FPGA Implementation of Bluetooth Low Energy Beacon-Based Indoor Positioning System

Chang Joo Song and Jeong Beom Kim

Abstract—**In this paper, we described the field programmable gate array (FPGA) implementation of Bluetooth Low Energy (BLE) beacon-based indoor positioning system. Indoor positioning system relies on received signal strength indication (RSSI) from indoor wireless devices. The accuracy of indoor positioning system is easily affected by several signal interference. In order to correct for unstable RSSI values, Kalman filtering technique that has faster and lower error rate is adapted in this system. Also, we adopted the improved trilateration algorithm that has an error range of less than 0.5 m. This system was implemented using Intel's FPGA design tools Quartus II on DE1-SoC board.**

Keywords— **Bluetooth low energy beacon, BLE, beacon, indoor positioning system, position-based service, Kalman filtering, improved trilateration algorithm**

I. Introduction

In recent years, a localization technique, which is one of the core techniques in the wireless communications, has been rapidly developed with a variety of applications. As information technology industries rapidly develop, the various research themes such as location, home automation, and health care have been actively carried out. In particular, positioning technologies that provide services based on the object locations are receiving attention as a key technology in the internet of things (IoT) area. Conventional positioning services are now used in a wide range of areas as the global positioning system (GPS) technology in outdoor environments. However, receiving GPS signals is limited in confined spaces, such as inside buildings or underground. In addition, the typical measurement error range for GPS is 30m, which makes it unsuitable for measuring indoor locations. There are several location-based approaches to indoor posing system [1]-[2]. Indoor posing system is a meaningful method in application of position-based services. Recent research is actively carried out using Beacon based on Bluetooth 4.0 with the benefits of lightweight, low-cost and low-power conditions [3-6]. Bluetooth Low Energy (BLE) beacons-based IPS is a promising method for indoor posing system. However, beacon-based positioning is still very unstable and many developers are concerned because of its use of the value of received signal strength (RSSI).

In this paper, we achieved the device drive and fast data access by using the real-time and parallel processing of the field programmable gate array (FPGA) built into the DE1-SoC board. Also, we implemented the signal filter algorithm and the improved trilateration algorithm by using hard process system (HPS). This paper is organized as follows; Section II provides Beacon and development environment. Section III describes RSSI filtering and coordinate calculation. Finally, we make conclusion in Section IV.

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II. Beacon and Development Environment

A. Beacon

A beacon is an intentionally conspicuous device designed to attract attention to a specific location. BLE beacons are transmitter devices that broadcast signals, which can be picked up by nearby devices using Bluetooth. Most commonly they are used for advertising, and for informational purposes. These devices can take advantage of RSSI information together with an appropriate localization algorithm to pinpoint a user's position. This is particularly useful in indoor environments where GPS is no longer an option. Compared to other indoor posing system, BLE beacons is a low-cost, low-power option [7]. BLE beacon technology has developed during the last few years, as a means of sending position-based data to nearby users. Apple's iBeacon and Google's Eddystone are both examples of these small devices that can be attached to almost any surface, and then broadcast a signal which can be picked up by smartphones and other devices that utilize Bluetooth. Typically, BLE devices are used for advertising and informing users of nearby points of interest. However, using RSSI information, an application can estimate the distance to a beacon. Consequently, with the use of three or more beacons together with an effective algorithm, the user's position can be pinpointed [8].

BLE beacons are small devices that can be applied to almost any surface, and communicate messages to nearby devices using Bluetooth. The technology mainly finds its use within advertising, and informing smartphone users of nearby points of interests. A BLE beacon broadcasts small packets of data, with a certain interval. The maximum payload of a Bluetooth 4.2 packet is 257 bytes, which is not enough to embedded media content. Instead, a beacon simply broadcasts a unique ID and the application on the receiving device must recognize the beacon and perform relevant tasks. This is one-way communication, since beacons just broadcast signals and does not receive information [7]-[8]. BLE operates in the 2.4 GHz license-free band (ISM band), which is the same frequency range as used in WiFi transceivers. This can cause some interference, resulting in packet loss, which can affect localization accuracy. On the other hand, a solution which utilizes both WiFi and Bluetooth simultaneously, gives better localization accuracy than using either technology individually. Beacon technology is a relatively low-cost solution, a single beacon generally ranging from 100-400 SEK, depending on how advanced the model. It is also a low-power device, as a beacon can have a lifespan of several years [5]. Availability is an advantage, since its features can be utilized by anyone with a smartphone. Broadcasting power can be adjusted on most beacons. This is a way to calibrate beacons for optimal distance estimation and positioning. For example, an estimated beacon has a power ranging between 4 dBm and -40 dBm, and the calibrated beacon ranges between 4 dBm and -30 dBm. Fig. 1 shows data packet structure of iBeacon.

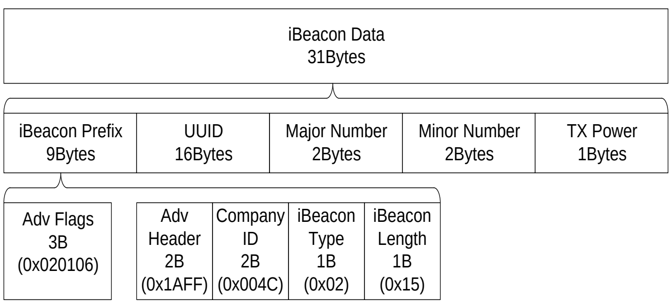

Fig. 1. Data packet structure of iBeacon

B. *System Configuration*

To implement the system, we used DE1-SoC board as the platform. The DE1-SoC board equipped with ARM Cortex-A processor integrated in HPS of the Altera Cyclone® V system on a chip (SoC) FPGA. We used Quartus Prime 16.0 development tool that unified IDE and Eclipse Neon 3 development tool for embedded Linux programing. On Quartus Prime 16.0, we designed FPGA logic circuit using VHDL (VHSIC Hardware Description Language) and generated Handoff of HPS using Qsys. We executed Linux programming with the generated Handoff file and SSH (Secure Shell) communication in Eclipse.

Fig. 2 shows the proposed hardware block-diagram. FPGA logic circuit designed by VHDL connected with HPS and 32-bit bus. The hardware implemented by FPGA receives and selects Beacon data. The data packet broadcasted in 4 Beacon nodes are scanned by observer (BLE module). The scanned data is applied to FPGA logic circuit through UART (Universal Asynchronous Receiver/Transmitter) with synchronization rate of 9600 Hz Baud. UART implemented by DE1-SoC board stores the data word to buffer. The 8-bit data stored in buffer is ASCII code. When the first scan period of BLE module is finished, ASCII code of carriage return is transferred. Filtered Mac address and RSSI value of 4 fixed nodes in the stored string is transferred to HPS with 32-bit bus. The coordinate calculated in HPS is displayed in TFT LCD.

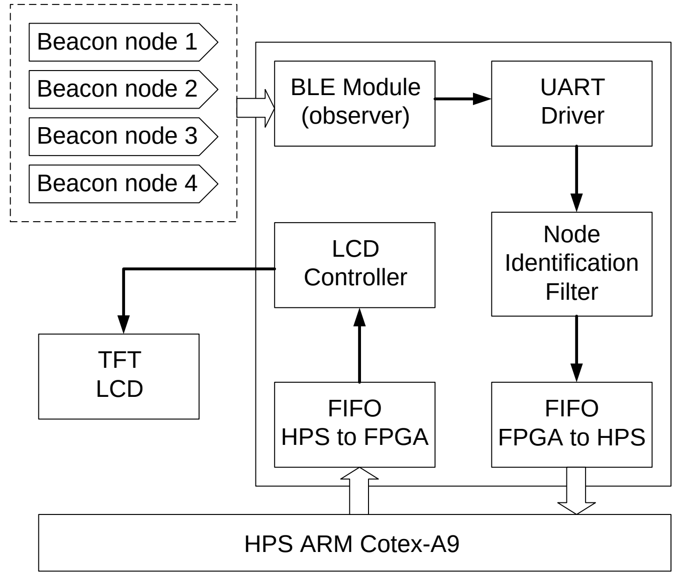

Fig. 2. Hardware block-diagram

Fig. 3 shows the software flowchart of the proposed system. To find the coordinate, the data from FPGA logic circuit is processed in HPS. The identified data with Mac address in FPGA logic circuit has the node numbers. The data in BLE module is randomly scanned. Therefore, beacon data with period of 12ms should store in first-in first-out (FIFO). When each four identified ID is stored in array, the value is retuned. Completing this process, the stabilization of the data is carried out through RSSI rectifying algorithm. Through the improved trilateration algorithm, the accuracy of stabilized data is improved.

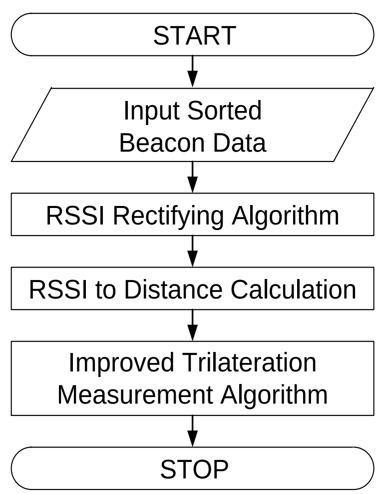

Fig. 3. Software flowchart

III. RSSI FILTERING AND COORDINATE CALCULATION

A. *RSSI Filtering*

RSSI, index of received signal strength, has -99 dBm to -35 dBm. When the signal has strong strength, the signal has the high RSSI value. When beacon and the receiving module are close, RSSI value is high. We can calculate the distance between beacon and receiving module through the RSSI distance conversion formula. Table 1 shows experimental conditions. Experimental space is 4 m x 4 m, the signal only operates the measured beacon.

TABLE I: EXPERIMENTAL CONDITIONS

Receiving mode	BoT- CLE110
Sending module (Beacon)	HM-10
Signal transmission interval	100ms
Distance between Beacon and receiving module	1m
Sending signal strength	-53dBm

To estimate the distance from a beacon, a path-loss model is needed. In this implementation, we adopted the path-loss model [9],

$$RSSI = -(10n\log_{10} d + A) \qquad (1)$$

Where parameter A is the absolute RSSI value represented by dBm at 1m away from the beacon; n is a parameter related to the signal propagation environment and d is the distance from the beacon. In this implementation, we use the method proposed in [10] to estimate the parameters.

The path-loss model with pre-defined parameter in this implementation is

$$RSSI = -(10 \times 2.5\log_{10} d + 30) \qquad (2)$$

Fig. 4 shows RSSI without filtering. We can find unstable signal distribution from Fig. 4.

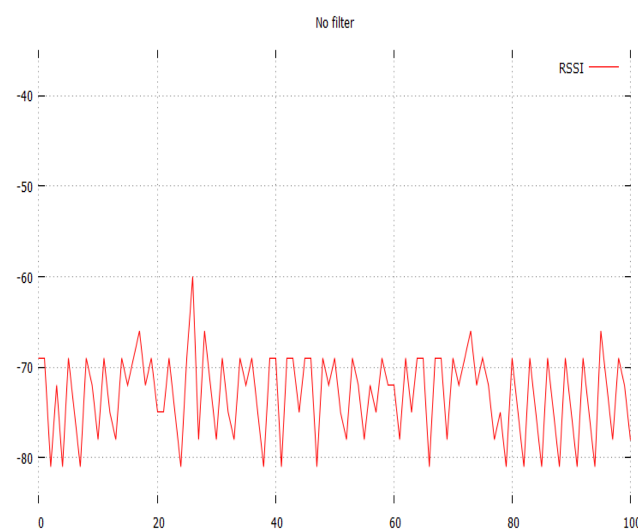

Fig. 4. RSSI without filtering

To stabilize the signal, we adopted Kalmam filtering. Kalman filtering is used for many applications including filtering noisy signals, generating non-observable states, and predicting future states. Filtering noisy signals is essential since many sensors have an output that is noisy too be used directly, and Kalman filtering lets is account for the uncertainty in the signal. Fig. 5 and 6 show Kalman filtering process and codes, respectively, where K is Kalman coefficient.

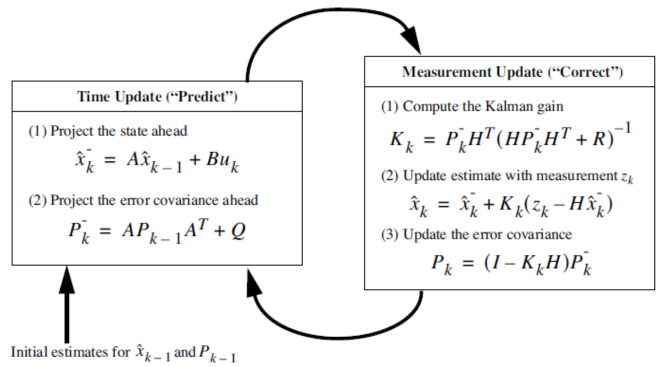

Fig. 5. Kalman filtering process

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P = P + Q
K = P / ( P + R ) ;
X = K * RSSI + ( 1 – K ) * X ;
P = ( 1 – K ) * P ;
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Fig. 6. Kalman filtering code

Initially, we set P to 1.0, Q to 0.001, and R to 0.25. By prediction and update process, error is reduced. Fig. 7 shows RSSI with filtering.

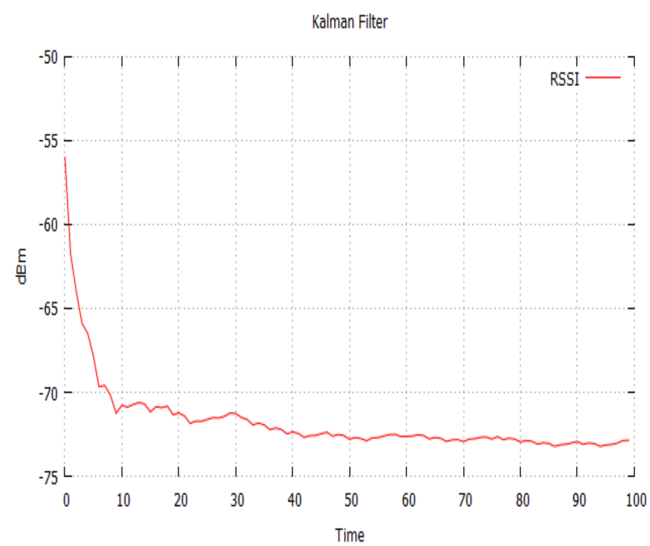

Fig. 7. RSSI with filtering

B. Coordinate calculation

Trilateration algorithm is widely used algorithm for recognizing location. However previous trilateration algorithm has some errors, exact coordinate calculation is difficult. To reduce error and to improve the accuracy, we adopted the improved trilateration algorithm. Fig. 8 shows the calculation of improved trilateration algorithm.

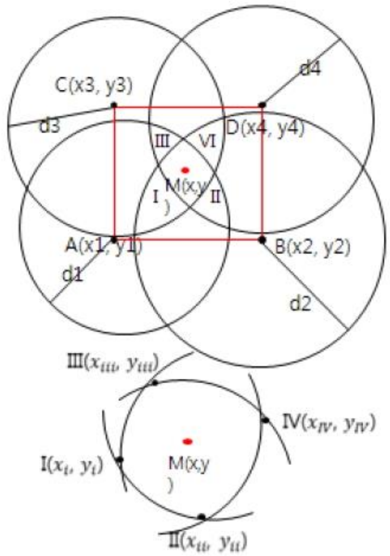

Fig. 8. Calculation of improved trilateration algorithm

This algorithm is set up as a zone with nine beacons and requires four coordinates. Due to the nature of the wireless signal, the accuracy decreases with the distance. Therefore, as a first step, we use the nine beacon signals to determine which zone the user is in, and then use four beacon signals in that zone to obtain the coordinates. The next step is to apply the improved trilateration algorithm to obtain the coordinates.

We can calculate the distance with Eq. (3) and modify Eq. (4). Finally, we can calculate the coordinates with Eq. (5).

$$d_1^2 = (x_i - x_1)^2 + (y - y_1)^2 \qquad (3)$$
$$d_2^2 = (x_i - x_2)^2 + (y - y_2)^2$$

$$x_i = \frac{d_1^2 - d_2^2 + x_2^2 - x_1^2}{2(x_2 - x_1)} \qquad (4)$$

$$x = \frac{x_i + x_{ii} + x_{iii} + x_{iv}}{4} \qquad (5)$$
$$y = \frac{y_i + y_{ii} + y_{iii} + y_{iv}}{4}$$

Fig. 9 shows the simulation results of the improved trilateration algorithm. In this work, we assume that there was a user in one of the four zones. We received one hundred RSSI data from four beacons installed at any given coordinate, and then simulated them using an improved trilateration algorithm. As simulation result, we can find that error range is reduced to less than 0.5 m.

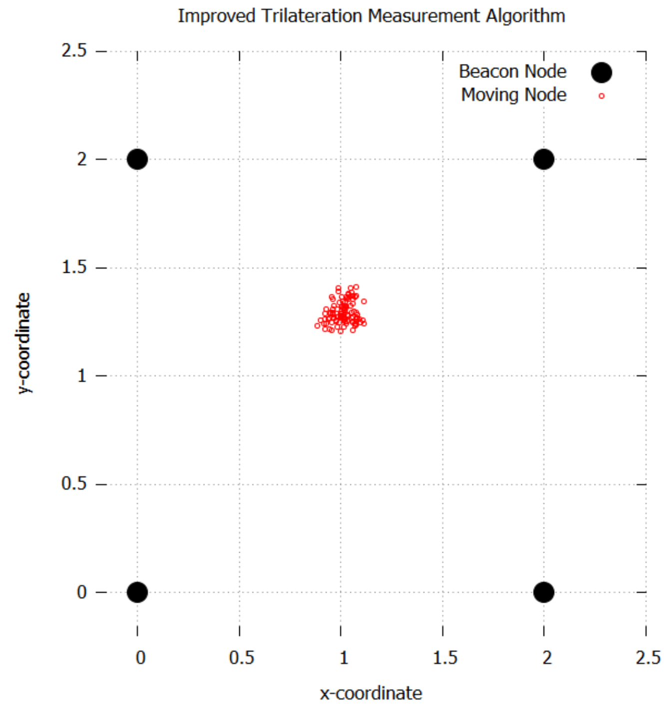

Fig. 9. Simulation results of the improved trilateration algorithm

IV. Conclusion

We described FPGA implementation of BLE beacon-based indoor posing system. The accuracy of indoor posing system is easily affected by several signal interference. For the accuracy of the system, we adopted Kalman filtering technique and the improved trilateration algorithm. The improved trilateration algorithm reduces the error range. Intel's FPGA design tools Quartus II and DE1-SoC boards are used in this system. Future works are to enhance the reliability using secondary sensors such as WiFi, camera, and infrared sensors.

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