*Sensors and Materials*, Vol. 35, No. 3 (2023) 703–722
MYU Tokyo



S & M 3205

# Using iBeacon Components to Design and Fabricate Low-energy and Simple Indoor Positioning Method

Cheng-Yi Chen,[1,2] Min-Hsien Cheng,[3] Marvin Cheng,[4*] and Cheng-Fu Yang,[5,6**]

[1]Department of Electrical Engineering, Cheng Shiu University, Kaohsiung City 83347, Taiwan
[2]Center for Environmental Toxin and Emerging Contaminant Research, Cheng Shiu University, Kaoshiung 804, Taiwan
[3]Department of Mechanical Engineering, National Kaohsiung University of Science and Technology, Kaohsiung 80778, Taiwan
[4]Department of Engineering, Embry-Riddle Aeronautical University, Daytona Beach 32114, Florida, USA
[5]Department of Chemical and Materials Engineering, National University of Kaohsiung, Kaohsiung 811, Taiwan
[6]Department of Aeronautical Engineering, Chaoyang University of Technology, Taichung 413, Taiwan

(Received September 12, 2022; accepted October 25, 2022)

***Keywords:*** indoor positioning method, low energy, iBeacon components, virtual digital electronic fences, fingerprint database

Indoor positioning technology plays an important role in many industrial applications of device localization in different environments. An appropriate indoor positioning system can significantly reduce the total cost of deployment and required searching time by sharing individual information. To achieve these goals, the system must have three important properties: light weight, low cost, and high precision. In this paper, an enhanced triangulation technique with strength signatures of transmitted signals is proposed. The proposed approach can simplify the indoor positioning algorithm as well as improve the positioning precision in planar locations. The physical system integrates a blind device and multiple established base stations using iBeacon components. Wearable devices or equipment tags moving in a targeted area can be considered blind (observation) devices. The base stations placed at certain locations can form virtual digital electronic fences and effectively receive iBeacon signals from blind devices. Using the measured strength of received signals and corresponding topology analysis, the location of a blind device can be accurately located in real time. In the proposed positioning method, the positioning area is divided into rectangular or triangular subareas with a side length of 8–10 m. Each area uses one side as the place of base station installation and establishes a loss value database of three or four endpoints measured in the area. Then, the coordinates of the blind device can be effectively estimated with a specified precision by the proposed triangulation method and the known fingerprint database. Experimental results show that this innovative positioning method has an average error of less than 0.5 m in the worst scenario. The proposed indoor positioning method can also be easily used in various environments.

*Corresponding author: e-mail: hmcheng@ieee.org
**Corresponding author: e-mail: cfyang@nuk.edu.tw
https://doi.org/10.18494/SAM4109

ISSN 0914-4935 

## 1. Introduction

The global positioning system (GPS) is well known for its positioning and tracking functions in various applications. It has been widely adopted by navigation systems in ships, aircraft, and motorized vehicles for decades. For civilian users, the positioning accuracy of current GPS technology is within a few meters. However, GPS cannot be applied to indoor activities since satellite signals cannot be acquired, resulting in unsatisfactory accuracy in indoor environments. The demand for indoor positioning is currently dramatically increasing due to the rapid development of smart cities,[1] home care systems,[2] health monitoring,[3,4] hospital patient-tracking technology,[5] factory equipment positioning,[6] and so forth. Indoor positioning systems can also help administrators track the locations of equipment and monitor/identify patients' locations for urgent care or lifesaving.

In the past decade, various indoor positioning technologies have been developed using different wireless techniques, such as ZigBee, Bluetooth, IR radiation, and Wi-Fi.[6] For instance, a radio technology employing ultra-wideband signals has been used in applications of short-range positioning with very low energy.[7] The drawback is that its multipath reception can affect the positioning accuracy due to the measurement signal between emitter and receivers. One research group has integrated an IR radiation emitter and receiver to build indoor positioning systems and determine the positions of specific objects in a targeted area.[8] Nevertheless, the multipath errors of this expensive system hardware and its high maintenances costs limit the localization accuracy and applicability. One low-power area network protocol, ZigBee, based on the IEEE 802.15.4 standard[9,10] has been developed to mimic the behavior of bees to form a communication network. The major advantages of a ZigBee network include a closer range, less complexity, self-organization, low power consumption, and lower data communication rate. The positioning performance is affected by the environment in which the application is used. In addition to these technologies developed for specific applications, the position detection of objects using Wi-Fi (IEEE 802.11) wireless communication has also been investigated with the aim of improving interoperability among wireless network products.[11] One major disadvantage of Wi-Fi technology is that the signal is strong enough to penetrate human bodies. An indoor positioning system based on this technology can be inaccurate due to its high power.[12] In addition to these popular technologies, Bluetooth (IEEE 802.15) is another tool that allows data exchange between fixed and mobile devices within a short range. Bluetooth devices can be used to build personal area networks using UHF radio waves, and the frequency band is between 2.4 and 2.485 GHz.[13] Using Bluetooth, two or more devices can be connected to form a decentralized network with one of the devices simultaneously acting as a master and as a slave in the network. However, these indoor positioning technologies often have high maintenance costs and energy consumption. The problem of high energy consumption has recently been mitigated by the latest revision of Bluetooth. By adopting the standard of 6LowPAN, a low-power Bluetooth area network based on the IPv6 protocol can be implemented. A button battery can provide sufficient power to a Bluetooth device for more than two years.[14] Its transmission rate has also been enhanced by recent standards. Owing to all these advantages, Bluetooth is considered as an excellent candidate for indoor positioning technology.

In this study, to implement an indoor positioning system using Bluetooth, an iBeacon component, introduced by Apple Inc. in 2013, was adopted to build base stations. iBeacon is a low-power and low-cost signal transmitter that can be detected by nearby handheld electronic devices. Because the iBeacon system is a set of protocols with a low-power and low-cost signal transmitter, it can be used in indoor positioning systems. This technology enables a smartphone or other communication devices to execute the corresponding commands within the sensing range of an iBeacon base station. An iBeacon device also has the advantage of providing precise positioning through Bluetooth low-energy (BLE) transmission.(15) Its BLE components are used to transmit signals from the base stations to observation devices. The base stations are beacon nodes serving as information towers, which broadcast beacon signals so that client devices can actively receive beacon signals without searching. When a human user carries a mobile device to the targeted area where the beacon signal can be received, a corresponding program in the mobile device can then actively prompt the user whether to access the signal network. However, such an application only allows the user to select the information for short, medium, or long distances from the device.(16) Many research groups have investigated how the accuracy of indoor positioning with BLE can be enhanced.(17–25) Guo *et al.* used the moving-average signal filtering method to eliminate the fluctuation of collected received signal strength indication (RSSI) values,(17) which were then compared with a database of strength signatures of transmitted signals using the K-nearest neighbor algorithm. The position of the targeted object can thus be estimated. Li *et al.* presented improved positioning accuracy by continuously adjusting the signature database through a neural network mechanism.(18) Tseng and Yen filtered the localized RSSI values through a Gaussian mixture model and used the Akaike information criterion (AIC) to reduce multipath effects.(19) They also adopted a quadrilateral positioning algorithm to project the target position. Although all these methods can improve the positioning accuracy, the cost of deployment can be significant if the number of beacon nodes is high or a beacon node must be used in a limited environment. Thus, accurate positioning with a limited number of beacon nodes becomes important to overcome interferences from environmental conditions.(20)

Considering the interference from the surrounding walls, the floor, diverse signals, and existing obstacles in the targeted area, an apparent beacon position estimation method has been studied to improve the accuracy by eliminating the errors resulting from signal reflections, multipathing, and inaccurate determination of beacon positions.(21) Chen *et al.* measured the transmitted power of different BLE signals when the attenuation levels of transmitted signals were different to establish an RSSI signature database.(22) By detecting the deviation of the received signal strength, the multipath effect can be reduced and the position of the targeted device can be estimated with 0.5 m positioning accuracy. However, it can be costly to set up an applicable environment and the condition of the area can still be limited. Thus, Gui *et al.* calculated the possible values of incidence and reflection by gridding an experimental site.(23) By considering a multiplicative distance-correction factor, an experimental system that can reduce the multipath effect and the unstable RSSI measurements of received signals was set up. The disadvantage of such a gridded area approach is its long calculation duration while positioning. To reduce the calculation load, Park *et al.* proposed a three-loop positioning method based on a triangulation positioning method. The measured RSSI value is used to allow a single node to synthesize two concentric circles of different diameters to form a circular ring.[24] The position of the targeted device can then be estimated as the intersection of individual measurements. To enhance the accuracy of the estimated position using a triangulation technique, a series of post-processor filters were proposed by Aitor and Diego.[25]

To build a low-cost indoor positioning system with satisfactory accuracy, in this study, we proposed a simple triangulation algorithm to improve the accuracy of location detection. By measuring the signal strengths of a blind device from multiple base stations, the projected position of the blind device can be calculated by a host server. This structure can reduce the computational load for individual devices while maintaining positioning accuracy. To ensure an accurate projected position of a blind device, a signature database of both RSSI and TxPower values was established at designated locations. Once the database was established, an indoor positioning algorithm using the strengths of measured RSSI values was employed to determine the positions of the blind devices in the targeted area. The position error estimated by the algorithm was less than 1 m. Such a method can help locate users and pieces of equipment in a building in healthcare applications. The important novelty of the proposed system is that the directional signal power values of base stations from blind devices are considered to enhance the accuracy with low-loss conditions using the simple positioning method.

The content of this paper is organized as follows. In Sect. 2, the architecture of the proposed indoor positioning system is introduced, then the modeling positioning algorithm for the experimental area is addressed in Sect. 3. In Sect. 4, the experimental results are used to demonstrate the advantages of the proposed system. Finally, experimental outcomes are summarized and directions for future work are suggested in Sect. 5.

## 2. Architecture of Indoor Positioning System

The proposed indoor positioning system integrates several devices, including a blind device, multiple base stations, and a host server, which emit and receive Bluetooth signals using iBeacon components. The blind device was fabricated to actively send messages to surrounding base stations. The base stations monitor the messages sent by the blind device and pass packets to a host server. Both the blind device and the base stations were implemented using Raspberry Pi microcomputers, and iBeacon components were adopted to transmit messages. An iBeacon component is a micro-positioning signal transmitter designed on the basis of Bluetooth 4.0 or a newer version. It uses BLE signals to implement wireless communication,[26] which operates within the frequency band between 2.4 and 2.4835 GHz. The iBeacon component is embedded in a blind device placed in the targeted area, and the device continuously broadcasts packet messages to surrounding devices at a constant frequency. However, the blind device only transmits messages and does not have any direct connection with other devices. Therefore, as long as the BLE-receiving function on the base station is active, the position information of the blind device can be received and identified within its communication range. The identification code in a packet message can be discriminated by the program installed on the base station, and the code included in the packet can help the base station identify the source and related information.

An iBeacon packet is defined as a fixed-size packet (31 bytes) expressed as hexadecimal values. The startup code of the packet is 1E (1 byte). After the first byte, the packet is divided into five parts, which are the iBeacon prefix (9 bytes), UUID (16 bytes), Major (2 bytes), Minor (2 bytes), and TxPower (1 byte). Note that UUID, Major, and Minor can be coded to meet the requirements of specific applications.[26] The one-byte TxPower part represents the power of the transmitted signal, which is the RSSI measured 1 m from the iBeacon component. The RSSI value automatically changes with the transmission power of the iBeacon component. The iBeacon packets broadcast by the blind device are received by the base stations. Packets collected by individual base stations are sent to the host server to determine the projected position of the blind device. Figure 1 shows the topological approach of the proposed indoor positioning in this study. To minimize the noises caused by the interference of wireless transmission using the same frequency band of Wi-Fi, a physical Ethernet connection is used to connect base stations and the host server. All the broadcasting, packet receiving, and projecting functions are coded using Python. Figure 2 shows the processing flow charts of both the blind device and base stations.

The operational procedures of the blind device include three steps, as shown in Fig. 3: 1) input the command to stop scanning, 2) adjust the Bluetooth status to be broadcast only and do not accept any connection (leadv 3), and 3) input the iBeacon command code so that the messages are periodically transmitted. The message between the first and the last bytes, which are 1E and C5, respectively, is the iBeacon packet identification code. In Fig. 3, the iBeacon prefix is fixed as (02 01 1A 1A FF 4C 00 02 15) or (02 01 06 1A FF 4C 00 02 15) in this case. Here, (02 01) in the beginning is the Bluetooth control flag and (1A 1A FF 4C 00) or (06 1A FF 4C 00) indicates the manufacturer of the Bluetooth device. The last two bytes (02 15) are the iBeacon protocol. The formats developed by individual companies can differ. Thus, different iBeacon sources can be easily identified from the received iBeacon packets. This also means that corresponding locations, functions, and product types can be actively identified by the coded functions on a mobile device.

The base stations continually actively listen to the broadcasting blind device. They can determine whether the received information must be transmitted to the host server. If a signal is

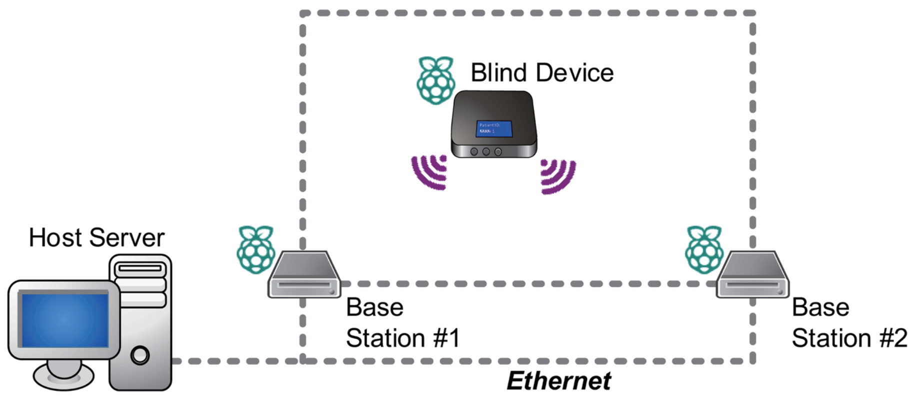
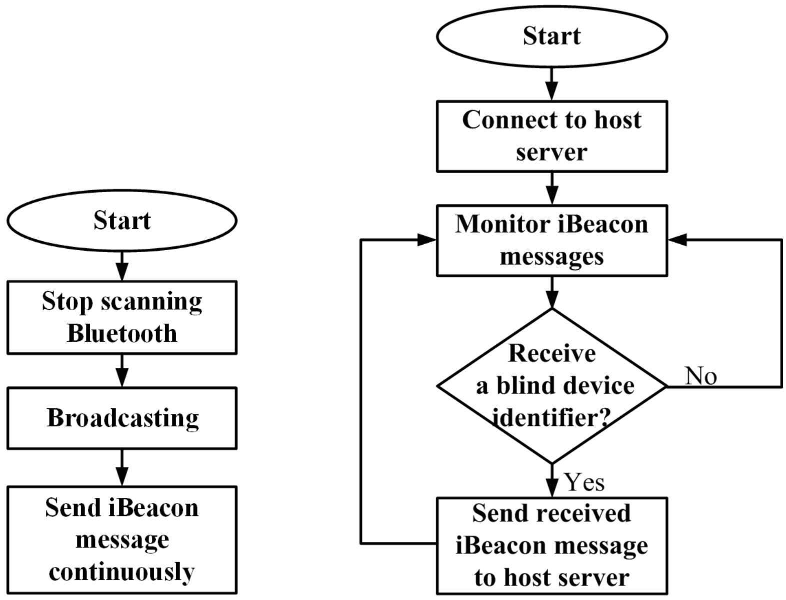
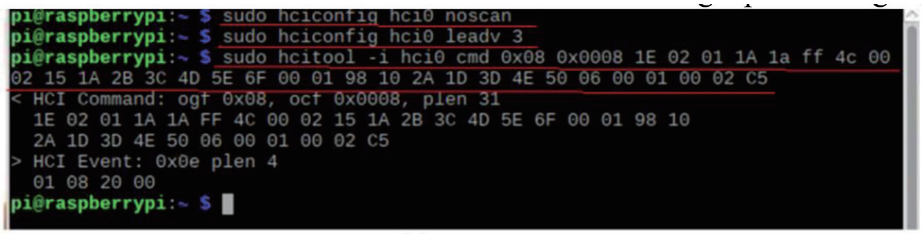



Fig. 1. (Color online) Architecture of the proposed indoor positioning system.

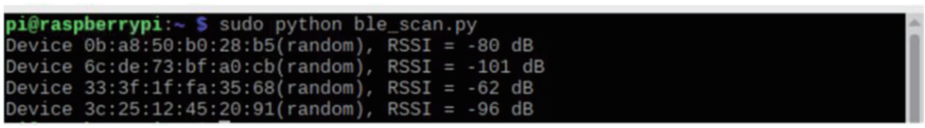



(a) (b)

Fig. 2. Flow charts of the indoor positioning system: (a) blind device and (b) base stations.




(a)




(b)

Fig. 3. (Color online) (a) Format of an iBeacon packet used by the blind device and (b) received RSSI values sent by iBeacon components.

sent by a blind device allowed in the network, then the base stations transmit the received data to the server. Figure 3(b) shows part of the data received from a blind device. As shown in this figure, a Python program installed on the base station actively scans Bluetooth signals and displays the scanned information value on a terminal window. The device address (dev.addr) "0b:a8:50:b0:28:b5" and the address type (dev.type) "random" are both listed. The Bluetooth address type is mainly divided into random and public types. The public type is defined in the Bluetooth standard protocol. For example, while sending an iBeacon advertising package, the

Bluetooth address type must be public. The information shown by dev.rssi is the RSSI value after an iBeacon packet is received by a base station. Once an iBeacon packet is received from any known blind device, the base station then transmits the received RSSI value to the host server. Based on the RSSI values collected from all base stations, a program on the host server processes the packets and obtains the indoor location of the blind device using a positioning algorithm.

To determine the precise location of a blind device, directional information of the device is required. The directional information of an iBeacon component can be evaluated using the RSSI values received by receiving devices placed at the same distance at different directions. According to experimental results, RSSI values received by a base station differ when a blind device is placed at a different direction with an identical distance. This also means that the energy losses along paths of certain angles can be higher while transmitting. Table 1 lists the received RSSI values of a blind device placed 1, 2, and 5 m from a base station at different directions. It is observed that the relative RSSI loss value is smaller if the emitting device is placed at 0 and 180° and larger when it is placed at 90 and 270°. Thus, the measured RSSI loss value varies with the direction. The values are stored as a database for use as a map of signal strength. This database can be used as a signal signature to estimate the location of a blind device from known RSSI values from two directions. Thus, considering the orientation effect, we suggest that the antennas of the base stations be aligned parallel to the ground so that the measured RSSI data is more accurate for a given distance, as shown in Fig. 4.

Table 1
RSSI values (dB) of two Raspberry Pi microcomputers in different directions.

| Distance (m) | Rotational angle (deg.) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0 | 45 | 90 | 135 | 180 | 225 | 270 | 315 |
| 1 | −61.11 | −67.33 | −69.66 | −62.07 | −60.14 | −61.83 | −64.51 | −68.79 |
| 2 | −65.80 | | −72.64 | | −65.62 | | −74.95 | |
| 5 | −71.45 | | −75.21 | | −69.80 | | −75.43 | |

Fig. 4. (Color online) Physical setup of the base station using a Raspberry Pi microcomputer.

## 3. Development of Indoor Positioning

The proposed positioning system is developed in a two-phase approach. Figure 5 shows the process for the individual phases. The first phase is the modeling phase. In this phase, the strengths of transmitted signals of the blind device at designated locations were acquired by the base stations. Two values, TxPower and RSSI, were recorded in the host server when the blind device was placed at different locations to build a fingerprint database system for compensating the receiving signal directionality of the base station using the maximum and minimum RSSI values. For a fixed distance between the blind device and the base station, the measured RSSI value changes when the blind device is placed in a different direction. The different RSSI value can then be used as a reference to determine the relative direction of the blind device. Once the database is established, the strength signature of transmitted signals (SSTS) can be used to project the possible location of an iBeacon component in the targeted area. The second phase is the positioning phase. In this phase, individual base stations transmit the received RSSI values to a host server. By comparing the strength signatures stored in the database, the position of the source signal can be projected using a positioning algorithm, which is described in the following sections.

### 3.1 Indoor positioning concept

To determine the position of the blind device, dimensional information must be defined beforehand. Figure 6 shows the indoor localization configuration mapped from a 3D space to a 2D plane when the vertical position of the iBeacon component on the blind device is a known parameter. In a real environment, the vertical location of equipment or personnel carrying a blind device can generally be given or approximated in advance. For instance, the average

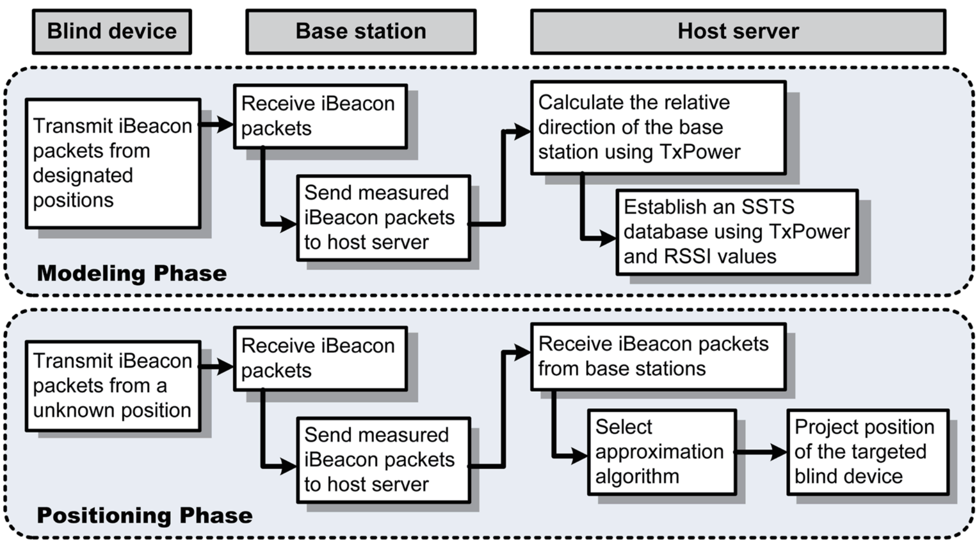



Fig. 5. (Color online) Process of the two-phase approach of the proposed indoor positioning system.

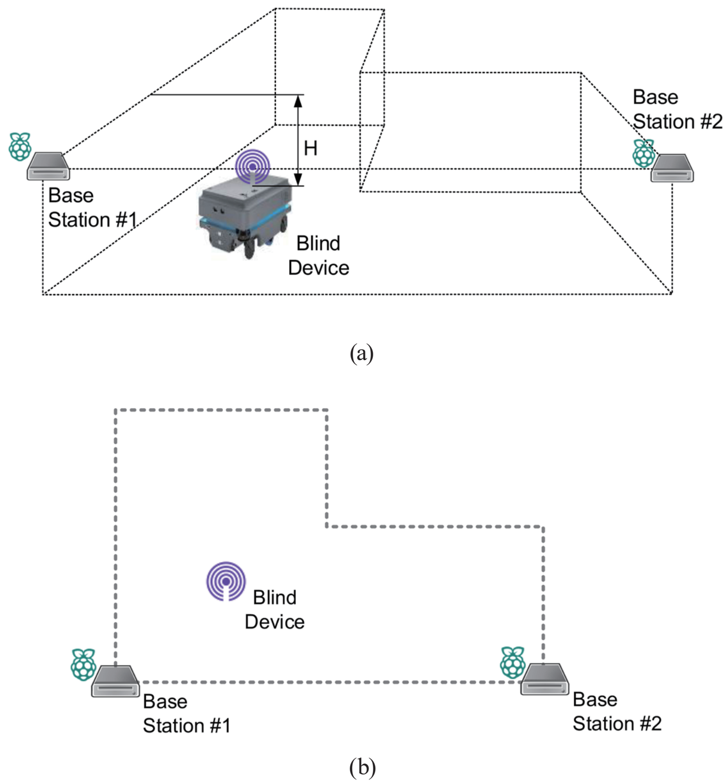



Fig. 6. (Color online) Localization of the proposed indoor positioning system in (a) 3D space and (b) 2D plane.

vertical position of a mobile phone, where the blind device is usually located, carried by a person is about 1 m. Therefore, indoor localization can be realized in a 2D plane using a simple algorithm to reduce the computational load while maintaining acceptable accuracy.

To determine the location of the blind device in a 2D plane, base stations are located at selected corners of the targeted area. Once the locations of base stations are determined, the targeted area can be approximated by the combination of multiple rectangular and triangular subareas. To divide the area into a corresponding number of triangular and rectangular shapes, the receivable range of an iBeacon component must be identified. The signal of an iBeacon can be strong if the distance is 6–8 m, and the maximum distance is suggested to be no more than 12 m.[15] We suggest that the area division can be approximated by the positioning spatial plane. Thus, the distance calculated from the received RSSI values can be used to roughly determine the area of the blind device.

### 3.2 Modeling phase

To provide an accurate indoor positioning result, a map of SSTS in the targeted area is necessary. From Table 1, it is clear that the strengths of transmitted signals differ if the blind device is placed in different directions with the same distance. The measured strength may also vary slightly when a base station is placed at different locations. The distribution of the signal strength can be used to form a map to estimate the location of an iBeacon component. In this section, we discuss the modeling of the strength distribution received by equipped base stations. However, it is unlikely that signals can be measured at all locations when there are numerous base stations. Thus, a model that estimates the precise locations of iBeacon components must be established for a limited number of base stations. To determine the directionality of an iBeacon device, we assume a linear decay rate with respect to distance of a transmitted signal measured at the same distance in different directions. The geometric configuration of the corresponding directional measurements is shown in Fig. 7. When a base station is placed at point $P_1$, the RSSI values received from an iBeacon component located at positions $P_4$ and $P_2$ are −50 and −56 dB, respectively. Although the measured strength of the BLE signal is assumed to be equally distributed on a circular path with a constant radius, the experimental results show different values in different directions. Considering the directional effect, it is assumed that the RSSI value received has a linear distribution between $P_2$ and $P_4$. By approximating the values along the path between $P_2$ and $P_4$ as a straight line, a right-angle triangle $\Delta P_1P_2P_4$ can be formed for approximation. By dividing the line $\overline{P_4P_2}$ into five equal segments, the received RSSI values can be linearly derived from −50 dB at $P_4$ to −56 dB at $P_2$. With this directional approximation, the error between the measured RSSI value and the approximate value at each point is within 0.5 dB. This approximation can be used to evaluate the direction information and is adopted by the indoor positioning method in this study.

To derive the RSSI value from a received iBeacon packet, a corresponding Python program is implemented in the base stations. When sending an iBeacon signal from an application that pushes advertisements to nearby devices through BLE, the TxPower value can be derived from the 30-byte iBeacon packet, as discussed in Sect. 2. The RSSI value can be calculated using the following equation:

$$RSSI = -\left(10 \times n \times \log d + TxPower\right), \tag{1}$$

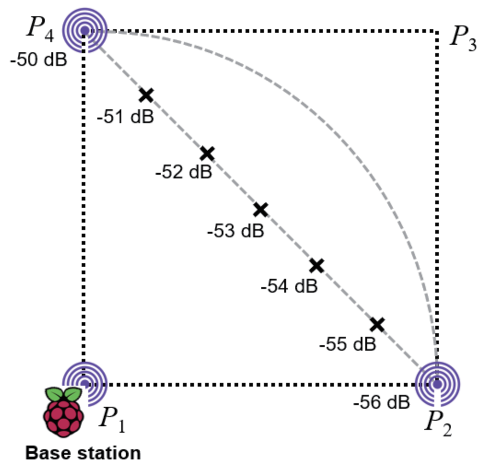



Fig. 7. (Color online) Geometric configuration of directionality of iBeacon component using Raspberry Pi microcomputer.

where $n$ is the path loss constant and is assumed to be 1.4, $d$ is the distance in meters between the blind device and the base station, and TxPower is the energy lost in dB at a distance of 1 m from the transmitting device. To evaluate the distance based on the measured RSSI, Qathrady *et al.* proposed the following distance approximation based on the RSSI value:(26)

$$d = 0.89976 \times \left( \frac{RSSI}{TxPower} \right)^{7.7095} + 0.111 \cdot \tag{2}$$

Thus, the distance of the blind device can be estimated from the received RSSI value. In addition, because the RSSI values differ when the signal is transmitted from different directions of the base station (Table 1), the transmitted power (TxPower) can also differ in different directions. Thus, if the distance and the measured RSSI value are both known, TxPower along a specific direction can be determined. For example, as shown in Fig. 7, the approximated RSSI values from $P_4$ to $P_2$ can be used to determine TxPower, and the database of the SSTS can be derived. In the modeling phase, the distance in Eq. (2) is a given parameter. Once the RSSI values in the horizontal and vertical directions relative to base stations at designated positions are acquired, the distribution of TxPower in the targeted area can be approximated. The distribution of TxPower can then be used as a map in an indoor positioning system.

### 3.3 Positioning phase

In the positioning phase, the only acquired information is the RSSI values received by the base stations located at designated locations. Using two RSSI values received at two locations, the indoor positioning system should be able to determine the location of the blind device. Traditional triangulation methods must deal with spatial information in the $x$-, $y$-, and $z$-axes. To simplify the calculation, the spatial information is converted into a planar configuration with the height information as a predetermined property. This approach can greatly reduce the required calculation load. In this study, two geometric approaches are proposed to project the location based on the acquired RSSI values.

#### 3.3.1 Rectangle positioning area

To determine the position of an iBeacon component placed in the targeted area, a geometric projection method using the SSTS database is proposed in this study. As long as the hardware and environmental conditions in the targeted area are not modified, TxPower of the iBeacon component remains unchanged. As discussed in the previous section, TxPower values in the horizontal and vertical directions, respectively denoted as $T_H$ and $T_V$, have been derived and stored in the SSTS database. Figure 8 illustrates that a blind device can be located by geometric projection using rectangular localization with two base stations located at $A$ and $B$. If the blind device is located at $D$, the coordinates of this position can be defined as $(x, y)$ relative to point $A$. The distance between the blind device and the base stations can be estimated from Eq. (2) using the RSSI and TxPower values if the TxPower value relative to $A$ ($T_{DA}$) is available. That is,

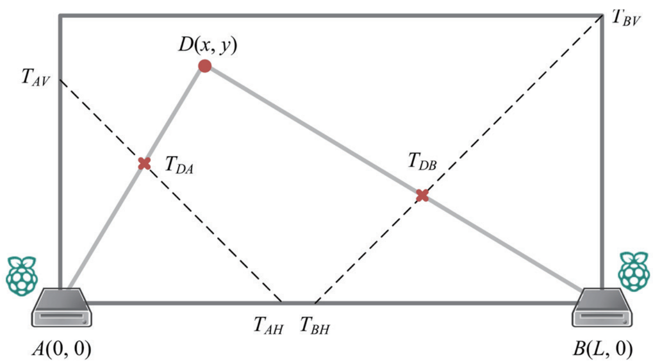



Fig. 8. (Color online) Relationship between blind device and base stations.

$$d = 0.89976\left(\frac{RSSI_{DA}}{T_{DA}}\right)^{7.7095} + 0.111 = \sqrt{x^2 + y^2 + H^2}\ , \tag{3a}$$

where RSSIDA is the measured RSSI value at $A$ and $H$ is the height difference between the base station and the blind device. Similarly, the base station located at point $B$ can also be used to form a hypothetical triangle $\Delta BT_{BV}T_{BH}$ to judge the direction from the blind device located at a known distance with measured RSSI and TxPower values. Using the RSSIDB value received by the base station at $B$ and TxPower values relative to $B$ ($T_{DB}$), the distances between the blind device and the base stations can be obtained as

$$d = 0.89976\left(\frac{RSSI_{DB}}{T_{DB}}\right)^{7.7095} + 0.111 = \sqrt{(L - x)^2 + y^2 + H^2}\ , \tag{3b}$$

where $L$ is the horizontal distance between base stations $A$ and $B$. Therefore, Eqs. (3a) and (3b) can be used to obtain the coordinates of the blind device at point $D$ through the TxPower values of $T_{DA}$ and $T_{DB}$ and the measured RSSI values. However, the values of TxPower at $T_{DA}$ and $T_{DB}$ from the blind device at $D$ cannot be obtained directly. In this configuration, TxPower values of existing vertical and horizontal blind devices respectively located at $T_{AH}$ (0°) and $T_{AV}$ (90°) were calculated from corresponding RSSI values beforehand. The TxPower ($T_{DB}$) value transmitted from point $D$ to point $B$ can also be approximated from the values at $T_{BV}$ (90°) and $T_{BH}$ (180°).

To determine the precise location of the blind device, Eqs. 3(a) and 3(b) must be modified. In these two equations, $x$, $y$, $T_{DA}$, and $T_{DB}$ are all unknown parameters. The TxPower values, $T_{DA}$ and $T_{DB}$, cannot be derived directly from measurements unless the precise location is available. Thus, an indirect approach using an isosceles right-angle triangle is proposed. Figure 9(a) shows measurements of the TxPower values from two endpoints of the isosceles right-angle triangle $\Delta AT_{AV}T_{AH}$. The directional TxPower of the blind device at $D(x, y)$ is $T_{DA}$, which is at the intersection of the lines $\overline{T_{AV}T_{AH}}$ and $\overline{AD}$. According to the relationship of similar triangles, TxPower can be approximated as follows:

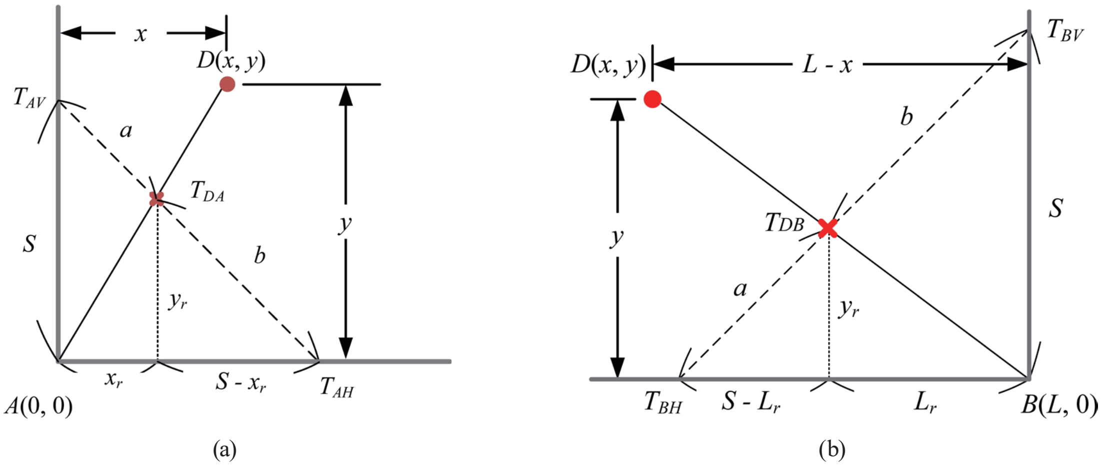



Fig. 9. (Color online) Rectangular configurations of position projection using directional TxPower with respect to the base stations located at (a) *A* and (b) *B*.

$$T_{DA} = T_{AV} + \frac{a}{a+b}\left(T_{AH} - T_{AV}\right) = \frac{T_{AV}\,y + T_{AH}\,x}{x+y}. \tag{4}$$

Using the same approach, the directional TxPower of the blind device at *D* with respect to base station B can be approximated by

$$T_{DB} = \frac{T_{BH}L - T_{BH}x + T_{BV}\,y}{L+y-x}. \tag{5}$$

By substituting the distance and TxPower in Eqs. (3a) and (3b) into Eqs. (4) and (5), the following equations are obtained:

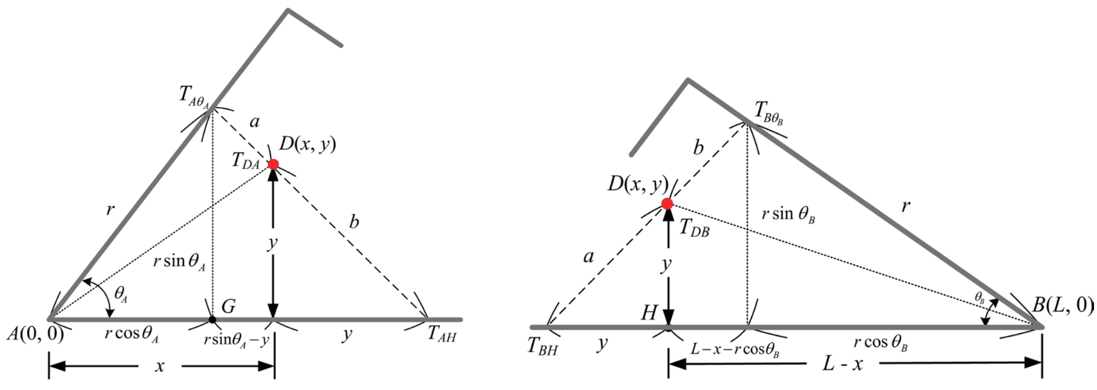
$$\sqrt{x^2+y^2+H^2} = 0.89976\left(\frac{(x+y)RSSI_{DA}}{T_{AH}\,x + T_{AV}\,y}\right)^{7.7095} + 0.111, \tag{6a}$$

$$\sqrt{(L-x)^2+y^2+H^2} = 0.89976\left(\frac{(L+y-x)RSSI_{DB}}{T_{BH}L - T_{BH}x + T_{BV}\,y}\right)^{7.7095} + 0.111. \tag{6b}$$

By solving these simultaneous equations, the coordinates ($x$, $y$) of the blind device at *D* located in the rectangular area can be obtained.

### 3.3.2 Triangular positioning area

In additional to a rectangular configuration, the targeted area can sometimes be configured as a triangular shape as shown in Fig. 10(a). One important issue of the triangular configuration




(a) (b)

Fig. 10. (Color online) Triangular configurations of position projection using directional TxPower with respect to the base stations located at (a) point $A$ and (b) point $B$.

is that the targeted area must include the location of the blind device at D, which is located at ($x$, $y$) relative to point $A$. In this configuration, the angle of the apex $A$ is $\theta_A$ and the length between the endpoint and $A$ is $r$. One of the required values of the transmitted power, $T_{AH}$, can still be derived directly from the SSTS database. The other value, $T_{AV}$, must be adjusted to $T_{A\theta_A}$ since the value is no longer the TxPower value in the vertical direction. This value must be approximated by the method shown in Sect. 3.3.1. Thus, a triangular area that combines the values of TxPower at two endpoints forms an isosceles right-angle triangle area $AT_{A\theta_A}T_{AH}$. Assuming that the blind device at $D$ ($x$, $y$) is located on the line $\overline{T_{A\theta_A}T_{AH}}$, then TxPower $T_{DA}$ can be approximated using the relationship of similar triangles. Thus, the directional TxPower of point $D$ can be determined as

$$T_{DA} = T_{A\theta_A} + \frac{a}{a+b}\left(T_{AH} - T_{A\theta_A}\right) = \frac{T_{A\theta_A} y\sin\theta_A + T_{AH} x\sin\theta_A - T_{AH} y\cos\theta_A + T_{A\theta_A} y\cos\theta_A}{x\sin\theta_A + y\sin\theta_A}, \tag{7}$$

where $a$ is the distance between $D$ and $T_{A\theta_A}$ and $b$ is the distance between $D$ and $T_{AH}$.

Similarly, Fig. 10(b) shows the configuration when the base station is placed at $B$. The directional TxPower $T_{DB}$ sent by the blind device at point $D$ measured by $B$ can be approximated as

$$T_{DB} = \frac{T_{BH} L\sin\theta_B - T_{BH} x\sin\theta_B + T_{B\theta_B} y\cos\theta_B + T_{B\theta_B} y\sin\theta_B - T_{BH} y\cos\theta_B}{\left(L - x + y\right)\sin\theta_B}, \tag{8}$$

where $T_{B\theta_B}$ is the directional TxPower measured at $B$ with angle $\theta_B$. By substituting Eqs. (7) and (8) into Eqs. (3a) and (3b), they become

$$\sqrt{x^2+y^2+H^2}$$
$$=0.89976\left(\frac{\left(x\sin\theta_A+y\sin\theta_A\right)RSSI_{DA}}{T_{A\theta_A}y\sin\theta_A+T_{AH}x\sin\theta_A-T_{AH}y\cos\theta_A+T_{A\theta_A}y\cos\theta_A}\right)^{7.7095}+0.111, \tag{9a}$$

$$\sqrt{\left(L-x\right)^2+y^2+H^2}$$
$$=0.89976\left(\frac{\left(L-x+y\right)\sin\theta_B RSSI_{DB}}{T_{BH}L\sin\theta_B-T_{BH}x\sin\theta_B+T_{B\theta_B}y\cos\theta_B+T_{B\theta_B}y\sin\theta_B-T_{BH}y\cos\theta_B}\right)^{7.7095}+0.111. \tag{9b}$$

After solving the simultaneous equations [Eqs. (9a) and (9b)], the coordinates ($x$, $y$) of the blind device at $D$ can be obtained.

### 3.3.3 Numerical method of positioning

For the rectangular and triangular configurations, Eqs. (6a) and (6b) and Eqs. (9a) and (9b) can be used to describe the relationship between the position of the blind device and the measured TxPower, respectively. Then, both the $x$ and $y$ coordinates can be obtained. However, these equations are difficult to solve due to their nonlinear relationships with the power terms. To solve for the positions, Eqs. (6) and (9) can be transformed to functions $F_1(x, y) = 0$ and $F_2(x, y) = 0$ for base stations at $A$ and $B$ since the other parameters are known in advance. Then, the scipy.optimize.fsolve method using MINPACK's hybrid algorithms is applied to a Python script to find the roots of these two sets of nonlinear equations with initial coordinates of (5, 4) m.[27,28] The middle $x$ position and top $y$ position of the rectangular or triangular area are set as the initial conditions. Note that the intervals of uncertainty are $x \in [0, 10]$ and $y \in [0, 4]$. Using our current host server, which is a desktop machine with an i7-9700 CPU and 8 GB memory, the required calculation time is less than 500 ms.

## 4. Experimental Results and Discussion

To verify the feasibility of the proposed approach, the proposed indoor positioning system was implemented in the lab area of room M213 at National Kaohsiung University of Science and Technology (NKUST). The experimental testing site is a $10 \times 4$ m$^2$ rectangular area that can be configured as a combination of different geometric shapes.

### 4.1 Projection of blind device with rectangular configuration

For the rectangular configuration, two base stations, which were implemented using Raspberry Pi devices, were located at (0, 0) and (10, 0) m. The configuration of the testing site is shown in Fig. 11. SSTS of iBeacon components must be established to project the location of the targeted blind device within the area. To obtain the SSTS, a blind device with an active iBeacon

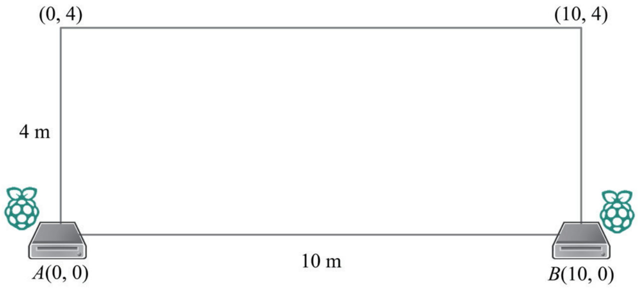



Fig. 11. (Color online) Rectangular configuration of the experimental testing site.

Table 2
Data sheet in the modeling phase.

| | Average RSSI value (dB) | | | | TxPower (dB) | |
|---|---|---|---|---|---|---|
| Blind device | (0, 0) m | (0, 4) m | (10, 0) m | (10, 4) m | Vertical | Horizontal |
| *A* | −51.103 | −71.378 | −73.352 | −69.725 | −58.164 (90°) | −53.749 (0°) |
| *B* | −79.269 | −83.529 | −50.342 | −67.423 | −48.819 (90°) | −58.06 (180°) |

Table 3
Estimations for eight positions obtained with rectangular configuration.

| Coords. ($x$, $y$) (m) | Coord. Avg. (m) | Coord. StErDe (m) | Error (m) | Best Coords. ($x$, $y$) (m) | Worst Coords. ($x$, $y$) (m) |
|---|---|---|---|---|---|
| (0, 1) | (0.242, 1.084) | (0.013, 0.122) | 0.256 | (0.247, 1.044) | (0.225, 1.241) |
| (2, 2.3) | (2.022, 2.274) | (0.294, 0.334) | 0.748 | (2.268, 2.148) | (1.605, 2.974) |
| (4. 1.5) | (4.579, 1.682) | (0.635, 0.157) | 0.607 | (4.020,1.670) | (4.798, 1.791) |
| (5, 1.5) | (5.334, 1.831) | (0.129, 0.011) | 0.470 | (5.150, 1.824) | (5.634, 1.850) |
| (5, 3) | (5.147, 2.147) | (0.793, 0.388) | 0.866 | (4.964, 2.291) | (5.846, 1.048) |
| (7, 1) | (6.373, 1.190) | (0.171, 0.899) | 0.655 | (6.556, 2.198) | (6.226, 0.433) |
| (8, 1.5) | (8.390, 1.465) | (0.358, 0.156) | 0.392 | (7.931, 1.276) | (8.934, 1.296) |
| (10, 1) | (10.279, 0.651) | (0.003, 0.047) | 0.250 | (10.275, 0.718) | (10.286, 0.544) |

component was placed at locations of (0, 0), (0, 4), (10, 0), and (10, 4) m to send out iBeacon signals. The RSSI and TxPower values at these locations received by base stations *A* and *B* are listed in Table 2. By applying the actual distance and RSSI to Eq. (2), the vertical and horizontal TxPower values related to base stations *A* and *B* were obtained as $T_{AV} = -58.164$, $T_{AH} = -53.749$ and $T_{BV} = -48.819$, $T_{BH} = -58.06$ dB, respectively.

Once the values of TxPower along the horizontal and vertical directions have been derived, Eqs. (6a) and (6b) can be used to project the locations of included blind devices. Table 3 shows the experimental results for eight positions in the targeted area obtained with the rectangular configuration. A single estimation of the projected position is based on the average RSSI value of five consecutive RSSI measurements. The average coordinates of the projected location of the blind device are then calculated from 10 estimations. The average positioning coordinates (Coord. Avg.) and standard error deviation (StErDe) are derived from these 10 estimations of each position. The error is defined as the distance between the actual position and the average estimated position. It was observed that the best estimated position is very close to the actual position and the worst estimated position is not far from the actual position. Figure 12 demonstrates the geometric deviations between the actual and estimated positions with the ranges of the corresponding StErDes. According to the results, the estimated positions are less accurate when the actual position is far from the base stations. This may be caused by the multipath effect, which results in an inaccurate measured RSSI signal if the relative distance from the base stations is greater than a certain threshold. It can be observed from Table 3 that StErDe is small, implying that the average estimation of the coordinates is very reliable when the blind device is close to the base station.

### 4.2 Projection of blind device with triangular configuration

Instead of adopting a rectangular configuration, the $10 \times 4$ m$^2$ testing area can be configured as a triangular area as shown in Fig. 13. Eight positions were randomly selected within the configured area, and 10 projected positions were estimated for each position from the acquired RSSI measurements. Figure 14 shows the geometric deviations between the actual and estimated positions. The average error between the actual position and average estimated position is less than 0.492 m. The experimental results show a highly concentrated projection and reliable indoor positioning reference. Compared with the indoor positioning outcome using a rectangular

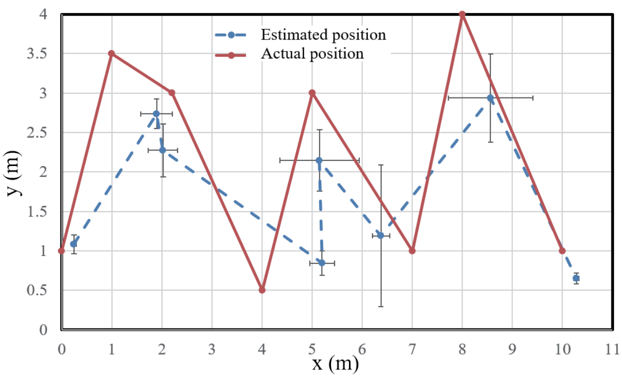



Fig. 12. (Color online) Comparison between actual locations and estimated positions with rectangular configuration.

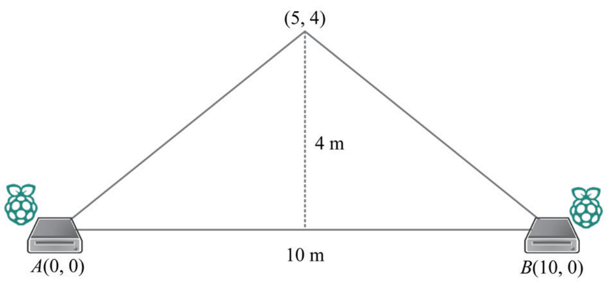



Fig. 13. (Color online) Triangular configuration of the experimental testing site.

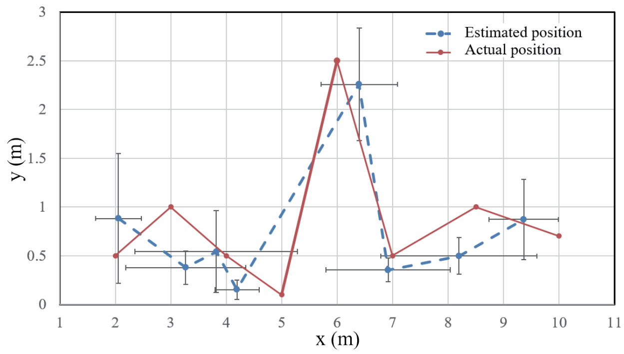



Fig. 14. (Color online) Comparison between actual locations and estimated positions with triangular configuration.

configuration, the average error of the triangular configuration is smaller. A possible reason for the better outcome is the smaller angles ($\theta_A$ and $\theta_B$) relative to the base stations.

### 4.3 Projection of blind device with hybrid configuration

Although both the rectangular and triangular configurations can be used to identify the location of a blind device, a more accurate result is desirable. Thus, instead of using a single configuration with either a rectangular or triangular shape, the target area can be configured as a combination of two different shapes. In this section, the hybrid configuration in Fig. 15 is used, which includes one triangular area and one rectangular area with three base stations. The pre-recorded SSTS database of the RSSI signal with respect to the base stations was applied to the base stations in both the triangular and rectangular areas. Eight randomly selected locations were tested to evaluate the projected outcomes. Figure 16 illustrates the projected results for these eight positions in the testing site. The maximal StErDes of $x$- and $y$-positions are less than 0.429 and 0.644 m, respectively. The hybrid configuration combines the advantages of both the rectangular and triangular types. The average error between the actual positions and average estimated positions is less than 0.508 m. In Fig. 16, it can be observed that the estimated positions are much closer to the actual positions compared with the results of the other two configurations.

### 4.4 Advantage of the proposed indoor positioning method

The average error of the experimental results for the hybrid configuration is 0.508 m and the greatest error is 0.781 m. The precision can be further improved by using filters, which can be deployed in applications requiring high precision. Because the experimental site in this study was a 10 × 4 m$^2$ area, the greatest distance from the base stations was almost 11 m. This value greatly exceeds the range of the best positioning distance (6 to 8 m) of individual iBeacon components suggested by the current standard.(15) If the experimental site can be divided into several subareas, the accuracy and stability of the proposed method can both be improved. Owing to its major advantage of low cost, the proposed indoor positioning system can be applied in various commercial applications.

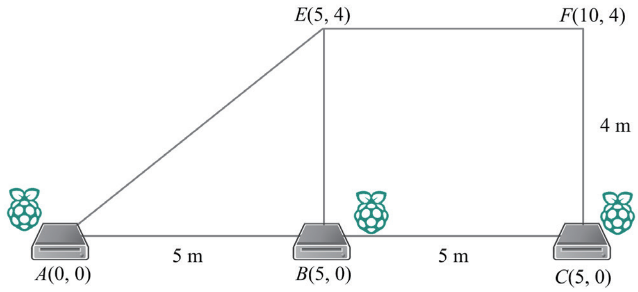



Fig. 15. (Color online) Hybrid configuration of the experimental testing site.

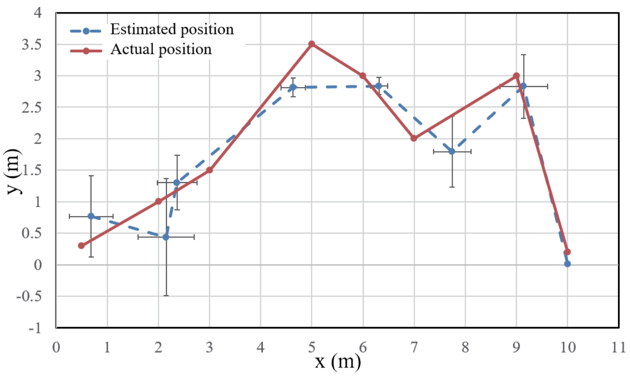



Fig. 16. (Color online) Comparison between actual locations and estimated positions using hybrid configuration.

## 5. Conclusions

In this study, a low-cost indoor positioning system, which was realized by integrating multiple BLE devices, was proposed. The proposed system integrates an STSS database and a triangulation method by evaluating the power values of received directional signals. By taking the height location of iBeacon components embedded in blind devices, the proposed approach converts the spatial relationship into a simple planar area. Compared with traditional triangulation technologies, this method has the advantage of better positioning accuracy with simpler implementation procedures while reducing the overall cost of deployment. Using an established SSTS database of targeted blind devices, their corresponding locations can be projected in real time. The experimental results also show accurate positioning outcomes using a limited number of base stations in a targeted area. Although the geometric configuration of the testing site must be determined beforehand using a console environment, a web-based interface that interacts with a human operator is currently under development. Thus, the establishment of an SSTS database of targeted blind devices and required commercial information can both be integrated into the human–machine interface for operation, modeling, positioning, and display to make indoor positioning simpler and more efficient.

## Acknowledgments

This work was supported by project numbers MOST 110-2622-E-390-002 and MOST 110-2221-E-390-020.

## References

1. Y. Liu, L. Yu, T. Chi, B. Yang, X. Yao, L. Yang, X. Zhang, Y. Ren, S. Liu, S. Cui, and L. Peng: Proc. 2017 Forum on Cooperative Positioning and Service (CPGPS, 2017) 330–332.
2 Z. Cao, R. Chen, G. Guo, and Y. Pan: Proc. 2018 Ubiquitous Positioning, Indoor Navigation and Location-Based Services (UPINLBS) 1–6.
3 C. C. Lin, M. J. Chiu, C. C. Hsiao, R. G. Lee, and Y.-S. Tsai: IEEE Trans. Inf. Technol. Biomed. **10** (2006) 694. https://doi.org/10.1109/TITB.2006.874196
4 Y. H. Lu and C. C. Lin: Proc. 2018 8th Int. Conf. Information Science and Technology (ICIST, 2018) 483–486.
5 Z. Li, Y. Yang, and K. Pahlavan: Proc. 2016 10th Int. Symp. Medical Information and Communication Technology (ISMICT, 2016) 1–5.
6 S. M. Razavi, F. Gunnarsson, H. Rydén, A. Busin, X. Lin, X. Zhang, and S. Dwivedi: Proc. 2018 IEEE Wireless Communications and Networking Conf. (WCNC, 2018) 1–6.
7 G. Schroeer: Proc. 2018 Int. Conf. Indoor Positioning and Indoor Navigation (IPIN, 2018) 1–5.
8 M. Ajmani, S. Sinanović, and T. Boutaleb: Proc 2016 Int. Conf. for Students on Applied Engineering (ICSAE, 2016) 357–361.
9 D. Zhe, M. Chen, and W. Liu, Proc. 29th Chinese Control and Decision Conf. (CCDC, 2017) 2654–2659.
10 D. Yan, B. Kang, H. Zhong, and R. Wan: Proc. 2018 IEEE 3rd Advanced Information Technology, Electronic and Automation Control (IAEAC, 2018) 1027–1030.
11 S. Gao and S. Prasad: Proc. 8th ACM SIGSPATIAL Int. Workshop on Indoor Spatial Awareness (ISA, 2016) 27–34.
12 K. Antevski, A. E. C. Redondi, and R. Pitic: Proc. 9th IFIP Wireless and Mobile Networking Conf. (WMNC, 2016) 41–48.
13 IEEE Std 802.15.4-2006, Part 15.4: https://doi.org/10.1109/WMNC.2016.7543928 (accessed April 2022).
14 H. Zou, H. Jiang, Y. Luo, J. Zhu, X. Lu, and L. Xie: Sensors **16** (2016) 268. https://doi.org/10.3390/s16020268
15 iBeacon. https://developer.apple.com/ibeacon (accessed 10 October 2019).
16 Z. He, B. Gui, W. Zhou, and S. Yokoi: Proc. 10th Int. Conf. Computer Science & Education (ICCSE, 2015) 427–430.
17 C. Guo, J. H. Shao, W. Ke, and C. Y. Zhang: Proc. 4th Annu. Int. Conf. Network and Information Systems for Computers (ICNISC, 2018) 71–77.
18 G. Li, E. Geng, Z. Ye, Y. Xu, J. Lin, and Y. Pang: Sensors **18** (2018) 2820.
19 C. Tseng and J. S. Yen: J. Syst. Archit. **81** (2017) 1. https://doi.org/10.1016/j.sysarc.2017.10.003
20 A. Issa, M. Kazmouz, P. Canalda, and F. Spie: Proc. Ubiquitous Positioning, Indoor Navigation and Location-Based Services (UPINLBS, 2018) 1–8.
21 A. Wolniakowski and M. Ciężkowski: Proc. 23rd Int. Conf. Methods & Models in Automation & Robotics (MMAR, 2018) 597–602.
22 Z. Chen, Q. Zhu, and Y. C. Soh: IEEE Trans. Ind. Inf. **12** (2016) 1540. https://doi.org/10.1109/TII.2016.2579265
23 L. Gui, M. Yang, P. Fang, and S. Yang: IET Wireless. Sens. Syst. **7** (2017) 98. https://doi.org/10.1049/iet-wss.2016.0085
24 H. Park, J. Noh, and S. Cho: Int. J. Distrib. Sens. Netw. **12** (2016) 1. https://doi.org/10.1177/1550147716671720
25 D. B. Aitor and L. Diego: Proc. 2nd Int. Multidisciplinary Conf. Computer and Energy Science (SpliTech, 2017) 1–6.
26 M. A. Qathrady and A. Helmy: Proc. 20th ACM Int. Conf. Modelling, Analysis and Simulation of Wireless and Mobile Systems (ACM, 2017) 79–83.
27 Y. C. Chang: Proc. 2nd Int. Conf. Biomedical Engineering and Informatics (2009) 1–6.
28 N. Saurabh, D. Sukanta, and P. Abhisek: Proc. 8th IEEE India Int. Conf. Power Electronics (IICPE, 2018) 1–5.