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Supporting Process of Independent Navigation Inside Buildings Based on Low-Energy Bluetooth Transmitters

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Abstract. Thanks to the use of satellite positioning systems (including GPS) the ability to determine a user's position in open spaces has become a necessary element of everyday life. Nowadays people cannot imagine moving in an "urban jungle" with paper maps without electronic support, but dozens of years ago those maps were more popular than satellite navigation. A similar revolution may also await navigations in closed spaces such as public or commercial buildings. Because as the urbanisation process, the surfaces of various buildings grow, which significantly impedes orientation in them, especially for the blind or visually impaired users. As satellite navigation systems are burdened with errors, which increase when trying to use them in confined spaces, it becomes necessary to use more accurate technology. As a step towards solving this problem, we propose a solution supporting the navigation of users, especially the visually impaired, inside buildings. Our approach is based on using low energy Bluetooth transmitters and a method of determining the user's position using the trilateration algorithm and the appropriate placement of transmitters in a space.

Keywords. Beacons, Indoor positioning, Bluetooth, Positioning of mobile devices

1. Introduction

Thanks to the use of satellite positioning systems (including GPS) the ability to determine a user's position in open spaces has become a necessary element of everyday life. Nowadays people cannot imagine moving in an "urban jungle" without the support of electronic software such as GPS or digital maps, only with the help of paper maps. A similar revolution may also await in the domain of navigations in closed rooms because as the urbanisation process, the surfaces of various buildings grow. It significantly impedes orientation in them, especially for blind or visually impaired people. As satellite navigation systems are burdened with errors, which increase when trying to use them in confined spaces, it becomes necessary to use more accurate technology. Facing such a task, we can choose between using RFID, IrDA or RSS based technologies with the use of Wi-Fi or Bluetooth Low Energy (BLE). They will all be discussed in the following sections of this paper. The analysis of existing solutions shows that one of the best solutions that could support navigation inside buildings is the use of beacons. Therefore, in line with this trend, we propose a beacon-based user positioning method that uses the true-range multilateration method. This approach has been implemented in Android application, a module of the future planned system called the NaviSecure, i.e. an indoor security and navigation system dedicated to blind, visually or hearing impaired users. The module receives data from transmitters, which it then sends to the server with additional information, thanks to which the coordinates of user's device (mobile phone) can be calculated. In the following sections, this beacon-based user positioning method will be presented and then its practical use in the application will be explained.

2. Comparison of Indoor Positioning Technologies

As we mentioned above, many technologies support user navigation in the space. Most of them are based on GPS, and today, they have had many commercial implementations. The situation is a bit worse when it comes to navigation inside buildings because they cannot use GPS to determine the user's position.

One of the leading technologies that aspired to solve this problem were RFID [4] tags. Although a single RFID transmitter is relatively cheap, due to its modest range of several meters, the system using this technology must be composed of many transmitters, resulting in high costs of its maintenance [7]. We will face the same problem when we try to use optical technologies based on infrared radiation e.g. IrDA. Moreover, the application of solutions mentioned above was hampered by the lack of generally accepted standards.

RSS based technologies seem to be a remedy for the above problems. The transmitters used in these solutions have a much greater transmission range, which unfortunately is often associated with lover accuracy of the obtained locations. Those technologies could be divided into two categories:

- Technologies based on fingerprints [3,8].
- Technologies based on log-distance path loss model [2].

Technologies that are based on fingerprints seem to be more accurate but they are more time-consuming in development, as they require two phase implementations: [6] which works as follows:

- **Offline training phase** - signal strengths obtained from many transmitters are added to the database.
- **Online operational phase** - the user sends the signal strengths from the transmitters to the system, which compares data with data acquired during the first phase. The closest match is returned as an estimated location.

Unfortunately, the training phase can be time-consuming and it causes changes in the environment what may change the "look of fingerprint" in a given location. As an undesirable result, we need to train the system again [9].

The second category of indoor positioning technologies is based on defining the distance from the transmitter to receiver using the propagation model mentioned above. It implies signal strength over a certain distance. If we have the approximate distance to each transmitter and their positions, we can determine the receiver's position using trilateration or multilateration techniques [5]. The technologies based on measuring signal strength were initially used with Wi-Fi, but since the Bluetooth Low Energy (BLE) protocol was developed and the emergence of BLE based beacons, it began to change. Beacons appear to be cheaper, smaller and less energy consuming devices [1,10]. The ability to power them from batteries allows us to place transmitters without significant problems in various places without frequent replacing them or recharge the battery. In addition, smartphones, which are usually used as devices communicating with these transmitters, can easily read the signal strength from many Bluetooth devices than from many Wi-Fi networks. For the previously presented reasons, this beacon-based indoor navigation development path seems very promising. For this reason, this solution has been selected for detailed presentation in this paper.

3. Concept and method

As we mentioned above, the use of BLE was chosen to solve the problem of assisting the user's navigation inside buildings. In their use, one of the most critical issues is the correct determination of the user's position in space based on signals reaching his device from many transmitters located in the space. For this purpose, true-range multilateration was selected, which, with given BLE transmitter coordination's and previously calculated distances to each of them, can determine coordinates of the receiver. How the true-range multilateration in the 2-D scenario is implemented is presented in Figure 1.

Let us notice that Circle centres (A, B, C) on the below figure have known coordinates. In such a situation, to obtain the Receiver coordinates, it is enough to derive a few equations based on the Pythagorean theorem. In the most straightforward, 2-D scenario, it is expressed as follows:

$$\begin{aligned}(x - xA)^2 + (y - yA)^2 &= r_1^2 \\ (x - xB)^2 + (y - yB)^2 &= r_2^2 \\ (x - xC)^2 + (y - yC)^2 &= r_3^2\end{aligned} \tag{1}$$

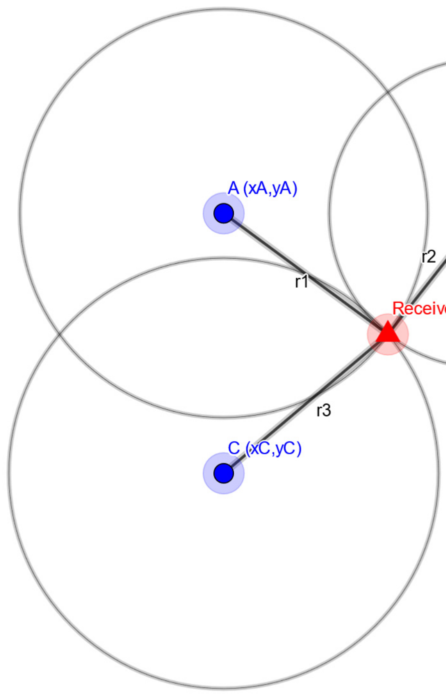

Figure 1. True-range multilateration in the 2-D scenario. Source: own study.

To obtain a correct location, we need to calculate the distance from the receiver to each of the transmitters. The distance between the transmitter (beacon) and the receiver (smartphone) is determined using the radio propagation model. This is because the radio signal loses its strength as the distance from the transmitter increases. The signals transmitted by the Bluetooth transmitters follow the path loss model:

$$RSSI = -10n \log \frac{D}{D_0} + C_0 \tag{2}$$

where:

- RSSI is an indicator of signal strength
- D is the distance between transmitter and receiver
- C0 is the signal strength at a distance of D0 (usually equals 1 meter)
- n is an environment variable, usually with a value around 2.

After transforming the above formula, we obtain the following formula that allows us to calculate a distance:

$$D = 10^{\frac{RSSI + C_0}{-10n}}. \tag{3}$$

Let us notice that N depends on the interference existing in a given place, so it should be determined experimentally during the beacon calibration process.

A necessary process leading to the implementation of our method was undoubtedly the configuration and calibration of beacons. The configuration process was based on using the GATT (Generic Attribute Profile) operation, which establishes how data will be organised and exchanged by BLE devices. GATT defines how data is organised in the form of bits or attributes. Most BLE devices provide the GATT API for carrying out various operations. In the transmitters used in our solution (NRF51822-Beacon), their essential parameters are: majorID, minorID, transmit interval and power level. Moreover, the possible transmitting power is expressed in dBm, i.e. a logarithmic unit of power measurement related to 1mW. In our solution, the 0x00 parameter was used to set the transmission power to 0dBm.

With the necessary parameters, the beacons could be configured. It was done as follows:

The transmit power was set to 0dBm, the transmit interval was set to 100ms, and majorID was set to 14. On the other hand, the beacon calibration process consisted of determining the environmental variable using an appropriate radio propagation model and measuring the average signal strength over one meter. The signals transmitted by the Bluetooth transmitters are in accordance with the following path loss model, as outlined in the earlier section:

$$RSSI = -10n\log\frac{D}{D_0} + C_0 \quad (4)$$

After transforming the above formula, we will obtain the following formula that allows us to calculate environmental variable n:

$$n = -\frac{(RSSI - C_0)}{10\log\frac{D}{D_0}}. \quad (5)$$

Using the above formula, it was possible to proceed to the beacon calibration process. The calibrations were performed as follows: the transmitter (beacon) was placed one meter away from the receiver (smartphone) and then moved to a distance of two meters. Every 50 centimetres, the devices were held in place for two minutes and the signal strength readings were recorded and averaged. The data was collected into a spreadsheet to determine: C0, the average signal strength at a distance of one meter as the value -68 dBm, while the calculated n was 2.27 in the testing room. The last step was to mount the beacons in the room where the applications were to be tested. To obtain the most optimal conditions, the transmitters should be located at the height of about three meters - in order to avoid attenuation of the signal in metals, and above all in water in the human body, which may appear in the possible signal path (Let us notice that the human body consists mainly of water). To better test, the beacons were set up in two different configurations.

The first configuration variant assumed the placement of beacons in three corners of the room as follows:

- The first beacon, upper left corner (0,0),
- The second beacon, upper-right corner (3.75,0),
- The third beacon, lower-right corner (3.75,4.40).

This configuration variant is shown in the figure 2.

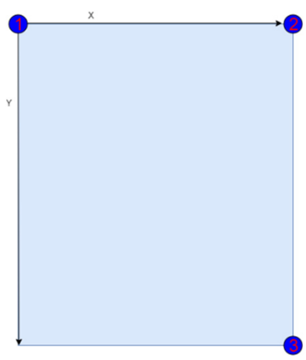

Figure 2. First configurations of beacons. Source: own study.

The second configuration of beacons is presented in the figure 3.

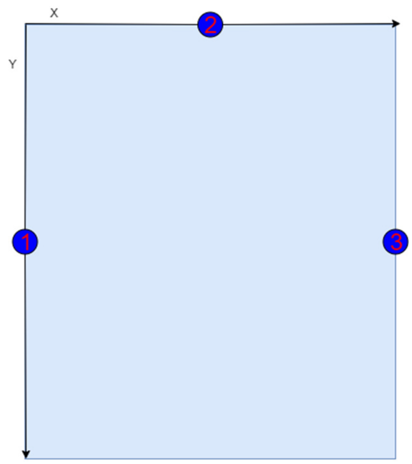

Figure 3. Second configuration of beacons. Source: own study.

Note that according to the second variant, beacons were placed on three centres of the walls as follows:

- The first beacon, the centre of the left wall (0,2.20),
- The second beacon, the centre of the top wall (1.875,0),
- The third beacon, the centre of the right wall (3.75,2.20).

After completing the calibration and location process of beacons, our testing environment's implementation and installation have been completed. It should be emphasised here that in changing the place where the system operates, the calibration process should be repeated, which practically means that the appropriate map should be drawn in the client application and beacons should be placed. Moreover, their locations with the minor ID of each transmitter should be again entered into the server application.

4. How it works

The method described in previous section has been implemented as a prototype Android application. More precisely, the system consists of two applications - a client, an Android application written in Java and a server application - written with the Node.js framework Express. One of the more essential parts of the system were physical devices - beacons. Communication in the system takes place on two lines:

- Client - server, which is carried out by means of HTTP requests. The communication scheme is relatively simple, the client (the application running on the Android operating system) sends the appropriate HTTP requests to the server which then sends the response back to the client in JSON format. The application does not have any database, but it records localisation queries and their results in a csv format report for testing purposes.
- Client - beacons, implemented using the Bluetooth 4.0 Low Energy standard protocol. In this case communication is one-way; scanning occurs while the client uses the BeaconList or Map fragment of the application at a specified time interval.

After starting the client application, it shows the home fragment with the logo and a short description of the system. There are three navigation buttons at the bottom of the window that allows users to go to the fragment with the list of beacons and the map.

The following fragment of the application has more functionalities because it implements a use case that allows users to display nearby beacons in the form of a list with data, such as MAC address, signal strength, MajorID, and MinorID. In this fragment, beacons that are available in the current room are scanned every 5 seconds. This situation is presented in the figure 4.

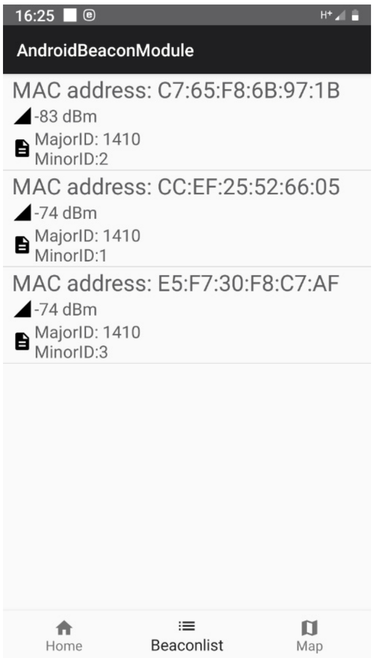

Figure 4. “Beaconlist” fragment of the application. Source: own study.

The following fragment (map fragment) implements the most crucial functionality of the application. It realises the functionality of locating the receiver (phone) in a given region covered with beacons, the data of which was previously entered into the server application. In addition to the standard three navigation buttons (Home, Beaconlist and Map), there is a button "Locate" above them in this fragment. It can be used when the beacon space scanning operation returns at least three detected transmitters. The indicator of the number of detected beacons is located in the upper left corner of the application screen. After sending the request using the button mentioned above, the server returns the calculated coordinates of the receiver to the client application, which are presented in two ways:

- The coordinates are presented as numbers under the indicator of the number of detected beacons.
- The coordinates are presented graphically - as a black circle on the map of the region covered with beacons, which are represented as blue circles. The view of the discussed map fragment is presented in Figure 5.
- To archive and better test the application, the above localisation queries are saved to a .csv sheet.
- In addition to downloading the query data in CSV format, the administrator can check what beacons are available in the system. This can be done by sending an appropriate request to the server application. This query is a JSON object containing such data as minorID and coordinates x, y, z.

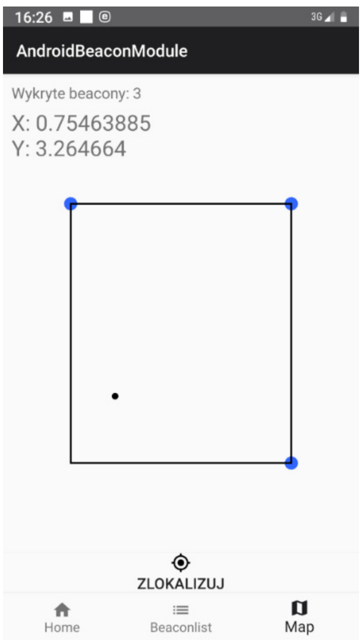

Figure 5. “Map” fragment of the application. Source: own study.

4.1. Test and results

Having all the tools at hand and demonstrating the operation of the application, it was possible to go to the stage of testing the correct operation of the main functionality of the system, namely the ability to determine the location of the phone in the area covered with beacons assigned to the server application.

The test was performed as follows: locating queries were sent from the phone in the stationary state for about 10 seconds and the actual coordinates were measured and then compared with those calculated by the server application. There was no need to write them down, as the server already performed this action.

Additionally, the extreme error values, which were about 10 per cent, were excluded from calculating the average accuracy of the measurements. Two tests were performed for the two variants of beacon distribution, which are presented in section 3. The tables 1 and 2 show the results of these tests.

Table 1. Results of tests for first variant of beacon placement. Source: own study.

X calculated	Y calculated	X real	Y real	Ranging error
2,409322774	2,349170308	1,66	1,99	0,8309560337
3,524609988	3,628843484	3,72	2,85	0,8029784735
0,09074026806	4,508041309	1,65	3,63	1,789482454
1,990400474	1,94731863	2,58	1,28	0,8904727706
-0,5831175959	-0,02609472472	0,2	0,2	0,8151024436
2,65333598	5,341210438	3,31	4,18	1,334022982
2,409563226	2,965423212	1,74	1,53	1,583904893
0,0526498655	2,48464679	0,65	1,52	1,134623555
1,254464652	2,154678642	0,95	2,45	0,4241620314
3,5461231	4,0212	2,12	3,42	1,547665512
1,45687654	0,6897844	1,51	1,12	0,4334830614
1,984756484	0,5498749615	4,21	1,48	2,411812864

The average ranging error for the above measurements was 1.167 m.

Table 2. Results of tests for second variant of beacon placement. Source: own study.

X calculated	Y calculated	X real	Y real	Ranging error
0,7455063063	2,787132056	1,03	2,2	0,6524267877
0,7326628711	0,5811156729	1,07	0,85	0,4313874359
2,401228983	1,78628215	3,55	2,2	1,220998488
2,785246967	-1,476856437	3,45	0,2	1,803813767
1,914567868	1,86629616	1,88	2,2	0,3354894783
0,854335432	1,015676521	1,12	1,52	0,5700173979
2,050012315	0,215487613	2,12	0,25	0,07803448538
3,134854321	1,05457861	2,35	0,11	1,228098146
2,156468463	0,1254687	2,97	0,14	0,8136613056
1,167684541	1,215656486	1,5	0,41	0,8715021157

The average ranging error for the above measurements was 0.8 m. It means that the tests proved that the main functionality of the system was working, and the error radius was on average 1 meter, which appears to be a relatively good result. However, it should be emphasised that due to the relatively small number of taken measurements, they are not entirely reliable. The test was mainly aimed at checking the correct operation of the application rather than a thorough error analysis. However, greater accuracy could be ensured by: a more complex calibration process, optimal placement of beacons (their height above the potential height of a human), an increase in their number and an increased frequency of their transmission. The latest, however, would be associated with a significantly increased energy consumption by these devices. Despite these inconveniences, the obtained results can be considered entirely satisfactory.

5. Conclusions

Our research aimed to find and use the most optimal solution to the lack of electronic support for effective navigation in closed spaces. For its implementation, we decided to choose Bluetooth Low Energy transmitters - beacons, which appear to be the best technology in profitability, which was analysed in section 2. In order to verify the developed solution in practice, a system consisting of a client and server application was made. It enables the location of mobile devices in closed rooms. It acts as a module that could be used in a fully-fledged indoor navigation system, i.e. NaviSecure application planned soon. The application tests presented in section 4.1 proved the correct operation of the system, and the obtained results are pretty promising and give rise to optimism, giving prospects for its further development.

A significant improvement in the accuracy of the obtained location could be brought by using beacons that support the Bluetooth 5.1 specification, which, unlike those used in the system (Bluetooth Low Energy 4.0), also enables the determination of the signal transmission direction not only the distance. This possibility would make the obtained precision of the results drastically increase - and the accuracy would then be up to several centimetres.

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