WiFi AP-RSS Monitoring using Sensor Nodes toward Anchor-Free Sensor Localization

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***Abstract*—Sensor localization is one of the big problems when building large scale indoor sensor networks since GPS is unavailable in indoor environments. Many indoor localization systems have been proposed to tackle the sensor localization problem, yet user cooperation or many anchor nodes are required. In this paper, we propose a sensor localization system using WiFi APs as anchors. WiFi APs are largely installed in indoor environments and are managed by a network system manager. Using WiFi APs as anchors, we can localize sensor nodes without newly deployed anchor nodes.**

As a first step of our sensor localization system, this paper presents a WiFi AP-RSS monitoring system using sensor nodes. Sensor nodes are equipped with IEEE 802.15.4 (ZigBee) modules, which cannot demodulate WiFi (IEEE 802.11) signals. We therefore developed a *cross-technology signal extraction scheme* on sensor nodes. We herein describe the design and implementation of our AP-RSS monitoring system. The experimental evaluations show that our AP-RSS monitoring system successfully retrieves AP-RSS with an average error of 1.26 dB.

***Index Terms*—WiFi AP anchors, sensor localization, cross-technology communication.**

I. Introduction

Sensor networks play an important role in many fields such as security, agriculture, fishing, forestry, construction, transportation, and environmental monitoring. In sensor networks, sensor location is important for recognizing sensing area, target tracking, and a network routing. Building sensor network systems always require to localize all the sensor nodes.

Sensor location is usually derived by using GPS or manual measurements. We face a sensor localization problem when we build a large scale sensor network in an indoor environment, where GPS is unavailable. The BEMS (Building Energy Management System) and a security system are typical examples of large scale indoor sensor network systems. The sensor localization problem is one of the reasons that prevent sensor networks from becoming more prevalent.

To mitigate sensor localization problem, there have been so much literature reporting indoor localization systems [1–3]. These studies have primarily investigated reduction in deployment costs [4–13] or accuracy improvement [14–20]. Although these studies have successfully reduced the cost of sensor localization, they require user cooperation or anchor nodes whose location is manually measured.

Our goal is to realize an indoor sensor localization system that requires no newly deployed anchor nodes. In this paper, we propose an indoor sensor localization system using WiFi APs as anchors. WiFi APs are largely installed in many indoor environments and their locations are managed by a network system manager. We send specific signals from multiple WiFi APs and monitor the received signal strength (RSS) on sensor nodes. We then calculate locations of sensor nodes using an RSS-based localization scheme.

As a first step of the sensor localization system using WiFi APs, this paper presents a WiFi AP-RSS monitoring system using sensor nodes. Sensor nodes are equipped with IEEE 802.15.4 (ZigBee) modules and cannot demodulate WiFi signals. To measure RSS of WiFi signals on sensor nodes, we developed a cross-technology signal extraction scheme. In this scheme, we employ a signal folding technique presented in ZiFi [21] and retrieve AP-RSS with a simple filtering method. We also present an AP recognition method to monitor RSS of multiple APs simultaneously.

By implementing the RSS monitoring system using a sensor node MICAz, we show the feasibility of our sensor localization system. We also conduct experiments to show that our monitoring system has enough performance to build a localization system.

Specifically, our main contributions are threefold:

- We propose a new indoor sensor localization system that uses WiFi APs as anchors. Using WiFi APs, we can localize every sensor node without newly deployed anchors.
- We present the design of a WiFi AP-RSS monitoring system with AP recognition using sensor nodes employing IEEE 802.15.4 (ZigBee) modules. Our design is based on an existing signal processing technique combined with a signal recognition method. We also apply a simple filtering method to mitigate some practical problems for RSS measurement.
- We show the feasibility of our sensor localization system by experimental evaluations of the AP-RSS monitoring system using a real sensor node.

The remainder of this paper is organized as follows. Section II describes our new sensor localization system as well as design challenges. Section III designs an AP-RSS monitoring system. In Section IV, we implement our AP-RSS monitoring

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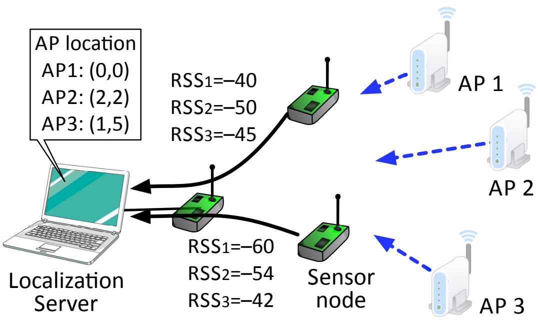

Fig. 1. Overview of a sensor localization system using WiFi APs as anchors.

system using a real sensor node and conduct experiments to evaluate the basic performance. We briefly look through related works in Section V. Section VI concludes the paper.

II. Sensor Localization System using WiFi APs

Figure 1 depicts an overview of a sensor localization system using WiFi APs as anchor nodes. The sensor localization system consists of sensor nodes, a localization server, and WiFi APs installed in the environment. The WiFi APs periodically transmit a specific signal that can be detected by sensor nodes.

To initiate localization process, sensor nodes first detect AP signals and monitor the received signal strength (RSS). The sensor nodes then send the RSS information to a localization server. Using the RSS information, the localization server calculates sensor location by a localization scheme such as multilateration. Here we assume that the localization server holds AP location data. This assumption is natural since the APs are usually managed by a network system manager.

Two challenges come up toward realizing the sensor localization system using WiFi APs.

1) *How to detect WiFi AP signals on sensor nodes?:* Sensor nodes cannot demodulate WiFi (IEEE 802.11) signals since sensor nodes are equipped with IEEE 802.15.4 (ZigBee) modules. We need to pick WiFi AP signals out from WiFi signals from many WiFi devices. We then measure RSS of the AP signals.
2) *How to recognize sender APs?:* Using the RSS information, we can calculate distance between a sensor node and an AP. For sensor localization, we need to associate the distance with a specific sender AP.

In the following section, we design an AP-RSS monitoring system that tackles the above two challenges.

III. AP-RSS Monitoring System

A. Design Overview

The design of our AP-RSS monitoring system is divided into three sub-designs: AP signal detection, AP recognition, and AP-RSS extraction. To detect AP signals on sensor nodes, we employ a simple signal processing technique presented in ZiFi [21]. ZiFi is based on periodicity of AP beacon signals. We can easily recognize APs by sampling RSS on different ZigBee channels since APs in the environment are typically

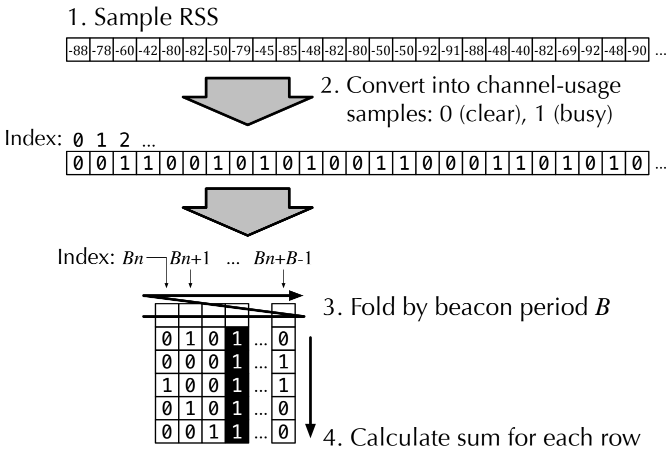

Fig. 2. AP signal detection by folding. 1) A sensor node periodically samples RSS and 2) convert the RSS samples into channel-usage samples. 3) The sensor node folds the channel-usage samples by beacon period and 4) calculate sum for each row to get channel-usage sums. Periodic beacon signals appear in a specific row, which results in a large channel-usage sum.

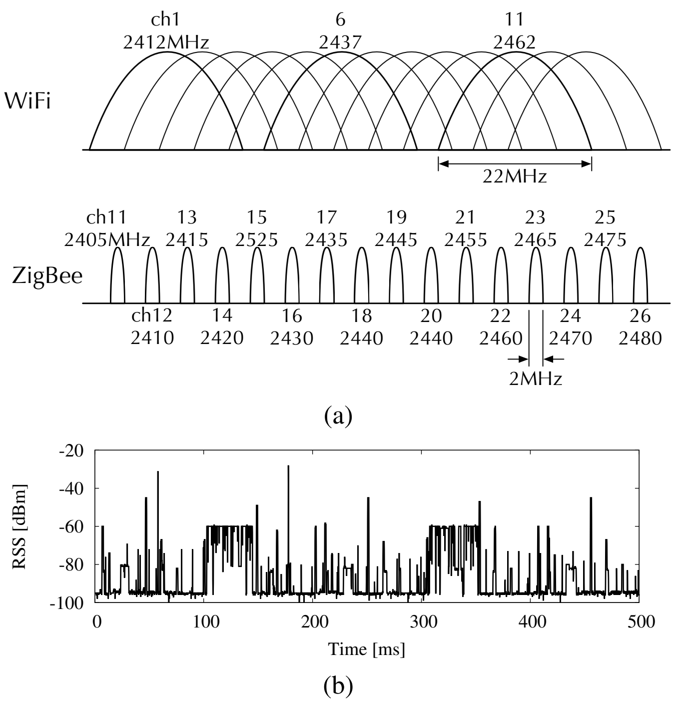

Fig. 3. (a) WiFi and ZigBee channels. (b) WiFi signals on ZigBee channel 19 retrieved by MICAz.

using non-overlapping channels. We finally retrieve AP-RSS with a simple filtering method based on beacon length.

The following three subsections give details of each subdesign.

B. AP Signal Detection

Figure 2 depicts a process of AP signal detection. To detect AP signals on a sensor node, the sensor node periodically samples RSS in a specified channel. Note that all IEEE 802.15.4 (ZigBee) modules have an RSS measurement function as an energy detection function defined in the standard [22]. The sensor node can detect WiFi signals since both ZigBee and WiFi are using the same 2.4-GHz band (Fig.3a). Figure 3b shows an example of WiFi signals on ZigBee channel 19 retrieved by a sensor node MICAz. Since IEEE 802.15.4 modules provide average RSS over 128 μs, we set the sampling period to 128 μs not to miss WiFi signals while minimizing the sampling rate.

The sensor node converts the each RSS sample into a channel-usage sample: `0` for clear and `1` for busy. We use -77 dBm as a threshold for channel-usage determination. This threshold follows after the default threshold of IEEE 802.15.4 module CC2420 for clear channel assessment [23].

We then fold the channel-usage samples on the AP beacon period and create a channel-usage matrix. Consider folding of beacon signals whose interval is t. Since time length of each channel-usage sample is 128 μs, we can calculate a beacon period B as $t/(128 \times 10^{-6})$. We then calculate sum for each row in the channel-usage matrix. We name this sum as *channel-usage sum*.

We can detect AP by finding the row whose channel-usage sum is above a threshold. Beacon signals whose interval matches to the folding period appear in a specific row. Large channel-usage sum therefore indicates that there are beacon signals whose interval matches to folding period, as shown in Fig. 2. We conduct a preliminary experiment and set the threshold of channel-usage sum to 70 % of the number of foldings.

C. AP Recognition

To recognize sender APs, we sample RSS on different ZigBee channels and detect AP signals whose interval is 100 TU (TU: time unit $=$ 1024 μs, defined in the WiFi standard [24]). Applying a signal detection scheme presented in the previous subsection, we can separately detect signals from different APs.

This simple approach is based on two observations.

1) Three non-overlapping WiFi channels: As shown in Fig. 3a, there are three non-overlapping WiFi channels: 1, 6, and 11. A network system manager tries to use these non-overlapping channels on each AP to minimize interference. We can assume that APs around a sensor node use different channels, which are typically non-overlapping channels.

We need three APs for sensor localization using multilateration. Coincidentally, there are three non-overlapping channels that are typically used on APs. We therefore sample RSS on ZigBee channels 12, 17, and 22 that overlap WiFi channels 1, 6, and 11, respectively. If no AP is detected on ZigBee channels 12, 17, and 22, the other channels are used for RSS sampling.

2) Identical default beacon interval: Almost all APs available today are configured to use beacon interval of 100 TU, which is the de facto standard default configuration. On some APs, we cannot even change the beacon interval from 100 TU. We can easily detect APs by folding channel-usage samples by period $B = 100 \times 1024 \times 10^{-6}/(128 \times 10^{-6})$.

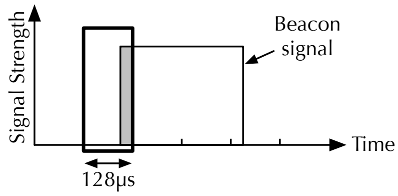

Fig. 4. Example of partial RSS problem. Only the gray part of a beacon signal contributes to RSS within a 128-μs window shown in the figure.

-91	-53	-53	-53	-53	-53	-53	-53	-53	-53
-51	-51	-51	-52	-51	-51	-52	-61	-97	-79
-52	-52	-52	-52	-52	-52	-52	-52	-52	-52

Fig. 5. Example of RSS filtering in a partial RSS matrix. Black and gray boxes indicate that the channel is busy. We first remove RSS samples less than the channel-usage threshold (white boxes) and then cut off both the beginning and the end of the signal (gray boxes).

D. AP-RSS Extraction

After we detect AP beacon signals, we need to extract AP-RSS from the sequence of RSS samples. Although we can intuitively extract RSS samples corresponding to the rows whose channel-usage sum exceeds a threshold, the extracted RSS samples are suffered from high RSS error. There are two main reasons for this RSS error.

1) *CSMA delay:*
   Due to the nature of CSMA (carrier sense multiple access) in WiFi MAC, beacon signals might be sent with some delays. The intuitive RSS extraction picks RSS samples on scheduled timing, which results in the extraction of signals from other WiFi devices.
2) *Average RSS on a ZigBee module:*
   ZigBee modules can measure an RSS averaged over 128 μs as defined in the standard. The ZigBee module might provide a *partial RSS*, i.e. average RSS of a part of WiFi signal, as depicted in Fig. 4.

To minimize effects of the above two problems, we remove RSS on both rising edge and falling edge of each beacon signal. We first create an RSS matrix in a same manner as the creation of a channel-usage matrix. We then extract the rows corresponding to channel-usage matrix rows whose channel-usage sum exceeds a specific threshold. Figure 5 shows an example of the extracted rows of an RSS matrix. We first remove RSS samples less than the channel-usage threshold defined in Section III-B (white boxes). We next remove the first and the last RSS samples on each column (gray boxes). These steps would extract RSS samples of the core of beacon signals.

This simple filtering technique effectively works because most of the beacons have length more than four RSS-sample length, i.e. 512 μs. Figure 6 shows an empirical cumulative distribution function of beacon length of WiFi APs in our university building. More than 90 % of APs are sending beacons whose length is more than 512 μs.

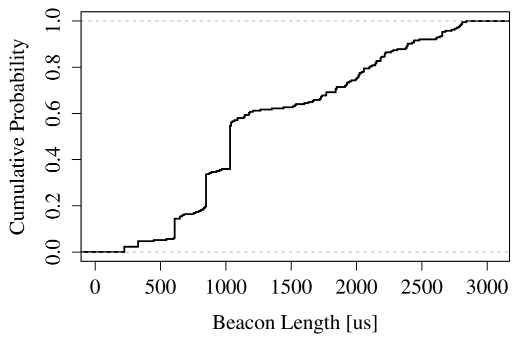

Fig. 6. Empirical cumulative distribution function of beacon length.

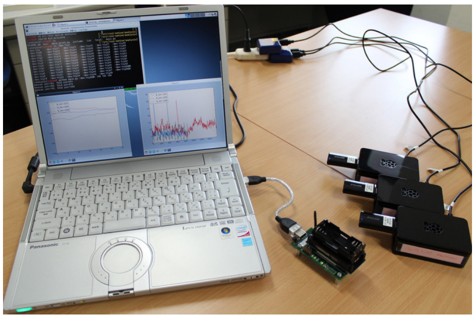

Fig. 7. AP-RSS monitoring system.

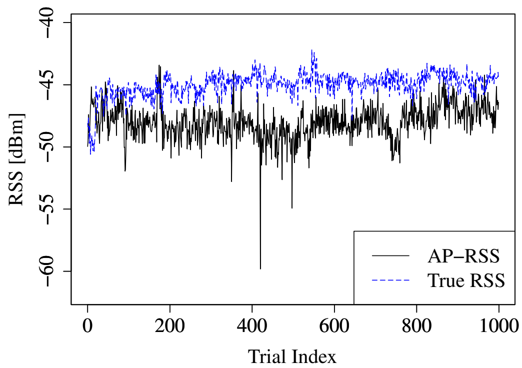

Fig. 8. AP-RSS and true RSS. The AP-RSS is RSS derived by our AP-RSS monitoring system. The true RSS is RSS derived from a WiFi module on a laptop.

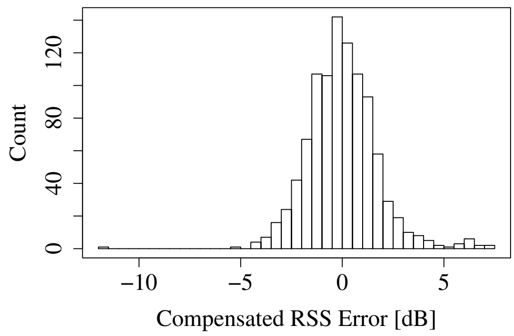

Fig. 9. Histogram of compensated RSS error.

IV. Evaluation

To demonstrate the feasibility of the sensor localization system described in Section II, we evaluated RSS error of our RSS monitoring system.

A. Implementation

Figure 7 shows our AP-RSS monitoring system. Our AP-RSS monitoring system can reveal RSS of three APs simultaneously.

We used a Raspberry Pi B+ employing a WiFi module WLI-UC-G301N from Buffalo as a WiFi AP. OpenWrt, an open source OS for WiFi APs, is running on Raspberry Pi.

We used a MICAz from Crossbow as a sensor node, which utilizes an IEEE 802.15.4 module CC2420 from Texas Instruments. We developed a C program that samples RSS every 128 μs and sends the RSS to a laptop via serial communication interface.

The laptop is CF-Y8 from Panasonic. We developed a python program that receives RSS from the sensor node and extract AP-RSS as described in Section III.

B. RSS Error

To calculate RSS error, we compared AP-RSS with true RSS. The AP-RSS is RSS derived by our system and the true RSS is RSS directly derived from a WiFi module. We first configured a WiFi AP to have beacon interval of 93 TU and put the AP 12-meter away from a sensor node which is connected to a laptop. We then collected a sequence of AP-RSS for 4 seconds using our AP-RSS monitoring system. At the same time, we measured true RSS by capturing beacon signals on the laptop using libpcap. The AP-RSS and the true RSS are averaged over 4 seconds. We collected the averaged 4-second AP-RSS as well as true RSS for 1,000 times.

Figure 8 shows AP-RSS and true RSS. The AP-RSS exhibits similar fluctuation pattern to that of the true RSS. However, there is an offset between the AP-RSS and the true RSS. This offset is due to the bandwidth difference between WiFi and ZigBee: WiFi bandwidth is 22 MHz, while ZigBee bandwidth is 2 MHz. Antenna gain is another source of the offset.

For RSS error calculation, we compensate the offset since the effect of bandwidth difference as well as antenna gain is almost constant. The offset is calculated as difference of the average AP-RSS and the average true RSS over 1,000 times.

Figure 9 shows a histogram of compensated RSS error. The RSS error follows Gaussian distribution. The standard deviation of compensated RSS error is 1.71 dB and the average absolute error is 1.26 dB. From this result, we can say that more than 95 % of error is within $2 \times \pm 1.71\,\mathrm{dB} = \pm 3.42\,\mathrm{dB}$. The RSS error is at the same order of RSS fluctuation due to the environmental change.

V. Related Works

In the field of indoor localization, previous studies have primarily investigated reduction in deployment costs and accuracy improvement. Most of these works are using WiFi devices, which still can be applied to sensor nodes with ZigBee modules.

Iterative multilateration [4, 5] uses localized nodes as new anchor nodes, which reduces the number of initial anchor nodes. However, many initial anchors are still required to achieve small localization error in a large building. Crowd-sourcing combined with fingerprinting localization [6–13] is another approach which reduces deployment costs. For a sensor localization system, it is difficult to get user cooperation since almost all users are carrying no ZigBee devices.

In this paper, we focus on cross-technology RSS extraction since we can employ existing localization method using RSS. Previous works on accuracy improvement [14–20] is therefore useful in our future work, i.e. localization using the extracted RSS.

There is a new fingerprinting localization named ZiFind which requires no anchor nodes [25]. ZiFind, however, requires many WiFi devices called ZiFind mappers instead of anchor nodes. Cross-technology communication have also been studied [26–28], which requires special hardwares or firmware modification on WiFi APs or sensor devices.

VI. Conclusion

In this paper, we present an AP-RSS monitoring system using sensor node, as a first step toward a sensor localization system using WiFi APs as anchors. We developed a cross-technology signal extraction scheme to overcome the wireless standard difference between WiFi and ZigBee. In our signal extraction scheme, a signal processing technique presented in an existing work is employed and combined with a simple filtering method to extract AP-RSS on sensor nodes. We also present a simple AP recognition technique that uses different sampling channels. The experimental evaluations show that our AP-RSS monitoring system successfully retrieves AP-RSS with an average error of 1.26 dB.

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