Comparative Evaluation of Bluetooth-Based Distance Measurement Techniques Across Multiple Performance Metrics

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***Abstract*—Accurate indoor distance measurement is crucial for applications where GPS is unavailable. Bluetooth Low Energy (BLE) techniques—RSSI, AoA/AoD, RTT, and Channel Sounding—offer varying trade-offs in accuracy, complexity, and device support. This paper compares these methods through experimental evaluation of RSSI and RTT using ESP32-C6 modules in library and corridor environments, demonstrating that RTT achieves significantly better stability than RSSI in multipath conditions. A comprehensive feature-based analysis of all four techniques provides practical guidelines for selecting the most suitable BLE approach based on application requirements.**

***Index Terms*—Bluetooth Low Energy, Indoor Positioning, RSSI, RTT, Channel Sounding, AoA/AoD, Distance Measurement**

I. Introduction

Indoor positioning and distance measurement are becoming increasingly important in environments where GPS is unavailable or unreliable, such as malls, airports, warehouses, and smart buildings. With the growing reliance on smart technologies, the demand for accurate indoor distance measurement has surged over the years, as shown in Figure 1.

Bluetooth Low Energy (BLE) has emerged as a popular solution due to its low cost, low power, and widespread device support. Its distance measurement techniques—RSSI, AoA/AoD, RTT, and channel sounding—offer varying trade-offs in accuracy, complexity, and hardware requirements.

This paper surveys and compares these Bluetooth-based distance measurement methods across accuracy, cost, infrastructure, device support, power, and robustness. The goal is to guide the selection of the most suitable BLE approach for specific applications, helping designers and researchers balance trade-offs between precision, deployment feasibility, and system requirements.

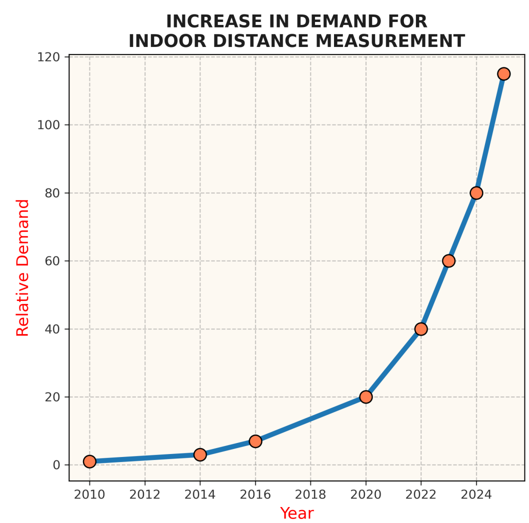


Fig. 1: Growth in demand for indoor distance measurement (2010–2024)

II. Literature Review

Wi-Fi-based indoor positioning has been widely explored due to the common availability of Wi-Fi infrastructure and devices. Techniques like RSSI fingerprinting, time-of-flight, and angle-based methods have shown moderate accuracy in controlled environments [1] [2] [3]. However, Wi-Fi systems often face challenges with signal fluctuation, interference, and power consumption in dense deployments [1] [4]. Moreover, accuracy is frequently limited to the meter-level unless Wi-Fi channel state information (CSI) or fine timing measurements (FTM/RTT) are used to obtain decimeter or sub-meter performance [2] [5].

LoRaWAN, as a low-power wide-area network, offers long-range connectivity and minimal energy consumption, which is advantageous for sparse or distributed sensor deployments [6]. Nevertheless, its low bandwidth, long RTTs, and coarse radio observables make high-precision indoor localization difficult; classical range-based methods (RSSI/ToA) give poor resolution in LoRa networks, and TDoA requires careful gateway synchronization to approach meter-scale errors in practice [7] [8].

Bluetooth Low Energy (BLE) emerged as a practical solution for indoor positioning due to its widespread use, low power consumption, and flexibility in deployment. BLE techniques, including RSSI, Angle of Arrival (AoA)/Angle of Departure (AoD), Round-Trip Time (RTT), and phase-based channel sounding, provide varying trade-offs between accuracy, infrastructure complexity, and device compatibility. This versatility, combined with the ability to operate effectively in indoor environments, justifies the choice of BLE over Wi-Fi and LoRaWAN for many smartphone-centric, low-power indoor distance measurement applications.

A. RSSI

RSSI-based distance measurement estimates the range between a transmitter and receiver by observing the received signal strength of Bluetooth signals [10], [11]. As electromagnetic waves propagate, the signal strength decreases with distance due to path loss. The relationship between RSSI and distance can be modeled using the log-distance path loss model, which is commonly used in indoor environments [10], as shown in Equation (1):

$$PL(d) = PL(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \tag{1}$$

where $PL(d)$ is the path loss in dB at distance d, $PL(d_0)$ is the path loss at a reference distance d_0, n is the path loss exponent (environment-dependent), and X_σ is a Gaussian random variable representing shadow fading and environmental noise [10].

The distance d is estimated from measured RSSI values as [10], [11]:

$$d = d_0 \cdot 10^{\frac{RSSI(d_0) - RSSI(d)}{10n}} \tag{2}$$

where $RSSI(d)$ is the received signal strength at distance d and $RSSI(d_0)$ is the signal strength at reference distance d_0. This formula provides an approximate distance estimate that is influenced by multipath, interference, and human body absorption, which are prevalent in indoor environments [11], [12].

RSSI-based ranging has several advantages: it is compatible with all modern Bluetooth devices, requires no additional hardware or antenna arrays, and is simple and cost-effective to deploy at scale [10]. Despite its simplicity, it suffers from significant errors in indoor scenarios due to multipath propagation, body blockage, and environmental variations [11]. To improve the accuracy, techniques such as fingerprinting, triangulation, or averaging over multiple measurements are commonly applied [10], [11].

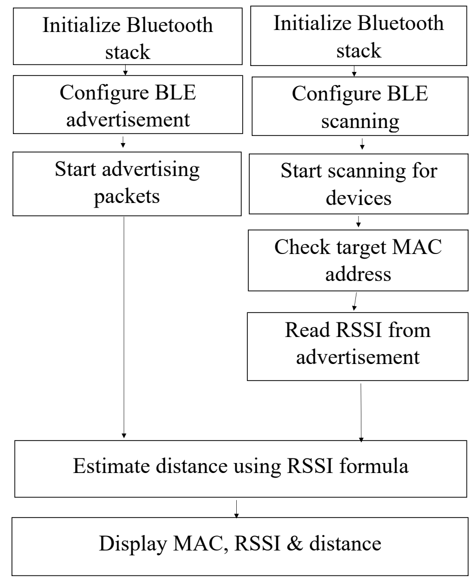


Fig. 2: Flowchart of the proposed system.

B. Angle of Arrival (AoA) and Angle of Departure (AoD) Based Distance Measurement

AoA and AoD techniques use the direction of transmitted or received signals to estimate relative device positions. In AoA, the receiver employs an antenna array to measure phase differences between signals at multiple antennas, while AoD measures the angle at which signals leave the transmitter. These angles, combined with signal measurements, allow triangulation of precise positions [13] [14].

The angle θ can be calculated from the phase difference $\Delta\phi$ between two antenna elements separated by distance d_a and signal wavelength λ as shown in Equation (3):

$$\theta = \arcsin\left(\frac{\lambda\Delta\phi}{2\pi d_a}\right) \tag{3}$$

AoA/AoD methods achieve sub-meter localization accuracy and are less affected by multipath than RSSI [14]. Multiple measurements from different anchors can be combined using triangulation for precise 2D or 3D positioning. These techniques require calibrated antenna arrays, adding cost and complexity, and have limited smartphone support [15]. They are suitable for applications requiring precise localization, such as asset tracking, indoor navigation, and real-time location systems (RTLS) [13] [14].

C. Round Trip Time (RTT) Based Distance Measurement

RTT-based distance measurement estimates the range between two Bluetooth devices by measuring the time taken for a signal to travel from the transmitter to the receiver and back. Since the signal propagates at the speed of light c, the distance can be directly inferred from the measured round-trip time. This method avoids many of the signal-strength-related inaccuracies that affect RSSI-based techniques [9] [17].

The estimated distance d is given by Equation (4):

$$d = \frac{c \cdot RTT}{2} \tag{4}$$

where c is the speed of light (3×10^8 m/s) and RTT is the measured round-trip time. The division by two accounts for the signal traveling to the receiver and back. To ensure accurate measurements, synchronization and precise timestamping are required at both ends of the communication [17].

RTT-based methods generally achieve higher accuracy than RSSI-based approaches, particularly in multipath-prone indoor environments. However, their performance depends on hardware and firmware capabilities, as very fine time resolution (in the nanosecond range) is needed to achieve sub-meter accuracy. This often demands specialized hardware support, which may not be available in all commercial Bluetooth chipsets [9].

In practical applications, RTT-based distance measurement is well-suited for indoor positioning systems that require higher precision, such as industrial asset tracking, proximity services, and navigation in dense indoor environments. While it offers improved accuracy compared to RSSI, its adoption is limited by hardware availability and energy consumption concerns [17].

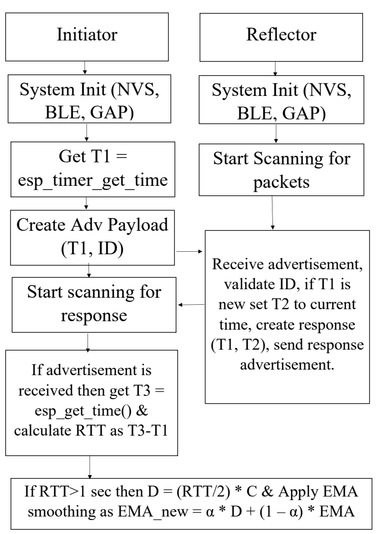


Fig. 3: Flowchart of the proposed system.

D. Channel Sounding (CS) Based Distance Measurement

Channel Sounding (CS), standardized in Bluetooth 6.0, is a comprehensive distance measurement framework that combines both Round Trip Time (RTT) and Phase-Based Ranging (PBR) to achieve high-accuracy localization. Unlike standalone RSSI or RTT, CS leverages in-phase (I) and quadrature (Q) samples across multiple subcarriers, enabling robust multipath mitigation and improved precision [16] [17].

In the RTT component, the coarse distance is estimated by measuring the round-trip propagation time of packets between the initiator and reflector, as shown in Equation (5):

$$d_{RTT} = \frac{c \cdot RTT}{2} \tag{5}$$

where c is the speed of light and RTT is the measured round-trip time [17].

For fine-grained measurement, PBR exploits the phase differences across multiple subcarriers. The received complex samples (I, Q) yield a phase response $\phi(f)$ for each subcarrier frequency f. The slope of phase over frequency provides the propagation delay Δt, as shown in Equation (6):

$$\Delta\phi(f) = 2\pi f \cdot \Delta t \tag{6}$$

From this, the refined distance estimate is derived as shown in Equation (7):

$$d_{PBR} = \frac{c \cdot \Delta\phi}{2\pi \Delta f} \tag{7}$$

where $\Delta\phi$ is the measured phase difference across subcarriers and Δf is the frequency spacing [17].

The final CS-based distance estimate combines both RTT and PBR results, where RTT provides coarse ranging and PBR refines the estimation to sub-meter precision:

$$d_{CS} = d_{RTT} + d_{PBR} \tag{8}$$

CS-based ranging thus achieves higher resilience to multipath and offers superior accuracy compared to traditional techniques. However, it requires Bluetooth 6.0-compliant devices capable of collecting and processing IQ samples, and it involves higher computational complexity and energy consumption [16] [17].

In practical applications, CS is particularly suitable for high-precision indoor navigation, industrial automation, and crowd management systems, where accuracy and robustness justify the additional infrastructure and device requirements [17].

III. Implementation and Results

A. Experimental Setup

The system was implemented using two ESP32-C6 development boards programmed via the ESP-IDF framework. One board was configured as a Bluetooth advertiser (transmitter) and the other as a scanner (receiver). For RSSI-based measurements, the scanner continuously captured advertisement packets and recorded the received signal strength values. For RTT-based measurements, a custom protocol was implemented where the initiator transmitted a timestamped packet and the reflector responded, enabling round-trip time calculation. Photographs of the deployed units are shown in Figure 4

Fig. 4: Deployed unit for the experiment

B. Measurement Environments

Testing was performed in two representative indoor environments. The first was a university library partially covered with bookshelves, introducing multipath reflections and signal attenuation. The second was a narrow passageway, approximately wide enough for four individuals to stand side by side, simulating a corridor. These environments were chosen to highlight performance under obstructed and constrained conditions typical of real-world deployments.

C. Methodology

Measurements were collected at distances ranging from 0.5 m to 5 m in steps of 0.5 m. At each distance, 50 measurements were recorded to enable statistical analysis. For RSSI, distance was estimated using the log-distance path loss model as described in Equation (2). For RTT, distance was derived from the round-trip time of packets corrected for baseline latency. The collected results were plotted as two graphs: RSSI-estimated distance vs. actual distance (Figure 5) and RTT-estimated distance vs. actual distance (Figure 6). In both cases, deviations from ground truth highlight the impact of multipath and noise in the library and corridor settings.

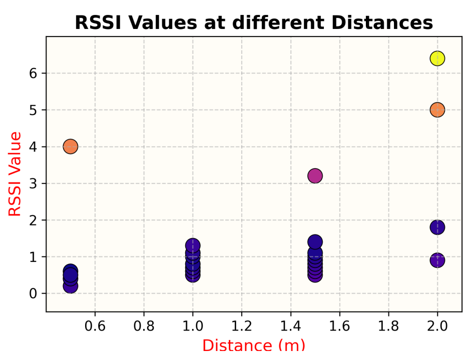


Fig. 5: Deviation between actual and predicted distances using RSSI-based measurements in library and corridor environments, with color grading indicating error magnitude.

D. Channel Sounding Limitation

While Bluetooth Channel Sounding promises sub-meter accuracy by combining RTT with phase-based ranging using IQ samples, implementation was not possible in this work due to hardware and software constraints. Currently, smartphone operating systems restrict access to raw IQ samples at the OS level, and ESP32-C6 boards do not expose IQ samples for Bluetooth ranging. Consequently, only RSSI and RTT methods were implemented, with Channel Sounding (Bluetooth 6.0) discussed as a future extension pending hardware availability.

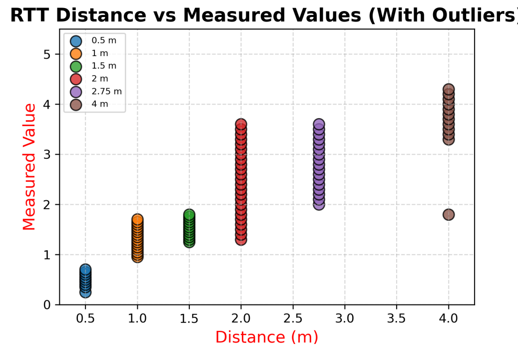
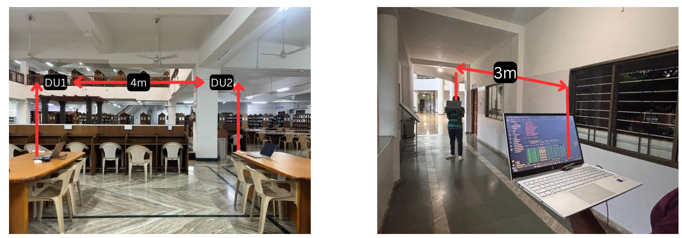


Fig. 6: Deviation between actual and predicted distances using RTT-based measurement in library and corridor environments



(a) Library environment (b) Corridor environment

Fig. 7: Experimental deployment setup in two indoor environments

E. Results and Discussion

The experimental results obtained from the university li brary and the narrow corridor environments highlight the con trasting performance of RSSI-based and RTT-based distance measurement. The RSSI method, while simple to implement, exhibited large fluctuations and poor correlation with the actual distance, particularly in the bookshelf-dense library environment where multipath reflections and shadowing were dominant. In contrast, RTT-based measurements demonstrated greater stability, producing estimates that more closely fol lowed the ground truth over the 0.5–5m range. The results confirm that RTT is inherently more robust to multipath effects than RSSI, although small deviations were still observed in the constrained corridor scenario. These observations emphasize the trade-offs between the two techniques: RSSI remains attractive for low-cost, large scale deployments where coarse zone-level accuracy is suffi cient, whereas RTT provides improved precision but requires tighter synchronization and hardware support.

TABLE I: Comprehensive Comparison of Bluetooth-Based Ranging Techniques

Feature	RSSI	RTT	Channel Sounding (CS)	AoA/AoD
Principle of Operation	Signal-strength attenuation-based	Distance from round-trip time	I/Q sample analysis for multipath-aware ranging	Phase-based angle estimation using antenna arrays
Accuracy	Low (2-5m)	Moderate (1-2m)	High with multipath mitigation (¡1m)	High directional accuracy (¡1m)
Range	Short (¡10m)	Moderate (¡30m)	Moderate-high (¡50m)	Short-moderate (¡20m)
Latency	Very low (¡10ms)	Moderate (50-100ms)	Moderate (100-200ms)	Low-moderate (20-50ms)
Environmental Robustness	Low	Moderate	High	High
Hardware Requirements	No special hardware	BLE 5.1+ timing support	BLE 6.0 chipset with I/Q sampling	Antenna array + calibration
Implementation Complexity	Very low	Moderate	High	Very high
Cost	Very low ($)	Moderate ($$)	Moderate-high ($$$)	High ($$$$)
Power Consumption	Very low (¡10mW)	Moderate (20-50mW)	Moderate-high (50-100mW)	Very high (¿100mW)
Scalability	Very high (1000s)	Moderate (100s)	Moderate (100s)	Low-moderate (10s)
Standard Support	BLE universal	BLE 5.1+	BLE 6.0+	BLE 5.1+ with AoA/AoD
Device Availability	All phones	Limited	Very rare	Special hardware
Privacy & Security	Low	Moderate	High	Moderate

IV. Feature-Based Comparative Study and Guidelines

Accurate indoor distance measurement using Bluetooth depends on the application requirements, including accuracy, cost, power consumption, device availability, and environmental conditions. Table I presents a comprehensive comparison of the four main Bluetooth ranging techniques across thirteen critical dimensions.

The comparison reveals clear trade-offs between universal compatibility versus precision, and simplicity versus robustness. Practitioners should first identify their accuracy requirements, then evaluate hardware constraints and device availability to narrow suitable options. Applications requiring sub-meter accuracy must adopt CS or AoA/AoD despite higher costs, while zone-level applications can leverage RSSI's simplicity and broad device support.

After reviewing the comparison, the selection of a Bluetooth distance measurement technique should be guided by the specific accuracy targets, hardware constraints, and operational environment of the application:

- **RSSI:** RSSI-based ranging relies solely on signal strength, making it the simplest and most widely supported technique across all Bluetooth devices. It is low-cost and energy-efficient but highly sensitive to multipath, obstacles, and device orientation, resulting in coarse distance estimates. *Suitable for:* crowd density monitoring, retail analytics, room-level presence detection, low-cost IoT tracking, and smart home automation triggers.
- **RTT:** RTT measures the round-trip propagation delay of packets, providing improved stability and accuracy compared to RSSI, typically within the 1–2 meter range. It does not require specialized antenna arrays and offers moderate robustness to multipath, though clock synchronization and hardware delays can still affect precision. *Suitable for:* indoor navigation (hospitals, warehouses, malls), industrial asset tracking, safety-related proximity alerts, and context-aware location services where moderate accuracy is sufficient.
- **Channel Sounding (CS):** CS, introduced in Bluetooth 6.0, enhances RTT by incorporating phase-based ranging using I/Q samples across multiple subcarriers. This significantly improves multipath resilience and supports consistent sub-meter accuracy. However, it requires higher computation, calibration, and CS-capable hardware. *Suitable for:* autonomous indoor robots, AGV guidance in smart factories, precise worker/asset localization in industrial automation, and advanced real-time indoor mapping.
- **AoA/AoD:** Angle-of-Arrival/Departure methods estimate both distance and direction using antenna arrays and

phase-calibrated hardware. Although more hardware-intensive, they enable highly accurate spatial localization with directional awareness, making them ideal for complex navigation systems. *Suitable for:* precision robotics with directional path planning, indoor drone docking, warehouse robot coordination, AR/VR systems requiring orientation tracking, and high-end logistics asset tracking.

V. Conclusion

This paper presented a comparative evaluation of four Bluetooth-based distance measurement techniques—RSSI, AoA/AoD, RTT, and Channel Sounding—analyzing their principles, hardware requirements, and real-world performance trade-offs. Experimental implementation using ESP32-C6 modules demonstrated the practical differences between RSSI- and RTT-based methods. While RSSI offers simplicity and broad compatibility, it suffers from high variability in multipath environments. RTT, on the other hand, provides significantly better stability and accuracy but requires tighter hardware synchronization and higher computational overhead. This study is limited to ESP32-C6 modules and did not experimentally implement AoA/AoD or Channel Sounding due to hardware constraints.

The broader comparative analysis highlights the rapid evolution of Bluetooth ranging technologies. Traditional signal-strength-based methods emphasize accessibility and low cost, whereas angle- and phase-based approaches show how modern Bluetooth standards are increasingly optimized for precision, robustness, and spatial awareness. This progression underscores Bluetooth's growing relevance in indoor localization, bridging the gap between lightweight IoT applications and advanced real-time positioning systems.

Future work will focus on implementing Bluetooth 6.0 Channel Sounding once hardware and firmware support become widely available, enabling fine-grained phase-based localization. Additionally, hybrid models combining RTT and RSSI could further enhance performance under dynamic indoor conditions. This study provides a holistic understanding of Bluetooth-based ranging technologies and offers practical guidance for selecting suitable methods based on system constraints, accuracy requirements, and deployment environments.

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