**The main aspects for comparing different Bluetooth based distance measurement techniques**.

1.Accuracy

* How close the estimated distance to the measured distance
* MSE and RMSE
* RSSI has low accuracy/AOD and CS have high accuracy

2. Range

* Maximum reliable distance the technique works at.
* RSSI has longer ranges but with less precision where as CS and AOA/AOD and RTT usually give reliable short-medium range

3. Cost/Hardware requirements

* Need of specialized antennas (AOA/AOD)
* Can it be run-on present-day smartphones and ESP32 boards (RSSI/RTT)
* Cost of deployment in malls, hospitals, transport places.

4. Complexity in implementation

* Software complexity like calibration, filtering, signal processing.
* Hardware complexity – like specialized antennas, clock synchronizations, multiple receivers.

5. Power Consumption

* Important for smartphones and IOT devices which are used (ESP32).
* High resolution timing in RTT and CS requires more power.
* RSSI requires low power but scanning make consume more power some times.

6.Robustness to the surroundings

* This is crucial for indoor environments.
* Multipath fading’s, interference from other WIFI and Bluetooth signals.
* RSSI highly affected. Others are a little less affected

7.latency/Real time performance

* How fast they are in the distance measurement
* RTT, RSSI can be fast
* AOA/AOD might be a little delayed because of signal processing.

8.Scalability

* Can it hundreds of users in crowded indoor places.
* Synchronization bw the devices.

9.Standars support and Availability

* Which are supported by the present Bluetooth versions on smartphones and ESP32 devices.
* RSSI and RTT (highly supported from Bluetooth 5.2 and 5.3)
* CS supported from Bluetooth 6.0 not available till now.
* AOA/AOD requires specialized antennas attached to the devices.

10.Security

* How resistant the technique is to signal tampering and spoofing attacks.
* In distance measurement the attackers can try to fake the distances.
* RSSI < AOA/AOD < RTT < CS

**Different use cases which can use Bluetooth based distance measurement and which features are important to be considered to decide which technique suites the requirements.**

1.Indoor navigation and Wayfinding:

* Where – malls, airports, hospitals, campus
* What – showing the people the path to the different locations.
* Accuracy, scalability, Availability on smartphones.

2.Crowd management:

* Where – stadiums, malls, concerts during emergency and panic situations.
* What – detect overcrowding at the exits and guide people to the less crowded exits to prevent stampedes.
* Scalability, latency, Robustness, Cost.

3. Asset tracking and inventory management (tracking machines and inventory):

* Where – industries and ware houses.
* What – track machines
* Power consumption, cost, robustness.

4.Smart homes and smart vehicles:

* Where – homes, offices and vehicles
* What – unlocking car doors, turning on the engines and controlling different devices in homes and unlocking the homes
* Security, power consumption, accuracy.

5. tracking of elderly people and giving alerts

* Where – any places
* What – tracking of the elders in homes and hospitals. Giving alerts if they are falling down etc.
* Robustness, latency, accuracy.

6.contact tracking in covid-19 like situations:

* Where – public health monitoring
* What – seeing who are the all the person meet by this person to track the spread of the disease
* Scalability, security, power consumption, availability on smartphones.

**Narrative explanations of different Bluetooth distance measurement techniques**

**1.RSSI – based ranging**

**Received signal strength indicator measures how strong a Bluetooth signal appears at the receiver. Since radio signals attenuate as distance increases RSSI values can be mapped to approximate distance.**

**Key features:**

* **Works with all Bluetooth present day available devices including the smartphone devices.**
* **Requires no additional hardware and antenna arrays for smartphones and compatible IOT devices.**
* **Cheapest and easiest method to deploy at scale.**

**Constraints:**

* **Multipath propagation and body absorption results in fluctuations.**
* **Very high errors and deviations in indoor environments.**
* **Requires extensive calibration & fingerprinting and triangulation more improving accuracy.**

**Applications:**

**Most suitable for zone level applications, occupancy monitoring and presence detection but not for high precision navigation**

**2.Angle of Arrival (AOA) / Angle of Departure (AOD)**

**AOA and AOD techniques utilize arrays to determine the phase difference between the incoming and outgoing signals. This phase information when combined with geometric methods provides the position or the distance estimation. For a measured linear array with with the element spacing delem  the measured phase difference Δφ between the elements for plane wave arriving at azimuth θ satisfies**

**=**

**Where lamda is the wavelength of the carrier signal. The direction of the arrival vectors is given by**

**Key features:**

* **Provides a little better accuracy compared to the RSSI and provides both angular and positional information.**

**Constraints:**

* **Limited support in smartphones and requires special antennas for the IOT devices also with precise calibaration.**

**Applications:**

**Real time localization systems, industrial asset tracking and ware house navigation.**

**3.Round trip time (RTT) ranging**

**RTT estimates distance by measuring the propagation delay of a signal transmitted from one**

**Device and echoed back by the another. The elapsed round-trip time is calculated and is combined with the known propagation speed of the radio waves, yields an estimate of the distance.**

**Where t corresponds to the RTT time when is usually calculated as**

**d = (CT-tprop)/2**

**key features:**

* **Does not relay on antennas arrays and less venerable to multipath effects relative to RSSI.**

**Constraints:**

* **Requires precise time synchronization and provides an accurate measurements in the range 1-5 m**

**Applications:**

**Well suited for room level positioning indoor way finding and context aware applications where meter level accuracy is acceptable.**

**4.Channel sounding based ranging**

**Phase based ranging technique exploit phase differences of the signals transmitted across multiple frequencies to derive precise distance measurement. Bluetooth 6.0 introduces standardized channel sounding which integrates phase-based ranging with RTT calculation provide submeter and even centimetre level accuracy.**

**d = c**

**Key features:**

* **Demonstrated potential centimetre level accuracy in trials.**
* **Does not require antennas and enhances stability.**
* **Provides resistance to relay and spoofing based attacks via secure distance measurement.**

**Constraints:**

* **Currently at n early stage of adoption with limited hardware in both the smartphones and IOT devices.**
* **Requires BlE 6.0 capable chipsets and specialized APIs**
* **Greater computational complexity when compared to the RSSI & RTT methods.**

**Table 1: Performance & Accuracy analysis:**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Feature** | **RSSI** | **RTT** | **Channel Sounding** | **AOA/AOD** |
| **Principle/Formula** | **Uses received signal strength to infer distance**  **d=10(ptx-prx)/(10n)** | **Measures round trip time**  **d=RTT\*c/2** | **Measures channel response over frequency or time to estimate distance/angle** | **Measures signal arrival/departure angle via antenna arrays uses phase differences** |
| **Accuracy (typically indoor)** |  |  |  |  |
| **Range** |  |  |  |  |
| **Latency** | **Very low** | **Moderate** | **Moderate** | **Low to moderate**  **(processing required)** |
| **Robustness to environment** | **Low**  **Affected by multipath** | **Moderate**  **RTT mitigates to some multipath but highly affected** | **High**  **CS handles multipath well** | **High**  **AOA/AOD sensitive to reflections but directional info helps.** |

**Table 2: Cost, Implementation and Energy:**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Feature** | **RSSI** | **RTT** | **CS** | **AOA/AOD** |
| **Cost** | **Very low**  **Does not require any special antennas and hardware** | **Moderate**  **Highly synchronized clocks** | **Moderate to high**  **Depends on the BLE hardware being used** | **High**  **Antennas arrays required** |
| **Implementation complexity** | **Very easy**  **Simple scanning is only need to be done** | **Moderate**  **Requires initiator & reflector setup** | **High**  **Advanced BLE stack & signal processing** | **High**  **Multiple antennas, calibration and signal processing** |
| **Power consumption** | **Very low** | **Moderate** | **Moderate to High** | **Very High**  **Power is also used by the antennas** |
| **Scalability** | **Very high**  **All BLE devices** | **Moderate**  **BLE 5.1+ devices** | **Moderate**  **BLE 6.0+ devices** | **Low to Moderate**  **Limited by hardware and antennas** |

**Table 3: Standards, Availability, Privacy & Security:**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Feature** | **RSSI** | **RTT** | **Channel Sounding** | **AOA/AOD** |
| **Standard supports and Availability** | **BLE universal** | **BLE 5.1 +** | **BLE 6.0 + & also in some CS extensions** | **BLE 5.1 + with AOA/AOD extensions** |
| **Device Availability** | **Almost all smartphones & BLE devices** | **Limited to BLE 5.1 + supported devices** | **Limited to BLE 6.0 + supported devices (presently not available in smartphones and IOT devices)** | **Very few devices with specialized hardware extensions** |
| **Privacy & Security** | **Low**  **Signal can be tracked and manipulated with the help of amplifiers** | **Moderate**  **Not affected by amplitude magnifications as mainly depends on the RTT** | **High**  **CS can be designed to minimise tracking and spoofing attacks** | **Moderate**  **Potential tracking of misused** |

**Coming to scalability CS has been low only because of the non-availability of the Bluetooth 6.0 in the present day but once it becomes available this can be highly increased.**

Which Bluetooth distance estimation method should be used?

RTT

CS

RSSI

AOA/AOD

CS

RSSI

Which BLE version is available?

Is angle/direction info required?

Is low power mode + wide device support important?

Is very high accuracy required?

Is low cost & simple implementation priority?

**Yes**

No

Yes

No

Yes

f

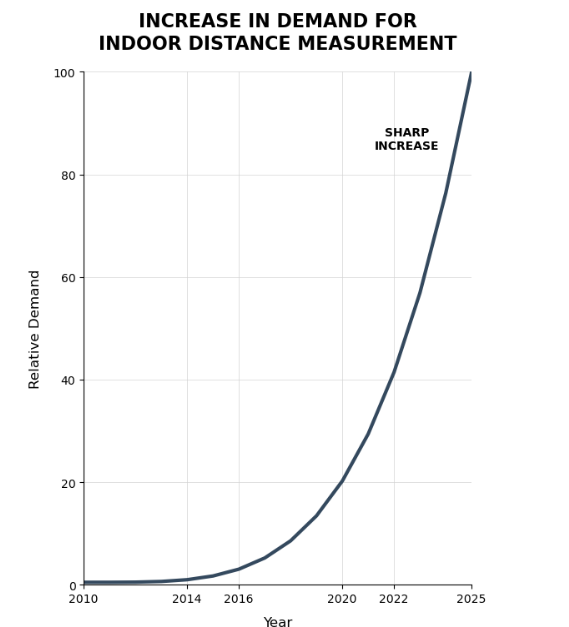
yes

No

BLE 5.1 + BLE 6.0 +

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.



[**Figure 1: Growth in demand for indoor distance measurement (2010–2024)**]

Bluetooth Low Energy (BLE) has emerged as a popular solution due to its low cost, low power, and widespread device support. Techniques like RSSI, AoA/AoD, RTT, and phase-based channel sounding vary in complexity, accuracy, hardware requirements, and smartphone compatibility. RSSI is simple but less accurate; AoA/AoD offers sub-meter precision with arrays; RTT improves over RSSI without arrays; and channel sounding promises centimetre-level accuracy but is still emerging in consumer devices.

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.

**Papers:**

1. **RSSI**

**Paper regarding the fluctuations of rssi -** [**https://onlinelibrary.wiley.com/doi/full/10.1002/ett.3793?utm\_source=chatgpt.com**](https://onlinelibrary.wiley.com/doi/full/10.1002/ett.3793?utm_source=chatgpt.com)

**Paper showing the fluctuations and outliers in rssi and non-reliability of rssi –**

[**https://www.mdpi.com/1996-1073/15/23/8832?utm\_source=chatgpt.com**](https://www.mdpi.com/1996-1073/15/23/8832?utm_source=chatgpt.com)

**paper showing the prone of attacks on rssi –**

**C:\Users\chsai\OneDrive\Desktop\materials\_paper\attacks.pdf**

**Paper showing the effect of robustness to surroundings of rssi-**

**C:\Users\chsai\OneDrive\Desktop\materials\_paper\Bluetooth\_Based\_Indoor\_Navigation\_System.pdf**

1. **AOA/AOD**

**Article/ paper on AOA/AOD working and setup –**

[**https://pubmed.ncbi.nlm.nih.gov/34064147/**](https://pubmed.ncbi.nlm.nih.gov/34064147/)

**paper showing the performance of AOA/AOD in different environments –**

[**https://ui.adsabs.harvard.edu/abs/2022ISPAr46W1..155Q/abstract**](https://ui.adsabs.harvard.edu/abs/2022ISPAr46W1..155Q/abstract)

**paper on impact of antennas on AOA/AOD –**

[**https://spacefrontiers.org/r/10.3390/s24144579?utm\_source=chatgpt.com**](https://spacefrontiers.org/r/10.3390/s24144579?utm_source=chatgpt.com)

1. **Channel sounding –**

**Bluetooth sig document on cs intro –**

[**https://www.bluetooth.com/learn-about-bluetooth/feature-enhancements/channel-sounding/**](https://www.bluetooth.com/learn-about-bluetooth/feature-enhancements/channel-sounding/)

**paper showing the PBR & RTT power consumption working in different environments fluctuations and improvising strategies. Shows methodology error comparison and also states about the implementation lacking capability in modern day phones. Accuracy, implementation complexity and scalability in the real world.**

**C:\Users\chsai\OneDrive\Desktop\materials\_paper\BLE\_Channel\_Sounding\_Novel\_Method\_for\_Enhanced\_Ranging\_Accuracy\_in\_Vehicle\_Access.pdf**

1. **Bluetooth technical overview on all Bluetooth based distance measurement techniques.**

[**https://www.bluetooth.com/channel-sounding-tech-overview/**](https://www.bluetooth.com/channel-sounding-tech-overview/)