3D Localization Techniques using RSSI with a Mobile Robot

A Project Report

submitted by

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This thesis entitled "**3D Localization Techniques using RSSI with a Mobile Robot"** by "**Vinod Kumar Netad**" is approved for the degree of Master of Technology from IIT Hyderabad.

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Project being a part of thesis needs a lot of efforts and concentration. But still efforts in wrong direction never becomes fruitful. Thus an able guidance and support are very must for any research assistant student.

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Abstract

Knowledge of sensor node 3D location in a sensor network is more important, because many practical applications needs to know the location of sensor data source. This report presents three new technique for finding indoor 3D location of a sensor node by using Received Signal Strength Indication (RSSI). First, Centroid based 3D localization technique is derived from centroid algorithm with composition of empirical path loss model. This algorithm has been implemented and analyzed by using IITH motes and a Mobile Robot.

Second, 3D localization technique with mobile robot would reduce the burden by measuring RSSI while cleaning floor instead if the anchors. This localization technique has been implemented with a floor cleaning robot. Experimental results show that the proposed localization technique provides the position of the device with approximately 1000mm of estimation error and useful for smart interaction system.

Last localization algorithm is developed by considering target node equipped with half wave dipole antenna which has omnidirectional radiation pattern. The results show that proposed algorithms estimate 3D location of sensor node in a sensor network with low average error (<0.5m), when compared to its actual location.

Contents

1 3D Localization with a Mobile Robot for Smart Interaction System

1.1 Objective

The aim of this project is to develop a complete mobile phone based system to control and access of devices in a smart room. The first step we wanted to find locations and create a 3-D map of devices in smart room by using RSSI based localization technique, the second step is providing mobile phone based smart interaction system to control and access each and every devices in smart room by making use of 3-D map.

1.2 Introduction

Developments in wireless communications and electronics enhanced micro sensors technology, this development brought smartness in controlling and monitoring sensors in a sensor network as discussed in [1]. Wireless sensor networks are used for sensing physical factors like temperature, humidity and also for monitoring and detecting environmental factors like chemicals, smoke etc. There are many theoretical and practical work for design and deployment of wireless sensor networks. In our past research we proposed a mobile phone based deployment adviser tool [2] which is robust as well as practically implementable. The tool advises a layman deployer to create a optimized Wireless Sensor Network by placing of the nodes according to application requirements.

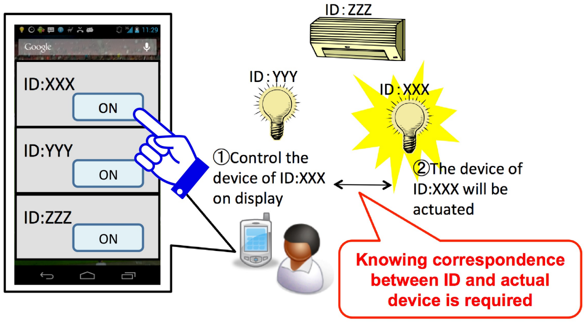

Figure 1: Typical existing system

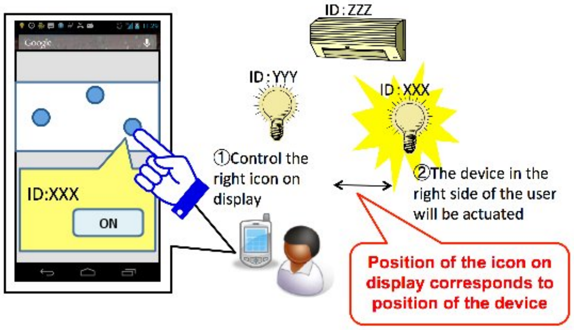

Figure 2: Smart Interaction System

The latest electrical devices including a light and an air conditioning have a wireless communication module and a smart phone can be used as a controller of the devices. Figure 1 shows an example where a user controls the lights and the air conditioning remotely with a typical existing system. In this example, the list of the device IDs is shown on the smart phone display. The user selects a device to control from the list. If the user does not know which device corresponds to ID:XXX in advance, he cannot tell which device will be actuated when he clicks the device of ID:XXX on the smart phone display. On the other hands, Figure 2 shows an example of a system using positions of the devices. In this system, the icon for the device is displayed at the position on the smart phone display associated with actual position of the device. This graphical indication would allow the user to identify the device to control easily. For instance, the system makes it possible to actuate the device in the right side of the user when the user controls the right icon on display. We call such a system "Smart Interaction System". To develop Smart Interaction System, the spatial information of devices is required. Assuming a dozen of the remote-control devices, from 10 to 20 devices, are installed in each house in the near future, it is hard or painstaking to manually measure the position of all the devices and input them to the system. Therefore Smart Interaction System with automatic semantic labeling would be more practical to improve operability of the remote-control devices. Achieving Smart Interaction System will need the development of localization technique of the device.

In literature most of the localization techniques are proposed on 2D localization. In [3] & [4] they discussed RSSI based localization algorithms. Our work is concerned with mobile phone based 3D localization and to give better user interface for controlling and accessing of Smart Interaction system. In [5] they did survey about 3D localization. These existing localization techniques require some anchors with the given position to measure RSSI. They still incur user burden to deploy the anchors and measure their positions. Thus alleviating the burden is still a technical challenge. As a solution to the challenge, we proposed two 3D localization techniques with a mobile robot such as a floor cleaning robot Roomba. The mobile robot would reduce the burden by measuring RSSI while cleaning floor instead of the anchors. Roomba provides user interface to program it easily. We used Roomba instead of using more number of anchor nodes. Here we place one sensor node on Roomba, called as beacon node(anchor node). Roomba moves in defined area to estimate location of a target node. Roomba will have its location details. The Roomba location will be the location of beacon node as it is placed on Roomba and also beacon node will have RSSI values with respect to target nodes (nodes which are placed at electrical devices). The entire system including the proposed localization techniques and Smart Interaction System has been implemented by using mobile cleaning robot and IITH Mote. IITH Mote is an in house developed sensor node shown in Figure 3, which makes use of IEEE 802.15.4 standard for PHY and MAC layers [6].

Figure 3: IITH Mote

The rest of the report is organized as follows. In Section 2 we discuss our first 3D localization algorithm, section 3 describes second 3D localization algorithm. Section 4, describes implementation of smart interaction system, finally section 5, shows objective of next year collaboration research.

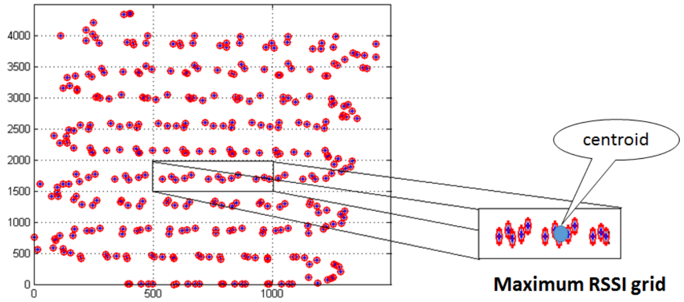

Figure 4: Max. RSSI value grid and centroid finding

2 3D Localization Technique Based on RSSI With a Mobile Robot

The First proposed 3D localization algorithm is composition of basic centroid finding method and RSSI based location finding method. For finding distance between two nodes in this algorithm, we use path loss model. In [7] and [8] authors discussed about basic centroid method considering RSSI values. Authors of [9] proposed a practical path loss model for indoor localization. In this paper we propose a 3D localization algorithm, which is less cost and will give less error in predicting 3D location of sensor node in a sensor network when compared to its actual location.

2.1 Proposed 3D localization algorithm

Centroid Location (CL) algorithm is well known for finding target node positions [27]. In CL algorithm, beacon nodes initially knows their location information, then broadcasts their position details to all the remaining nodes which are in network range. After the target node gets all beacon nodes information, it calculates position $T_e(x,y)$ from n beacon nodes as shown in equation (1). The localization error E(x,y) is defined as distance between estimated target position $(T_e(x,y))$ to actual target position $(T(x,y))$ as shown in equation (20).

$$T_e(x,y) = \frac{\sum_{j=1}^{n} B_j(x_j,y_j)}{n} \tag{1}$$

$$B_j(x_j,y_j) \rightarrow j^{th} \text{ beacon position.}$$

$$E(x,y) = |T(x,y) - T_e(x,y)| \tag{2}$$

In this paper, it is assumed that target node is placed above the ground level within considered experimental area. Mobile Robot moves on the ground within the experimental area and passes below the target node. In our proposed 3D localization algorithm, the defined area is divided into grids and average RSSI value is computed over each grid. The grid with maximum average RSSI value is considered, then the centroid (X_e, Y_e) of the grid is calculated using equation (1) as shown in Figure 25. After finding centroid in 2D plane, to estimate height of the target node we need distance between target node and beacon positions which are in maximum averaged RSSI value grid. In order to estimate distances between beacon positions and target node path loss model is used. Here we estimate distances between each beacon node position to target node by using RSSI value of known beacon positions. In our algorithm, Revised Hata Okumara model [11] is used to calculate distance from RSSI values of beacon positions for indoor localization as shown in equation (3).

$$logD_{ei} = \frac{1}{10\eta}[P_{TX} - P_{RXi} + G_{TX} + G_{RX} - X_{\alpha} + 20log\lambda - 20log(4\pi)] \tag{3}$$

Where D_{ei} → estimated distance between the target node (X_e, Y_e, Z_e) and i^{th} Beacon node (X_i, Y_i).
$G_{TX}(dBi)$ → Transmit antenna gain
$G_{RX}(dBi)$ → Receiver antenna gain
$P_{TX}(dBm)$ →Target node transmit power
$P_{RXi}(dBm)$ → Measured received power at i^{th} beacon position
η → Measure of influence of obstacle like partitions and obstacles in indoor environment ranges from 4 to 5 and for free space it is equal to 2.
X_{α} → Normal random variable with standard deviation of α and varies from 3dB to 20dB.

$P_{RXi}(dBm)$, measure received power at beacon positions from respective RSSI values is given by equation (4). This is specified in IITH Mote radio IC [12].

$$P_{RXi} = -91 + 3(R_i - 1) \tag{4}$$

Where R_i →RSSI value of i^{th} beacon position.

Parameter	Value
P_{TX}	-17.2 (dBm)
G_{TX}	0 (dBi)
G_{RX}	0 (dBi)
X_{α}	3 (dB)
λ	0.1250 (meters)
η	2

Table 1: Path loss model parameter values used

Table 1 shows path loss model parameters considered for experimentation. To estimate height of target node i.e Z axis value, we used Euclidian distance formula (21).

$$D_{ei} = \sqrt{(X_i - X_e)^2 + (Y_i - Y_e)^2 + (Z_{ei})^2} \tag{5}$$

Where D_{ei} can be computed from path loss model (3), (X_e, Y_e) values from Centroid location algorithm (1). Maximum range expected between beacon positions and target node is 5.95m, calculated from experimental area and height of the room.

(X_i, Y_i) values are beacon positions of maximum average RSSI value grid. Substituting these values in (21) gives unknown values Z_{ei}, which is estimated Z-axis value of target node with respect to i^{th} beacon position. From all n beacon positions we get n size vector of Z_{ei}. To estimate Z_e, we find mean of it as given in (22).

$$Z_e = \frac{\sum_{i=1}^{n} Z_{ei}}{n} \tag{6}$$

The pseudo code for proposed 3D localization algorithm is described in Algorithm 1.

Algorithm 1 Estimate (X_e, Y_e, Z_e)

```
Require: Beacon positions $(X_i, Y_i)$ with respective RSSI values $R_i$
Take starting point, stopping point from $(X_i, Y_i)$
Divide area in to $m$ no. of grids (1 ≤ m ≤ M )
Let in each grid have $n$ points (1 ≤ n ≤ N )
Calculate average RSSI value of each grid
while $m > 0$ do
    while $n > 0$ do
        $avg - rssi_m = \frac{\sum_{i=1}^{n} R_i}{n}$ (1≤ i ≤ n)
    end while
end while
Consider grid which has maximum averaged RSSI value($avg - rssi_m$)
From maximum averaged RSSI value grid calculate estimated 2D location
    $(X_e, Y_e) = \frac{\sum_{i=1}^{n} B_i(x_i, y_i)}{n}$
        $B_i(x_i, y_i) \rightarrow i^{th}$beacon position of maximum
            averaged RSSI value grid.
        $(X_e, Y_e)$ →estimated (X,Y) location of target node
Calculate received power from respective RSSI at $i^{th}$ beacon position $(R_i)$
    $P_{RXi} = -91 + 3.(R_i - 1)$
Calculate estimated distance from each $i^{th}$ node to target node
    $logD_{ei} = \frac{1}{10\eta}[P_{TX} - P_{RXi} + G_{TX} + G_{RX} - X_\alpha + 20log\lambda - 20log(4\pi)]$
Calculate $Z_{ei}$ from
    $D_{ei} = \sqrt{(X_i - X_e)^2 + (Y_i - Y_e)^2 + (Z_{ei})^2}$
$Z_e$=mean($Z_{ei}$)
```

2.2 Experimental setup for 3D localization using Roomba

The experiment is performed in a room by considering area 1700mm*4500mm. Height of the room is 3500mm and the area is divided into grids size of 0.5m*0.5m. Considered experimental area is empty and remaining area of the room is having furniture. We took a moving Robot Roomba [13] and fixed one sensor node (Beacon node IITH Mote) as shown in Figure 5. The beacon node is programmed to give instruction of movement to Roomba through serial port communication. Beacon node sends command to Roomba to move in zigzag way in a defined area as shown in Figure 23. Target node is placed in defined 3D location and it is also programmed to

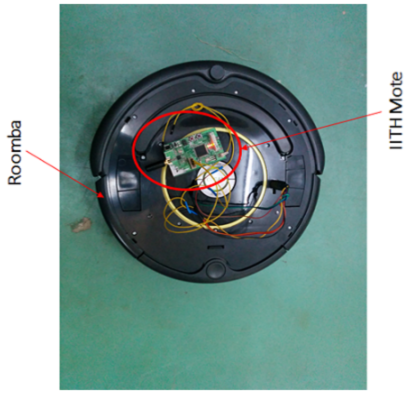

Figure 5: IITH Mote interfacing with Roomba

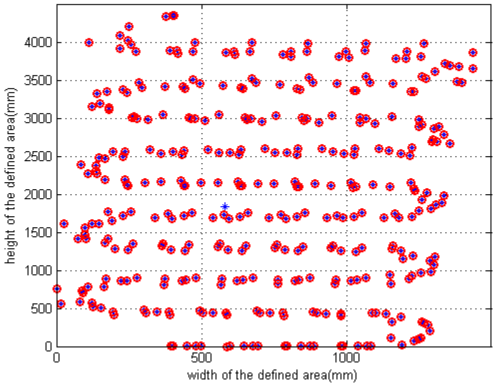

Figure 6: Roomba moved path in defined area from top view

send periodical dummy packets through wireless communication to beacon node with a period of 250 milliseconds. While Roomba moving in zigzag way in the defined area, beacon node get packets periodically from target node. Beacon node calculates RSSI values and has its position details received from Roomba (by sending commands through serial communication to Roomba) with respect to Roomba movement. ZigBee 802.15.4 with frequency of 2.4GHz is used for wireless communication and to get RSSI values. After getting RSSI values and respective position details from Roomba it will send a Location packet (a packet consists RSSI values and respective position details) through wireless communication to base node which is connected to Server (Server is a PC which takes data from base node through serial port). Base node is a sensor node which is programmed to receive data from beacon node and send it to Server. At Server our algorithm runs to estimate 3D location of target node. For the communication between base node and Server through serial port we used java program. After getting results of RSSI values with respective position details we used matlab to analyze data and to apply our algorithm. For programming beacon node, target node, base node we used Tinyos-2.1.1 nesC Script. In brief all software's used for experimental setup are tabulated in Table 2.

nesC	Program to IITH Motes
Matlab	proposed algorithm implemented at the Server
Java	Data collection at Server

Table 2: Programming languages used

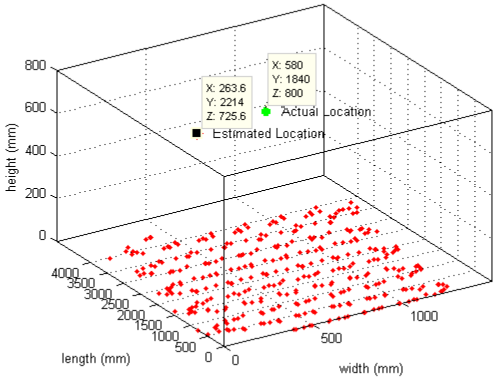

Figure 7: Estimated position and actual position at height = 800mm

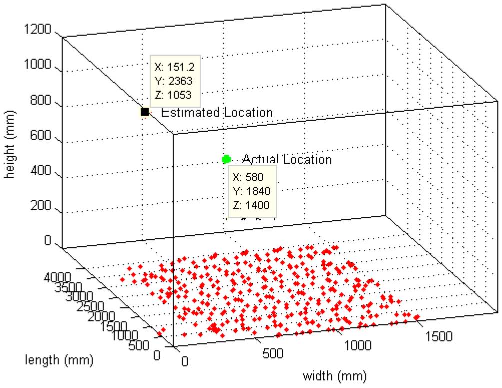

Figure 8: Estimated position and actual position at height = 1400mm

2.3 Experimental Results analysis

Experiment is performed by placing target node at three different heights. Actual and estimated positions for this three different heights are shown in Figure 7, Figure 8 and Figure 9. Let us consider the scenario of 3D localization as shown in Figure 7 for further analysis. From Figure 7 11^{th} grid has maximum average RSSI value of -66.0750 dBm. This grid consists 13 beacon locations (X_i, Y_i), and calculated centroid (X_e, Y_e) is (263.6, 2214)mm by using equation (1). From 13 beacon positions (X_i, Y_i) and respective RSSI values R_i, distance vector D_{ei} of size 1x13 is calculated by using equation (3). Z_{ei}(1x13) is obtained by substituting (X_i, Y_i), (X_e, Y_e) and D_{ei} values in equation (21). Finally Z_e calculated from equation (22) using Z_{ei} vector of size 1x13 and Z_e value is 725.6mm. Locations of estimated and actual target node positions and error is tabulated in Table 3. Error versus height of the target node is plotted in Figure 10. Experimentation results show that proposed algorithm can estimate target node location with

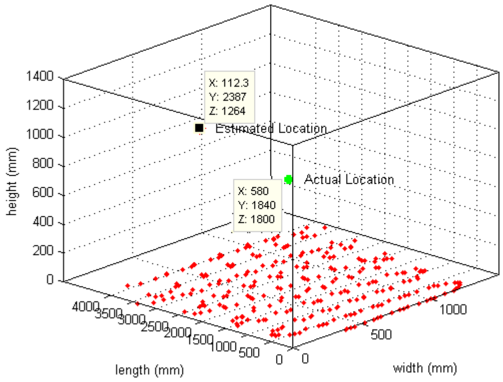

Figure 9: Estimated position and actual position at height = 1800mm

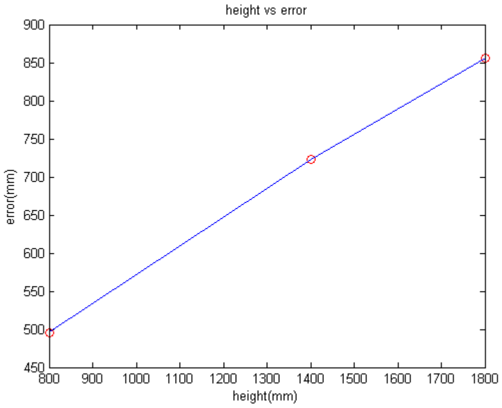

Figure 10: Predicted Location error

less than 1 meter estimation error.

Actual location(X,Y,Z)	Estimated location(X_e, Y_e, Z_e)	Error
(580, 1840, 800)mm	(263.6, 2214, 725.6)mm	495.7mm
(580, 1840, 1400)mm	(151.2363, 2363.5, 1053.1)mm	722.4mm
(580, 1840, 1800)mm	(112.2869, 2386.5, 1263.7)mm	855.8mm

Table 3: Error comparison

From Figure 10 we can say that estimated 3D-location error increasing with respect to height of sensor node. To get still more accurate 3D location of a desired sensor node we proposed one more algorithm, it is presented in next section. **(This work is published in International Symposium on Wireless Personal Multimedia Communications (WPMC 2014))**.

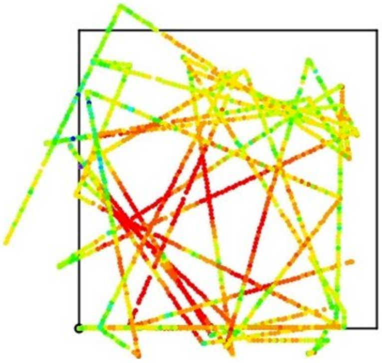

Figure 11: An example of collected RSSI by a mobile robot

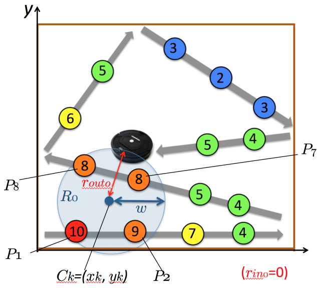

Figure 12: Example 1: R_0 with r_{in0}, r_{out0}

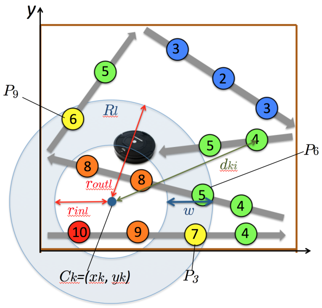

Figure 13: Example 2: R_l with r_{inl}, r_{outl}

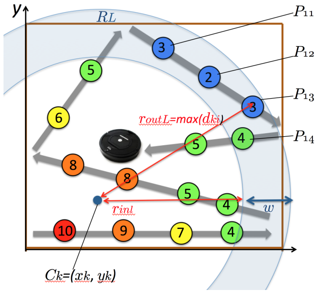

Figure 14: Example 3: R_L with r_{inL}, r_{outL}

3 3D Localization Technique With a Mobile Robot for Improving Operability of Remote-Control Devices

The proposed technique consists of the following 2 steps.

- Step A: RSSI collection with a mobile robot
- Step B: 3D Localization with collected RSSI
    1. 2D localization
    2. Height estimation

In Step A, a mobile robot collects RSSI of the devices. The mobile robot moves around autonomously while calculating its own position. That would cut out the need of deployment of the anchors and measurement of their positions. We assume that a floor cleaning robot is used as the mobile robot. By using the wide-spreading floor cleaning robot, the RSSI collection can be piggybacked on cleaning chores.

In Step B, the positions of devices are estimated from RSSI collected in Step A. In addition to the 2D localization like many of existing techniques, we estimate the height of the devices to distinguish the devices placed at the different heights in Smart Interaction System. The proposed 3D localization technique works without the channel parameters which are required in the existing localization techniques. These steps will be detailed below.

3.1 RSSI collection with a mobile robot

We assume that a mobile robot has wheels and moves on the floor of area where the devices are deployed. The robot measures RSSI of each device repeatedly while cleaning. After finish cleaning, the robot will be connected to a charger which is fixed on the floor. The position of the charger is defined as a reference point $(0, 0)$. X-axis is determined with the direction of the wheels when the robot is connected to the charger and Y-axis is at 90 degree angle of the wheels, respectively. While the robot measures RSSI, the relative position of the robot (x, y) from the reference point is calculated by odometry. The odometry is a simple technique to determine the relative position of a robot as explained in [16]. The relative position of robot is calculated from the number of rotations of the robot's wheels. An example of RSSI collected by the mobile robot is shown in Figure 11. A red point represents higher RSSI while green one represents lower RSSI (in black and white printing, a darker point represents higher RSSI while a brighter one represents lower RSSI).

3.2 3D Localization with collected RSSI

For 2D localization, we harness the characteristic of omnidirectional antenna that the radio wave is emitted concentrically in a horizontal direction. For height estimation, we use the maximum likelihood algorithm with no prior knowledge of the propagation model parameters.

3.2.1 2D localization

An omnidirectional antenna emits the radio wave concentrically in a horizontal direction. Thus, RSSI measured at the same distance from a transmitter should be about the same value like a circular pattern. Conversely, the center of the circular pattern of RSSI is likely to be the 2D position of the device. The main idea of the proposed 2D localization technique is to find the center of the circular pattern of RSSI. To find the center of the circular pattern of RSSI, first the defined area is divided into some circular rings centered at an arbitrary point. Next, the variance of RSSI is computed over each ring. Finally, the point which minimizes the mean of the variances will be regarded as the center of the circle, which is the 2D position of the device.

Specifically, the proposed technique estimates the 2D position of the device $X_e = (x_e, y_e)$ as follows. Figure 12 to Figure 14 show examples how the proposed technique works. The points in Figure 12 to Figure 14 represent the positions where the mobile robot measures RSSI. The number in each point represents RSSI. RSSI measured at the position $P_j = (x_j, y_j)$ is denoted by $rssi_j$. For an arbitrary point $C_k = (x_k, y_k)$ in the defined area, R_l denotes l^{th} ring centered at C_k. r_{inl} denotes the radius of the inside circle of the ring R_l and r_{outl} denotes the radius of the outside circle of the ring R_l. The width of each ring is a constant parameter w. We set $r_{in0} = 0$ and $r_{out0} = w$, then R_0 is a circle of radius w (Figure 12). r_{inl+1} and r_{outl+1} are increased as below.

$$r_{inl+1} = r_{inl} + w, \tag{7}$$

$$r_{outl+1} = r_{outl} + w. \tag{8}$$

The set of points P_j in the ring R_l is denoted by $A_l = \{P_j \mid P_j \text{ is located in } R_{kl}\}$. For example, $A_0 = \{P_1, P_2, P_7, P_8\}$ in Figure 12. E_l denotes the mean of RSSI values in ring R_l and can be calculated by equation (9).

$$E_l = \frac{\sum_{P_j \in A_l} rssi_j}{n_l} \tag{9}$$

where n_l is the number of the points P_j in the ring of R_l. We also calculate the variance of RSSI values V_l by equation (10).

$$V_l = \frac{\sum_{P_j \in A_l} (rssi_j - E_l)^2}{n_l}. \tag{10}$$

For instance, in the case shown in Figure 13, V_l is calculated from $rssi_3 = 7$, $rssi_6 = 5$ and $rssi_9 = 6$. V_l is repeatedly computed while $r_{outL} \leq \max_j(d_{kj})$. L represents the index for the ring which contains the point with largest distance from C_k (Figure 14). d_{kj} denotes the distance between C_k and P_j. Equation (11) is used to find the mean of the variance in the rings centered at C_k.

$$EV_k = \frac{\sum_l (V_{kl})}{m_k} \tag{11}$$

Where m_k is the number of the rings for C_k. Finally the estimated position (x_e, x_e) is determined as shown in the following equation (12).

$$(x_e, y_e) = \{C_k \mid \min_{C_k} (EV_k)\} \tag{12}$$

3.2.2 Height estimation

After estimating the 2D position of the device, the proposed localization technique estimates the height of the device with the estimated 2D position. The proposed localization technique is based on the maximum likelihood localization technique. The existing localization techniques require the preliminary experiment to determine the channel parameters. To eliminate the need of the preliminary experiment, in the proposed localization technique, the channel parameters are considered as the unknown variable as well as the height of the device. Then likelihood of received RSSI for each potential height and the potential channel parameters are computed. The height which maximizes the likelihood is selected as the estimated height. Specifically, the proposed technique estimates the height z_e of the device as follows. First one postulated height z' is given and then the postulated RSSI p_j for each point P_j is calculated from equation (13).

$$p_j = A' - 10N' \cdot log_{10} \left(\frac{d_j}{d'_0} \right). \tag{13}$$

d_j is the distance between the postulated position (x_e, y_e, z') and the point P_j. A' is mean received power at the reference distance d'_0. N' is the postulated channel parameter. We consider the postulated height z' as the reference distance ($d'_0 = z'$) and compute A' by the equation (14).

$$A' = \frac{\sum_{P_j \in A_0} rssi_j}{n_0}. \tag{14}$$

In reference to [14], the likelihood L that the postulated height z' and postulated channel parameter N' are correct is represented as:

$$L = \prod_j \left\{ \exp\left[-\frac{1}{2} \left(\frac{p_j - rssi_j}{\sigma_{dB}} \right)^2 \right] \right\} \tag{15}$$

where σ_{dB} is the standard deviation of RSSI. Here we give $\sigma_{dB} = \sqrt{V_0}$ (V_0 is computed in 2D localization). From the above, the likelihood L is a function of z' and N', thus it can be represented by the equation (16).

$$L = f(z', N') \tag{16}$$

Finally the estimated height z_e is determined as shown in the following equation (17).

$$z_e = \arg\max_{z'} (L(z', N')) \tag{17}$$

3.3 Experiment and analysis

3.3.1 Experimental settings

In our system implementation, instead of using anchors a moving robot, Roomba is used. Roomba is a cleaning robot produced by iRobot corporation. It provides a user interface to program it easily and specification of the interface is available on [15]. An anchor called beacon node is interfaced with Roomba through serial port. The beacon node controls the Roomba by sending commands through serial port. As the beacon node is placed on Roomba, Roomba's mobility will be considered as beacon node mobility. To determine the position of Roomba, we implemented odometry as [16] and validated the accuracy of odometry was enough for our application. The beacon node will have RSSI with respect to target nodes through wireless communication with a period of 250 milliseconds while Roomba is moving in random way inside defined area and calculate RSSI values from target nodes. After this beacon node will form a location packet (a packet which contains location details of Roomba and respective RSSI value from target nodes) and send it to a server. The server computes the position of the devices based on the proposed localization algorithm explained in section 3.2.

To analyze the estimation error of the proposed localization technique and evaluate the operability of Smart Interaction System, we conduct experiments with the implemented system. In this paper, we assume the situation where from 10 to 20 devices are installed in a house. To cover the situation, we placed total 45 devices in a room over the experiments. The experiments are performed in a room by considering an area of 7000mm*6500mm and height 2500mm. The size of the room can be regarded as an average room size. For each experiment, 9 target nodes are arranged at 9 locations at intervals of 2000mm, (1800, 1370, H)mm, (3800, 1370, H)mm, (5800, 1370, H)mm, (1800, 3370, H)mm, (3800, 3370, H)mm, (5800, 3370, H)mm, (1800, 5370, H)mm, (3800, 5370, H)mm and (3000, 5370, H)mm. All the target nodes (X,Y) co-ordinates are fixed, H indicates height of the target nodes. Total 25 experiments are performed for 5 different height and 5 different transmit power. The target nodes are placed at height H=500mm, 1000mm, 1500mm, 2000mm and 2500mm for 3D localization. Transmit power P_{tx} is set to 3dBm, 1.6dBm, -0.2dBm, -3.2dBm and -7.2dBm for the target nodes. For beacon node, transmit power is set to 3dBm. Each experiment consists of 20 trials. Duration of each trial is 2 minutes. In each trial, Roomba with beacon node moves randomly in the defined experimental area and collects RSSI values from target nodes. We analyze 3D estimation error and 2D estimation error of the proposed localization technique. The 3D estimation error err_{3D} and 2D estimation error err_{2D} are calculated by equations (18) and (19), respectively.

$$err_{3D} = \sqrt{(x_e - x_a)^2 + (y_e - y_a)^2 + (z_e - z_a)^2} \tag{18}$$

$$err_{2D} = \sqrt{(x_e - x_a)^2 + (y_e - y_a)^2} \tag{19}$$

x_e, y_e and z_e represent the estimated coordinates of a target node for each axis. x_a, y_a and z_a represent the actual coordinates of a target node for each axis. For comparison, we also analyze the estimation error of Min-Max [17]. For both proposed protocol and Min-Max, the same input of RSSI are used to estimate the positions of the devices. Although Min-Max can be used for 3D localization, it requires RSSI collection in 3D space. Here we analyze only 2D estimation error for Min-Max because the Roomba moves on the floor (2D space) to collect RSSI.

In the proposed localization, we used $w = 100$ (mm) to find the positions of the devices. In Min-Max, $A = -61.8$ (dBm) and $n = 1.89$, which are derived from prior experiments are used.

3.3.2 Experimental results analysis

Figure 15 shows the mean estimation error of proposed localization technique and Min-Max. The 3D and 2D estimation error of both the proposed localization technique and Min-Max decrease

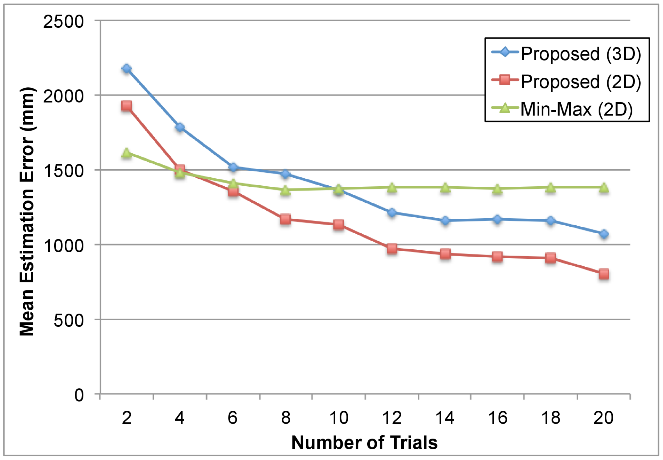

Figure 15: Number of trials vs. Mean estimation error

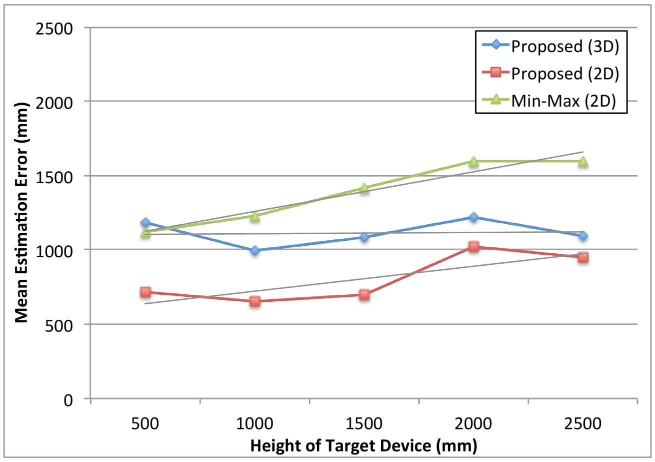

Figure 16: Height of target device vs. Mean estimation error

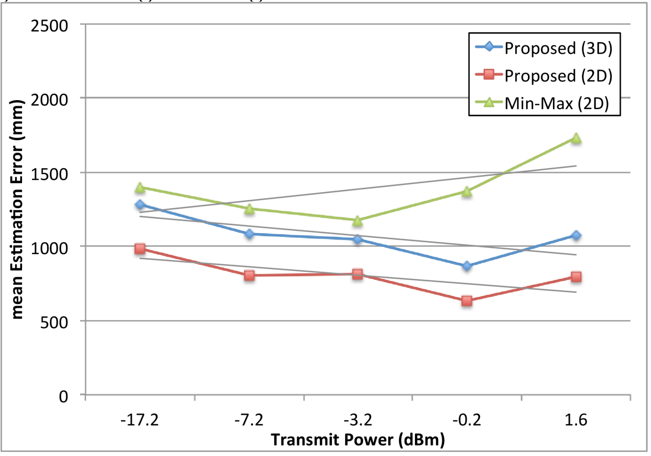

Figure 17: Transmit power vs. mean estimation error

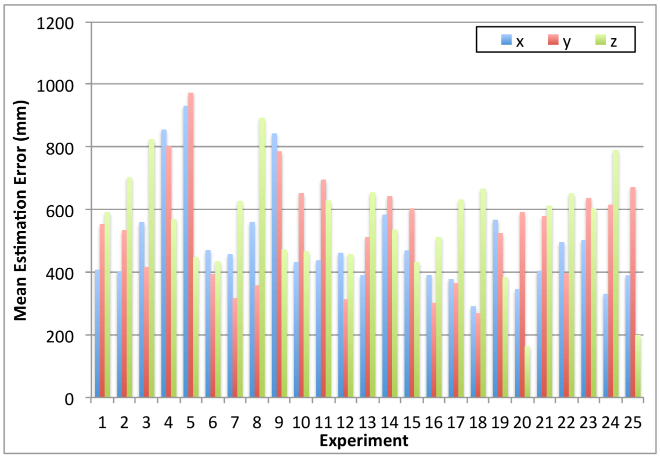

Figure 18: Mean estimation error for each axis

as the number of trials. The proposed localization technique gives the smaller 2D estimation error compared to Min-Max after 6 trials (12 minutes) are performed. According to [17], 3D estimation error of Min-Max in similar experimental setting is approximately 2m, which is higher than one of the proposed localization technique. Figure 16 shows that the mean estimation error for the different heights of the target nodes. The graph shows the trend that the mean estimation error increases as the height of the device. This can be caused by the longer distance between the node at higher place and the Roomba on the floor. The radio wave will be exposed through the long distance and affected by various factors such as a multipath fading. Figure 17 shows the mean estimation error for the different transmit power. From the result, the estimation error of the proposed localization technique is less affected by the transmit power. Although the transmit power of all devices might not be always the same if a variety of remote-control devices are installed in house, the proposed localization technique can be useful for identify the devices. Figure 18 shows the mean estimation error for x-axis, y-axis and z-axis in 25 experiments. From the graph, the mean estimation errors for x-axis, y-axis and z-axis are smaller than 1000mm.

3.3.3 Discussion

As long as the estimation error is smaller than 1000mm for each axis, the icons of the devices in Smart Interaction System will not be interchanged left and right on the smartphone display. This means that a user can identify a device to control by finding the position of the icon on the display corresponding to the actual position of the device. As shown in Figure 18 the mean estimation error of the proposed localization technique is enough small for Smart Interaction System.

Besides, in case of the estimation error is larger than 1000mm, we expect that longer-term RSSI collection will reduce the estimation error from Figure 15. Even if the estimation error is larger than 1000mm and the icons are interchanged left and right on the display, the user can find the error of the icons once he operates the device from smartphone. The burden to modify positions of only few nodes is relatively smaller compared to one to input the position of all the nodes. Thus we consider the proposed localization technique and Smart Interaction System are practical to improve the operability of remote-control devices.

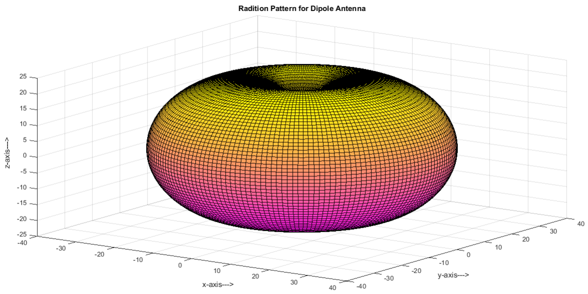

Figure 19: 3D radiation pattern of half wave dipole antenna.

4 Antenna Radiation Pattern Based 3D Localization Technique

4.1 Proposed 3D localization algorithm

This section describes the proposed radiation pattern based 3D localization technique. We assumed that target node (the sensor node which location has to be estimated) is equipped with half wave dipole antenna, which has omnidirectional radiation pattern. In all directions, omnidirectional antenna radiation pattern is not same. It radiates less power in the axial direction of antenna.

4.1.1 Estimating 2D location of target node

We considered that target node is placed above the XY-plane with antenna in Z-axis direction. Omnidirectional antenna radiates power concentrically in horizontal direction with circular patterns as shown in Fig. 20. Received power from transmitting antenna at equidistant beacon locations is almost same on 2D plane (ground plane). The 2D location of the target node can be estimated by locating center of the circular patterns. To find out center of the circular patterns on 2D plane where beacon nodes are placed, the plane is divided in to circular patterns which are having arbitrary center point. These circular patterns form rings on 2D plane. Variance of received powers is computed over each ring. The mean of variances of received power where it goes to minimum, that center point of circles is regarded as 2D location of the target node.

To estimate target node 2D location (X_e, Y_e), we considered n beacon nodes in 2D plane. Location of beacon nodes are (x_i, y_i) where $i = 1, \ldots, n$ (a sensor node which is placed on mobile robot can be used as beacon node to get n beacon node locations [28]). Received power of i^{th} beacon node is Pr_i. Rn_{kl} represents l^{th} ring centered at an arbitrary point $C_k = (x_k, y_k)$, where the radius of inner circle is ri_l, outer circle is ro_l and the width of each ring is w. Consider D_{ki} is the Euclidean distance between each points on 2D plane (x_i, y_i) and an arbitrary point $C_k = (x_k, y_k)$ which is calculated from equation (20). d_{1l} is the minimum distance between l^{th} ring's inner circle circumference and the points lying inside the ring. d_{2l} is minimum distance between l^{th} ring's outer circle circumference and points lying outside the ring i.e. points which distance $D_{ki} > ro_l$. Pt_i is the set of points of beacon node locations. Algorithm starts at an arbitrary point C_k with $ri_l = 0$ and $ro_l = w$. In next step if $d_{1l} < d_{2l}$ then $ri_l = d_{1l}$, $ro_l = ri_l + w$ else $ro_l = d_{2l}$, $ri_l = ro_l - w$. Fig. 27 shows plot of two iterations. In iterative process d_{2l}, d_{1l}, ri_l, ro_l will be update until $A_{kl} = \{\emptyset\}$.

$$D_{ki} = \sqrt{(x_i - x_k)^2 + (y_i - y_k)^2} \tag{20}$$

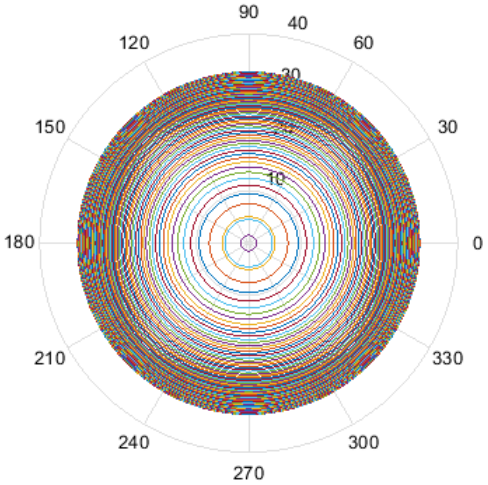

Figure 20: Power distribution of the omnidirectional antenna in horizontal plane.

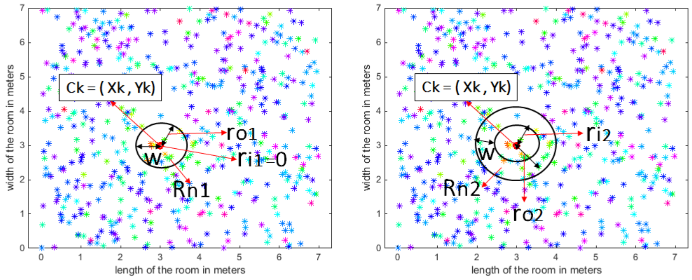

Figure 21: The defined area is divided in circular rings.

Here the set of points located in the ring Rn_{kl} are represented by $A_{kl} = \{Pt_i \mid Pt_i \in Rn_{kl}\}$. E_{kl} represents the mean of received power at different beacon nodes in the ring Rn_{kl} and calculated by equation (21).

$$E_{kl} = \frac{\sum_{Pt_i \in A_{kl}} Pr_i}{n_{kl}} \tag{21}$$

n_{kl} is the number of point of the set A_{kl}. Variance of received power values of each ring V_{kl} calculated using equation (22).

$$V_{kl} = \frac{\sum_{Pt_i \in A_{kl}} (Pr_i - E_{kl})^2}{n_{kl}} \tag{22}$$

$$EV_k = \frac{\sum_l (V_{kl})}{M_k} \tag{23}$$

Equation (23) is used to find the mean of the variances of the rings centered at C_k. Here M_k is the total number of rings for C_k. Finally the estimated position (X_e, Y_e) is determined using the following equation (24).

$$(X_e, Y_e) = C_k \text{ which minimizes } EV_k \tag{24}$$

4.1.2 Estimating height of the target node

The gain of omnidirectional antenna in vertical direction is lower than horizontal direction [36] as shown in Fig. 23. Thus, received power measured at the beacon nodes under the target node will be low. The average value of received power at beacon nodes from target node will decrease as target node height increases. This fact helped us to propose a new relative height estimation method for 3D localization.

To calculate average received power of beacon nodes under target node, a circle with radius r from estimated 2D location of the target node (X_e, Y_e) is considered. Set of Beacon positions M, which distance from (X_e, Y_e) is less than r is considered, i.e. $M = \{Pt_i \mid D_{ki} < r\}$. N_M is the number of beacon node in the set M. Average received power of beacon nodes P_{avg} is calculated using equation (25).

$$P_{avg} = \frac{\sum_{Pt_i \in M} Pr_i}{N_M} \tag{25}$$

Specifically, the proposed algorithm estimates the relative height Z_{ej} of target nodes N_j. Here we assumed that all target nodes heights are uniformly distributed along Z-axis with different 2D locations. First we find the average received power of all target nodes (inside the circle with radius r under target nodes). The minimum P_{avg} value is denoted by $P_{avg_{min}}$, the corresponding height of $P_{avg_{min}}$ is H_{max}. To estimate relative height of other target nodes, received average powers of all target nodes are divided in to groups. K-means clustering algorithm is used for grouping the received average powers of different target nodes with different heights. K-means algorithm will give group numbers according to received average powers. All the target nodes are classified into M groups from G_1 to G_M depending on its P_{avg}. The height of a target node in group G_h (where group number $h = 1, 2, ..., M$) is estimated by following equation (26).

$$Z_{ej} = \frac{H_{max}}{M} * h \tag{26}$$

4.2 Algorithm implementation and simulation setup for 3D localization

The proposed algorithm is implemented using Matlab software. Radiation pattern of the half wave dipole antenna is generated with reference of [38], [?] using Matlab. To implement the algorithm we considered beacon nodes are randomly deployed on 2D plane. Target node is considered above 2D plane (which is placed in 3D location). Received power Pr_i at randomly deployed beacon nodes (x_i, y_i) depend on gain of the antenna at respective positions. Antenna Transmit gain $G_t(\theta, \phi)$ and antenna receive gain $G_r(\theta, \phi)$ are function of azimuth angle ϕ and elevation angle θ. Transmit and receive antenna gain of beacon nodes will be different for different azimuth angle ϕ and elevation angle θ with respect to target node. Depending on these azimuth and elevation angles, antenna gains are mapped to different beacon node's location. To find received power at beacon node's location Revised Hata Okumara path loss model [37] is used (27).

$$\begin{aligned} logD_i = \frac{1}{10\eta}[P_t - Pr_i + G_t(\theta, \phi) + G_r(\theta, \phi) \\ -X_\alpha + 20log\lambda - 20log(4\pi)] \end{aligned} \tag{27}$$

Figure 22: Predicted location error vs height of the target nodes

Where $D_i \rightarrow$ distance between the target node to
all beacon nodes (X_t, Y_t, Z_t)
and i^{th} Beacon node (x_i, y_i).
$G_t(\theta, \phi)(dBi) \rightarrow$ Transmit antenna gain
$G_r(\theta, \phi)(dBi) \rightarrow$ Receiver antenna gain
$P_t(dBm) \rightarrow$Target node transmit power
$Pr_i(dBm) \rightarrow$ Measured received power at i^{th}
beacon position
$\eta \rightarrow$ Measure of influence of obstacle like
partitions and obstacles in indoor
environment ranges from 4 to 5 and for
free space it is equal to 2.
$X_\alpha \rightarrow$ Normal random variable with standard
deviation of α and varies from 3dB to
20dB.

Table 4: Path loss model parameter values used for simulation

Parameter	Value
P_t	-3 (dBm)
X_α	3 (dB)
λ	0.125 (meters)
η	2.5

4.3 Simulation setup

For simulation purpose we considered area of 7m*7m, number of beacon nodes are 1000 which are placed at random locations. All beacon nodes are placed on 2D plane with random azimuth angle. We considered all target nodes and beacon nodes are equipped with half wave dipole antenna. Along with this setup 10 target nodes are considered which are placed at different 3D locations. Considered number of groups are $M = 10$ and considered maximum height is $Hmax = 7m$ which is maximum height of the considered target nodes. To calculate average received power of beacon nodes under the target node, a circle with radius $r = 0.5m$ which centered at estimated 2D location is considered. TABLE I shows path loss model parameters considered for simulation.

4.4 Simulation Results analysis

Estimated location error with different heights is plotted in Fig. 25. Actual, estimated locations are tabulated in TABLE II:

Table 5: Estimated and actual location of the sensor node at different heights

Actual locations (m)			Estimated locations (m)		
Xt	Yt	Zt	Xe	Ye	Ze
0	0	1	0.2	0	0.7
1	2	2	1	1.7	1.4
2	3	2.5	2	3	2.1
4	1	3	4.1	0.9	2.8
3	3	3.25	3	3	3.5
5	2	3.75	5.1	2	4.2
6	6	4	6	6	4.9
3.5	1.5	5	3.5	1.6	5.6
4	2	6	4	2	6.3
2	4	7	2	4	7

The error of the estimated 3D location of the target node to actual location of the target node is calculated by using equation (28).

$$E_{rr} = \sqrt{(X_t - X_e)^2 + (Y_t - Y_e)^2 + (Z_t - Z_e)^2} \tag{28}$$

Where (X_t, Y_t, Z_t) $\rightarrow$target node real location.
(X_e, Y_e, Z_e) $\rightarrow$ target node estimated location.

Estimated average error for 10 different locations with 10 different heights given in TABLE II is $0.4196m$. This result is more accurate compared to existing algorithms [28].

5 Smart Interaction System implementation

The complete system architecture is shown in Figure 23. Implementation of the system is divided in to two parts, one is localization and another one is smart interaction, the clear division of these two parts architecture is shown in Figure 24.

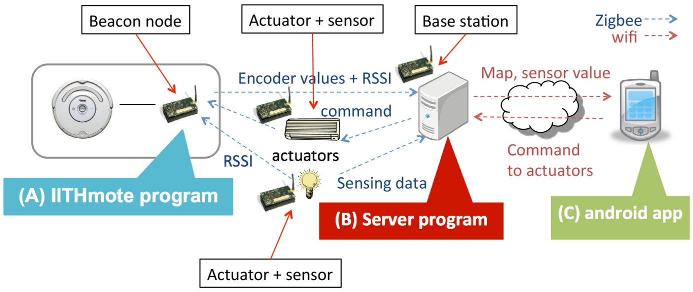

Figure 23: Complete system architecture

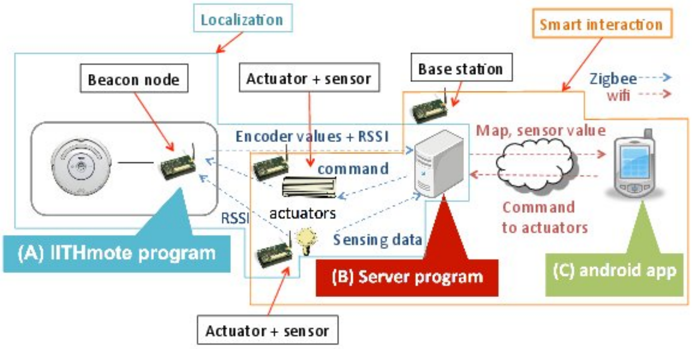

Figure 24: Mapping and smart interaction as two parts

5.1 Localization

For first part of the Smart Interaction System, we proposed two localization algorithms and evaluated performance of the algorithms and described in above sections. A sensor node is placed on the Roomba and is called as beacon node. Beacon node is interfaced with Roomba through serial port. Beacon node receives packet from target nodes and also control the Roomba by sending commands through serial communication. Beacon node controls the Roomba movement in a defined area to estimate locations of target nodes. As beacon node is placed on Roomba, The Roomba's mobility will be considered as beacon node mobility, beacon node will have RSSI values with respect to target nodes. Target nodes will send continuously dummy packets to beacon node through wireless communication with a period of 250 milliseconds. Beacon node will receive dummy packets while Roomba is moving in random way inside defined area and calculate RSSI values from target nodes. After this beacon node will form a location packet (a packet which contains location details of Roomba and respective RSSI value from target nodes) and sends to base node. Base node is a sensor node which is connected to Server through serial communication. Base node is programmed to receive location packets from beacon node and is send to server through serial communication. Server is a PC which takes data from base node through serial communication. At server localization algorithm will be run to estimate the location of target nodes.

The target nodes will be interfaced with electrical appliances through power electronic switch as shown in Figure 25. the location of target nodes will be the respective location of electrical devices. Therefore the location knowledge of target nodes will be required to access and control the electrical appliances and will be used further in smart interaction system. Sever creates 3D map for room or building with electrical appliances locations indication which will be displayed in GUI of smart interaction application (explained in next subsection).

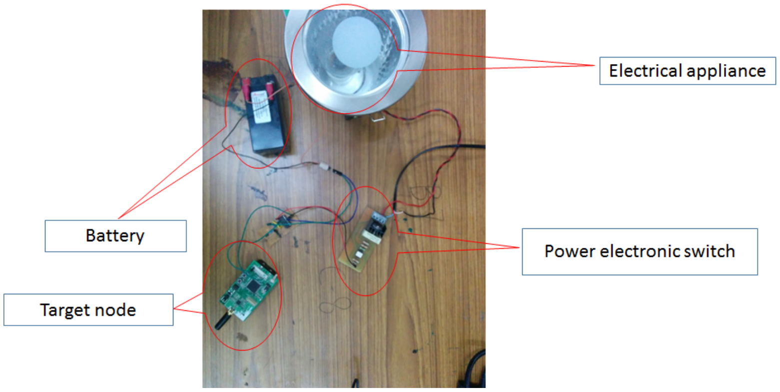

Figure 25: Device node interfacing with power electronic switch and electrical appliance

5.2 Smart Interaction

The second part of the system is smart interaction. Smart interaction application will be running on smart devices like mobile phone or tab which are having internet connectivity. This smart interaction application is programmed to control and access all the electrical devices inside the room or building. Smart interaction application has access to current status of electrical application like on, off, working or not working from the server database. This information can be viewed in application GUI by clicking update button. Smart interaction will show 3D map of devices location inside room which is the result of localization system. The location of devices is shown as small sphere. When user click on sphere, it will show the respective electrical appliances information in terms of its current status. Form this user can decide to switch on or off and this data will send to the server. Then server will update the database and send the same user command to the base node. Base node will send the command sent by server to particular target node which will give actuation signal according to server command(On or Off) to power electronic switch. Smart interaction application command flow for making an electrical appliances on or off is shown in Figure 26 and Figure 27.

Server programming is implemented by using java. At server localization algorithm will be running and it also has to perform actions like, taking data from mobile application, base node and sending back commands to base node. For programming beacon node, target node, base node we used Tinyos-2.1.1 nesC script. Mobile phone application is developed in android platform. In brief all software's used for experimental setup are tabulated in Table 4.

nesC	Program to IITH Motes
Android	Smart interaction application
Java	Server programming

Table 6: Programming languages used

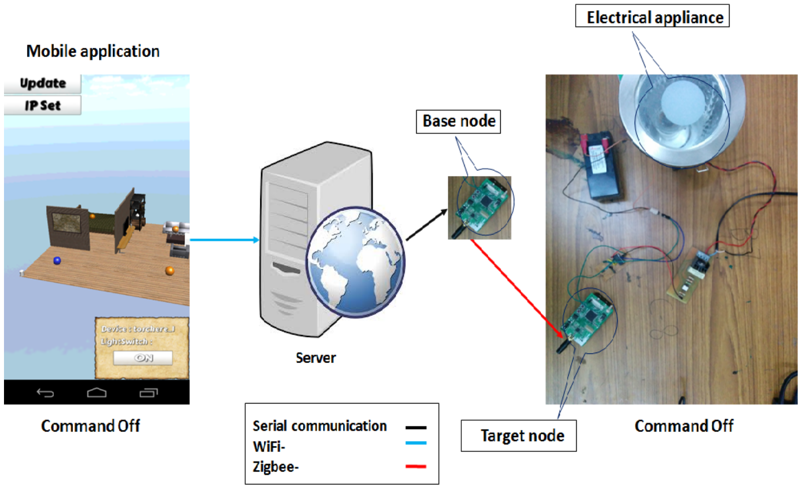

Figure 26: Smart interaction application command flow for making an electrical appliance off

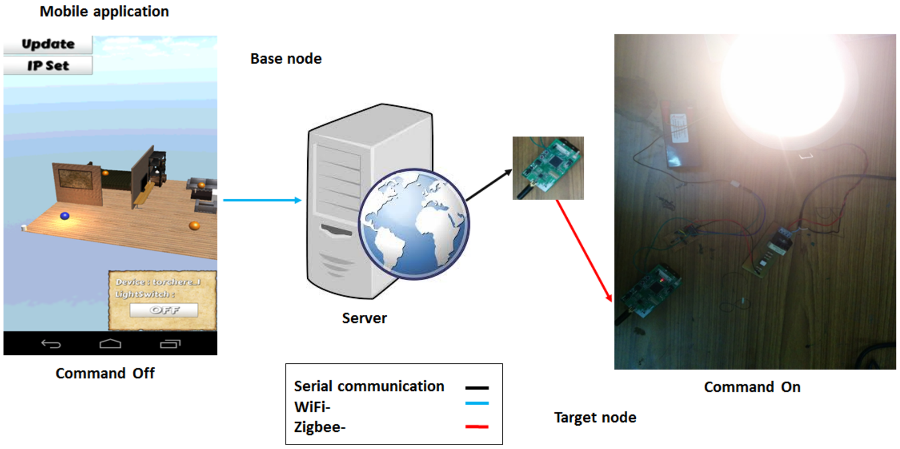

Figure 27: Smart interaction application command flow for making an electrical appliance on

5.3 Conclusion

To improve operability of the remote-control devices, we proposed two 3D localization techniques, we used IITH Mote and mobile Robot to perform experiments in real field deployment area (Indoor). In the proposed localization techniques, a mobile Robot reduces the burden of deployment of anchors required in some existing techniques. The first proposed localization algorithm is showing The experimental results gives very less error of 3D location of target node (< 1 meter). But as device height increases the estimation error also increasing. To get better performance we proposed one more 3D localization algorithm.

The second proposed 3D localization technique takes into account the gain of omnidirectional antenna to estimate the position of the devices without the prior knowledge of channel condition. We conducted experiments with the implemented system to analyze the estimation error of the proposed localization technique. The experimental results show that the mean estimation error is approximately 1000mm. We have implemented the proposed localization technique and the Smart Interaction System with a mobile robot, sensors, a server and a smartphone. We consider that the proposed localization technique and the Smart Interaction System are practical for remote-control devices because the estimation error is enough small to allow a user to identify each device in a room with less burden.Thus my proposed algorithm gives very less error of 3D location of target node(<1 meter).some possible direction for future work is develop a dynamic algorithm to get still more accurate 3D location of a desired sensor node

6 Publications

[1] Amarlingam M, P Rajalakshmi , Vinod kumar Netad, Masaya Yoshida, Kiyohito Yoshihara. "Antenna Radiation Pattern Based 3D Localization Technique" accepted in 18th International Symposium on Wireless Personal Multimedia Communications (WPMCâĂŹ15), Dec,2015.
[2] Masaya Yoshida, Kiyohito Yoshihara, Amarlingam M, Rajalakshmi P, Vinod Kumar Netad, "3D Localization Technique with Mobile Robot for Improving Operability of Remote-Control Devices", Accepted for ACMs International Wireless communications Mobile Computing conference (IWCMC), 24-27 August 2015, Croatia, Dubrovnik.
[3] Amarlingam M, P. Rajalakshmi, Vinod Kumar Netad, Masaya Yoshida, Kiyohito Yoshihara. "Centroid Based 3D Localization Technique Using RSSI With a Mobile Robot", 17th International Symposium on Wireless Personal Multimedia Communications (WPMC2014).7-10 Sept, 2014, Sydney.

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