Framework for Real-Time User Positioning in GPS Denied Environments

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***Abstract* — In the paper, a system for real-time positioning is proposed. Developed signal processing algorithms for precise user localization and navigation are described. It is demonstrated that proper calibration and received signal filtering leads to improvement of positioning accuracy. Peculiarities of Bluetooth Low Energy beacons as signal sources are considered. Key components of the created software development kit are described. Experimental results of testing on mobile platforms are given.**

Keywords— Indoor navigation; trilateration; beacons; user localization; navigation graph.

I. INTRODUCTION

Millions of people use positioning and navigation services in daily basis. The most common way is based on global positioning systems (GPS) [1], [2] which provide satisfactory accuracy and can be easily used by everyone who has a GPS receiver in a smartphone or tablet. However, the problem is that the accuracy of GPS positioning strictly depends on a sky view. Hence, the application is limited in megapolises with compact planning and, what is more important, in indoor environments [1]. This fact led to the development of indoor positioning and navigation systems (IPNS) [3]. Indeed, in this case guiding of a user in multilevel parkings, airports, museums, hospitals, hotels become possible [3], [4].

Different technologies can be applied for design the indoor positioning system (Fig. 1). For instance, radio frequency identification (RFID) is widely used, however its operating range is limited. Geomagnetic sensors have some benefits while being highly sensitive to metal objects, thus, sometimes providing low accuracy. LTE direct systems are not cheap in deploying and maintaining, require external power supply and continuous data connections between nodes of the navigation network. This limits the areas of possible applications. A closed attention should be given to Wi-Fi and Bluetooth-based technologies [4]. The former has two main disadvantages: external energy requirement and not changing locations of Wi-Fi routers. In the paper, potential of Bluetooth low energy (BLE) beacons is investigated. Such devices are low cost, autonomous and can provide quite high positioning accuracy.

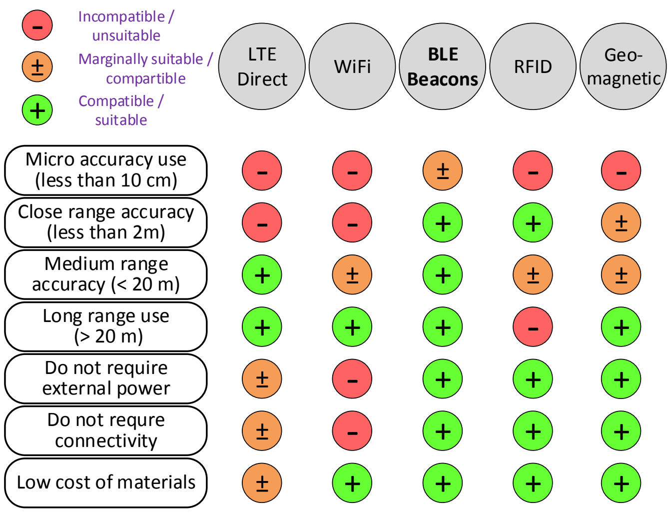

Fig. 1. Different technologies for the indoor navigation problem

A key idea of user positioning using BLE beacons is based on the analysis of the received signal strength indicator (RSSI). From mathematical point of view one can show that user 2D-location coordinates can be retrieved using the RSSI from three beacons (at least) and their coordinates [5], [6], [7]. This task is known as trilateration. However, there are several factors that complicate the positioning process. In particular, multiple signal reflections and attenuation arise due to obstacles in buildings [8], [9].

Due to the strong interest to IPNS development many leading companies, such as Navigine, Estimote, Kontakt.io, Atlas, etc., proposed their solutions for problems in this field. Despite of the many approaches to design the beacons-based IPNS, the accuracy that can be practically reached is about 1m [3], [9]. Most of working solutions are hidden due to the commercial usage and that is why cannot be analyzed properly. In the paper, we analyze the most crucial steps of user positioning and navigation in buildings. A working IPNS prototype is demonstrated.

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The paper is organized as follows. Main principles of user positioning and navigation are described in Section II. Section III contains information about peculiarities of signal processing in real conditions. Main components of mobile indoor software development kit (SDK) are highlighted. Section IV contains experimental results.

II. Indoor Navigation: Main Principles

This section contains introductory information about user positioning and navigation based on BLE beacons.

A. Data Processing Basics

A typical beacon represents a small BLE transmitter which performs broadcasting with a particular period. A common beacon package contains ID and some additional metadata such as building floor information or index of a particular proximity area. RSSI can be considered as a main parameter since it is directly related to the distance to the receiver (user mobile device or tablet). Fig. 2 contains an example of sequence of RSSI values measured at two distances for static user position.

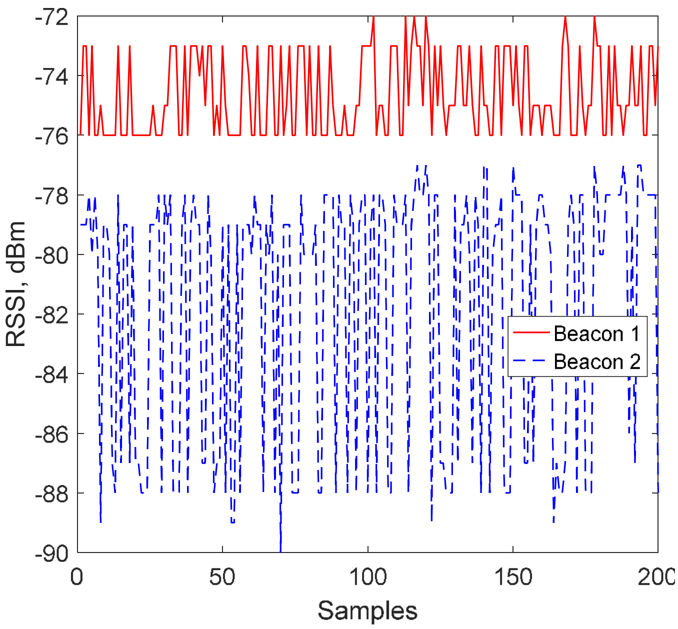


Fig. 2. Example of RSSI values from different beacons

One can observe considerable fluctuations. This is caused by multiple signal reflections and interference, which is inherent for indoor scenes. An important thing is that the slow RSSI changes are usually due to the user motion while fast changes should be properly filtered. Application examples of different RSSI filters [10] are considered in next section.

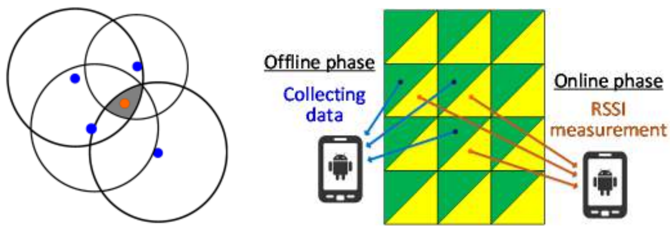
Basically, user positioning can be divided into two steps. Firstly, the received RSSI should be recalculated to the distance to the beacon. Secondly, based on the obtained ranges to several beacons (at least three) user localization can be derived. It is known that correct distance evaluation is strictly related to the physical model of signal decay. We have found the following dependence is a good candidate:

$$D = 10^{\frac{\mathrm{Tx}_{\mathrm{power}} - RSSI}{10 \cdot \mathrm{n}}} \quad (1)$$

where D is a distance to a beacon, $\mathrm{Tx}_{\mathrm{power}}$ is an RSSI value measured at 1 m distance from the beacon and n denotes a damping factor or path loss parameter.

Damping factor is known to be one of the main environmental characteristics. It is worth noting that all beacons in a system should be properly calibrated. It means that the values of pass loss parameter as well as $\mathrm{Tx}_{\mathrm{power}}$ should be properly tuned after the system deployment [11].

After calculating the distances to the beacons, two main procedures can be used for derivation of user coordinates (Fig. 3).



(a) (b)

Fig. 3 Multilateration and fingerprinting.

Let discuss those two procedures in details.

The first way is known as multilateration [11] (or trilateration, in case of 3 reference points), see Fig. 3a. The idea is quite straitforward. Let us denote the distances between an unknown user location (x, y, z) and each beacon (x_i, y_i, z_i) as:

$$d_i = (x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2, \; i \in [1;k] \quad (2)$$

where k is a total amount of available beacons.

One can show that (2) can be rewritten as:

$$\begin{bmatrix} 1 & -2x_1 & -2y_1 & -2z_1 \\ 1 & -2x_2 & -2y_2 & -2z_2 \\ 1 & -2x_3 & -2y_3 & -2z_3 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & -2x_k & -2y_k & -2z_k \end{bmatrix} \cdot \begin{bmatrix} x^2 + y^2 + z^2 \\ x \\ y \\ z \end{bmatrix} = \begin{bmatrix} d_1^2 - x_1^2 - y_1^2 - z_1^2 \\ d_2^2 - x_2^2 - y_2^2 - z_2^2 \\ d_3^2 - x_3^2 - y_3^2 - z_3^2 \\ \vdots \\ d_k^2 - x_k^2 - y_k^2 - z_k^2 \end{bmatrix} \quad (3)$$

Then user location can be found as a solution of (3).

An alternative and different way for user localization is the so-called fingerprinting [12]-[14] (Fig. 3b). Instead of distance estimation using RSSI value and finding a solution of (3), a radio map of the bulding is acquired. The process is commonly has the offline and online phases. Initially, RSSI values from available beacons in an area of interest are stored as a sequence of data points (so-called fingerprints). Each point corresponds to green triangle in Fig. 3b. In online phase (real conditions) user collects the RSSI vector (yellow triangles). The current

RSSI vector at an unknown location should be compared to those stored in the fingerprint and the closest match is returned as the estimated user location. The following criterion may be used for comparison of RSSI value and fingerprint [13]:

$$diff(rssi_i^e, rssi_j^r) = \sqrt{\sum_{k=1}^{w} (rssi_k^e - rssi_k^r)^2}\,, \quad (4)$$

where *e* and *r* are referred to estimated and reference points.

Position estimation includes two main stages [13]:

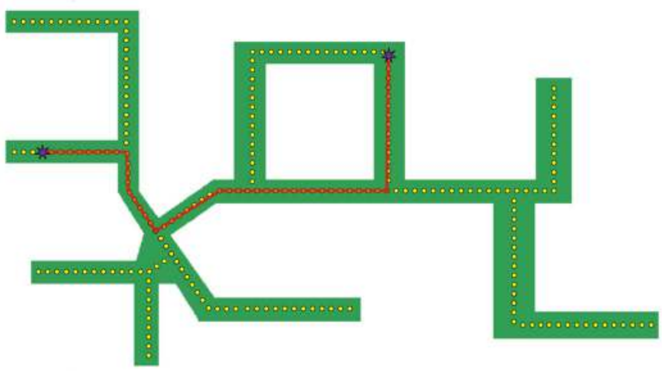
- identify the subarea, where the mobile target is located in, based on comparing the collected RSSI values with the features assigned to each subarea;
- find out the nearest reference points (fingerprints) to the measured point in the identified subarea based on the difference in the RSSI readings in the selected subarea (Fig. 3b).

The main drawback of fingerprinting is that some changes in a building (addition or removing of objects, etc.) lead to performance degradation and radio map should be measured again.

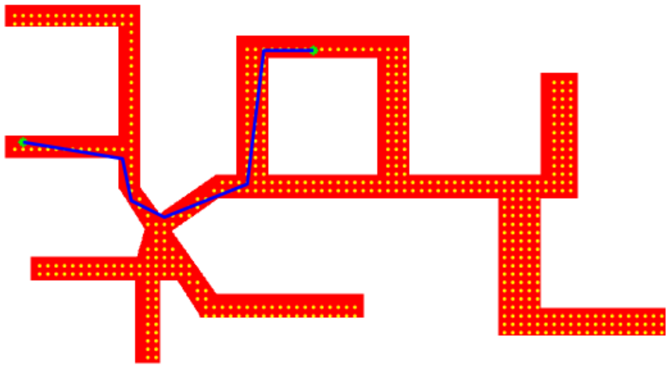
B. Navigation and Map Preparation

User navigation is the second important task of IPNS. A common way to implement the route planning is to use graphs. However, some preparation steps should be accomplished with the building map. Firstly, allowed zones should be marked. Such areas can be stored using a binary image (containing logical zeros for forbidden areas and ones for allowed zones).

Assuming that building mask is created, let's consider possible options for graph construction. Two alternatives can be implemented for graph extraction (Fig. 4). The first option is based on skeletonization algorithms. Such methods are intended to apply for specific image processing in order to perform the consequent thinning while keeping the same image topology.



(a)



(b)

Fig. 4. Graph extraction algorithms
(a – skeletonization, b – navmesh)

Fig. 4a contains an example of skeletonization algorithm application. Graph nodes are obtained via simple decimation of the skeleton. An advantage of such approach is that the resulting graph is quite compact.

Another option is based on navigation mesh algorithms [15]. The idea of such procedure is based on the division of the mask image into the squared blocks. At the next step, we check does all the pixels of the block belong to the allowed area. Such consequent checks allow to generate the nodes of the graph structure (Fig. 4b). One can see that the graphs are distinguished in the way of the path provided. The advantage of navigation mesh solution is its property to cope with the intersections areas on the maps, where skeletonization technique may provide incorrect results.

It is known that a conventional graph structure contains nodes and edges (connecting lines). Nodes connectivity is described via adjacency matrix. Edges are added based on simple checks. If there are no obstacles between a given pair of nodes, the graph edge is created. As a result, a full input for user navigation is ready. As soon as graph structure is constructed, routing algorithms can be applied for user navigation. This is considered as a shortest-path problem. There are a special group of algorithms which can be applied there. Two most known of them are A* and Dijkstra's algorithms [17].

III. INDOOR NAVIGATION IN REAL CONITIONS

This section contains the description of signal processing methods applied for user positioning. Also key steps of the constructed SDK are described.

A. User Localization in Real Conditions

Numerous measurements have shown that RSSI sequence is quite unstable and fluctuating. In order to improve the positioning accuracy, we propose to apply filtering algorithms. It was found that good options for RSSI filtering include moving average (MA), alpha-beta (AB) or alpha-trimmed mean (ATM) filter. Each of these methods can be used in real-time. The principle of MA and ATM filters is quite simple: a sliding window of configurable size *w* is applied for a collected buffer of RSSI values.

In case of MA filter average value of a local window is taken. The ATM filter is based on sorting of window samples and "trimming" some number of the least and the greatest RSSI values. The number of trimmed values is calculated as

$$round(w \cdot \alpha / 100) \quad (5)$$

where α is a trimming parameter, which indicates what part of samples is to be excluded at each side of the sorted sequence, in % (that is α the least and α the greatest values).

The AB filter estimates the speed of signal variation and predicts the following signal samples [1]. Based on past, current and predicted values, RSSI fluctuations can be reduced. An update of current RSSI and its variation speed can be found using the following expressions:

$$R_{est(i)} = R_{pred(i)} + \alpha_{AB}(R_{prev(i)} - R_{pred(i)}) \quad (6)$$

$$R_{pred(i+1)} = R_{est(i)} + V_{esr(i)} \cdot T_s \quad (7)$$

$$V_{est(i)} = V_{pred(i)} + \frac{\beta_{AB}}{T_s}(R_{prev(i)} - R_{pred(i)}) \quad (8)$$

$$V_{pred(i+1)} = V_{est(i)} \quad (9)$$

where $R_{est(i)}$, $R_{pred(i)}$ and $R_{prev(i)}$ are the i^{th} estimated, predicted and previous values of RSSI correspondingly, $V_{est(i)}$, $V_{pred(i)}$, and $V_{prev(i)}$ are the i^{th} estimated, predicted and previous values of RSSI variation speed correspondingly, α_{AB} and β_{AB} are the gain ("confidence") factors.

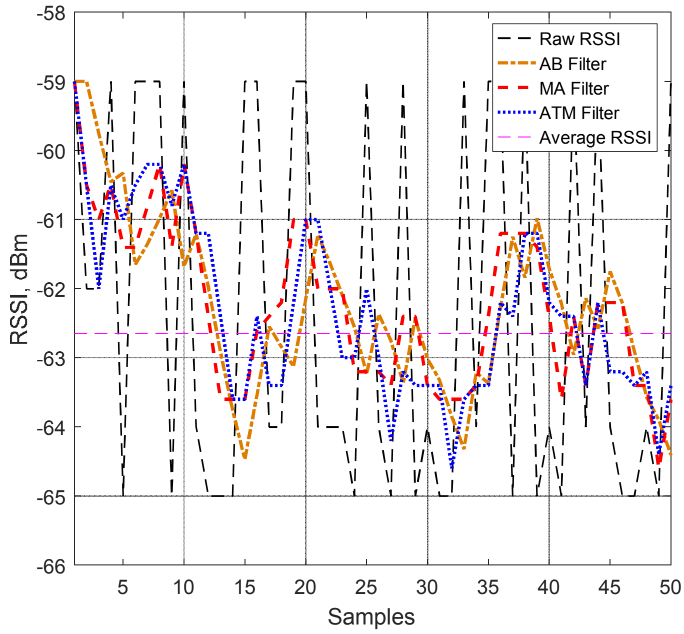


Fig. 5. Measured and filtered RSSI sequences.

Fig. 5 contains an experimental example of application of filters described above.

The following filter parameters were used: *MA filter, w* = 5 samples; *ATM filter, w* = 7 samples, trimming parameter α=10%; *AB filter,* α_{AB} = 0.25, β_{AB} = 0.25, T_s = 1. One can observe that all three options allow to smooth the data and filter the high-frequency RSSI fluctuations. However, ATM filter helps to filter out the fluctuations with the highest amplitudes, while AB filter can handle situations where RSSI changing rapidly.

B. Indoor Navigation SDK

Let's consider how IPNS can work in real conditions on mobile devices (Fig. 6).

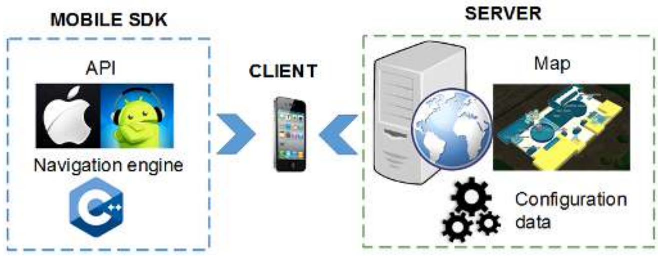


Fig. 6. High-level diagram of indoor navigation system.

Initially, calibration process is initiated by the engineer. All beacons are placed in the building. A set of RSSI measurements are performed. Specifically developed calibration procedure allows to estimate pass loss and Tx_{power} parameters of each beacon. Building's map and all metadata are stored on the application server. Metadata contains beacons locations, calibration data and previously calculated navigation graph structures. Important, that such preparation steps are done only once at system start.

As for the user, he just needs to install the client application (Fig. 6). Any developer who wants to implement indoor navigation in his own application just need to download SDK. It consists of two main parts: navigation engine which contains the algorithmic routines implemented in C++, and corresponding API written in native code such as Java or Objective C. API is considered as a bridge between the navigation engine and the developer's client applications.

Next section contains initial experimental results.

IV. Experimental Results

In order to demonsrate the system performance, we have conducted a set of experiments. A common scenario was the user movement along a specified trajectory. His location was reconstructed using trilateration technique. We applied the developed RSSI filters in order to smooth the fluctuations. Fig. 7 illustrates obtained positioning results. One can see that system calibration allows to significantly improve the localization acccuracy. The achieved precision was around 1m-2m.

Currently we are working on integration of mobile sensors and optical data (video stream from mobile camera) in order to make positioning more precise.

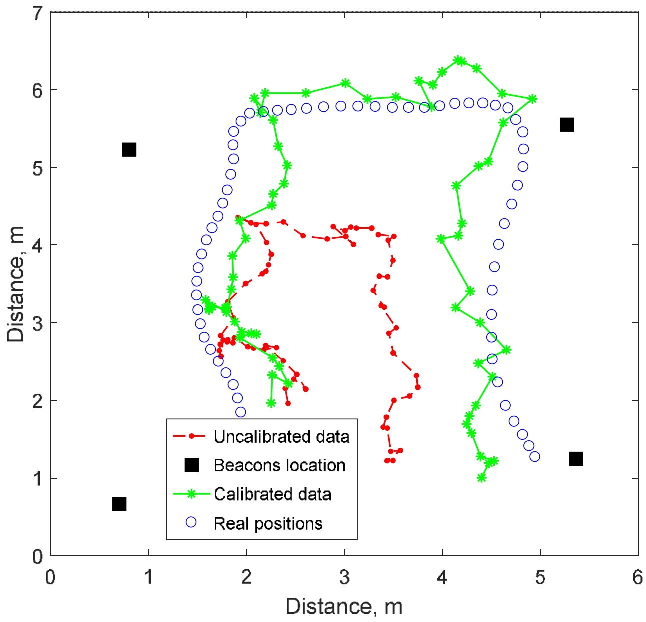


Fig. 7. User positioning results.

V. Conclusion

IPNS based on BLE beacons technology has been presented. Important aspects of both user positioning and navigation were analyzed. Signal processing approaches were considered. The description of main stages for precise user position estimation has been given. Also, all required steps for preparation of configuration data were mentioned. Experimental results indicate good potential of the framework for user navigation in indoor environments. In the near future we are planning to improve the accuracy of the system via development of more intelligent data processing approaches and integration of the visual methods such simultaneous localization and mapping (SLAM) technology.

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