Fingerprinting Localization with Cruciate Directional Antennas for Wireless Sensor Networks

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Abstract: This paper proposes a novel fingerprinting localization scheme, called FLCDA (Fingerprinting Localization with Cruciate Directional Antennas), using only one anchor node equipped with four directional antennas whose orientations are perpendicular to adjacent ones. The proposed FLCDA consists of two phases. In the RSSI gathering phase, a sensor node is placed at reference positions to send signals. And the RSSI values of the signals received by the four antennas are stored in the anchor node as the positions' fingerprints. In the localizing phase, the anchor node localizes a target sensor node by receiving its signals with the four directional antennas. The position associated with the fingerprint most matched with the received signals' RSSI values is assumed to be the target node's position. We also design and implement some techniques to accelerate FLCDA without affecting the accuracy too much. FLCDA and its variants are also compared with related ones.

Keywords: fingerprinting; directional antennas; localization; wireless sensor networks

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1 Introduction

A wireless *sensor network (WSN)* consists of many tiny-sized sensor nodes that have computation power, communication capability, and sensing functions. Each sensor node can sense physical phenomena, like temperature, vibration, light, electromagnetic strength, humidity, and so on, and can transmit the sensed data to the sink node through a chain of multiple intermediate nodes that help forward the data. Because of its powerful and versatile functions, the WSN has been widely used in many areas such as military affairs, patient healthcare, and environment inspection, etc. In many applications, location information of the sensor node is desirable besides the sensed data. In addition, the location information of the deployed sensor nodes can be used to improve routing efficiency. Hence, how to find the locations of sensor nodes becomes one of the most critical issues in WSNs.

Localization is the process for determining the absolute or relative physical *location* or *position* of a specific node or the *target node*. Although global positioning system (GPS) (Hofmann-Wellenhof, 2001) can provide precise location information, the costly hardware and large size make it unsuitable for WSNs. Furthermore, GPS can only be used outdoors since it depends on the signals directly received from satellites for localization. Besides GPS, numerous localization methods (Amundson et al., 2010; Amundson et al., 2011; Bahl and Padmanabhan, 2000; Chen et al., 2003; Cong and Zhuang, 2002; Gustafsson and Gunnarsson, 2003; Hood and Barooah, 2011; Jiang et al. 2010; Li et al., 2011; Nasipuri and Li, 2006; Niculescu and Nath, 2003; Ou, 2011; Pataeari and Hero, 2002; Peng and Sichitiu, 2006; Suroso et al., 2011) have been proposed. Most of the methods deploy some *anchor nodes* which periodically broadcast beacon signals containing its own location or receive signals of target nodes to help with the localization of target nodes.

Localization schemes take various kinds of measurement for the purpose of localization. They measure the time of arrival (ToA) (Chen et al., 2003; Pataeari and Hero, 2002), time difference of arrival (TDoA) (Cong and Zhuang, 2002; Gustafsson and Gunnarsson, 2003), angle of arrival (AoA) (Amundson et al., 2010; Chen et al., 2003; Cong and Zhuang, 2002; Peng and Sichitiu, 2006) and received signal strength indicator (RSSI) (Bahl and Padmanabhan, 2000; Jiang et al. 2010; Li et al., 2011; Pataeari and Hero, 2002) to estimate the distances or angles between pairs of nodes, which in turn are used to calculate the locations of nodes. Most kinds of measurement are taken with extra auxiliary hardware. For example, ToA and TDoA are very sensitive to timing errors; hence, their measurement relies on highly accurate synchronized timers. AoA, which is defined as the angle between the propagation direction of an incident RF wave and a reference direction, can be measured by an array of antennas. Unlike the above-mentioned three kinds of measurement, RSSI can be output by most commercial off-the-shelf sensor nodes, and is thus widely used by localization methods.

RSSI-based localization methods can be further classified as propagation model methods and fingerprinting methods. The former analyze the relationship between RSSI values and transmitter-receiver distances to calibrate parameters such as path loss exponent of the propagation path loss model in the calibration phase. The calibrated propagation model is then applied to convert an RSSI value to an estimated distance in the localization phase. The latter first measure RSSI values of a set of anchor nodes at several *reference locations*. The measured RSSI values at a particular reference location are used to be the *fingerprint* of the location. Then, a target node measures RSSI values of the same set of anchor nodes and estimates its location by finding the fingerprint which is the closest match with the measured RSSI values.

This paper proposes a novel fingerprinting localization scheme, called FLCDA (Fingerprinting Localization with Cruciate Directional Antennas), which can do localization by a sole anchor node equipped with four directional antennas arranged in a cross pattern so that an antenna's orientation is perpendicular to those of adjacent ones. The proposed FLCDA consists of two phases: the RSSI gathering phase and the localizing phase. In the RSSI gathering phase, for each reference location, the RSSI values of the anchor node's four antennas are measured to form a 4-tuple as the fingerprint of the reference location. Fingerprints of all reference locations are then stored in the anchor node. In the localizing phase, when the anchor node receives a request signal from a target node with its four antennas simultaneously, it compares the received RSSI values with all the fingerprints to find out the most matched fingerprint. The target node is then assumed to be at the location associated with the most matched fingerprint. Our experiments demonstrate that the average localization error is 24.4 centimeters for an indoor 12-meter-diameter circle area with 802.15.4 transceivers.

The rest of this paper is organized as follows. Some related localization schemes are reviewed in section 2, and the proposed localization scheme FLCDA is described in detail in section 3. Section 4 shows experiment results and section 5 proposes techniques to produce FLCDA variants to accelerate the procedure for localizing sensor nodes and building the fingerprint database. Section 6 describes comparisons of FLCDA and other related protocols. Finally, section 6 concludes the paper.

2 Related Work

In this section, we introduce some recent related localization methods using fingerprints and/or directional antennas.

2.1 Fingerprinting Localization Schemes

Li et al. proposed Sierpinski triangle search strategy to shorten the search time of fingerprinting localization (Li et al., 2011). The proposed search strategy recursively performs two operations, split and select, to find out the best matched fingerprint. The area covered by anchor nodes is first split into several separate triangles in a manner similar to Sierpinski triangles in fractals. This strategy calculates the centroid of each triangle and then derives the RSSI values of the centroid as the fingerprint of the centroid by applying a radio propagation model. The distance between a triangle and a target node is calculated as the Euclidean distance between the fingerprint of the centroid of the triangle and the observed RSSI values of the target node. The triangle having the smallest distance to the target node is then selected for further splitting and searching in the next round. In this way, the search time of fingerprinting localization is shortened, while the localization error is almost the same as that of the traditional completely searching strategy.

Suroso et al. utilized fuzzy c-means clustering (FCM) for improving the time efficiency of fingerprinting localization schemes (Suroso et al., 2011). FCM is a clustering method which allows one piece of data belongs to two or more clusters. In Suroso et al.'s method, the collected fingerprints are grouped by FCM at first. Then the clusters or groups of the fingerprints returned by FCM, instead of the original fingerprints, are stored in the database for localization. The authors conducted experiments in a 5×5 m square area with 4 anchor nodes located at the corners of the area. They deploy 25 grid positions in the area for collecting fingerprints. The average localization error of their experiment results is 0.512 m.

2.2 Localization Schemes Using Directional Antennas

In RAL (Jiang et al., 2010), an anchor node is equipped with a rotatable directional antenna. It regularly rotates its antenna to emit beacon signals at different directions. A sensor node determines the angle from the anchor node to itself by observing the RSSI values of the received beacon signals which contain the location of the anchor node and the current orientation of its antenna. RAL can estimate the angle by finding out the strongest signal. With the estimated angles and locations of two distinct anchor nodes, a target node can calculate its own location with a localization error of 76 cm within a 10×10 m indoor area. Two enhanced methods are further proposed to reduce the localization error by a factor of 10%. One drawback of the research about RAL is that the only simulation results, rather than practical experiment results, are provided for the localization errors.

ALRD (Jiang et al. 2013), standing for AoA Localization with RSSI Differences, estimates the AoA of beacon signals for localization by comparing the RSSI values of beacon signals emitted by two perpendicularly-orientated directional antennas installed at the same place. In ALRD, the AoA of a beacon signal is defined to be the angle from the propagation of the signal to the orientation of the directional antenna emitting the signal. The authors fit the RSSI values of directional antenna signals into a parabola function of the AoA between 0° and 90°. Besides, they set up an anchor node with two perpendicularly-orientated directional antennas and fit the difference of the signal RSSI values of the two antennas into a linear function of the absolute AoA values between 0° and 90°. By two anchor nodes, ALRD can then allow a sensor node to self-localize itself by observing the RSSI values of the beacon signals emitted from the two anchor nodes. The fitting functions can easily be stored in a WSN node having limited storage space, and their inverse functions can be used to speed up the localization process. The experiments demonstrate that the average localization error is 124 cm in a 10×10 m indoor square area.

In 2011, Ou proposed DIR (Ou, 2011) to localize target nodes with mobile anchor nodes. In DIR, each mobile anchor node determines its position via GPS and then broadcasts its position while it moves through the WSN field. The mobile anchor nodes are equipped with four fixed directional antennas which are orientated in such a way that two of them are parallel to the horizontal axis while the others are parallel to the vertical axis. During the localization process, a mobile anchor node moves through the field along a line which is parallel to the horizontal axis or the vertical axis and broadcasts beacon signals containing its positions. On receiving the beacon signals, the target node derives its position by calculating the median of the positions contained in the beacon signals received.

3 The Proposed Scheme

3.1 FLCDA Setup

Fig. 1 shows the setup of FLCDA. We assume all sensor nodes are randomly deployed in a planar square area of interest. The anchor nodes are arranged in such a manner that each sensor node can communicate with at least one anchor node (i.e., every sensor node has at least one neighboring anchor node). Each anchor node is equipped with four directional antennas arranged as a cross shape so that the orientation of an antenna is perpendicular to those of adjacent ones. We assume that each anchor node knows its location and the orientations of the equipped antennas. The orientations of the antennas can aim at any direction in FLCDA. However, for simplicity, we assume that the antennas, numbered from 1 to 4, of each anchor node aim at East (1), North (2), West (3), and South (4), respectively.

Figure 1 Setup of FLCDA

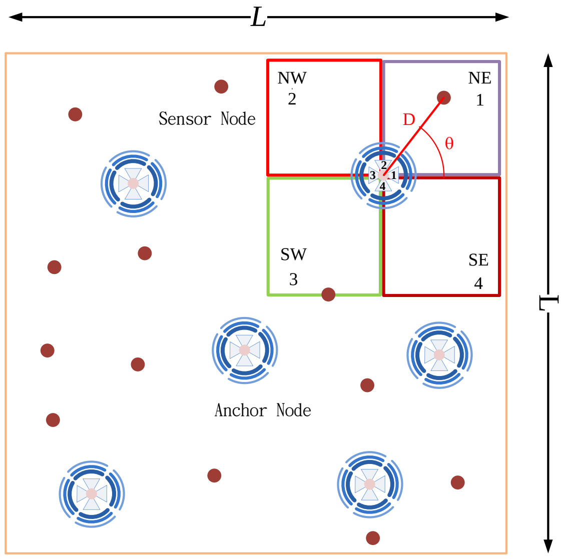
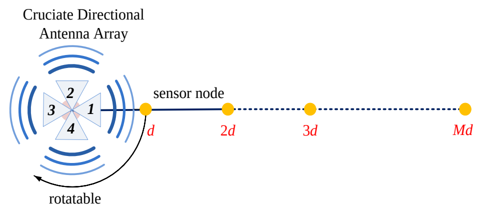


Figure 2 The setup for gathering and analyzing RSSI values



The proposed FLCDA consists of two phases: the RSSI gathering and the localizing phases. In the RSSI gathering phase, we rotate the anchor node's antennas by θ degrees (θ=0, 1,…, 359) to receive signals sent by a sensor node which is d meters (d=0.5, 1,..., 6) away from the anchor node. The pair (θ, d) is regarded as a reference position, and the RSSI values of the signals received by the four antennas are regarded as the fingerprint of the position. These fingerprints are stored in the anchor node before deployment. During the localizing phase, a target node sends a signal to request the nearby anchor nodes for helping with localization. The nearby anchor nodes receive the request signal via the four directional antennas simultaneously, and then estimate the position of the target node by finding out the most matched fingerprint with the RSSI values of the signals received by the antennas. Finally, the anchor nodes utilize the antenna having the largest received RSSI value of the request signal to send a reply message to the target node for notifying the localization result. The target node takes the result of the reply message having the largest received RSSI value as its estimated location.

3.2 RSSI Gathering Phase

FLCDA needs to gather and analyze the RSSI values of the signals which an anchor node receives from a sensor node with the four equipped directional antennas at different distances and angles. As shown in Fig 2, we set up a rotatable anchor node equipped with four directional antennas, numbered from 1 to 4, which initially aim at East (0°), North (90°), West (180°), and South (270°), respectively. A sensor node is placed on the X-axis (East) at a distance of d, $2d$, …, Md meters for emitting signals continuously, where d and M are specified values (say, d=0.5 and M=12). The anchor node is then clockwise rotated by the angle of θ degrees (θ=0,1,..,359) to receive signals sent by the sensor node with four directional antennas simultaneously for several (say 50) times. The RSSI values of the signals received by the directional antennas are averaged and stored separately. We denote the average of the RSSI values gathered by antenna i as $G_{i\_kd}(\theta)$, where i (i=1, 2, 3 or 4) stands for the number of the antennas, k=1, 2,…, M, and θ=0, 1, …, 359. The 4-tuple ($G_{1\_kd}(\theta)$, $G_{2\_kd}(\theta)$, $G_{3\_kd}(\theta)$, $G_{4\_kd}(\theta)$) is regarded as the fingerprint of the reference position $P_{kd\_\theta}=(\theta, kd)$ related to the anchor node. Before deployment, we store the reference positions and the corresponding fingerprints into the anchor node to localize neighboring target nodes during the localizing phase.

3.3 Localizing Phase

In FLCDA, the following steps are executed by a target node and its neighboring anchor nodes to estimate the location of the target node.

1. Broadcasting the request message: A target node, whose position is unknown, broadcasts a message to request the nearby anchor nodes to help with localization.

2. Receiving the request signal: The nearby anchor nodes receive the request message with the four equipped antennas simultaneously, and then records the observed RSSI values of the signals received by the four antennas as R_1, R_2, R_3 and R_4.

3. Comparing: An anchor node receiving the request message compares the observed RSSI values (i.e., R_1, R_2, R_3 and R_4) with the fingerprints in its storage to find out the most matched one. In FLCDA, we use the Manhattan distance to calculate the distance between the observed RSSI values and a fingerprint. For example, the distance between the observed RSSI values and the fingerprint ($G_{i\_kd}(\theta)$, i=1..4) of the reference position $P_{kd\_\theta}=(\theta, kd)$ is calculated as:

$$D_R=\sum_{i=1}^{4}\left|R_i-G_{i\_kd}(\theta)\right|.$$

The anchor node selects the fingerprint having the smallest distance to the observed RSSI values as the most matched one. The corresponding reference position $P_{kd\_\theta}=(\theta, kd)$ of the most matched fingerprint is then chosen to be the position of the target node related to the anchor node.

4. Calculating the location: Once knowing the related position $P_{kd\_\theta}=(\theta, kd)$, the anchor node can estimate the location of the target node with its own location (x_a, y_a) by calculating

$$(x_t, y_t)=(x_a+kd\times\cos\theta,\ y_a+kd\times\sin\theta).$$

The anchor node utilizes the antenna having the largest received RSSI value of the request message to send a reply message to the target node for notifying the localization result.

5. Choosing the proper result: In general, we obtain better localization results as the anchor node and the target node getting closer. Hence, the target node selects the localization result of the reply message having the largest RSSI value as its estimated location.

4 Experiment Results

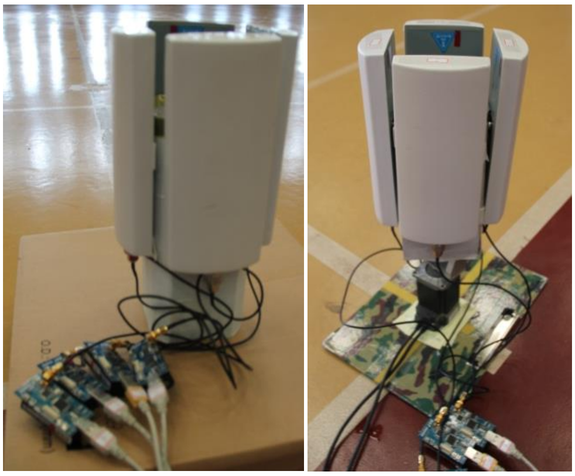
In this section, we describe the implementation of FLCDA and the results of the experiments using the implementation.

4.1 Implementation

The sensor nodes and the anchor nodes of the proposed FLCDA scheme are implemented in the nesC code with TinyOS support on the Moteiv BAT mote sensor. The BAT mote sensor has a Texas Instruments MSP430 F1611 microcontroller running at 8 MHz with 10 kB RAM and 48 kB flash memory. It is equipped with Chipcon CC2420 IEEE 802.15.4 compliant wireless transceiver using the 2.4 GHz band with a 250 kbps data rate. With an integrated onboard omnidirectional antenna, the BAT mote sensor has a maximum of 50 m (indoor) or 125 m (outdoor) transmission range.

As shown in Fig. 3(a), the anchor node is composed of four sensor nodes, each of which is attached with a Maxim AP-12 panel antenna. The anchor node is rotated by a Fastech Ezi-Servo 28L step motor for receiving signals sent by a sensor node during the RSSI gathering phase, as shown in Fig. 3(b). The horizontal and vertical beamwidth of the AP-12 panel antenna are 65 and 28 degrees, respectively.

Figure 3 (a) The anchor node used in localization (b) The anchor nodes used in RSSI gather and analysis



(a) (b)

Figure 4 FLCDA experiment setup

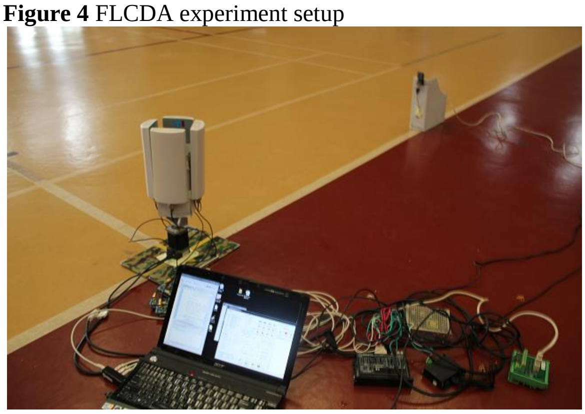
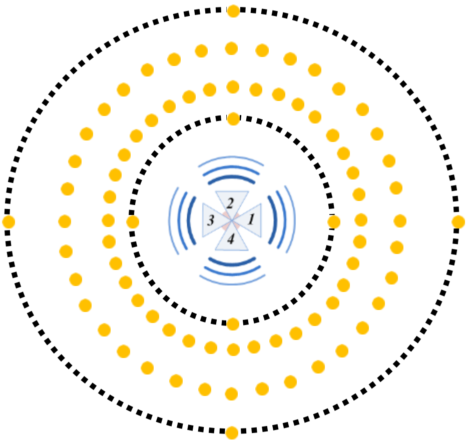


Figure 5 FLCDA experiment setup and points for testing

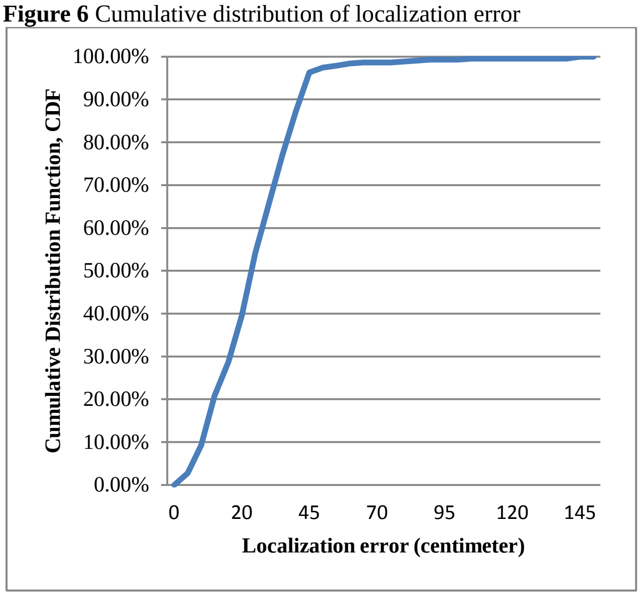


4.2 Localization Results

We have installed FLCDA in an indoor gym which has two basketball courts for conducting experiments (refer to Fig. 4 and Fig. 5). A rotatable anchor node, as shown in Fig 3(b), is set up at the center of the gym for gathering RSSI values sent by a sensor node. We gather and analyze the RSSI values of signals sent by a sensor node located at the distance of 0.5, 1, 1.5,…, and 6 m, for every degree from 0° to 359°. Therefore, we obtained totally 3420 (=360×12) fingerprints. The RSSI values corresponding to a reference position are obtained by averaging 50 measurements. The measured RSSI values are then stored as the fingerprint database.

The localization accuracy is tested at the distance of 0.5, 1, 1.5,…, and 6 meters for every 10 degrees from 0°, 10°,…, to 350°. There are total 432 (=12×36) test points as shown in Fig. 5. For each test point, we set up a sensor node to send signals 10 times per second. An anchor node, as shown in Fig 3(a), is then used to receive the signals sent by the sensor node with the four antennas arranged in a cross shape. We record 50 4-tuple RSSI values to localize the sensor node for each test point. We take the average of 50 localization results to plot the cumulative distribution of localization errors in Fig. 6. The average localization error of the localization experiment is 24.4 centimeters.

Figure 6 Cumulative distribution of localization error



5 FLCDA Variants

As the experiment results show, FLCDA can accurately localize sensor nodes by comparing the observed RSSI values of a request signal with the fingerprints in the database. However, the anchor node must compare lots of fingerprints to localize a target node. In our experiments, we measure the RSSI value at every degree and every 0.5 meter to collect fingerprints in the RSSI gathering phase. As we have shown, an anchor node needs to compare 3420 fingerprints for localizing a target node. Besides, numbers of anchor nodes need to be deployed while applying FLCDA in a large field. In this case, it will take too much time to create the fingerprint database for each anchor node. In this section, we propose techniques to produce FLCDA variants to accelerate the procedure for localizing sensor nodes and building the fingerprint database.

5.1 *Accelerating the localizing phase*

In our experiments, we have two observations which can be applied to accelerate the localizing phase. As shown in Fig. 7, we define the AoA as the angle from the propagation direction of an incident RF wave to the orientation of the directional antenna receiving the RF wave. The AoA is positive if it is counterclockwise; negative, otherwise. By the experiment results shown in Fig. 8, we observe that if the distance between the sensor node and the directional antenna is fixed, the RSSI values vary like a parabola function of the AoA ranging between –90° and 90° with a symmetry axis at the AoA=0°. Furthermore, we set up two perpendicularly-orientated directional antennas installed at the same location (refer to Fig. 9) to receive the signals sent by a specific sensor node located between the antennas' orientations. By the experiment results shown in Fig. 10, we can observe that the differences of the RSSI values of the signals which are received simultaneously by the two antennas from the sensor node vary like a linear function of the absolute AoA ranging between 0° and 90°. Since we take absolute values of AoAs associated with two perpendicularly-orientated antennas, when one absolute AoA value is θ, the other absolute AoA value is 90–θ. We then take only one absolute AoA value as the representative AoA in the linear function without ambiguity.

Figure 7 AoA of a sensor node and a directional antenna

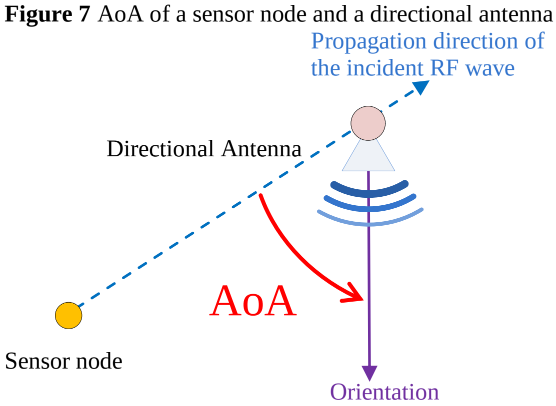


Figure 8 RSSI values of signals received by a directional antenna

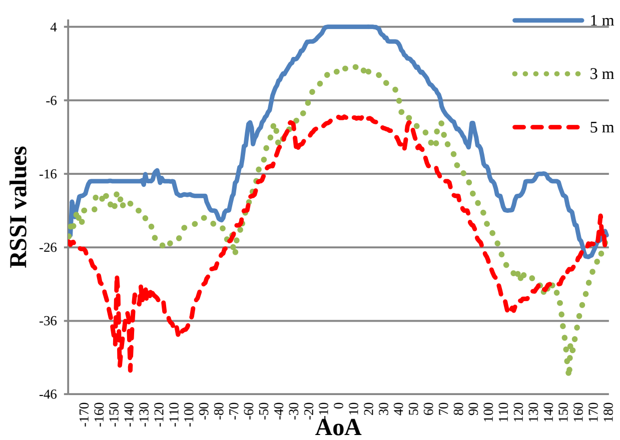


Figure 9 AoAs relative to directional antennas with perpendicular orientations

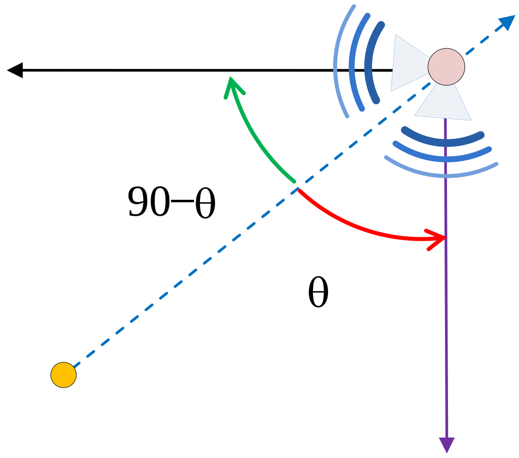
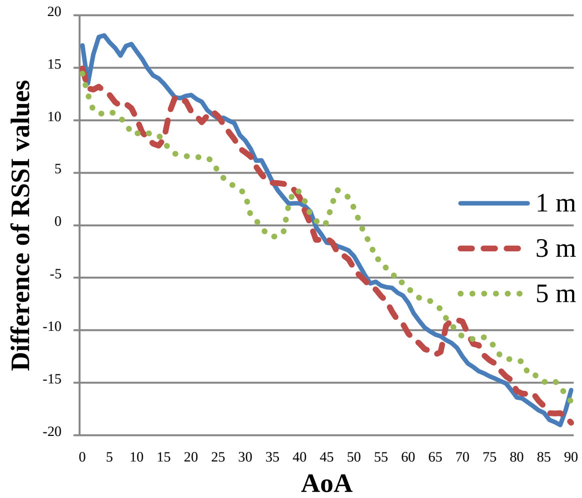


Figure 10 Difference of the signal RSSI values received by two directional antennas with perpendicular orientations



We can utilize the linear relationship described above and shown in Fig. 10 to accelerate the localizing phase. We first fit the difference of the RSSI values into a linear function of the absolute AoA ranging between 0° and 90° by linear regression analysis. Instead of the whole fingerprint database, the linear functions are then used to select a subset F of fingerprints to be compared with the observed RSSI values of the request signal sent by the target node in the localizing phase.

After the RSSI values have gathered, the following steps are executed to generate linear regression fitting functions.

(1) Calculating RSSI differences: The communication range of an anchor node is divided into four quadrants by its four directional antennas' orientations. As shown in Fig. 2, the quadrants are denoted as 1 (Northeast, *NE*), 2 (Northwest, *NW*), 3 (Southwest, *SW*), and 4 (Southeast, *SE*). Note that the quadrant q is bounded by the orientations of antennas q and q+1 (mod 4). (Note that we may omit "(mod 4)" in the following context.) Therefore, we have to calculate the differences of RSSI values of signals received by antennas q and q+1 for the quadrant q. For each distance kd (k=1,…,M) and each quadrant q (q=1,…,4), we obtain the differences of the RSSI values of the signals received by antennas q and q+1 by calculating

$$D_{q\_kd}(\alpha)=G_{q\_kd}(\theta) - G_{q+1\_kd}(\theta),\ \alpha=0,\ldots,90,$$

where $\theta=90\times(q-1)+\alpha$. Note that α is the absolute AoA between the orientation of antenna q and the propagation direction of an incident RF wave.

(2) Performing the linear regression analysis: For each distance kd, (k=1,…,M), and each quadrant q, (q=1,…,4) the RSSI difference $D_{q\_kd}(\alpha)$ at angle α (α=0,…,90) is approximately fitted into a linear function $L_{q\_kd}(\alpha)$ by linear regression analysis. Therefore, there are 4×M linear functions being created for an anchor node.

(3) Storing linear functions: The linear fitting functions are loaded into the storage of the anchor node along with the fingerprint database before deployment.

With the linear functions, the anchor node can choose a subset F of fingerprints, instead of the whole database of fingerprints, as the candidates to be compared with the observed RSSI values of a request signal. We adopt two methods, point candidate selection (PCS) and sector candidate selection (SCS), to pick up fingerprint candidates for comparison.

(1) Point Candidate Selection (PCS): In this method, the anchor node selects candidates by estimating the target node signal's AoA. At first, the anchor node utilizes the antenna having the largest observed signal RSSI value to determine the direction of the target node. Then, for each distance kd (k=1 to M) and either adjacent quadrant q of the antenna having the largest RSSI value, the anchor node calculates AoA α_q by applying the linear function and the RSSI difference corresponding to the adjacent quadrant q. Finally, the anchor node uses kd and α_q to select the fingerprint of the reference position $p=(\alpha_q+90\times(q-1), kd)$ as a candidate. Note that we may refer to p or the fingerprint of p when we mention a selected candidate in the following context.

The detailed procedure of the PCS method is shown in Fig. 11 and described as follows.

a. Determining the direction: At first, the anchor node determines the direction of the target node by picking up the largest one among the observed RSSI values. For example, the target node is assumed to be located on the east side of the anchor node if antenna 1 (East) has the largest RSSI value.

b. Calculating RSSI differences: Let antenna j be the antenna having the largest RSSI value, then the two neighboring quadrants of antenna j are quadrant $j-1$ and quadrant j, for j=2 to 4, or quadrant 1 and quadrant 4 for j=1. For each adjacent quadrant q of antenna j, we calculate the RSSI difference as:

$$D_q = R_q - R_{q+1\ (mod\ 4)},$$

where R_q and R_{q+1} are the observed RSSI values corresponding to the two adjacent antennas of quadrant q.

c. Generating candidates: For each distance kd and each neighboring quadrant q, the anchor node computes the AoA α_q corresponding antenna q by calculating $\alpha_q = L_{q\_kd}^{\ -1}(D_q)$, where $L_{q\_kd}^{\ -1}$ is the inverse function of the linear function $L_{q\_kd}(\alpha)$. Then the fingerprint of the reference position $p=(\alpha_q+90\times(q-1), kd)$ is chosen to be one of the candidates for comparing with the observed RSSI values.

(2) Sector Candidate Selection (SCS): In our experiments, we have found that the average angular error is 5 degrees while applying linear functions to estimate the AoA. Therefore, we pick up more candidates, denoted as sector candidates, by extending 5 degrees either clockwise or counterclockwise from the candidate selected in the point candidate selection method. For example, the fingerprints of reference positions ($\alpha-5$, kd), ($\alpha-4$, kd), ($\alpha-3$, kd), ($\alpha-2$, kd), ($\alpha-1$, kd), (α, kd), ($\alpha+1$, kd), ($\alpha+2$, kd), ($\alpha+3$, kd), ($\alpha+4$, kd), ($\alpha+5$, kd) are selected as candidates if the fingerprint of the reference position (α, kd) is picked up as a candidate by the PCS method.

Figure 11 The algorithm of the point candidate selection (PCS)

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Algorithm PCS (Point Candidate Selection)
Input: R1, R2, R3, R4 //RSSI values of the target node
Output: F //a set of fingerprints
 j=Arg Max{ R1, R2, R3, R4}
P←∅  //an empty set of reference positions
For k=1 to M {
   D=kd
   If j=1{
      α1= L1_kd^−1 ( R1− R2)  //for quadrant 1
      α2= 270+L4_kd^−1 ( R4− R1) //for quadrant 4  }
   Else {
      α1= 90 × (j−1) + Lj_kd^−1 ( Rj−1− Rj)  //for quadrant j
      α2= 90 × j +Lj+1_kd^−1 ( Rj− Rj+1)  //for quadrant j+1  }
   P←P∪(α1, kd)∪ (α2, kd)
}
F←the set of the fingerprints of all positions in P
Return F
```

Table 1 Comparisons of average localization errors of FLCDA and its variants

	FLCDA	**FLCDA/PCS**	**FLCAD/SCS**
No. of compared fingerprints	3420	24	264
Localization errors (cm)	24.4	48	34.8

Table 1 shows the number of the compared fingerprints and the average localization errors of FLCDA and its variants with the point candidate section (PCS) and sector candidate selection (SCS) methods. Fig. 12 plots the cumulative distributions of the localization errors while using different subset of fingerprints as the chosen candidates. As shown in Table 1, the PCS and SCS methods only pick up 24 and 264 fingerprints from the database, respectively, while the average localization errors are less than 50 centimeters. Hence, both of them can be used to accelerate the localizing phase without affecting the accuracy too much.

5.2 *Accelerating the RSSI Gathering phase*

In this subsection, we discuss how to reduce the time spent for building the fingerprint database. First, we can reduce the total fingerprint gathering time by using coarse angle and distance measurement intervals. In our experiments, we measure the RSSI values at every degree and every 0.5 meter to gather fingerprints. To have the effect of coarse measurement intervals, we remove some measured RSSI values from the database. The deleted data are then reconstructed by linear interpolation with the remains. Table 2 demonstrates the localization errors while applying different measurement intervals. Note that the localization errors are almost the same as the angle measurement interval varies from 1° to 10°. However, the localization errors observably rise while the distance measurement interval increases. To sum up, we can build the fingerprint database with coarser angle measurement intervals without affecting the localization errors to much. According to Table 2, 10° angle measurement interval and 0.5 m distance measurement interval are recommended to be applied to gather the RSSI values of fingerprints for accelerating the RSSI gathering phase.

In order to apply FLCDA in a large field, there is one more issue needs to be overcome. Numbers of anchor node have to be deployed while applying FLCDA in a large field. In such a case, it will take much time to generate the fingerprint database for each anchor node. To save time, we can use the measured RSSI values of one directional antenna to represent the ones of all other same-type antennas. Table 3 shows the localization errors while the RSSI values of one representative antenna are used to replace those of other antennas. Compare with the results in Table 2, the localization errors increase to about two times of the original ones. However, the localization error remains about 1 meter even in the worst case.

Figure 12 Cumulative distributions of localization errors

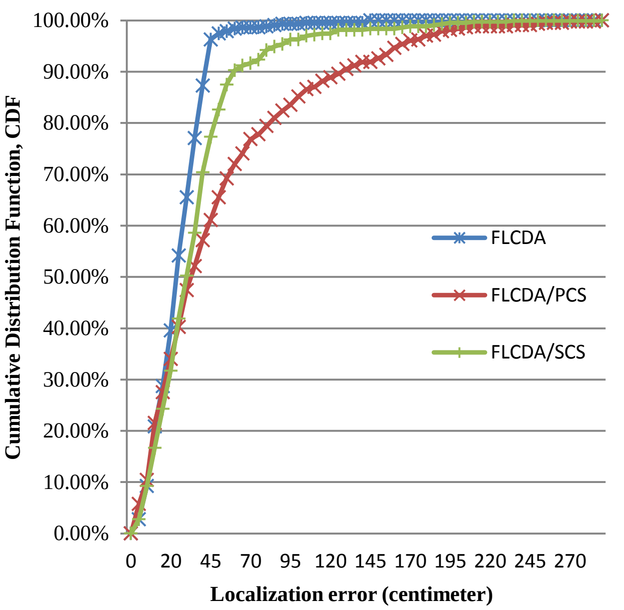

Table 2 Average localization errors (cm) for different measurement intervals

Distance interval \ Angle interval	1°	3°	5°	10°
0.5 m	24	28	31	42
1 m	50	53	53	58
1.5 m	64	66	65	70
2 m	65	66	67	70

Table 3 Average localization errors (cm) with the fingerprint database using the data of only one representative antenna

Method \ Rep. antenna no.	1	2	3	4
FLCDA	107	98	121	87
FLCDA/PCS	107	94	108	87
FLCDA/SCS	107	90	119	86

6 Comparisons

In this section, we compare the proposed FLCDA with other localization schemes. Table 4 compares FLCDA with other two fingerprinting localization schemes, namely the Sierpinski (Li et al., 2011) scheme and the FCM scheme (Suroso, 2011). As Table 4 shows, the proposed FLCDA has smaller localization error even when PCS and SCS schemes are used to select only 0.3% and 6% of the total fingerprints to be compared with the observed RSSI values of the target node signals. The Sierpinski scheme has largest localization error because the fingerprints are generated by the radio propagation model rather than empirical results. In most fingerprinting localization schemes, the compared fingerprints increased while the field size gets larger. However, the anchor nodes can localize sensor nodes independently in FLCDA. That is, the amount of the fingerprint being compared during localization is only related to the communication range of the anchor node rather than the field size.

Table 4 Comparison with fingerprinting localization schemes

Scheme	Field size	#AN	#FP	#CFP	LE
FLCDA	12-m-diameter circle (113 m^2)	1	4320	4320	24.2 cm
FLCDA/ PCS	12-m-diameter circle (113 m^2)	1	4320	12 (0.3% of 4320)	48 cm
FLCDA/ SCS	12-m-diameter circle (113 m^2)	1	4320	264 (6% of 4320)	34.8 cm
Sierpinski	1 m × 22 m rectangle (22m^2)	4	1024 4^{M-1}N	20 (2% of 1024) N+4(M−1)	213 cm
FCM	5 m × 5 m square (25m^2)	4	36	10 (28% of 36)	60 cm

#AN: The number of anchor nodes
#FP: The number of total fingerprints
#CFP: The number of fingerprints compared during localization
M: The times of executing the search operation
N: The number of edges of the polygon covered by the anchor nodes

Table 5 Comparison with localization schemes using directional antennas

Method	Field size	#AN	#Antenna	Time	LE
FLCDA /PCS	113 m^2	1	4 / BN	<1 s	48 cm
DIR	100 m^2	2	4 / BN	<180 s	N/A
ALRD	100 m^2	2	2 / BN	<1 s	89 cm
RAL	100 m^2	2	1 / BN	180 s	76 cm

#AN: The number of anchor nodes
#Antenna: The number of antennas per anchor node (AN)
LE: Localization error

Table 5 shows the comparisons of FLCDA/PCS with localization schemes using directional antennas, namely DIR (Ou, 2011), RAL (Jiang et al., 2010) and ALDR (Jiang et al., 2013). DIR and RAL both take a long time to localize sensor nodes because they have to rotate the antennas or move the anchor node across the whole field. The localization error of DIR is not available because it has only conducted simulations instead of practical experiments of real implementation. By Table 5, we can see that FLCDA/PCS has the smallest localization error among all schemes. It is also among the fastest schemes. It also has the advantage that it uses only one anchor node to help localize target nodes within a 12-m-diameter circle covering a total area of 113 m^2.

7 Conclusion

In this paper, we propose FLCDA to localize sensor node by comparing the received RSSI values of a cruciate directional antenna array. In FLCDA, the anchor nodes store its own fingerprints which have a constant size to localize neighboring sensor node independently by receiving a request message from the sensor node with the four equipped antennas simultaneously. We have implemented and installed an anchor node of FLCDA in an open indoor environment for localizing nearby sensor nodes. Our experiment results show that a sensor node can be localized by only one request signal with an average localization error of 24.4 cm. Furthermore, we propose two methods, PCS and SCS, to choose a subset instead of the whole fingerprint database for comparing with the received RSSI values to shorten the localization time. The PCS and SCS methods only pick up 24 and 264 fingerprints from the database, respectively, and cause the average localization errors both less than 50 cm. Hence, the FLCDA/PCS and FLCDA/SCS localization schemes can be utilized to localize or trace mobile devices. In our experiments, we have also analyzed the influence of measuring intervals of fingerprints on the localization error. The experiment results demonstrate that gathering RSSI values with 10-degree angle interval and 0.5-meter distance interval is sufficient for building good fingerprint databases.

Currently, we have only implemented, installed and experimented FLCDA in a small open indoor area. Because the anchor node can localize the sensor nodes on its own, it is believed that FLCDA can be easily applied to large areas, and is expected to have localization errors as small as our experiment results. As our experiment results show, the average localization errors remain about 1 m while only one of the same type antennas is used to gather RSSI values for building the fingerprint database. Therefore, we may utilize the gathered RSSI values of one antenna to be representative data of all same type antennas deployed in a large area if the localization error is tolerable. We will focus on applying FLCDA to realize a large-area localization system in the future. Moreover, we will also try to apply FLCDA to other environments such as outdoor space and indoor obstructed areas.

References

I. Amundson, J. Sallai, X. Koutsoukos, and A. Ledeczi (2010) ‘Radio interferometric angle of arrival estimation’, Lecture Notes in Computer Science, Vol. 5970, pp. 1-16.

I. Amundson, J. Sallai, X. Koutsoukos, and A. Ledeczi (2011) ‘Mobile Sensor Navigation using Rapid RF-based Angle of Arrival Localization’, in Proc. of the 17th IEEE Real-Time and Embedded Technology and Applications Symposium, pp. 316-325.

P. Bahl, V. N. Padmanabhan (2000) ‘Radar: An In-Building RF-based User Location and Tracking System’, in Proc. of INFOCOM, Vol. 2, pp. 757-784.

T. Y. Chen, C. C. Chiu, and T. C. Tu (2003) ‘Mixing and Combining with AOA and TOA for Enhanced Accuracy of Mobile Location’, in Proc. of the 5th European Personal Mobile Communications Conference, pp. 276-280.

L. Cong, and W. Zhuang (2002) ‘Hybrid TDOA/AOA Mobile User Location for Wideband CDMA Cellular Systems’, IEEE Transactions on Wireless Communications, Vol. 1, No. 3, pp.439-447.

F. Gustafsson, and F. Gunnarsson (2003) ‘Positioning Using Time-Difference of Arrival Measurements’, in Proc. of the IEEE International Conference on Acoustics, Speech, and Signal Processing, pp. 533-536.

B. Hofmann-Wellenhof, H. Lichtenegger, and J. Collins (2001) ‘Global Positioning System: Theory and Practice’, Berlin, Springer-Verlag.

B. N. Hood, and P. Barooah (2011) ‘Estimating DoA From Radio-Frequency RSSI Measurements Using an Actuated Reflector’, IEEE Sensors Journal, Vol. 11, No. 2, pp. 413-417.

J. R. Jiang, C. H. Lin, and Y. J. Hsu (2010) ‘Localization with Rotatable Directional Antennas fro Wireless Sensor networks’, in Proc. of the 39th International Conference on Parallel Processing Wrokshops, pp. 542-548.

J. R. Jiang, C. M. Lin, F. Y. Lin and S. T. Huang (2013) ‘ALRD: AoA Localization with RSSI Differences of Directional Antennas for Wireless Sensor Networks’, International Journal of Distributed Sensor Networks, Vol. 2013, Article ID 529489, 10 pages.

T. P. Lambrou, and C. G. Panayiotou (2006) ‘Improving area coverage using mobility in sensor networks’, in Proc. of the International Conference on Intelligent Systems And Computing: Theory And Applications, pp. 1-8.

H. Li, X. Zhao, and M. Tan (2011) ‘A New Search Strategy of Radio Fingerprint Match Method in Wireless Sensor Network’, in Proc. of the 1st International Conference on Robot, Vision and Signal Processing, pp. 18-22.

A. Nasipuri, and K. Li (2006) ‘Experimental evaluation of an angle based indoor localization system’, in Proc. of the 5th International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks, pp. 1-9.

D. Niculescu, and B. Nath (2003) ‘DV based positioning in ad hoc networks’, Telecommunication Systems, Vol. 22, No. 1, pp. 267–280.

C. H. Ou (2011) ‘A Localization Scheme for Wireless Sensor Networks Using Mobile Anchors With Directional Antennas’, IEEE Sensors Journal, Vol. 11, No. 7, pp. 1607-1616.

N. Patawari, and A.O. Hero (2002) ‘Location Estimation Accuracy in Wireless Sensor Networks’, in Proc. of the 36th Asilomar Conference on Signals, Systems and Computers, pp. 1523-1527.

R. Peng, and M. L. Sichitiu (2006) ‘Angle of Arrival Localization for Wireless Sensor Networks’, in Proc. of the 3rd IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks, pp. 374-382.

D. J. Suroso, P. Cherntanomwong, P. Sooraksa, and J. Takada (2011) ‘Location Fingrprint Technique using Fuzzy C-Means Clustering Algorithm for Indoor Localization’, TENCON, pp. 88-92.