Qualcomm® Wi-Fi Ranging: Delivering ranging and location technologies of tomorrow today.

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1. Executive Summary

Wi-Fi ranging technology uses time-of-flight measurements to estimate the distance between two Wi-Fi devices. For over a decade this technology has been enabling application developers and other solutions implementers to provide a variety of services including indoor navigation, asset tracking, geofencing, access control (locking/unlocking), and device operation, all with increased accuracy and performance without sacrificing real estate or overall BOM cost. Since their implementation in 2009, the Qualcomm Wi-Fi ranging technologies have been shipping in billions of devices globally with clear signs of accelerated adoption. Ranging capabilities have also continued to improve over multiple generations.

When it comes to performance, there are four key characteristics of a Wi-Fi radio that determine the accuracy of its measurements: the frequency bandwidth utilization, the use of multi-antenna technology, the transmit power, and the receiver sensitivity. Beyond this, application developers can improve measurement accuracy even further by applying statistical approaches such as averaging across multiple individual measurements and location tracking algorithms. For this reason, high ranging speeds can also improve accuracy by supplying more measurements per second to utilize in these calculations.

Qualcomm Technologies conducted extensive testing to highlight the accuracy of our Wi-Fi ranging technology in various implementations. When analyzing the capabilities of the Qualcomm Wi-Fi ranging technology in the context of its use in actual applications and devices across two test scenarios—indoor line of sight and automotive (mostly non-line of sight)—the following conclusions can be made:

- By averaging across multiple bursts of ranging measurements, decimeter-level accuracies are achievable in a real-world environment with a 21 cm accuracy* for indoor use cases and an 11 cm accuracy* for peer-to-peer use cases at the 90th percentile.

- The use of location tracking algorithms, such as the application of the Kalman filter, can provide a significant performance boost with an accuracy of less than 10 cm both at the 90th and 99th percentile.

These performance levels can be achieved across Qualcomm Wi-Fi devices shipping today. In the near term, additional standards-based capabilities will be added, further increasing accuracy, security, scalability, and support for an extended set of use cases.

** A 21 cm accuracy level at the 90% percentile means that in 90% of the cases the accuracy of the measurements is less than 21 cm, and in 10% of the cases it is more than 21 cm.*

2. Introduction and Objectives

Modern mobile devices leverage Wi-Fi location (as well as other technologies such as Bluetooth® and Ultra-Wideband) and ranging technologies for a wide range of applications and use cases.

Wi-Fi ranging technology uses time-of-flight measurements to estimate the distance between two Wi-Fi devices. Since its introduction, significant progress has been made with new industry standards and subsequent generations of chipsets and end products that support Wi-Fi. This progress has led to greater levels of accuracy and performance, enabling a wide range of potential use cases.

The purpose of this whitepaper is to provide insights into the history, use cases, performance factors, and near-term innovations of Wi-Fi ranging technology. We also discuss statistical methods that application developers and other solutions implementers can use to enhance ranging accuracy in their applications. We draw on the results of extensive measurement campaigns using the Qualcomm Wi-Fi ranging technology to demonstrate achievable ranging accuracies in real-world scenarios.

3. History and Status of Wi-Fi Ranging Technology

Wi-Fi Round Trip Timing (RTT) ranging technology was first introduced in 2009 as a way to measure the distance between two Wi-Fi devices based on the travel times of a round-trip wireless signal between them. These travel times, along with the speed of the wireless signal (333 nanoseconds per 100 meters), provided the means to calculate an estimate of the physical distance between the two devices. In 2015, Wi-Fi chipsets with 802.11 standards-based Fine Timing Measurement (FTM) technology entered the market.

In 2017, the Wi-Fi Alliance launched its interoperability certification program for products that implement FTM, with Android introducing its first API that supports Wi-Fi FTM in the following year. Since this program launched, there has been a massive proliferation of smartphone devices shipped with Wi-Fi FTM capability. Figure 3.1 provides a brief timeline of the Qualcomm Wi-Fi ranging technology evolution and the overall industry.

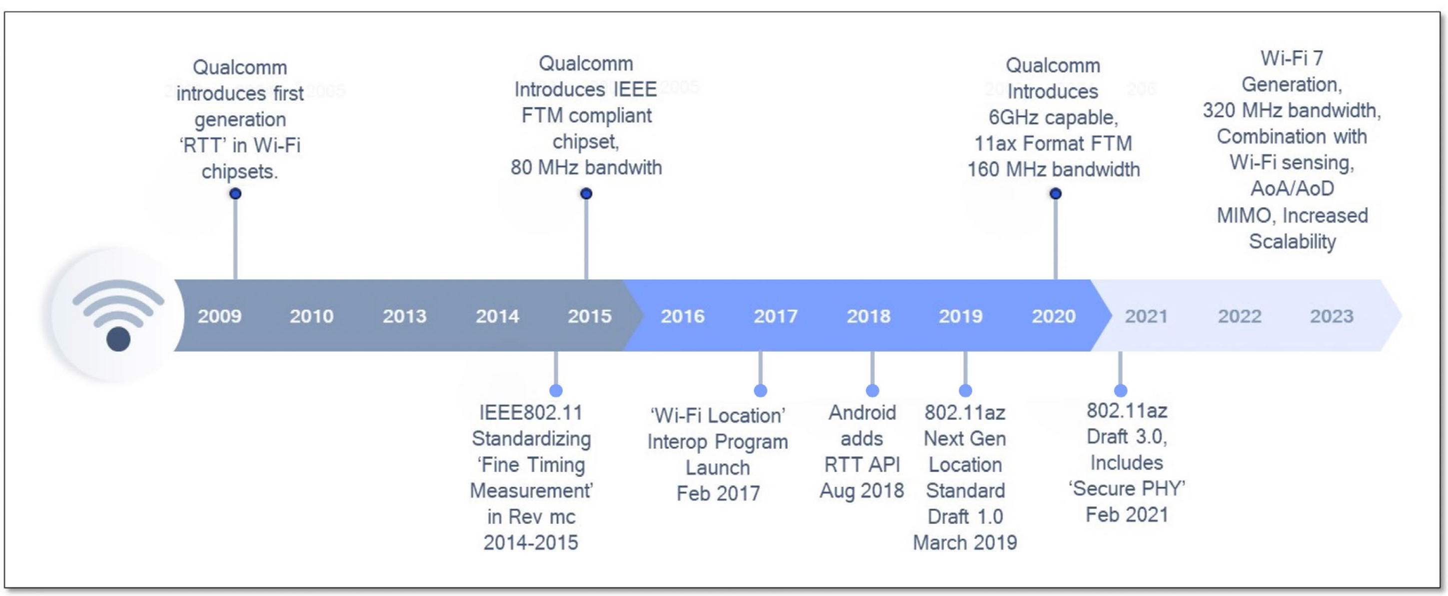


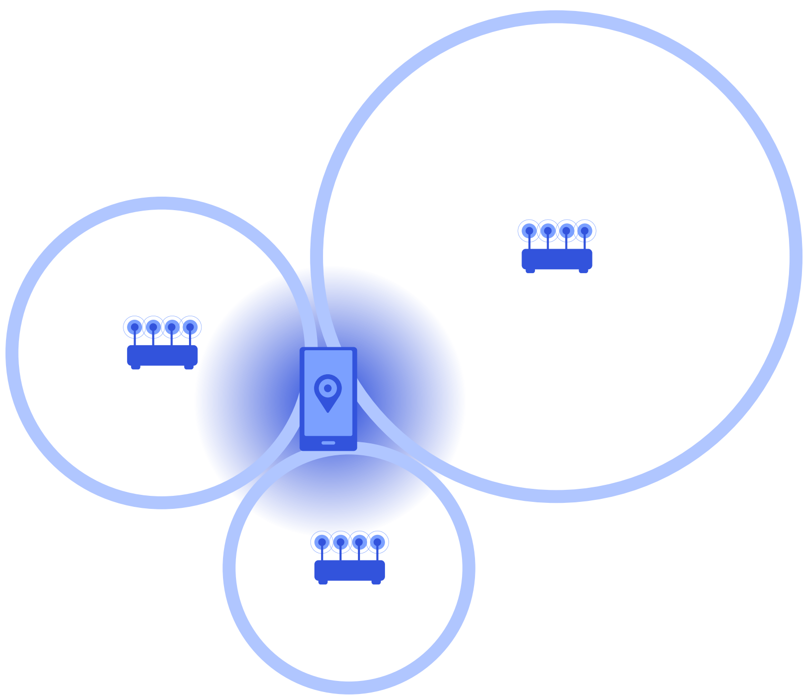
Figure 3.1 Wi-Fi Ranging Technology Timeline

The initial market driver for Wi-Fi ranging technology was expected to be a broad use category called Precise Indoor Location, which includes uses such as indoor navigation, asset tracking, network management, geofencing, hyper-local marketing, and emergency services.

As multi-vendor interoperability and end-to-end management has evolved over the years, Wi-Fi ranging capabilities have continued to evolve and applications continue to emerge. Today, increasingly popular peer-to-peer mobile applications, the deployment of Wi-Fi ranging applications by enterprise network infrastructure vendors, and the emergence of Wi-Fi Sensing (whose applications are often paired with Wi-Fi ranging applications) look to be driving increased awareness and momentum for Wi-Fi ranging solutions across the industry.

4. Uses of Wi-Fi Ranging Technology

There are key benefits to using Wi-Fi technology for device-to-device ranging. In addition to the existence of a multi-vendor interoperability program from the Wi-Fi Alliance, Wi-Fi has widespread proliferation throughout billions of devices. Ranging is simply an additional use of Wi-Fi technology that is already included in various networking devices. Furthermore, as we will discuss in this paper, modern Wi-Fi ranging technology can offer decimeter-level accuracies in real-world scenarios. This level of precision combined with the proliferation of Wi-Fi throughout so many devices enables a wide range of potential use cases depending on the topology in which the Wi-Fi devices are used.



4.1. Infrastructure Use Cases

Infrastructure use cases take place in indoor settings using enterprise/public Wi-Fi networks. In such settings, the location of a mobile device can be pinpointed with a technique called trilateration, which involves measuring the distance between the device and multiple access points (e.g., routers). Examples of infrastructure use cases include:

- Asset tracking (e.g., packages)
- Geofencing (triggering an action when a user enters a particular location)
- Hyperlocal marketing
- Indoor navigation assistance
- Network Management (e.g., locating a particular device)
- Personal delivery (e.g., sending food to restaurant tables, or drinks to customers in a bar)
- Retail analytics

4.2. Peer-to-Peer Use Cases

Peer-to-peer use cases take place between two Wi-Fi devices. Having a secure method to measure the distance between them enables many potential use cases. Examples include:

- Access control (e.g., unlocking a vehicle)
- Asset tracking
- Assistance in docking
- Device finding
- Device operation (e.g., connecting to the closest monitor or home entertainment system)
- Electronic ticketing
- Geofencing
- Home automation control (e.g., lighting adjustment or temperature control based on user presence)
- Social gaming

4.3. Security Considerations

For most of the use cases listed above, ranging security threats are not a major concern. The cases most frequently brought up in the context of security enhancement discussions are ones involving access control, such as unlocking a high-value asset like a car. A popular concern is a man-in-the-middle attack where an attacker intercepts a wireless communication, typically using Bluetooth technology, leading to them gaining unauthorized access to an asset.

To address such concerns, industry standardization bodies have paid considerable attention over the last couple years to hardening the security aspects of device-to-device ranging technologies. For implementations using existing generations of Wi-Fi ranging that may not have the latest built-in security features, they can be made considerably more secure by including additional handshake steps, outlier detection methods, and challenge/response sequences above the MAC layer. IEEE 802.11az generation technology will include further MAC and PHY-level enhancements for secure ranging, suited for contexts such as access control applications involving very high-value objects.

5. Drivers of Ranging Performance

The performance of a ranging technology amounts to the speed and accuracy of its ability to measure distances between devices. Ranging applications can substantially improve accuracy by using statistical approaches such as averaging across multiple individual measurements and location tracking algorithms. These approaches use multiple individual measurements of a particular distance to calculate a more accurate final measurement of that distance. This makes speed particularly important because they provide more individual measurements per second to use in these calculations. Existing generations of Wi-Fi ranging can conduct at least 250 individual measurements in the span of a second.

However, these statistical approaches still rely on making accurate individual distance measurements in the first place. There are four key characteristics of a Wi-Fi radio that determine the accuracy of its individual measurements: the frequency bandwidth, the use of multi-antennas, the transmit power of the transmitting device, and the receiver sensitivity of the receiving device. Our decades-long investment in leading Wi-Fi technology has contributed to the advancement and highly optimized implementation of these critical elements to increase accuracy for many common applications.

Table 5.1 High-level overview of the drivers of distance measurement performance of a wireless radio

Ranging Performance Driver	Explanation
Frequency Bandwidth	With each doubling of the bandwidth, ranging error roughly halves when comparing between the 20/40/80/160 MHz frequency bands.
Multi-Antenna	Using multiple antennas reduces ranging error. For example, a configuration that uses two receive antennas enables a nearly 30% lower ranging error than a configuration with only one receive antenna.
Transmit Power	A device's transmit power determines how far its wireless signals can travel. Sufficient transmit power is required to effectively conduct distance measurements at range and in non-line of sight conditions. Transmit power is affected by regulatory limits and battery consumption considerations.
Receiver Sensitivity	A device's receiver sensitivity determines the minimum signal strength it can detect. Receiver sensitivity is mainly driven by the frequency bandwidth used (in terms of MHz) and the quality of the receiver, with quality being determined by both the inherent noise it generates and the level at which a received signal can be identified for the ranging estimate.

6. Enhancing Ranging Accuracy

In the case of smartphones or other mobile devices, the Wi-Fi radio passes its ranging measurements on to the mobile device's operating system (e.g., Android), which in turn makes these measurements available to the application environment for application developers to use in their location-based solutions (e.g., indoor navigation, access control, asset tracking, etc.). To increase the accuracy of these range estimations, application developers use statistical approaches such as averaging across multiple measurements and location tracking algorithms, which use multiple individual measurements of a particular distance to calculate a more accurate final measurement of that distance.

6.1. Averaging

As the name implies, averaging involves taking multiple measurements of a particular distance and calculating their average. This approach is more reliable than using only one measurement and offers a lower rate of error. The graph in Figure 6.1 shows the impact that averaging has on ranging error. The data was collected as part of an extensive measurement campaign conducted for an Automotive Digital Key use case, but the concept and results can apply to solutions in different application spaces. For this particular example, one of the Wi-Fi devices involved in the distance measurement was placed inside a closed vehicle on the floor next to the brake pedal, while the user had the other Wi-Fi device (his/her smartphone) in a back pocket. In this context, a 'burst' or 'measurement burst' is simply a collection of individual distance measurements.

Example: Automotive Digital Key Use Case

Impact of averaging across multiple measurements on ranging error (90% in cm)

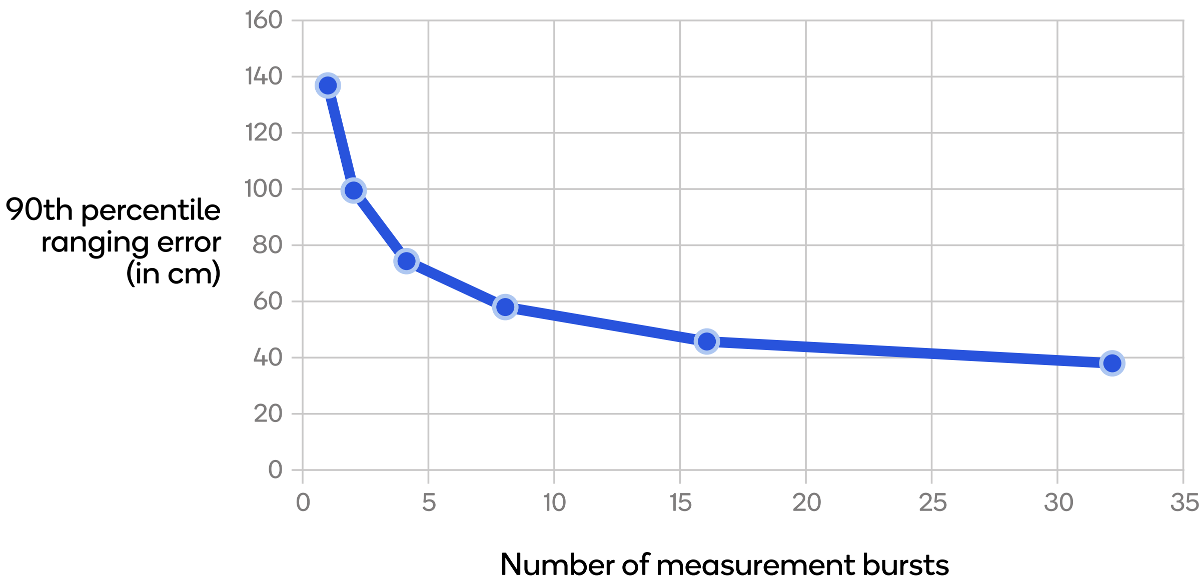


Figure 6.1 Impact of averaging across multiple measurement bursts on ranging error using 2x2 Wi-Fi devices accessing the 5GHz band and 80MHz channels

In this graph, ranging error is represented as the 90th percentile case, which means the ranging error is lower than the number quoted in 90% of the cases, and is higher in only 10% of them. The 90th percentile ranging error drops from 135 cm in the case with one burst down to 39 cm in the case where the measurements are averaged over 32 bursts. Each burst contains up to 5 distance measurements and takes between 20 to 30 ms. The total measurement time for 32 bursts is less than a second with today's generation of Wi-Fi technology.

6.2. Location Tracking Algorithms

Location tracking algorithms such as Kalman filtering are another way to greatly enhance the accuracy of range estimates. To demonstrate this, Kalman filtering algorithms were applied to the data collected in the Automotive Digital Key use case discussed in the previous section. Figure 6.2 shows the use of Kalman filtering applied to a scenario where the user (and his/her smartphone) moves towards the vehicle in a linear fashion. The Kalman filter predicts and corrects the estimate of the phone's trajectory to improve ranging accuracy. In less than 0.5 seconds the ranging errors fall well below 10 cm (5 cm for the 90th percentile, 7 cm for the 99th percentile).

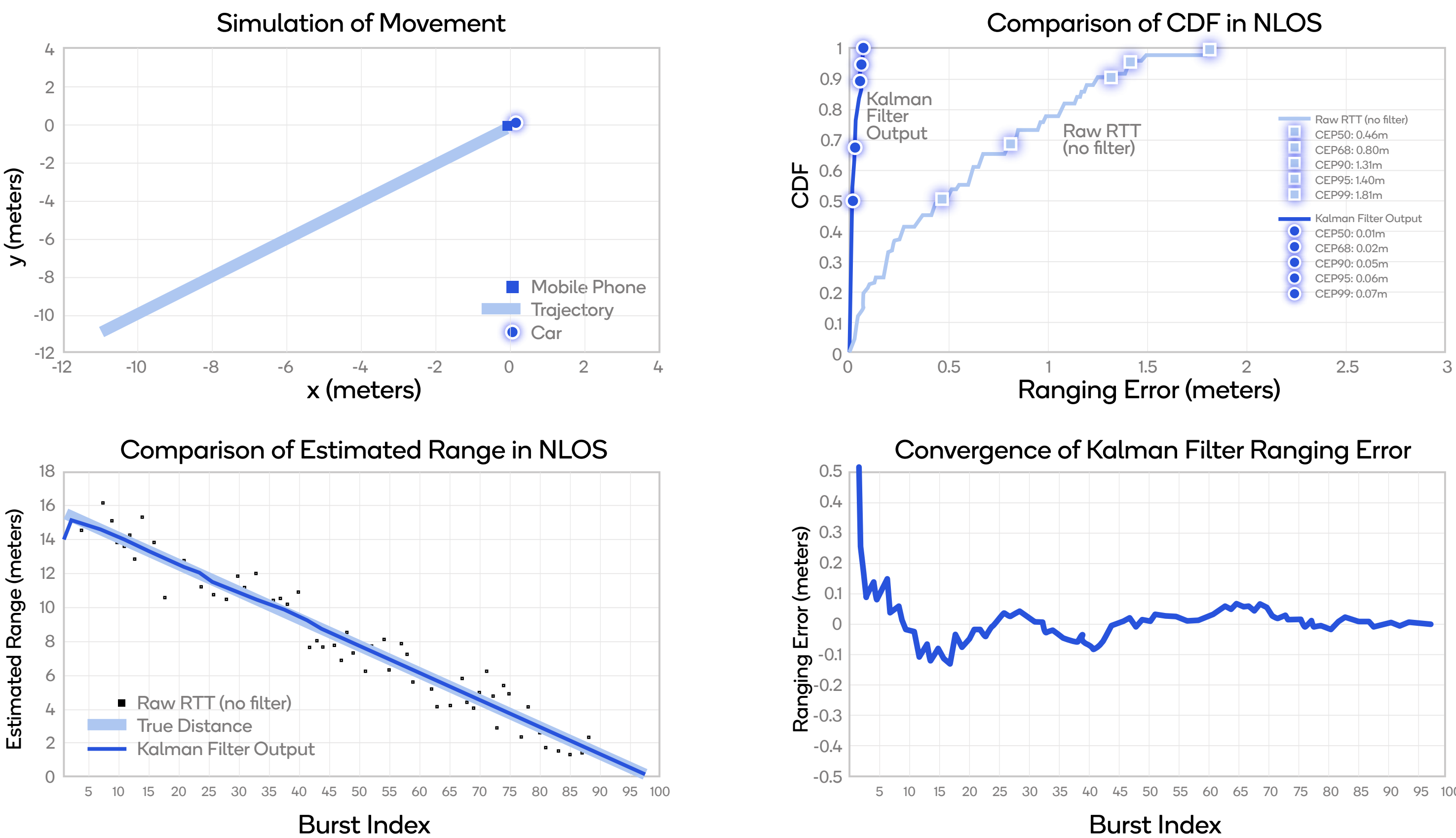


Figure 6.2 Kalman filtering applied to the Automotive Digital Key use case—Linear movement towards a vehicle using 2x2 Wi-Fi devices accessing the 5GHz band and 80MHz channels

In Figure 6.2, the upper-left plot shows the direction of the phone's movement. The lower-left plot shows the measurement bursts taken (red dots), the true distance between the phone and vehicle (green), and the Kalman Filter Output (blue). In this plot the green and the blue curve are practically on top of each other after the Kalman filter has converged, which shows that the estimate derived from the Kalman filter is extremely close to the actual distance. The upper-right plot is the Cumulative Distribution Function (CDF), which shows that for the 90th percentile case the initial, unaveraged results have an accuracy of 131 cm whereas the output of the Kalman filter has an accuracy of 5 cm. Finally, the lower-right plot shows how quickly the Kalman filter converges. It takes only three measurement bursts for the Kalman filter to converge and reach a ranging error less than 20 cm.

In addition to the linear movement scenario, Kalman filtering was applied to a scenario which the phone moves in a circular movement around a vehicle and one in which the phone is stationary. All cases assume no prior knowledge of movement. Table 6.3 lists the ranging error levels achieved with Kalman filtering in all three scenarios.

Table 6.3 Achievable ranging accuracies when using Kalman filtering for different movement scenarios in an automotive setting

Scenario	90% Accuracy	99% Accuracy
Linear Movement	5 cm	7 cm
Circular Movement	4 cm	6 cm
Stationary	4 cm	7 cm

This accuracy has even more potential for improvement when application developers and other solutions implementers can factor in additional information such as prior behaviors or information from other sensors in the device (e.g., compass, accelerometer).

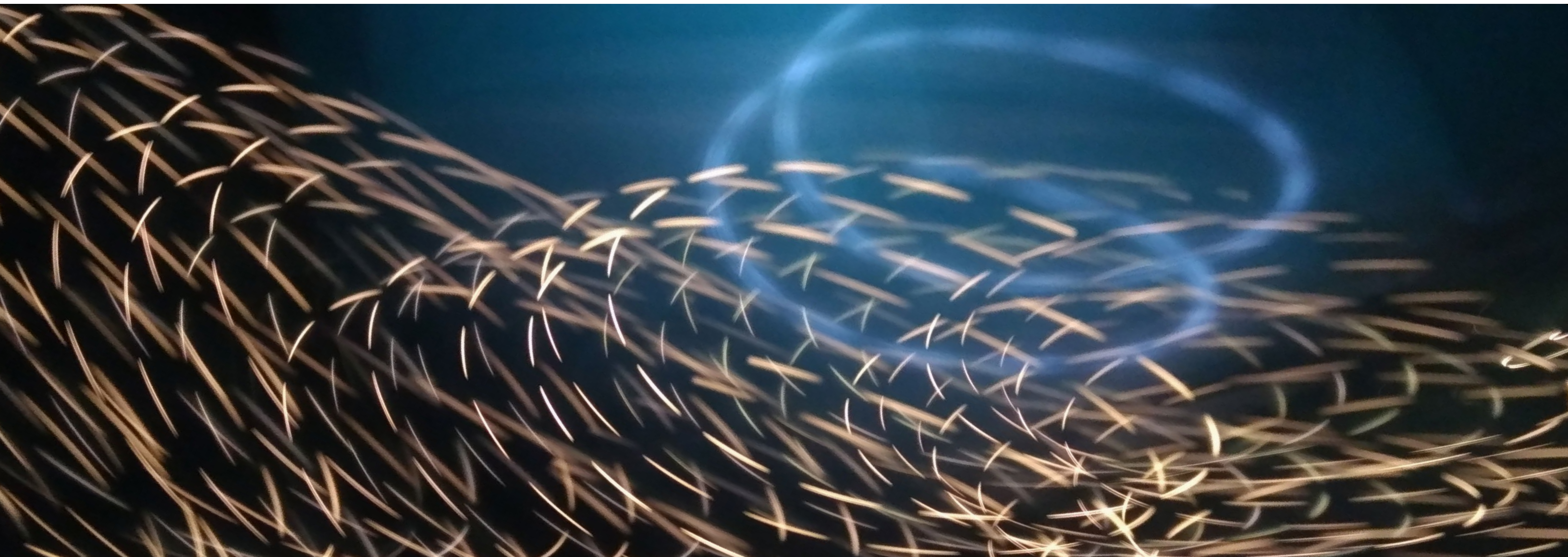
7. Wi-Fi Ranging Measurement Results

When scanning the scientific literature for measurement results from actual Wi-Fi ranging tests, it becomes clear that very few measurement campaigns have been conducted with published results. This section shares the results of two measurement campaigns, both conducted using existing generations of Qualcomm Wi-Fi technology. The first test was conducted in an indoor setting at a Wi-Fi Alliance test lab, and the second was conducted in a vehicular setting to analyze the technology's potential applicability to automotive use cases.

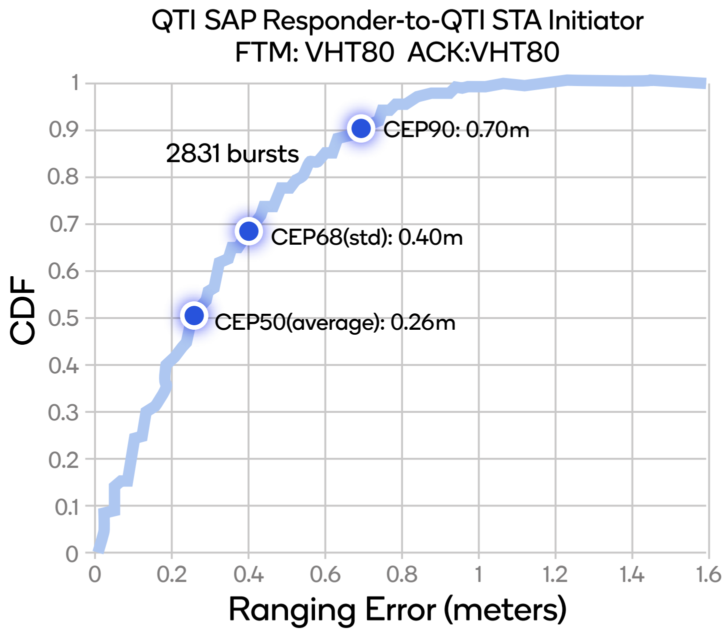
7.1. Indoor Line of Sight Measurements

The measurements below were collected during a Wi-Fi Alliance interoperability event at the Wi-Fi Alliance lab in Santa Clara. The measurements were conducted in an indoor line of sight (LOS) setting with mild multipath conditions. The Wi-Fi devices used were a Qualcomm Technologies-based Soft Access Point reference design and a Qualcomm Technologies-based client reference design using 80 MHz mode.

Figure 7.1 illustrates the ranging accuracy of these measurements. When interpreting these results, please keep in mind that they do not yet include the application of averaging across multiple bursts, nor any use of location tracking algorithms.



Average FTM ranging Accuracy: 26 cm



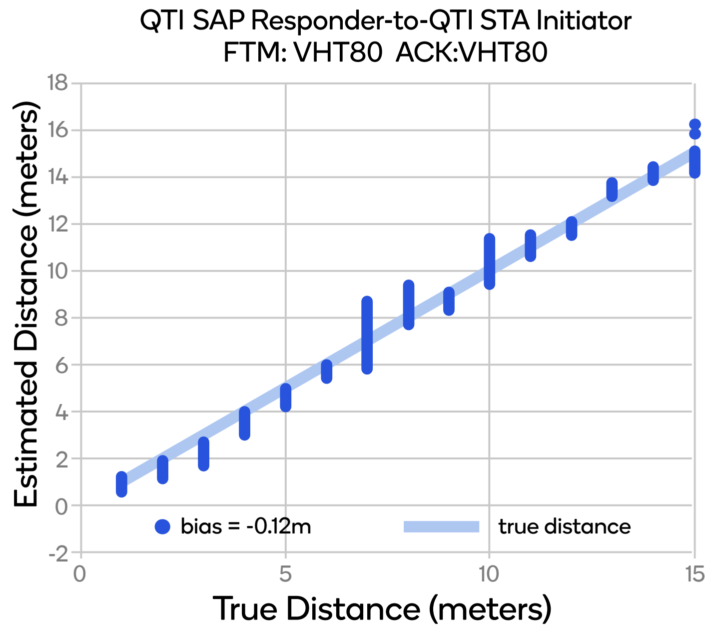


Figure 7.1 Ranging accuracy in an indoor LOS setting

Figure 7.2 illustrates the improvement in accuracy after averaging over 32 bursts. Once this is done, the 90th percentile accuracy improves to 21 cm with an average of 12 cm.

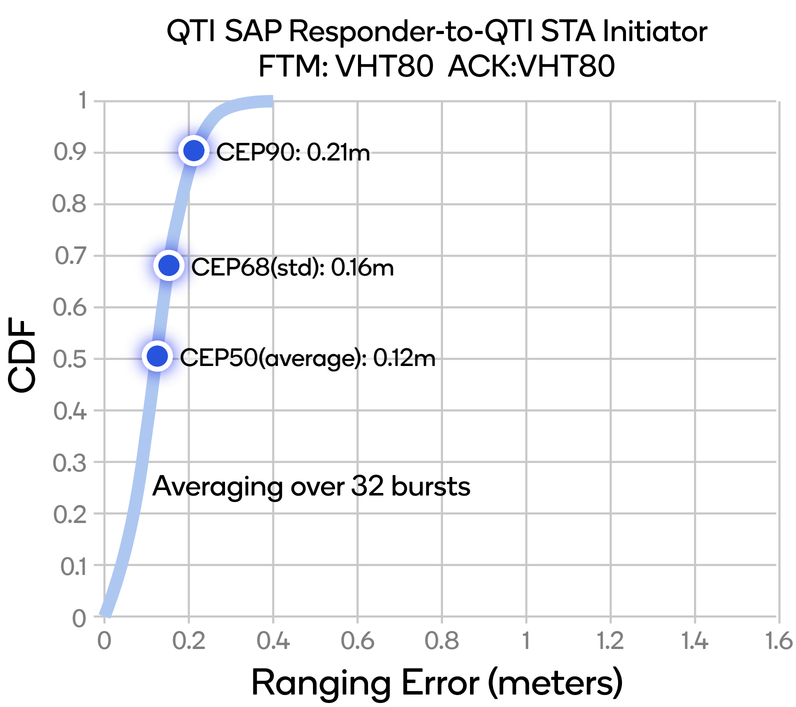


Figure 7.2 Indoor LOS ranging accuracies when averaging over 32 bursts

7.2. Automotive Ranging Measurements

To analyze the potential applicability of Wi-Fi ranging in Automotive Digital Key use cases, we conducted an extensive measurement campaign to assess the ranging accuracies for a set of placements of a Wi-Fi radio in a fairly large vehicle (Lexus SUV RX350, 2016 model).

The Wi-Fi radio was placed in the following locations in the vehicle:

- On top of the dashboard
- On the floor next to the brake pedal
- By the rear windshield
- Inside the glove compartment
- Outside, on the driver side mirror

The phone used to signal the Wi-Fi radio was placed in the following locations on the user/vehicle owner's person:

- In a back pocket
- In a backpack
- In hand

Finally, for each permutation of the Wi-Fi radio and phone placements, the user stood in six different points around the vehicle at which the ranging measurements were collected. The devices were operating in 80 MHz, 11ac modes.

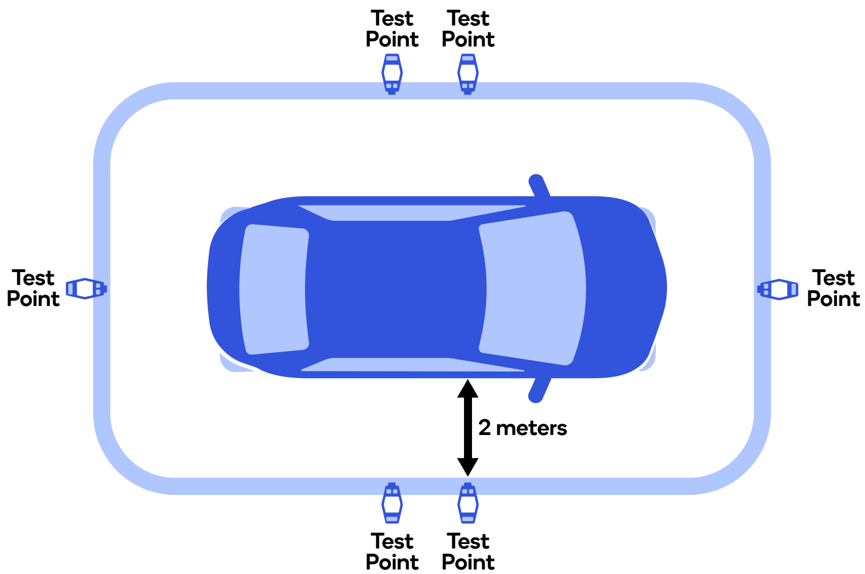


Figure 7.3 Location of test points for Automotive Access Control ranging performance

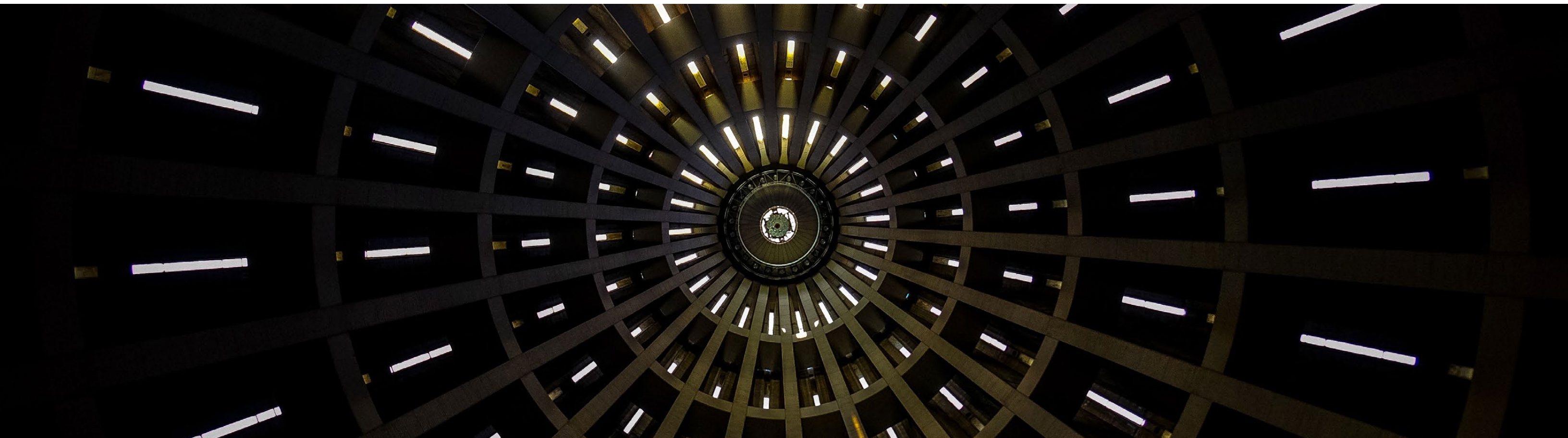


Table 7.4 shows the 90th percentile accuracies for the ranging measurements between the Wi-Fi radio and phone in the various positions mentioned above. The results are averaged over 32 bursts.

Table 7.4. Wi-Fi ranging accuracy measurements for Automotive Digital Key use case, 90th percentile ranging error in centimeters, 80 MHz mode, 32 burst averaging

		Placement of Wi-Fi Radio in Vehicle					
		Front Dashboard	**Next to brake pedal**	**Rear wind shield**	**Inside glove box**	**Outside sideview mirror**	***Average***
Position of Phone on User	Back Pocket	70	39	40	35	31	***43***
	In Backpack	57	60	29	58	53	***51***
	In Hand	42	29	46	34	11	***32***
	Average	**56**	**43**	**38**	**42**	**32**	***42***

Please keep in mind that the results in Table 7.4 do not incorporate the use of location tracking algorithms. Applying these algorithms would yield even greater accuracy.

8. Near Term Innovations in Wi-Fi Ranging Technology

Within the next few years, new capabilities will be added to Wi-Fi ranging to further enhance its accuracy, security, scalability, and support for additional use cases. Some examples of these new capabilities include:

- Use of wider bandwidths (up to 320 MHz channel bandwidth in the 6 GHz band)
- Use of MIMO Multi-Antenna technology
- Support of Angle of Arrival or Angle of Departure
- Secure Ranging (MAC and PHY security enhancements)
- Trigger-based Multi-User Ranging
- Passive Location
- Combined use with Wi-Fi Sensing

Table 8.1 provides a high-level mapping of the potential benefits of these new capabilities.

Table 8.1 Benefits mapping of new or near-term Wi-Fi ranging capabilities

	Benefits			
New Capability	**Increased Accuracy**	**Enhanced Security**	**Enhanced Scalability**	**Extended Use Case Support**
Wider bandwidths (e.g. 320 MHz)	X			
MIMO Multi-Antenna technology	X			
Angle of Arrival/Angle of Departure	X			X
Secure Ranging (PHY & MAC)		X		X
Trigger-based Multi-User Ranging			X	
Passive Location			X	
Combined use with Wi-Fi Sensing		X		X

To illustrate just a couple examples, one of the benefits of Angle of Arrival (AoA) detection is that even in single access point networks, the actual location of a device in a given space (for example, in a home) can be determined, whereas without AoA only the physical distance to an access point can be determined. Wi-Fi Sensing, on the other hand, can enhance security in access control situations by giving the device in control of the lock the ability to sense whether a person is in close proximity. This cannot be spoofed since it is a one-sided action coming from the locking/unlocking device.

9. Qualcomm Technologies Differentiation

The Qualcomm Wi-Fi FTM technology is a performance leader in ranging accuracy for the following reasons:

- Over a decade of technology development experience, spanning multiple product generations
- Development and inclusion of proprietary techniques that increase performance
- Holistic approach to the development and implementation of FTM technology for both Wi-Fi access points and Wi-Fi clients
- Long-standing experience in supporting OEM customers with the integration and calibration of Wi-Fi FTM in numerous OEM product designs over multiple generations of chipset products

Furthermore, Qualcomm Technologies Wi-Fi 6-generation platforms are designed to be fully backwards compatible with Wi-Fi 5 and earlier generations. Qualcomm Technologies' and other leading Wi-Fi silicon providers have shipped hundreds of millions of Wi-Fi FTM-capable devices, leading to an installed base of over 2 billion devices. With backwards compatibility, devices based on Qualcomm Wi-Fi 6 technology can benefit from the scale of this installed base from day one of product introduction.

Finally, with the wider bandwidth capabilities that Wi-Fi 6 brings (up to 160 MHz), accuracy levels between Wi-Fi 6 devices are expected to be even higher than the accuracies reported in the previous sections of this whitepaper.

10. Conclusion

The strength of the value proposition of Qualcomm Wi-Fi technology for device-to-device ranging is driven by the large installed base in mobile phones, accuracies up to 10cm of precision, and the fact that the Wi-Fi ranging capabilities are inherent in Wi-Fi radios already in devices for data networking purposes. When analyzing the capabilities of Qualcomm Wi-Fi ranging technology in the context of its actual use in applications and devices across two test scenarios—indoor line of sight and automotive (mostly non-line of sight)—the following conclusions can be made:

- By averaging across multiple bursts of ranging measurements, decimeter-level accuracies are achievable in a real-world environment. For example, in the line of sight testing at the Wi-Fi Alliance lab, at the 90th percentile a 21 cm accuracy* was achieved when averaging over 32 bursts (which lasts less than one second overall); see **section 7.1**. In **section 7.2,** the results of an extensive measurement campaign in an automotive (mostly non-line of sight) case indicates that depending on the placement of the Wi-Fi radios in the vehicle and on the user, the worst-case setup at the 90th percentile is 70 cm while the best case is 11 cm.

- However, the most significant tools at the disposal of application developers and other solutions implementers are the use of location tracking algorithms. Our analysis shows that with application of the Kalman filter location tracking algorithm, accuracies of less than 10 cm can be achieved, both at the 90th percentile and 99th percentile.

These performance levels can be achieved with Qualcomm-based products shipping today. In the near term, additional standards-based capabilities will be added, further increasing accuracy, security, scalability, and support for an extended set of use cases.

** A 21 cm accuracy level at the 90% percentile means that in 90% of the cases the accuracy of the measurements is less than 21 cm, and in 10% of the cases it is more than 21 cm.*