WHITE PAPER

Getting Back to Basics with Ultra-Wideband (UWB)

Abstract

This white paper highlights the fundamental principles of UWB, a cutting-edge wireless communications technology optimized for secure micro-location-based applications. In addition to focusing on UWB's fundamental principles, this white paper discusses the key features and advantages of UWB technology and the different topologies used in UWB applications. It also covers FCC regulations for this technology and outlines the main consortiums/alliances working to ensure interoperability and scalability of UWB products.

Introduction

UWB is an IEEE 802.15.4a/z standard technology optimized for secure micro-location-based applications. It enables distance and location to be calculated indoors or outdoors with unprecedented accuracy – within a few centimeters – by measuring the time it takes radio signals to travel between devices. Along with centimeter-level ranging accuracy, emphasis was placed on defining a standard that would make UWB robust and immune to various forms of interference, assuring a high level of reliability. The standard was also designed with low power and low cost in mind, and with the requirement to support large numbers of connected devices.

The engineers who created the standard had a vision: to make every connected object 'location aware'. UWB is being incorporated into leading smartphones and a wide range of other devices, and ultimately will become ubiquitous. It is already being applied to solve problems in many different industries and applications, including keyless car entry, improving efficiency and safety in factories, locating essential supplies in hospitals, and controlling smart devices in homes.

The biggest potential for UWB is in a completely new generation of micro-location-based systems. Just as Wi-Fi and GPS paved the way for applications that were previously inconceivable, UWB will enable a wave of applications that use highly accurate location and distance sensing to deliver new experiences and capabilities. Today, people and businesses want to be able to locate pretty much anything in real time, whatever its size. Let's say you're at home and misplaced your car keys, or you're in a grocery store and can't find your favorite brand of coffee. Or maybe you're working in a factory and need a particular tool from a storage bin, or you're a site manager dealing with an emergency and need to make sure everyone's exited the building. Indoor positioning at the micro level helps in all these situations because it can locate items and guide you to where they are. To offer enough accuracy, reliability and real-time capability, the underlying technology needs to be designed for precise location. UWB is changing the game by delivering accurate location information that can be used in a myriad of ways.

UWB is a cutting-edge wireless communications technology optimized for secure micro-location-based applications.

UWB is Best When Precise Location Matters

Unlike other radio frequency (RF) technologies, UWB was specifically designed to enable precise, secure, real-time measurement of location, distance, and direction, while concurrently supporting two-way communication.

One of UWB's key strengths is that it uses the time-of-flight (ToF) of signals to calculate the distance between devices. This method is much more accurate than the received signal strength indicator (RSSI) method that's typically used with other wireless technologies such as Wi-Fi and **Bluetooth®.**

UWB signals also use much greater bandwidth than prevalent narrowband technologies. As a result, UWB signals are extremely short, due to the inverse relationship between time and bandwidth. This means that the time resolution of UWB signals is very high, enabling accurate determination of ToF. Additionally, the high time resolution and short wavelength of UWB signals make it much more resistant to multipath interference and fading.

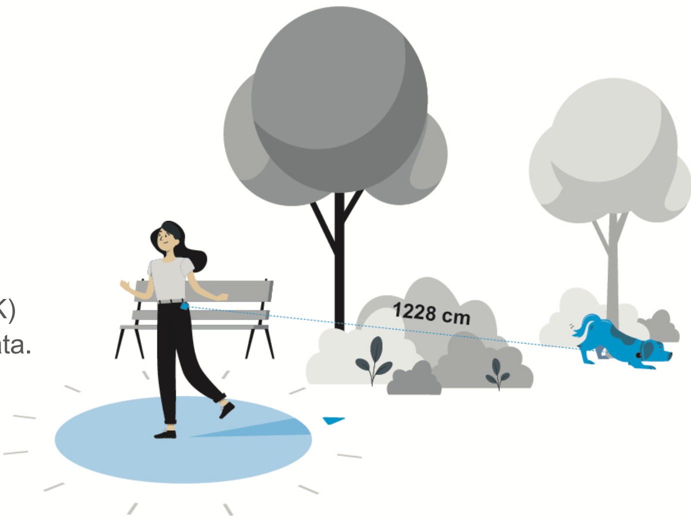
These capabilities enable UWB to pinpoint people and things with great accuracy. In fact, UWB is 100 times more accurate than other RF technologies for location, like Wi-Fi or Bluetooth low energy (BLE), delivering accuracy within centimeters instead of within meters. This is very important when tracking/locating small objects or if your application requires you to know if something is on one side of a wall versus the other.

Furthermore, UWB has very low latency, which means that – unlike Wi-Fi and Bluetooth – it can be used for real-time location. It is 50 times faster than GPS with updates up to 1,000 times per second – that's three thousand times faster than a standard BLE beacon. This makes UWB ideal for automation systems and applications involving fast-moving objects, like drones, and it opens the door to many exciting new use cases.
The large bandwidth also makes UWB systems suitable for high-speed communications.

Because UWB leverages ToF information combined with distance bounding communication techniques defined by the IEEE 802.15.4a/z standards, it also provides much greater security than other wireless technologies used for sensing distance and location.

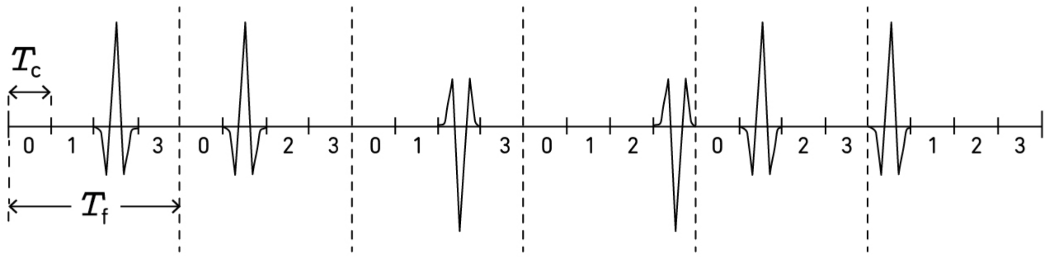
How UWB Measures Location

Unlike other radio technologies, UWB does not use amplitude or frequency modulation to encode the information that its signals carry. Instead, UWB uses short sequences of very narrow pulses (only 2 nanoseconds) using binary phase-shift keying (BPSK) and/or burst position modulation (BPM) to encode data. These narrow pulses also have clean edges, allowing precise determination of arrival time and distance in the presence of multi-path effects caused by signal reflections.



In the following BPSK example (Figure 1), two consecutive impulse radio (IR) signals represent one symbol. The IR signal can occupy one of the chip-intervals (T_c) within a frame (T_f). A time-hopping (T_H) code is used for determining the accurate position of a signal in a dedicated time frame to decrease the chance of interference between UWB systems. In the following example, the T_H codes for the symbols are {2, 1}, {2, 3} and {1, 0} respectively, so the first and second signals are shifted by two and one chip-intervals respectively and so on. In this example the information corresponds to the polarity of signals, so the IR stream represents the binary data "101".

Figure 1: UWB transmits information using short sequences of extremely narrow pulses.



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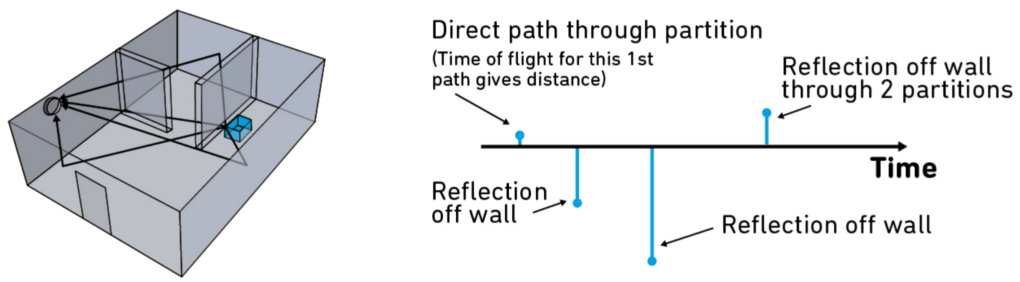
This approach, combined with the use of ToF information, enables UWB to calculate precise distance estimates even in indoor environments where multipath reflections are widespread. Using timestamped signals, UWB calculates the time for signals to travel between devices, then multiplies the time by the signal speed (speed of light) to obtain the distance.

Figure 2 shows the advantage of using ToF to calculate distance in an indoor environment. In the diagram, a UWB signal transmitted by the yellow device reaches the red device via several different paths. One path reaches the red device directly through an intervening wall; the other paths are longer because they involve reflections. Because the direct path is the shortest, it reaches the red device first and is used to calculate ToF. The other signals can be ignored. Think of it like a race: many runners arrive at the finish line, but only the first runner wins. This method works regardless of the signal strength, so it doesn't matter if the direct signal has been attenuated by passing through the intervening wall.

Figure 2: UWB is resistant to multi-path effects because it uses ToF to calculate distance.



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In contrast, technologies that rely on RSSI can produce misleading distance and location measurements in indoor environments. A weak signal strength may lead the receiver to think the transmitting object is farther away, when in fact the signal has been attenuated because it passed through a wall. Also note that UWB requires single measurements to determine your position accurately and reliably, while other RF technologies require multiple samples plus filtering to get to a location result.

UWB Topologies

UWB technology can be implemented in different ways to address a wide range of different needs. The principal topologies are:

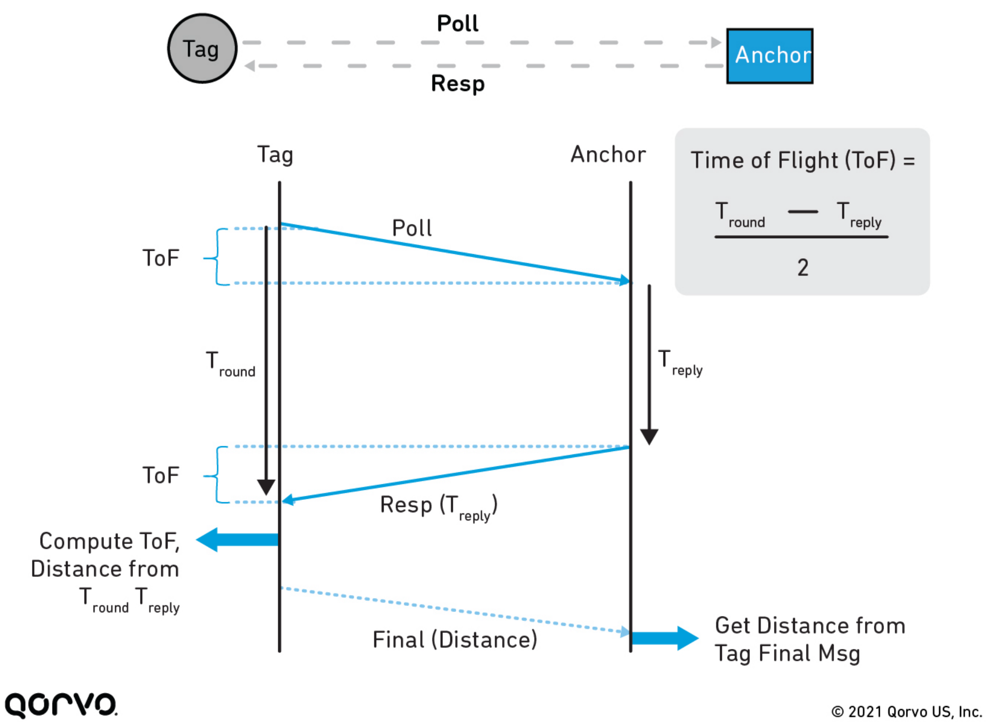
- Two way ranging (TWR)
- Time difference of arrival (TDoA)
- Reverse TDoA
- Phase difference of arrival (PDoA)

To understand distance and location measurement with UWB, it's important to know the terms "anchor" and "tag." An anchor is generally a fixed UWB device with a known location. A tag generally refers to a mobile UWB device. An anchor and tag exchange information to establish the distance between them. The exact location of a tag can be determined by communication with multiple anchors.

Some devices can act either as an anchor, as a tag, or both. For example, when two mobile phones use UWB to calculate the distance between them, they may switch roles during the process, alternately acting as tag and anchor.

Two-Way Ranging (TWR). The TWR method calculates the distance between a tag and an anchor by determining the time it takes for UWB RF signals to pass back and forth between them (ToF) and then multiplying that time by the speed of light. A keyless car entry system is an example of an application that uses TWR for secure and accurate distance determination.

Figure 3: Secure two-way ranging between UWB tag and anchor.



As shown in Figure 3, the tag initiates TWR by sending a poll message with the known address of an anchor. The anchor records the time that it receives the poll message and sends a response. When the tag receives the response, it calculates the signal ToF based on the signal round-trip time (T_{round}) and the time it took for the anchor to process and reply to the initial poll message (T_{reply}). The distance is calculated by multiplying the ToF by the speed of light. The tag can then pass the calculated distance to the anchor in a final message if required.

With multiple anchors, each requiring its own antenna, TWR can be used to determine the absolute position of mobile devices or other tags. By determining the distance to three or more anchors in known locations, the device can estimate its location with great accuracy. It can then communicate the distance via UWB or other wireless technologies to location-based applications or gateways, as shown in Figures 4 and 5 below. The disadvantage of using TWR for location measurement in this way is that the tag has to do a lot of communication, which increases its power consumption and limits scalability.

Figure 4: Two-way ranging with 2D/3D assets and listener.

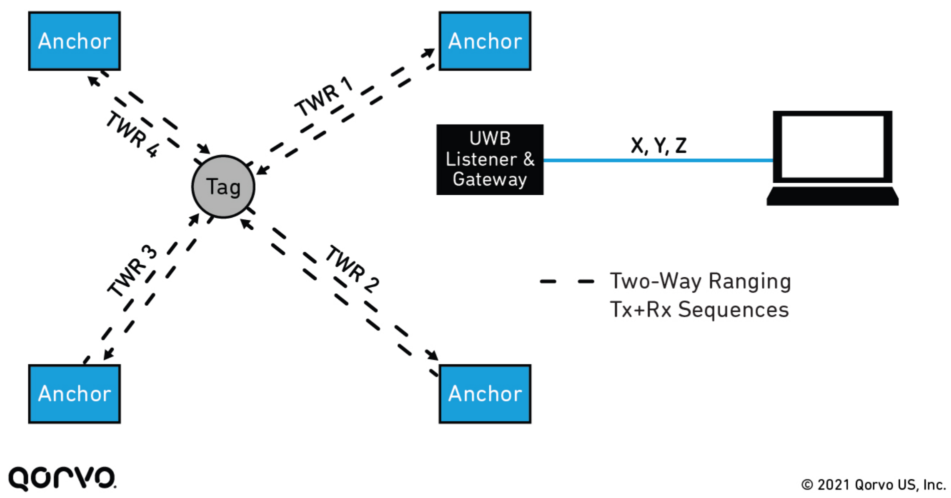
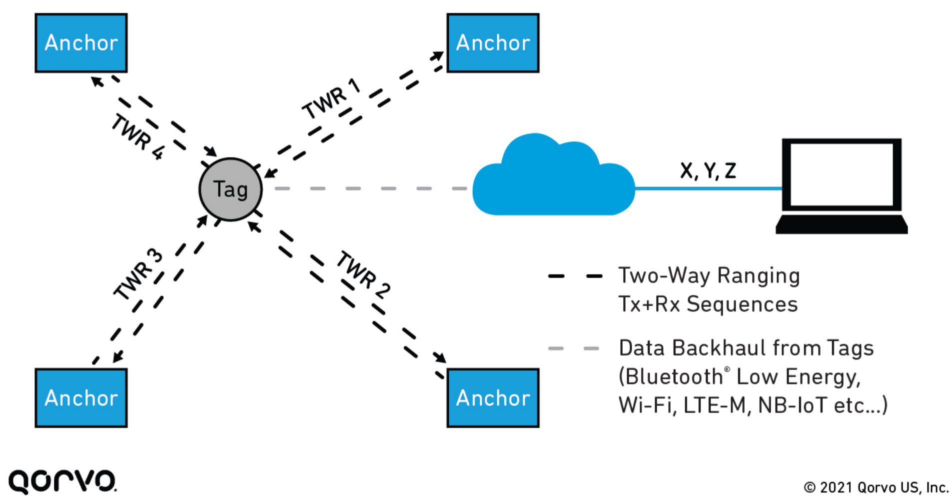


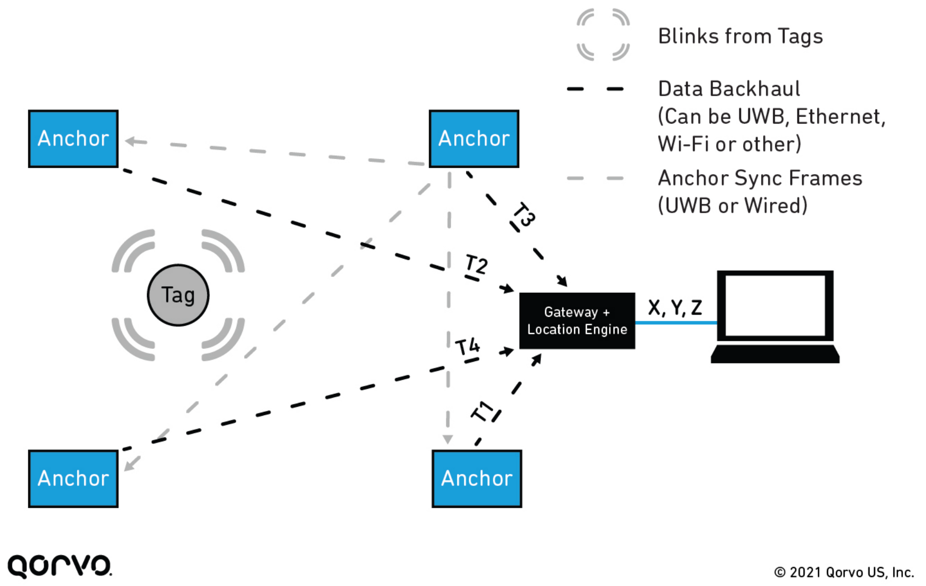
Figure 5: Two-way ranging with 2D/3D assets and data tag backhaul.



Time Difference of Arrival. The time difference of arrival (TDoA) method is an extremely scalable method for determining the location of tags within a venue. Because tags only need to transmit once during the process, they use very little power and therefore have a very long battery life.

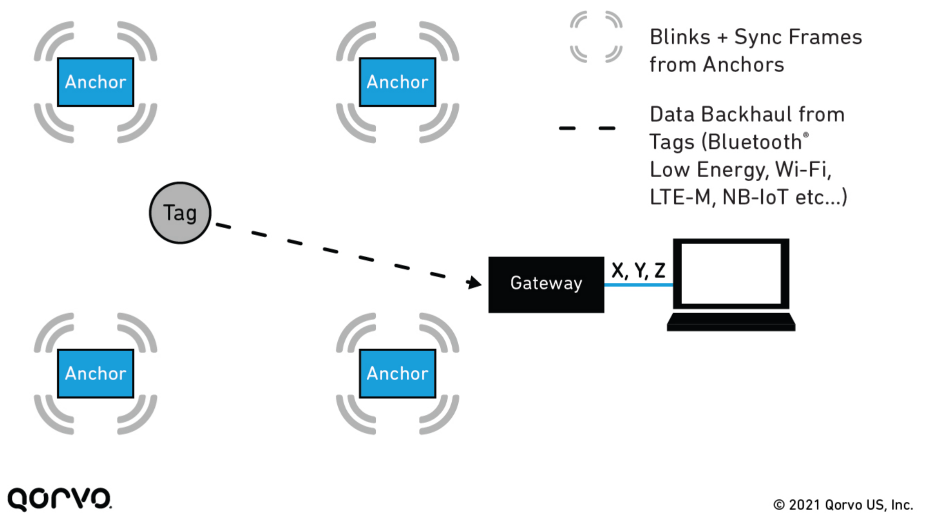
Multiple anchors are deployed in fixed and known locations and are tightly time synchronized. When a mobile device sends a “beacon” or “blink” signal, each anchor that receives the signal timestamps its arrival, based on the common synchronized time-base. The timestamps from multiple anchors are then forwarded to a central location engine, which runs multilateration algorithms to determine the device’s location based on the differences in the time that the signal arrived at each anchor. The result is a 2D or 3D position for the mobile device, as shown in Figure 6.

Figure 6: Determining location with time difference of arrival (TDoA).



Reverse Time Difference of Arrival. It is also possible to implement a reverse TDoA system, which works a bit like GPS. The anchors transmit synchronized blinks (with fixed/known offsets to avoid collisions) and the mobile devices use TDoA and multilateration algorithms to compute their location, as shown in Figure 7.

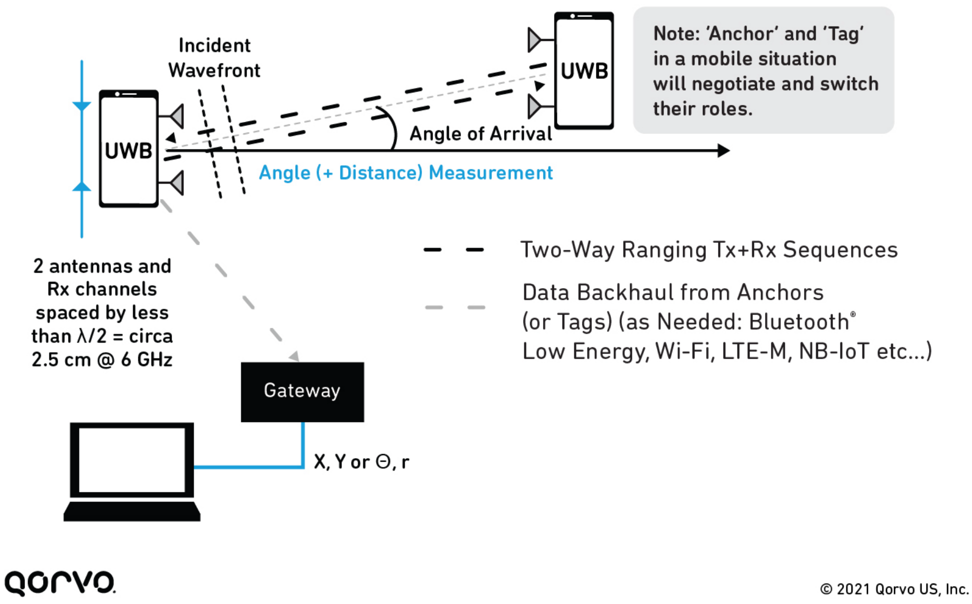
Figure 7: Reverse time difference of arrival (TDoA).



Phase Difference of Arrival. This method enables two devices to calculate their relative positions without the need for any other infrastructure, using a combination of distance and directional information. This is very important for peer-to-peer applications or to reduce the amount of infrastructure that needs to be deployed.

For PDoA, one of the devices must carry at least two antennae. When this device receives a signal from the other device, it measures the difference in the phase of the arriving signal at each antenna. Based on this information, it can calculate the angle from which the incoming signal arrived. The receiving device now knows both the direction and the distance of the transmitting device.

Figure 8: Using phase difference of arrival to calculate direction as well as distance.



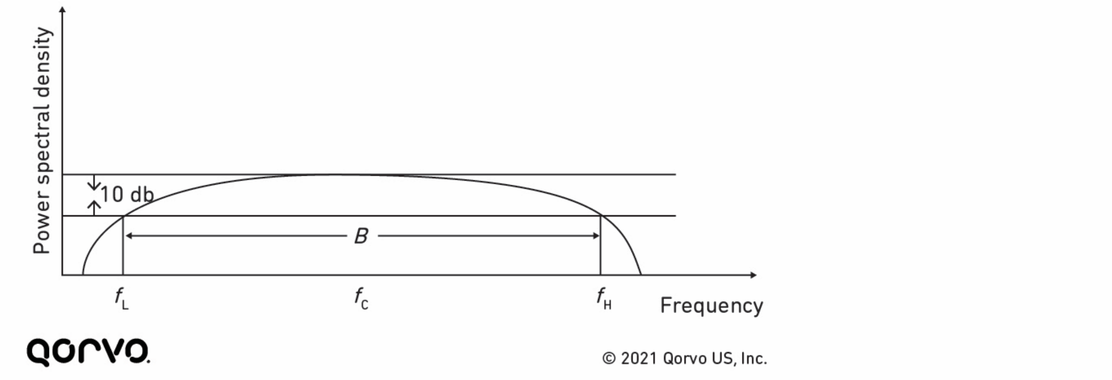
UWB Regulations

UWB operates in regulated unlicensed spectrum, so anyone can implement UWB communications without a telecommunications license as long as their system operates within the regulated frequency and power range.

The Federal Communication Commission (FCC) has defined UWB systems as those operating with an absolute bandwidth (larger than 500 MHz) at a maximum power density at a central frequency (f_c) above 2.5 GHz, or fractional bandwidth greater than 0.2 with f_c lower than 2.5 GHz.

Figure 10 illustrates the calculation of absolute bandwidth (B) and fractional bandwidth. Maximum power density is at the central frequency f_c, and f_H and f_L are the high and low frequencies at which the power spectral density is 10 dB below f_c. B_{frac} is defined as B/f_c. In terms of high and low frequencies, we have $f_c = \frac{(f_H + f_L)}{2}$ so $B_{frac} = 2 \times \frac{(f_H - f_L)}{(f_H + f_L)}$

Figure 10: Low, central and high frequencies of a UWB system.

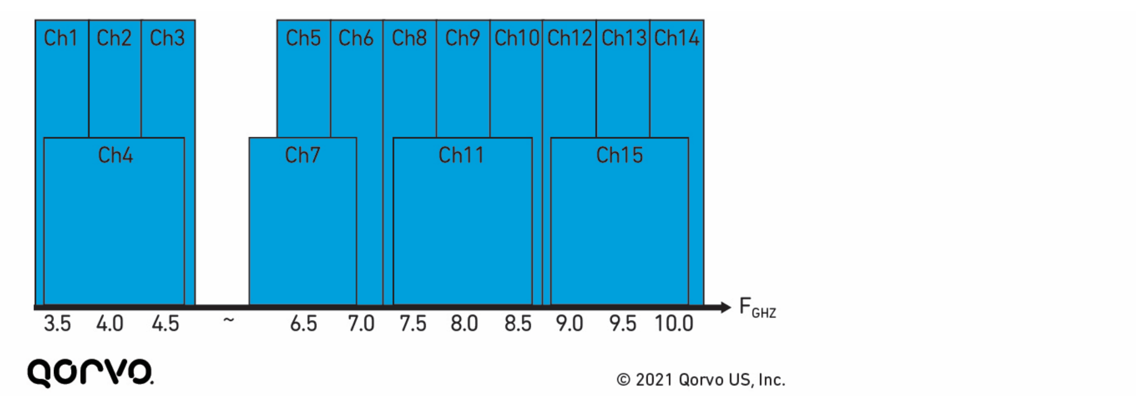


The FCC-defined UWB radio frequency range is between 3.1 GHz to 10.6 GHz (Figure 11).

Table 1: UWB channels and their use in different regions.

Channel	Carrier Frequency (MHz)	Bandwidth (MHz)	Region
0	499.2	499.2	Proprietary
1	3494.4	499.2	USA, EU
2	3993.6	499.2	USA, EU, JP, KOR
3	4492.8	499.2	USA, EU, JP, KOR
4	3993.6	1331.2	USA, EU
5	6489.6	499.2	USA, EU, China
6	6988.8	499.2	USA, EU, China
7	6489.6	1081.6	USA
8	7488	499.2	USA, EU, KOR, China
9	7987.2	499.2	USA, EDU, JP, KOR, China
10	8486.4	499.2	USA, EDU, JP, KOR, China
11	7987.2	1331.2	USA, JP, KOR
12	8985.6	499.2	USA, JP, KOR
13	9484.6	499.2	USA, JP, KOR
14	9984	499.2	USA, JP, KOR
15	9484.8	1354.97	USA, JP, KOR

Figure 11: UWB frequencies.



The FCC and other organizations also limit the power of UWB transmissions to avoid interference with other technologies, as shown in Figure 9 and Table 1 below. Although UWB's large bandwidth is a very useful property, it means that the frequencies used by UWB overlap with those used by other communications technologies.

The FCC limits radiated power to -41.3 dBm in the 3.1 GHz-10.6 GHz range, with even tighter restrictions in other some other frequency ranges.

Figure 9: UWB coexists with other wireless technologies.

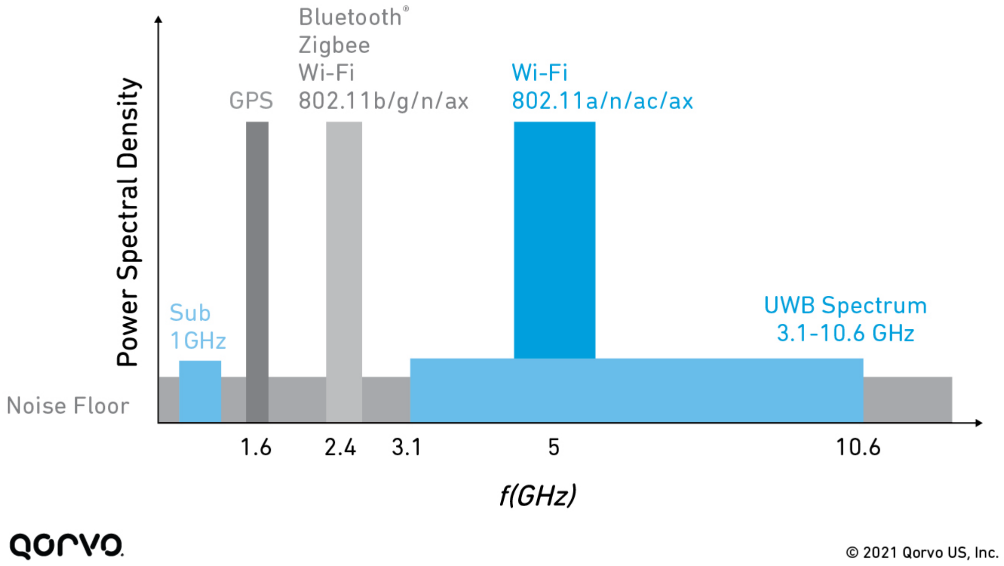


Table 2: UWB EIRP limits.

Frequency (MHz)	EIRP (dBm)
960-1610	-75.3
1610-1990	-53.3
1990-3100	-51.3
3100-10600	-41.3
Above 10600	-51.3

UWB Consortiums and Alliances

Interoperability is critical to ensure mass adoption of UWB. Because every user expects their electronic devices to easily connect and operate with minimal or no effort, it's vital that products, systems, applications, and services from different vendors work together reliably and predictably. Different players within the UWB industry – from semiconductor suppliers to device manufacturers and test equipment vendors – have already started to address the need for interoperability.

Notably, several key consortiums/alliances are collaborating to ensure interoperability of UWB products. Among the goals are to create protocols that ensure your car can talk to your phone, your phone can talk to your door lock, and your phone can communicate with location infrastructure:

- **FiRa Consortium:** As an industry consortium, FiRa believes UWB technology will transform the way people experience connectivity and is committed to the widespread adoption of UWB applications. FiRa stands for fine ranging, a term that highlights UWB technology's unique ability to deliver unprecedented accuracy and security when measuring distance to a target or determining position. The consortium is developing use cases across many industries, including hands-free access control, indoor location, and navigation, as well as peer-to-peer applications. The mission of the consortium involves developing test specification, certification programs and events to support the interoperability between UWB products.

- **Car Connectivity Consortium (CCC).** The CCC is a cross-industry organization advancing global technologies for smartphone-to-car connectivity solutions. CCC stakeholders include car manufacturers, tier 1 automotive suppliers, phone manufacturers, semiconductor suppliers, and app developers. CCC is developing the digital key, a new open standard that allows smart devices, like smartphones and smartwatches, to act as a vehicle key. This standardized ecosystem enables mobile devices to store, authenticate, and share digital keys for vehicles over UWB in a secure, privacy-preserving way that works everywhere.
- **UWB Alliance**: The UWB Alliance is working with global regulation bodies and organizations to provide a favorable regulatory and spectrum management landscape to maximize UWB's market growth. The UWB Alliance is also involved in optimizing spectrum sharing to minimize interference from other new and existing standards.

Summary

UWB is a technology on the brink of mass adoption. It is already being incorporated into leading smartphones and a wide range of other devices, and ultimately will become ubiquitous. UWB is uniquely capable of calculating location, distance and direction with unprecedented accuracy, indoors and outdoors, securely and in real time. These capabilities will unleash a new wave of applications that use this highly accurate location and distance information to deliver new experiences and capabilities – including many applications that were not previously possible.

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