Experimental Assessment of Moving Targets Localization Performance Based on Angle of Arrival and RSSI

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Abstract. Localization based services are in the process of being ubiquitous, it is then essential to find a low-cost and low-energy solution for localization of moving targets. Bluetooth-based solutions for indoor localization have become increasingly popular in recent years. In addition to its availability (e.g., BLE is available on most modern smart devices), Bluetooth Low Energy technology is an economical and simple solution to the industry. To the best of our knowledge, none of the existing indoor localization systems use both Angle of Arrival and Received Signal Strength Indication. This paper presents the experimental assessment of a single device localization system that uses Angle of Arrival and Received Signal Strength Indication for localization of moving targets using Bluetooth. The results demonstrate that the developed system is an important step towards a new generation of real-time indoor localization systems that can locate targets with high accuracy (e.g., AoA accuracy: 89.2%), and an improvement concerning the cost of the implementation.

Keywords: Moving target localization · Received signal strength indication · Bluetooth low energy

1 Introduction and Related Work

With the widespread of the Internet of Things (IoT), wireless localization technology is gaining importance due to its low-cost and ubiquitous availability. Because of its excellent identification ability, Global Navigation Satellite Systems (GNSS) such as Global Positioning System (GPS) have made great success in map navigation, people and objects tracking, etc. However, GNSS are unavailable when building localization systems for indoor environments because of the great attenuation of the satellite signal causing by the obstruction from buildings. Nevertheless, with the fast development of the IoT, there is a growing demand for indoor Location Based Services (LBS). Indoor LBS applications (e.g., shopping navigation, and fire rescue, etc.) provide services relying on the target's location, which is the key factor for the performance, accuracy, reliability of LBS applications.

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Many indoor localization methods were previously assessed, including Infrared (IR) systems [1], Ultrasonic (US) systems [2], and Optical-based frameworks. These systems share several common underlying properties, such as being sensitive to multipath effects, high costs, and complexity. Consequently, the focus of researchers has been shifted to Radio Frequency (RF) indoor localization technologies, including Radio-Frequency Identification (RFID) [3], ZigBee [4], Wi-Fi, Bluetooth Low Energy (BLE), and Ultra-Wide Band (UWB). Several notable factors should be considered in selecting base technology for developing an indoor localization system, such as cost, accuracy, robustness, scalability, power requirements, reliability, and coverage. Over the last few decades, there has been a significant surge of interest for BLE-based technologies, as one of the most reliable RF-based localization frameworks due to its availability, low power consumption, and low cost. The merits and defects of these technologies are compared in Table 1.

BLE [5] is a range-based localization, it performs localization by estimating the distance between a target sensor node and reference nodes. BLE has been studied intensively for localization and user tracking in recent years. Its low complexity due to the availability of Received Signal Strength Indication (RSSI) measurements [6], the low power consumption, low cost, and the ease of device deployment make it an attractive technology for localization. In addition, Angle of Arrival (AoA) localization is a non-linear estimation problem. It determines the source position based on the propagation direction of an incident radio frequency wave from an antenna array, such as Switch Antenna Array (SAA), which has been an active research field for several decades [7]. Both localization methods (AoA and RSSI), generate a new localization strategy that can dynamically locate targets.

Table 1. Comparison of indoor localization technologies [3].

System	Advantages	Disadvantages
Infrared	High accuracy	High cost; Easily be disturbed by light, smoke, etc
AOAWLAN	Available everywhere	High power consumption; Only locate the wireless terminal
ZigBee	Low power	Short-range; Low data transmission rate
RFID	Real-time localization	Sensitive to environment
Bluetooth 5.1	High accuracy; Low power consumption; Low cost; Real-time localization	Sensitive to obstacles

With respect to previous systems in the literature, the contribution lies within the reliability of the proposed system. It is Low-cost, low power consumption, and a standalone system that can locate multiple moving targets. To the best of the author's knowledge, these are the first results of their kind and on this scale.

2 Proposed Localization Methods

Bluetooth proximity solutions and positioning systems were used to date using signal strength to estimate distance. The new direction-finding feature in Bluetooth Core Specification v5.1 makes it possible for Bluetooth devices to determine the direction of Bluetooth signal transmission. In addition, Bluetooth 5.1 specification allows low-energy transmissions to sacrifice data rate for more range. Next, the used localization methods will be explained.

2.1 Angle of Arrival

Bluetooth 5.1 AoA measures the angle or direction a BLE transmitted signal approaches a Bluetooth receiver. To calculate the AoA, two or more antennas are required to measure the phase of an incoming signal (Fig. 1).

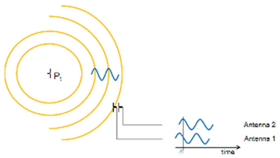

Fig. 1. Transmitter phase measured by antenna array

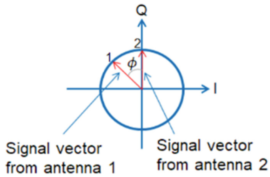

Fig. 2. Constellation diagram

The phase measurements from each antenna are used to calculate the AoA and determine the direction of the transmitted signal. To calculate the AoA, the incoming RF carrier phase must be measured with minimal impact to the signal phase of the carrier itself using two or more co-located antennas. Phase Difference (Φ) is measured by connecting at least two antennas to the same receiver sequentially (more antennas can be added). Figure 2 shows the constellation diagram which illustrates signal vectors from 2 antennas. Last step is converting the phase shift (Φ) back to AoA (Θ). This idea is described in detail in [8]. This way, the direction of the target will be known.

2.2 Received Signal Strength Indication

It is an estimated measure of power level that an RF client device is receiving from an access point, router, or antenna. RSSI indicates the power level being received after any possible loss at the antenna and cable level. The higher the RSSI value, the stronger the signal. When measured in negative numbers, the number that is closer to zero usually means a better signal. As an example, -50 is a pretty good signal, -75 - is reasonable, and -100 is no signal at all.

2.3 Locate the Target

The eligible question now is, how would it be possible to locate the target after collecting AoA and RSSI values? After measuring the phase different and converting it to AoA.

The direction of the target is now known. The only missing feature is distance. This is where we convert the measured RSSI value to a distance estimation (see Sect. 4.2.1).

3 System Architecture

This testing system is based on the AoA Booster Pack (BOOSTXL-AOA) [8] that is mounted on top of the CC26X2R [9] board. The Booster Pack (antenna) is responsible for determining the direction (AoA) and the RSSI of the target and sending this data to the CC26X2R board. The CC26X2R board is responsible for sending the received data using USB to a Raspberry Pi board that is preprogrammed to watch the UART connection and wait for incoming data stream (from the CC26X2R board). This data is then stored and transmitted using MQTT protocol to a Mongo database for later use. On the other side, the multi-band CC1352R wireless MCU Launchpad Sensor Tag kit (LPSTK-CC1352R) by Texas Instruments is used as an RF target (Fig. 3).

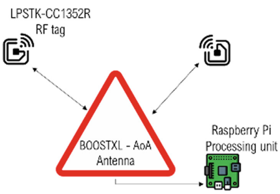

Fig. 3. System architecture

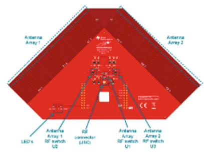

Fig. 4. BOOSTXL-AoA antenna

The Texas Instruments™ Angle of Arrival Booster Pack (BOOSTXL-AoA) assesses the performance of the AoA and RSSI localization methods using BLE 5.1. The BOOSTXL-AoA board contains two orthogonal arrays, each with three dipole antennas. Each antenna array can theoretically cover an angle on the incoming signal up to ±90°. When using both arrays combined, coverage of up to ±135° is achievable (The two antenna arrays overlap 45° on each side). Dipole antennas are by nature differential and need to be fed with a balanced signal. A balanced signal is created using a march and balun that is integrated into the PCB. The single-ended side of the baluns is fed to the antenna switches (U2 and U3). The array switch, U1, is used to connect each array to the JSC connector.

4 Experimental Assessment

In this section, experiments using the antenna and several RF tags are presented. The experiments have been conducted in different scenarios to assess different aspects of the system. The accuracy of the AoA and RSSI values are the most important metrics for this system (to ensure localization quality). In addition, it is important to measure the duty cycle, latency, coverage area, and power consumption of the proposed system to prove that the proposed system is reliable. The testing protocol is presented in this section where the results are presented in the following Sect. 5 (Results).

4.1 Setup

As described in the previous Sect. 3 (System architecture), the testing setup was built as a proof of concept of the reliability of the system. As shown in Fig. 5 below, all the components of the system were installed on a base structure and connected to a touch monitor screen to see the results in real-time.

Fig. 5. Test setup

The antenna is mounted on top of the CC26X2R Launchpad and connected using USB to the Raspberry Pi (in the black box in Fig. 4). The Raspberry Pi is then connected using an HDMI connection to the monitor screen and it is getting its power from the power bank placed under the screen. The system as shown in Fig. 4 above is completely standalone.

4.2 Experimental Methods.

A testing protocol was chosen for each experiment following the specification of each measured metric. Such protocols are explained below.

4.2.1 Received Signal Strength Indication

To start with, a user moves away from the base station to test the maximum radio transmission range of the node, which was thirty meters. Since an RSSI value cannot be a decimal or a fraction, it cannot offer enough resolution to distinguish fine-grained changes in distances. Instead, it can only provide resolution to distinguish between distances that are large enough to cause at least a unit change in dBm of the signal power at the receiving node. Therefore, it is unnecessary to test RSSI values by using small increments in distances. In this experiment, the RSSI value is tested every meter, each test lasting for 30 s. By averaging all the values obtained during this time, the valid RSSI at each testing location can be calculated.

There are different scenarios to be covered to fairly quantify the performance of the antenna with what concerns the RSSI measure. For example, elevation between the antenna and the target is an important factor that certainly affects the performance of the RSSI measurement. The experiment was being carried out in a long corridor made up of two concrete walls. The testing platform was used as a base station directly connected to a 7″ monitor screen via an HDMI cable to retrieve data. The RF target was mounted on three different elevations with reference to the coordinator. Both nodes operated with a full battery. No additional obstacles were standing in the communication path between the two nodes during the experiment. Thereafter, three scenarios were tested. For each scenario, we will take five measurements for each distance from one to thirty meters, equally distributed with a one-meter difference: Antenna higher than the target - Antenna lower than the target - Antenna and target on the same level. For each of the previously mentioned cases where the antenna and target are in the line of sight without additional obstacles, measures for thirty seconds were performed for each distance, and they were averaged to provide a fair result.

4.2.2 Angle of Arrival

Measurement of AoA can be done by determining the direction of propagation of a radio-frequency wave incident on an antenna array or determined from maximum signal strength during antenna rotation. The performance of AoA was tested in an indoor situation. These tests were conducted in a large empty closed room where the AoA antenna was positioned on a table, and a set of different angles orientations of the RF tag was tested. Those tests covered the 200° range of the antenna. Since an AoA value cannot be a decimal or a fraction, but only a number between minus one hundred to plus one hundred. It cannot offer enough resolution to distinguish fine-grained changes in angle. Therefore instead, it can only provide resolution to distinguish between angles that are large enough to cause at least a unit change in angle. Therefore, it is unnecessary to test AoA values by using small increments in angle. In our experiment, the AoA value was tested every ten degrees for a five meters distance, each test lasting for 30 s. By averaging all the values obtained during this time, the valid AoA at each testing location was calculated. The antenna and target were in the line of sight, same elevation, and without additional obstacles.

4.3 Evaluation Metrics

The following measurements are the evaluation metrics concerning our system. In this section, the measurement protocol for each metric is explained.

4.3.1 Duty Cycle

The duty cycle is the number of localization messages that are sent/received per minute. A localization message includes AoA and RSSI measures. The measurement of this factor was assessed by counting the number of received messages for ten minutes and finally averaging them.

4.3.2 Coverage Area

The radius of the area that is covered by the antenna, considering that the antenna only covers a 135° space. To assess the maximum coverage distance, an outdoor test was needed (large empty car parking space). A person holding the RF tag walked away from the antenna, when the connection stopped between the RF tag and the antenna, the measure between the antenna and the person holding the RF tag was measured. This test was repeated five times and the distance was eventually averaged. This value is presented in meters.

4.3.3 Latency

The latency is the time needed by the system to detect a new target that enters the coverage area. To test the latency, we used a large empty outdoor area (car parking space), and placed the target on a distance that is larger than the coverage area, where is antenna cannot detect it. Then, and while the antenna was looking for targets, a person holding the RF tag entered the coverage area. The time between the RF tag entering the coverage area and its detection was calculated using a stopwatch and repeated twenty times before averaging the results. This value was represented in seconds.

4.3.4 Power Consumption

The amount of power used by each of the components of the system (Antenna and Raspberry™ Pi). This factor was assessed using a USB multi-meter that indicates the amount of energy consumed by the USB attached to it.

5 Results

The results of the predefined metrics are divided into two sections. The first section presents the performance of the proposed system as a localization method. The second section presents the results of the evaluation metrics that are relevant to the proposed system.

5.1 Localization

The localization method used consists of two elements: AoA and RSSI. Both elements should give a reasonable performance so that the localization system works well. Figure 6 shows the average RSSI received along thirty meters of the indoor range. It shows three different lines, each represents an elevation state between the antenna and the target.

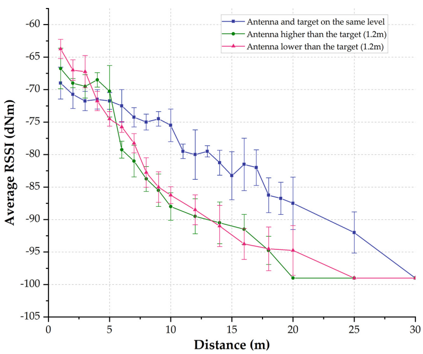

Fig. 6. RSSI received

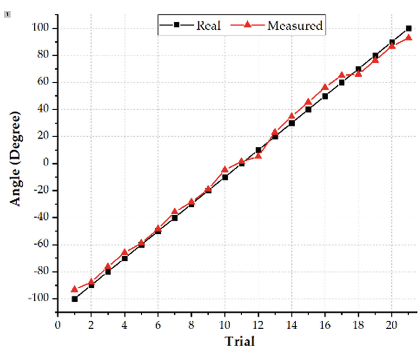

Fig. 7. AoA received

With reference to the AoA calculation, Fig. 7 above shows the AoA received with comparison to the real angle. The RF tag was placed five meters away from the antenna for each angle measurement. The RF tag was placed on the same elevation as the antenna. Each triangular point in the graph below is respective to one of the twenty-one trials that were done for different angles; the incoming stream of data was collected for thirty seconds and averaged.

5.2 Evaluation Metrics

Alongside the localization performance, it was important to track the performance of key metrics (latency, power consumption, scalability, and cost…). The duty cycle was 4.28 s, which means that the system sends fourteen localization messages every minute. These and further metrics are compared with the state-of-the-art technologies in Table 2. With reference to the proposed method, the accuracy was between 0.5 and 1 m for the presented scenario, the implementation cost was very low (twenty dollars for an antenna), and the system is easily scalable.

Table 2. Comparison of indoor localization technologies [10].

Technology	Method	Accuracy (m)	Cost	Scalable	Coverage	Latency (s)	Power consumption
Bluetooth 5.1	AoA + RSSI	0.5–1	Low (20$)	Yes	Floor level (around 100 m)	Very low (1.5–2)	Low
Ultrasonic Based	Trilateration	0.01–1	High	No	Room level	Low (5)	High
Wi-Fi	Proximity; Trilateration; Fingerprinting; RSS-Propagation model; Angulation	1–5	Low	Yes	Floor level (around 35 m)	High (10–20)	Low-Medium
ZigBee	Proximity; Trilateration; Fingerprinting; RSS-Prop model	3–5	Medium	Yes	Floor level	Medium	Low-Medium
RFID	Proximity; Trilateration; Fingerprinting; RSS-Prop model; Angulation	1–5	Low	Yes	Room level	-	Medium

Figure 6 shows that the value of RSSI and the distance are inversely proportional, which is the expected pattern from an RSSI receptor (see Sect. 3.2). Regarding the AoA, Fig. 7 shows that the real and incoming AoA over 21 trials (measurements) are consistent. The average accuracy per trial is around 89.2% which is reasonable [11]. Therefore, the BLE 5.1 localization technology that uses AoA and RSSI was effective under the presented circumstances and scenarios. In addition, with comparison to the state-of-the-art technologies, BLE 5.1 has a respectively lower accuracy than the Ultrasonic Based (UWB), but on the other hand, BLE 5.1 is lower in cost, has a larger coverage area, has less latency, and has a very low power consumption (see Table 2).

6 Conclusion

This paper presented a wireless system for the indoor localization of targets using a single wireless device. The system uses new BLE 5.1 features based on AoA and RSSI methods. The time latency and accuracy of the system have been measured. The proposed system operates in real time with 1.5–2 s delay and with an accuracy of 89.2%. Although more extensive experimentation is needed to fully evaluate our system, with respect to available systems in the literature, the proposed system is reliable, has low power consumption, low-cost, scalable and covers around 100 m. The results of this study are important for future design of new indoor localization systems and scenarios. The future work will involve a finer analysis of the BLE 5.1 performance with the existence of obstacles.

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