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Design of an Indoor Navigation System

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***Abstract*—Indoor navigation has become an important research topic due to the rapid growth of large infrastructures such as hospitals, airports, shopping malls, and university campuses. The Global Positioning System (GPS) provides reliable navigation outdoors, but it performs poorly in indoor environments because satellite signals cannot effectively penetrate building structures. In practice, indoor environments introduce additional difficulties such as signal attenuation, non-line-of-sight propagation, multipath fading, and obstruction caused by walls, furniture, and moving people. These effects reduce the reliability of traditional positioning technologies and create the need for low-cost and practical indoor localization methods.**

This paper presents a Bluetooth Lo Energy (BLE) based indoor navigation system that uses Received Signal Strength Indicator (RSSI) measurements collected by ESP32 receiver nodes to estimate the position of users inside buildings. Smartphones act as BLE transmitters, and ESP32 modules measure RSSI values of received signals continuously in real time. The localization algorithm processes RSSI measurements using distance estimation and trilateration techniques to determine the user's approximate position within the indoor environment. By using smartphones as transmitters and ESP32 boards as receivers, the overall hardware cost is kept low while still providing useful localization performance.

To enhance user interaction and navigation efficiency, a digital indoor environment is developed using the Unity game engine and navigation paths are generated using NavMesh pathfinding algorithms. Furthermore, augmented reality visualization is used to overlay navigation guidance directly on the smartphone camera interface, providing an intuitive and user-friendly experience. Instead of forcing users to interpret static maps, the system attempts to guide them through real-time visual instructions aligned with the surrounding environment. Experimental evaluation demonstrates that the proposed system achieves localization accuracy between one and three meters depending on environmental conditions, making it suitable for practical indoor navigation applications such as smart campuses, hospitals, office buildings, and public service areas.

***Index Terms*—Indoor Navigation, RSSI Localization, ESP32, Bluetooth Low Energy, IoT, Augmented Reality**

I. INTRODUCTION

Indoor positioning has become a major research challenge because satellite-based navigation systems such as GPS are designed primarily for outdoor environments. Buildings often block or attenuate satellite signals, which prevents accurate positioning in indoor spaces [1]. In addition, signal reflections caused by walls, glass surfaces, metallic objects, and other structural elements introduce multipath effects that further degrade positioning accuracy. As a result, the location returned by satellite-based systems is either highly inaccurate or completely unavailable once a user enters a building.

As modern infrastructures such as airports, hospitals, shopping malls, railway stations, universities, and corporate offices become larger and more complex, the demand for reliable indoor navigation systems continues to increase. Users often face difficulty in locating specific rooms, departments, service counters, laboratories, or exits within such environments, especially when visiting for the first time. Printed signboards and static floor maps provide only limited assistance because they do not react to the current location of the user and cannot offer step-by-step guidance. Therefore, efficient indoor navigation systems are required to provide accurate positioning and real-time route assistance.

Indoor navigation systems guide users from their current position to a desired destination inside a building. Unlike outdoor navigation systems that rely on satellite signals, indoor navigation requires alternative technologies such as wireless communication, sensor fusion, computer vision, and map-based path planning [2]. Various wireless technologies including Wi-Fi, Bluetooth Low Energy (BLE), Radio Frequency Identification (RFID), and Ultra-Wideband (UWB) have been investigated for indoor localization applications. Each technology has its own trade-offs in terms of infrastructure cost, power consumption, deployment complexity, and positioning accuracy.

Among these technologies, BLE has emerged as one of the most promising solutions due to its low power consumption, cost-effectiveness, and compatibility with modern smartphones [3]. BLE devices periodically transmit advertisement packets that can be detected by nearby receivers. The signal strength of these packets can be measured using Received Signal Strength Indicator (RSSI) values, which can be used to estimate the distance between transmitter and receiver. Although RSSI-based localization is sensitive to environmental conditions, it remains attractive because it avoids expensive hardware and can be implemented using commonly available devices.

Recent advancements in Internet of Things (IoT) technologies have enabled the development of low-cost wireless localization systems. Microcontrollers such as the ESP32 integrate Bluetooth communication and processing capabilities, making them suitable for RSSI-based localization systems [4]. These systems provide scalable, flexible, and cost-efficient solutions for indoor navigation while reducing deployment costs and maintenance complexity. In addition, integration with mobile computing platforms and cloud-connected systems allows indoor navigation to become part of broader smart building applications.

Another important requirement in indoor navigation is user interaction. Even if the localization system provides a correct position estimate, the overall usefulness of the application depends on how effectively navigation instructions are presented. Traditional two-dimensional maps may be difficult to interpret in unfamiliar or crowded environments. For this reason, augmented reality has gained attention as a promising visualization approach. AR can place virtual navigation markers directly onto the user's camera view, thereby reducing confusion and improving direction comprehension.

In this work, an indoor navigation system is developed using BLE signal broadcasting from smartphones, RSSI measurement using ESP32 receiver nodes, localization through distance estimation and trilateration, and route generation through Unity NavMesh. The proposed approach combines low-cost IoT hardware with an interactive software environment to create a practical and extensible indoor navigation platform.

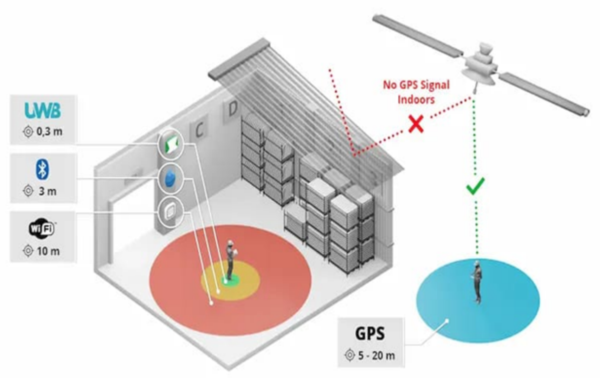

Fig. 1. Problem of GPS in indoor environments

II. RELATED WORK

Indoor localization techniques have been widely studied in recent years, with various approaches proposed to improve positioning accuracy, reliability, and system efficiency. Ting compared fingerprinting and trilateration algorithms for indoor localization and demonstrated their performance differences [5]. The study highlighted that fingerprinting generally provides higher localization accuracy because it relies on previously collected signal maps, but it also requires extensive site survey data and repeated calibration. Trilateration, in contrast, offers a simpler and more scalable approach, though its accuracy strongly depends on signal stability and distance estimation quality.

Faragher and Harle analyzed BLE signal behavior and demonstrated that BLE technology can provide localization accuracy within a few meters under controlled conditions [3]. Their work showed that BLE can be a practical indoor positioning technology when signal processing and calibration are performed carefully. Mainetti et al. presented a comprehensive survey of indoor positioning technologies including Wi-Fi, BLE, and RFID systems, discussing their advantages, limitations, and practical applications [2]. Their survey emphasized that no single technology is universally optimal, and system designers must select methods according to cost, required accuracy, and deployment conditions.

Ji et al. investigated the relationship between beacon density and localization accuracy in BLE systems, showing that increasing the number of nodes improves accuracy but also increases system cost and complexity [6]. This observation is particularly important for large buildings, where the trade-off between infrastructure cost and localization performance becomes a major design consideration. Dickinson et al. implemented a BLE-based indoor positioning system for tracking users in retail environments and analyzed user movement patterns [7]. Their work demonstrated the usefulness of indoor positioning not only for navigation but also for analytics and behavior understanding.

Campana et al. proposed a smartphone-based indoor navigation system using BLE signals and demonstrated its effectiveness in real-world scenarios [8]. Their approach highlighted the advantage of using devices that users already carry, thereby reducing the need for dedicated client hardware. Recent studies have also explored machine learning techniques for indoor localization, including RSSI fingerprinting and sensor fusion approaches [9], [10]. These techniques improve system adaptability and accuracy by learning complex relationships between signal patterns and physical locations. However, they often require larger datasets, additional training time, and more computational resources.

Sophia et al. implemented a BLE positioning system using ESP32 microcontrollers, demonstrating that ESP32 boards can serve as a practical and economical hardware platform for indoor localization [11]. This is particularly relevant for academic and prototype systems, where budget constraints are important. Advanced research explores hybrid localization and deep learning models to address signal instability and environmental variability [12]–[18]. These methods attempt to improve robustness in environments where standard RSSI-distance models perform poorly.

Despite these developments, many existing solutions either require dense infrastructure, complex calibration, or expensive devices. There remains a need for a system that balances simplicity, cost, and practical accuracy. The present work addresses this need by combining smartphone BLE transmission, ESP32-based RSSI collection, conventional distance estimation, and an augmented reality interface for user-friendly navigation.

III. SYSTEM ARCHITECTURE

The proposed indoor navigation system consists of four major components: smartphone BLE transmitter, ESP32 receiver nodes, localization module, and augmented reality navigation interface. Each component plays a crucial role in ensuring accurate localization and effective navigation. The architecture is designed to separate sensing, localization, and visualization functions so that each part can be improved independently in future versions.

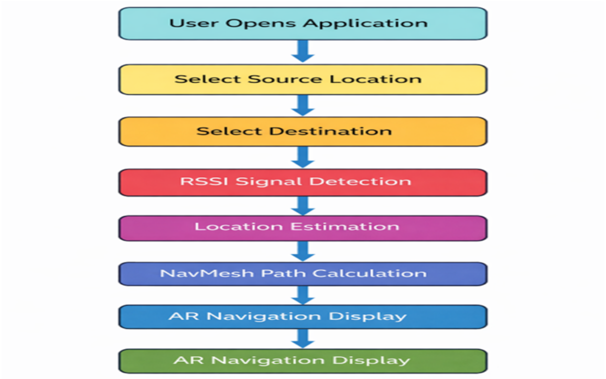

Fig. 2. System architecture of the proposed indoor navigation system

Smartphones periodically broadcast BLE advertisement packets, which act as signals for localization. These signals are detected by ESP32 receiver nodes deployed at fixed indoor locations. Proper placement of receiver nodes is important because localization performance depends heavily on geometric coverage. If nodes are placed too close together or too far apart, the resulting distance estimates may not be sufficient for stable position calculation. Therefore, nodes should be installed at points that maximize coverage of corridors, rooms, and decision intersections.

The ESP32 modules measure RSSI values and forward them to the localization module. Due to signal fluctuations caused by environmental factors, multiple readings are collected over time and averaged to improve stability. This step is important because instantaneous RSSI values are often noisy and may vary even when the transmitter remains stationary. By collecting repeated measurements, the system reduces the effect of random fluctuations and improves the reliability of subsequent distance estimation.

The localization module estimates user position using path loss modeling and trilateration. In this module, RSSI values are first converted into approximate distances using a calibrated signal model. The estimated distances from multiple ESP32 nodes are then used to compute the user's position relative to the known coordinates of the receivers. Once the position is estimated, the navigation module determines the route from the current location to the selected destination.

The navigation module then computes optimal paths using NavMesh algorithms in Unity. Navigation points are placed at meaningful locations such as corridor intersections, room entrances, and turning points. These points define a traversable indoor graph on which shortest or most convenient paths can be calculated. The use of Unity also makes it easier to visualize indoor geometry and integrate the route with a user-facing application.

Finally, AR visualization provides real-time directional guidance. Instead of only marking start and destination points on a static map, the augmented reality interface overlays path information onto the smartphone camera feed. This enables users to interpret directions more naturally because the guidance appears aligned with the surrounding environment. Such visualization can reduce hesitation, wrong turns, and confusion, especially in unfamiliar buildings.

The architecture also supports modular extension. For example, future work could replace the localization algorithm with fingerprinting or machine learning methods while keeping the same visualization layer. Similarly, additional data sources such as inertial sensors, gyroscopes, or floor-wise map data could be integrated without requiring a complete redesign of the system.

IV. RSSI BASED LOCALIZATION

Fig. 3. RSSI based indoor localization

RSSI based localization estimates distance using signal strength measurements. The general principle is that the received signal becomes weaker as the distance between transmitter and receiver increases. Although the exact relationship is affected by the environment, a mathematical model can be used to approximate this behavior and convert signal levels into distance estimates.

The log-distance path loss model is used to relate RSSI and distance [3], [9]. This model is widely used in wireless communication because it provides a simple mathematical relationship between received power and propagation distance. It is represented as

$$P_r(d) = P_r(d_0) - 10n \log_{10}\left(\frac{d}{d_0}\right) \tag{1}$$

where $P_r(d)$ represents received signal strength at distance d, $P_r(d_0)$ represents reference signal strength at a known distance d_0, and n represents the path loss exponent. The path loss exponent depends on the environment and typically varies between open space and obstructed indoor regions. Therefore, the model must usually be calibrated for the specific building in which the system is deployed.

Indoor environments introduce noise due to reflections, shadowing, absorption, and interference. Signals can bounce from walls, doors, ceilings, and metallic objects, leading to multipath propagation. In such situations, the RSSI value measured by the receiver may not correspond directly to the shortest path between devices. As a result, distance estimation becomes uncertain. Human movement and temporary obstacles also cause fluctuations in signal strength over time.

To reduce errors, multiple samples are averaged and filtering techniques are applied. Averaging smooths out random short-term variations and helps produce more stable signal measurements. In addition to simple averaging, more advanced filtering techniques can be employed to reject outliers and reduce the impact of sudden signal changes [15], [16]. Although the current system focuses on practical simplicity, such filtering can significantly improve performance.

After distance estimation, trilateration is used to compute the approximate user position. In trilateration, the estimated distances from at least three known receiver nodes are used to determine the point at which the corresponding distance circles intersect. In real environments, the circles may not intersect perfectly because of measurement error. Therefore, the estimated position is usually obtained as an approximate solution that minimizes the mismatch among distances.

Although simple and cost-effective, RSSI localization accuracy depends strongly on environmental conditions and calibration quality. In locations with heavy obstruction or strong multipath effects, position error may increase. Nevertheless, RSSI remains attractive for low-cost indoor navigation because it requires only standard wireless hardware and can provide room-level or near room-level accuracy under practical conditions.

V. IMPLEMENTATION

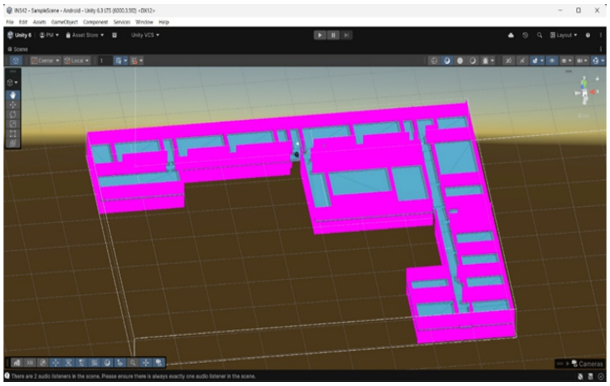

Fig. 4. Indoor environment model created in Unity

The proposed system is implemented using ESP32 microcontrollers and Android smartphones. The ESP32 platform was selected because it provides integrated BLE capability, adequate processing performance, low power operation, and low hardware cost [4], [11]. This makes it suitable for educational, research, and prototype deployments where cost and ease of programming are important considerations.

ESP32 receiver nodes continuously scan BLE advertisement packets transmitted by smartphones. During operation, the smartphone functions as a mobile transmitter and periodically broadcasts packets that can be observed by the surrounding ESP32 modules. Each receiver node records the RSSI of the packets it receives and associates those measurements with its own known installation position. This distributed sensing approach allows the system to collect multiple RSSI values simultaneously from different points in the building.

The firmware running on the ESP32 modules records RSSI measurements and transmits them to the localization module. This module processes the incoming values, filters them if required, and converts them into distance estimates. The system then calculates the approximate user position by combining the data from multiple receiver nodes. Implementation at this stage emphasizes reliable communication and repeatable measurement collection, since unstable input data would directly affect position estimation accuracy.

The indoor environment is modeled using the Unity game engine. Unity provides tools for creating interactive virtual environments and supports pathfinding algorithms through the NavMesh system. A digital floor plan of the building is recreated in Unity using corridors, rooms, and obstacle boundaries. This model serves as the foundation for route computation and user visualization. It also enables testing of navigation logic before field deployment.

Navigation nodes are placed at key locations such as corridor intersections, room entrances, stair access points, and turning regions. These nodes form a navigation graph that allows the system to compute the shortest path between the user location and destination. By connecting important decision points rather than attempting continuous free-space routing everywhere, the system simplifies path planning while still producing practical navigation guidance.

The integration of localization with Unity-based navigation creates a complete workflow. Once the user position is estimated, it is mapped onto the digital environment. The destination selected by the user is also represented in the same model. Unity then calculates the path and renders it either as a visual guide in the digital model or as an overlay in the augmented reality interface. This coupling between sensing and visualization is one of the major strengths of the system.

From an implementation perspective, the proposed system is also extensible. Additional features such as voice instructions, floor switching, dynamic rerouting, or cloud data logging can be added in future versions. Because the sensing layer, localization layer, and visualization layer are logically separated, improvements can be introduced without redesigning the full system architecture.

VI. RESULTS AND DISCUSSION

Experiments were conducted inside a university building to evaluate localization accuracy and practical usability. Multiple ESP32 receiver nodes were deployed along corridors and at selected indoor locations, and RSSI measurements were collected at different distances between transmitter and receiver devices. The test environment included typical indoor obstacles such as walls, doors, and furniture, which allowed the system to be evaluated under realistic conditions rather than ideal laboratory settings.

Fig. 5. Real-time indoor navigation visualization

Localization accuracy was evaluated by comparing the estimated position with the ground truth location. The positioning error was calculated using the Euclidean distance between estimated and actual coordinates. Multiple measurements were taken across different positions in order to observe how performance varied with geometry, signal strength, and environmental obstruction. This evaluation method provides a direct indication of how well the system can support practical navigation tasks.

Experimental results indicate that the proposed system achieves an average positioning accuracy between one and three meters depending on environmental conditions such as obstacles, signal interference, and building structure materials. These results are consistent with BLE localization studies reported in the literature [15], [16]. In open corridor regions with fewer obstructions, the estimated position was generally more stable. In cluttered or partitioned areas, greater RSSI fluctuation produced somewhat larger localization errors.

The results also show that the proposed system is particularly suitable for room-level guidance and corridor navigation. Even when exact coordinate precision is reduced by noise, the system can still correctly identify the general user region and provide useful route assistance. This is important because many indoor navigation applications do not require centimeter-level precision; instead, they require clear direction to rooms, offices, or service areas.

The augmented reality interface improved the interpretability of the navigation output. Users can more easily follow directional overlays than static text instructions or floor maps. By presenting guidance visually in the context of the surrounding environment, the system reduces cognitive load and supports more intuitive movement. This feature is especially useful in buildings with repeated corridor layouts or visually similar sections.

Despite the encouraging results, some limitations were observed. RSSI-based methods remain sensitive to environmental changes, including crowd density, temporary obstacles, and device orientation. The current implementation is also focused on a single-floor setting, and therefore does not yet address vertical navigation between floors. Furthermore, the use of a simple path loss model may limit performance when signal behavior becomes highly irregular.

Overall, the results demonstrate that the proposed system provides a practical balance between cost, simplicity, and performance. The achieved accuracy is sufficient for many real-world indoor guidance applications, and the combination of ESP32 hardware, Unity pathfinding, and AR visualization shows strong potential for future expansion into more intelligent smart building services.

VII. CONCLUSION

This paper presented an IoT-based indoor navigation system using RSSI localization and ESP32 receiver nodes. The system integrates wireless signal measurements, IoT hardware, Unity-based path planning, and augmented reality visualization to provide real-time indoor navigation guidance. By using smartphones as BLE transmitters and ESP32 boards as low-cost receivers, the system avoids expensive dedicated infrastructure while maintaining useful indoor localization capability.

The proposed approach demonstrates that practical indoor navigation can be achieved with moderate complexity and affordable hardware. Experimental observations show that the system can provide localization accuracy in the range of one to three meters under typical indoor conditions. This level of performance is sufficient for many applications such as room finding, corridor guidance, campus assistance, and public building navigation.

An important contribution of the work is the integration of localization with an intuitive user interface. The use of augmented reality improves the way navigation instructions are delivered, making the system easier to use in unfamiliar environments. In addition, the modular structure of the implementation supports future enhancement and adaptation to different buildings and use cases.

Future work will focus on improving localization accuracy using machine learning techniques, adaptive filtering, and enhanced signal modeling. Support for multi-floor navigation, voice-guided assistance, and dynamic route updates may also be incorporated. With these improvements, the proposed system can be extended into a more robust indoor navigation platform for next-generation smart environments.

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