V5/23

Using Bluetooth as a Location Technology

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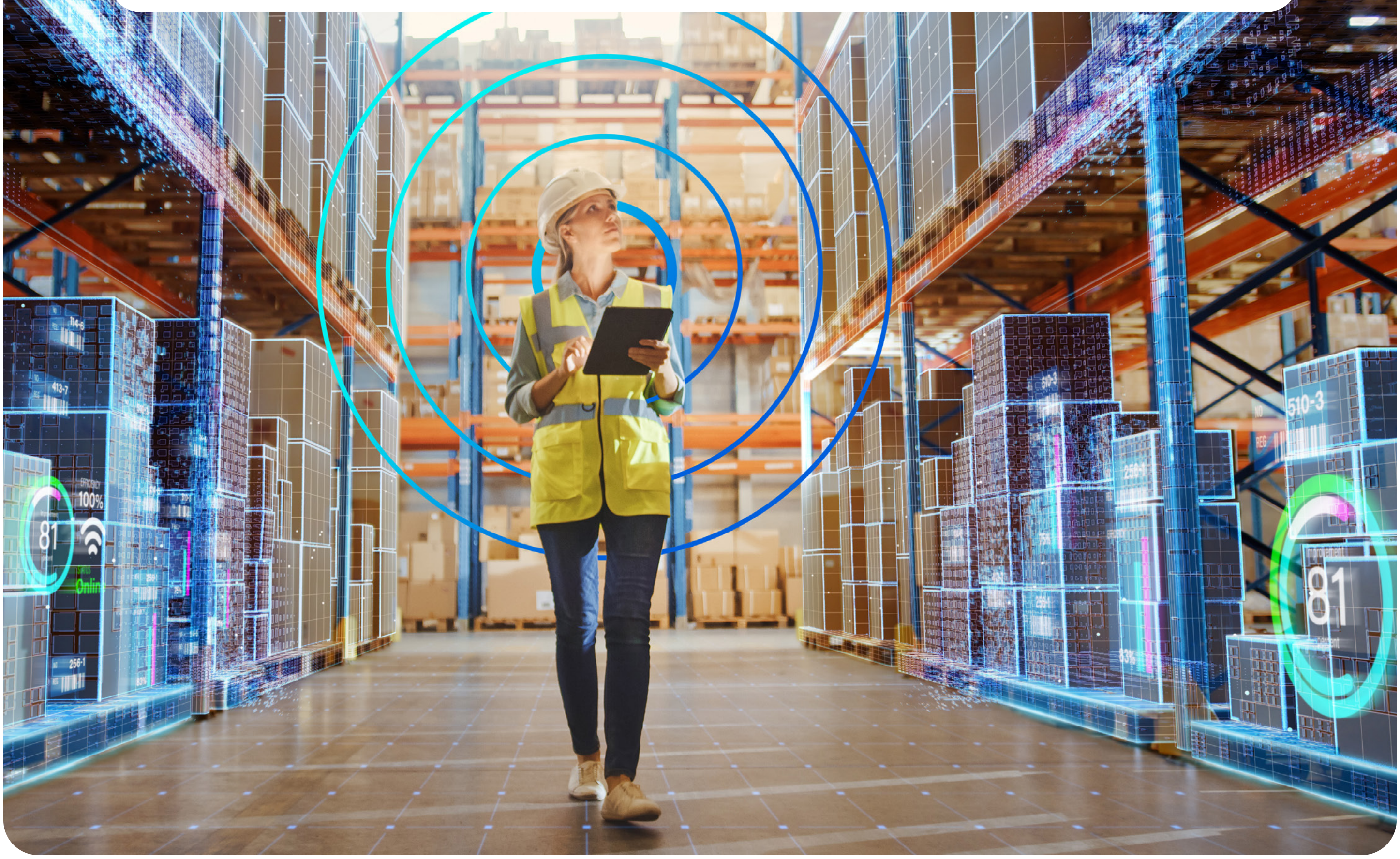
Introduction

For a prolonged period, RFID technology has been the cornerstone of location-tracking applications, owing to its RF-based communication capabilities. However, as advancements in technology progressed, the limitations of RFID in terms of security vulnerabilities and unidirectional communication have become more apparent. Although NFC technology, which is another RF-based communication method, has mitigated some of the security concerns and added bidirectional communication, it is still not a versatile solution for the location tracking applications that are emerging.



However, with the recent proliferation of Bluetooth technologies, there are many benefits that individuals and industry alike can experience by selecting Bluetooth as a location technology instead of traditional RF-based devices. Supported by the [Bluetooth Special Interest Group](https://www.bluetooth.com) (SiG), Bluetooth technology offers a standardized wireless technology solution that is readily available in many existing products that can be leveraged as universal receivers, such as smartphones. Therefore, many organizations are heavily investing in Bluetooth to extend functionality, further enhance battery life, and improve affordability. As a result, Bluetooth ranging technology, which uses the distance between one or more devices through signal properties or packet transmission details, is now used for a variety of targeted ranging applications instead of RFID or NFC. These applications can be categorized into two groups – proximity awareness systems such as digital keys, and localization applications, where an object can be tracked using trilateration or triangulation. Examples of localization applications include asset tracking, personal item finding, and indoor wayfinding.

This whitepaper explores the benefits of using Bluetooth technology for these types of location-based applications as it exists today and it will dive into the details on how Bluetooth ranging technology can be extended using different ranging techniques. It also looks at some emerging Bluetooth technologies and discusses how Silicon Labs is providing an ecosystem that supports the development of robust, reliable, and secure Bluetooth connectivity technologies.

Key Applications for Bluetooth Location Services

From the healthcare industry to manufacturing facilities and government agencies, many location-based proximity awareness and localization systems can benefit from using Bluetooth for location services. For example, a hospital is shown in Figure 1. In the facility, there are departments where, for health and safety reasons, access must be restricted to certain patients and doctors. With Bluetooth-based digital key technology, access control and access security alerts can be easily managed.

Bluetooth-based smart asset management makes it possible to track critical assets such as portable medical equipment including hospital beds and various life-saving machinery within the facility. Smart asset management not only increases productivity, but it can potentially save lives by reducing the time needed to track down the right equipment. Additionally, since hospitals are large facilities, indoor wayfinding can be enabled with Bluetooth technology.

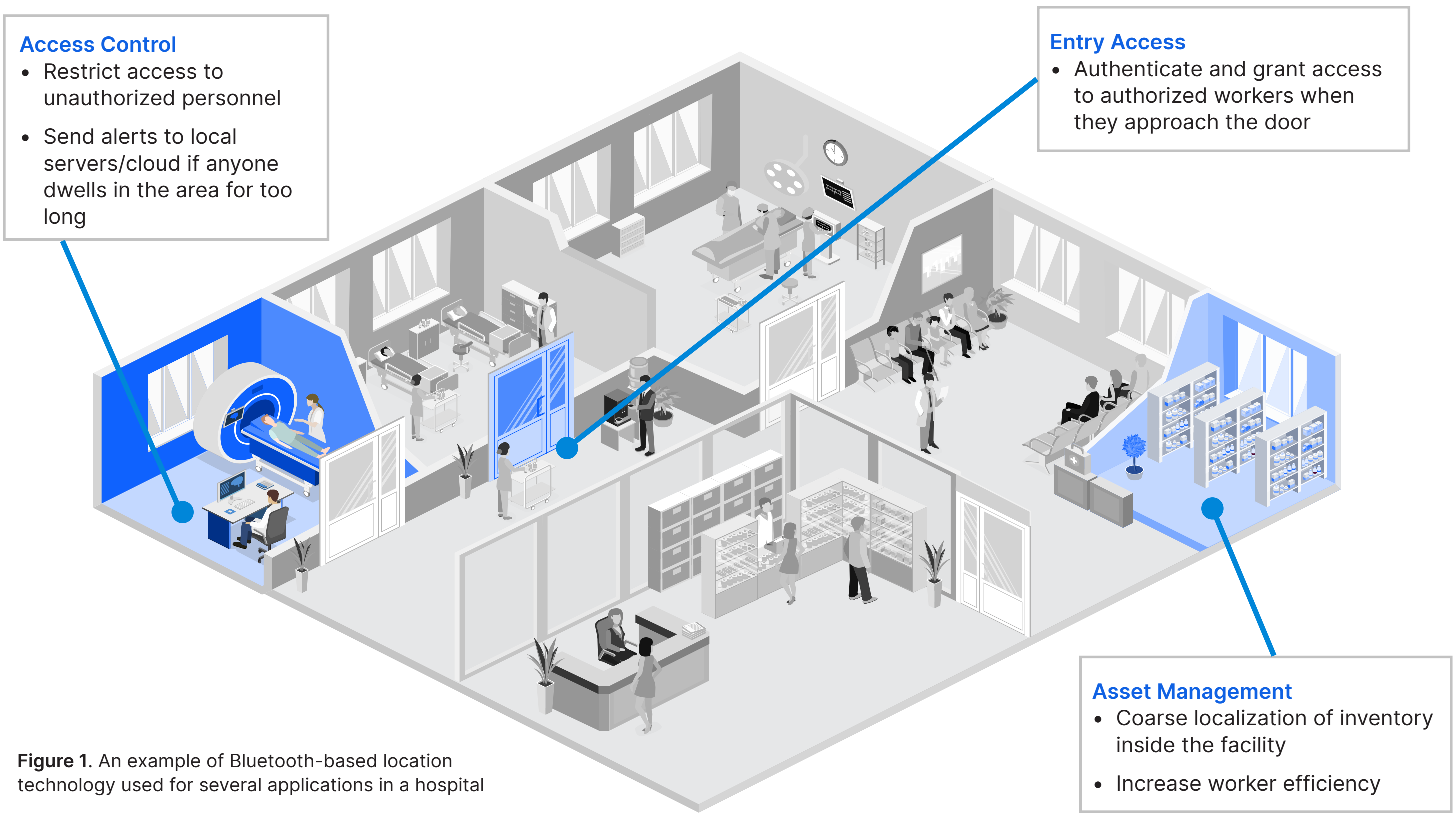


Figure 1. An example of Bluetooth-based location technology used for several applications in a hospital

Let's explore more details on how each of these location-based technologies functions using Bluetooth.

Indoor Asset Tracking

To increase efficiency, productivity, and employee safety, large facilities ranging from hospitals to production plants need systems that allow accurate tracking of critical assets inside their facilities. Subsequent sections of this paper explore several different implementations of Bluetooth real-time location systems (RTLS) that offer different levels of tracking accuracy and proximity details for asset tracking.

For applications that do not require precise location detection, the most common solution today is to use the received signal strength indicator (RSSI), which is a measure of the power level of the Bluetooth signal at the receiver. In short, RSSI data allows you to determine the approximate location of an asset just by looking at the strength of the received signal. Since RSSI values are negative, as the RSSI value approaches zero, the asset is in closer proximity to the receiver. These days, since most enterprise-grade Wi-Fi access points have built-in Bluetooth radios capable of measuring RSSI, if you need to know roughly where an asset is located within a facility, RSSI is an excellent budget-friendly option that can usually achieve accuracy of around five meters.

More precise location data requires a direction-finding technology. Angle of arrival (AoA), released in Bluetooth 5.1, enables sub-meter accuracy for asset detection. To track an asset using AoA, a Bluetooth transmitter chip is attached to the asset that constantly sends out Bluetooth packets. The packets are captured by an antenna array, which may be mounted on the ceiling.

The Bluetooth signals sent by the asset tag have a constant tone extension (CTE) added to the end of the Bluetooth packet. Once these packets are received by the antenna array, it then runs it through all the antennas to capture the phase difference of the signals. Data captured by the antennas is then sent to a real-time locating (RTL) library where triangulation is performed to compute the x, y, z coordinates of the asset.

A specification is also currently in development to enable high-accuracy distance measurements (HADM) between Bluetooth-enabled devices, which will provide centimeter accuracy. While this specification has not been released by Bluetooth SIG yet, it will be possible to extend HADM technology for more accurate asset tracking.

Indoor Wayfinding

While using GPS for outdoor navigation is ubiquitous today, location-based wayfinding in large, complex indoor spaces such as hospitals or airports is challenging as these facilities lack a navigation infrastructure to pinpoint a person's current location. However, Bluetooth technology offers multiple options to enable reliable indoor navigation.

One option is to incorporate Bluetooth beacon technology into existing infrastructure. The beacons can provide constant radio transmission that can be discovered by any Bluetooth scanner in the beacon's radius. For most commercial facilities, one option is to add beacons to existing Wi-Fi access points and gateways. Another option is to incorporate wireless or Bluetooth connectivity to lighting networks, which can then send out beacons and has an added advantage of cutting down the number of cables. Once the beacons are in place and visitors are given access to an indoor floor map on a Bluetooth-capable device such as their smartphone, a Bluetooth-based beacon system can be easily used for indoor wayfinding similarly to using a GPS outside.

The accuracy of a beacon-based technology can depend on factors such as number of beacons installed, environmental factors, or extent of multipath fading. For higher accuracy needs, the newer AoD tech, which was introduced in Bluetooth 5.1, is a great option. AoD technology works in the opposite manner of the AoA technology discussed. With AoD, the antenna array acts as the transmitter that constantly sends out packets received by an AoD-enabled mobile device. The receiver then calculates the relative signal direction and position using those signals. Although some smartphones support the Bluetooth 5.1 protocol currently, phones do not support direction finding. Once this capability is enabled, AoD has a huge potential to make indoor wayfinding more common.

Digital Key

The technology to enable digital key applications is already well developed since 100 percent of smartphones have Bluetooth technology, and about 83 percent of people around the world own a smartphone. While RFID and NFC technology have traditionally been used for digital key technology, there are several benefits to using Bluetooth instead. Bluetooth-based digital keys stored on a smartphone, add an extra layer of security since a passcode or Face ID is required to log in to the phone to access the digital key.

Smartphone-based digital key makes it easy to share a key for a vehicle or home. For example, if you have a digital car key, you could securely grant access to another user through an app without physically needing to exchange keys.

Personal Item Finding

While not shown in the hospital example above, personal item finding is another key location technology that can benefit from using Bluetooth technology. Today, devices such as the Apple AirTag and the Samsung Galaxy SmartTag are already leveraging Bluetooth technology to enable personal item finding. This is also a fast-growing market segment as experts project that 140 million device trackers for personal item finding will be shipped by 2026.

For example, each Apple AirTag sends out a unique Bluetooth identifier that can be detected by nearby iPhones, iPads, and Mac devices that are a part of the Apple Find My network. The device in the Find My network that receives the signal relays the identifier to the Apple servers along with location data. So, to find a lost item, log in to your Apple Find My app on your phone and see the location of the item on a map. To further improve accuracy, work is underway to enable HADM between the Bluetooth devices as well.

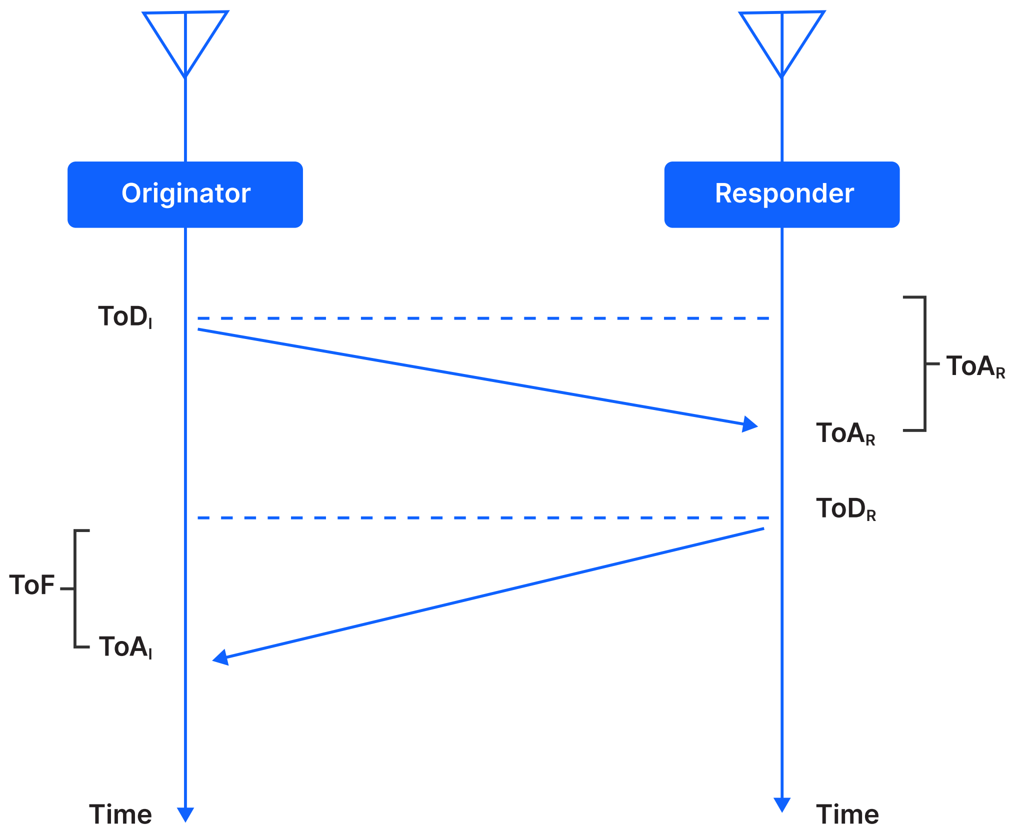
Improving Bluetooth Ranging Techniques by Going Beyond RSSI

As location tracking Bluetooth technologies become more popular for personal and commercial purposes, it is becoming clear that existing ranging techniques will not be able to satisfy performance requirements, especially in dense indoor environments. While RSSI combined with direction-finding technologies such as AoA or AoD as discussed above offers a significant increase in accuracy over using RSSI alone, adding these newer capabilities to devices raises infrastructure cost and design complexity. Instead, simpler alternative solutions that use a single antenna rather than phased arrays can reduce cost for the required system resources and deployment. Beyond requirements for greater accuracy, Bluetooth RSSI ranging is also not ideal for high-confidentiality applications since the received signal strength of a device is vulnerable to manipulation via RF signal amplification.

Measuring packet transmission time between two devices (or time of flight) and measuring the phase of the RF signal can be used to further increase accuracy, simplicity, and security of Bluetooth ranging

Measuring Packet Transmission Time

Measuring packet transmission time between two devices requires knowing the roundtrip time it takes to send a signal between devices. The roundtrip time is measured when a packet is sent from the originator to the responder, and it ends when a packet is received from the responder back to the originator. When the first packet is sent, a timer is started on the originator, and a timer is started on the responder when a packet is received. On the responder side, the timer ends when it sends a packet, and on the originator side, the timer ends when it receives the packet. By using the time of arrival and time of departure on both devices, we have two timer values that can be used to find the time of flight. The figure below shows how packets are sent and the calculations performed.



$$RTT = 2\ ToF = (ToA_I - ToD_I) - (ToA_R - ToD_R)$$

Since the speed of light is fast compared to the crystal frequency used in the radio, fractional timing techniques are used to improve accuracy and resolve sampling uncertainty that occurs in the IQ sampling process, resulting in meter-level accuracy when only one channel is used. However, for multiple Bluetooth channels, averaging can help achieve a higher level of accuracy.

Additionally, because measurements are performed during Bluetooth connection intervals, if the connection interval is longer, more measurements can be performed, which will also help improve accuracy. This means that the duration of the entire measurement procedure is variable depending on the configured parameters such as the number of channels and the connection interval time. Also, when using time of flight to find range, security is inherently better than using RSSI since these measurements are time-based and time cannot be reversed.

Measuring the Phase of RF Signals

Measuring the phase of RF signals is based on the fact that the phase of an electromagnetic wave can be modeled as a function of frequency and the distance traveled. Therefore, the phase difference due to spatial propagation can be used to calculate range. Measuring the propagation phase requires using the phase offsets at the local oscillator on both the originator and the responder, assuming the frequency is the same. In reality, the frequencies will likely not be the same, but that can be calibrated.

If you look at the measured phase at the responder when it receives a signal, it is equal to the originator phase plus the propagation phase, minus the responder phase. Likewise, the measured phase at the originator when it receives a signal is equal to the responder phase plus the propagation phase, minus the originator phase. By adding these measurements together, you are left with the propagation phase of interest, which means that you get the roundtrip phase measurement. Here the measurements are done on at least two frequencies.

Let's now look at the entire range estimation process in three separate stages. The first stage is calibration, where the frequency offset between devices must be compensated with an offset estimation. Next, is the measurement stage where the phase difference is measured through the exchange of unmodulated carrier tones on multiple channels. And lastly, is the calculation stage, where the ranging algorithm takes the IQ samples derived from the originator's demodulator for post filtering and range calculation.

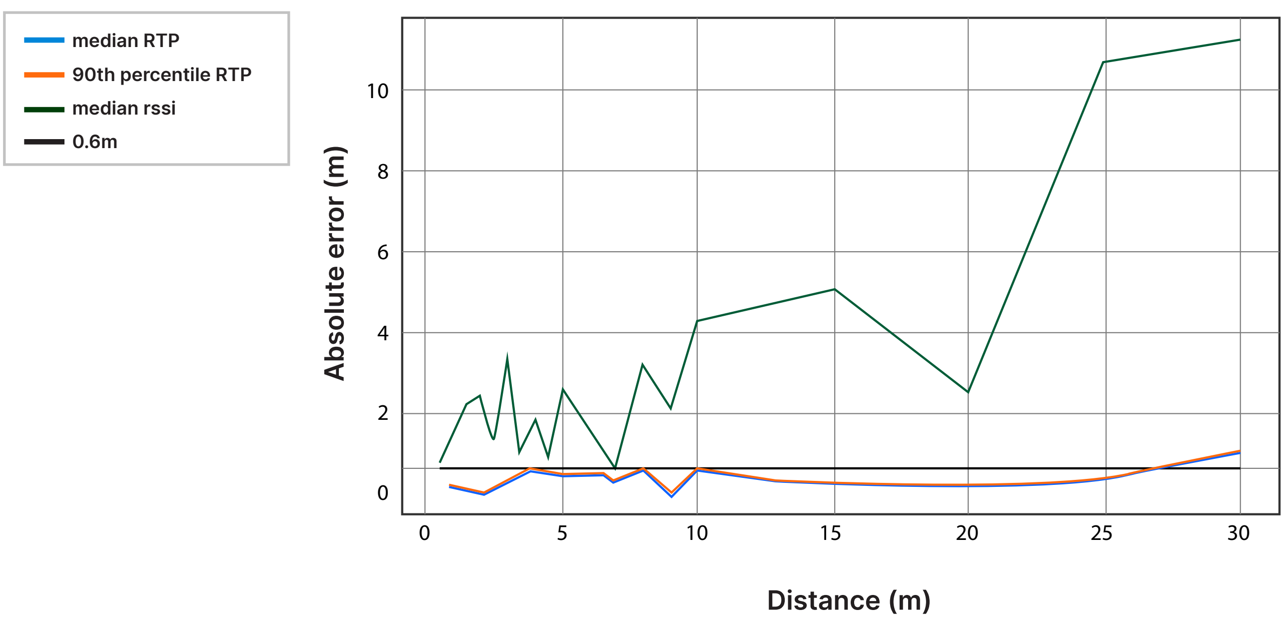
It is also important to note that security wise, it is quite complicated for an attacker to manipulate phase as it requires precise spatial knowledge of the nodes and advanced RF generation logic. Therefore, compared to RSSI-based solutions, using phase to determine range is considered relatively secure.

An RF Phase Measurement Example for Asset Tracking

In a real-world example, you can use an access point and tag to replace the originator and responder roles discussed above. Imagine that you want to find the distance between the tag and the access point to track the asset. This requires a connection-based two-way ranging solution; therefore, a Bluetooth connection is first established between the two devices. The connection is encrypted and secured, and then the ranging algorithm parameters are configured, including the number of channels, transmit power, and connection interval. The access point initiates the phase measurement procedure on the first channel, and the measurement is repeated on the number of configured channels. In general, a minimum of 40 channels is needed to achieve submeter accuracy, however, if the end application does not require sub-meter accuracy, the number of channels can be reduced.

Finally, once all phase measurements are taken, the ranging algorithm software takes the IQ samples as input, processes them, and applies filtering to remove any outliers and mitigate the multi-path effects to calculate the range. This is repeated continuously as long as the connection is maintained and the devices have the ability to produce multiple range calculations per second.

To illustrate how phase ranging is superior to RSSI-based ranging, let's compare the error rate using both techniques measured at several distances up to 30 m. In this example, the measurements were taken in an indoor office environment where multi-path interference is inevitable. Hundreds of samples were taken per distance to determine the absolute error and compile the dataset shown below.



In general, the goal for phase ranging accuracy is less than 60 cm. As shown above, phase range measurements are stable and below the 60 cm error threshold up to 25 m and within one meter accuracy up to 30 m. With RSSI, it's unlikely to achieve sub-meter accuracy even over small distances, plus the error rate will only increase with distance, reaching more than 10m error above distances of 25m.

Bringing Bluetooth as a Location Technology to Market with Silicon Labs Technology

At Silicon Labs, we have a broad range of Bluetooth system on chip (SoC) and module options as well as a vast collection of development tools to provide a single-stop resource for developing robust, reliable, and secure Bluetooth connectivity solutions. Whether you need an ultra-compact footprint, low-power consumption, long-range, or ultimate RF sensitivity, we have an optimal solution for every application.

For example, our BG24 family of 2.4 GHz wireless SoCs and modules feature large flash and RAM capacities and PSA Level 3 Secure Vault protection, making this SoC an ideal option for home, medical, and industrial applications. If battery life and size are key concerns, we also offer our BG22 SiP modules and SoCs that can operate for up to ten years on a coin cell battery and feature software to track assets and improve indoor navigation with sub-meter accuracy. All our Bluetooth modules and SoCs provide a cohesive developer experience, which means you can future-proof device designs and evolve your applications across your product portfolio.

See how Silicon Labs is prepared to support all your Bluetooth application development needs