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Experimental evaluation of using BLE beacon for outdoor positioning in GPS-denied environment

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Abstract. Although Global Positioning System (GPS) is widely used in outdoor location-based services, it still lacks precision due to obstacles that reduce its performance, such as near tall buildings, with bad weather conditions, and under tree canopies. In some situations, inaccurate localization or delay in getting location locks can adversely affect some location-based services' functionality. Furthermore, it might make these services less efficient or even completely useless, especially when the receiver device has no SIM card or when the service requires a precision higher than three meters. As a solution to this issue, this study designs, develops, and evaluates a prototype location-based system that uses Bluetooth Low Energy beacons for short-range positioning in outdoor environments as a GPS alternative. The proposed system is a game that includes navigational tasks, which can be accomplished by reaching the proximity of two meters from the beacon's location. The study involved conducting an experiment outdoors with a focus on areas where GPS signals are degraded to assess our proposed system's efficiency and feasibility compared to the usage of GPS. The results proved BLE beacons' ability to provide better positioning results than GPS, not only in terms of accuracy but also in terms of stability of positioning results over time. Based on the findings, the study outlines a set of guidelines to be considered in choosing a suitable positioning technology.

Keywords. Outdoor positioning, LBS, beacon, Bluetooth Low Energy, GPS

1 Introduction

Nowadays, various mobile services rely on device location; This dependence is rapidly increasing with the remarkable advancements in research related to localization and accuracy improvement. The dominant technology currently used for outdoor positioning is the Global Positioning System (GPS), which can provide a mean accuracy of about five meters radius under an open sky (Van Diggelen and Enge, 2015). However, GPS signals transmitted from satellites have low power; therefore, they are prone to some sources of disturbance and noise, which degrade their positioning accuracy (Karaim et al., 2018). One significant disturbance source is the presence of local obstacles that prevent line of sight communication with the satellites. These barriers could be in the form of tree canopies, bridges, or tall buildings. Another cause of GPS error is the atmospheric condition, which has an unpredictable state and varies over time of the day (Lin et al., 2012; Olynik et al., 2002). With current limitations, GPS technology can't always meet the requirements of some outdoor location-based services, particularly the ones requiring more accurate and stable localization for their functionalities than what GPS can provide.

One example of systems that require stable and accurate positioning is location-based games, especially those created for learning. In these systems, reliable positioning information is essential for delivering context-aware services (Benford et al., 2004). The common environment for playing such games are urban areas where line of sight with satellites is not guaranteed everywhere. Besides the inaccuracy of GPS, mobile devices that don't support SIM cards and have no internet connection ends up waiting for minutes to be localized as the existence of a network can reduce the search area and shorten the time duration required for acquiring satellite signals for the first time to seconds (Djuknic and Richton, 2001). These drawbacks make GPS technology not a good option when reliability is a requirement.

With the witnessed growth of smartphones and tablets, and their equipment with sensors, Wireless Fidelity (WiFi) and Bluetooth Low Energy (BLE) technologies are adapted for providing accurate positioning in indoor environments. BLE is a low-energy version of classic Bluetooth that enables low-cost, low-power, and short-range wireless communication (Siekkinen et al., 2012; Pugaliya et al., 2017).

BLE beacon is a small proximity sensing device that uses BLE for signal transmission (Pugaliya et al., 2017). With its advantage over other indoor positioning technologies in offering low cost and low power communication, many indoor positioning systems that utilize BLE beacons were developed; Yet few literatures exist about using this technology for outdoor positioning.

In this study, we systematically evaluate the efficiency and complexity of utilizing BLE beacon outdoors compared to GPS in terms of localization accuracy and installation. For this purpose, our work involves designing and developing a location-based mobile game that uses BLE beacon technology for outdoor short-range positioning in situations where GPS signals are degraded. Furthermore, the study includes analyzing factors that need to be considered in choosing either GPS or BLE beacon for outdoor positioning. The contribution of this paper is twofold. First, we compare and evaluate the usage of GPS versus BLE for outdoor positioning in a GPS denied environment. Second, we outline guidelines for choosing a suitable positioning technology.

The rest of the paper is organized as follows. Section 2 presents an overview of the related work. Section 3 describes the technical set-up of our proposed system. Section 4 describes the design and procedure of the evaluation process and presents results. Section 5 presents data interpretation and discussion of evaluation results. Finally, we conclude the paper in Section 5 with future work.

2 Related work

2.1 Overview of Positioning Systems

The past few years have witnessed a significant growing interest in systems that provide services using past or current objects' locations. This interest resulted in developing new positioning systems and enhancing existing ones (Zekavat and Buehrer, 2012; Jasim et al., 2019). Applications of positioning systems became an essential part of human daily life activities. In Particular, it eases outside activities, including tracking, navigation, and situational awareness (Zekavat and Buehrer, 2012). Services that depend on a mobile device's location using either a coordinate system or relative to an object are called location-based services. Location-based services (LBS) became popular and available for everyone with the advancement of mobile phones and their embedded sensors. It's used for various purposes, for instance, as a navigation system that guides users with direction and explores environments such as Google maps. Another widespread usage for LBS is geo-social networks (GSNs), where users can share their current location and activities on their social network and add reviews for visited places such as restaurants (Jasim et al., 2019).

There are many technologies used in positioning systems. They are divided into two main categories according to the system's environment, either outdoors or indoors. The usage of a particular technology depends on the intended system's required characteristics, including accuracy, precision, power consumption, latency, and availability (Huber, 2011). With modern smartphones, it's common for positioning systems to use multiple technologies at once. It helps make the mobile device's localization process occur precisely and quickly (Huber, 2011; Djuknic and Richton, 2001).

Among outdoor positioning technologies, GPS is the most popular system due to its wide coverage and availability. GPS can provide acceptable accuracy for both commercial and personal applications according to the coordinate system. However, it lacks precision in some circumstances, where it loses line-of-sight with satellites (Zekavat and Buehrer, 2012). Furthermore, GPS utilizes network connection to reduce the search area and shorten the duration required for acquiring satellite signals for the first time. Therefore, when mobile device doesn't support SIM card such as tablets, a delay may occur in localizing the receiver device (Djuknic and Richton, 2001). These drawbacks led to research for enhancements or even the evolution of new technologies that can compensate for the gap where GPS signals are degraded.

For locating objects in environments where transmitted signals from satellites are partially or entirely blocked as inside buildings, indoor positioning technologies are adapted. These technologies include Radio Frequency Identifier (RFID), Wireless Fidelity (WiFi), and Bluetooth Low Energy (BLE), which can provide accurate positioning with less than one meter of error (Roberts, 2006; Siekkinen et al., 2012; Zaim and Bellafkih, 2016). Target object position is detected by measuring the distance between the receiver and transmitter. Furthermore, indoor positioning systems use various techniques such as time of arrival and received signal strength that employ signal travel time and signal strength, respectively, for detecting object proximity (Zekavat and Buehrer, 2012).

2.2 GPS Sources of Error

With an error that may reach fifty meters, GPS still meets the accuracy requirements of many location-based applications (Ross and Hoque, 2020). However, for some applications, inaccurate localization or delay in getting location locks can affect their functionalities and make them less efficient or even completely useless. In particular, when the receiver device has no SIM card and when the service requires a precision higher than 3 meters (Djuknic and Richton, 2001). Even though anywhere on earth at any time of day, at least four satellites can detect receiver position accurately (Zekavat and Buehrer, 2012), the signals transmitted from satellites have low power, making them prone to some sources of disturbance and noise. Especially when satellite signals are received under adverse circumstances (e.g., near tall buildings, with bad weather conditions, and under tree canopies), resulting in inaccurate positioning (Karaim et al., 2018; Lin et al., 2012). Taczanowska et al. (2008) discussed the potential limitation of GPS-tracking, focusing on errors caused due to the quality of GPS signals in areas covered by dense forests. The study results showed that dense forest could disturb satellite signals and adversely affect positioning. Furthermore, DeCesare et al. (2005) revealed that GPS error under high canopy could add about 27.5% of the length to true position, representing equal to or less than 7.98 meters. This error length value might be greater based on the forest's width, topographic condition, and season. Several GPS errors occur during the signal travel from the satellite to the receiver, called signal propagation errors, including relativistic error, atmospheric error, and multipath error (Karaim et al., 2018).

Many researchers attempted to reduce the effects of GPS errors and improve its performance using models, tools, or augmentation with other technologies. DeCesare et al. (2005) suggested considering the tree canopy effect and handling it using smoothing algorithms before conducting measures interpretation. Another approach to improve GPS performance is using FAGPS (Fiducial Augmented Global Positioning System) as proposed by Ross and Hoque (2020). For SIM card-enabled devices, Assisted GPS (AGPS) is used to improve Time to First Fix (TTFF), which can save up to 12 minutes. Zirari et al. (2010) proposed a GPS-WiFi positioning algorithm for assisting GPS accuracy when collected under obstacles such as urban canyons.

Although some GPS sources of errors are resolved, almost all proposed solutions are considered expensive and may require additional equipment (Karaim et al., 2018). Furthermore, the unstable state of some errors makes it impossible to predict their behaviour to find a proper solution accordingly (Olynik et al., 2002). Hence, there is still a demand to utilize a technology that can provide accurate outdoor positioning in situations where GPS signals are denied or spoofed, either as a stand-alone technology or in combination with GPS.

2.3 Beacon Technology

Beacon is a small proximity sensing device that broadcasts a piece of information using advertisement at predefined time intervals (Faragher and Harle, 2015; Pugaliya et al., 2017). It uses Bluetooth low energy for signal transmission. Each signal contains a received signal strength indicator (RSSI) value that represent the strength of the transmitted signal (Zafari et al., 2015). Unlike GPS signals, RSSI is less sensitive to line-of-sight availability (Zekavat and Buehrer, 2012). The RSSI value is received and utilized by nearby smartphones to estimate the distance to beacon location (Lin et al., 2015). Due to BLE technology's low energy consumption, beacons can run for about two years on a single coin-cell battery (Zafari et al., 2015). Beacons are used in various applications, including tracking, navigation, security, interaction, and analysis. When a smartphone acts as a receiver, it should be Bluetooth-equipped and includes a specific software to pick up transmitted signals passively. The communication between beacon and receiver is considered a one-way communication, where the receiver can't reply to incoming beacon signals (Kohne and Sieck, 2014). This technology uses different protocols; the most common protocols are iBeacon from Apple and Eddystone from Google (Dalkilic et al., 2017).

3 Approach

In this section, we describe the technical set-up of our proposed system, while the actual comparison of the two localization approaches for different tasks in different environments will be described in chapter 4.

3.1 Proposed System Architecture

Our proposed system architecture is divided into four main components: positioning technology, mobile application, mobile device, and server-side. These four components aggregate the system tasks' information, beacons' position information, and users' results information (see Fig. 1).

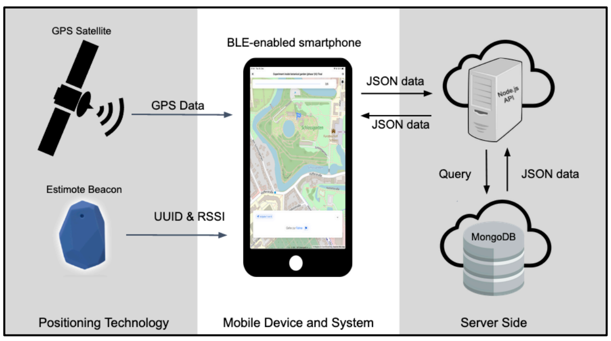


Figure 1. System Architecture.

Positioning technology: our system support both GPS and BLE beacon, which allow the game creator to choose one of them as a positioning technology for solving the navigation tasks. We utilised beacons manufactured by Estimote. It's a tiny computer that contains CPU, RAM, and Bluetooth antenna; Estimote beacons use iBeacon protocol.

Mobile device: the system should be installed on a Bluetooth-enabled and GPS-enabled mobile device, either a smartphone or tablet. Then it starts scanning and collecting RSSI signals broadcasted from nearby beacons or GPS signals from GPS satellites.

Remote server: it deals with storing and updating game information sent from the application, including tasks' target locations, beacons' UUID, GPS coordinates, and results of playing the game. As the game will be used outdoors, the server is hosted in the cloud, enabling easy real-time access anywhere and anytime; This protects system data from accidental data loss. Thus, the proposed system needs an internet connection to retrieve and update game information and upload game results.

Mobile application: is a map-based game that contains navigational tasks which users can solve by heading to a flagged marker viewed on digital map. Each navigational task's target position is represented in real world with a BLE beacon. The application uses the RSSI transmitted from beacons to check the real-time distance between beacon and smartphone. The task is considered achieved if the measured distance meets task's threshold value.

3.2 Integration with GeoGami

GeoGami is a location-based geogame where each game is composed of a series of navigational tasks to different locations. The app allows users to create map-based games (e.g., treasure hunt games, thematical rallies, and NMR training) in a chosen location (Bistron and Schwering, 2021). The current version of GeoGami contains two main categories of tasks (navigational and thematic). In the navigational tasks, the GPS position of the target location is displayed either as a flag on the map or as an arrow that illustrates which direction the user should follow to solve the task. On the other hand, thematic tasks are created to allow the user to interact with the game by answering questions related to the target position.

The integration of BLE beacon functionality into GeoGami is meant to be used in the evaluation process of this study. It allowed us to take advantage of GeoGami's features, especially GPS usage for positioning and providing a variety of navigational tasks with different types of theme questions. The integration process focused on adding the usage of BLE beacons to solve the navigational tasks, including inserting new beacon information, using beacons in parallel with GPS, updating the server, and adding further enhancements.

3.3 Functionality of collecting data

Our proposed system is designed to collect data related to tasks' results which is generated during playing the game by users. The collected data included the start and end times of each task, measured distance between the device and task's location at time of solving the task (using BLE beacon and GPS technologies), and other tasks' details.

4 Evaluation

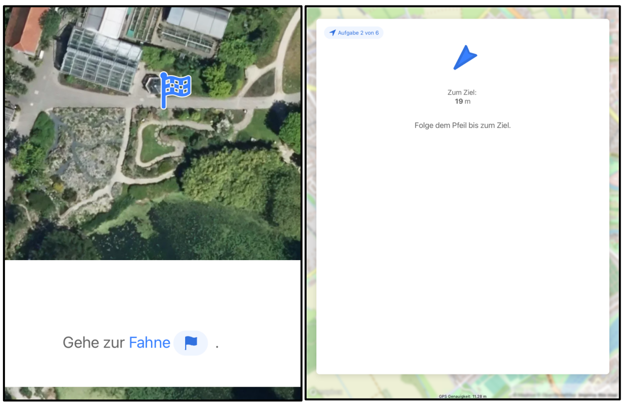
To evaluate our proposed system performance and compare its efficiency and suitability with the usage of GPS technology in different locations, we conducted an experiment. In this section, we describe the design and procedure of the evaluation process and present the results.

4.1 Experimental design

Participants: ten university students participated in the study. The primary criteria for participation in our study involved basic knowledge and experience with maps.

Study area: the experiment was carried out inside a botanical garden and near Münster castle in Münster, Germany. In both places exist tall buildings, tree canopies, and an open space that potentially influences the precision of GPS.

Game setup: we created a game using our proposed system that consists of twelve navigational tasks divided into two categories based on the medium used to solve the task, either using a digital map or direction detection (see Fig. 2). Half of the tasks were placed in GPS-denied environments where obstacles existed that might have an



(a) (b)

Figure 2. (a) Navigate to flag task; (b) Navigate with arrow task.

effect on the accuracy of GPS, such as the existence of tall buildings and tree canopies. The other half of tasks were placed in GPS-enabled environments where line of sight with satellites is available.

In digital map task type, the target location is viewed as a flag on the map, indicating the task's target position. On the other hand, in direction detection task type, a real-time estimation of the distance between the beacon and the tablet was viewed on the application screen. The distance value decreases when the user gets closer to the beacon, which allows participants to find out the right direction to task location based on monitoring the distance variations. Furthermore, we utilized the tablet's built-in magnetometer sensor to determine the device orientation and show the correct direction to the task location as an arrow displayed on the screen (see Fig. 2 b). The arrow source is the participant's GPS location, and the destination is the task's target location. Each task in the experiment had a unique characteristic, which allowed us to evaluate the proposed system and compare its efficiency with GPS in multiple situations. The tasks' features included the medium used to solve the task, the availability of a line of sight with satellites from the task's position, and distance to the initial user location or building.

Beacons deployment: the estimote beacons were deployed in the study area in positions corresponding to those selected using the digital map of the proposed system (see Fig. 3). This enables triggering an event when participant reach target location. Besides BLE beacons, we utilised GPS as well, to measure both technologies' efficiency and accuracy.

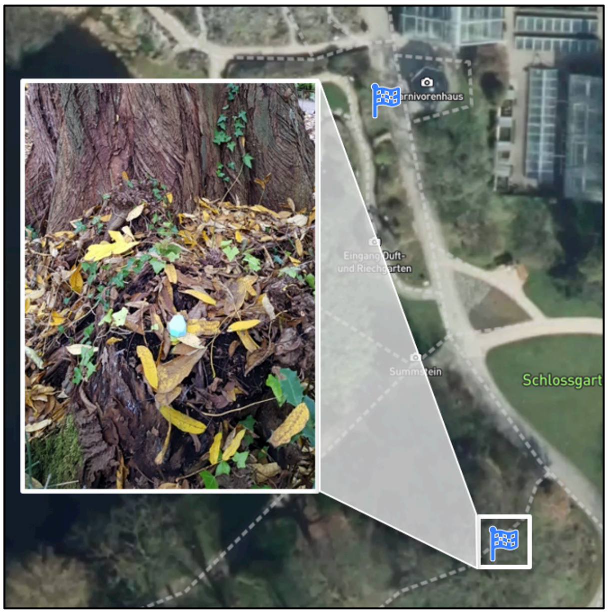


Figure 3. Deployment of beacon in study area corresponding to the position on digital map.

4.2 Data collection

The evaluation process included two methods for collecting data. In the first method, we used our proposed system to collect data related to tasks' results generated during playing the game by participants. In the second method, we used a measuring tape for measuring the actual distance between the device and the task's location. These measurements will be used in the data analysis process for evaluating the proposed system efficiency by comparing the distance in reality with the ones recorded with the proposed system using both BLE beacon and GPS technologies.

4.3 Experimental Procedure

After getting a tablet with our proposed system installed, participant starts solving a list of tasks. Each experiment session lasts approximately fifty minutes; only one student can participate at a time. When completing each task using either BLE beacons or GPS, the experimenter puts a mark on the ground exactly under tablet's location. Then, the distance from the mark - which represent tablet location - to the target object is measured at the end of the task manually (using a measuring tape). The task is considered completed when getting notification sounds of solving the task using both BLE beacon and GPS. A participant may reach the correct position of the task, and one or both technologies don't push notifications about completing the task. In this case, the experimenter requests the student to skip the task to the next one. At the end of the experiment, game results were uploaded automatically to the server. During the experiment, the participants were accompanied by the experimenter.

4.4 Result

The results of the experiment conducted to evaluate the performance of BLE beacon compared to GPS technology were divided into two groups based on the availability of a line of sight with satellites from the task's position. Fig. 4 illustrates the average distance error of all tasks, which

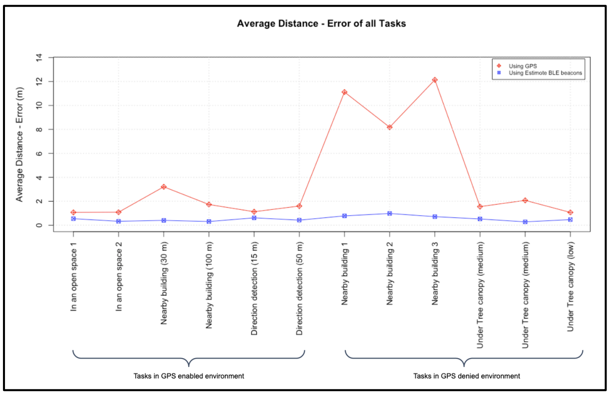


Figure 4. Average distance - error of all tasks using GPS and BLE beacons.

shows clearly that the difference between BLE beacon and GPS in distance error was less in GPS enabled environments than in GPS denied environments.

5 Discussion

5.1 Efficiency in GPS - denied Environments

The evaluation of our proposed system in GPS-denied environments took place in two areas: beside tall buildings and under tree canopies. In tasks assigned directly beside a tall building, BLE beacons achieved accurate results, where the task was solved in all sessions with an average accuracy of 0.78 m. On the other hand, using GPS, only 30 % of the tasks were achieved with an average distance error of 11 m, which is attributed to the fact that GPS signals can't penetrate solid objects such as buildings.

Other tasks were placed under tree canopies. In these tasks, GPS showed more accurate results compared to tasks beside a tall building, where 83% of sessions achieved the task with an average accuracy of 1.6 m and a maximum distance error of 7 m. The results indicate that tree canopies have less effect on GPS signals than solid objects, and in general, this effect depends on the canopy's thickness, as demonstrated by Taczanowska et al. (2008). However, the measured distance using GPS was not stable over time. The case with BLE beacons was almost the same as beside high buildings; It successfully achieved all sessions of the tasks with an average accuracy of 0.5 m. The overall results of tasks conducted in circumstances where GPS signals are degraded showed that BLE beacon technology could be a suitable alternative to GPS for short-range positioning in such areas.

5.2 Efficiency in GPS - enabled Environments

Evaluating our proposed system in a GPS-enabled environment aims to investigate how efficient GPS is when LOS is available compared to BLE beacon technology. For this purpose, we deployed beacons in situations where the target positions are in the distance of 30 and 100 meters to a nearby building and in areas that don't have nearby buildings.

Two tasks were placed nearby buildings in the ranges of 30 and 100 meters from the target location. While in the range of 100 m from a building, the task was achieved in all sessions using GPS with an average distance error of 1.7 m, the task placed in the range of 30 m showed less accurate results where it was solved in only half of the sessions with an average distance error of about 3 m. Tasks results showed a positive relationship between closeness from building and the error range of GPS results. Furthermore, the results indicate that for getting an optimal accuracy using GPS, the receiver should be away from nearby buildings at a distance that depends on those buildings' height. In our case, 100 meters was enough to get optimal results using GPS. However, in both cases (30 m and 100 m from a building), BLE beacons achieved more accurate and stable accuracy with the task solved in all sessions with an average distance error of 0.35 m.

Another phase of testing our proposed system in GPS - enabled environments took place in an open area where there are no tall buildings nearby, and the receiver has LOS with satellites. The results revealed that difference between GPS and BLE beacons is minimal in open spaces where no buildings are nearby. Although the average distance error using GPS was one meter, the task was achieved in 80% of the sessions. It failed in 20 % due to the instability of GPS performance, which will be further investigated in the positioning stability subsection. With the inability of GPS to provide stable accuracy in all sessions, our proposed system using BLE beacons achieved better results in the open environments, as the task was solved in all sessions with an average distance error of 0.4 m.

5.3 Direction Deduction using BLE Beacons

Besides using a BLE beacon to detect if a mobile receiver reached specified proximity, we created direction detection tasks that employ the RSSI transmitted from beacons to detect the correct direction to the target object. This type of task doesn't require a digital map but needs to show the corresponding distance of collected RSSI value in a real-time manner. The user uses this distance value to identify the correct direction to follow in order to solve the task. Since the BLE beacon loses accuracy when the receiver gets farther from its position, we created two tasks in the ranges of 15 m and 50 m from the participant's initial location to evaluate the performance in both ranges.

The results showed that in both ranges, the tasks were achieved in all sessions, but with the range of 50 m, the time duration of solving the task was approximately double the one in the range of 15 m. This occurred as the target was placed at a longer distance and more importantly, due to the misleading distance received from the beacons in the range between 20 m to 50 m. In the latter case, the viewed distance value keeps increasing and decreasing dramatically, making participants think they are going in the wrong direction until they reach the range of 15 m from the target location, where the distance becomes more stable. By then, the user can detect direction easily.

Furthermore, the results showed a relationship between the duration spent before reaching the beacon and the resulting accuracy. For instance, in the range of 50 m from the beacon location, the accuracy was better than in the range of 15 m. This is due to the time that BLE beacons need for ranging, which lasts for a few seconds until reaching the correct measurement. So, when the initial distance between the participant and target position is short, the participant can reach the BLE beacon faster and should wait for the beacon's ranging to finish. In this case, while the application does the ranging, the distance decreases until the value reaches the predefined proximity we set. As the user location is already close to the beacon position, it assumes that the user location is farther than reality, which generates a higher distance error than when the initial distance between the participant and target position is long.

5.4 Positioning Stability

From the overall experiment results, it was obvious that measured accuracy using GPS is not stable from time to another. This instability was observed not only in GPS - denied environments, which was expected, but also when the mobile device has a line of sight with satellites. The distance error can be attributed to the weather condition that day, which proves the findings in Olynik study (Olynik et al., 2002). Furthermore, the GPS accuracy results showed a high difference in the measured distance beside the building. On the other hand, positioning using BLE beacons provided stable results in all tasks. This observation adds another advantage to the use of BLE beacons even in GPS-enabled environments where accuracy and stability of the results are required.

5.5 Guidelines for Choosing a Suitable Positioning Technology

Based on the experiment results and observations, choosing a suitable technology, either GPS or BLE beacon depends on the application's requirements such as accuracy, stability, and target environment. Tab. 1 shows an overview of situations where to utilize GPS or BLE beacon. Furthermore, it is possible to utilize both technologies at once to include all situations.

5.6 Study Limitations

The study involved several challenges that we had to overcome. One limitation is the lack of an ideal height to place the beacons in the experiment area, especially inside the botanical garden, where it is recommended not to touch the plants. This made BLE signals transmitted from beacons to be vulnerable to some obstacles that degrade their strength and affect the measured distance. Another limitation of the study is placing all the 12 beacons at once before starting the experiment session as the experiment area is a public place where beacons' locations could be vulnerable to intentional or accidental change by visitors or employees in the experiment area. This made us decide to divide the experiment into four phases where

Table 1. Overview of situations where to utilize GPS or BLE beacon

Positioning Technology	Usage situations
GPS	• In an open environment • When required accuracy is less than or equal 4.9 m • In direction detection(1) when distance to target position is more than 15 m • When monitoring the mobile device movement is a requirement (navigation)
BLE beacon	• In short-range target positioning (indoor and outdoor environments) • When required accuracy is less than 3 m • In direction detection(1) when distance to target position is less than 15 m • When monitoring if the receiver device reached a specifc proximity from the target position is a requirement • When results stability is a requirement • When the receiver doesn't support SIM card and has no network connection

participants had to wait for about 4 minutes before the beginning of each phase so we can place only three beacons in the tasks' locations. Moreover, With the current corona epidemic, the process of finding participants for evaluating our proposed system was more difficult than in the normal status.

6 Conclusion and Future Work

With the current GPS sources of errors that occurred due to multiple reasons and affect its performance adversely, there is a demand to utilize an alternative technology outdoors as a stand-alone or in combination with GPS. In this research, we aimed to examine the potentials of using Bluetooth low energy beacons for short-range positioning in outdoor environments, including areas where GPS signals are degraded. For achieving this purpose, we designed and developed a system that uses the built-in BLE module in all modern mobile devices for proximity sensing of nearby BLE beacons. The proposed system is a game that includes navigational tasks, each of which can be accomplished by reaching a predefined level of proximity from the beacon location. BLE beacon and GPS efficiency were analysed and discussed in this research based on data collected through an experiment conducted in the botanical garden area in Münster, Germany. The evaluation results showed how stable and accurate are the positioning results using BLE beacon compared to GPS accuracy, which was less accurate with an average error that reached twelve meters near tall buildings. However, unlike GPS, BLE beacons require an additional cost and extra effort for deployment. Furthermore, the research discusses the efficiency of using BLE beacons for direction detection and the influence of including landmarks in solving the navigational tasks. Moreover, the study provides guidelines that help in choosing a suitable positioning technology.

Although the proposed system achieved high accuracy in the outdoor environment, some issues remain open for further research. As we utilized estimote BLE beacons in this study, further research should focus on testing a variety of other beacons to compare their accuracy and feasibility. Another issue is evaluating the beacon's performance in different altitudes for observing its effect on resulting accuracy. Moreover, in the experiment, we used a tablet supported with a SIM card, which assists GPS in acquiring satellite signals for the first time. Further study should investigate the usage of a mobile device with no SIM card and network connection to evaluate GPS accuracy, considering utilizing an offline map and local storage for storing results.

7 Data and Software Availability

Data and code that reproduce Fig. 4 in result section 4.4 are available at: https://doi.org/10.17605/OSF.IO/E48HX. The source code of our proposed system GeoGami, alongside instructions about building and deploying the application to Android or iOS mobile devices, is accessible at: https://github.com/origami-team/origami/tree/ibeacon_integration_v3.

The computational workflow underlying this paper was reproduced by an independent reviewer during the AGILE reproducibility review and a reproducibility report was published at https://doi.org/10.17605/osf.io/8b7mr.

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