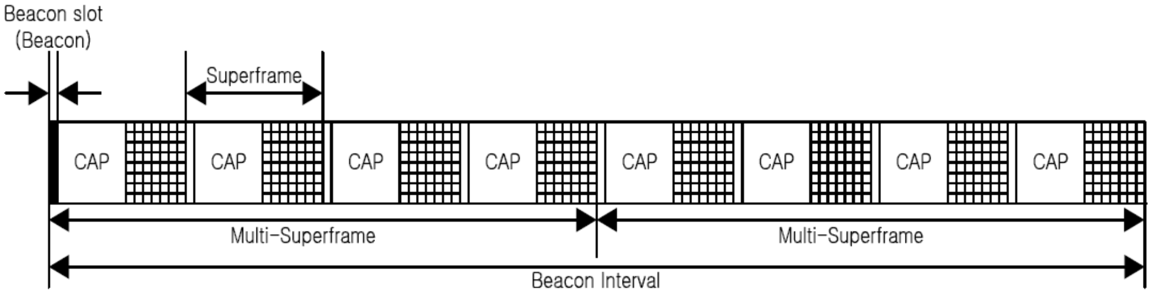

Figure 2. Multi-superframe structure

An ED scan allows a device to measure the energy of each requested channel. During the ED scan, the MAC sublayer discards all of the frames received over the PHY data service. The time needed for the ED scan process can be calculated as

$$T_{ED} = BSD \times (2^n + 1) \; symbols \tag{4}$$

where n is a chosen integer value between 0 and 14, called the scan duration parameter at the standard. As this n increases, the time for scanning increases exponentially and one symbol is equal to 16 μs in the IEEE 802.15.4 standard.

3. Predictive Channel Scanning and Switching Algorithm.

3.1. Algorithm.

In the early period of an IEEE 802.15.4/ZigBee network's operation, each coordinator selects a default channel on the basis of the coordinator ID, and thereby the channel of each cluster is not duplicated. Each coordinator sends the beacon frame through the default channel and measures the RSSI value with the GTS request message sent by the devices that received the beacon. The devices that do not want GTS allocation, and thus did not send a GTS request message, send a message to the coordinator requiring zero GTS. This prevents the coordinator from misunderstanding that the GTS request message failed to be received because of interference, and it allows the coordinator to obtain the RSSI value with the received GTS request message.

The coordinator determines the channel's availability by comparing the RSSI value with the threshold value established by the network manager. When the coordinator senses that the default channel is busy, it changes the current channel to a channel that is not being used by the nearby clusters. The coordinator determines that the device is located in the interference range when the GTS request message is not received and RSSI cannot be measured. The device determines that interference has occurred when the GTS response message does not arrive, then it switches the channel using the proposed channel switching algorithm. A flow chart for the proposed channel switching algorithm is shown in Figure 3.

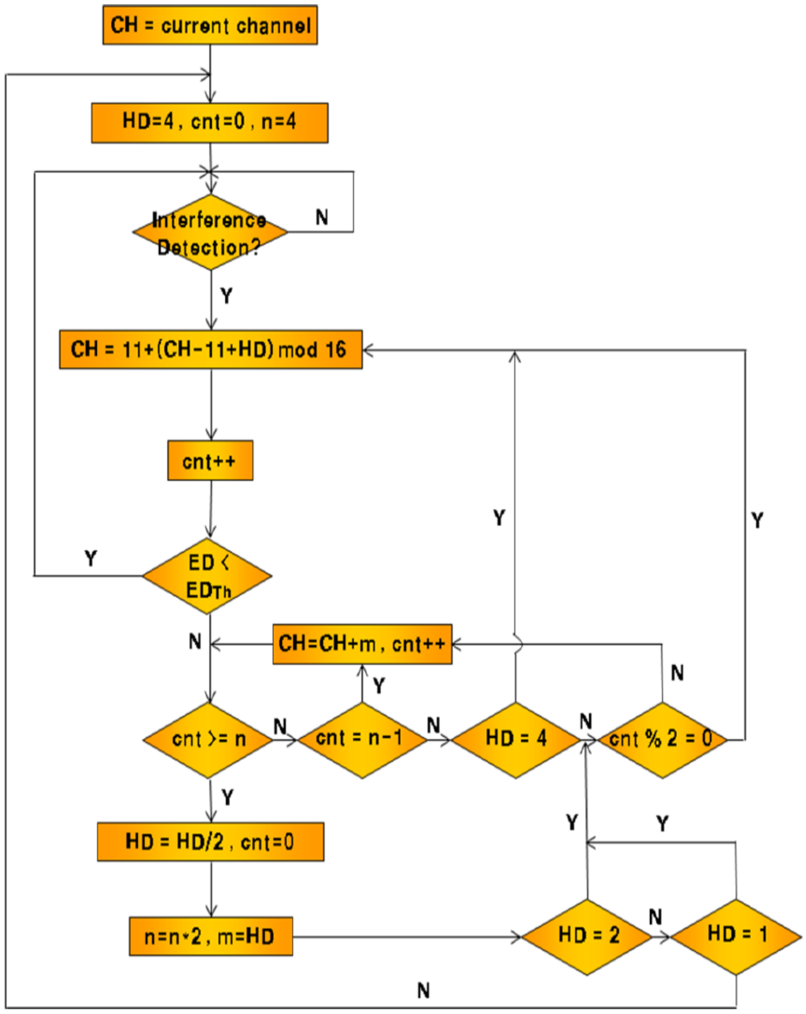

Figure 3. Flow chart of proposed channel switching algorithm

The hopping distance (HD) needed to switch the channel is set to 4 in the initial stage. When interference occurs in a channel being used among the 16 channels (ranging from the 11th to the 26th channel of IEEE 802.15.4), the device can avoid WiFi interference by hopping as many as four channels from the current channel of the IEEE 802.15.4/ZigBee network. The hopping distance to avoid WiFi interference is derived from the relation between WiFi and IEEE 802.15.4 channel frequencies, as shown in Figure 4. Using the algorithm

$$CH = 11 + (CH - 11 + HD) \bmod 16 \tag{5}$$

which determines the next channel to hop, the device switches to a channel separated from the current channel by the HD. In every case where channel switching is attempted, the counter value is increased by 1 (cnt++), which controls the number of attempts selected for each HD.

Whether to switch the channel or not is determined based on the coordinator's measurement of the energy detection (ED) for the channel that one intends to switch. When the value of ED is smaller than the threshold, $\mathrm{ED_{Th}}$ ($\mathrm{ED} < \mathrm{ED_{Th}}$), the IEEE 802.15.4/ZigBee network switches the channel and returns to the interference detection stage.

When the interference stems from non-WiFi or multiple WiFi stations, or from the same IEEE 802.15.4/ZigBee network, hopping four channels may not prevent interference. However, in our proposed algorithm, four-channel hopping is conducted first because there

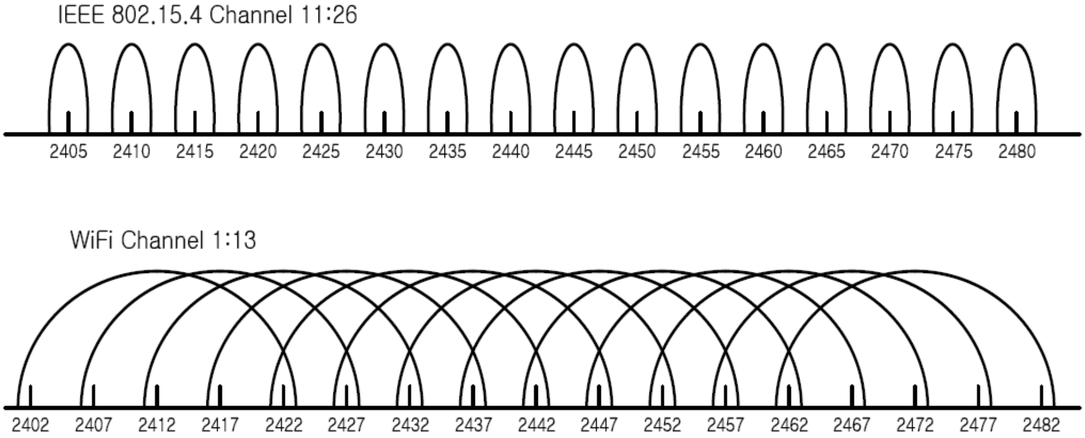

Figure 4. Channel frequencies of IEEE 802.15.4 and WiFi

is a strong possibility of WiFi interference according to the existing studies [12,13], and thus WiFi interference should be preferentially considered.

Let *cnt* denote the number of attempts of channel switching. The four-channel hopping is continued until *cnt* is 4 (that is n), as shown in Figure 3. *cnt* becomes 4 when the channel hopping returns to the default channel, which means that the four-channel hopping has failed to find an available channel. The hopping distance of 4 is changed to 2 by HD = HD/2, as seen in Figure 3. When hopping is conducted with an interval of four channels, the maximum value of *cnt* is 4, but when HD is changed to 2, the maximum value of *cnt* becomes 8, or double. However, the number of channels switched by (5) is four because the channels judged to be unavailable in the previous process of hopping four channels are skipped in the "$cnt\%2 = 0$" stage of Figure 3.

The proposed PCSS algorithm first considers WiFi interference, predicts a stochastically high quality channel, and forces the nodes to switch to that channel. Therefore, the 16 channels of an IEEE 802.15.4/ZigBee network can be used efficiently, with a reduction in the overhead and redundant procedures for the channel switching process compared with the existing methods. This has the advantage of reducing delay.

Let us describe channel hopping based on PCSS through the example of the channels used in the IEEE 802.15.4/ZigBee network. As noted, an IEEE 802.15.4/ZigBee network using the 2.4-GHz ISM band uses channels 11 to 26. It is assumed that the default channel is set to 11 by the coordinator ID. When interference is detected, PCSS predicts that it is WiFi interference and repeatedly takes four hops forward within the limited hop count until a clear channel is found. If no clear channel is discovered, even after going through the four iterations of the hopping process, the channel returns to the default channel. Because the previous channel hopping has already determined that channels 11, 15, 19, and 23 (with four-hop intervals) cannot be used PCSS investigates the availability of channels using intervals of two hops from channel 11. The channels considered using two hop intervals from channel 11 are 13, 15, 17, 19, 21, 23, and 25, and PCSS considers the availability of channels 13, 17, 21, and 25, excluding 11, 15, 19, and 23, which have already been judged to be unusable. If no available channel can be found until it returns to the default channel, 11, HD is reduced to 1, which is half the value of the last HD, and *cnt* increases to 16, which is double the last *cnt*. This channel switching makes a maximum of eight attempts because every other channel has already been scanned.

3.2. **PCSS in channel diversity modes.**

The proposed PCSS algorithm can be applied to the channel diversity mode and utilized for multi-channel switching to avoid interference in IEEE 802.15.4/ZigBee networks. The PCSS algorithm also can be applied to the channel adaptation mode, in which the communication channel is switched to a new channel when ED reflecting the channel state becomes higher than a threshold. For example, as shown in Figure 5, when nodes use channel 11 and it is determined that this channel is impossible to use due to interference, the PCSS algorithm determines the availability of channel 15. If channel 15 is available, the coordinator makes devices switch the current channel to 15. Subsequently, if channel 15 is affected by interference, it is changed to channel 19 by the PCSS algorithm, as shown in Figure 5.

This shows a case in which a device is selected as one that can use the next channel on the first attempt. If the switching to an available channel was conducted after many channel switching attempts, the result is different from Figure 5. The channel adaptation method using the PCSS algorithm is a channel diversity approach; devices are switched to a new channel using the PCSS algorithm whenever the channel state becomes worse than a predefined value.

The second channel diversity mode is a channel hopping method in which nodes send and receive frames at different channels using the reserved frequency channel sequence. For example, as shown in Figure 6, nodes send and receive frames changing the channel from 11 to 16. However, when channels 15 and 16 become hard to use because of interference, the PCSS algorithm detects the availability of channels 19 and 20, which are the first candidates for the next available channels. When they are available, the nodes

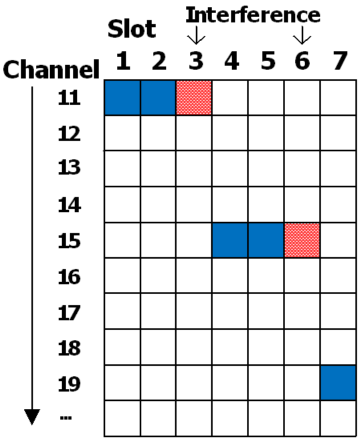

FIGURE 5. Example of the channel adaptation method

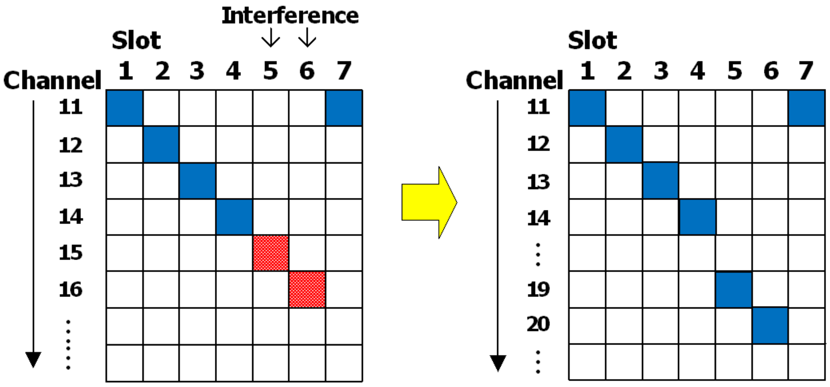

FIGURE 6. Example of the channel hopping method

change channels into them. Among the reserved channel sequences that are used, if there is a channel whose ED becomes higher than a threshold, the PCSS algorithm changes the channel sequence.

The multi-channel network in this paper selects a channel diversity mode using the PCSS algorithm, becoming a more reliable network based on the IEEE 802.15.4 protocol through the channel selection and switching process.

4. **Performance Evaluation.** To evaluate the performance of PCSS, a simulation was conducted using the cluster-tree network in an IEEE 802.15.4/ZigBee network. In this simulation, a channel adaptation method that used PCSS was applied as a channel diversity mode. In this simulation, the proposed PCSS algorithm was compared with the sequential channel scanning and switching (SCSS) and random channel scanning and switching (RCSS) methods, which switch channels in a sequential or random order, respectively, to select an available channel when interference occurs.

The parameters listed in Table 1 were used for the simulation. The ScanDuration parameter in [11] was changed from 0 to 9, and the average traffic generation period of each node in the network was set as 500 ms. The average packet size was established as 3840 bits.

Figure 7 shows the average channel scan times for different ScanDuration parameters measured in three different interference environments. The channel scan time is defined here as the time needed to find an available channel after scanning begins. The three interference environments were the case in which four WiFi APs use channels 1, 5, 9, and 13, respectively, the case of channels 2, 4, 6 and 8, and the case of channels 1, 4, 7, and 10.

Table 1. Parameters for performance evaluation

Parameters	Values
BO (Beacon order)	6
MO (Multi-superframe order)	5
SO (Superframe order)	3
IEEE 802.15.4 radio range	10 m
WiFi radio range	100 m
Link speed	250 kbps

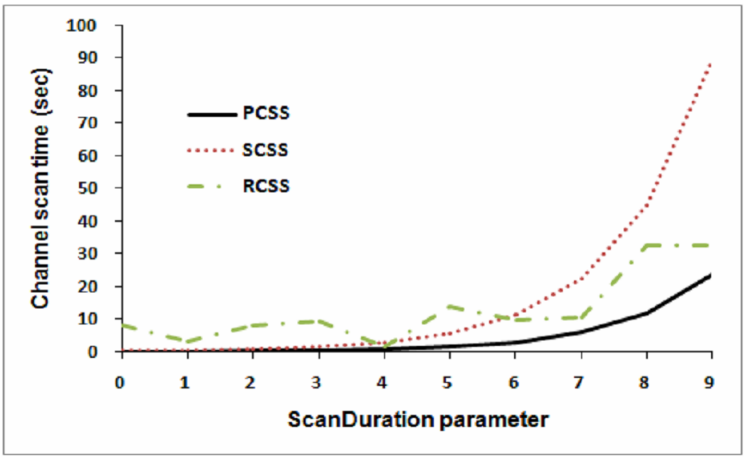

Figure 7. Channel scan time vs. ScanDuration parameter

When entering the influence of interference, the SCSS and RCSS methods change the channel in a sequential or random manner and check the channel's availability. The PCSS algorithm first considers WiFi interference to have the highest probability of being the source of interference and changes the HD. The channel scan time of PCSS can theoretically be reduced up to 1/4 of SCSS. In the simulation, when SCSS and RCSS methods scanned channels, the average scan time was 17.98 sec and 13.01 sec, respectively. When the PCSS method scanned channels, the average scan time was 4.76 sec. Therefore, PCSS outperformed SCSS by 73.53% and RCSS by 63.41% in terms of the average scan time required to find available channels.

We measured the channel scan time when changing the number of Wi-Fi APs. The ScanDuration parameter was fixed as 3, among the possible values of 0 through 14, and the number of Wi-Fi APs as sources of interference was increased by one from 0 to 7. In this simulation, the average values were computed under three different interference environments, where the Wi-Fi APs used different channels, as mentioned in previous simulations. The average traffic generation period was 500 ms, and the average packet size was 7680 bits. Figure 8 shows the average channel scan times for SCSS, RCSS, and PCSS obtained under such conditions. According to the simulation results, when changing the number of APs, the average channel scan time was 9.20 sec and 7.19 sec when using SCSS and RCSS, respectively. The average channel scan time was 4.75 sec when using PCSS.

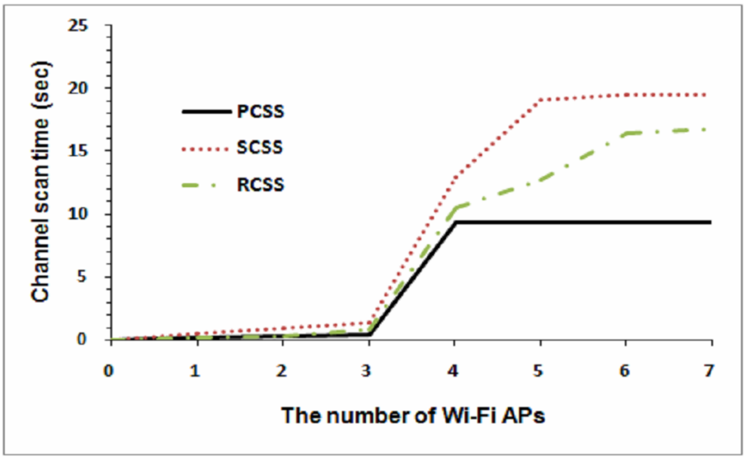

FIGURE 8. Channel scan time vs. number of WiFi APs

In the next simulation, the average waiting delay of the wireless nodes was obtained whereas changing the average traffic generation period. The ScanDuration parameter was fixed as 2. The simulation was conducted under three different environments: three WiFi APs using channels 1, 5, and 9; four WiFi APs using channels 1, 5, 9, and 13; and five WiFi APs using channel 1, 3, 4, 7, and 10.

Figure 9 shows the average times that the nodes waited for transmission when the traffic generation period was increased from 100 ms to 1100 ms by increments of 200 ms, using SCSS, RCSS, and PCSS. A traffic generation period of less than 100 ms was not used because the traffic rate is more than the maximum data rate of IEEE 802.15.4 using 2.4 GHz. For example, if six nodes generate traffic with an average of 3840 bits per 90 ms, (3,840 bits × 6 nodes × 11.11 times/s = 255,974 bps), the traffic rate exceeds 250 kbps, which is the maximum data rate of IEEE 802.15.4 using 2.4 GHz. SCSS, RCSS, and PCSS have different waiting delays to avoid interference because of differences in the processes used to select and switch to a new channel. The average waiting delay of SCSS,

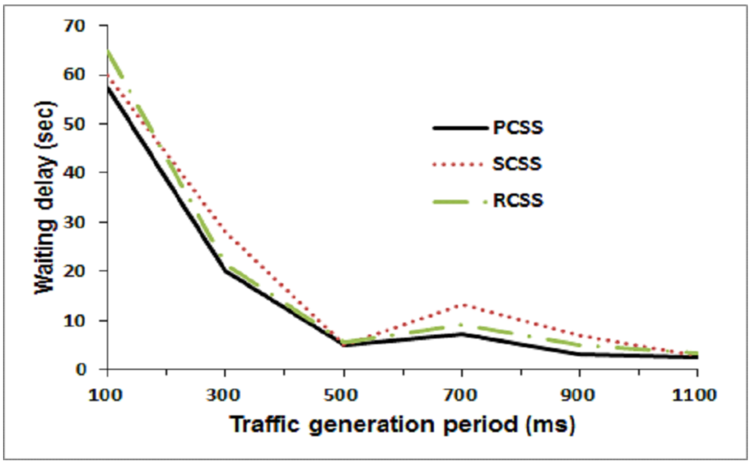

FIGURE 9. Waiting delay vs. traffic generation period

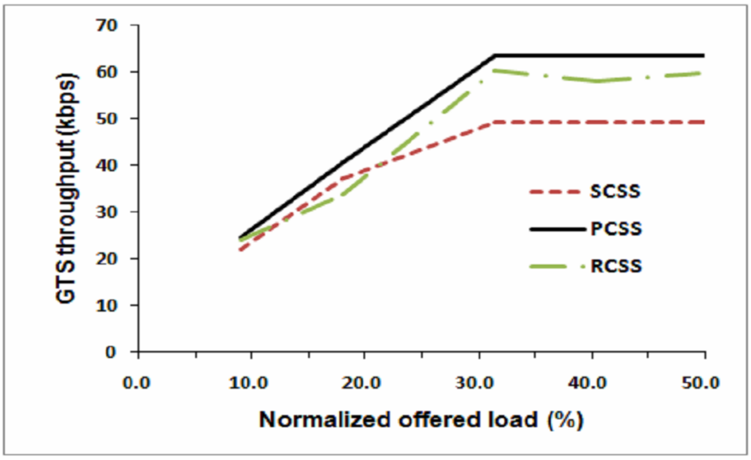

FIGURE 10. GTS throughput vs. normalized offered load

RCSS, and PCSS was 19.32 sec, 18.24 sec, and 15.89sec, respectively. The PCSS is better than the SCSS and RCSS methods by 17.75% and 12.88% in terms of waiting delay.

The next simulation was conducted using the parameters listed in Table 1 under the interference of WiFi APs that used channels 1, 5, 9, and 13. The average GTS throughput was measured with the ScanDuration parameter set to 0, 2, or 4. The average packet size that nodes generated every period was set to 1920 bits, and the average traffic generation period was varied. The offered load was defined as the amount of incoming traffic to the network. In a 2.4-GHz IEEE 802.15.4/ ZigBee network, the maximum data rate is 250 kbps. The normalized offered load is a percentage of the offered load to the maximum data rate and is used as the x axis of the graph in Figure 10. When the average traffic generation period of nodes is 45 ms or less, the normalized offered load becomes 1 or more, that is, the offered load exceeds the maximum data rate (250 kbps) at the 2.4-GHz frequency. Thus, we only conducted the simulation for a period of 45 ms or more.

As shown in the simulation results of Figure 10, as the amount of traffic in the network increased, the GTS throughput increased. The normalized offered load in SCSS, RCSS, and PCSS increased up to about 31.5% and then reached the limit. It was saturated because SCSS, RCSS, and PCSS used multi-channel communications in GTSs. Thus, the generated traffic was handled in GTSs, excluding CAP in the superframe. The GTS throughput was an average of 41.26 kbps when using SCSS in the simulation, 47.22 kbps when using RCSS, and 48.04 kbps when using PCSS. PCSS minimized the waiting delay by rapidly switching to an available channel to avoid interference. Thus, it demonstrated better results in the aspect of GTS throughput. The GTS throughput of PCSS was 16.43% higher than that of SCSS and also 1.74% higher than that of RCSS.

As a result, in the case of the proposed PCSS, the channel scan time can be reduced by up to 26.47%, and throughput can be increased by 16.43% compared with that of the original method in a GTS interval. Using the proposed PCSS algorithm in multi-channel ZigBee networks can be beneficial since it offers more real-time traffic.

5. **Conclusion.** An IEEE 802.15.4/ZigBee network has several advantages: it is inexpensive and requires less power than other networks. It is used in various areas such as consumer electronics for home automation and smart grid and sensor network systems for surveillance and healthcare monitoring. However, it has one major drawback: WiFi interference; it can only provide continuous and reliable service if this is addressed. In this paper, a PCSS algorithm was proposed as a solution to the problem of interference from WiFi APs and terminals. Its performance was compared with the existing SCSS and RCSS algorithms. The simulation results showed that the performance of the PCSS algorithm was better in terms of channel scan time, waiting delay, and GTS throughput. PCSS can thus make it possible to search for available channels predictively and promptly, considering WiFi interference.

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