I^3BM Zigbee Positioning Method for Smart Home Applications

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Abstract

This paper presents a smart home system prototype which employs an indoor positioning system called the III Beacon Match (I^3BM) positioning method to intelligently trigger the appropriately services for the home members. To overcome the ninja problem in the I^3BM method, the signal filtering, adjustment and smooth procedures are proposed. The proposed system prototype employs the Zigbee module to implement the prototypes of the components for the I^3BM positioning method, and the prototypes had passed the ZigBee Compliant Platform (ZCP) certification test. The proposed system prototype which intelligently controls the air condition and light system for smart home applications is also verifying in our demo room and in the smart house in National Taiwan University.

1. Introduction

Home automation is the primitive function of smart home. In Wikipedia, the contributors make the following descriptions to the building automation: Building automation is a programmed, computerized, "intelligent" network of electronic devices that monitor and control the mechanical and lighting systems in a building. The intent is to create an intelligent building and reduce energy and maintenance costs. [1] The goal of this study is proposing an automatic method for reducing the energy consumption for smart home.

In most buildings, lighting and air condition systems consume most energy usages. Some intelligent buildings attempt to reduce the power consumption of lighting and air conditions through the help of sensors. One typical example is to turn the lights in a space on for a half hour since the last motion was sensed.[1] This approach seems works in reducing the power consumption of the lighting system, however, it may bring uncomfortable scenarios. On typical example is the motion detector senses no mobile object in a room where some people sit there without move. Since the priority of providing comfortable environment is generally higher than reducing the power consumption, most users do not accept the motion detection solution.

This study attempts to employ the indoor positioning mechanisms to reduce the power consumption of the lighting and air condition system. If the positions of the building members are detectable, then the proposed system can turn on the corresponding systems such as lighting and air condition whenever the building members are approaching. And the system can turn off the corresponding systems after no building members stay there for a period of time.

Developing a power-efficient accurate positioning service has been critical for indoor context aware applications which construct a smart space to interact with users. The challenge to receive applicable GPS signals in the indoor environment has driven the position sensing capabilities for the advanced wireless networks. In the literatures, several positioning techniques have been proposed for mobile computing environment. They could be classified into three categories. The first category applies the Time of Arrival (TOA) or Time Difference of Arrival (TDOA) schemes to estimate the position of mobile users [2, 3]. The principle of TOA and TDOA is estimating the distance between the receiver and each sender according to the traveling time from the senders to the receivers and then calculating the position of the receiver with the help of the known positions of at least three senders [2]. The second category applies the Angle of Arrival (AOA) scheme to estimate the position of mobile users. The principle of AOA is estimating the angle of arrival signal and then calculating the position of the sender by the known positions of the receivers and the angles of arrival signals detected by each receiver [3]. The last category utilizes the attenuation of signal strength of the senders nearby to estimate the position of mobile users. The principle of the methods in this category is applying the propagation law to estimate the distance from the receiver and each sender [3, 4].

Although TOA and TDOA are simple and concrete, however, the derived technologies are difficult in practice. The main difficulty arises from time synchronization among the senders and time-delay (or arrival time difference) detection in the receivers. Without perfect time synchronization and time-delay detection technologies, the positioning results would be inaccurate. Besides, the distance between the senders should be large enough to ensure the difference of the positioning signal arrival time distinguishable. The above constrains make TOA and TDOA approaches not appropriate for positioning most users in the indoor environment. On the other hand, the AOA approach also requires the sender to be able to detect the direction of arrival signals. This also requires the access point to equip extra components such as the smart antennas [5]. Besides, the reflection problem due to the indoor natures such as walls and pillars often causes inaccurate positioning results.

Driven by the above regards, this study adopts the signal strength approach of the third category since it requires no cheap equipments for both the access points and mobile users. Although the numerous huge obstructions such as the walls and the pillars make the propagation law invalid, however, they make the signal strengths of each access point vary significantly in adjacent regions. This phenomenon implies that we can apply the sensed signal strengths to determine the region of each mobile user. For the functions of reducing the power consumption of the lighting and air condition systems, the ability of estimating the region of mobile users is sufficient.

This study proposed a novel positioning method called the III[+] Beacon Match (I^3BM) method by improving the best access point ID sequence match positioning method [6]. The I^3BM requires the mobile users to equip with a mobile device which can sense the Received Signal Strength Indicator (RSSI) of the nearby beacon which are pre-installed inside the

[+] III is the abbreviation of the Institute for Information Industry. The proposed method adopts this term since the inventors are engineers from III.

interesting area. Since the power consumption of the mobile device decides the maintenance cost of the mobile device, therefore, power-saving is a crucial issue for the mobile device.

The Zigbee technology [7] provides short-range, low-cost and low power consumption wireless solutions in various applications, for instance, industrial automation, sensor network, home networking, replacement for wired computer peripherals, personal healthcare, remote control, monitoring etc. [8]. Based on those features, the proposed system employs the Zigbee technology to reduce the power consumption of the mobile device.

The rest of this paper is organized as follows. In Section 2, we present the architecture of the proposed system. The I^3BM positioning algorithm is presented in Section 3. Section 4 presents the application prototypes for smart home application. We make some discussions in Section 5. The conclusions and the future works are drawn in Section 7.

2. System Architecture

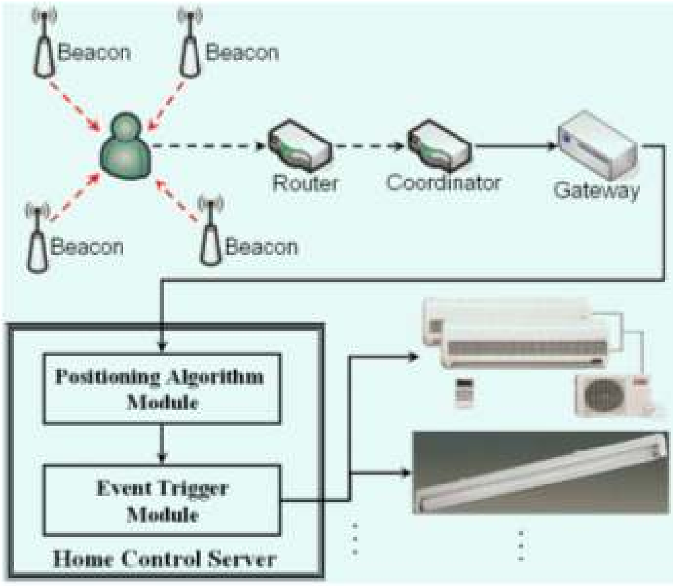

Figure 1. The smart home system architecture

Figure 1 shows the proposed smart home system architecture. In this system, several devices called the beacons were pre-installed in the interesting area. The mobile users are required to equip with a mobile device called the badge which periodically broadcasts echo requests to collect the positioning signals from the beacons and then forward the positioning signals to a nearby router. The positioning signal of a beacon contains the ID and the signal strength of the beacon.

Whenever a router received the positioning signals from a badge, it forwards the positioning signals to its coordinator directly or through the help of other routers. In Zigbee network, the coordinator is used to coordinate the operation of all the routers in the same network and collect packets from the routers. The packets are then forwarded to the home control server through the gateway which equips with the Zigbee communication module and the Ethernet communication module.

The positioning module in the home control server is used to estimate the positions of the badges according to the positioning signals from the badges. The estimate positions of the badges are then forwarded to the event trigger module. The event trigger module maintains numerous rules which control the household appliances. If the estimate position of a badge satisfies certain rules, the corresponding events will be triggered and some commands will be sent to corresponding household appliances to change their states.

3. I^{3}BM Positioning Algorithm

3.1 The Principle of the I^{3}BM Positioning Method and Its Challenges

The principle of the I^{3}BM method is simple and concrete. If a badge detects the signal strength of the beacons B_1, B_2, ..., B_n and the signal strength of B_i is S_i, then the position of the badge estimated by the I^{3}BM method is the position of B_j where $S_j = max\ \{S_1, ..., S_n\}$. Although the distance between a badge and a beacon is not in proportion to the signal strength of the beacon received by the badge, however, this method is simple and sometimes brings better effects. In Figure 2, the signal strengths of the beacons 6 measured by the badge of the mobile user A are often stronger than that of the beacon 7 since there is a wall between them. In this scenario, the I^{3}BM method often estimates the position of A as the position of beacon 6. Although the nearest beacon of mobile user A is the beacon 7, set the position of A as the position of beacon 6 is much appropriate for most indoor applications.

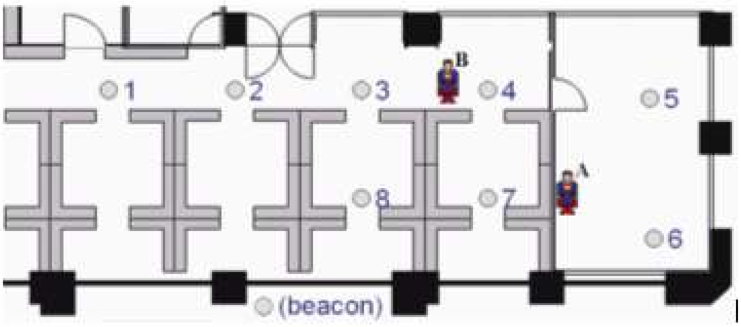

Figure 2. The I^{3}BM Method Scenarios

The I^{3}BM method conceals numerous problems. Those problems arise from the fact that the signal strengths of any beacon measured at any fixed position varies with time. According to our observations, the signal strengths of the beacon 7 measured by the badge of A are sometimes stronger than that of other beacons especially when the mobile user A closes and faces to the wall. Therefore, applying the I^{3}BM method directly without any improvement will bring a poor result: The position of the mobile user A is set to the positions of the nearby beacons (beacons 5, 6, and 7) randomly, and changed quickly. We call this problem as the ninja problem since the position of the mobile users changed quickly and unreasonably like a ninja. The main challenge of the I^{3}BM method is to determine the region of each mobile user while overcoming the ninja problem.

3.2 Improve the I^{3}BM Method by Signal Filtering and Adjustment

If the current position of the mobile user A is given as Figure 2, it is clear that the mobile user A will not move to the region nearby beacon 7 within a short enough time, and the mobile user A must pass through the regions nearby by the beacon 4 and 5 before it reached the region nearby the beacon 7. This shows that the I^{3}BM method can only consider the signal strength of the nearby beacons. It should be note that two beacons B_i and B_j are adjacent if all mobile objects in the region nearby the beacon B_i can reach to the region nearby the beacon B_j without pass through the regions nearby other beacons. Figure 3 below shows the adjacent relationship of the beacons in Figure 2. In Figure 3, two circles *i* and *j* are connected by a solid line means the two beacons B_i and B_j are adjacent.

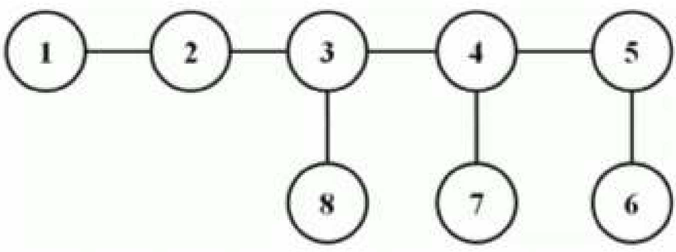

Figure 3. The adjacent relationship of the beacons

Signal Filtering

The signal filtering procedure is proposed based on the assumption that the next position of each mobile object is still inside the region of the beacon it connects, or the regions of the adjacent beacons. Therefore, if the previous position of a mobile object is in the area of beacon B_i, then the signal filtering procedure ignores the signal strength of B_j if $B_i \neq B_j$ and B_i is not adjacent to B_j. This procedure ensures that the mobile objects will not pass through the wall like ninja.

Although the signal filtering procedure ensures that the mobile objects will move reasonably, however, it brings another problem called the straying problem. The straying problem occurred when the mobile object receives only the signal from the ignored beacons. It may happen in the fast-moving object. If a mobile object detects no signals for a period of time, it should be conscious that it suffers the straying problem. In this situation, it has to re-initialize it position by sensing the signal strength of all the beacons. The position re-initialization procedure chooses the beacon with the strongest signals as the position of the mobile object.

Signal Adjustment

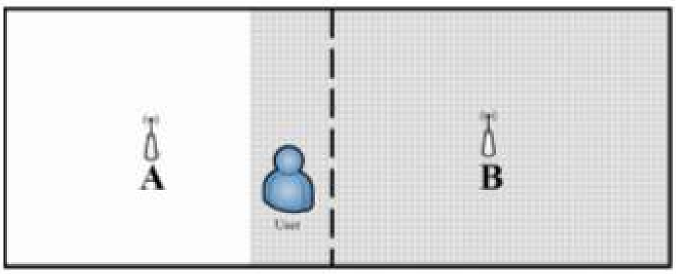

Figure 4. The boundary identification problem

The recognition of the boundary of the adjacent regions is also a problem. Since the I^{3}BM method applies the signal strength to identify the position of mobile objects, the boundary of two adjacent regions recognized by the I^3BM method is not often identical to that recognized by human begins. Figure 4 shows the boundary identification problem.

In Figure 4, there are two adjacent beacons A and B. In the gray region the signal strength of B is stronger than A. The dotted line is the perpendicular bisector of the two beacons A and B, or a wall with a door. Although the dotted line should be the boundary of the region A and B, the I^3BM method still set the position of the mobile user as the position of the beacon B. In this paper we call this problem the ambiguous boundary problem. The ambiguous boundary problem is common and in real cases the boundary of the gray region is often irregular.

If the previous position of the mobile user in Figure 4 is the position of the beacon A, appropriately subtract the signal strength of B measured by the mobile user is a strategy in reducing the errors caused by the ambiguous boundary problem. This shows that the signal strength collected by the badge of the mobile users should be adjusted before applying them to make position estimation.

After the beacons were installed in the interesting area, the proposed system suggests the system manager to collect the mean value of the signal strength of each two adjacent regions in their boundary. Let BS_A is that the mean value of the signal strength of the beacon A measured in the boundary of A and B, and BS_B is the mean value of the signal strength of the beacon B. If the previous position of the mobile user is in the region of the beacon A, the signal adjustment procedure adjusts the signal strength of B measured by the mobile user (denoted as S_B) as $S_B + BS_A – BS_B$.

The signal filtering and adjustment procedure can be performed simultaneously. To formally state the combination procedure, we make the following assumptions and definitions.

1. Assume that the previous position of a mobile user X is in the region of the beacon Y, and $Z_1, Z_2, ..., Z_k$ are all adjacent beacons of Y.
2. For each $1 \le j \le k$, $S_B(Y, j)$ is the mean value of the signal strength of the beacon Y measured in the boundary of Y and Z_j and $S_B(Z, j)$ is the mean value of the signal strength of the beacon Z_j.
3. For each $1 \le j \le k$, $S_X(Z, j)$ is the signal strength of Z_j measured by X and $S_X(Y)$ is the signal strength of Y measured by X.
4. The current position of X is denoted as CL_X, where $CL_X \in \{Y, Z_1, Z_2, ..., Z_k\}$

Based on the above assumptions and definitions, the signal filtering and adjustment procedure in the I^3BM algorithm applies the following rules to determine the value of CL_X.

Rule 1. $CL_X = Y$ if $S_X(Y) \ge S_X(Z, i) + S_B(Y, i) - S_B(Z, i)$ for all $1 \le i \le k$.

Rule 2. $CL_X = Z_j$ if Rule 1 failed and $S_X(Z, j) - S_B(Z, j) \ge S_X(Z, i) - S_B(Z, i)$ for all $1 \le i \le k$.

3.3 Improve the I^3BM Method by Signal Smooth

Given a beacon B and a position P, the signal strength of B measured at the position P is a random variable. In most cases the values generated by the random variable are close their mean but sometimes abnormal signal strength whose strengths are far from their mean appears. Since the signals with abnormal power strengths often misguide the I^3BM method, eliminates the signals with abnormal power strengths would be helpful in improving the ninja problem. In this paper, the procedure which eliminates the signals with abnormal power strength is called the signal smooth procedure. To formally state the signal smooth procedure, we make the following assumptions and definitions.

5. Assume that the badge applies *m* time slots to learn the signal strengths of all the beacons. For each beacon *B*, the communication module of the badge either senses no signal from *B* or returns a value as the signal strength of the signals form *B*.
6. For each beacon *B*, $S(B, i)$ is defined to be the signal strength of the signals from the beacon *B* measured by the badge in the i^{th} time slot. $S(B, i) = NULL$ if the communication module of the badge sense no signal from *B* in the i^{th} time interval.
7. $$\mu_B = \frac{\sum_{i=1, S(B,i) \neq NULL}^{m} S(B,i)}{\sum_{i=1, S(B,i) \neq NULL}^{m} 1}$$

Based on the above assumptions and definitions, the signal smooth procedure in the I^3BM algorithm can be stated as follow.

Step 1. Let $SB_1 = \{ S(B, i) \mid 1 \leq i \leq m \text{ and } S(B, i) \neq NULL\}$, $SB_2 = \phi$ and $j = 0$.

Step 2. Find *s* in SB_1 satisfying $\| s - \mu_B \| \leq \| t - \mu_B \|$ for all $t \in SB_1$

Step 3. Let $SB_1 = SB_1 - \{s\}$, $SB_2 = SB_2 \cup \{s\}$ and $j = j + 1$

Step 4. If $j \leq u$, go to Step 2. Otherwise terminates this procedure.

It should be noted that the values of *m* and *u* are system parameters satisfying $u < m$. The greater values of *m* and *u* usually improve the correctness of the positioning results but also enlarge the positioning response time.

4 The Zigbee-based Smart Home System Prototypes

4.1 The Zigbee-based Positioning System Prototypes

The positioning module in Figure 1 has been detailed presented in Section 3. This subsection presents the prototypes of other components of the Zigbee positioning system.

Figure 5. The III badge prototype and its layout

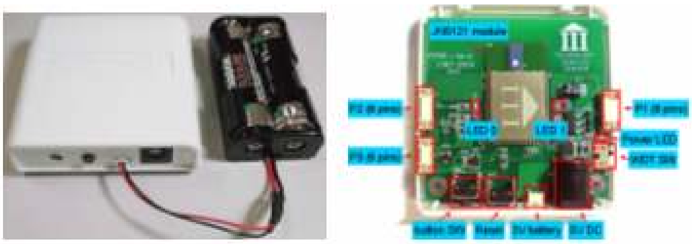

Figure 6. The Zigbee hardware platform

Figure 5 shows the badge prototype and its layout, and Figure 6 shows the Zigbee hardware platform for performing the beacon, router and coordinator functions. With one AAA Alkaline battery, the life time of a badge is about 6 weeks (continuous use without sleeping). We design the badge and Zigbee hardware platform and we cooperate with the Jennic to implement those prototypes.

In May 2005, our prototypes successful passed the ZigBee Compliant Platform (ZCP) certification test using the TI/Chipcon platform. We therefore became the first organization in Asia to receive the certification proof. In July 2006, we passed the ZCP test using both the Jennic platform and the UBEC platform. Our institute and Freescale are both considered in obtaining the largest number of ZigBee certified platform in the world. Those remarkable records show that the proposed components are reliable for smart home applications.

The event trigger module contains a set of rules. Whenever it received an event, it sends the event to all the rules. The rules perform the corresponding procedure after they accept this event. Section 4.2 briefly presents the rules for controlling the lighting system and the air condition.

4.2 The Zigbee-based Positioning System for Controlling the Air Condition and Lighting System

In current stage, the system prototype employs the RS816WP monitoring and control platform to monitor and control the air condition and lighting system. Remotely turn on/off the light through the help of this platform is trivial. To control the air condition, the system prototype applies this platform to control the thermometers of the air condition which detect the temperature of the return and outside air.

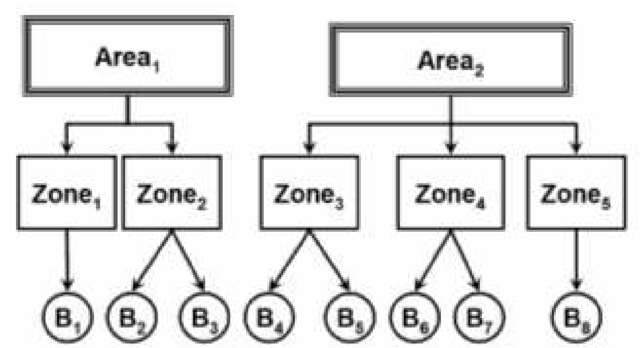

Figure 7. The area hierarchy for the event trigger rules

The event trigger module partitioned all the beacons into several zones according to the natural of the interesting area, and the zones are furthered partitioned into several areas as Figure 7. Rule 3 blow shows the rule for controlling the lighting system and Rule 4 below shows the rule for controlling the air condition.

Rule 3. Turn on all the lights in $Zone_i$ if and only if there is a badge in this zone.

Rule 4. Set the temperature of the return air as the temperature of the outside air if there is no badge in the area where the air condition is.

This system prototype is now verifying in our demo site and in the smart house of the Nation Taiwan University. Figure 8 shows the layout of the second demo site. In the smart house of the National Taiwan University, the beacons in each room form a zone and the beacons in the yard is a zone. Each floor is an area and the yard is also an area. There is no air condition for the yard.

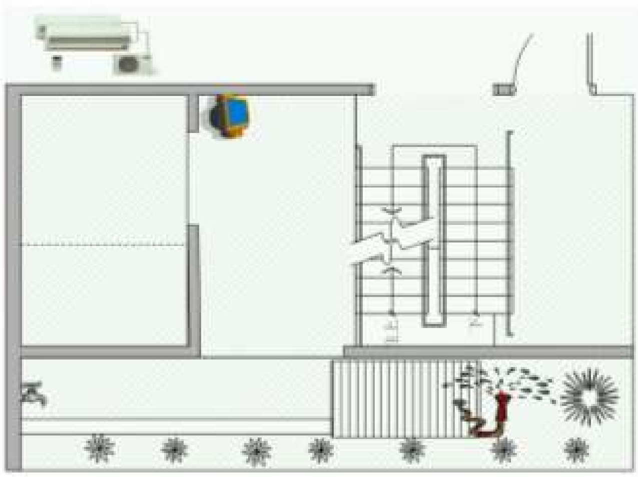

Figure 8. The Smart House in the Nation Taiwan University

4.3 Some III Systems for Intelligent Building Applications

The Smart Skin System

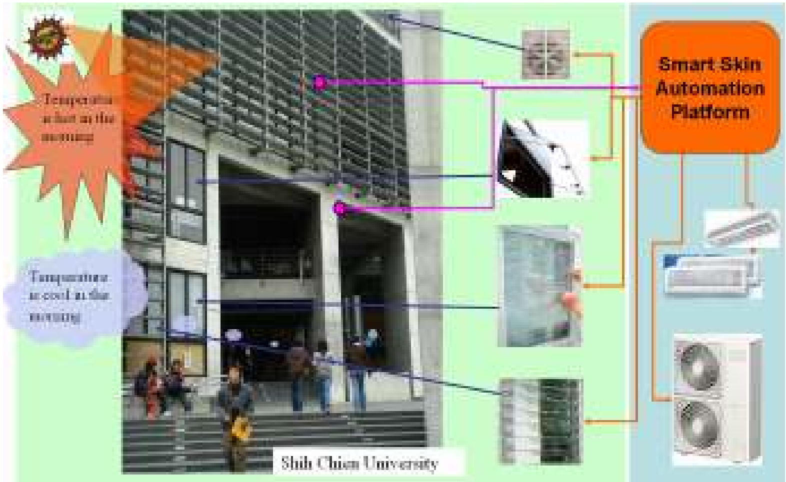

Figure 9. The Smart Skin System in the Shih Chien University

Figure 9 shows the smart skin system implemented in the Shih Chien University. The smart skin system proposed by the III can immediately adjust the intelligent door, window, sun visor, …, etc according to the outdoor environment parameters. This system now applies the anemometer, illumination gauge, thermometer and rain detector to measure the interesting outdoor environment parameters. The detectors apply the Zigbee communication network to upload the detected environment parameters to the smart skin system controller. This system can reduce the unnecessary heat (63% at most) from outdoor to indoor environment and hence can achieve the goal of reducing the energy consumption for green building.

The Communication Follow Me System

Figure 10. The Communication Follow Me System Architecture

Figure 10 shows the system architecture of the Communication Follow Me system. This system integrates the proposed I^3BM positioning system and a VOIP system to provide the intelligent phone adapter services. In this architecture, each mobile subscriber is required to equip with a Zigbee badge. Once the Communication Follow Me system receives a phone to its subscriber, it applies the I^3BM positioning method to estimate the position of the subscribers and then forward the phone to the nearest extension.

5 Discussions

In this study, there are many theoretical strategies which are difficult in practices. Performance and accuracy are the main theoretical issues for this topic, but the cost and system reliability are the main practical issues. Although the proposed positioning method is not accurate enough, it is stable and reliable.

In Section 3.2, the signal adjustment procedure samples the signal strengths in the boundary of the adjacent beacons and then applies them to adjust the signal strength to overcome the ambiguous boundary problem. Although we realize that boundaries are irregular and sampling the signal strength in only one or two positions is not accurate enough, we state this in the SOP of constructing this system because the construction cost is limited.

In Section 3.3, the signal smooth procedure seems rough with no theoretical foundation. Some previous studies such as [6] employed some statistical methods to define the abnormal signals. Those methods seem reasonable, but they require larger values of m and u in the signal smooth procedure. This approach not only increase the system response time but also increase the system and maintenance cost.

6 Conclusions and Future Works

This paper presented an intelligent system prototype for smart home applications. The system prototype employs the position of the home members to trigger appropriate services for the home members. The design and implementation of the Zigbee positioning system were presented detailed presented. The prototypes of the badge and the Zigbee hardware platform for the beacons, routers and coordinators were implemented and are passed the ZigBee Compliant Platform (ZCP) certification test. Two smart home system prototypes were built and are verifying their performance and reliability.

Testing the performance in larger demo site with Zigbee embedded home appliances is desired. We are now contacting some home appliances manufacturers. Since Z-Wave is another wireless sensor network proposal which focus on the home applications, and the expected power consumption and cost are both less than the Zigbee standard, we are now considering applying the Z-Wave module and are process the corresponding feasibility researches. Since the ambiguity boundary problem may arise from the change of the layout, we are now designing automatic maintaining system to overcome this problem.

7. References

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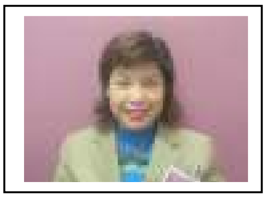

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