Bluetooth Low Energy Local Positioning for Museum Navigation

N.D.C.D. Kannangara, W.D.S.S. Bandara*

Department of Electrical and Computer of Engineering, The Open University of Sri Lanka, Nawala, Nugegoda, Sri Lanka.

*Corresponding Author: email: wdban@ou.ac.lk, Tele: +948774674793

Abstract *– Bluetooth Low Energy (BLE) is a new specification of Bluetooth available for all new smart-devices. It is a new low power consumption technology aimed to transmit small amount of data. In addition to the transmitting data, BLE can be used to locate objects. iBeacon® protocol, which uses BLE, is aimed at that objective with special attention in proximity location with BLE beacons. This is a new technology and as yet it is unclear how it will be used. In conventional museums, information or explanation of exhibited artifacts is presented by using panels or leaflets. Some museums are complicated places to navigate within. They may not have a clear path through the museum and may offer many alternatives. The problem is even complicated, given the fact that a visitor usually has limited time for a visit and missed some important places. However, such paper maps may be inconvenient and not easy to use, especially when a group of visitors is visiting the museum together. The objective of this project was to implement an Android application(app) "Museum Navigation System" based on Bluetooth Low Energy beacons and the iBeacon® protocol. Here the Android app illustrates navigation and information on the smart device by using received signal strength indicator(RSSI)power, universally unique identifier (UUID), major and minor of beacon frame. Here 3 Beacons were used in a cluster to find the position. First scanned for beacons and then RSSI power values are saved in an array. Then it selects 3 most strong beacons by sorting values of RSSI power. RSSI-based triangulation method is used to find the position in a cluster and when the user moves to the next cluster region it is identified by scanning the route. Then, user position coordinate and direction on the map were displayed by app.*

Keywords*: Bluetooth Low Energy, BLE proximity location, iBeacon protocol, 3 Beacons cluster, triangulation.*

1 INTRODUCTION

One of the main objectives of a "Museum" is to provide visitors a chance to learn. In conventional museums, information or explanation of exhibited materials is presented by using panels or leaflets. Some museums are complicated places to navigate within. They may not have a clear path through the museum and may offer many alternatives. The problem is even complicated given the fact that a visitor usually has a limited time for a visit and may miss some important places. The classic navigation aid is the paper map of the museum, which is based on the museum floor plan and enables the visitor to orient themselves and find the way in the museum. However, such paper maps may be inconvenient and complicated to use, especially when a group of visitors is visiting the museum together. Current mobile technology opens new possibilities for supporting indoor navigation. Compared to classic Bluetooth, Bluetooth Low Energy consumes much less power (e.g. 0.01 W instead of 1W), the BLE devices are considerably cheaper to build, while the data transfer rate is much lower (e.g. 0.27 Mbit/s). Meanwhile the power consumption must be low and the data rate is not important to transmit context based information to smart device such as iPhone and iPad. Beacons are small wireless sensors that communicate with Bluetooth-enabled smart devices such as iPhones or iPads by continuously advertising their location using a Bluetooth low energy radio transmitter. In turn, smart devices monitor the received signal strength indication (RSSI) and determine the device's proximity to the beacon. This is a new technology and as yet it is unclear how it will be used. Therefore, aim of the project is to develop a museum navigation system to be used in museums.

2 PROJECT BACKGROUND

2.1 Museum Navigation Systems

Similar museum navigation systems can be found in two technologies.

Museum Navigation System using Augmented Reality Technologies － Noboru Koshizuka

Tokyo University Digital Museum, has started developing a new information-providing system for exhibited materials by using "augmented reality" technologies in the computer science field. Augmented reality technologies realize some kinds of un-natural and artificial images in the real world. In other words, augmented reality technologies build unrealistic images in real world, while the virtual reality technologies build realistic images in virtual world. In this system, a visitor wears a "glass", called as Head Mounted Display (HMD). The visitor can see real images through this "glass", and the "glass" contains an LCD screen in front of the user's eyes, which can display information from a computer over the real images. Wandering around the museum wearing the "glass", the visitor can see explanation and/or information of exhibit in front of his/her eyes. If he/she puts earphones in his/her ears, he/she can listen to aural information at the same time. Approaching exhibited materials, the display will switch to more detailed explanation of the materials.

Personalized Digital Museum Assistant － Ken Sakamura

Personalized digital museum assistant (PDMA) is a tool that uses computer technology to strengthen "exhibitions" which enable visitors to achieve more enjoyment as well as greater knowledge and excitement from museums. PDMA is a term created to encompass the meaning of a tool to enjoy the personalized digital museum by using a personal digital assistant (PDA) which is the mobile terminal. A variety of formats were devised in the course of achieving the PDMA, and at the University Museum the University of Tokyo a number of formats of PDMA were researched and developed, and subjected to repeated trial testing. In principle, electronic tags are attached to exhibits, and the PDMA reads off data from the electronic tags, thereby detecting what visitors want to know about what exhibits. In response, the PDMA displays or provides a voice commentary about information related to that exhibit. The key feature of PDMA is the ability to personalize. By setting the services required by visitors when the PDMA is lent out, a commentary that meets the needs of the individual is provided. This may include aspects such as the language used, the size of the font, the degree of specialized knowledge, and being for children, etc.

2.2 Beacons Structure and Other Beacon Applications

Beacon is a small computer. Its 32-bit ARM® Cortex CPU is accompanied by an accelerometer, temperature sensor, and most importantly 2.4 GHz radio using Bluetooth 4.0 Smart, which is also known as BLE or Bluetooth Low Energy. Beacon other applications are retail, stadium and air-port navigation systems. But those applications are still in trail condition.

3 CONCEPTUAL DESIGN

Museum Navigation System is an android application which illustrates navigation and information on the smart device by using beacons. Received Signal Strength Indicator (RSSI) power, Universally Unique Identifier (UUID), major and minor of beacon frame are used to describe the power of a beacon's signal.

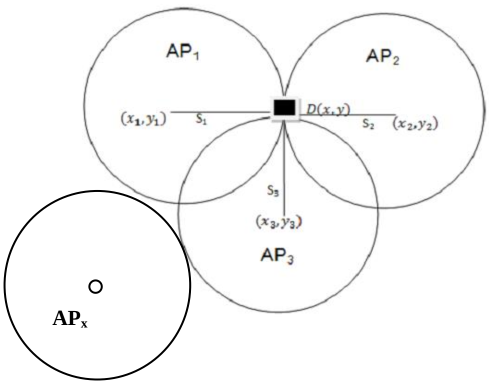

Figure 1: Cluster plan

Figure 1 shows the cluster plan with beacons and they behave as access points (APs). Here three beacon clusters are used to find the position. First beacon signals are scanned and then RSSI power values are saved in an array. After that, it selects three beacons with highest value of RSSI power. RSSI-based triangulation method is used to find the position in a cluster and when the user moves to the next cluster region it identified by scanning the route. Then it uses the identified new beacon and previous beacon to find the new position in the new region. Scan runs within constant time and updates the beacons initial position with user position on the map.

3.1 Bluetooth RSSI vs. Distance

Anti et al. presented the design and implementation of a Bluetooth Local Positioning Application (BLPA) in which the Bluetooth received signal power level is converted to distance estimate according to a simple propagation model as follows and the RSSI in dB is given by

$$RSSI = P_{TX} + G_{TX} + G_{RX} + 20\, log\,(4\pi f c) - 10n\, log\,(d) \tag{1}$$

$$= P_{TX} + G - 40.2 - 10n \log(d) \qquad (2)$$

Where P_{TX} is the transmit power; G_{TX} and G_{RX} are the antenna gains and G is the total antenna gain: $G = G_{TX} + G_{RX}$, c is the speed of light ($3.0 \times 10^8 m/s$), f is the central frequency ($2.44\ GHz$), n is the attenuation factor (2 in free space), and d is the distance between transmitter and receiver (in m). d is therefore:

$$d = 10^{[(P_{TX} - 40.2 - RSSI + G)/10n]} \qquad (3)$$

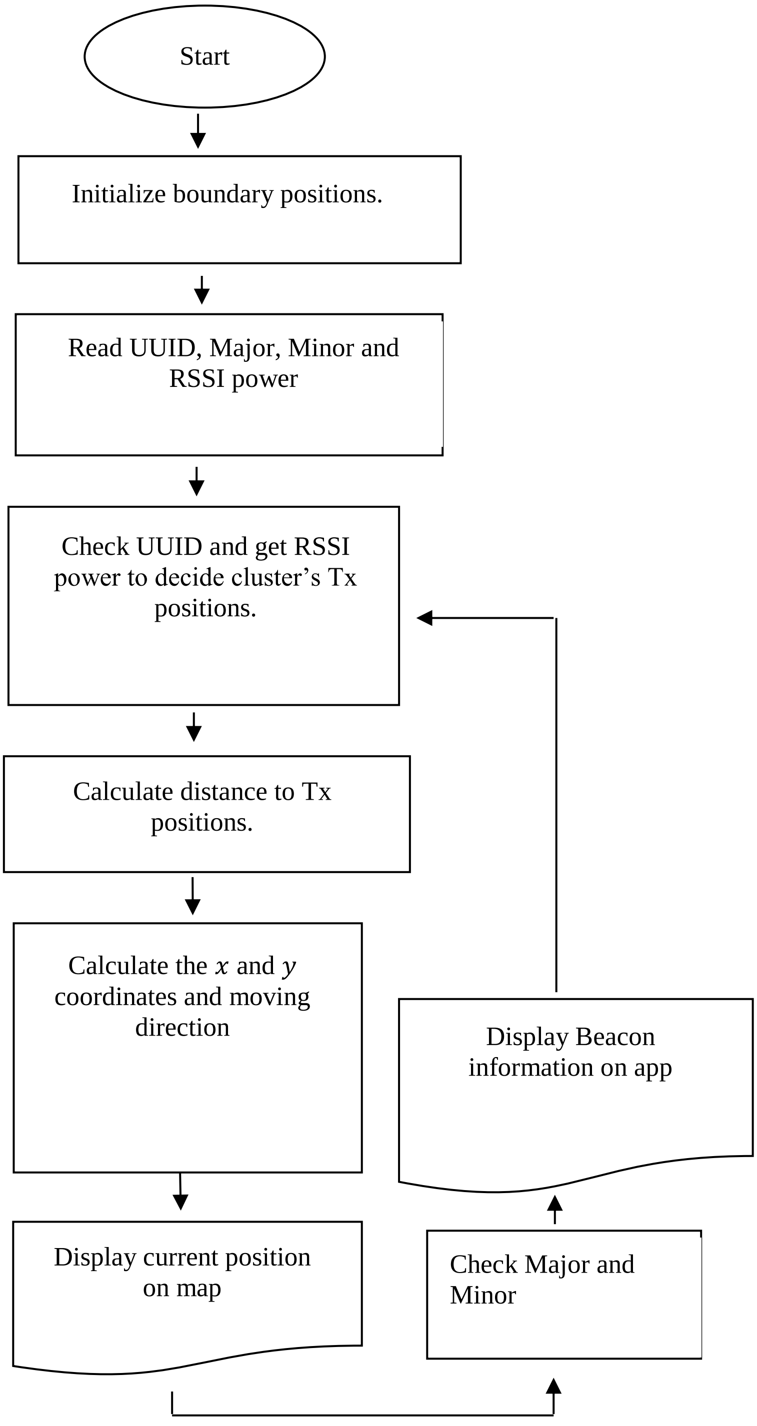

Figure 2: Flow Chart

However, such a model can only be utilized as a theoretical reference. Due to reflection, obstacles, noise and antenna orientation, the relationship between RSSI and distance becomes more complicated. Further it influences on Bluetooth RSSI values. Therefore, several experiments were carried out to understand how the Bluetooth indicators fade with distance under these environmental influences.

Let $A = P_{TX} + G - 40.2$ (4)

Therefore,

$$RSSI = -10n\, log\,(d) + A \quad (5)$$

where A is the received $RSSI$ power at $1m$

3.2 Beacon Navigation Algorithms

The algorithm is based on three beacons which can communicate with a smart device and those Beacons measures the signal coming from smart device.

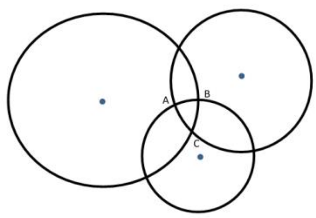

Figure 3: Measuring the signal

Let beacons coordinates be $A \equiv (x_1,\ y_1)$, $B \equiv (x_2,\ y_2)$ and $C \equiv (x_3,\ y_3)$

Then,

$$x^2 + y^2 - 2x_i x - 2y_i y + y_i^2 + x_i^2 = r_i^2 \quad (6)$$

Where r_i is represented as: $r_i = 10^{[A_i - RSSI_i]\,/\,10n}$;$i \in \{1,2,3\}$

Solving (1) – (2) and (2) – (3), the above equations reduced to two equations as:

$$2(x_2 - x_1)x + 2(y_2 - y_1)y = r_1^2 - r_2^2 - x_1^2 + x_2^2 - y_1^2 + y_2^2 \quad (7)$$

$$2(x_3 - x_2)x + 2(y_3 - y_2)y = r_2^2 - r_3^2 - x_2^2 + x_3^2 - y_2^2 + y_3^2 \quad (8)$$

Let us define: $a = 2(x_2 - x_1), b = 2(y_2 - y_1), c = 2(x_3 - x_2), d = 2(y_3 - y_2),$

$e = r_1^2 - r_2^2 - x_1^2 + x_2^2 - y_1^2 + y_2^2$ and $f = r_2^2 - r_3^2 - x_2^2 + x_3^2 - y_2^2 + y_3^2$

Then,

$$ax + by = e \tag{9}$$

$$cx + dy = f \tag{10}$$

Finally, the coordinate of the device being tracked is:

$$x = \frac{de-bf}{ad-bc} , \qquad y = \frac{ce-af}{bc-ad} \tag{11}$$

Here $ad = bc$ case appears when $(x_2 - x_1)(y_3 - y_2) = (x_3 - x_2)(y_2 - y_1)$ and it occurs when the beacons are only overlapped. But practically no two beacons are overlapped. The actual motion is the most important things to improve model's accuracy. In this case higher order equations are used to determine the distance that user moves in time period (here able to use scanned time duration).

$$S_x = U_x t + \frac{A_x}{2} t^2 + \frac{B_x}{6} t^3 + \frac{C_x}{24} t^4 + \ldots \tag{12}$$

$$S_y = U_y t + \frac{A_y}{2} t^2 + \frac{B_y}{6} t^3 + \frac{C_y}{24} t^4 + \ldots \tag{13}$$

For the velocity

$$U_x = \frac{(x - x')}{t} , \qquad U_y = \frac{(y - y')}{t} \tag{14}$$

For the acceleration

$$A_x = \frac{(U_x - U_x')}{t} , \qquad A_y = \frac{(U_y - U_y')}{t} \tag{15}$$

For the rate of change of acceleration or jerk

$$B_x = \frac{(A_x - A_x')}{t} , \qquad B_y = \frac{(A_y - A_y')}{t} \tag{16}$$

Assume all the beacons transmit same signal power and average of velocity, acceleration etc. can be obtained. Therefore, by substituting equation 9 and 10 to 11 and 12 then A_i, B_i related to x_i and y_i are calculated. Then the values of S_i which are related to x_i and y_i are finally calculated and the position of x and y. Every dash (') values are previous values and t is scan time.

Error of the motion and distance ~ $Ct^4/24$

$$X_{current} = X_{previous} + S_x \tag{17}$$

$$Y_{current} = Y_{previous} + S_y \tag{18}$$

Then here used pointer rotation to indicate user moving direction by using current and previous coordinates.

$$\theta = \tan^{-1}\left(\frac{y_{current} - y_{previous}}{x_{current} - x_{previous}}\right) \tag{19}$$

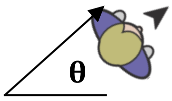

Figure 4: Direction of pointer

3.3 Error Calculation

Root mean square error is used to find the error between actual point and calculated point. It is a frequently used as the measure of the differences between values predicted by a model or an estimator and the values observed. It represents the sample standard deviation of the differences between predicted values and observed values.

$$\text{Root Mean Square Error} = \frac{1}{N}\sum_{i=1}^{N}\sqrt{(x_{true} - x_{final,i})^2 + (y_{true} - y_{final,i})^2}$$

4 PROPOSED METHODOLOGY

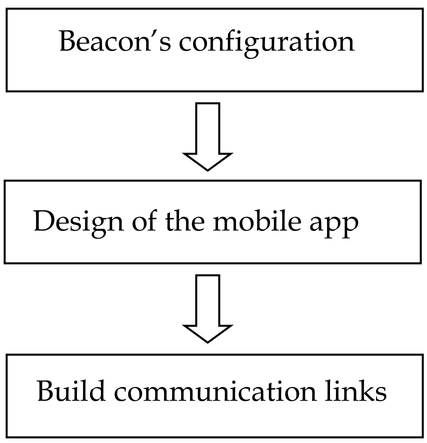

Figure 5: Project steps

4.1 Beacon's Configuration

Beacons broadcast in regular intervals (e.g. something between 100ms and 1 second) and can paired with neighbouring Bluetooth devices by sending out their ID. The ID consists of three parts, they are UUID (organization or company), Major (arbitrarily, e.g. specific museum) and Minor (e.g. location in museum). For example, UUID will be the same for the whole museum, while the major number can identify a large group (King's jewellery), and the minor number can identify a specific beacon for a specific object (crown).

4.2 Communication Links

Beacon frames are transmitted by the Access Point (AP) in an Infrastructure Basic Service Set (IBSS). The android platform includes support for the Bluetooth network stack, which allows a device to wirelessly exchange data with other Bluetooth devices. The application framework provides access to the Bluetooth functionality through the Android Bluetooth APIs. These APIs let applications wirelessly connect to other Bluetooth devices, enabling point-to-point and multipoint wireless communication. Using the Bluetooth APIs, an Android application can establish radio frequency channels, connect to other devices through service discovery, transfer data to and from other devices and manage multiple connections.

4.3 BLE interference with Wi-Fi

The BLE physical layer divides the 2.4GHz ISM band into 40 channels. Three of them are dedicated for advertising (finding and connecting other devices). These channels are located between the commonly-used Wi-Fi channels 1, 6, and 11, with the idea that these frequencies will be free of interference. (Wi-Fi bandwidth is 20MHz, but the channel spacing 5MHz, making 1, 6, and 11 the only set of three channels with no overlap.) The remaining 37 channels are for data. The frequency hopping algorithm simply increments the channel number by a hop value every transmission. Since the number of data channels is a primer, all channels get an equal chance.

4.4 Interference with Mobile

When the received data packet contains UUID, Major, Minor and Tx Power, it is detected as a beacon by the Android application and otherwise omit the data.

Preamble (1 byte)	Access Address (4bytes)	PDU (2-39 bytes)	CRC (3 bytes)

PDU

Header (2 bytes)	MAC Address (6 bytes)	Data (Up to 31 bytes)

Data

Prefix (9 bytes)	UUID (16 bytes)	Major (2 bytes)	Minor (2 bytes)	TX Power (2 bytes)

Figure 6: BLE packet structure and beacon data structure

5 IMPLEMENTATION

At this point, all necessary concepts related to indoor navigation have been explained. Information about the technologies used in this project as well to use them in positioning algorithms has been also covered. In this section all this information is put together and implemented into a navigation system consisting a group of beacons and an Android application. The system works as follows: first, few beacons are positioned around an area. Then the application scans for them and gathers their RSSI readings. These readings are, in turn, used to calculate the distance between the user and each beacon. Since no information being broadcasted by the beacons indicates their position relative to the receiver, the application makes use of calculated x and y coordinates to indicate direction of the user is moving. Both the beacons' and the user's position, as well as the distance between them, are shown in a map.

5.1 Testing Environment

The system was tested inside a 30 m^2 apartment where three beacons, separated by approximately 5 m, were placed. The map of the apartment as well as the placement of the beacons is shown in figure. The reason for setting this kind of testing environment is to test the accuracy of the system based on its capability to calculate the distance from beacons that are positioned close to each other. This situation will give an idea of how beacons should be configured regarding their output power, which will affect the range they can achieve and the RSSI readings collected by the application. For example, if the area is no more than 100 m^2 there is no point using several beacons operating with an output power of 0 dBm (around 50 m range). This will only cause the beacons to consume unnecessary power and affect the accuracy of the distance calculations as RSSI values will barely change.

5.2 The Application

At the start, a dialog is displayed on the screen asking permission from the user to turn on the Bluetooth adapter. Once this dialog is cleared, the application immediately starts scanning for beacons.

5.3 Scanning

The BLE adapter scans for nearby BLE devices and the results of the highest three RSSI power in every scan are passed through an algorithm of positioning. Then from that previous and current values direction of moving is calculated and displayed on the map. During that time, context based data captured by using major and minor values are also indicated on the display.

5.4 User's Movement

Note that the application knows how far the user is from each of the beacons, it can also estimate its position and display it in the map. This is done by displaying a black arrow with man, referred to as "pointer", representing the user and moving it through the screen as the user walks around the navigation area. In order to calculate the user's initial location, distance calculations to the closest beacons are selected and used to position the pointer as accurately as possible within the map. However, the pointer is located relatively to the configured beacons as shown in Figure 6. It is also important to have in mind that the pointer is only used to roughly show the user's position and might not be always 100% precise. Considering the accuracy of the distance calculations, the pointer may not behave as expected and might appear closer or further from the actual position of the beacon. This inaccuracy may be tolerated as long as the position shown is not too far from reality and the user can have an idea of where he/she is.

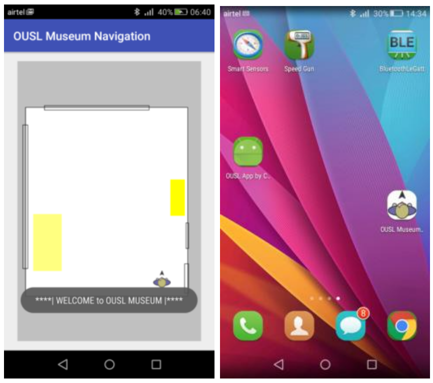

Figure 7: Screen prints of navigation app

6 SIMULATION RESULTS

A test Android application is used to measure RSSI power at given distances. Figure 8 shows the RSSI power values by changing the beacons and observing for 20 samples.

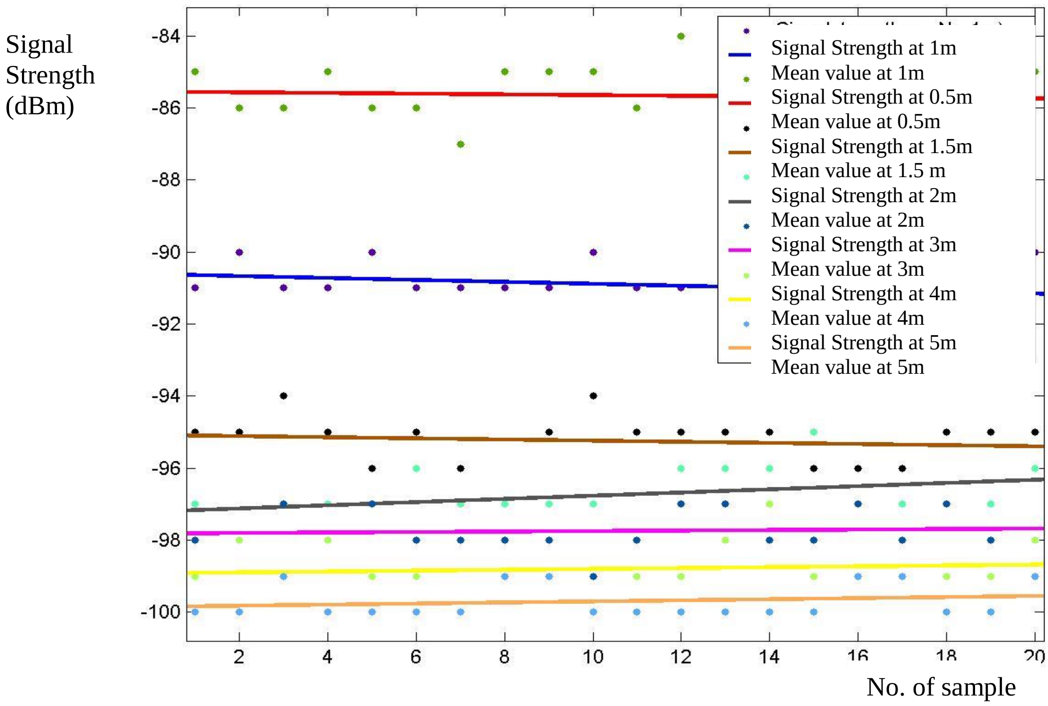

Figure 8: RSSI Power Vs Distance

Linear model Poly1: $F(x) = p_1 x + p_2$

Table 1: Static result for data

Distance	Coefficients (with 95% confidence bounds):		Goodness of fit:			
(m)	P1	P2	SSE:	R-square	Adjusted R-square:	RMSE
0.5	-0.0097(-0.072, 0.0524)	-85.55(-86.3, -84.8)	10.49	0.006022	-0.0492	0.7633
1	-0.027 (-0.092, 0.037)	-90.62(-91.4, -89.84)	11.31	0.04129	-0.01197	0.7928
1.5	-0.015 (-0.075, 0.0436)	-95.08(-95.1, -94.37)	9.584	0.017	-0.03761	0.7297
2	0.044 (-0.0114, 0.1002)	-97.22(-97.8, -96.55)	8.441	0.1342	0.08612	0.6848
3	0.0067 (-0.039, 0.0527)	-97.82(-98.3, -97.27)	5.72	0.005296	-0.04997	0.5637
4	0.012 (-0.045, 0.069)	-98.93(-99.6, -98.23)	9.104	0.01046	-0.04451	0.7112
5	0.01504(-0.024, 0.054)	-99.86(-100, -99.39)	4.05	0.0358	-0.01776	0.4743

The above table shows the coefficients p_1 and p_2 of linear the linear models with considering 95% confidence bound.

6.1 Decision for Obtaining Value of RSSI Power at 1m

Here, it is very important to get “A” value for logarithm function.

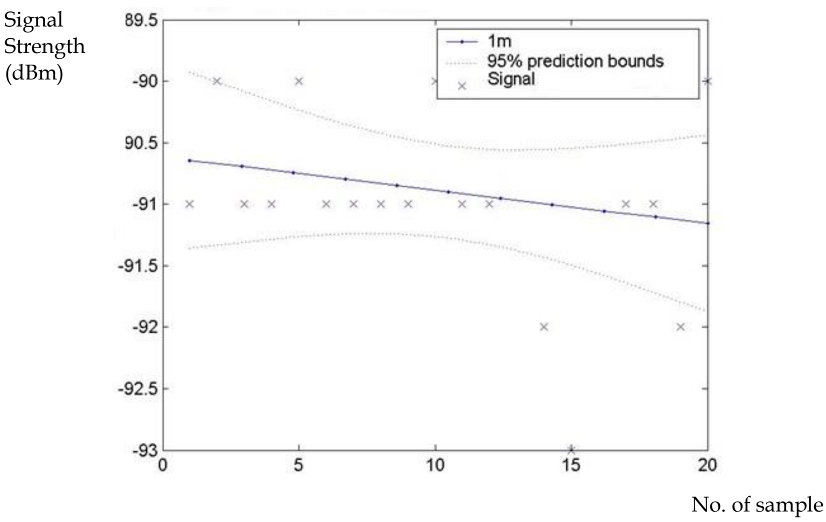

Figure 9: Analysis of fit 1m for data set

Therefore,

$$RSSI = -10n \log(d) + A$$

$$= -10n \log(d) - 91$$

From the above data, n = 1.5; which is the attenuation constant and it is depend on the environment.

6.2 Simulation Results

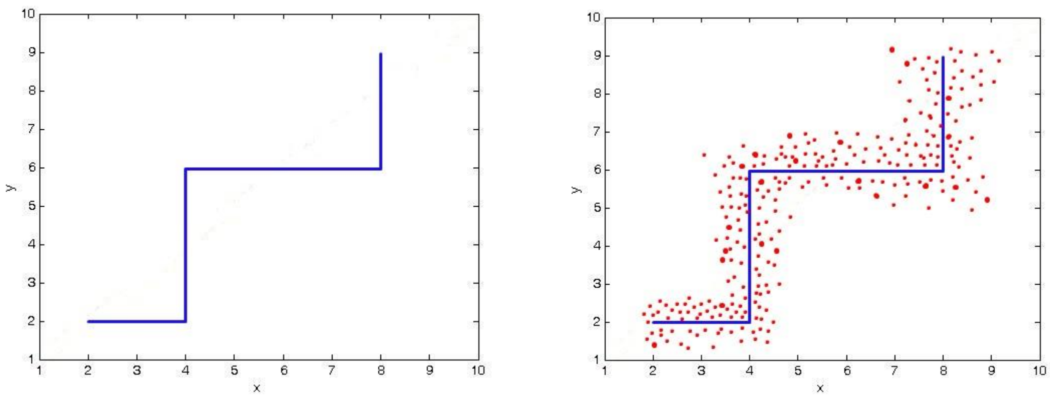

Figure 10: Actual path of smart device and points measured by smart device

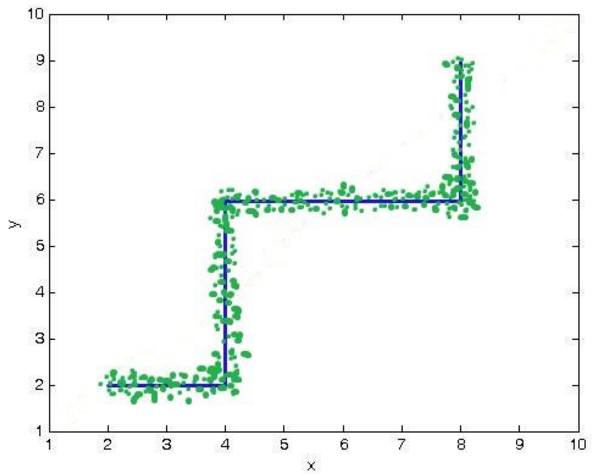

Figure 11: Final points

6.3 Product Test Results

Product was tested at research laboratory in the department of Electrical and Computer Engineering of the Open University of Sri Lanka.

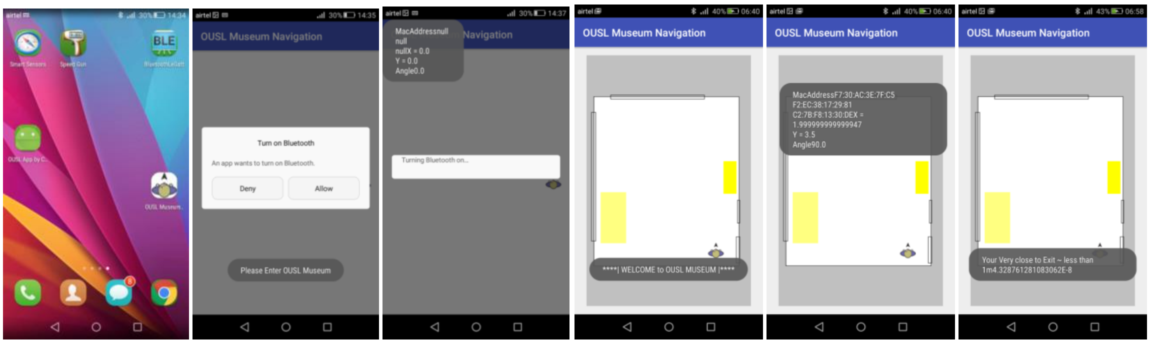

Figure 12: Screen prints of product test

7 CONCLUSION

As opposed to the well-established concept of outdoor navigation, indoor navigation must still overcome many challenges before becoming an everyday use commodity. One example is the limited amount of technologies that can be used for this purpose, as well as the accuracy offered by these. Furthermore, how to make indoor navigation systems available to the public is still a great challenge. This work represents only a small part of what indoor navigation really is. As technology advances, more sophisticated and interesting solutions related to this topic will continue emerging. At the same time, more people will have access to these and they will, eventually, become part of the everyday life.

The developed application will continue to be improved and will eventually be published in the Android marketplace. Future work will focus on finding new ways to improve the application functionality regarding both the positioning algorithm and the hardware configuration. Making the system adaptable to different environments will be a top priority since the results of the distance calculations previously shown can only relate to a very specific environment.

8 ACKNOWLEDGEMENT

The authors wish to express their sincere gratitude to the Department of Electrical and Computer Engineering, Faculty of Engineering, The Open University of Sri Lanka for the support given in various phases of this project design and implementation.

REFERENCES

1 Heydon, R. (2013). Bluetooth Low Energy: The Developer's Handbook, New Jersey: Pearson.

2 Gupta, N. (2013). Inside Bluetooth Low Energy, U.S.A: Artech House.

3 Townsend, K., Cufi, C., Akiba and Davidson, R., (2014). Getting Started with Bluetooth Low Energy, Califonia: O'Reilly Media.

4 www.bluetooth.org, Bluetooth (2016). Core specification v 4.1. [online] Available at: < https://www.bluetooth.org/en- us/specification/adopted - specifications> [Accessed 3/12/2013].

5 www.bluetooth.org, Bluetooth (2016). Supplements to the Core Specification (CSS) v6. [online] Available at: < https://www.bluetooth.org/en- us/specification/ adopted - specifications> [Accessed 14/07/2015].

6 www.infoworld.com (2014). What you need to know about using Bluetooth beacons. [online] Available at:<http://www.infoworld.com/article/2608498/mobile-apps/what-you-need-to-know-about-using-bluetooth-beacons.html>[Accessed 22/07/2014].

7 www.umbel.com (2016). 15 Companies from Airports to Retail Already Using Beacon Technology. [online] Available at: < https://www.umbel.com/blog /mobile/15-companies-using-beacon-technology>. [Accessed 2016].

8 www.bluetooth.org, Bluetooth (2016). *Core System Architecture*. [online] Available at: < https://developer.bluetooth.org/TechnologyOverview/Pages /Core.aspx> [Accessed 2016].