A 2D positioning system using WSNs in indoor environment

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Abstract;
This paper describes a 2D location determination system using wireless sensor nodes (WSN) in indoor environment. The system is based on radio-location fingerprinting algorithm. It uses WSN technology and programmable Zigbee wireless network protocols. The important point in this study is to estimate the location of a mobile sensor. WSNs, transmitters and receivers, have been deployed in an experimental test bed for location estimation. K-nearest neighborhood algorithm has been implemented together with weight functions over a set of radio location fingerprints collected in a 2D space. Experimental results show the effects of different weight functions to achieve accurate and stable position detection in indoor environments.

Keywords: WSN, transmitter, receiver, RSSI, LQI, AP, weight function, fingerprints, k-NN algorithm.

1. Introduction
Wireless sensor network (WSN) technology is used as a possible method to realize the positions of objects in different environments. It is becoming a widespread technology for variety of indoor navigation, people and object tracking, [1]. At present there are many other types of position identification systems using optical [2,3], ultrasonic [4,5] and RF wireless technologies [6-9]. Each has their own strengths as well as limitations. For example optical systems using interferometer techniques give position accuracy in mm level. But they are very expensive. Similarly Ultrasonic techniques use RF radiation and ultrasonic pulses together to detect the unknown positions. These systems also give cm accuracy but their cost factor is again quite substantial. All the systems have obstacle limitations. Hence different transmitter and receiver lay out techniques are employed to get around these limitations.

WSN technology has several advantages such as having no contact and none line-of-sight nature. All transmitters can be read in extreme environmental conditions, [10]. In the study, WSN transmitters are strategically placed in indoors and identified as fixed nodes. An unknown sensor node which is a WSN receiver has been identified as an unknown mobile node. It receives the broadcasted signal packets from fixed nodes, and measures the signal strength values of each received packet and sends them to a server PC. The topology is illustrated in Figure 1.

Figure 1: Topology of wireless sensor nodes [17]
The wireless sensor node localization can be defined as finding the location of a mobile node with respect to a radio location fingerprint.
Fingerprint based positioning systems are divided into off-line and on-line phases. In the off-line phase the location fingerprints are collected by performing a site survey of received signal strengths identified as Link Quality indicator (LQI)s from rectangular grid points across the entire area. The vector of LQI values at the grid point is called the location fingerprint of that point.

In the on-line phase, a sample measured vector of LQI values will be obtained by a mobile node at an unknown location in the area and will be sent to a central server.

A visual C# based application program (AP) has been developed on the server to control entire data manipulation and calculation process. The server uses an algorithm to estimate the coordinates of the unknown location. The algorithm computes the Euclidean distance between the measured LQI vector with unknown position and each fingerprint vector in the fingerprint database. The coordinates associated with the fingerprint which provides the smallest Euclidean distance is identified as the estimate of the unknown mobile node position.

2. Mathematical Model

The signal distance between the unknown LQI vector and the LQI vectors in the fingerprint database is used to determine which of the grid points correspond to the unknown position coordinates (x,y). The grid point with the smallest signal distance to the unknown LQI vector is chosen as the estimated location of the unknown LQI vector.

As shown in Figure 2, the wireless fixed nodes B_i (i(1,2,3,4)) are configured as transmitters and their tasks are to transmit their own positions and link quality indicator (LQI) values [11]. The distances between the B_i fixed nodes and the grid point G are shown by d_i distances as seen in Figure 2.

![Figure 2: Grid formation of the test bed showing a grid point G and an unknown point P](image)

The fingerprint vector F contains all the LQI values from B_i fixed nodes at a particular grid position G. The vector F is denoted as F=(f_1, f_2, f_3, f_4) at every grid position and each fingerprint vector in the fingerprint database. The coordinates associated with the fingerprint which provides the smallest Euclidean distance is identified as the estimate of the unknown mobile node position.

The Euclidean distance between F and R vectors at every grid point is given by:

\[ D_i = \left( \sum_{i=1}^{N} (f_i - r_i)^2 \right)^{\frac{1}{2}} \]  

N=4 is the number of fixed nodes B [12]. The simplest way to find the nearest grid point to the unknown position is to use the coordinates of the grid point with the smallest D value as the unknown position coordinates. This is identified as 1-nearest neighborhood algorithm. 2 nearest grid points can be chosen as 2 nearest neighbors and the algorithm is called 2-nearest neighborhood algorithm. When k nearest neighborhood coordinates where k=4 are used to locate the unknown position this is called 4-nearest neighborhood algorithm.

The unknown position coordinates (x,y) of the mobile node is obtained by:
\[(x, y) = \sum_{i=1}^{k} w_i (x_i, y_i) \tag{2}\]

Where \[X = \sum_{i=1}^{k} w_i x_i\] and \[Y = \sum_{i=1}^{k} w_i y_i\]

\(w_i\) is the weight factor of the \(i^{th}\) neighboring grid point in \(k\)-nearest neighborhood and \((x_i, y_i)\) is the coordinates of the \(k\)-nearest neighbor grid points. The choice of weight factors is an important factor in contributing to position accuracy.

Data elements with high weight contribute more to position coordinates than the elements with a low weight [18]. When the weights are normalized such that they sum up to 1, i.e. \[\sum_{i=1}^{k} w_i = 1\]

then the weighted mean for such normalized weights simply becomes weighted mean position coordinate \((x, y)\) in equation 2.

Different weight factors, obeying the above normalization rule, were assigned empirically in equation (2) in order to calculate the unknown position coordinates.

Position estimation of unknown mobile node depends on the \(D_i\) Euclidian distances of \(k\)-nearest neighbors. \(w_i\) values are formulated to express this dependency with \(D_i\) values and the unknown position of the mobile node. Selected \(w_i\) values are listed as seen in Table 1.

<table>
<thead>
<tr>
<th>(w_i)</th>
<th>(A)</th>
<th>(B)</th>
<th>(C)</th>
<th>(D)</th>
<th>(E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(w_i = \frac{1}{k})</td>
<td></td>
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</tr>
<tr>
<td>(w_i = \frac{\sqrt{D_i}}{\sum \sqrt{D_i}})</td>
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<tr>
<td>(w_i = \frac{\sqrt{D_i^2}}{\sum \sqrt{D_i^2}})</td>
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<td>(w_i = \frac{\sqrt{D_i^4}}{\sum \sqrt{D_i^4}})</td>
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</tbody>
</table>

Table 1: A list of selected weight factors

These empirical weight factors are implemented with equation (2) and the unknown position coordinates are calculated. The weight factor which provided the minimum distance between the estimated and the actual unknown position coordinates is found and employed in experiments.

3. Implementation

JENNIC JN5139 wireless sensor nodes were deployed in the test bed in order to test the 2D wireless localization algorithm and various weighting schemes which are introduced in this paper [14]. The Zigbee Home Sensor demo program was used to program JN5139 active devices to work as fixed nodes (transmitters) and mobile node (receiver) respectively. The active transmitter/receiver pair used in this study is shown in Figure 3.

JN5139 receiver was interfaced to a server through a USB port for data transfer. ZigBee protocol which is based on the IEEE 802.15.4 protocol in the 2.4 GHz band is used during the communication and data transmission between the fixed and mobile nodes.

![Figure 3: Transmitter (Left), Receiver (Right)](image)

The layout of the test bed is on a single empty floor inside a building with no obstacles. A rectangular grid of 5m x 3m is defined over the two-dimensional floor plane and any estimate of unknown location is limited to the points of this grid. The test bed is shown Figure 4.

Any position in the rectangular test area on the floor plane is implemented by \((x, y)\) coordinates.
WSN transmitters are placed in the 4 corners of this test area. WSN receiver representing the unknown mobile node is positioned at any point in the test area interfaced to a computer.

The results of site survey are collected by using the WSN receiver at each grid point. For a grid area of 5mx3m, there are 24 grid points. 4 LQI readings at each grid point will be recorded by the receiver. A total of 24x4 = 96 LQI entries are recorded in the database. Each entry in the database includes a mapping of the grid coordinate (x,y) and d distances of each grid point to 4 transmitters.

Received signal strengths, hence LQI values, exhibit a strong correlation with the receiver aerial orientation as well as its location. The LQI measurement at the same location varies depending on the orientation recording. The analytical model in this paper assumed that the variations due to aerial orientation have been averaged out when the LQI is recorded for 4 compass directions by the receiver.

Zigbee Home sensor Demo program [15,16], is employed to transfer data between WSN transmitters and the Receiver. For different distances between the fixed transmitter nodes and the mobile receiver, the request was made by the receiver to fixed nodes to transmit LQI values and their position coordinates. The received LQI values and the position coordinates are sent to server by the receiver to produce the fingerprint database. Signal packet format which is used during these transmission and reception activities and the database format is shown in Figure 5.

**Figure 5: Signal packet and database format**
As a result of communication between the mobile receiver at every grid point and 4 fixed nodes, a set of LQI values and their corresponding grid coordinates are transferred to the server through the mobile receiver. All the data in the server is further analyzed and put in the form of Fingerprint database by using Microsoft access as seen in Table 2.

Additionally, the distances,(dA,dB,dC,dD), between each grid point and 4 fixed nodes are calculated and included in the fingerprint data base.

<table>
<thead>
<tr>
<th>Grid coordinates</th>
<th>Grid LQI values</th>
<th>Grid distances</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>Y</td>
<td>A</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>297</td>
</tr>
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**Table 2: Fingerprint database**
To estimate the position of an unknown mobile node in the test area, measured mobile node fingerprint is compared with the elements in the fingerprint database using Euclidean distances as calculated by equation 1.

k number of smallest Euclidean distances are selected and k-nearest neighborhood algorithm is applied. This algorithm averages the coordinates of the k-nearest neighbors of the mobile node to give its location estimate as seen in Table 3.
Table 3: Actual and estimated position coordinates by using k-NN methods
Secondly, the unknown position coordinates \((x,y)\) of the mobile node is determined by using equation (2) and the weight factors in Table 1. During the experiments, LQI recordings of the mobile node at unknown locations in the test area are measured. These LQI recordings corresponded to measured fingerprint database of mobile node as seen in Table 4.

Table 4: Measured fingerprints of mobile node
Euclidean distance calculations are carried out at every unknown mobile node position and 4-nearest Euclidean distances and the corresponding grid coordinates are obtained as seen in table 5.

Table 5: 4-nearest Euclidean distances and their grid coordinates
\(w_i\) weight functions in table 1 are calculated at each unknown mobile node position by using 4-nearest Euclidean distances. Once the \(w_i\) values are determined, the coordinates of the unknown mobile node at different positions in the test area are calculated by using equation 2. The results are identified as estimated unknown position coordinates and they are tabulated in table 6.

Table 6: Estimated position coordinates by using different weight factors
The location estimation error, \(e\), is defined by the linear distance between the unknown mobile node’s estimated coordinates \((x_e,y_e)\) and the real coordinates \((x_r,y_r)\) [1]. It is given by:

\[
e = \sqrt{(x_e - x_r)^2 + (y_e - y_r)^2}
\]

(3)

Error calculations with the results of k-NN algorithm (k=1,2,3,4) revealed an average error of \(e=0.82m\). Error calculations with the results in table 6 are displayed in table 7.

Table 7: Error distances
It can be seen from table 7 that the minimum average error distance was obtained with weight function D. Hence the position of the unknown mobile node in the test bed is estimated most accurately by using the weight function D. Additionally the average error distances of three
weight functions (C,D,E) were observed to be close to each other. 3D representations of error distances at unknown locations are given for reader’s attention in figure 6.

Figure 6: error plots at the unknown mobile positions for different \( w_i \) values

4. Conclusions
In this paper we presented a 2D indoor location determination and tracking approach by using ZigBee wireless sensor networks. The approach uses the radio location fingerprinting technique. A 2D signal strength matrix is constructed by using LQI values of the radio signals and identified as fingerprint data base. Jennic5139 wireless transmitters and receivers are deployed and implemented in this study. Unknown position coordinates are evaluated in a planer and obstacle free test bed. Node localization using WSNs is a significant research area with broad range of applications in indoor location tracking such as in buildings. Although LQI is an easy and less expensive way to predict the object locations, there are still many problems due to indoor RF multipath interference and fading. Different k-NN and weight factor techniques were implemented to determine the unknown object positions in indoors. Our empirical weight functions C,D and E provided the most accurate average position determination. The minimum average error distance, \( e \), between the estimated and the actual position of the unknown mobile node was with weight function D. This is seen in Figure 7. It was generally concluded that the weight functions with square and cubic inverse order Euclidean distances in their equations produced more accurate position determination.

Figure 7: Average error distances for different weight functions
Position accuracy degraded and error distances increased with weight functions containing higher inverse orders of D, such as fourth order. The most important factor in this study is the recording of LQI values and the generation of the fingerprint data base. LQI recordings were displaying randomness in time domain. Two recordings of the LQI values from the same transmitter with a small time interval between them were showing a large difference. These differences were also apparent with the unknown mobile node recordings. In the study these differences were reduced in some degree by taking LQI measurements in 4 compass direction and recording the average of these readings.

Data transfer from receiver to server and the position calculations are carried out by an AP developed on the server. The program transfers the LQI data with manual control at every location. They are stored in a file with respect to position coordinates as shown in table 2. Different weight functions in table 1 are used to calculate the unknown position coordinates by
using this data file. Calculated unknown (x,y) coordinates are displayed on GUI for each weight function. See GUI in figure 8. Although an obstacle free test area is used, the effects of the external room walls and the floor were still considerable. The electromagnetic wave reflections from these generated a cancelling effect and resulted false LQI readings. In this study, the best weight function is determined by using raw LQI data to give the minimum average position error. In future studies, the system accuracy will be enhanced further by using this weight function and different filtering techniques with the LQI recordings in the same test area to reduce their random behaviour.

References:

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