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An Experimental Analysis of Effects of IEEE 802.11 Channels on RSSI-based Indoor Localization System with IEEE 802.15.4

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ABSTRACT

Many indoor localization studies are now actively underway. Generally, the indoor localization algorithms are based on the IEEE 802.15.4 wireless sensor networks. However, because of the sensor nodes' limitations, their radios are more susceptible to noise and interference than other wireless technologies. These are critical factors in the rigorous indoor environment, whose effects may not be the same on all channels of a sensor network. Many buildings are equipped with IEEE 802.11 access point (AP) to provide internet service. IEEE 802.11 AP can have a serious impact on the IEEE 802.15.4 performance if the channel allocation is not carefully taken into account. In this paper, we analyze the effect of IEEE 802.11 AP on location errors in received signal strength indicator (RSSI)-based indoor localization system with IEEE 802.15.4. We performed several tests in a house in order to minimize the influence of other IEEE 802.11 APs. We performed transmitting/receiving test by varying the location of IEEE 802.11 AP. Also, we composed an indoor localization system, and measured the location error of mobile node by varying the location of IEEE 802.11 AP. Our study shows that co-channel interference due to use IEEE 802.11 AP affects the RSSI value of sensor node. Ultimately, it has a harmful influence on location error.

Keywords:
Channel interference, IEEE 802.11, IEEE 802.15.4, Localization, Location error, Received signal strength indicator.

1. INTRODUCTION

Wireless sensor networks (WSNs) offer a diverse range of applications in many fields including indoor localization, healthcare, environmental monitoring, military, and smart homes [1]. One of the main concerns in this area is to design and deploy highly reliable sensor networks with excellent energy efficiencies. To do so, there are several power-saving protocols, but the quality and stability of the wireless channels are also critical. In reality, most wireless networks including WSNs are deployed using the default or a random channel since most people assume that all channels in a standard have identical characteristics (reliability, signal strength, etc.) [2]. However, a defining characteristic of wireless communication is the varying signal strength as functions of time and frequency, which leads to an unsteady radio signal strength with losses. Furthermore, the radio frequency (RF) wave is influenced by multiple factors such as interference, noise, multi-path, and shadowing. These factors affect the error rate, delay, and signal strength in the WSNs and, therefore, the reliability and quality of the service. Consequently, it is necessary to have mechanisms to evaluate and measure the quality and stability of a wireless channel. Although there are numerous models available to theoretically predict the channel variations as functions of time and frequency, it is very difficult to develop an applicable model for accurately estimating and evaluating the liabilities and characteristics of different channels in a wireless standard. As a result, experimentation can be considered as the most suitable method for measuring and evaluating the differences between channels in a wireless network.

In this study, we did our experiments on WSNs operated on the channels of Industrial Scientific Medical (ISM) band. We analyzed the effect of IEEE 802.11 access point (AP) on the location error of received signal strength indicator (RSSI)-based indoor localization with IEEE 802.15.4. We performed several tests in a house in order to minimize the influence of other IEEE 802.11 APs. We performed transmitting/receiving test by varying the location of IEEE 802.11 AP. Also, we composed indoor localization system, and measured the location error of mobile node by varying the location of IEEE 802.11 AP. Our study shows that co-channel interference due to use IEEE 802.11 AP affects the RSSI value of sensor node. Ultimately, it has a harmful influence on the location error.

The remainder of this paper is organized as follows. First, we present related works in Section 2. In Section 3, we present the characteristics of IEEE 802.15.4 channels in environments with IEEE 802.11 AP. In Section 4, we analyze the characteristics of localization system in environments with IEEE 802.11 AP. Section 5 discusses our point of view about the results. Finally, we conclude the paper in Section 6.

2. RELATED WORKS

2.1 IEEE 802.15.4 vs. IEEE 802.11

IEEE 802.15.4 WSNs typically operate on the 2.4 GHz ISM band, which is used by IEEE 802.11 (wireless LAN) networks as well [3]. Overlap between the channels used by IEEE 802.15.4 and IEEE 802.11 networks may adversely impact the operation of IEEE 802.15.4, since it is a low-power protocol with a low channel width compared to the transmitted power levels and channel width used by IEEE 802.11. Their overlapping frequency allocations are shown in Figure 1.

The IEEE 802.11 divides the 80-MHz-wide 2.4 GHz band into 5-MHz-wide channels with an IEEE 802.11 network operating over a 20-MHz-wide range, henceforth referred to as the control channel. The 2.4 GHz band can support up to three non-overlapping control channels, centered at IEEE 802.11 channels 1, 6, and 11, in the same location. Thus, IEEE 802.11 networks centered at IEEE 802.11 channels 1, 6, and 11 in 2.4 GHz range are popular. IEEE 802.15.4 also defines a number of 3-MHz-wide channels in the 2.4 GHz band. There are several IEEE 802.15.4 channels (namely channels 15, 20, 25, 26) that do not overlap with the IEEE 802.11 networks centered at IEEE 802.11 channels 1, 6, and 11. To avoid interference from IEEE 802.11 networks, IEEE 802.15.4 networks typically operate in one of such WiFi-free channels.

3. THE CHARACTERISTICS OF IEEE 802.15.4 CHANNELS IN ENVIRONMENTS WITH IEEE 802.11 AP

3.1 Test Setup

The test bed environment chooses TelosB affiliation as the platform for the sensor network and the wireless module uses CC2420 RF as a transmitter–receiver. The microprocessor used the sensor node loading MSP430 (8 MHz) at Texas Instruments (TI / www.ti.com). The network size of the test bed was 5 m × 5 m.

Figure 2 represents the basic test setup. There are two kinds of sensor nodes. One is a transmitting node which transmits a packet once per 0.1 s. The transmitted power in the experiments was set to 0 dBm. The other kind is a receiving node which is like a base station node. This node receives a packet from a transmitting node and transmits the packet to a task manager. The receiving node is connected to a task manager in order to collect and record the packet for analysis. The task manager measures the RSSI using the received packets.

3.2 Test Method

We performed transmitting/receiving test in each channel (ch 11–26) by varying the location of IEEE 802.11 AP. This test was performed in a house because many IEEE 802.11 APs that we cannot control exist in buildings or laboratories. The IEEE 802.11 APs have an effect on our test. Therefore, we performed the test in a relatively low-impact house. Also, we performed the test in various

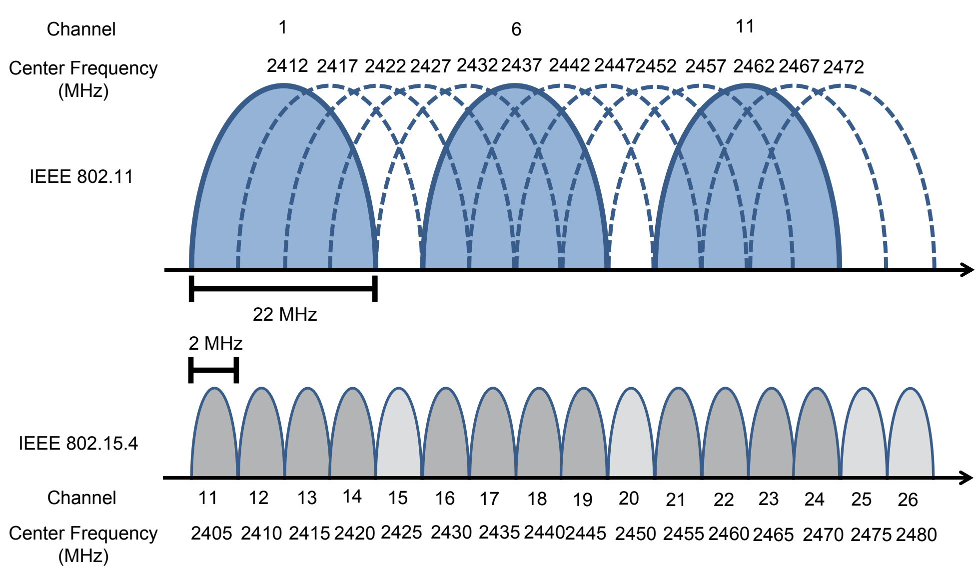

Figure 1: IEEE 802.15.4 and IEEE 802.11 channels in the 2.4 GHz ISM band.

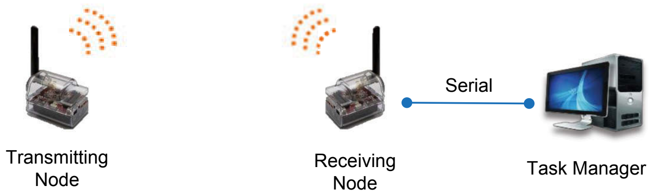

Figure 2: Basic test setup.

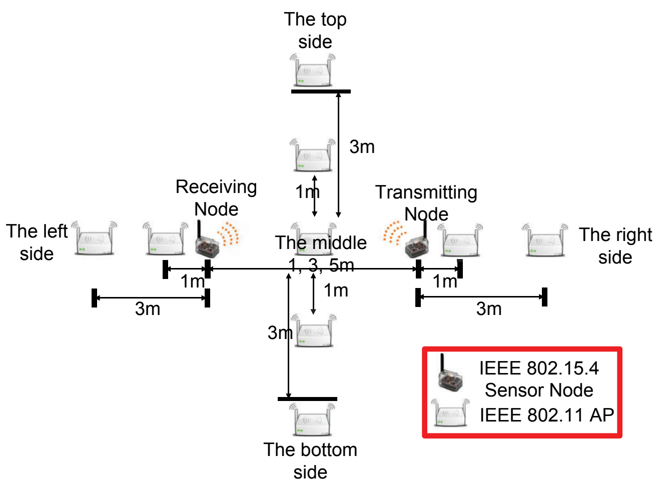

Figure 3: The test location of IEEE 802.11 AP.

locations and various distances to analyze the effect of IEEE 802.11 AP on IEEE 802.15.4 WSN.

The test location of IEEE 802.11 AP is shown in Figure 3 and Table 1.

We conducted a test to see how IEEE 802.11 AP affects the performance of IEEE 802.15.4 WSNs in five locations. IEEE 802.11 AP is initially assigned channel number 1. Generally, IEEE 802.11 AP users use its channel number 1.

In our test, the following data were collected to study the characteristics of different channels of the IEEE 802.15.4 WSNs:

- Channel number
- Message sequence number
- RSSI of each packet
- Standard deviation of received RSSI
- Received packet number.

Although the communication between two sensor nodes cannot represent the traffic model of a typical real WSN, it is enough to study the characteristics of channels of IEEE 802.15.4.

3.3 Test Results

In the first test, we intended to study the characteristics of the IEEE 802.15.4 WSNs in the house, with interference from IEEE 802.11 AP and no obstacles.

Table 1: The test location of IEEE 802.11 AP

Channel of IEEE 802.11 AP	Location of AP	Distance between AP and sensor node (m)	Distance between two sensor nodes (m)
1	The middle of two sensor nodes	-	1, 3, 5
	The left side of a sensor node (receiving node)	1 3	1, 3, 5
	The right side of a sensor node (transmitting node)	1 3	1, 3, 5
	The top side of two sensor nodes	1 3	1, 3, 5
	The bottom side of two sensor nodes	1 3	1, 3, 5

IEEE: Institute of Electrical and Electronics Engineers; AP: Access point

We performed several tests in five locations of IEEE 802.11 AP (the left side, the right side, the top side, the bottom side, and the middle of two sensor nodes). A transmitting node broadcasts 3000 packets to a receiving node, and the receiving node transmits the packets to a task manager Personal Computer (PC) over serial cable. The task manager PC measures the RSSI value, standard deviation of the RSSI value, and total number of received packets.

Figure 4 shows the measured RSSI value at each location, and Figure 4a shows the case that IEEE 802.11 AP exists the left side of the receiving node. As mentioned earlier, even if the distance between two sensor nodes is same, RSSI value is measured differently in each channel. We assigned channel number 1 to IEEE 802.11 AP and then traffic was generated on that channel.. As explained in Section 2, IEEE 802.11 channel 1 uses the same frequency band as IEEE 802.15.4 channels 11, 12, 13, and 14. As shown in Figure 4a, RSSI value measured at IEEE 802.15.4 channels 11, 12, 13, and 14 is small compared to that measured at the other channels. When the distance between two sensor nodes is 1, 3, and 5 m, the same phenomenon appears. This is because channel 1 of IEEE 802.11 AP affects IEEE 802.15.4 channels 11, 12, 13, and 14. RSSI value is measured by receiving node. Therefore an IEEE 802.11 AP placed nearer to receiving node will affect RSSI of receiving node more as compared to when IEEE 802.11 AP is placed away from receiving node. As shown in Figure 4a, when the distance between IEEE 802.11 AP and a transmitting node is 3 m, RSSI value is smaller than when the distance between IEEE 802.11 AP and a transmitting node is 1 m. This is because IEEE 802.15.4 channels and IEEE 802.11 channels compete with each other to occupy channel, and distortion caused by co-channel interference. When a receiving node receives the packets, the RSSI value is small compared to the other channels (ch 15-26) because IEEE 802.11 AP channel 1 affects IEEE 802.15.4 channels 11, 12, 13, and 14.

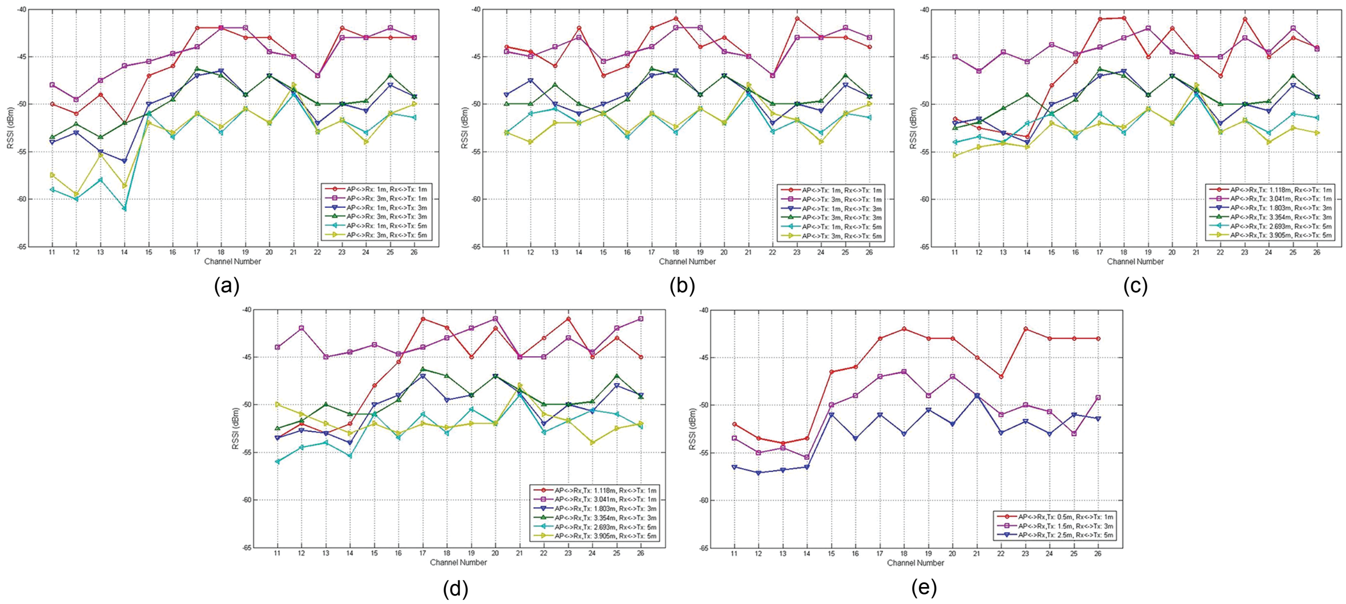

Figure 4: RSSI on each channel according to the location of AP: In case that AP exists on the (a) Left side of receiving node; (b) Right side of transmitting node; (c) Top side of two sensor nodes; (d) Bottom side of two sensor nodes; (e) Middle of two sensor nodes.

On the other hand, when the IEEE 802.11 AP exists on the transmitting node side, the results are different. Figure 4b shows the measured RSSI value of the case that IEEE 802.11 AP exists on a transmitting node. IEEE 802.11 AP almost does not affect IEEE 802.15.4 channels 11, 12, 13, and 14. This is because a receiving node to measure RSSI value is far away from IEEE 802.11 AP.

In Figure 4c and d is given area graphs measuring the RSSI value of the case that IEEE 802.11 AP exists at the top side and the bottom side of sensor node, respectively. In these instances, the distance between a transmitting node and IEEE 802.11 AP and the distance between a receiving node and IEEE 802.11 AP are same. As shown in Figure 4c and d, IEEE 802.11 AP affects the RSSI value when the distance between IEEEE 802.11 AP and two sensor nodes is 1.118, 1.802, and 2.6 m. Especially, when the distance between IEEE 802.11 AP and two sensor nodes is 1.118 m, IEEE 802.15.4 channels 11, 12, 13, and 14 are much more affected by IEEE 802.11 AP compared to the other distance (1.802 and 2.6 m). This is because IEEE 802.11 AP affects both a transmitting node and a receiving node. On the other hand, IEEE 802.11 AP almost does not affect IEEE 802.15.4 channels when the distance between IEEE 802.11 AP and two sensor nodes is 3.041, 3.354, and 3.905 m.

Finally, Figure 4e the shows case that IEEE 802.11 AP exists at the middle of a transmitting node and a receiving node. The location of IEEE 802.11 AP is not changed, and only the distance between a transmitting node and a receiving node changes to 1, 3, and 5 m. In all three cases, RSSI value becomes smaller, when the channels of IEEE 802.15.4 are 11, 12, 13, and 14. Especially, we can see that the more the distance between two sensor nodes is closer, the more the RSSI value of IEEE 802.15.4 channels 11, 12, 13, and 14 varies.

Next we calculate the standard deviation of measured RSSI values. Figure 5 represents the standard deviation of measured RSSI values. Standard deviation shows how much variation or dispersion exists from the average (mean, or expected value). A low standard deviation indicates that the data points tend to be very close to the mean; a high standard deviation indicates that the data points are spread out over a large range of values. Therefore, the small standard deviation of RSSI values means that localization system stably operates.

Figure 5a shows the case that IEEE 802.11 AP exists on the left side of the receiving node. In most cases, standard deviation of RSSI values increases at IEEE 802.15.4 channels 11, 12, 13, and 14. This is because channel 1 of IEEE 802.11 AP affects IEEE 802.15.4 channels 11, 12, 13, and 14. This means that the variation of RSSI values is high. As shown in Figure 5a, standard deviation increases in case the distance between IEEE 802.11 AP and a receiving node is 1 m. This means that the smaller the distance between IEEE 802.11 AP and a receiving node, the more IEEE 802.11 AP affects the performance of WSNs.

On the other hand, if the IEEE 802.11 AP exists on the transmitting node side, the results are different. There is no difference in the standard deviation for each channel [Figure 5b]. This means that the IEEE 802.11 AP scarcely affects a transmitting node.

In Figure 5c and d is given the graphs calculating the standard deviation of RSSI value of the case that IEEE

802.11 AP exists at the top side and the bottom side of sensor node. The standard deviation increases when the distance between IEEE 802.11 AP and the sensor nodes is 1.118 and 1.803 m, but IEEE 802.11 AP scarcely affects the standard deviation if the distance between IEEE 802.11 AP and the sensor nodes is over 2.6 m.

Figure 5e shows the case that IEEE 802.11 AP exists at the middle of a transmitting node and a receiving node. As shown in Figure 5e, the standard deviation increases because channel 1 of IEEE 802.11 AP affects IEEE 802.15.4 channels 11, 12, 13, and 14.

Finally, Figure 6 is a graph showing the number of packets received by a receiving node. The transmitting node transmits 3000 packets to the receiving node.

First, Figure 6a shows the case that IEEE 802.11 AP exists on the left side of the receiving node. The number of received packets decreases at IEEE 802.15.4 channels 11, 12, 13, and 14 because IEEE 802.11 AP exists on the receiving node side. On the other hand, in case IEEE 802.11 AP exists on the transmitting side, the number of the received packets shows some changes in IEEE 802.15.4 channels 11, 12, 13, and 14 [Figure 6b]. In case

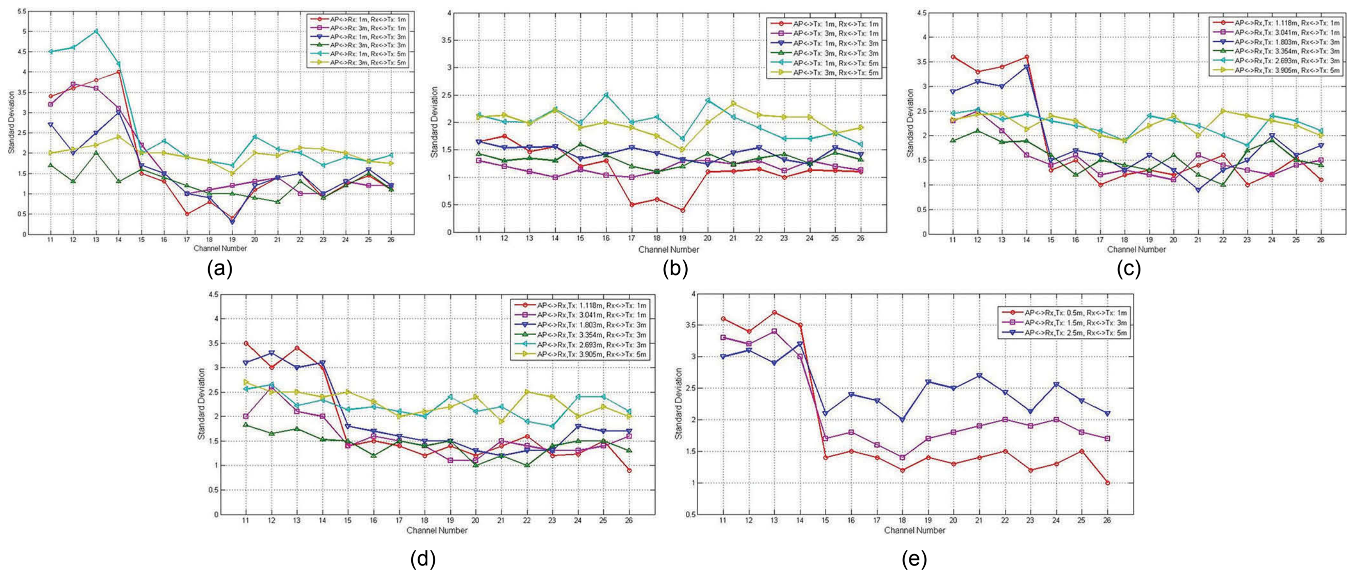

Figure 5: Standard deviation on each channel according to the location of AP: In case that AP exists on the (a) Channel left side of receiving node; (b) Right side of transmitting node; (c) Top side of two sensor nodes); (d) Bottom side of two sensor nodes; (e) Middle of two sensor nodes.

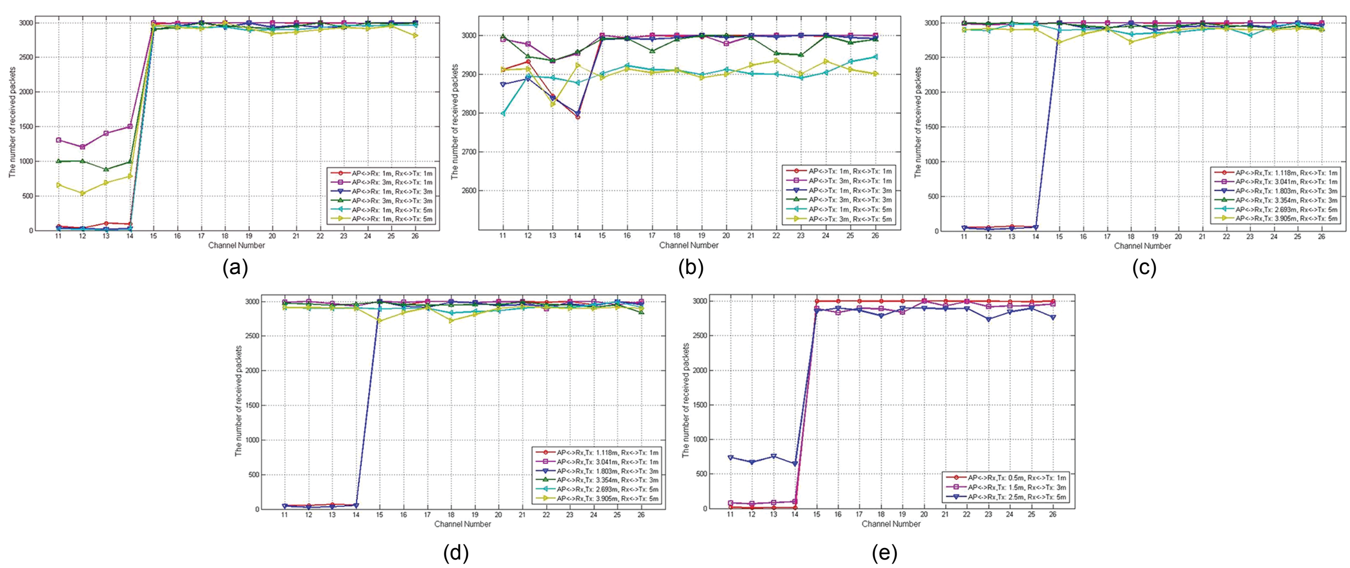

Figure 6: Standard deviation on each channel according to the location of AP: The number of received packets on each channel in case that AP exists on the (a) Left side of receiving node; (b) Right side of transmitting node; (c) Top of two sensor nodes; (d) Bottom of two sensor nodes; (e) Middle of two sensor nodes.

IEEE 802.11 AP exists at the top side and the bottom side of sensor node, there is no observable change in the number of received packets except when the distance between IEEE 802.11 AP and the sensor nodes is 1.118 and 1.803 m [Figure 6c and d]. Finally, in case the IEEE 802.11 AP exists at the middle of a transmitting node and a receiving node, the number of received packets decreases, when the distance between the IEEE 802.11 AP and a sensor node is 0.5, 1.5, and 2.5 m [Figure 6e].

We analyzed the test results of RSSI value, standard deviation of RSSI value, and the number of received packets. In short, IEEE 802.11 AP affects the IEEE 802.15.4 channels much when the IEEE 802.11 AP exists on the receiving node side, but IEEE 802.11 AP scarcely affects the IEEE 802.15.4 channels when IEEE 802.11 AP exists on the transmitting node side. Also, IEEE 802.15.4 channels are affected by IEEE 802.11 AP when the distance between IEEE 802.11 AP and the receiving node is over 2.5-3 m. The next section presents the test study of the characteristics of localization system in environments with IEEE 802.11 AP.

4. THE CHARACTERISTICS OF LOCALIZATION SYSTEM IN ENVIRONMENTS WITH IEEE 802.11 AP

4.1 Test Setup

We prepared test setup indoor location system to analyze the characteristics of localization system in environments with IEEE 802.11 AP. Figure 7 shows the indoor localization test setup. The indoor localization system was composed of three reference nodes, one mobile node, one sink node, and task manager PC. The operation process of indoor localization system is as follows:

1. The reference node periodically transmits a beacon message to the mobile node
2. The mobile node measures the RSSI value of each of the reference nodes using the received beacon messages
3. The mobile node transmits the packets including the RSSI value information of each of the reference nodes to the sink node
4. The sink node receives the packets of the mobile node and transmits them to the task manager over serial cable
5. The task manager calculates the location of mobile node using trilateration [4,5].

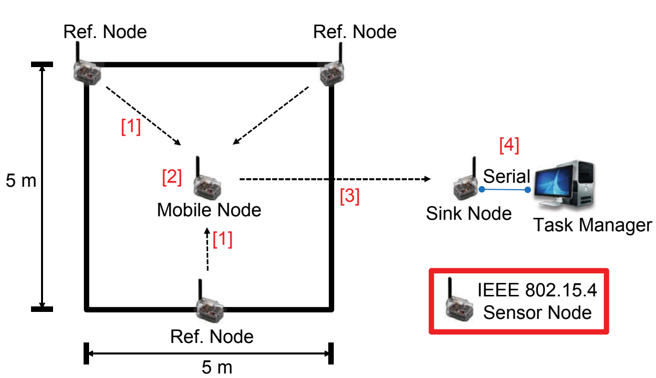

Figure 7: Indoor localization test setup.

We developed a test UI program based on C# to analyze the characteristics of indoor localization system in environments with IEEE 802.11 AP. This test UI program confirms the location of mobile node in real time. The trilateration was applied to the test UI program. We set the channel of IEEE 802.11 AP to 1 and the channel of IEEE 802.15.4 to 11.

4.2 Test Method

We constructed an indoor localization system to analyze the characteristics of indoor localization system in environments with IEEE 802.11 AP. Also, we analyzed the location error of mobile node according to the location of IEEE 802.11 AP.

Figure 8 shows the location of IEEE 802.11 AP in indoor localization system.

For test setup we have chosen four different location for IEEE 802.11 AP as shown in Figure 8. First, in the case of the middle of indoor localization system (1); second, in the case of distance between reference node and IEEE 802.11 AP is 1 m (2); third, in the case of distance between reference node and IEEE 802.11 AP is 3 m (3); finally, in case IEEE 802.11 AP exists near the sink node (4). We measure the location error of mobile node in case to move in a straight line and square line. Also, we measure the location error of mobile node in a clean environment, with no interference from IEEE 802.11 AP in order to identify the influence of IEEE 802.11 AP.

Figure 9 shows the movement path of mobile node. The movement path of mobile node is straight movement and square movement.

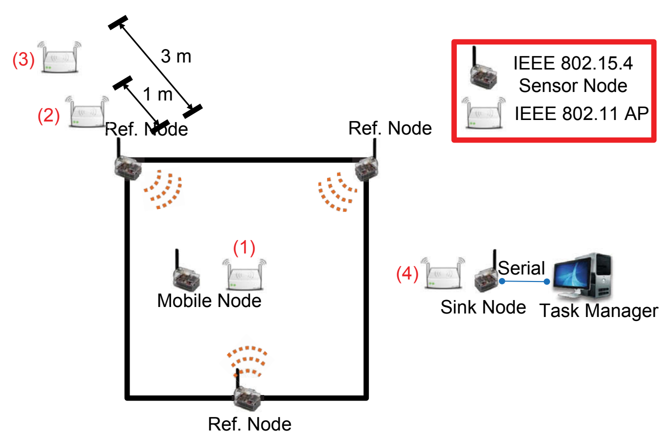

Figure 8: The location of IEEE 802.11 AP.

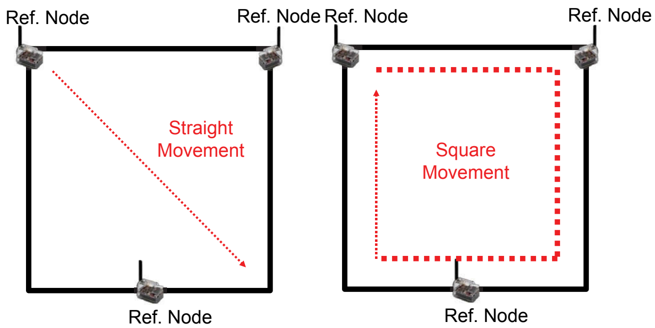

Figure 9: The movement path of mobile node.

The indoor localization system is based on RSSI value. The indoor localization system must receive a distance reference node and mobile node. Therefore, the indoor localization system needs translating RSSI value into distance phase.

First, the parameter calculation is performed to obtain the distance between the reference node and mobile node. The calculation of the parameters is performed after the RSSI measurement process. The parameters are the elements that are needed when translating an RSSI value into a distance where the elements are "A" and "n." A is an empirical parameter which is determined by measuring the RSSI value 1 m from the transmitting unit. The parameter n describes how the signal strength decreases when the distance from the transmitter increases. The relationship of the distance, d, between the reference node and the sink node and the associated RSSI value can be expressed as follows:

$$RSSI = -(10n\log_{10} d + A) \tag{1}$$

The parameters A and n are calculated for each channel because the parameters differ depending measurement channel environments. The parameter A can be obtained by calculating the average RSSI value for a sensor node as follows:

$$A = -\frac{\sum_{k=1}^{m} x_k}{m} \tag{2}$$

where X_k is the measured RSSI and m is the sample number

The distance between the reference node and sink node can vary within a meter. The measured RSSI value is then used to determine the parameter n. The parameter n is calculated by substituting the measured RSSI value and the parameter A is calculated using equation (2) into equation (3).

$$n = \frac{-(mA + \sum_{k=1}^{m} x_k)}{10m\log_{10} d} \tag{3}$$

4.3 Test Results

Figure 10 shows comparison of the location error according to the location of IEEE 802.11 AP. The mobile node moves straight. As shown in Figure 10, when the distance between reference node and IEEE 802.11 AP is closest, the location error of mobile node is largest (Ref. Node<-> AP: 1 m). Also, as the mobile node moves closer to middle area, the location error of the mobile node increases (the middle). The remainder (Ref. Node<->AP: 3 m, near sink node, no interference) shows similar location error.

Figure 11 shows comparison of the location error according to the location of IEEE 802.11 AP. The mobile node moves in a square. As shown in Figure 11, when the distance between reference node and IEEE 802.11 AP is closest, the location error of mobile node is largest (Ref. Node<-> AP: 1 m). Also, in the case of IEEE 802.11 AP existing in the middle area, when the mobile node moves closer to IEEE 802.11 AP, the location error of the mobile node increases (the middle). The remainder (Ref. Node<->AP: 3 m, near sink node, no interference) shows similar location error.

Figure 12 shows a comparison of the average location error according to the location of IEEE 802.11 AP. As shown in the figure, when the distance between reference node and IEEE 802.11 AP is 1 m, the average location error of mobile node is largest (3.504 m). When the IEEE 802.11 AP exists in the middle area, the average location error of mobile node is second largest (2.769 m). The remainder shows similar average location error of mobile node.

Figure 13 shows comparison of the average location error according to the location of IEEE 802.11 AP. As shown in Figure 13, when the distance between reference node and IEEE 802.11 AP is 1 m, the average location error of mobile node is largest (3.469 m). When the IEEE 802.11 AP exists in the middle area, the average location error of mobile node is second largest (2.846 m). The remainder shows the similar average location error of mobile node.

5. DISCUSSION

From these results we can realize that IEEE 802.11 AP channel 1 affects IEEE 802.15.4 channels 11, 12, 13, and 14 because their RSSI value, standard deviation of RSSI value, and the number of received packets are not good. Over the various tests, the channels 15–26 have proven to be relatively stable.

Also, we can observe that if IEEE 802.11 AP is close to reference node, the location error of mobile node is very large.

From the test results, the location of IEEE 802.11 AP must be considered to increase the performance of indoor localization system.

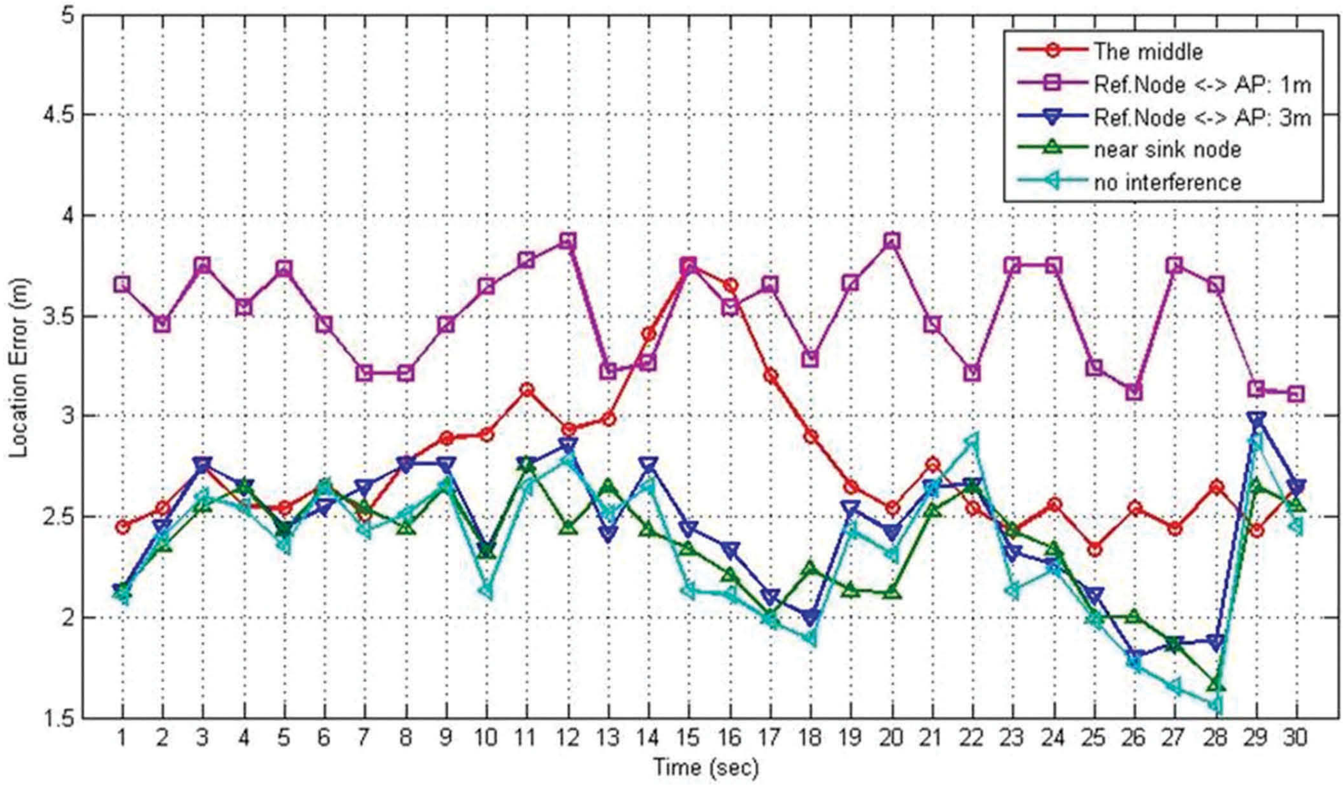

Figure 10: Comparison of the location error (straight movement).

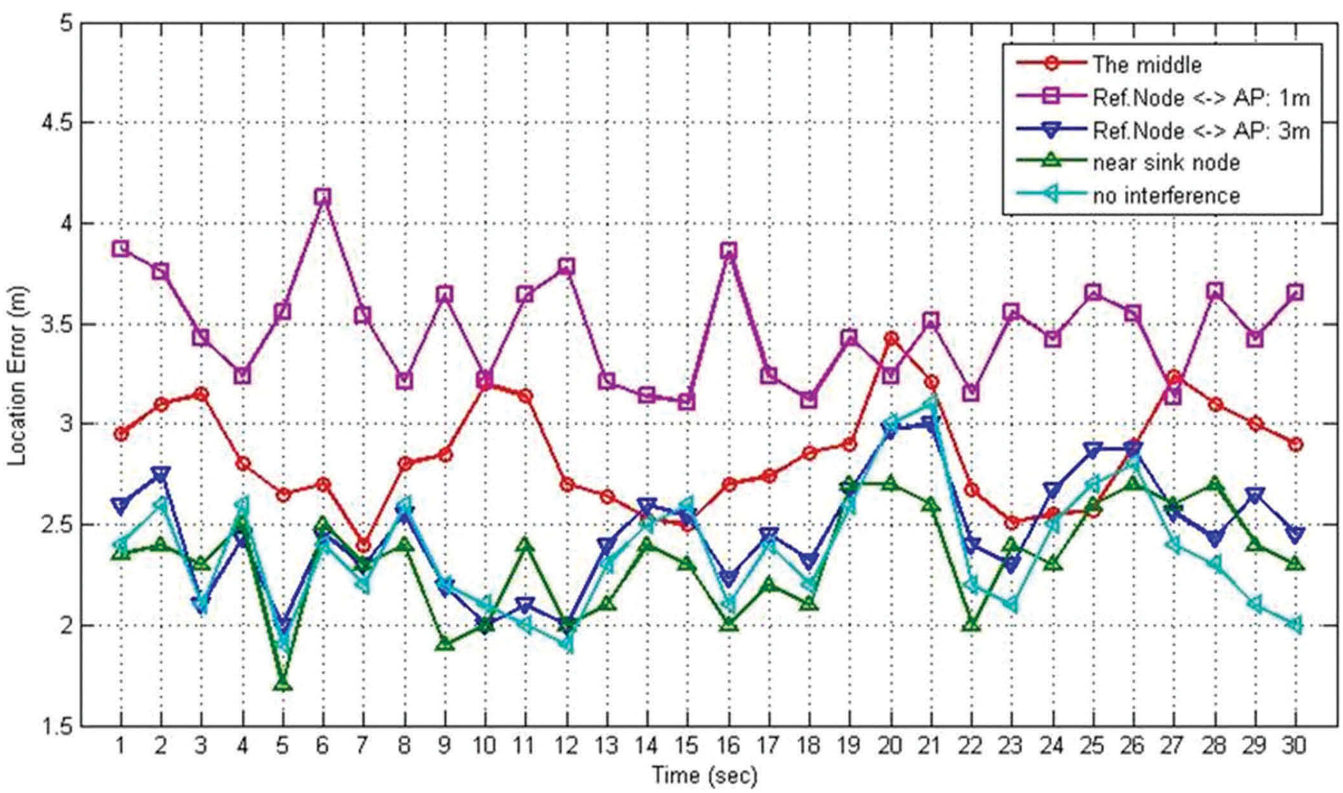

Figure 11: Comparison of the location error (square movement).

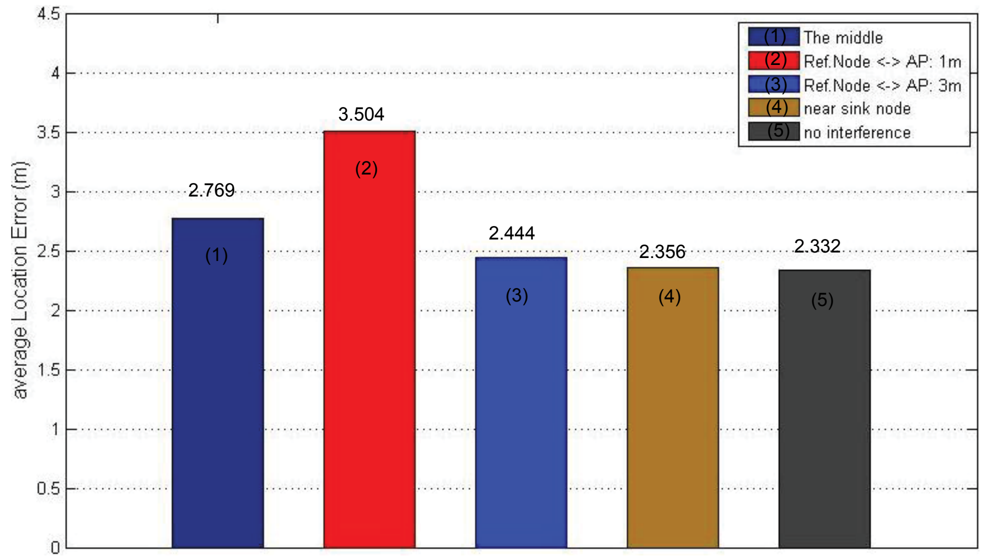

Figure 12: Comparison of the average location error (straight movement).

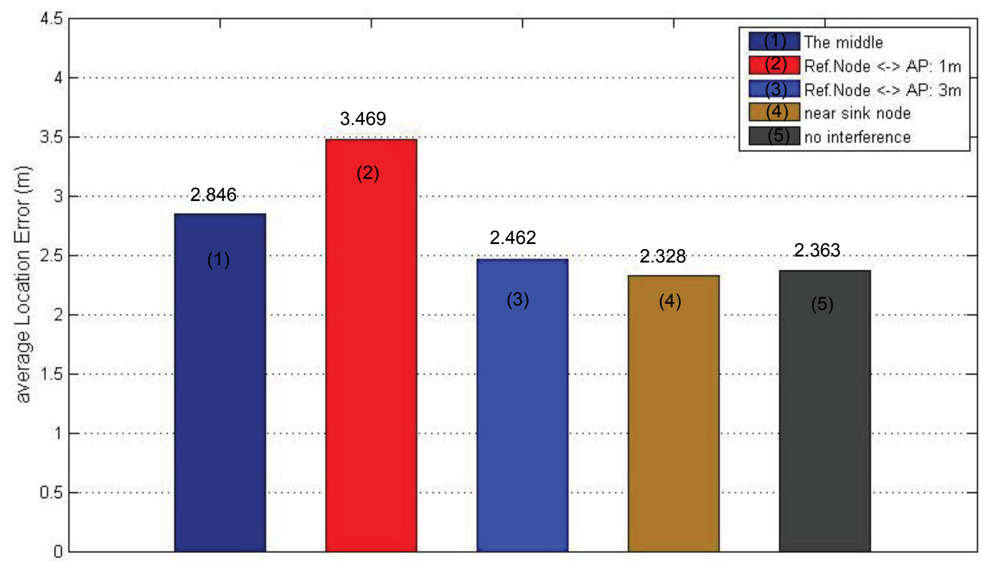

Figure 13: Comparison of the average location error (square movement).

6. CONCLUSION

In this paper, we described several empirical studies about the characteristics of different channels of IEEE 802.15.4 in environments with IEEE 802.11 AP and the characteristics of localization system in environments with IEEE 802.11 AP. From these studies, we observed that IEEE 802.11 AP affects IEEE 802.15.4 WSNs since IEEE 802.11 and IEEE 802.15.4 use the same frequency bandwidth.

From the results of our tests, we can conclude that when constructing indoor localization system, especially sensor networks, it is necessary to have a test evaluation phase. Therefore, the indoor localization system should use different channels to IEEE 802.11 AP channel.

REFERENCES

1. C Jie, "RSSI-based Indoor Mobile Localization in Wireless Sensor Network", *International Journal of Digital Content Technology and it Applications,* Vol. 5, no. 7, pp. 408-416, 2011.
2. T Tranh, S Ricardo, N David, and S Jorge, "Characteristics of Channels of IEEE 802.15.4 Compliant Sensor Networks", *Wireless Personal Communications,* Vol. 67, Issue. 3, pp. 541-556, 2011.
3. S Minchul, J Hyunjin, and J Inwhee, "An Indoor Localization Pre-Processing with Optimal Channel Selection considering Channel Interference", *International Conference on Convergence and Hybrid Information Technology (ICHIT),* Vol. 310, pp. 78-85, 2012.
4. Wikipedia [online]. Available from: http://en.wikipedia.org/wiki/Trilateration [Last accessed on 2013 Jan 30].
5. EEL Lau, "Enhanced RSSI-Based High Accuracy Real-Time User Location Tracking System for Indoor and Outdoor Environments", *International Journal on Smart Sensing and Intelligent Systems,* Vol. 1, no. 2, pp. 534-548, 2008.

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