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Reference Tag-based Indoor Localization Techniques ⋆

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Abstract: In WSN-based localization, there are many challenging points. The difficulty lies in the fact that communication signals in a space-limited indoor office environment are interfered and attenuated by multi-path, reflection, channel fading, deflection, diffraction, etc. In fact, it is quite difficult to develop a reliable signal propagation model in an office environment because it is challenging to accurately estimate the signal path loss parameter. This paper proposes using reference tags for online estimation of signal propagation model and for the reliable calculation of the time of flight of radio signals. Thus main contribution of this paper is to suggest localization schemes based on reference tag, which is so-called reference tag-based indoor localization (RTIL).

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1. INTRODUCTION

Wireless sensor network (WSN) can be referred to as networked-systems that have distributed sensing nodes connected by wireless communication protocols. In the point of distributed sensing nodes, which are placed around a space, the WSN can be considered as ubiquitous sensor network (USN) as well. The cutting-edge technologies of WSN or USN have been used in various industrial/service areas even though lots of technical issues still have to be resolved. It was expected that the USN/WSN technologies would be well demonstrated and used in ubiquitous robotic companion (URC) Oh (2005) and ubiquitous city (U-City) businesses Cho et al. (2006). The URC seeks to improve the robot intelligence by way of networking between the robot client and central main server. The goal of U-City is to manage and maintain the city through intelligent soil/water/ atmosphere managements; autonomous surveillance, monitoring; e-learning; intelligent transportation system; health monitoring, etc. One of the key challenging technical problems encountered in these URC and U-City is to locate a small mobile tag, which can be easily attached to pedestrian, mobile object, and stationary target, in a real time with reliable accuracy Ahn et al. (2007a). From literature searches, we could see that localization is divided into the outdoor cases and indoor cases. In the case of the outdoor localization, there is a global positioning system (GPS), which is a dominant and reliable positioning system. However for the indoor case, there is no particular solution even though vision-based navigation systems Patwari et al. (2005); Sun et al. (2005) have been actively used for tracking pedestrian and object. However, in the vision-based systems the object recognition is still a tough topic; hence usually it cannot be used for indoor localization. As an alternative of the vision systems, recently WSN-based navigation systems based on UWB Oppermann et al. (2004), ZigBee, RFID, or WLAN Rehim (2004), have been widely studied, where the signal detection and time synchronization between sensors are important considerations. There are however lots of challenging points in WSN-based localization. The difficulty lies in the fact that communication signals in a space-limited indoor office environment are interfered and attenuated by multi-path, reflection, channel fading, deflection, diffraction, etc. In fact, it is quite difficult to develop a reliable signal propagation model in an office environment because it is challenging to accurately estimate the signal path loss parameter. For a detailed discussion and comprehensive categorization about the WSN-based localization, refer to Ahn and Yu (2007). This paper proposes using reference tags for online estimation of signal propagation model and for the reliable calculation of the time of flight of radio signals. Thus main contribution of this paper is to suggest localization schemes based on reference tag, namely reference tag-based indoor localization (RTIL).

2. REFERENCE TAG-BASED INDOOR LOCALIZATION

The reference tag-based indoor localization (RTIL) proposed in this paper is illustrated in Fig. 1. The left figure shows the traditional approach for localizing the tag. The reference beacon and the tag organize a localization sensor network. The reference tags either broadcast radio signals or receive signals from the tag. Using time of arrival (TOA), time difference of arrival (TDOA), angle of arrival (AOA), or received signal strengths (RSS) Ahn and Yu (2007), the localization network calculates the position of the tag. In traditional approaches, only TOA, TDOA, AOA, or RSS between the reference beacons and the tag are considered and processed. The right figure

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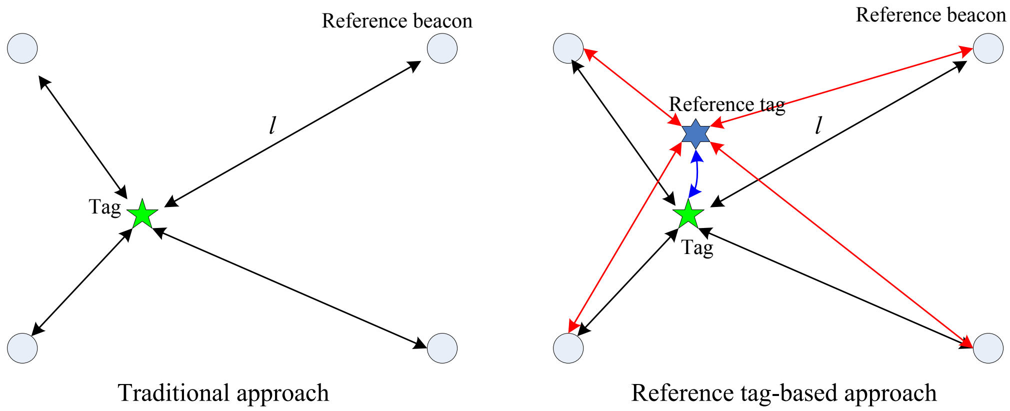

Fig. 1. Left: Traditional approach. Right: Reference tag-based localization.

shows the reference tag-based approach proposed in this paper. In this RTIL, another tag whose position is known is used. The motivation of using another tag is that signal attributes such as TOA, TDOA, AOA, or RSS between the tag and reference beacons can be estimated more accurately if the signal attributes between the reference tag and reference beacon are used as reference attributes. Note that the signal attributes between the reference tag and reference beacon can be precisely estimated since the position of the reference tag is known. Thus, the fundamental concept of RTIL is to make use of information of the reference tag whose position is known, for the localization of the tag whose position is unknown. In this paper, we present two different techniques, which are developed based on RTIL idea. In the following subsection, we present UWB-based wireless localization via internal hardware delay calibration. In this approach, the internal hardware delays are compensated using the signal coming from a reference tag. In Subsection 2.2, we present indoor localization technique based on online parameter estimation of received signal strength (RSS).

2.1 UWB-based wireless localization via internal hardware delay calibration

In the UWB-based localization, two approaches are noticeable. The first approach is TDOA-based method and the second approach is RTT method. In TDOA, time synchronization between sensors is a key requirement, which is not easy to achieve. As an example, in Ubisense system,[1] for the time synchronization between beacon nodes, wired-cables are used. However installing wired-cables is not good for a plug-and-play style application; for instance, the ubiquitous robotic space Ahn and Yu (2006); Ahn et al. (2007b) requires a less hardware installation and requests an easily relocatable networking system. The RTT technique is well described in IEEE 802.15.4a standard. Since the client and sensors exchange signals, the RTT system is a two way communication system. However, since transceiver is used for the data acquisition and transmission, the actual hardware size of the client gets bigger, which is not good for the mobile object tracking either. In this subsection we present a new method that is a single way communication system and does not require any timing synchronization between sensors. Furthermore in the new method, reference sensors receive signal emitted from the client. That is, the mobile client does not receive any RF signal from the reference node; instead it only sends a RF signal, which is received by the reference beacons. The reference beacons consist of two different types of nodes. The servant nodes send their acknowledgement signals to the master node when they receive the RF signal emitted by the mobile client. The master node then tags the time when it receives the acknowledgement signal from individual servant node. The key issue in this new approach is to estimate the internal hardware delay of individual reference node. Let us consider Fig. 2, which depicts wireless signal flow from a mobile tag to master node through a servant node. The mobile tag (named as C in the figure) just emits its RF signal encoded with its identity. Then the servant reference node (B) receives the signal and immediately sends an acknowledgement signal to the master note (A). In the figure, a, b, c, d, e, and f represent time elapses along the temporal axis. Initially a RF signal is sent inside the media C, where there is a time elapse by amount of a. Then, the signal propagates the free space between C and A. The sensor B sends an acknowledgement signal to the master sensor A. It takes $c + d$ duration to relate the signal. It takes e to propagate the free space between B and A.

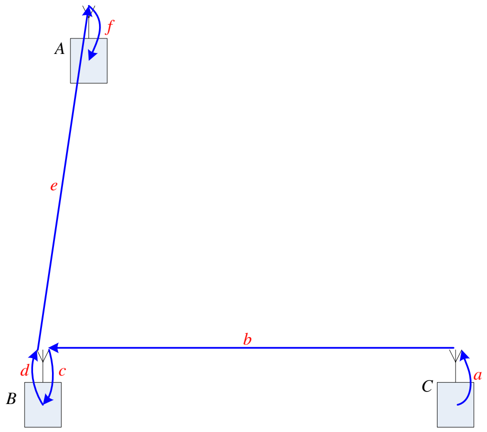

Fig. 2. Wireless communication among master node, servant node, and mobile tag.

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[1] www.ubisense.net

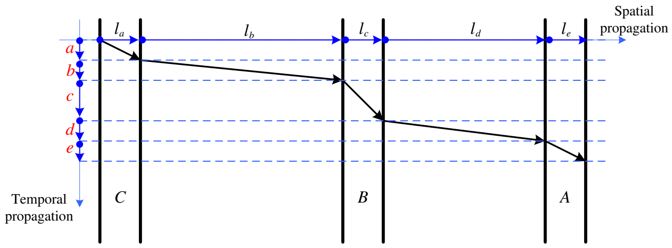

Fig. 3. Temporal and spatial domain representation of the wireless communication among master node, servant node, and mobile tag.

Then, when the master A perceives the signal detection, it also takes f for the process. The temporal and spatial relationship of Fig. 2 can be represented by Fig. 3. For the propagation through the physical distance l_a, it takes a duration; and for the propagation through the physical distance l_b, it takes b duration; and so on. Now the problem of this approach is to find the position of the media C with respect to the local reference coordinate frame.

For a generalized result, based on illustrations of Fig. 2 and Fig. 3 we define symbols like below (all time instants and elapses are presented in a global timer, which is located within the master node):

- t_o: The instant when the tag transmits RF signal. This is the just instant when the tag releases the signal.
- t_1^o: The time elapse for the free space propagation between the tag and master node.
- t_m^o: The internal hardware (master node) delay for the processing of the signal received directly from the tag.
- t_1^i: The time elapse for the free space propagation between the tag and the node i.
- t_d^i: The internal hardware (node i) delay for the processing of the signal received from the tag.
- t_2^i: The time elapse for the free space propagation between the node i and master node.
- t_m^i: The internal hardware (master node) delay for the processing of the signal received directly from the node i.
- T_o: The tagged time of the signal directly received from the tag at the master node.
- T_i: The tagged time of the signal received via the node i.

It is supposed that the positions of master node and reference node i are known apriori. Also it is considered that the number of reference nodes is N; i.e., $i = 1, \ldots, N$. Then, by calibrating the internal delay of individual reference node, we can estimate the distances between the tag and reference nodes. Now, using the above symbols, we can find the following relationships:

$$T^o = t_o + t_1^o + t_m^o \tag{1}$$

$$T_i = t_o + t_1^i + t_d^i + t_2^i + t_m^i, \;\; i = 1, \ldots, N \tag{2}$$

Based on experimental observation McCrady et al. (2000), the internal hardware delays are modelled as random variables such as:

$$\widetilde{T}_0 = t_o + t_1^o + \overrightarrow{t}^{o}_{m} \tag{3}$$

$$\widetilde{T}_i = t_o + t_1^i + \overrightarrow{t}^{i}_{d} + t_2^i + \overrightarrow{t}^{i}_{m}, \;\; i = 1, \ldots, N \tag{4}$$

where $\overrightarrow{t}^{o}_{m} = t_m^o + n_m^o$, $\overrightarrow{t}^{i}_{d} = t_d^i + n_d^i$, and $\overrightarrow{t}^{i}_{m} = t_m^i + n_m^i$. Here, since the same master node receives signals from the tag and node i, it is further supposed that $t_m^o = t_m^i$; but $n_m^o \neq n_m^i$. Now the required task is to estimate the internal hardware delay t_d^i. Note that this hardware delay cannot be directly measured; but only can be inferred using the tagged time information $\widetilde{T}_0$ and $\widetilde{T}_i$. Now subtracting (3) from (4), we have

$$\widetilde{T}_i - \widetilde{T}_0 = t_1^i + \overrightarrow{t}^{i}_{d} + t_2^i + \overrightarrow{t}^{i}_{m} - t_1^o - \overrightarrow{t}^{o}_{m} \tag{5}$$

$$\cong t_1^i + \overrightarrow{t}^{i}_{d} + t_2^i + n_m^i - t_1^o - n_m^o \tag{6}$$

In the above relationship, only $\widetilde{T}_0$ and $\widetilde{T}_i$ are measured time instants at the master node. However if we place the tag at a known position initially for the internal delay calibration, then t_1^i, t_1^o are calculated as $t_1^i = l_i/c$ and $t_1^o = l_o/c$ where l_i is the distance between the tag and node i, l_o is the distance between the tag and master node, and c is the speed of light. Also since the reference nodes are placed at known positions, t_2^i is calculated as $t_2^i = l_i^m/c$ where l_i^m is the distance between the master node and node i. Therefore, the internal delay t_d^i is given by

$$t_d^i = \widetilde{T}_i - \widetilde{T}_0 + (l_o - l_i^m - l_i)/c + n_m^o - n_m^i - n_d^i \tag{7}$$

However, since n_m^o and n_m^i are random variables, we can calibrate the internal hardware delay as $\bar{t}_d^i = \widetilde{T}_i - \widetilde{T}_0 + (l_o - l_i^m - l_i)/c$, where $\bar{t}_d^i$ is the calibrated value.

Using the calibrated internal hardware delay $\bar{t}_d^i$ of individual reference node, we can obtain

$$t_1^i - t_1^o = \widetilde{T}_i - (\overrightarrow{t}^{i}_{d} + t_2^i + \overrightarrow{t}^{i}_{m}) - \widetilde{T}_0 + \overrightarrow{t}^{o}_{m} \tag{8}$$

$$= \widetilde{T}_i - \overrightarrow{t}^{i}_{d} - t_2^i - n_m^i - \widetilde{T}_0 + n_m^o \tag{9}$$

$$\cong \widetilde{T}_i - \bar{t}_d^i - t_2^i - n_m^i - \widetilde{T}_0 + n_m^o \tag{10}$$

which is the time difference of arrivals of a signal. That is, from the above relationship, we can find $l_i - l_o$ such as, with noises $-n_m^i + n_m^o$:

$$l_i - l_o \cong (\widetilde{T}_i - \widetilde{T}_0 - \bar{t}_d^i - t_2^i)c \tag{11}$$

where $\widetilde{T}_i$ and $\widetilde{T}_0$ are measured values, $\bar{t}_d^i$ is a calibrated value, and t_2^i is known apriori. Now using (11), the position of the tag ($\mathbf{p} = [x, y]^T$) can be estimated as Sayed et al. (2005):

$$\widehat{\mathbf{p}} = (H^T H)^{-1} H^T (l_o \mathbf{u} + \mathbf{v}) \tag{12}$$

where

$$H = \begin{pmatrix} x_1 & y_1 \\ x_2 & y_2 \\ x_3 & y_3 \\ \vdots & \vdots \\ x_N & y_N \end{pmatrix}; \; \mathbf{u} = \begin{pmatrix} -l_{1o} \\ -l_{2o} \\ -l_{3o} \\ \vdots \\ -l_{No} \end{pmatrix}; \; \mathbf{v} = \frac{1}{2} \begin{pmatrix} K_1^2 - l_{1o}^2 \\ K_2^2 - l_{2o}^2 \\ K_3^2 - l_{3o}^2 \\ \vdots \\ K_N^2 - l_{No}^2 \end{pmatrix}$$

$$l_{io} = l_i - l_o; \; K_i = \sqrt{x_i^2 + y_i^2}$$

In (12), l_o is unknown; so assuming the master node is located at the origin, the following quadratic form should be solved for x and y:

$$\begin{pmatrix} x \\ y \end{pmatrix} = (H^T H)^{-1} H^T \left(\sqrt{x^2 + y^2}\mathbf{u} + \mathbf{v} \right) \tag{13}$$

If we define

$$\begin{pmatrix} \alpha \\ \beta \end{pmatrix} = (H^T H)^{-1} H^T \mathbf{u}; \ \begin{pmatrix} \gamma \\ \delta \end{pmatrix} = (H^T H)^{-1} H^T \mathbf{v} \tag{14}$$

we can obtain the relationship between x and y as $x = \frac{\alpha}{\beta} y + \eta$, where $\eta = -\frac{\alpha}{\beta}\delta + \gamma$. Then, y is the solution of the following quadratic equation:

$$(\alpha^2 + \beta^2 - 1)y^2 + 2(\eta\alpha\beta + \delta)y + \eta^2\beta^2 - \delta^2 = 0 \tag{15}$$

If there are two pairs of solution from (15) (let us denote these as $(\widehat{x}_1, \widehat{y}_1)$ and $(\widehat{x}_2, \widehat{y}_2)$), the true solution is selected by the following rule:

$$(x, y) = \begin{cases} (\widehat{x}_1, \widehat{y}_1), \text{ if } \|\vartheta^1\| \leq \|\vartheta^2\| \\ (\widehat{x}_2, \widehat{y}_2), \text{ else} \end{cases} \tag{16}$$

where $\vartheta^j = (\vartheta_1^j, \vartheta_2^j, \ldots, \vartheta_N^j)^T$, $j = 1, 2$, and $\vartheta_i^j = \widehat{d}_i^j - l_{io}$ and

$$\widehat{d}_i^j = \left\| \begin{pmatrix} x_i \\ y_i \end{pmatrix} - \begin{pmatrix} \widehat{x}_j \\ \widehat{y}_j \end{pmatrix} \right\| - \left\| \begin{pmatrix} \widehat{x}_j \\ \widehat{y}_j \end{pmatrix} \right\|, \ i = 1, \ldots, N \tag{17}$$

2.2 Indoor localization based on online parameter estimation of RSS

The received signal strength (RSS) method uses signal strength arrived, and uses a relationship between the signal-loss and the propagation distance. The following formula is usually used for this relationship:

$$I(r) = \frac{c}{r^a} \tag{18}$$

where $I(r)$ represents signal strength at distance r and c can be a constant or environment-dependent variation. However, the signal attenuation parameter a is not fixed, but it depends on the situation. In Eq. (18), we need to calculate model parameters a and c based on received signal strengths. If the model parameters a and c are known, then using the measured signal strength $I(r)$, we can reversely calculate the distance between reference nodes and the tag. In what follows, we will explain a new algorithm for this. The signal attenuation parameter a is sensitive to the environmental variation and the initial signal strength c is a function of time. It is assumed that the positions of reference nodes are known. Also it is supposed that when the tag and receivers receive signals, they can know where the signal comes from. For convenience, let us say that the receiver of the reference node i receives its own signal with strength c_i and receives the signal of reference node j with strength c_i^j. Also, the tag receives the signal of the reference node i with strength I_i. The distance between the reference node i and the tag is denoted as r_i, and signal attenuation parameter is a_i. Then, unknown parameters are r_i and a_i, and measured values are c_i^j and I_i. Now, the problem is to find r_i and a_i as accurately as possible using measurements c_i^j and I_i.

A simple solution for the parameter estimation is to use the fixed length between the reference node i and the reference node j, $i \neq j$. That is, since reference nodes are fixed at known points, and c_i and c_j are related by the following equation

$$c_i^j = \frac{c_j}{(r_i^j)^{a_j}} \tag{19}$$

where r_i^j is the distance between the reference node i and the reference node j, c_i^j is a signal strength of the node j received by the node i. Therefore, a_j is simply calculated as

$$a_j = \frac{\ln^{c_j / c_i^j}}{\ln^{r_i^j}} \tag{20}$$

Thus, attenuation parameters a_i, $i = 1, \ldots, N$ calculated by Eq. (20) are used with together I_i for the distance, r_i, $i = 1, \ldots, N$, calculation in Eq. (18). However, Eq. (20) calculates the attenuation parameters in a simple manner and it does not filter out measurement noises. So, as an alternative, we can conceive a method that uses average of received signals. That is, for the calculation of a_j, we use all c_i, $i = 1, \ldots, N (i \neq j)$ in the following way:

$$a_j = \frac{1}{N-1} \sum_{i=1,\ i \neq j}^{N} \frac{\ln^{c_j / c_i^j}}{\ln^{r_i^j}} \tag{21}$$

which will remove some high frequency noise and uncompensated bias errors. The overall procedure can be summarized in the sequel. The receivers, which are placed in reference nodes, and the tag receive signals emitted from the transmitter of individual reference node. Then, reference nodes send information of measured signal strengths to the tag using wireless local area network so that the tag can estimate a_j using Eq. (20) or Eq. (21). Then, using Eq. (18), the tag calculates distances between reference nodes and it such as

$$r_i = (c_i / I_i)^{1/a_i} \tag{22}$$

Now, using Eq. (22) it is straightforward to estimate the position of the tag. A nice review on the localization algorithms is presented in Sayed et al. (2005). In Sayed et al. (2005), if the positions of reference nodes are known as (x_i, y_i), then the position of the tag is calculated as

$$[\hat{x}, \hat{y}]^T = (H^T H)^{-1} H^T b \tag{23}$$

where

$$H = \begin{pmatrix} x_2 & y_2 \\ x_3 & y_3 \\ x_4 & y_4 \\ \vdots & \vdots \\ x_N & y_N \end{pmatrix}; \ b = \frac{1}{2} \begin{pmatrix} K_2^2 - r_2^2 + r_1^2 \\ K_3^2 - r_3^2 + r_1^2 \\ K_4^2 - r_4^2 + r_1^2 \\ \vdots \\ K_N^2 - r_N^2 + r_1^2 \end{pmatrix}$$

and $K_i^2 = x_i^2 + y_i^2$. So far, we have presented a localization method using reference nodes which include both transmitter and receiver.

3. ILLUSTRATIONS

3.1 UWB simulation

In Fig. 4, the left plots are calibrated internal hardware delays of five reference nodes. In the simulation, the actual hardware delays are fixed as 2.0×10^{-6} seconds. Three different cases are tested as shown in these plots. In the case of the top plots, the internal hardware delays are calibrated within 0.001×10^{-6} second accuracy. In the case of the middle plots, delays are calibrated within 0.03×10^{-6} second accuracy, and the bottom case shows that delays are calibrated within 0.125×10^{-6} second accuracy. The right plots show the measurement errors when internal hardware delays are calibrated by the left plots. Note that the variance of n_m^o (σ_{n^o})is assumed as $(1.0 \times 10^{-9})^2$ and the variance of n_m^i (σ_{n^i})is assumed as $(2.0 \times 10^{-9})^2$. It is obvious that the accuracy of the internal delay calibration is critical for overall performance. To test the performance degrade due to the noise amount, we change the variances of n_m^o and n_m^i; but we fix $\bar{t}_d^i$ as $[2.0076657173526 \times 10^{-6},\ 1.9761702136919 \times 10^{-6},\ 1.9796196565197 \times 10^{-6},\ 2.0097119708386 \times 10^{-6},\ 1.9704032170970 \times 10^{-6}]$. Fig. 5 shows the errors of the calculated positions according to the noise amount. Left-top is the case of $\sigma_{n^o} = (1.0 \times 10^{-9})^2$ and $\sigma_{n^i} = (2.0 \times 10^{-9})^2$; Right-top is the case of $\sigma_{n^o} = (5.0 \times 10^{-9})^2$ and $\sigma_{n^i} = (1.0 \times 10^{-8})^2$; Left-bottom is the case of $\sigma_{n^o} = (1.0 \times 10^{-8})^2$ and $\sigma_{n^i} = (2.0 \times 10^{-8})^2$; and Right-bottom is the case of $\sigma_{n^o} = (5.0 \times 10^{-8})^2$ and $\sigma_{n^i} = (1.0 \times 10^{-7})^2$. It is also clear that the performance is degraded according to the measurement noises.

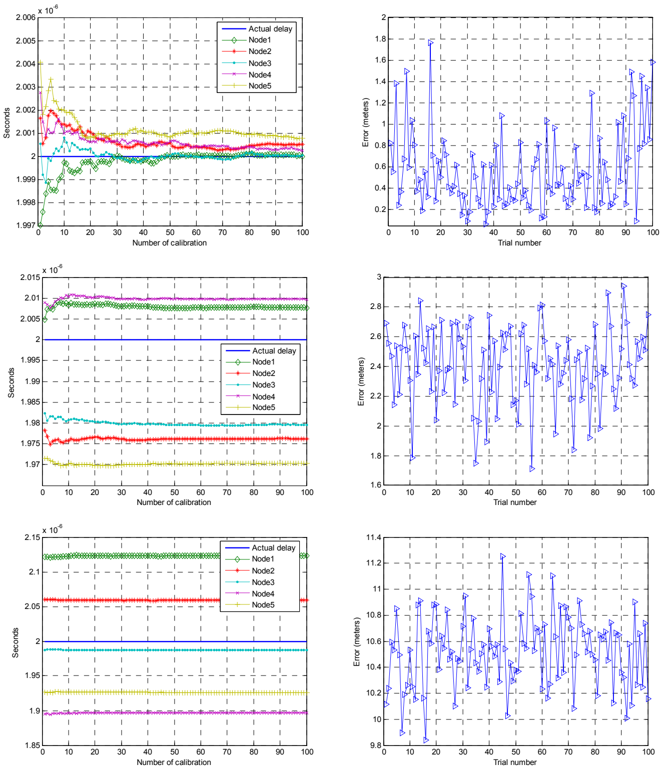

Fig. 4. Calibrated internal hardware delays and measurement errors when $\sigma_{n^o} = (1.0 \times 10^{-9})^2$ and $\sigma_{n^i} = (2.0 \times 10^{-9})^2$.

3.2 *Experimental test for RSS-based localization*

For the experimental verification of the RSS-based localization, we developed hardware chipset as shown in Fig. 6.

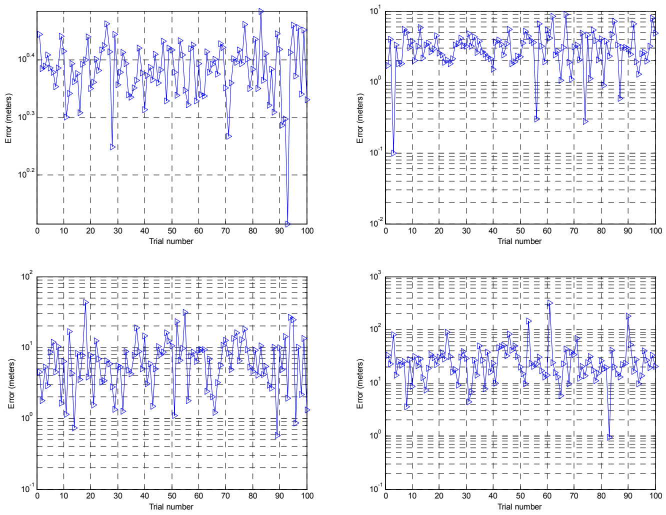

Fig. 5. Performance degradation according to the noise amount.

The left picture shows the localization tag developed. The same tag is used for both reference tag and mobile tag. The right picture is reference beacon developed. For the experimental test in an indoor environment, three reference beacons are located on partition walls as shown in Fig. 7. In this figure, IS tags are used to measure the initial strength of radio signal when it is emitted from reference beacon. Mobile tag has been located at five different places. One reference tag is used. Fig. 8 shows the test results. On each place, 10 sampling points are used to estimate the position of tag. In Fig. 8, the first place is corresponding to sampling points $1-10$; the second place is corresponding to sampling points $11-20$; the third place is corresponding to sampling points $21-30$; the fourth place is corresponding to sampling points $31-40$; the fifth place is corresponding to sampling points $41-50$. Scheme 1 is a method without using IS tag; scheme 2 is a method with using IS tag measurements. For the comparison of the performance, a commercial localization chipset CC2431 [2] has been used for a comparison purpose. As shown in the plots, scheme 1 and scheme 2 are better than CC2431 except the fifth place. In the fifth place, scheme 1 is slightly worse than CC2431.

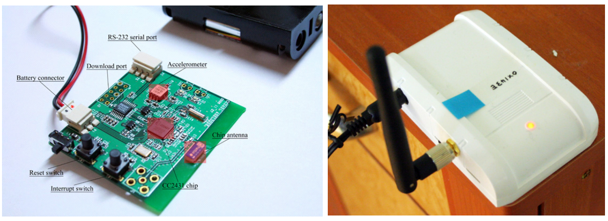

Fig. 6. Left: the localization tag (the tag is used as reference tag and mobile tag. Right: reference beacon.

4. CONCLUDING REMARKS

In this paper, we have presented localization methods based reference tag, which is placed within ubiquitous indoor space. The first method is to use time-of-flight

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[2] www.chipcon.com

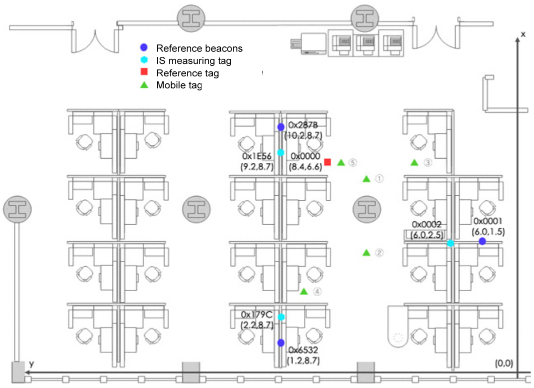

Fig. 7. Experimental test environment. Three reference beacons are located. IS tags are used to measure the initial strength of radio signal when it is emitted from reference beacon. Mobile tag has been located at five different places.

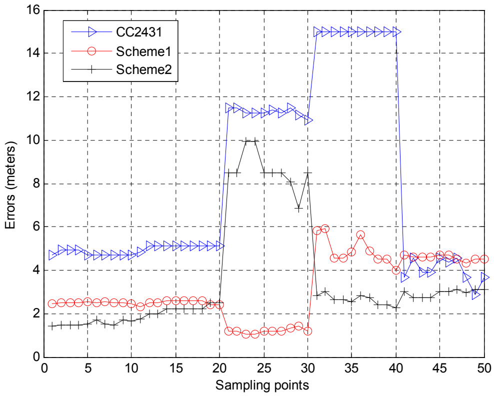

Fig. 8. Test results: for the comparison of the system, CC2431 has been used for a comparison purpose. Scheme 1 is a method without using IS tag; scheme 2 is a method with IS tag.

between the tag and reference beacon. In this approach, a reference tag is used for the calibration of hardware delay of individual beacon. Although, the reference tag is used for the initial calibration, when the environment is variant, which is time dependent, the reference tag is continuously used for the online estimation of hardware delay of individual beacon. However, since the TOA is the attribute used in this approach, the first method is only valid for UWB systems. The validity of the idea has been demonstrated through computational simulations. Since the idea of using hardware calibration is a new method, we could not compare the performance with existing methods. The second method is for the accurate estimation of received signal strength. In this approach, signal attenuation parameter is estimated in a real time. Using the distances between reference beacons and reference tag, which are known, the unknown distances between reference beacons and mobile tag have been estimated. For the second method, we developed actual hardware equipment and implemented the system in an indoor office environment. From the comparison with commercial LBS chipset CC2431, we found that the new method had a better performance than CC2431 in most of tests. Thus we were able to reach the conclusion that localization schemes based on reference tag, which is so-called reference tag-based indoor localization (RTIL), could provide a better performance than typical approaches.

5. ACKNOWLEDGEMENT

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