Comparative Analysis of the Bluetooth Low-Energy Indoor Positioning Systems

Danijel Čabarkapa[1], Ivana Grujić[2] and Petar Pavlović[3]

Abstract – **A key requirements in the Internet of Things (IoT) concept are context-aware computation, smart connectivity with existing networks and cost efficient low-power wireless solutions. Bluetooth Low Energy (BLE) is one of the latest developments of IoT and especially well-suited for ultra-low power sensors running on small batteries. BLE is successful alternative for indoor positioning systems (IPS) which offers reasonable accuracy and low cost deployment. This paper presents a comparative analysis of contemporary BLE indoor positioning solutions, taking into account the classification, comparison and variety considerations of parameters that are required for designing a new indoor positioning approaches.**

Keywords – **IoT, BLE, indoor positioning, fingerprinting, iBeacon**

I. Introduction

Bluetooth Low Energy is a low-power wireless technology developed by the Bluetooth Special Interest Group (SIG) and distinctive feature of the Bluetooth 4.0 specification [1]. In contrast with previous Bluetooth standards, BLE has been introduced to facilitate a short range communication for devices that do not require large amount of data transfer. The main idea of BLE was to provide an efficient technology for monitoring and control applications where data amounts are typically very low, such as sending sensor values or short control messages with minimal overhead [2].

Many features of Classic Bluetooth are inherited in BLE. Several new features make BLE devices easy to setup and make it powerful solution to indoor radio-frequency (RF) signal propagation. BLE devices operate in the 2.4GHz Industrial Scientific Medical (ISM) license-free band. This wireless communication defines 40 RF channels with 2MHz channel spacing. BLE only has two types of dedicated channels: advertising and data. Advertising channels are used for device discovery, broadcast message transmission and connection setup. BLE devices operating in advertising mode periodically transmit advertising information in three dedicated channels (37, 38, and 39), which have been specifically allocated to minimize collision with the most commonly used Wi-Fi channels (1, 6 and 11) [3]. BLE has to switch „ON" for just 0.6 to 1.2 ms to scan for other devices using advertising channels. Data channels are used for bidirectional communication between connected devices, and Adaptive Frequency Hopping (AFH) mechanism selects one of the remaining 37 available channels for communication. All physical channels use a Gaussian Frequency Shift Keying (GFSK) modulation scheme, which allows reduced peak power consumption. The coverage range of BLE is typically over various tens of meters. The modulation rate for BLE is fixed at 1 Mbps, which is the upper physical throughput limit for this technology. BLE is optimized for sending small pieces of information with minimal delay (latency). The total time of sending data is generally less than 6 ms (compared to 100 ms with Classic Bluetooth). The accuracy represents distance error between the real position and the estimated one. An accuracy of a 1-2 meters is possible to achieve using BLE. Table I shows some of the main characteristics of BLE [4].

TABLE I
BLE Technical Specifications

Frequency band	2400-2483.5 MHz
Distance/Range	<100m (330ft)
Nominal data rate	1 Mbps
Modulation (Technique/Scheme)	AFH/GFSK
Channels (Number/Bandwidth)	40/2MHz
Latency	<6ms
Peak/Average current	<15mA/~μA
Accuracy	1-2m
Security	128-bit AES

II. BLE Protocol Stack and Working Modes

BLE protocol stack is not compatible with the previous Bluetooth stack and consists of two sections: the controller and the host [1-4]. The controller represents two of the lowest layers of stack: the physical layer (PHY) and the link layer (LL). BLE controller is a chip implemented as System-on-Chip (SoC). PHY takes care of transmitting/receiving bits and LL provides medium access, error/flow control and connection establishment. The host consists of the upper layer protocols and runs the following services: Logical Link Control and Adaptation Protocol (L2CAP), Security Manager Protocol (SMP), Attribute Protocol (ATT), Generic Attribute Profile (GATT) and Generic Access Profile (GAP). Communication between the host and the controller is standardized as the Host Controller Interface (HCI). GAP is very important protocol because allows BLE devices to interoperate with each other and provides a framework that any BLE implementation must follow to allow devices to discover each other, broadcast data, establish secure connections, and perform other operations [4].

A BLE device may operate in several modes, depending on required functionality: Standby (does not transmit/receive

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packets), Advertising (broadcasts advertisement messages), Scanning (looks for advertisers), Initiating (initiates connection to advertiser) and Connection. BLE generally uses a Client/Server model. A Client (device that "wants data") connects and accesses one or several Servers (that "has data"). The Client typically operates in the Central role and the Server operates in the Peripheral role. Sensor or a BLE accessory is the Server device and a smartphone, laptop or tablet is the Client device, as shown in Figure 1. In order to get the devices connected, a device must use a connectable advertising event. When the Client receives the advertisement packet, it sends a connect request to the Server. Once the advertiser receives the connect request, the devices are connected and can exchange data packets.

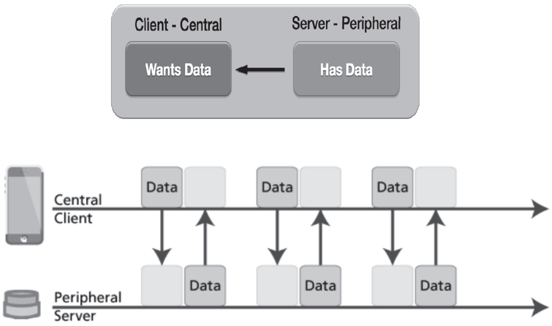

Fig. 1. BLE client-server naming and connected devices

BLE device can operate either in master or slave role. A master can manage multiple simultaneous connections with a number of slave devices, but a slave can only be connected to a single master. Master scans designated advertisement channels in order to discover slaves. After discovery, data transmission happens in the form of connection events in which the master and the slave wake up in synchrony to exchange frames. Both devices sleep the rest of time. High bit rates allow the BLE devices to use the RF signal in short time periods transmitting the information fast. Low duty-cycle of signal keeps the small consumption as small as possible. The BLE device only transmits when is asked for it. Low packet overhead of BLE affects also on consumption [5].

In the context of IPS systems, the first step is to measure distances to at least three known reference points (RP). In most IPS, these reference points are made up of beacon nodes or access points (AP). Advertising BLE mode uses beacon, as very short message at very flexible update rates.

III. BLE Indoor Positioning Techniques

This section of paper describes the various positioning techniques, taking into account the characteristics of BLE technology. There are mainly two techniques that are used in BLE IPS systems today: trilateration and fingerprinting. Bluetooth IPS operation principle is based on obtaining and exploring unknown device locations using various algorithms. Because there is no direct way of measuring distance between two devices, BLE provides several kinds of parameters related with location estimation, such as RSSI (*Received Signal Strength Indicator*) and LQI (*Link Quality Indicator*) [6]. The RSSI is used to evaluate distance between the receiving device (which needs to be located) and beacon node, accordingly to current RF signal propagation model. Received power can be calculated from RSSI [7, 8]. Good results have been obtained by fingerprinting technique. Constructing a RSSI map is based on received RF signal strengths in the area of interest.

BLE beacon device is a fixed signal transmitter, usually placed on walls, near ceilings (to avoid obstacles), that broadcasts typical signals as a navigation aid. Beacon messages can be used to allow a device to detect close proximity to a specific location, based on the received signal strength. In this way, location specific triggers, notifications, adverts and information can be provided to the user.

Functioning of a BLE IPS based on three steps: beacons placement, calibration and real-time positioning. Beacon placement (deployment phase) is based on deploying a certain number of beacon devices. An important question is where the beacons should be placed in order to achieve the most accurate localization [8]. Calibration is the offline part of the positioning, and depending on the localization technique adopted it can include manually tuning of propagation parameters (path loss model needs to be optimally calibrated through RSSI measurements). Positioning process is presented in Figure 2.

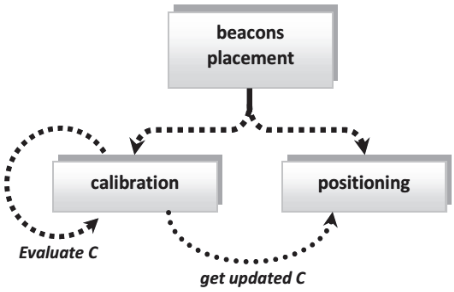

Fig. 2. BLE positioning process

Here C represents the calibration parameter for the adopted positioning function, periodically updated with a rate $f_{calib}=1/t_{calib}$. The time period between two consequent updating steps is denoted as t_{calib} and varies from the adopted IPS algorithm. The positioning time frame [t_{start}, t_{end}] represents time between start and stop of the positioning [9]. Last step of IPS process is real-time positioning which based on positioning algorithm. Estimated calibration parameters are passed, as an input, to positioning routine. Final results of positioning algorithm should be as accurate as possible. Various methods, like Kalman filtering, based on multiple noisy observations, should be adopted for location refinement to reduce output final error [10].

A. BLE Trilateration

Trilateration is trigonometric based position estimation algorithm. This technique uses measurements of distances to at least three known reference points (beacon nodes or APs).

The distance is obtained from RSSI received at the RPs. The RF propagation model is used to convert RSSI readings into distances for locating their position. This approach does not give the most accurate estimate, related to the fact that the indoor RF propagation channel is strongly variable, but requires no efforts in configuration and calibration steps. There are several mathematical methods to solve the equations of trilateration. In [11] three methods are discussed: Least Square Estimation (LSE), three-border positioning and centroid positioning.

B. BLE Fingerprinting (scene analysis)

Fingerprinting is a RSSI-based scene analysis that first collects features (fingerprints) of a surrounding reference points at every location in the areas of interest, and then builds a fingerprint database. After that, system estimates the location of an object by matching online measurements with the closest location fingerprints. The BLE location fingerprinting method consists of two phases, as shown in Figure 3.

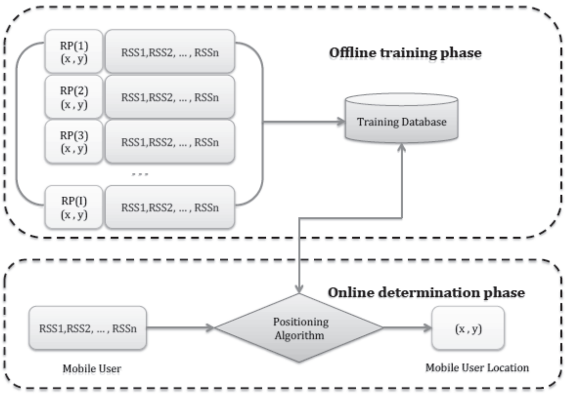

Fig. 3. The diagram of the BLE fingerprinting method

During the offline (training) phase the RSSI fingerprints are sampled at each reference point [RP(i)(x,y)] as a vector [RSSI1, RSSI2, ..., RSSIn] from a number of RPs to build RSSI database. Note that *n* is the number of RPs. This is done for a certain number of locations, and the set of fingerprints is called the radio-map [12]. In the online (determination) phase, a mobile user measures a vector of RSSI values at an unknown location, then compares the RSSI vector records in the training database using a positioning algorithm, and finally calculates the most likely location of a mobile user. Fingerprinting algorithms use several deterministic and probabilistic pattern recognition techniques: K-nearest-neighbor (KNN), artificial neural networks, Bayesian rule determination, support vector machine (SVM) or their combinations [13]. The main challenge to the fingerprinting BLE is sensitivity to environment changes such as object moving into the building (people, furniture etc.), diffraction, and reflection which result in changes in signal propagation. To maintain the positioning accuracy, the calibration process should be periodically repeated to a recalculation of the predefined signal strength map [14].

C. BLE Proximity Detection

Proximity based IPS consists in locating a device depending on its distance from another BLE device or beacon. Proximity algorithms provide symbolic relative location information. The simplest proximity-based method is to select the location of the node with the highest signal strength. Information about RF signal strength is used to define a relative ordering of nodes based on their proximity to the target device. When the user is closer to the BLE beacon, they push notifications in order to offer some actions on the user smartphone or tablet [15].

This method does not give the exact position of the device. To achieve the highest accuracy, this method requires a dense deployment of BLE beacons. Proximity methods do not require calibration and they are relatively simple to implement.

IV. BLE POSITIONING CONSIDERATIONS

There are a lot of classifications of BLE IPS services presented in the literature so far, while new solutions continue to emerge. Various IPS systems, slutions and methods available on the market and presented in literature are reviewed in Table II, along with the accuracy and technical approach required by a particular BLE IPS service. BLE fingerprinting is currently the state-of-the-art indoor positioning scheme readily available on standard smartphones, tablet and laptop computers [16]. The implementation of fingerprinting with BLE is useful since trilateration is not a good technique due to problems with reading RSSI. Apple has been embedding BLE in its devices since iPhone 4s. Since iOS7 release, Apple has released iBeacon API. iBeacon is a programming interface to low energy BLE sensors and de-facto, iBeacon technology and BLE beacons became synonyms [19-22]. There are several other vendors except Apple (Estimote, Indoo, SenionBeacon), as shown in Table II. RSSI-based BLE IPS is a random process and its path loss needs to be modelled. In cases where there is no line-of-sight (LOS), the distance measurement is more complicated and needs reconfiguration algorithms to get good estimations of distance [9, 17].

V. CONCLUSION

This paper gives an overview of the methods, technologies and solutions involved in the development of indoor BLE IPS systems. Different solutions are presented, and several known IPS algorithms are compared. Requirements for different application environments are accuracy, RF signal coverage, availability, power consumption and minimal costs for indoor installations. If the IPS requires higher accuracy (~1.5m) with 80% probability of the time, there is a need for deployment and maintenance of a RSSI based BLE infrastructure with a series of optimization to improve positioning accuracy. However, there is no general framework that considers all of these influence factors for a performance evaluation of the BLE IPS solutions that has been proposed.

TABLE II

A REVIEW OF BLE TECHNICAL AND COMMERCIAL SOLUTIONS

Reference	*BLE technical approach*	*Positioning results description*
Evaluation of IPS based on Bluetooth Smart technology [16]	Trilateration, Particle filter, Fingerprinting	Accuracy of a few meters with high precision; The response time is good or excellent with the changes done to the RF properties; Advertisement support and power efficiency; Problematic factor is scalability
RSSI based BLE indoor positioning [17]	RSSI propagation model; Gaussian filter; Piecewise fitting for offline training; Weighted distance filter	Probability of locating error less than 1.5m is higher than 80%
Adaptive RSSI based BLE indoor positioning [9]	Path loss model with particle filter to estimate parameters	It was shown better positioning accuracy with respect to linear regression and; Good precision with 50% probability of being within ~1.5 meters of the actual position
DeepBLE Android application [18]	Triangulation; Peer-to-peer messaging communication	Application developed on Google Android API; Additional information about immediate surroundings; Each anchor represents a node in a graph with knowledge of its neighbors
iBeacon [19]	An iBeacon is a BLE proximity beacon that is submitted under an Apple licensing program	Location-based advertising with low accuracy; iBeacon are not primarily designed to provide high precision positioning, instead distance estimation to each beacon is consider
Estimote (commercial) [20]	Dedicated iBeacon development kit; Beacon stickers and sensors (motes); Development API for iOS	High precision positioning is not the primary goal because of the changes in indoor environment; Target device completely must be in LOS with the iBeacon sensors
Indoo.rs (commercial) [21]	Fingerprinting indoor positioning approach; Software called Measurement Tool; Android and iOS API	Indoo.rs guarantees an accuracy of <5m radius in 95% of the cases; Accuracy can be improved by adding more beacons
SenionBeacon (commercial) [22]	iBeacon technology; Positioning achieved by a BLE fingerprinting or Wi-Fi combined with sensors	High precision real-time positioning; The calibration app which the customer uses collects a database of fingerprints

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