Indoor Localization for Bluetooth Low Energy Devices Using Weighted Off-set Triangulation Algorithm

Xiaoyue Hou, Tughrul Arslan, Arief Juri, Fengzhou Wang, *University of Edinburgh in Edinburgh*

BIOGRAPHY

Xiaoyue Hou is a Ph.D. candidate in the Department of the Integrated Micro and Nano Systems (IMNS) Institute in the school of Engineering, University of Edinburgh, Edinburgh, UK. He is a member of embedded and wireless sensor systems group in the University. His research interests are indoor positioning algorithms under Non-line-of-sight environments with a focus on hybrid indoor localization network design.

Professor Tughrul Arslan holds the Chair of Integrated Electronic Systems in the School of Engineering, University of Edinburgh, Edinburgh, U.K. He is a member of the Integrated Micro and Nano Systems (IMNS) Institute and leads the embedded and wireless sensor systems group in the University. His current research focuses on enhancing personal mobility and the design of high performance embedded wireless systems. Professor Arslan was an Associate Editor for the IEEE Transactions on Circuits and systems I and IEEE Transactions on Circuits and Systems II. He is a member of the IEEE CAS Committee on VLSI Systems and Applications and is involved in the organization of numerous conferences.

Arief Juri is a Ph.D. candidate at the University of Edinburgh. He is currently carrying out research in the area of indoor positioning systems, specifically using Bluetooth Low Energy. He received his MSc from University Malaysia Perlis with a dissertation on Low Power H.264 Video Compression. His prior education is Microelectronic bachelor degree, also from University Malaysia Perlis.

Fengzhou Wang received the B.S. (Hons) degree in Electrical Engineering from Birmingham City University and M.S. from the University of Southampton. He is currently working towards a Ph.D. degree in the School of Engineering, University of Edinburgh. His research addresses the area of RF sensor systems design and integration.

ABSTRACT

This paper proposes a new indoor positioning algorithm for Bluetooth Low Energy (BLE) devices, such as mobile phones and tablets. The algorithm integrates an Off-set triangulation algorithm and a multi-stage weighted framework. An off-set triangulation algorithm was used to provide a general method to locate the user's position. Results are integrated into a weighted framework in order to increase the adaptability of the proposed localization algorithm to different complex environments and increase the accuracy of the localization. Three experiments in different environments have been examined in order to test the performance and the limitations of this algorithm. Results show that the proposed algorithm demonstrated strong adaptability to complex non-Line-of-Sight (LOS) environments.

INTRODUCTION

In recent years, GPS and cellular signal-based outdoor positioning systems have attracted the attention of researchers in areas such as car navigation systems and digital maps [1][2]. Meanwhile, with the development of positioning technologies, operators and manufacturers have begun to pay attention to the design of indoor positioning systems. Since then, Indoor Location Based Services (ILBS) have begun to play an increasingly important role in driving future applications, especially for mega-structure buildings in areas such as 'healthcare' and 'smart living'. Providing accurate indoor positioning systems is of significant practical importance, as people spend a large amount of time in both private and public indoor areas. An indoor positioning and navigation system could, for example, help visitors to locate their destination within an unfamiliar complex.

Since the invention of the BLE and smart mobile devices with Bluetooth 4 (Smart Bluetooth) access functions have grown in popularity, the latest Bluetooth based indoor positioning technologies are attracting increasing attention. Instead of using a Wi-Fi router [4], Bluetooth 4 based localization systems locate the position of a mobile device with reference to low-energy Bluetooth beacon routers in an indoor area.

Compared with Wi-Fi, BLE devices have advantages of lower power consumption, lower costs and a smaller size [5]. Newer Bluetooth 4 beacons do not require an AC power supply, and can last half a year on only a 3V button battery. A lower cost and smaller beacon without an AC power supply could reduce the Bluetooth 4 signal transmitter's deployment limitations, and signal cover density can also be increased dramatically by deploying more beacons than Wi-Fi routers in indoor areas. As a result, the latest Bluetooth based localization techniques could provide a higher level of accuracy than Wi-Fi based techniques because of the deployment cover density, and they do not require significant additional expenditure.

RSSI based indoor localization techniques still have certain limitations. Channel propagation parameters between signal transmitters and receivers fluctuate dynamically [6]. A complex indoor environment with multiple obstacles could increase the uncertainty of variation in the transmit parameters, and this variation is unpredictable. It is therefore not easy to estimate the distance accurately from just the RSSI value. Most of the current research on RSSI-based indoor positioning algorithms could work only in a LOS environment, but ideal LOS is practically non-existent in a real environment.

The motion of this paper is to present a solution for the problem discussed above. This paper will propose the use of two novel algorithms: an off-set triangulation algorithm and a weighted framework. In the first section, the principle of off-set triangulation will be described and the theory of the weighted framework will be explained. The result of experiments will be analysed in section three, which will be followed with a conclusion in the last section.

I. OFF-SET TRIANGULATION AND WEIGHTED FRAMEWORK

A. Path loss Module

RSSI is a power value measured by the unit of mW which can be used to direct the electromagnetic energy of the transmission medium. According to the Pass Loss Model, a known distance of r_0 and the received power at this distance $P(r_0)$ have the following relationship [6]:

$$P\,(r_0)/\,P(r) = (r/\,r_0)^n \qquad (1)$$

Where:

r_0 is the known reference distance. $Pl\ (r_0)$ is the received power at this distance $r0$.

n is the path loss coefficient with a range between 2 and 6.

For the receiving end, the formula for the received signal strength is shown below:

$$\triangle P\,(r_0) = Pt - \triangle Pl\,(r) \qquad (2)$$

Where,

Pt is the signal transmit power. $Pl\,(r)$ is the received signal strength RSSI. $\triangle P\,(r_0)$ is the path loss when the distance is r_0.

This equation can be extended to Gaussian distribution with the unit dBm. The equation (3) is shown below [7]:

$$Pl\,(r) = Pl\,(r_0) - 10n \times lg\,(r/\,r_0) + X\sigma \qquad (3)$$

Where,

$Pl\,(r)$ is the received signal power of the unknown node at the distance r.

$Pl\,(r_0)$ is the received signal power of the unknown node at the distance r_0.

$X\sigma$ is a zero mean Gaussian random variable.

According to the equation (2) and (3), the RSSI equation is described as follows:

$$\text{RSSI} = Pt - \Delta P\,(r_0) - 10n^*(r/\,r_0) + X\sigma \qquad (4)$$

Equation 4 shows the relationship between distance and signal power level.

The majority of recent Path Loss Model-based RSSI algorithms have certain limitations. The received signal strength is not always accurate under real conditions, due to the effects of the $X\sigma$. This will decrease localisation errors, especially when the distance between the user and the AP is greater than five metres; signal strength is also decreased or increased by signal reflection and the obstacles in the transmission path. In this case, RSSI values cannot provide an accurate distance result under real conditions. However, the path loss model could be applied in a different way. Signal strength is usually higher when users stand closer to the AP. As a result, RSSI value and a path loss model can be used to calculate the relative position under an estimated area organised by selected APs, rather than directly calculating the distance between users and APs.

B. Off-set triangulation algorithm

Triangulation is a common technique used for RSSI-based indoor positioning on account of its low level of computation [7]. The traditional triangulation algorithm is shown below in Figure 1.

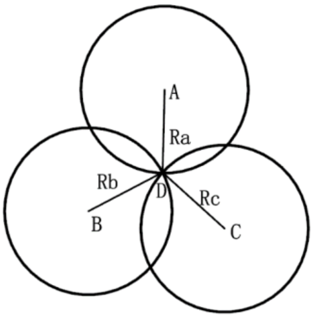


Figure. 1. Triangulation algorithm under ideal LOS environment

A, B and C are the access points with locations $A(x_1, y_1)$, B (x_2, y_2) and $C(x_3, y_3)$. If the unknown coordinate D is D(x, y), the position of node D can be calculated using the position of nodes A, B and C and the calculated distance Ra, Rb and Rc. The distance between the unknown anchor node D and the known anchor nodes Ra, Rb and Rc can be calculated using the path-loss module RSSI algorithm.

In a real environment, the distance calculated by the RSSI algorithm would not be accurate because of issues such as reflection and other effects. Most of the results calculated by the path-loss module RSSI algorithm will be larger than the actual distance [8]. As a result, the three circles A, B and C will not cross at one point. The three common points E, F and G between the circles will be selected instead of the unknown anchor node D, as shown in Figure 2.

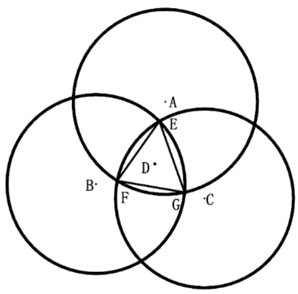


Figure. 2. Centroid core based triangulation algorithm under real environment

To solve this problem, the centroid core of the triangle created by the three common points E, F and G is calculated as the position of the unknown anchor node D. Assuming that the locations of the common points are $E(x_4,y_4)$, $F(x_5,y_5)$ and $G(x_6,y_6)$, the position of D(x,y) is shown as follows:

$$\begin{cases} x = \frac{x_4 + x_5 + x_6}{3} \\ y = \frac{y_4 + y_5 + y_6}{3} \end{cases} \tag{1}$$

This algorithm has certain limitations. The user's position will only be calculated when the three circle have cross points between each other. Two examples of an unexpected situation are shown in Figures 3.

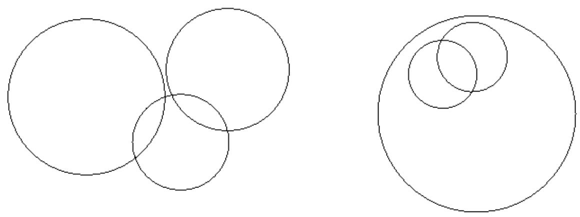
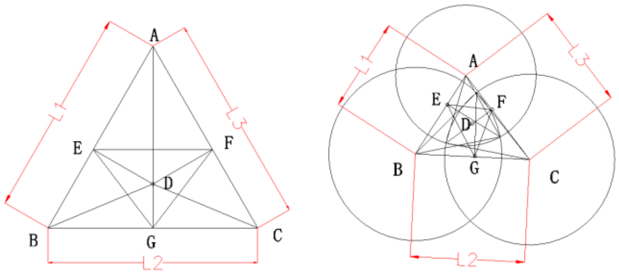


Figure. 3. Three circles do not have cross points between each other

In Figures 3, one or two circles do not have cross points between each other. In this case, at least one root of the equation is an imaginary number which will stop the calculation process. In order to solve this problem, the use of algorithms such as least-square algorithm [9] has been proposed. However, many additional cases which are not limited in Figures 3 must be considered, and creating corresponding sub-algorithms for each unexpected case is difficult. An excessive number of sub-algorithms could not only decrease the compatibility of the algorithms, but may also increase the computation and hardware workload dramatically.

This paper proposes the use of off-set triangulation in order to provide a solution to the problem mentioned above. This algorithm is different from the traditional triangulation algorithm, and the cross point based triangulation principle has been abandoned. Instead of calculating the centroid core coordinate of the triangle generated by the three cross points, the centroid core of the triangle generated by the three APs which the user position belongs to is used as a datum point. The user's specific position is calculated by achieving the offset to the datum point and the offset margin according to the distance ratio between the user's position and each AP. As long as three Bluetooth signals have been received by the mobile device and the three APs were not deployed in one line, this algorithm can be employed no matter whether the result is accurate or not. In this case, if the triangle consisting of APs where the user position belongs to can be determined accurately, the localization error will normally no larger than half of the distance between two beacons.



a b

Figure. 4. (a) Off-set triangulation algorithm under idea environment (b) Off-set triangulation algorithm under real environment

According to Figure 4a, three APs named A, B and C were deployed on the map in a triangular formation with measured coordinates. The user's mobile device was located within the triangle. The reference distance between the mobile device and each AP (L1, L2 and L3) were calculated according to equation 4. Next, three reference points – E, F and G - were calculated by applying the distance ratios L1/L2, L2/L3 and L3/L1. The centroid core of the triangle EFG will then become the coordinates of the mobile device.

C. *Weighted framework*

The user's position can be determined by employing the off-set triangulation algorithm. The results will be accurate if the received signals are provided by the correct APs. The function of the weighted framework is to produce a verification system to increase the accuracy of the localization. Three key parameters are employed in this weighted framework: absolute signal strength W_A, relative signal strength W_R, and quality of triangle W_Q.

1) *Absolute Signal Strength*

The value of RSSI presents the accuracy of the received signal intuitionally. As mentioned above, the channel propagation parameters between the signal transmitters and receivers fluctuate dynamically. In this case, the RSSI value fluctuates even if the user's position does not change. However, it cannot be denied that the trend of the signal strength complies with the following rule: when the mobile device is close to the AP, the signal strength is stronger. Meanwhile, a strong signal strength also means that the effectiveness of the interference and noise from the environment is weaker than the signal power. In this case, those APs with higher signal strengths are usually more likely to produce accurate results than the APs which have weaker signal strengths. According to this theory, weight parameter W_A is employed to increase the performance of the off-set triangulation algorithm.

Another condition is also believed to adjust the value of the W_A. Assume that more than three AP signals with similar signal strengths have been received by the mobile device, and that some of these APs are deployed in other rooms. According to the path-loss module, the propagation channels of the APs in the other rooms are more complicated than the APs with LOS propagation channels located in the room with the mobile device. The accuracy of the signal from those APs deployed in different rooms are also inaccurate. The APs with LOS propagation channels should therefore have higher priority, which means a higher W_A will be given to those APs. These circumstances usually occur in simple environments with multiple rooms, such as office areas.

2) *Relative signal strength*

When three APs are selected, a triangle will be produced by the selected APs if these are not deployed in one line. Next, the centroid of this triangle will be calculated as a reference point. The distance between the mobile and each AP is calculated in the meantime. The distance is applied to offset the reference point according to the distance ratio. The weight of relative signal strength W_R is implemented in this stage to restrict the relationship between the offset margin and the distance ratio.

W_R is controlled by the following conditions: the shape of the triangle and the value of the distance ratio. For example, when the shape of the triangle produced by the APs is close to an equilateral triangle, each AP will be given a similar initial W_R value as the coverage density generated by the three APs are balanced. In the meantime, if the user's position is located very close to one of the APs then the W_R of this AP will be increased to compensate for the offset margin.

3) *Quality of triangle*

When many signals (more than three) are received from different APs, multiple triangles will be produced. Applying good-quality triangles as optimal solutions will increase the localization accuracy dramatically. W_Q in this weighted framework is used in these circumstances to integrate these signal providers together and increase the influence of APs with high-quality signals. The value of W_A and W_R will be major factors to determine the W_Q. A comprehensive evaluation of each triangle will be generated according to the W_A and W_R. Higher priority will be given to the triangle consisting of APs with high W_A and to triangles with similar side lengths. Meanwhile, obtuse triangles will not be considered to take part in the calculation most of the time, as their centroid cores are located outside of the triangle. Each triangle will be employed to calculate the specific user position: high W_Q triangles will play a major role in locating the user's position, and low W_Q triangles will be used as a reference result and to revise the calculated result slightly.

II. EXPERIMENT RESULT

The performance of this proposed algorithm combined with the weighted framework has been examined in three different environments: Figure 5 shows the third floor of the Noreen and Kenneth Murray library [10] in Kings Building located in Edinburgh (King's Buildings, Thomas Bayes Road, Edinburgh EH9 3FG); Figure 6 shows a small cabin being part of the Scottish Microelectronics Centre (SMC) building [11] (Scottish Microelectronics Centre, Kings Buildings, Edinburgh, EH9 3JF) and Figure 7 shows a Sainsbury's supermarket located in the Cameron Toll [12] shopping mall (Cameron Toll Shopping Centre, 6 Lady Road, Edinburgh, EH16 5PB). The features of the three environments are all different. The library had multiple small rooms and separated by walls made of reinforced concrete, the small cabin was made of plywood and can be delimited as a LOS environment, and the supermarket is an open Non-LOS environment with many shoppers.

In the library in Figure 5, one or two Bluetooth beacons were deployed in each room. The average distance between each beacon was around 4 meter to 6 meter. Three different types of Bluetooth 4 beacons and two different mobile device were used during the test. Two different reading periods (30 readings in 3 seconds and 10 readings in 1 second) in each position were examined separately. The results show that in most cases the average localization error is less than 1.6 meters under the deployed area when the reading period is 1 second. For the 3 second readings, the error fell to 1.4 meter. The error will be slightly larger when mobile devices was located in the bottom of the valid area as the distance between two beacons was around 6 meter.

Figure.5.Beacons and experiment layout in Library

In Figure 6, 7 beacons were deployed with a cellular layout. The distance between each beacon was 2.75 meter. The environment in the small cabin approximated a LOS environment. The aim of this experiment was to determine the minimum average error for this proposed algorithm. The reading period in each position is 3 seconds (30 readings). Due to the effect of the unstable transmission channel, a ±5dBm error is exist during the experiment. This error causes a minimum one meter error when the distance between mobile device and Bluetooth 4 beacon is less than two meter. As a result, the experiment outcome of the localization error was 1.2 meter on average even the cases when mobile devices are located very close to one of the beacons (less than 0.5 meters) have been ignored as the user's position will be forcibly set to the coordinate of the nearest beacon because of the effect of WR. Result shows that it is difficult to decrease the localization error to less than 1 meter at this stage by applying the proposed algorithm, which consistently matches the predicted result. Localization errors will not decrease dramatically under the LOS environment with a very high signal cover density.

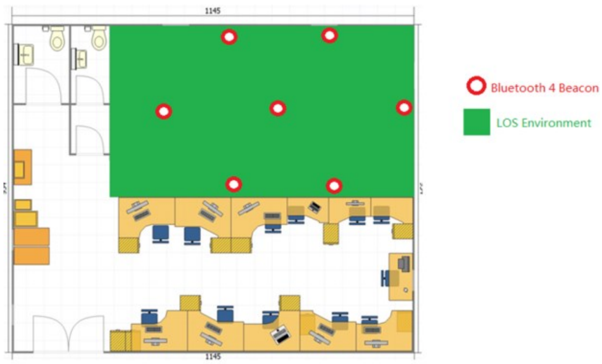


Figure.6.Beacons and experiment layout in Cabin

The shopping mall in Figure 7 was an open area which integrated dynamic non-LOS propagation channels. The aim of this experiment was to test the performance of the proposed algorithm in an extremely complex environment. 6 beacons were deployed symmetrically in two shelves, and the maximum distance between each beacons was 7 meter. The propagation channels between each two beacons were non-LOS. During the test many unexpected RSSI values were detected. For example, a 50-meter distance between user position and the Bluetooth 4 beacons was detected when the actual distance was 5 meter, which is extremely inaccurate. The complexity of the testing environment was strongly underestimated because of the negative effects produced by stacked goods. As mentioned above, the average error will no larger than 3.5 meter in general. However, the accuracy of the localization was higher than expected. The average error was less than two meters when mobile devices were deployed in the effective area (inside the triangle area generated by the Bluetooth 4 beacons). The results show that the proposed algorithm demonstrated its strong adaptability in a complex environment with a medium-level deployment density.

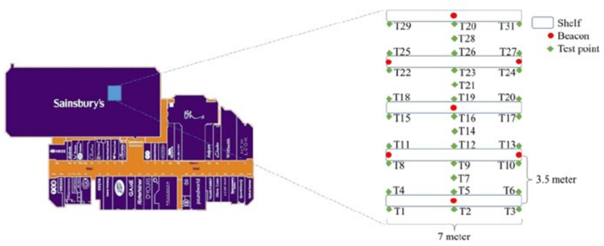


Figure.7. Beacon and experiment layout in Shopping mall

III. CONCLUSION

This paper proposed the use of an RSSI based off-set triangulation algorithm combined with a weighted framework targeting indoor positioning with the aim of employing localization in complex environments. An off-set triangulation algorithm was used to provide a general method to locate a user's position. Results are integrated into a weighted framework in order to increase the adaptability of the proposed localization algorithm to different complex environments and increase the accuracy of the localization. Three experiments in different environments have been examined in order to test the performance and the limitations of this algorithm. The proposed algorithm demonstrated strong adaptability to complex environments.

This proposed algorithm has certain limitation. The localization result is inaccurate when the mobile device is deployed outside of the effective area. Future work will be directed towards improving the accuracy by integrating more weight parameters into the weighted framework. A novel weight parameter is currently being designed to increase the localization accuracy when the mobile device is moving. A multiple point offset algorithm will be built to increase the stability further.

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