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The Coming of UWB Technology

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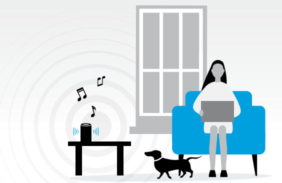

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Introduction

The Coming of UWB Technology

Ultra-wideband (UWB) is the latest wireless standard moving to mass market adoption, some 20 years after the U.S. Federal Communications Commission authorized low power, unlicensed use of the band from 3.1 to 10.6 GHz. UWB, defined by IEEE standard 802.15.4z, can accurately determine distance and location, even in the presence of noise and multipath. This eBook, sponsored by Qorvo, provides an overview of the technology and explores several of its applications.

We begin with an outlook on the ever-changing state of consumer wireless standards. Market research firms Yole Développement and System Plus Consulting describe the market trends shaping Wi-Fi, Bluetooth and UWB and forecast how these trends will drive the demand for RF front-ends.

The second article, "Exploring Ultra-Wideband Technology for Micro-Location-Based Services," is a tutorial on UWB. It explains how UWB determines distance and location, how it compares with Wi-Fi and Bluetooth and the regulatory parameters governing it, including allowable power levels and global frequency allocations.

One the most compelling applications for UWB is improving automotive safety. "UWB: Enhancing Positioning, Safety and Security for Connected Vehicles" outlines how UWB could be integrated into V2X and advanced driver assistance systems to improve security and reduce collisions.

As with any wireless system, UWB systems must be tested and certified to ensure interoperability with other UWB equipment and compliance with the IEEE standard and national regulatory requirements. "Test and Certification of UWB devices according to IEEE802.15.4z" summarizes the latest UWB standard and provides guidance for testing and certifying devices in R&D and production.

The capabilities and benefits of UWB are achieved because of its wideband operation, i.e., 3.1 to 10.6 GHz. While solid-state components covering this bandwidth are relatively common, designing an antenna with this bandwidth is challenging. "A Comprehensive Survey of Ultra-Wideband Dielectric Resonator Antennas" describes the techniques, geometries, fabrication technologies and materials with UWB characteristics for dielectric resonator antennas (DRA). For UWB applications, the novel 'OM'-shaped air-spaced DRA, cross-shaped parasitic strip-based MIMO rectangular DRA and rack-shaped MIMO DRA are discussed.

The eBook concludes with a second compelling application for UWB: enhancing the capabilities of a factory or process. UWB's micro-location precision — down to centimeters — has many applications in a manufacturing operation, such as tracking work-in-process or measuring the utilization of expensive capital assets. Qorvo's white paper "Ultra-Wideband (UWB) Enables Smart Factory of the Future" explains how UWB obtains such centimeter precision and describes four interesting cases where UWB is being used to improve performance.

Gary Lerude, Microwave Journal *Editor*

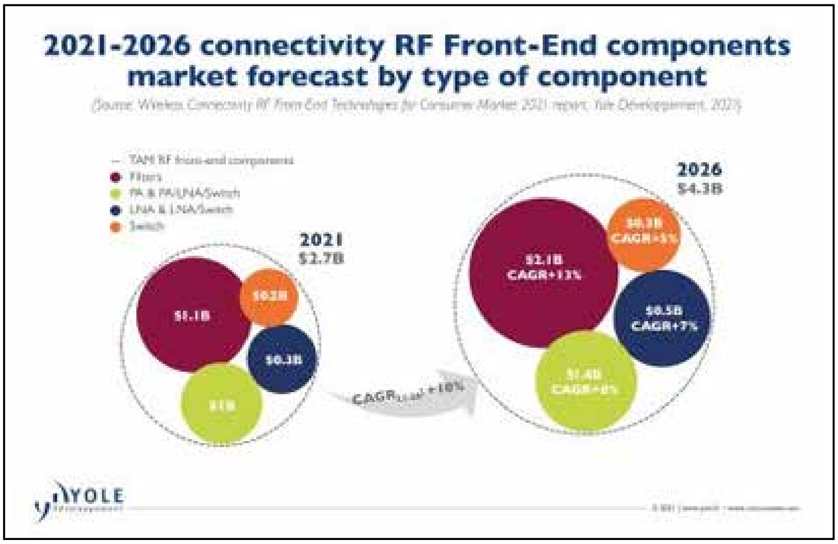
Beyond 5G, Other Wireless Connectivity Standards Are Coming...

Yole Développement (Yole), Lyon-Villeurbanne, France

"While all eyes are on 5G, other connectivity standards such as Wi-Fi, Bluetooth and ultra-wideband are also evolving." asserts Mohammed Tmimi, Ph.D., technology and market analyst, RF Devices & Technologies at **Yole Développement (Yole).** He added, "One thing we all learned during the repetitive COVID-19 lockdowns is that broadband internet became essential for survival, as observed with data traffic peaking due to streaming and video calls."

This is due to a higher data consumption per device and an increase in the number of connected devices per user. This increase was enhanced significantly by the wireless standards that provide freedom of mobility, such as Wi-Fi, Bluetooth and ultra-wideband (UWB) technologies. Although its evolution is less noticeable than cellular standards, Wi-Fi is as important as 5G in this acceleration of the digital transformation.

In this context, Yole and its partner, System Plus Consulting, investigated the disruptive RF technologies and more globally, connectivity technologies in depth. The two companies highlight the latest innovations and underline the business opportunities in a dedicated collection of reports and monitors.



The Wireless Connectivity RF Front-End Technologies for Consumer Market 2021 report from Yole delivers a comprehensive overview of consumer connectivity with key examples of RF architecture and evolution for each RFFE device.

In parallel, the *RF Front-End Module Comparison 2021 – Volume 4 – Focus on Wi-Fi 6/6E* report from System Plus Consulting provides insights into technology and cost data for Wi-Fi chipsets – specifically, the SoCs, FEMs, and several components found in four of the latest smartphones: the Huawei P50 Pro, iPhone 13 Pro Max, Samsung Galaxy S21 5G and Xiaomi Mi 11 Ultra.

Discover this snapshot of the wireless connectivity industry from Yole and System Plus Consulting.

Consumer premises equipment devices such as routers and mesh systems, will also benefit from the latest innovations.

According to Cédric Malaquin, senior technology and market analyst specializing in RF devices & technologies within the Power & Wireless division at Yole. "We estimate that consumer mesh systems will penetrate the market more rapidly, growing from 15 million units shipped in 2021 to 56 million units in 2026. At the same time, the volume of consumer routers will remain stable YoY, but the RF BoM will further increase with the higher penetration of 4x4 MIMO, Wi-Fi 6E and the future Wi-Fi 7 6 GHz band."

However, Wi-Fi is not the only standard seeing significant developments.

Bluetooth standards are also being optimized for specific use cases; for example, Bluetooth Low Energy audio (BLE Audio) is becoming crucial to serving the true-wireless stereo hearables market. The new BLE Audio offers a new high-quality codec (LC3 Codec) that provides a good power consumption/audio quality compromise; this was completed with the multi-stream capability that enables simultaneous transmission to multiple audio sink devices. This new capability comes at a crucial time for the hearables market, where the volume of TWS earbuds and wireless headsets is expected to more than double, from 387 million units shipped in 2021 to over 900 million units expected to be shipped yearly by 2026, with Apple leading this market.

With its highly precise positioning and localization capabilities, UWB technology has also benefited from the COVID-19 situation. As it gains traction in the consumer market for contract tracing, touchless access control use cases, like touchless door opening, are expanding. This technology pull initiated by Apple, then extended by Samsung, Xiaomi and the like, is also being introduced in the automotive industry by, for instance, BMW, Volkswagen and others. It could ultimately replace the keys.

Each year, the reverse engineering and costing tools company System Plus Consulting tears down hundreds of FEMs and components in select flagship smartphones to provide an overview of the RF FEM market. Gathering the information in one report offers an opportunity to track the evolution of this technology market. The *RF Front-End Module Comparison 2021 – Volume 4 – Focus on Wi-Fi 6/6E* report features a comprehensive overview of the connectivity architecture in the market, comparing Wi-Fi AC (aka 5.0) to Wi-Fi AX (aka 6/6E).

For Stéphane Elisabeth, Ph.D., senior technology and cost analyst at System Plus Consulting. "As the architecture is central on the SoC, PAs, switches and LNAs, a detailed analysis (including a cross-section and technology analysis) is also provided. Furthermore, different choices of architecture are revealed between MediaTek, Broadcom, Qualcomm and Huawei."

According to Yole, two factors will lead to significant growth in the connectivity RFFE device market analyzed. The first is the volume growth of specific devices, such as wearables embedding a 2.4 GHz SAW filter, while the second is the addition of new RF chains for 2x2 and 4x4 MIMO devices, plus the 6 GHz band RF chains. The number of 6 GHz chains will vary depending on the device, whereas the use of 46 GHz RF chains is increasingly popular for backhaul in mesh Wi-Fi devices. Yole's analysts estimate that the RFFE market of the products analyzed will grow from US$2.7 billion in 2021 to US$4.3 billion in 2026 with a 10 percent CAGR between 2021 and 2026, excluding the chipsets' market value.

Smartphones, tablets and laptops take the lion's share. Here Yole's RF team estimate that Wi-Fi/Bluetooth/UWB is responsible for an RFFE market valued at US$2 billion in 2021, while by 2026, this connectivity RFFE market will grow to US$3 billion with an 8.4 percent CAGR between 2021 and 2026, excluding the chipsets' market value. This increase is driven by the rapid implementation of UWB, Wi-Fi 6E, and 2x2 MIMO in smartphones, translating into a higher connectivity RF BoM.■

Exploring Ultra-Wideband Technology for Micro-Location-Based Services

Mickael Viot, Alexis Bizalion and Jervais Seegars
Qorvo, Greensboro, N.C.

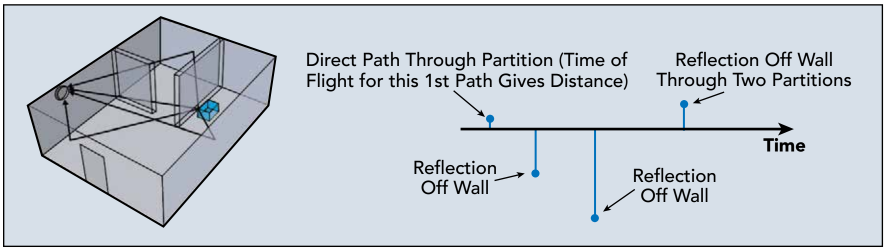
Ultra-wideband (UWB) is an IEEE 802.15.4a/z standard radio technology that can measure distance and location with unprecedented accuracy—within a few centimeters—by calculating the time it takes radio signals to travel between devices. It is uniquely suited to a new generation of micro-location-based systems that require secure real-time positioning information, indoors or outdoors. The standard was also designed with low-power and low-cost in mind and with the requirement to support large numbers of connected devices. UWB operates in regulated unlicensed spectrum and coexists with other wireless technologies using the same spectrum. UWB is on the brink of mass adoption; it has been incorporated into leading smartphones and many other devices and, ultimately, may become as ubiquitous as Wi-Fi and Bluetooth® Low Energy (BLE).

Today, it's hard to imagine life without easily navigating anywhere in the world—both indoors and outdoors. GPS, popularized in the 1990s, was a huge advance in location technology and changed our lives. It allowed users to electronically locate the nearest gas station, track fitness, map out travel plans and find the way home. It has helped companies increase efficiency and build new business models. Without GPS, how would e-commerce companies efficiently navigate deliveries to your doorstep?

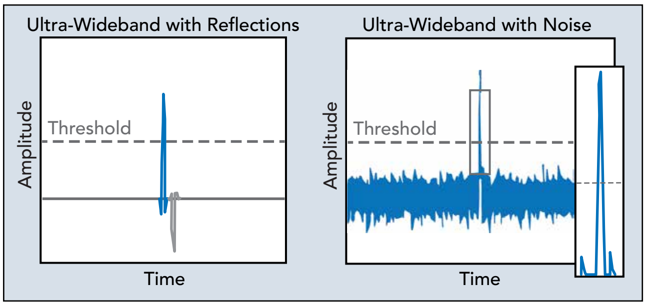
Ten years later, another breakthrough brought navigation inside, aptly called indoor navigation or positioning. Think Google Maps for malls, airports and other large buildings. When designing these first indoor location systems, engineers used the technologies widely available at the time, usually Wi-Fi and BLE. Though these technologies are excellent for data communications, they're only capable of determining location within a few meters.

Now we're seeing the rise of micro-location-based systems that have much greater precision. People and businesses want to be able to locate and find pretty much anything in real time, whatever its size. Let's say you're at home and have misplaced your car keys or TV remote control, or you're in a grocery store and can't find your favorite brand of coffee, or you're in a hospital urgently trying to find the infusion pump in an emergency. UWB is uniquely capable of supporting these micro-location applications because it was specifically designed for precise, secure, real-time measurement of location, distance and direction while concurrently supporting two-way communication. It is 50x faster than GPS, with updates up to 1000x per second, which is 3000x faster than a standard BLE beacon! It is also extremely reliable, with high immunity to interference, including reflected signals or multipath effects common indoors.

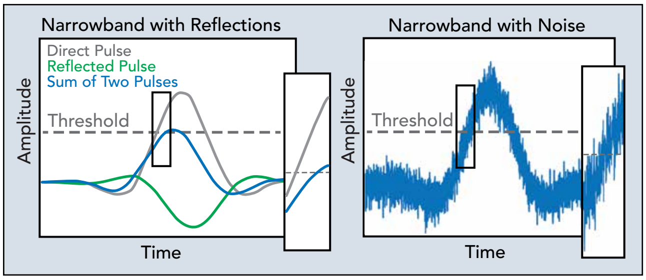
UWB technology is being incorporated into leading smartphones and many other devices and is poised for mass adoption worldwide, with a potential market of billions of units. It is already being used in more than 40 different industries, in consumer and business systems for healthcare, factory automation, automotive and others. But its greatest potential is in new generations of micro-location-based applications. Just as Wi-Fi and Bluetooth enable many applications that extend far beyond the original uses of those technologies, UWB will become ubiquitous and enable applications that haven't yet been conceived.



▲ **Fig. 1 UWB is resistant to multipath because it uses ToF to calculate distance.**



▲ **Fig. 2 UWB pulses are not affected by reflections or noise.**



▲ **Fig. 3 Impact of reflections and noise on measuring ToA with narrowband signals.**

HOW UWB WORKS

UWB has unique characteristics that enable it to determine distance and location more accurately than other technologies, even in the presence of noise and multipath interference. One of UWB's key strengths is using time-of-flight (ToF) information to calculate distance and direction. Using timestamped signals, UWB calculates the time for signals to travel between devices, then multiplies that time by the signal speed (i.e., the speed of light) to obtain the distance between them.

In contrast, Wi-Fi and BLE rely primarily on the received signal strength indicator (RSSI) method. This measures the strength of received signals to determine the distance from a transmitter, since a radio signal's strength varies according to the inverse square of the distance from the transmitter in free space. A key problem using the RSSI method is signal strength being affected by other factors, such as whether the signal is passing through walls or reflected by objects. A weak signal strength would lead the receiver to estimate the transmitting object is farther away—when, in fact, the signal has been attenuated only because it passed through a wall. Technologies that rely on RSSI can yield misleading distance and location measurements in indoor environments.

Figure 1 shows the advantage of using ToF indoors to calculate distance. In the diagram, a UWB signal transmitted by the blue device on the right reaches the gray device on the left via several different paths. One path reaches the gray device directly through an intervening wall; the other paths involve reflections and are longer. Because the direct path is the shortest, it reaches the gray device first and is used to calculate the ToF. The multipath signals can be ignored because the system relies on ToF to determine distance. This method works even if the direct signal is weaker than the reflected signals. Note that UWB only requires a single measurement to determine position accurately and reliably, while other RF technologies require multiple samples with filtering to determine location.

Because radio signals travel at the speed of light, extremely accurate measurement of ToF is necessary to determine distance within centimeters. The UWB signal is designed to help achieve this goal. Unlike other radio technologies, UWB does not encode information using amplitude or frequency modulation. Instead, UWB communicates information with short sequences of brief pulses using binary phase-shift keying and/or burst position modulation to encode the data. UWB signals also use much greater bandwidth than narrowband technologies, typically 500 MHz. As a result, each pulse is extremely short—only 2 ns—due to the inverse relationship between time and bandwidth. These pulses have much faster rise and fall times than narrowband signals, making it possible to precisely measure the time of arrival (ToA) of the signal. This also helps UWB signals maintain their integrity and structure in the presence of noise and multipath. As shown in ***Figure 2***, because the UWB pulse is so short, it is separate from and unaffected by a reflected signal. Even under noisy conditions, the time is barely affected.

The ToF-based approach has also been tried with narrowband radio technologies; however, as shown in ***Figure 3***, a narrowband signal is very sensitive to multipath. A reflected signal may combine destructively with the direct signal to cause errors at the receiver. Destructive interference shifts the time when the signal crosses the threshold, which is used to measure the signal's ToA, resulting in poor accuracy. Noise also adds uncertainty to the ToA of the signal.

Knowing where people and assets are in real time can also provide new methods of security. If physical presence cannot be faked, a person's location can be used as a security credential, restricting access to areas and protecting physical assets, data and communications. Effectively, secure location information can be used to create virtual walls and boundaries for wireless networks. For example, because UWB uses ToF instead of RSSI to determine distance, it guards against relay attacks. In a relay attack, a malicious actor picks up a signal and amplifies it to trick the receiver into concluding a transmitting device is closer than it really is.

UWB TOPOLOGIES

UWB technology can be implemented in different ways to address a wide range of needs. Depending on the implementation, UWB can be used to measure distance, 2D or 3D location and direction. The principal topologies are:

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

The concepts "anchor" and "tag" are important to understand distance and location measurement with UWB. 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 communicating with multiple anchors. Some devices can act as either an anchor or tag. For example, when two mobile phones use UWB to calculate the distance between them, they may switch roles during the process, alternating between tag and anchor.

TWR — This method calculates the distance between a tag and an anchor by determining the time it takes for the UWB RF signals to pass between them (ToF), then multiplying that time by the speed of light. A keyless car entry system is an application that uses TWR for secure and accurate distance determination (see ***Figure 4***). As shown in the figure, the tag initiates TWR by sending a poll message with the known address of an anchor. The anchor records the time 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 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, TWR can 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 (see ***Figures 5*** and ***6***). The disadvantage of using TWR for location measurement in this way is the tag does frequent communication, which increases its power consumption and limits scalability.

TDoA — This method is extremely scalable for determining the location of tags within a venue. Because tags only transmit once during the process, they use very little power and 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 "time stamps" 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 arrival times at each anchor (see ***Figure 7***). The result is a 2D or 3D position for the mobile device.

RTDoA — It is also possible to implement a reverse TDoA system, which works a bit like GPS. The anchors transmit synchronized blinks with fixed or known offsets

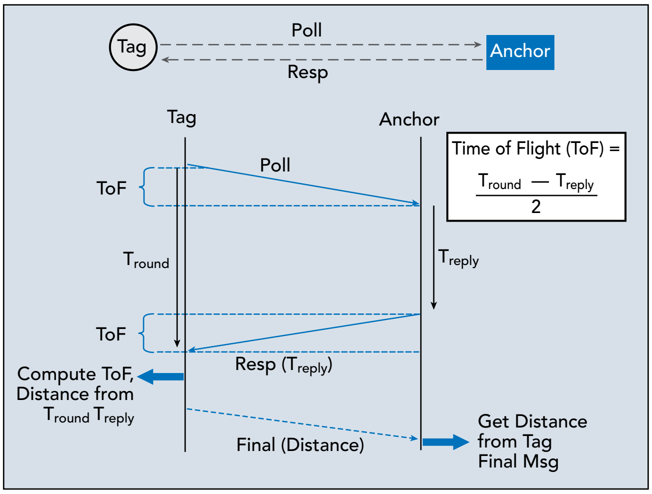


Fig. 4 Secure two-way ranging between UWB tag and anchor.

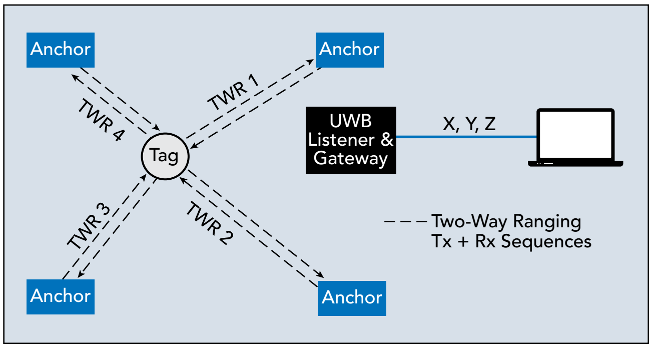


Fig. 5 Two-way ranging with 2D/3D assets and listener.

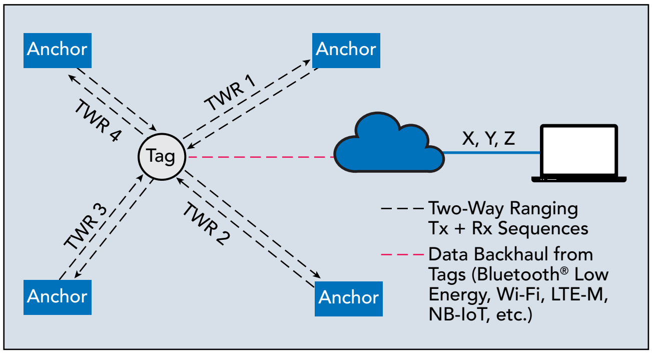


Fig. 6 Two-way ranging with 2D/3D assets and data tag backhaul.

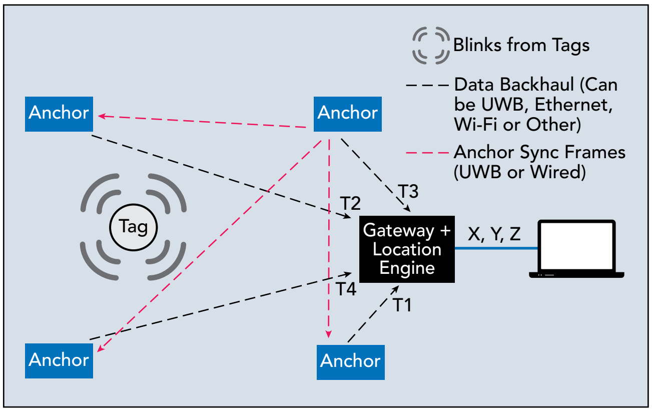


Fig. 7 Determining location with TDoA.

to avoid collisions, and the mobile devices use TDoA and multilateration algorithms to compute their respective locations (see ***Figure 8***).

PDoA — This method enables two devices to calculate their relative positions without needing any other infrastructure by using a combination of distance and directional information. This is important for peer-to-peer applications or to reduce the infrastructure to be deployed. For PDoA, one of the devices must have at least two antennas (see ***Figure 9***). 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 difference, it calculates the angle from which the incoming signal arrived. The receiving device now knows both the direction and the distance of the transmitting device.

For simplicity, Figures 5 through 9 only show one tag; however, UWB applications can support many tags.

UWB FREQUENCIES

UWB operates in regulated unlicensed spectrum, so anyone can implement UWB communications without a telecommunications license if the system operates within the regulated frequency and power range. The Federal Communication Commission (FCC) defines the UWB frequency range from 3.1 to 10.6 GHz and UWB systems as those operating with 1) an absolute bandwidth larger than 500 MHz at a maximum power density at a central frequency (f_C) above 2.5 GHz or 2) a fractional bandwidth greater than 0.2 with f_c lower than 2.5 GHz. UWB spectrum is divided into channels; not all channels are used in all regions (see ***Table 1***).

Although UWB's large bandwidth is very useful, it means the frequencies used overlap with those of other communications technologies (see ***Figure 10***). The FCC and other regulatory organizations therefore limit the power of UWB transmissions to avoid interference (see ***Table 2***). The FCC limits the radiated power to -41.3 dBm from 3.1 to 10.6 GHz, with tighter restrictions in other frequency ranges.

THE FUTURE OF UWB

UWB is on the brink of mass adoption, now used in more than 40 market verticals for a range of applications, including:

- Secure keyless entry to cars
- Locating essential supplies in hospitals
- Improving operational efficiencies and safety in factories
- Controlling smart devices in homes, based on user's location.

Integrating UWB into smartphones is a key step to the use of UWB in our daily lives. UWB-enabled smartphones will trigger the development of a broad ecosystem of new devices and applications that cannot be implemented with other technologies. UWB is a potentially revolutionary technology that will ultimately become ubiquitous—impossible to imagine today all the ways that it might be used in the future.

However, it typically takes time to realize the full potential of a new technology and have it adopted into main-

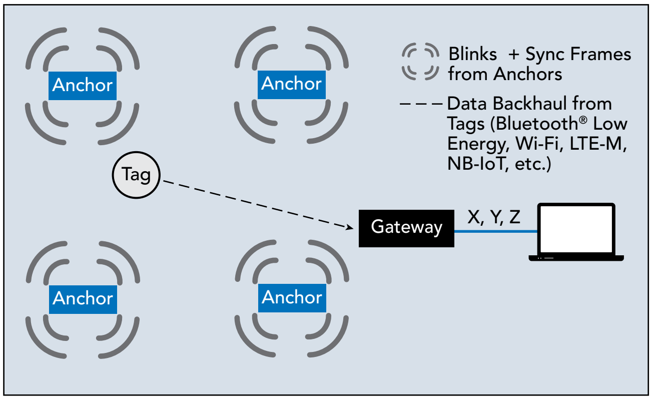


Fig. 8 Reverse TDoA.

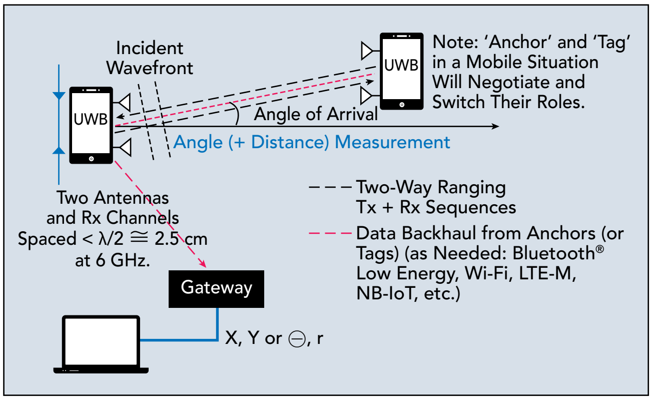


Fig. 9 Using PDoA to calculate direction and distance.

TABLE 1

UWB CHANNELS AND GEOGRAPHIC USE

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

stream use. It is therefore difficult to predict the future of UWB adoption. Yet history gives us some hints about its possible trajectory. For example, Wi-Fi started as a proprietary wireless communications solution for cash registers in the early 1990s. Apple's endorsement of Wi-Fi in 1999 helped spur its rapid adoption, with development of a rich ecosystem of devices and a network effect that led to annual shipments of billions of units.

Interoperability is key to mass adoption, as is the development of full-featured software stacks and hardware solutions developers can use as application building blocks. Several industry consortia are working on interoperability, UWB use cases and regulation. Participants include a wide range of companies, from semiconductor suppliers to device manufacturers, carmakers, test equipment vendors and app developers. The FiRa 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 consortium's mission includes developing test specifications, certification programs and events to ensure interoperability between UWB products. The Car Connectivity Consortium (CCC) is working on smartphone-to-car connectivity solutions. CCC is developing the Digital Key, a new open standard that enables smart devices like smartphones and smartwatches to act as vehicle keys. The UWB Alliance is working with global regulation bodies and organizations to ensure a favorable regulatory and spectrum landscape to maximize UWB's market growth.

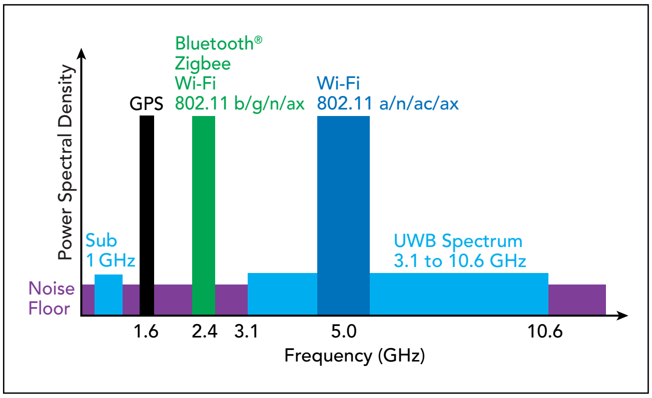
CONCLUSION

UWB is uniquely capable of calculating location, distance and direction with unprecedented accuracy, indoors and outdoors, securely and in real time. These capabilities will lead to a new wave of micro-location-based applications delivering new experiences and capabilities, no doubt many that weren't previously possible.■

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



▲ **Fig. 10 Spectrum used by common wireless technologies.**

UWB: Enhancing Positioning, Safety and Security for Connected Vehicles

Kerry Glover and Bror Peterson
Qorvo, Greensboro, N.C.

Ultra-wideband (UWB) is an RF wireless technology that could enhance advanced driver assistance systems (ADAS) and connected autonomous vehicle (CAV) sensor suites. The addition of UWB could increase the number of lives saved by avoiding deadly collisions and ensuring the trusted rollout of vehicle-to-everything (V2X) connections.

Technology advancements are changing our everyday lives and significantly impacting whole industries. This holds true for the automotive industry, which continues to adopt new technologies to enhance consumer experiences, safety and security. Among today's biggest concerns are severe traffic collisions, an area where technology can be applied to save lives. Many efforts are underway to define, develop, standardize and implement the best technologies to improve road safety. Initially, manufacturers have used stand-alone ADAS technologies inside vehicles, such as radar and cameras. With these technologies, each manufacturer could implement its own system without the need for standardization.

The next big leap in safety will be for vehicles to share information, enabling them to cooperate with each other. This will require standardization to ensure connectivity of vehicles from different manufacturers. Efforts are underway to provide the basis for connected vehicles by standardizing V2X connectivity, including vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and vehicle-to-pedestrian (V2P) protocols. V2X standardization efforts open the way for the adoption of new technologies that enhance the ADAS and CAV sensor suites.

UWB is a low-cost RF technology that can be used to accurately measure the distance between two points. This leads to the perfect marriage: UWB + V2X. The adoption and standardization of UWB + V2X can add capabilities, including precise positioning, secure identification and ultra-low latencies at high update rates. This article will focus on a few critical life-saving applications of UWB + V2V and UWB + V2P. However, it is important to note that there are also many applications where UWB + V2I could greatly improve consumer convenience, such as automated valet parking and alignment with electric vehicle chargers.

UWB TECHNOLOGY

IEEE 802.15.4z provides a specification for the standardization of UWB for secure ranging. The security aspects of the standard ensure distance measurements are accurate and not spoofed by external sources. UWB secure ranging works by measuring the time it takes for very narrow RF pulses to travel from a transmitter to a receiver. This "time of flight" is multiplied by the speed of light to obtain the distance. Narrow pulses enable the system to accurately understand multi-path interference and choose the first path, ensuring identification of the nearest object.

Many pulses are grouped together to form frames. Each secure ranging frame contains a scrambled time stamp, which is created using cryptographic techniques to ensure the reliability of the distance measurement. A single frame can be transmitted in less than 200 μs. Frames are sent back and forth between the transceivers of all nodes in a group, providing round-trip distance measurements between all nodes. For a simple one-sided, two-way ranging operation, round-trip measurements can be completed in under 1 ms, enabling an update rate of 1000/s.

UWB operates with a bandwidth greater than 500 MHz and, when coupled with the proper signal processing techniques, can provide distance measurements with an accuracy down to 10 cm. All these capabilities can be implemented on a single low-cost CMOS device. More background information and an overview of UWB technology can be found in the Qorvo publication *Ultra-Wideband for Dummies*.[1]

COOPERATIVE DRIVING

The automotive industry is beginning to envision its connected future, ushering in a new era of cooperative autonomous driving. This includes use cases such as group start from traffic lights, intersection crossing, vehicle platooning and merging between lanes. These use cases require knowing vehicles' relative position to an accuracy better than 1 m and down to 10 cm in some cases. By sharing accurate positioning information, vehicles can work together to perform these functions more safely and with faster reaction times than a human, allowing them to operate with minimal or no human intervention.

One of the basic functions of V2V communications is the exchange of basic safety messages (BSM) in the U.S. or cooperative awareness messages (CAM) in Europe. These messages include information such as vehicle position, speed and heading. From this rough positional data, a vehicle's autonomous navigation system (ANS) can determine which other vehicles are in the vicinity. Groups can then be formed for cooperative maneuvers.

In complex cooperative maneuvers of connected vehicles, maintaining proper separation is imperative to avoid fatal contact between vehicles. According to the 5G Automobile Association (5GAA), a global organization working on future connected mobility and intelligent transportation solutions, precise positioning is one of the critical problems to be solved. Keeping vehicles separated requires technology that can provide exact position measurements with fast update rates.

UWB can perform this function with accuracy down to 10 cm, which is one of the reasons the technology is growing globally. UWB can also save lives by preventing collisions between vehicles and vulnerable road users (VRUs) such as bicycles, motorcycles and pedestrians. UWB is rapidly proliferating in many consumer products and applications. Many of the leading cell phones include UWB, and the technology is being added to cars to enable phones to act as secure digital keys.

Wouldn't it be great if UWB in vehicles and UWB in cell phones could be used together to save lives? If a vehicle could talk to a pedestrian's cell phone (V2P) and use UWB to measure the distance between them, then vehicle-pedestrian collisions could be avoided. UWB can increase the security of communications by preventing malicious spoofing, which is a significant concern with CAVs. By verifying a vehicle's ID and position, UWB can validate communications are with the intended vehicle instead of someone impersonating that vehicle for malicious purposes. Recent reports have demonstrated the impact of costly infrastructure blackmail exploits that have compromised many systems and led to loss of service. Can you imagine traveling down the highway in a CAV and receiving blackmail demands to pay or else the vehicle might be crashed?

UWB WITH LARGE OBJECTS

Most of the literature about UWB focuses on determining the distance to a small object. But when UWB is applied to large objects such as vehicles, knowing the distance to a single point somewhere on the vehicle is not adequate. In the case of moving vehicles, the measurements must be relative and continuous. Using multiple UWB sensors, each vehicle can continuously calculate the relative position of all four corners of another vehicle. Throughout the rest of this article, the term position will refer to relative position.

For a cooperative maneuver, the ANS could identify the appropriate vehicles and form a group using the V2V link. After a group has been formed, the ANS would identify, initialize and start continual measurements with the appropriate UWB sensors, again using the V2V link. ***Figure 1*** shows how UWB sensors near the corners of two vehicles could form a crossbar arrangement. With two sensors located on each of the front, rear and side surfaces of each vehicle, the position and orientation of both vehicles could be determined. Each of the UWB links provides a unique, secure method of measuring the precise distance, as well as supporting data communications. Data communications can further enhance security by enabling the exchange of additional details.

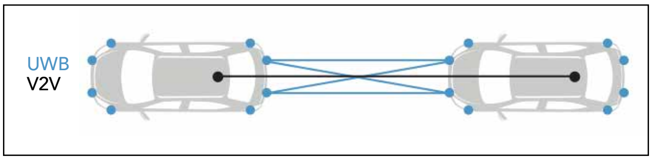


Fig. 1 Two vehicles using an UWB crossbar connection.

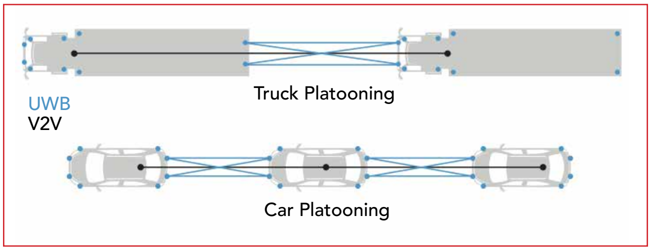


Fig. 2 Vehicle platoon using UWB to maintain separation and orientation.

SAFETY AT HIGH SPEED

During high speed maneuvers involving several vehicles, it is vital that the CAVs function without failure. One common example is platooning (see ***Figure 2***), where several vehicles travel in tight formation, drafting each other to save fuel. Platooning will help the trucking industry increase safety while reducing fuel costs and emissions, as well as reducing congestion and delivering goods faster. It could also help maximize the range of electric vehicles with limited battery capacity.

UWB links enable platooning vehicles to accurately measure the distance between them and maintain proper separation and orientation. In a platoon, each vehicle follows another at a close distance. Reaction time is critical. If the platoon is traveling at 60 m/s (135 MPH) and the separation between the vehicles is 6 m (20 ft), vehicles in the platoon must react in less than 100 ms to avoid a collision if the lead vehicle suddenly applies its brakes. This can easily be achieved with UWB.

With four sensors in a many-to-many UWB architecture, a ranging round should be completed in well under 10 ms, with the exact timing dependent on implementation. A ranging round is the time it would take for the four sensors to measure the four distances shown in Figure 2. For a vehicle traveling at 60 m/s, a ranging round time of 10 ms means the vehicle would travel only 60 cm between messages, giving each vehicle adequate time to react safely to speed changes of the lead vehicle. Multiple UWB links enable the platooning vehicles to maintain the correct orientation to each other. This could enable each vehicle's ANS to follow the lead vehicle around curves, staying in the same track as the lead vehicle.

VEHICLE MERGING

Merging is another process where CAVs can benefit from UWB sensors. Examples of situations where vehicles need to merge include entering a highway from an on-ramp or joining the middle of a platoon. ***Figure 3*** shows a situation where one vehicle needs to merge with two other connected vehicles. The ANS first establishes a connection using V2V, forms a group and communicates the need to merge. The system would then determine the UWB sensors needed for the operation, initialize those sensors and launch continuous UWB sensing (see Figure 3a).

The next step is for the two vehicles to form a gap for the merging vehicle to join. The merging vehicle would then move into the lane between the two other vehicles as shown in Figure 3b. The ANS determines the appropriate UWB sensors required to participate. After joining the platoon, the UWB sensors maintain continuous operation to regulate the distance and orientation of the vehicles.

UWB AND V2P

Another key potential life-saving application takes advantage of UWB coupled with V2P communications using a VRU's smartphone or other UWB-enabled device. This works similarly to V2V: the ANS, coupled with V2P, can determine if a VRU is in the vicinity and then start the UWB distance measurement process. UWB tracks the exact position of the VRU and determines the possibility of a collision. As an example, vehicles stopped at an intersection, such as the three-way stop shown in ***Figure 4***, could use UWB sensors to determine the distance to the VRUs and avoid a collision.

VALIDATING FOR IMPROVED SECURITY

UWB can also be used to mitigate risk for connected car threat scenarios. The Car Connectivity Consortium already includes UWB in its Digital Key 3.0 specification, which enables drivers to securely use their phones to open and start their cars. UWB increases security by measuring the distance between the owner and the vehicle. Ensuring the owner is in the proximity of the vehicle prevents "person in the middle" vehicle attacks where thieves intercept and relay distant signals from an owner's phone to gain access.

With V2V communications, it is vital for safety that vehicles can trust the information received from other vehicles. Detecting misbehaving actors transmitting inaccurate information, whether unintentionally or maliciously, is an important security and safety concern. UWB can provide the required trust between vehicles by ensuring they know each other's position, validating their identity and detecting misbehavior. This is especially important when the communication includes life-critical information. The analysis in ***Table 1*** summarizes the most critical 5GAA cooperative driving use cases where inaccurate information could be deadly.

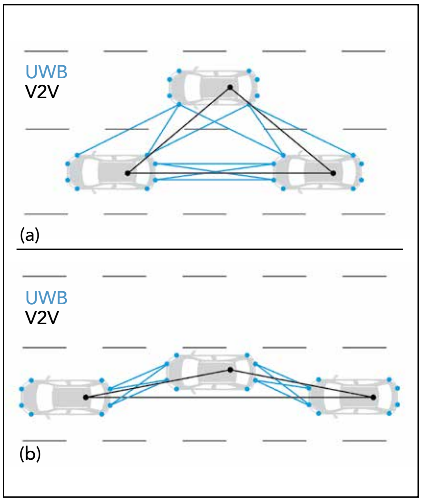


Fig. 3 A vehicle joins a vehicle group with V2V and UWB before merging (a), then completes the merge (b).

UWB sensors could be used to verify that the vehicle being communicated with over V2V is really in the position indicated. If the position does not correlate with the GPS coordinates transmitted in the BSM or CAM, then any transaction between the vehicles would be in doubt and appropriate precautions could be taken. Identification of misbehaving actors in the system and then revoking their certification will help ensure a trusted V2V system.

In one potential example of fatal spoofing (see ***Figure 5***), a spoofing vehicle (SV) traveling behind a pass-

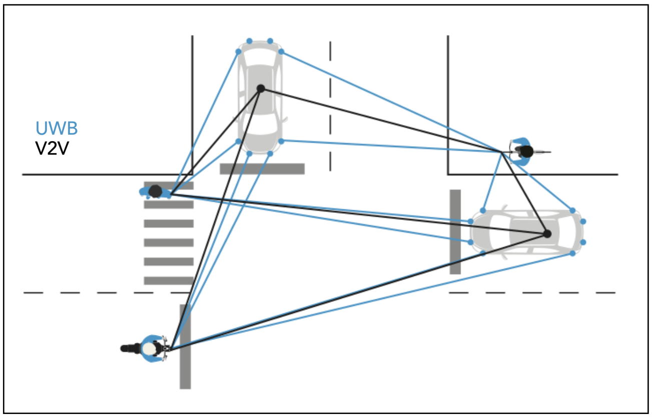


Fig. 4 Three VRUs at a three-way stop.

TABLE 1

SCENARIOS WHERE SPOOFING CAN BE FATAL

Spoofing Use-Cases	*Location*	*Type*	*Speed*	*Spoof Result*	*UWB Safety Verification*	*UWB Precise Positioning*
High-definition sensor sharing	Highway	ADAS	Any	Fatal	×	
See-through for passing	Passing	ADAS	High	Fatal	×	
Vehicles platooning in steady state	Highway	CAV	High	Fatal	×	×
Cooperative maneuvers of autonomous vehicles for emergency situations	Highway	CAV	High	Fatal	×	×
Cooperative lane merging	Highway	CAV	High	Fatal	×	×
Cooperative coordinated driving maneuver	Any	CAV	Any	Fatal	×	×
Cooperative traffic gap	Highway	CAV	High	Fatal	×	×

ing vehicle (PV) pretends to be in front of the vehicle by transmitting incorrect GPS coordinates, falsely indicating it is in front of the PV instead of behind it. If the PV requests "see through for passing" information, the SV could then transmit an image of a clear road. Based on this false information, the PV would start to pass and could collide head-on with an oncoming vehicle. This can be avoided if the PV is able to verify, using UWB, whether the SV is truly the vehicle in front.

UWB can also be used to accurately identify vehicles in other use cases. Following directly behind two vehicles closely tailgating each other, it could be difficult to know with which of the two your vehicle was communicating. UWB distance measurement could confirm communication with the appropriate vehicle. Another example: following two vehicles traveling side by side in adjacent lanes. If one vehicle is using real-time kinematics to adjust its GPS coordinates and the other vehicle is not, the two vehicles could be reporting the same location.

AUGMENTING THE CAV SENSOR SUITE

UWB provides an excellent augmentation to the existing CAV sensor suite. Its high frame rate provides much faster reaction times than any other system. The ability to provide communications in addition to sensing enables UWB to provide secure distance measurements and accurately identify other vehicles. Being an RF technology, it operates much better than optical systems in poor weather. UWB's small size, low complexity and low cost make placing multiple sensors around a vehicle feasible.

UWB sensors offer the benefit of simplicity, which helps vehicles process and respond to information more quickly. The processing power required to implement UWB secure ranging is relatively small. To provide the same information about the relative distance and orientation of two vehicles without using UWB requires both radar and cameras. The camera would need to look at the scene, analyze the image, extract key features and determine orientation. The radar would measure the distance between the vehicles, with the accuracy dependent on the radar's resolution and its short distance performance. The camera and radar data would then be merged using sensor fusion, which may require raw source data and an extensive library of 3D image processing algorithms to combine and then extract the information. The maximum frame rate of such a system could be more than 3x slower than UWB frame rates. The simplicity of a UWB based system also reduces the probability that an issue with the code could cause an accident.

Figure 6 compares CAV sensors. The introduction of UWB into the CAV suite provides a robust, faster, secure and accurate system with superior price for the performance.

SUMMARY

Many of the techniques discussed in this article already exist. The 802.15.4z specification provides for a many-to-many UWB architecture, providing the basis for a secure

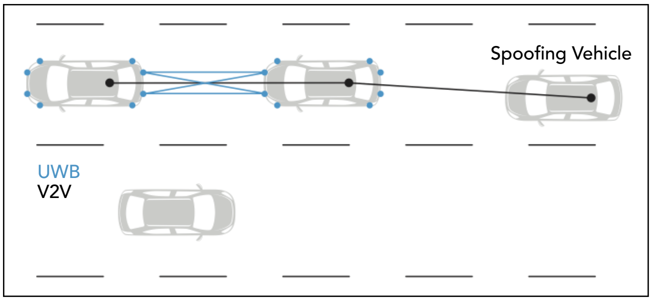


Fig. 5 "See through for passing" scenario using UWB to detect spoofing.

multi-point ranging area network (RAN). V2V defines the ability for vehicles to form a group, which is the basis for selecting the vehicles to participate in the UWB many-to-many RAN. Once a group is formed, there is a need for specifications covering how the system using the V2V link can identify, select, initialize and operate a secure UWB RAN. For broad adoption, standards need to be developed to enable UWB devices on vehicles from different manufacturers to interoperate. Qorvo is leading an effort to have its patent-pending UWB + V2X concept adopted as a key part of the connected vehicle rollout.

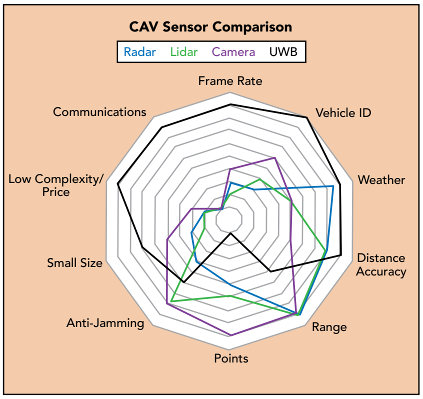


Fig. 6 CAV sensor comparison.

UWB technology is a much simpler system than radar or cameras, requiring far fewer lines of code and less processing resources. With a low cost for implementation, centimeter accuracy and low latency, UWB provides a high performance to cost ratio, enabling manufacturers to implement a more robust CAV sensor suite.

Connected vehicles will introduce a new era of vehicle safety. The key to this will be the creation of a trustworthy communication environment between vehicles. UWB can provide the required trust between vehicles by ensuring they know each other's position, validating their identities. This is especially important when communicating life-critical information. High speed cooperative maneuvers are some of the most critical CAV operations. UWB can provide the speed and accuracy needed to enable the ANS to avoid life threatening situations by reacting much faster than a human, even faster than existing radar and camera systems. Even at slow speeds, vehicle maneuvering can result in fatal accidents, especially when a VRU is involved. By using UWB to measure the distance to VRUs, the navigation system can help ensure that accidents can be avoided.■

Reference

1. Qorvo, "Ultra-Wideband for Dummies," www.qorvo.com/design-hub/ebooks/ultra-wideband-for-dummies.

UWB Reloaded: Test and Certification of UWB Devices According to IEEE802.15.4z

Joerg Koepp and Nikola Serdar
Rohde & Schwarz

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Ultra-wideband (UWB) communication, as standardized by IEEE 802.15.4, enables very low power communication and very accurate ranging in the license-exempt spectrum. Well established in several industry applications for years, the technology is now entering the consumer market. Testing of UWB devices is first of all related to regulatory requirements for UWB communication and UWB standard requirements. In addition, performance and interoperability aspects as covered by the fine ranging (FiRa) certification program are of utmost importance. This article will give a brief introduction of the new 802.15.4z standard, followed by some guidance for the test and certification of UWB devices in research, development and production.

A SHORT HISTORY OF PULSE RADIO COMMUNICATION

Pulse radio communication goes back to the early days of radio communications, as first demonstrated by Heinrich Hertz and Guglielmo Marconi more than 120 years ago. In the late 1950s, pulse radio was used in radar systems for marine systems. UWB communication as used in several applications today was first standardized in 2007 as alternative technology for low-rate wireless personal networks (LR-WPAN) in IEEE 802.15.4a-2007.[1] In general, UWB communication systems are characterized by the transmission of extremely narrow pulses with a duration of few nanoseconds, which form an ultra-wide signal with a bandwidth of equal to or wider than 500 MHz – a characteristic that makes UWB signals relatively resistant to interference and allows very accurate time of flight measurements.

The high rate pulse repetition frequency (HRP) version of UWB was becoming quite successful in a wide area of industrial applications for ranging and low power device-to-device communication. In recent years, UWB has been entering additional application areas including consumer applications on mobile phones. Typical use cases are keyless entry, asset finding, indoor navigation, mobile data sharing and secure payment. In this context, in 2018 first the UWB alliance was formed to support the development of the growing UWB ecosystem, followed by the FiRa™ consortium in 2019. FiRa was launched by key industry players with the mission to provide seamless user experiences by using the secured FiRa and positioning capabilities of inter-operable UWB technology.

Especially driven by the application demands for low power operation and secure ranging, the standard was further developed over the last years with the IEEE 802.15.4z Amendment "Enhanced Ultra Wideband (UWB) Physical Layers (PHYs) and Associated Ranging Techniques."[2]

SECURE RANGING WITH IEEE 802.15.4Z

In a nutshell, of all the additions to the standard, the three most important aspects of IEEE 802.15.4z-2020 addressing secure ranging are:

- Higher pulse repetition rates and optimized modulation schemes to improve power consumption and to allow reliable communication to ranges of up to 100 m.
- Secure ranging by cryptographic and random num-

ber generation used for scrambled time-stamp sequence (STS).
- Specifying variants of two-way ranging procedures including simultaneous ranging.

PHYSICAL LAYER

The standard distinguishes two UWB physical layers (PHY): the low rate pulse repetition frequency (LRP) and the high rate pulse repetition frequency (HRP). ***Figure 1*** shows the operation bands for HRP and LRP. As can be seen, the HRP UWB PHY supports operation in three bands: a single 499 MHz wide channel in the sub-gigahertz band; four channels in the mid band from 3.1 to 4.8 GHz; and 11 channels in the high-band from 6.0 GHz to 10.6 GHz.

The HRP UWB waveform is based on an impulse radio signaling scheme using band-limited pulses. The reference pulse is a root raised cosine pulse with a roll-off factor of ß = 0.5. The duration of the pulses is in the order of two nanoseconds based on the maximum pulse repletion rate of 499.2 MHz.

In the new standard IEEE 802.15.4z-2020, UWB HRP PHY was extended for so called enhanced ranging devices (ERDEV) by a backward compatible physical layer working on the base pulse repetition frequency (BPRF) and a new physical layer using a higher pulse repetition frequency (HPRF), as ***Figure 2*** shows.

The BPRF physical layer applies a burst position modulation with binary phase shift keying (BPM-BPSK). In each symbol interval, a single burst is transmitted. This polarity-scrambled pulse burst can occur depending on the first bit output of the encoder either in the first or second burst position interval of the two halves of the symbol interval. The second bit output determines the polarity of the scrambled pulse sequences, that is generated as time-varying spreader sequence from a PRBS scrambler. In addition, BPRF is applying hopping between hop bust positions to avoid multi-user access interference. ***Figure 3*** shows the modulation and coding principle for a BPRF signal exemplary with a burst of eight pulses within the first burst position at the first hop. Eight pulses during the symbol interval duration of 128 ns results in a mean pulse repetition rate of 62.4 MHz, which allows a data rate of 6.8 Mbps.

Contrary to that, the HPRF physical layer applies a slightly modified modulation scheme for the higher pulse repetition rates of 124.8 or 249.6 MHz. Pulse bursts are transmitted in both halves of the symbol interval. The polarities of the pulse bursts are defined by both encoder outputs using a mapping function as shown in ***Figure 4*** and hopping is not applied.

For example, the two bursts of 4 pulses each per symbol interval duration of 32 ns result in the mean pulse repetition rate of 249.6 MHz.

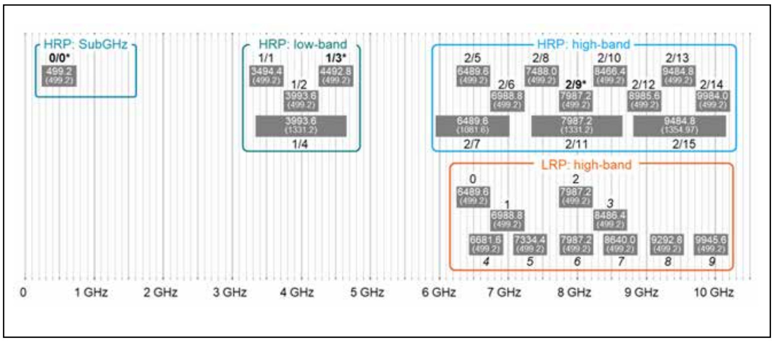


Fig. 1 UWB operation bands for high rate pulse repetition (HRP) and low rate pulse repetition frequency (LRP).

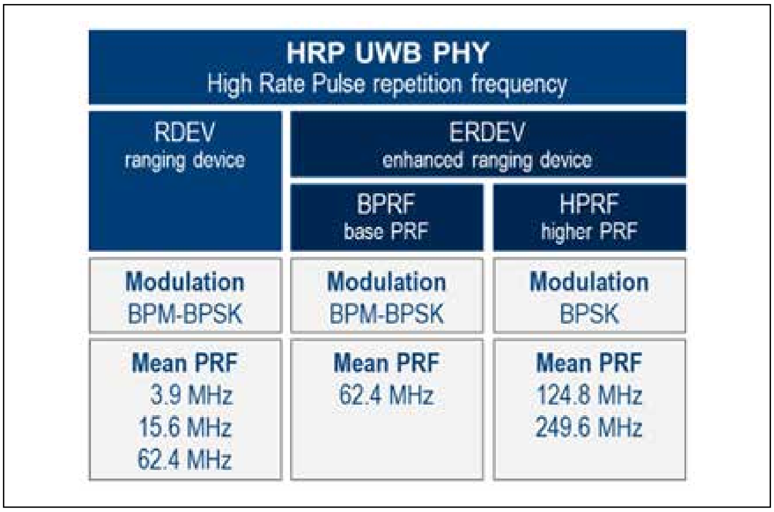


Fig. 2 HRP UWB variants based on IEEE 802.15.4z-2020.

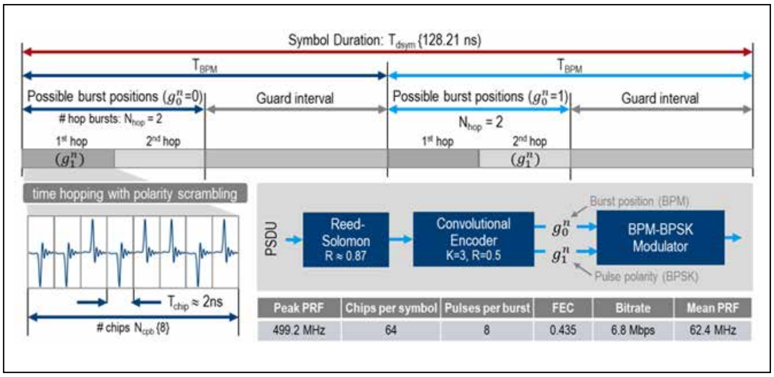


Fig. 3 Modulation and coding of HRP UWB BPRF PHY.

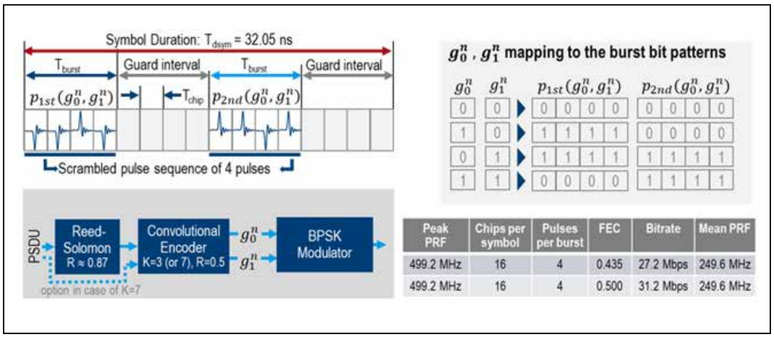


Fig. 4 Modulation and coding of HRP UWB HPRF PHY @ 249.6 MHz.

Depending on the applied coding (with or without Reed-Solomon coder) a data rate of 27.2 or 31.2 Mbps can be achieved.

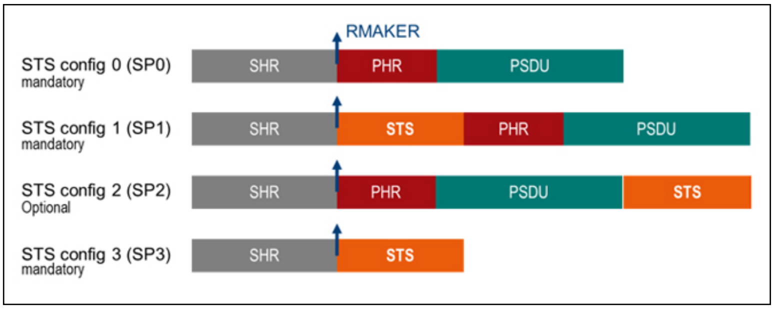
In case of the second HPRF PHY variant with a mean pulse repetition frequency of 124.8 MHz, each burst consists of 8 pulses distributed over 16 chirps. Consequently, with the symbol interval duration of 128 ns (same as for BPRF PHY) data rates of 6.8 or 7.8 Mbps can be achieved.

In summary, higher pulse repetition rates and optimized modulation schemes introduced with IEEE 802.15.4z-2020 improve power consumption and allow more reliable communication to ranges of up to 100 m.[3]

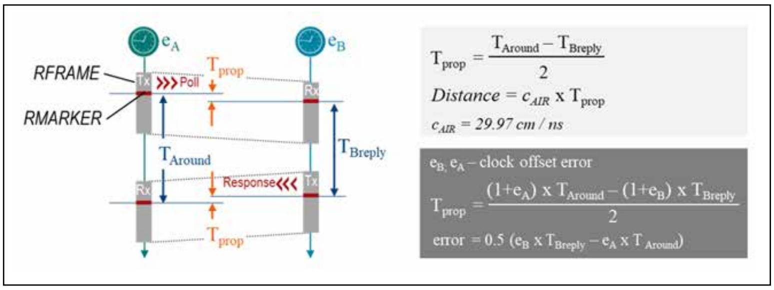
SCRAMBLED TIMESTAMP SEQUENCE FOR SECURE RANGING

In order to enable secure ranging functionality, IEEE 802.15.4z introduced a sequence of pseudo-randomly generated pulses called scrambled timestamp sequence (STS) for enhanced ranging devices in HRP mode. The STS sequence is generated using an AES128 based deterministic random bit generator based on a seed value (128 bit STS key and data) aligned in advance between the transmitter and receiver using the secure private data communication service. The frame structure of HRP-ERDEV with STS in different positions is shown in ***Figure 5.*** The support for configurations 0, 1 and 3 are mandatory and configuration 2 is optional. The ranging marker (RMARKER) used as reference point for time measurements in the ranging procedure is the peak pulse location associated with the first chip following the start-of-frame delimiter.

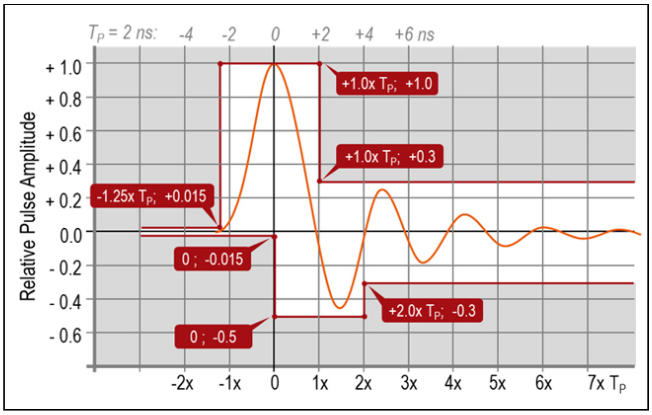
One to four segments of STS sequences per STS are supported for improved security. For BPRF only one STS segment is supported, for HPRF the support of one or two segments is mandatory, three and four optional. With the STS also additional STS ranging makers (SRMAKER) are defined.



▲ **Fig. 5 STS packet structure configurations of physical protocol data unit (PPDU).**



▲ **Fig. 6 Single-Sided Time of Flight measurement.**



▲ **Fig. 7 Recommended time domain mask for the HRP UWB PHY pulse.**

NEW VARIANTS OF TWO-WAY RANGING FOR TIME OF FLIGHT MEASUREMENTS

The new standard describes several relative positioning and locating methods including single-sided and double-sided two-way ranging (SS-TWR, DS-TWR). Both methods use relative time measurements of the RMARKER at the antennas of two devices exchanging messages. The SS-TWR method is a kind of low-power variant with limited accuracy. It is using round-trip delay measurements of a single message exchange.

The operation of SS-TWR is shown in ***Figure 6.*** Device A initiates the exchange and device B responds to complete the exchange. The times T_{Around} and T_{Breply} are measured independently on the devices A and B using their local clocks so that no time synchronization between the devices is required. Based on the calculated propagation time T_{prop} – also known as time of flight (ToF) – it is possible to estimate the distance by multiplying with the propagation speed of the radio wave e.g. the speed of light.

The double-sided variant (DS-TWR) is an extension of the SS-TWR in which two round-trip time measurements initiated by device A and B are applied to get rid of the impact of clock offset error for more accurate distance measurements.

TEST AND CERTIFICATION

Test and certification of UWB devices is of utmost importance to achieve regulatory conformance, interoperability, desired RF performance and accurate ranging results. In general, there are three areas of conformance related measurements to consider.

First of all, there is regulatory conformance based on related regional requirements e.g. specified in FCC CFR 47 Part 15.250[4] or for Europe the specifications ETSI EN 303 883[5] and ETSI EN 302 065.[6] Typical measurement is the maximum allowable output power spectral density of -41.3 dBm/MHz.

Second, there are conformance requirements and recommendations defined in Section 15.4 RF requirements of IEEE 802.15.4. Besides typical RF measurements like spectral density measurements they include some specific measurements related to the transmitted pulse shape: For example, the measurement of a normalized cross-correlation magnitude of the pulses is used to check the main lobe duration and the maximum relative magnitude level of the side lobes. In order to improve the interoperability in ranging applications it is recommended that a transmitted pulse exhibits minimum precursor energy. Therefore, the standard defines a time domain mask as illustrated in ***Figure 7*** that constraints the transmitted pulse shape accordingly. The peak magnitude is scaled to the value of one. The time unit is related to the defined pulse duration time Tp (e.g. 2 ns).

There are a couple of other measurements of interest like chip rate clock and chip carrier alignment, transmit center frequency tolerance or normalized root mean square error (NRMSE) metric used to evaluate the transmit signal quality.

Third, there is the interoperability aspects driven by organizations like the FiRa™ consortium. For this purpose, FiRa has established a certification framework with conformance specifications for the physical layer and the MAC layer in line with the related UWB standards like IEEE 802.15.4z and extended by additional requirements important for the interoperability of ranging applications. Example for such additional test cases are the transmit signal quality (NRMSE), packet reception sensitivity, dirty packet receiver tests and first path dynamic range verification. Moreover, a common UWB command interface (UCI) for the testing of UWB devices was specified.

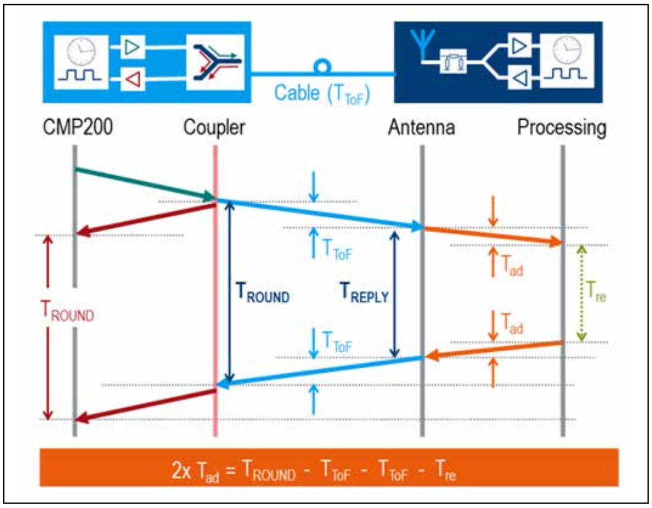
Test & measurement companies provide comprehensive UWB test solutions covering the full range from generating signals for any kind of receiver tests to analyzing the different UWB parameters in time or frequency domain of transmitted signals in R&D, integration, conformance and production testing. As an example, Rohde & Schwarz offers a dedicated UWB signal generation option for the vector signal generators R&S SMW200A, R&S SMM100A and the R&S WinIQSIM2 signal generation software running on PC or in the cloud. Comprehensive UWB signal analysis functionalities are available on the spectrum analyzer R&S FSW and the vector signal analyzer software R&S VSE.

There are also dedicated wideband communication testers like the R&S CMP200, which provides all-in-one box for testing in production, R&D and FiRa conformance. The tester is complemented by a unique graphical user interface (see ***Figure 8***) and enriched with a software for automated manufacturing. Moreover, the R&S CMP200 allows time of flight testing and calibration in conducted and over the air test setups.

TIME OF FLIGHT TESTING AND CALIBRATION

Accurate ToF measurements – a key feature for many UWB applications – require ToF verification and calibration on the physical layer. The reference point for the time of flight related measurement is the antenna. Time measurements should start or stop when the RMARKER of a frame passes the antenna. In practice, the measurement will be executed inside the UWB chip before the frame is forwarded to the antenna, or after the frame was received from the antenna. This means the measured time needs to be adjusted depending on the time the signal is traveling from the chip to the antenna or vice versa. This onboard antenna delay depends on the concrete implementation e.g. length and material of wire and can slightly vary from device to device in production.

▲ **Fig. 8 Graphical user interface of the R&S CMP200 tester showing UWB transmitter measurements.**



▲ **Fig. 9 R&S CMP200 initiated ToF calibration.**

Measurements show that the onboard antenna delay can easily vary by 1 ns which could result in a ranging error of more than 30 cm. Therefore, it is highly recommended to perform a calibration in production. For this kind of measurement, a well-defined test setup applies a ranging procedure defined in 802.15.4z to measure the time of flight and calculate the calibration value.

For example, the R&S CMP200 acting as a UWB ranging device can initiate a single-side two way ranging procedure to perform these measurements. In preparation of this, it is necessary to calibrate the test setup to exactly determine the propagation time from the tester to the antenna of the DUT and vice versa. As shown in ***Figure 9,*** it is possible to calculate the correction value (T_{ad}) based on T_{ROUND} value measured by the tester and T_{re} measured by the UWB device, when the exact time of flight between the coupler and the antenna is known.

PERSPECTIVE

As a technology, UWB is celebrating a big comeback. The new 802.15.4z-2020 standard focuses on features that aim to address the real-world problems of the use cases. For example, the added security aspect helps to realize the remote keyless entry feature for UWB key fobs in the automotive industry.

In addition, the 802.15.4z-2020 standard introduced improvements in the radio (e.g. new PRF's, enhancements for the PHY) and new ranging features which reduce power consumption and ensure interoperability among devices. Additional features like angle of arrival (AoA) will enable additional applications. The strength of the UWB technology is to enable reliable communication and excellent localization accuracy, which will also be a quality indicator for UWB devices. This, in turn, will make validation and calibration processes mandatory. Interoperability of UWB devices will be key for the success in an open UWB ecosystem and makes the UWB device certification efforts as driven by the FiRa consortium essential.

Adding to these characteristics the possibility to exchange data with good data rates, UWB is a strong contester to establish itself as the third big non-cellular technology besides Bluetooth and Wi-Fi.

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A Comprehensive Survey of Ultra-Wideband Dielectric Resonator Antennas

Sachin Kumar Yadav, Amanpreet Kaur and Rajesh Khanna
Thapar Institute of Engineering and Technology, Punjab, India

Techniques, geometries, fabrication technologies and materials with ultra-wideband (UWB) characteristics for dielectric resonator antennas (DRAs) are discussed. DRAs are placed on ground planes or dielectric substrates (rigid or flexible) and excited by different feed mechanisms. With the development of rectangular, cylindrical and other geometries, the fundamental goals are electrical size miniaturization, greater bandwidth to meet commercial requirements and radiation pattern stability. The focus is on applications related to portable devices, handheld devices, radio base stations, radar and satellite communication. The novel 'OM'-shaped air-spaced DRA, cross-shaped parasitic strip-based MIMO rectangular DRA and rack-shaped MIMO DRA for UWB applications are also addressed.

Compact UWB antennas have recently been investigated for wireless communication systems. In 2002, the Federal Communications Commission (FCC) allowed a UWB range of unlicensed bands from 3.1 to 10.6 GHz.[1] For a UWB system, a broadband antenna is required. The challenges of UWB antenna design include impedance matching, compactness (size), radiation stability and low cost. Several types of UWB antennas were proposed.[2,3]

Since the development of low-loss ceramics in the 1960s, dielectric resonators (DRs) have been used in microwave circuit applications.[4-6] Early research to determine the resonant frequencies of DRs resulted in advances in the design of antennas utilizing such resonators as antennas. The DRA has attracted much attention over the last two decades because of its many attractive features such as low profile, high radiation efficiency, low conductor loss, light weight, ease of fabrication and low-cost.[7-10]

DRAs are available in various forms, such as: rectangular, cylindrical, triangular, L-shaped, conical, T-shaped, trapezoidal, A-shaped, E-shaped, P-shaped, C-shaped, F-shaped, H-shaped U-shaped, V-shaped, Z-shaped and super-shaped.[11-25] Size and bandwidth are controlled by changing the material permeability (εDR). Being a 3D radiating structure, it enjoys greater design flexibility and adaptability than conventional antennas.

Short-range communication operates in a rich scattering environment, which can cause fading due to multipath, power loss due to disintegrating conditions or mismatches due to transmitter-receiver antenna orientation.[26] A DRA can easily produce circular polarization characteristics through various techniques such as: shape modification, metallic strips, cross-slot-coupling and single/dual feeding structures.[27-30]

In recent years, there has been an increasing demand for MIMO antennas with high data rates, high reliability, high channel capacity, low channel interference and low envelope correlation coefficient (ECC).[31-34] MIMO DRAs can be categorized by single or multiple radiator elements. A two DR radiator element was chosen in the MIMO system described by Das et al.[35] MIMO diversity parameters such as ECC, mean effective gain and total active reflection coefficient were calculated.[35]

DRAs are used in various configurations to provide significant improvements in bandwidth, radiation efficiency and gain as well as reduced antenna size. The number of papers related to UWB DRAs published between 2005 to 2021 (see ***Figure 1***) shows an increasing interest in this area.

The most common DRA shapes are cylindrical, rectangular and hemispherical. DRA resonant mode excitation depends upon input excitation, cavity volume and boundary conditions. Standing waves are generated based on these parameters at resonance. The standing waves are converted into traveling waves due to transparent walls (boundary conditions). Resonant modes such as TE, TM, TEM, HE and HEM can be excited. These are also known as transverse electric, transverse magnetic and hybrid modes. Fundamental or higher order modes can be excited, such as (TE_{111}–TE_{lmn}) and (TM_{111}–TM_{lmn}).[10] UWB performance can be achieved through mode merging. Modified shapes and the use of defective ground structures (DGS), stubs and other techniques are also used to enhance antenna performance.

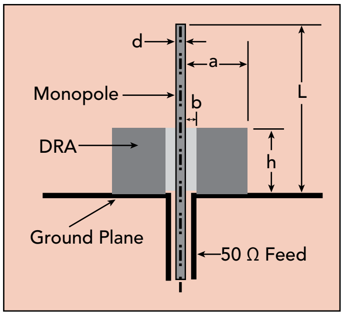
The following sections describe some of the techniques used to design UWB DRAs. Examples are also presented, addressing their advantages and disadvantages.

UWB DRA BASED ON A THIN MONOPOLE

A monopole-loaded single annular ring DRA with the same axial reference was designed for UWB applications by Lapierre et al.[36] The cylindrical DR was set on a finite ground plane and excited by a probe fed with a quarter-wave monopole (see ***Figure 2***). Prototype Antenna #1 covered a frequency range between 6.3 and 16.2 GHz with ε_{r1} = 10 and L = 10 mm. Prototype Antenna #2 covered a frequency range between 4.2 and 10.1 GHz with ε_{r2} = 20 and L = 15 mm. Results for several other monopole DRAs have also been reported.[37-48]

UWB ELECTROMAGNETICALLY COUPLED DRA

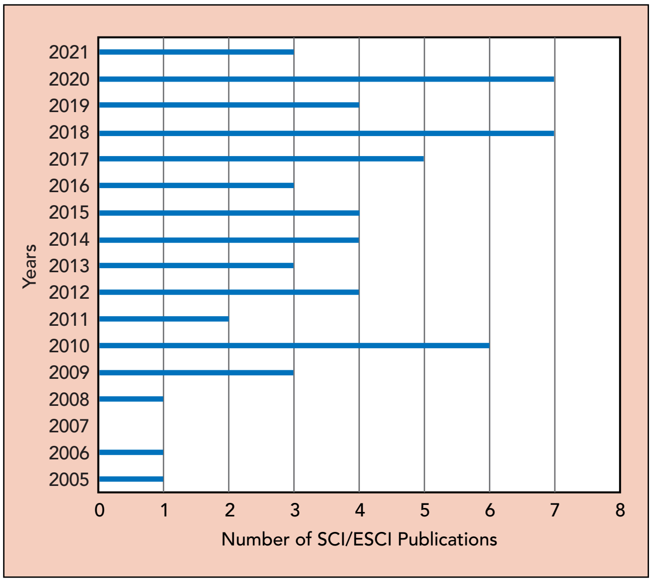
Denidni and Weng[49] introduced a new rectangular-shaped DRA (RDRA) for UWB applications. The RDRA comprised a DR excited by a bevel-shaped patch coaxial feed, providing an air gap between the DR and the infinite ground plane (see ***Figure 3***). The 27.2 × 12.6 × 19.1 mm^3 RDR made of Rogers TMM 10i was mounted on a 75 × 90 mm^2 ground plane. The Q-factor and effective permittivity were reduced by the air gap and bevel-shaped feed, providing mode transition and the widening bandwidth. Radiation efficiency of the antenna in the operating band was greater than 90 percent. Its reported impedance bandwidth was 120 percent (2.6 to 11 GHz). Many other authors have also published electromagnetically coupled DRAs for UWB operation.[50-52]



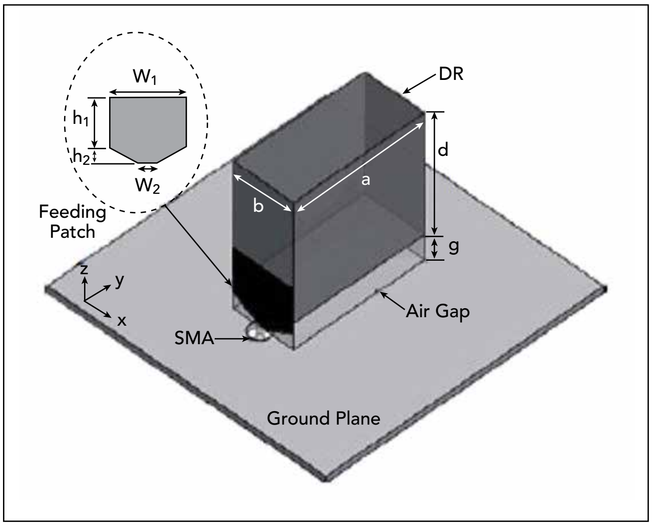
▲ **Fig. 2 Single annular ring DRA.[36]**

UWB PATCH-BASED DRA

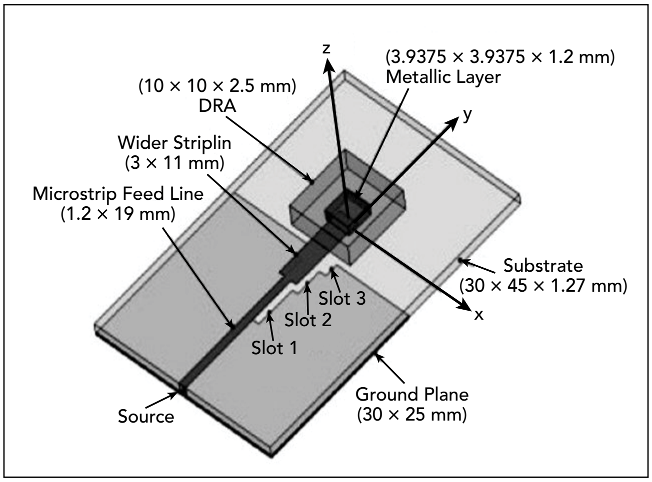
Aoutoul et al.[53] investigated a compact RDRA with permittivity ε_r= 10.2 with a low profile substrate of permittivity ε_r=3 and modified ground. The 10 × 10 × 2.5 mm^3 RDR sat on a 30 × 45 ×1.27 mm^3 substrate. The dimensions of the truncated ground plane were 30 × 25 mm^2 (see ***Figure 4***). A 3.94 × 3.94 × 1.2 mm^3 metallic layer was placed beneath the DRA to improve its bandwidth (31 percent, 6.86 to 9.41 GHz) and impedance matching. An impedance bandwidth of 46 percent (6.9 to 11 GHz) was achieved using a stepped slot in the ground plane. Other patch-based DRA designs developed for UWB applications have been reported.[54-57]



▲ **Fig. 1 UWB DRA papers published per year.**



▲ **Fig. 3 Rectangular DRA with the air gap.[49]**



▲ **Fig. 4 Compact RDRA.[53]**

UWB INSERTED DRA

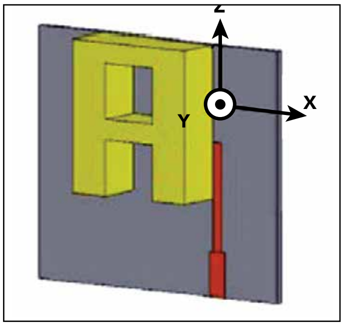
Ryu and Kishk[58] described a novel portable DRA for UWB wireless applications. The antenna provided a broadside radiation pattern using a solid RDR mounted on the edge of a vertical ground plane. The total size of the DRA was 18.3 × 14 × 5.08 mm^3. It had a 10.2 permittivity and was bonded to an RT6002 substrate. Its impedance bandwidth was 84 percent. A wide impedance bandwidth (93 percent from 3.5 to 9.6 GHz) was obtained with a modified version of the RDR, which consisted of two dielectric fragments configured into an A-shape (see ***Figure 5***). Similar structures have been reported by other researchers.[59]

UWB DRA WITH BAND REJECTION CHARACTERISTICS

Sabouni et al.[60] proposed an A-shaped DRA for UWB applications. The radiating element was excited by a transformer type of microstrip feed printed on the substrate. It covered 3.5 to 10.5 GHz, which supports the UWB range. Shorted stubs produced the notch features of the antenna. These elements were parasitically coupled to the feedline (see ***Figure 6***). Two notches were created in the UWB when two U-shaped parasitic elements were used with lengths of 8.96 and 10.65 mm, and a width of 1 mm. The peak gain of the antenna was 5.46 dB without a notch. UWB DRAs with band notch characteristics have been investigated by several researchers.[61-63]

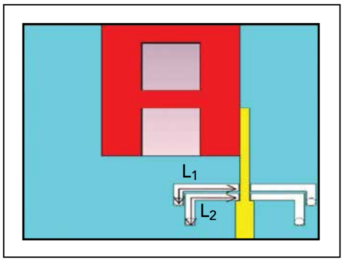
UWB STACKED OR SEGMENTED OR COMPOSITE DRA

Ge et al.[64] designed a rectangular DRA for UWB operation. The RDRA exploited multiple low-Q modes with overlapping bandwidths to achieve a wide contiguous bandwidth. This was achieved using a full-length, low permittivity, insert between a higher permittivity dielectric volume and a ground plane (see ***Figure 7a***). The volume of the DR was reduced with a finite conducting wall fixed on the side of the DR layer. The impedance bandwidth of the DRA was 110 percent from 3.1 to 10.7 GHz.

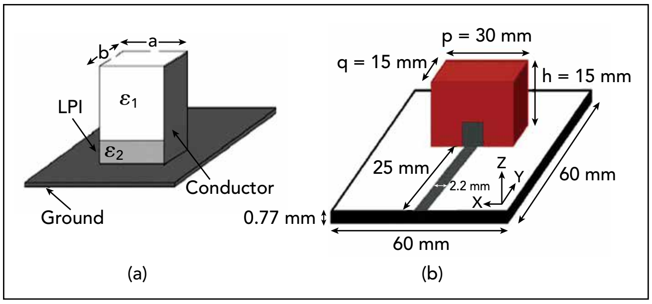


▲ **Fig. 5 A-Shaped DRA with modified ground.[58]**

Kshirsagar et al.[65] proposed a two-segment RDRA combination of half-size RDRAs made up of materials placed side-by-side with ε_r= 4.3 and ε_r= 9.2 and excited by a common microstrip feed (see Figure 7b). The effect of a defected ground was also investigated. A parametric study of the DGS angle was conducted at 0, 30 and 45 degrees. The antenna covered the UWB at an angle of 45 degrees from 2.9 to 11.6 GHz (120 percent bandwidth). The antenna exhibited a peak gain of 7.2 dBi. Many authors have used this same concept for enhancing the antenna characteristics.[66–70]



▲ **Fig. 6 A-shaped DRA with U-shaped parasitic elements.[60]**



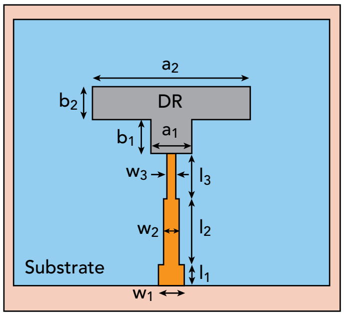
▲ **Fig. 7 Stacked DRA with LPI[64] (a) and RDRA based on a patch or conformal strip[65] (b).**

UWB RECONFIGURABLE DRA

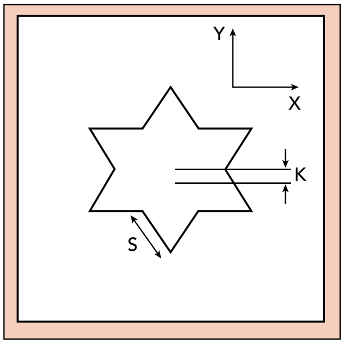
Abioghli et al.[71] developed a reconfigurable DRA antenna, with dimensions 40 × 40 × 7.3 mm^3. The ground plane was constructed by connecting an L-shaped stub and cutting two slots. It used a T-shaped DR of Rogers RT6010 with relative permittivity ε_r= 10.2 placed on a 1.6 mm thick FR4 substrate (see ***Figure 8***). Reconfigurability was achieved with a PIN diode that modified the current distribution path in the ground. The diodes were biased at 0.7 V and a suitable impedance match was provided for the 17 mm ground length. Further work by Abioghli et al.[72] on narrow band reconfigurable DRAs for cognitive radio application has been reported.

OTHER UWB DR SHAPES

Sankaranarayanan et al.[73] proposed a unique and compact modified Koch snowflake DRA geometry for broadband use. The radius and height of the cylindrically shaped DRA (CDRA) were 2.68 and 1.5 cm, respectively. An FR4 substrate was used with a ground plane of 10 × 10 cm^2. Initially, a Koch snowflake design was developed on a basic CDRA (see ***Figure 9***); however, a fractal ring structure was used to increase the overall impedance bandwidth and gain. The DRA covered the microwave frequency band from 4.7 to 12.4 GHz for a 90 percent bandwidth. Furthermore, the final geometry yielded a 76.6 percent reduction in DRA size. It had a 78 percent radiation efficiency across the entire impedance bandwidth with a maximum gain of 8.76 dBi. Other DRA shapes, such as bi-



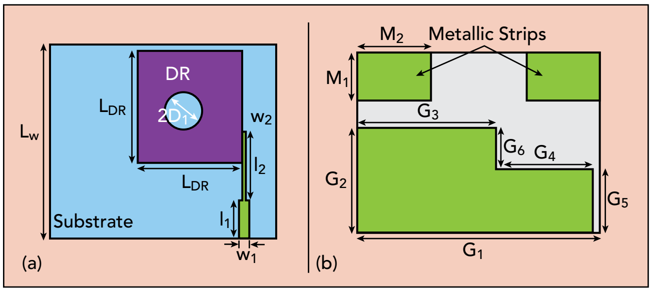
▲ **Fig. 8 T-shaped reconfigurable DRA.[71]**



▲ **Fig. 9 Modified Koch snowflake DRA.[73]**

cone shaped, laterally fixed cylindrical, Turtle-shaped, T-shaped and E-shaped have also been investigated.[74-80]

A proposed rectangular DRA designed for UWB applications is shown in ***Figure 10***.[80] It comprised a cylindrical air gap based RDRA, modified ground plane and metallic strips on a Rogers 5880 substrate. A cylindrical DR (CDR) with a diameter of 2xD1 enhanced its gain and bandwidth, and metallic strips improve its impedance characteristics. The antenna's near field supported dominant, second and third-order TE modes for a wide 103.9 percent impedance bandwidth covering the frequency range from 3.28 to 10.4 GHz.



▲ **Fig. 10 Air-spaced RDRA (a) with modified ground (b).[80]**

ELLIPTICALLY OR CIRCULARLY POLARIZED UWB DRA

Haraz et al.[81] described a half-cylindrical DRA (HC-DRA) with CP characteristics for UWB applications. The HCDR was mounted on a finite ground plane on the bottom side of the substrate (see ***Figure 11a***). The impedance bandwidth of the antenna was 90 percent covering the frequency range from 4 to 10.5 GHz. It exhibited an axial ratio bandwidth of 27 percent from 5.3 to 7 GHz.

Chakraborty et al.[82] described a dual-band antenna covering 3.7 to 4.4 GHz (17.28 percent bandwidth) and 5.8 to 6.2 GHz (11.56 percent bandwidth). It consisted of a pair of symmetrically positioned DRs on a flat I-shaped monopole. The fundamental modes were excited at 3.8 and 6 GHz to generate CP with the DRs placed orthogonally on the substrate (see ***Figure 11b***).

Yadav et al.[83] achieved UWB performance with an OM-shaped DRA and DGS (see ***Figure 11c***).[83] It covered a frequency range from 3.1 to 11.1 GHz with a peak gain of 7.68 dB and reported a band from 6 to 11.1 GHz with elliptical polarization characteristics.

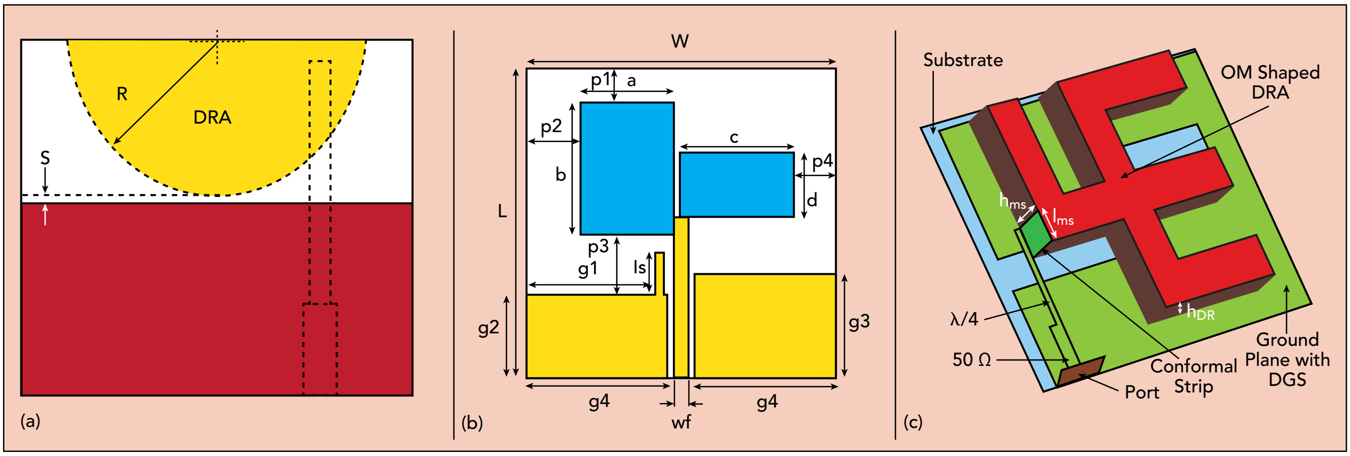
UWB MIMO DRA

Abedian et al.[84] designed a WLAN band rejection MIMO DRA. It was compact with dimensions of 29 × 29 × 5 mm^3 and utilized a Taconic-35 substrate (see ***Figure 12a***). A ground stub was used to improve isolation as well as impedance matching, and two L-shaped parasitic strips created a notch in the WLAN band from 5.15 to 5.85 GHz. The length and width of the strips could be adjusted to create a notch from 4.98 to 6.08 GHz. The compact DRA provided a broadside radiation and an impedance bandwidth of 106 percent (3.29 to 10.74 GHz), high radiation efficiency, and an ECC < 0.16.

Yadav et al.[85] proposed a rack-shaped DRA with an inverted T-shaped parasitic strip designed for UWB applications. This MIMO antenna consisted of two radiators, a partial ground, stub and parasitic strip (see ***Figure 12b***). Two DRA designs (one with and one without a parasitic strip) demonstrated impedance bandwidths of 72.67 percent (4.8 to 10.28 GHz) and 101.87 percent (3.54 to 10.89 GHz) with isolations greater than 21 and 15.6 dB, respectively. Reported diversity parameters were: directive gain (DG) ≥ 9.93 dB, TARC, group delay, ECC ≤ 0.0059 and channel capacity loss within the limits.

Sani et al.[86] presented a stair-shaped rectangular DRA for UWB applications. The measured input impedance bandwidth of the antenna was 153.6 percent (1.6 to 12.2 GHz) with a minimum of 25 dB isolation between the radiators in the operating band. It demonstrated a low ECC and low mutual coupling throughout the desired frequency range.

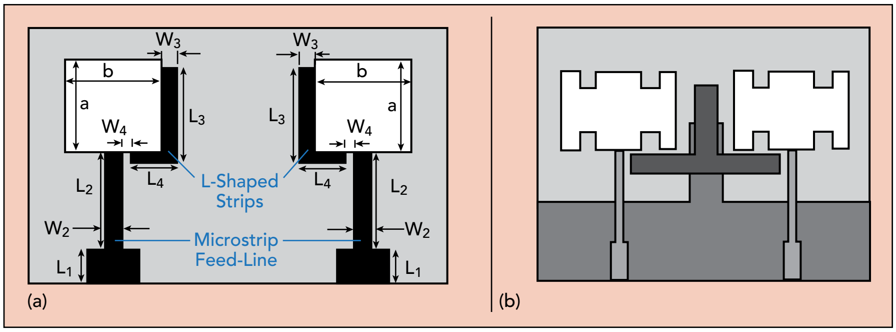
A two-radiator, element-based, MIMO with cross-shaped metallic parasitic strips (MPS) and an inverted T-shaped parasitic strip were designed for improved isolation as well as impedance bandwidth for UWB.[87] The antenna consisted of two DRs, a partial ground with a scissor-shaped DGS, stub and parasitic strip (see ***Figure 13***). Its impedance bandwidth of 104.6 percent covered the frequency band from 3.3 to 10.8 GHz. A cross-shaped metallic strip placed on the RDRA improved isolation, which was greater than 20 dB within the band. Its reported DG was 9.98 dB and ECC was 0.0059.



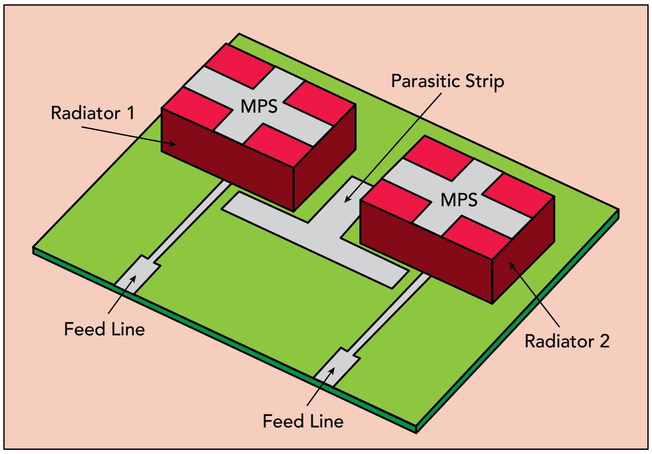
▲ **Fig. 11 (a) Half-cylindrical CP DRA[81] (b) DRA with symmetrically positioned DRs[82] (c) OM-shaped DRA with DGS[83]**

CONCLUSION

The basic geometries of DRAs are rectangular, cylindrical and hemispherical. Various shapes of DRs, DGS, modified grounds, parasitic elements, stubs, arrays and other techniques are used in the examples discussed to achieve UWB performance.



▲ **Fig. 12 (a) Two-port MIMO DRA loaded with L-shaped strip[84] (b) rack-shaped MIMO DRA with inverted T-shaped strip[85].**



▲ **Fig. 13 RDRA loaded with cross-shaped MPS.[87]**

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WHITE PAPER

Ultra-Wideband (UWB) Enables Smart Factory of the Future

Introduction

Micro-location is essential to digitalizing industrial operations through Industry 4.0, smart factory and LEAN initiatives. Process optimization and safety – the two prime considerations to most industries – become more informed through tying who, what, when and where to people, tools, supplies, goods, machinery and events – in real-time.

Current location-based technologies – GPS, Wi-Fi, and **Bluetooth®** Low Energy – cannot achieve micro-location at the precision industry requires. GPSs under ten-meter precision enabled an explosion of retail e-commerce and allowed us to dump those big map books; Wi-Fi helped nail down even finer location precision; and Bluetooth Low Energy locates within a few feet in ideal conditions. But industrial and business applications need finer precision and much higher reliability.

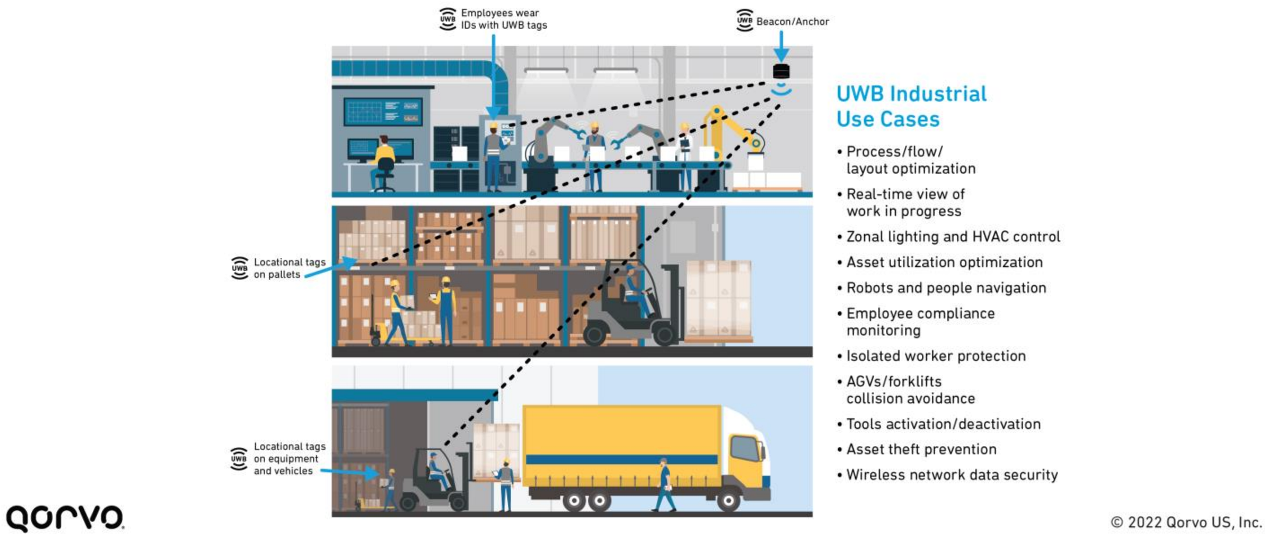
Micro-location in Industrial Settings

UWB technology's centimeter-scale precision has enabled a level of location and communications unmatched by these previous technologies. It is the driving technology behind *micro-location* services, where radio anchors locate tags within as little as a few centimeters. Micro-location delivers information in real-time and allows analytics systems to measure, analyze and alert – instantly. Consider these scenarios with UWB technology in place.

- Process flow – in a production workflow where materials are inches from each other, strategically placed UWB tags and anchors can track material, goods, processes and tasks across the entire production process, while updating production systems that measure and calculate efficiency in real-time and identify – and even predict bottlenecks.
- Asset utilization and retrieval – a tagged tool or other asset in a plant can be quickly located, and workers guided to it through high-precision plant maps on handheld devices.
- Material control – tagged equipment, medical devices and sensitive items, such as controlled substances in hospitals, can be located anywhere in a building and their usage clearly monitored.
- Safety – tags on machinery, such as robotic arms and forklifts, and employee badges, allow automated safety systems to track proximity to sub-meter precision and real-time accuracy to stop machinery and alert personnel when a safety zone violation occurs.
- Emergency events – UWB tags in employee badges identify each worker and location to either be sure they are out of danger or where to direct rescue operations. With location information passed to rescue personnel enroute to the site, they can be more strategic when they arrive onsite, possibly eliminating precious seconds to save a life.

And there are many other potential use cases that enhance efficiency and effectiveness, production, safety and security (Figure 1).

Figure 1. UWB in industrial environments can enhance efficiency and effectiveness, productivity, safety and security.



How UWB Can Be So Precise

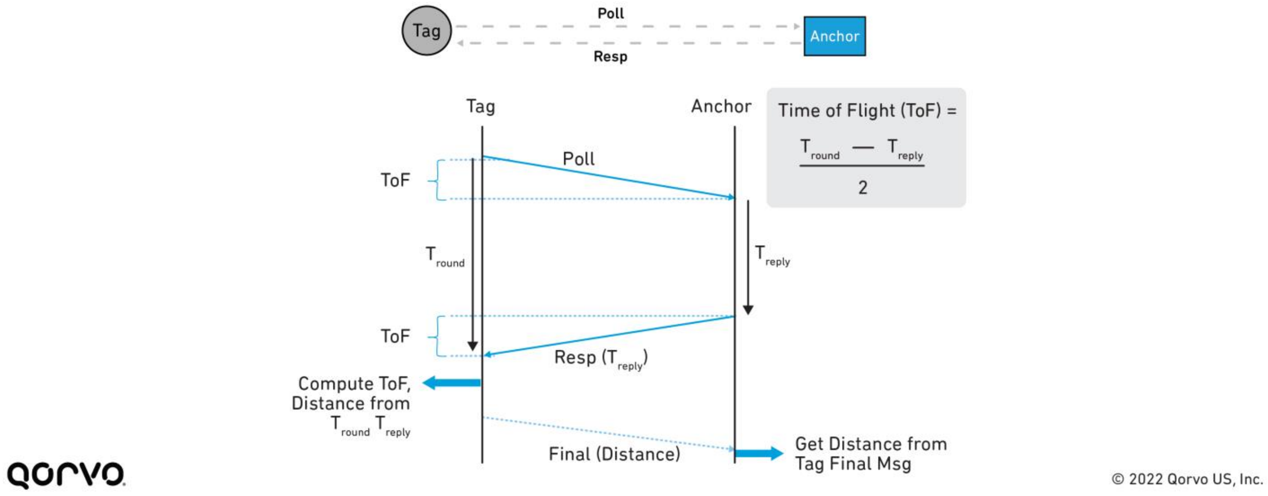
Industrial and commercial sites are full of large objects – often metal and possibly moving – such as walls, vehicles and machinery, and electrical signal noise. GPS signals often cannot effectively penetrate industrial structures. And narrow-band Wi-Fi and Bluetooth Low Energy radio energy is often attenuated, reflected as multi-path signals or lost in such environments as the distance from objects increases.

UWB is impervious to the challenges of narrow-band Wi-Fi and Bluetooth Low Energy for ranging and location. In communicating between anchors and tags, UWB radios use very low signaling energy spread out over a greater bandwidth with much faster pulse rise and fall times than narrow-band signals (Figure 2). This approach helps ensure signal integrity, reduces the impact of reflections and noise spikes, and contracts the number of components needed for an infrastructure.

Figure 2. UWB is impervious to noise spikes that can affect narrow-band signals, degrading location capabilities.

UWB uses time of flight (ToF) to measure the distance to a tag (Figure 3). Multiple methods for ToF improve the accuracy of measurement and reduce infrastructure costs. Two-way ranging (TWR) and time difference of arrival (TDoA) ranging methods eliminate the impacts that reflections from walls and machinery (multi-path) have on signal strength. Other ranging methodologies in UWB include phase difference of arrival (PDoA) and reversed TDoA (RTDoA), offering benefits for various types of deployments. These different ranging techniques can be used to identify the distance and direction (vector) to an object.

Figure 3. Calculating distance with ToF.

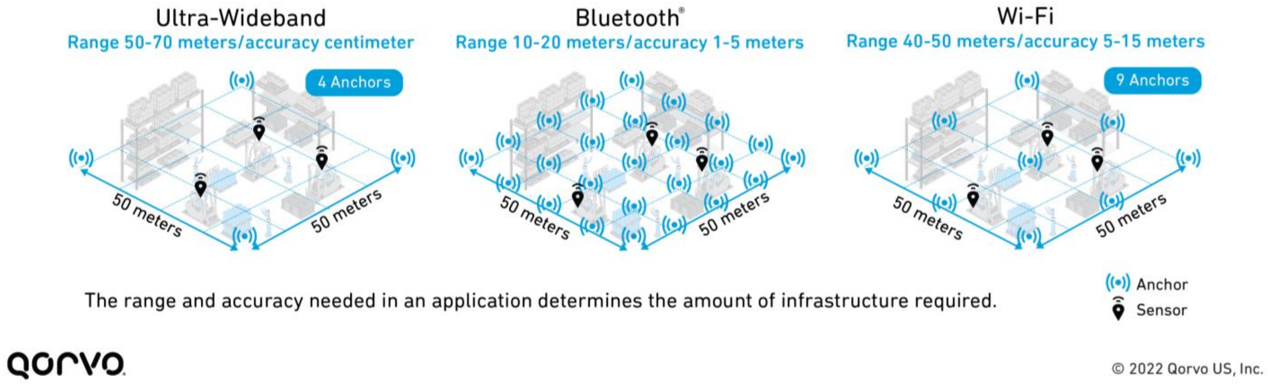


Depending on the need for micro-location services, different infrastructures can be deployed, different ranging techniques implemented and the location can be determined (computed):

- Within the tag itself for navigation purposes, a method called downlink TDoA (DL-TDoA).
- Within the infrastructure when a centralized platform needs to track tags.

With its signal integrity and ranging abilities, UWB can cover greater distances than other location and ranging technologies (Figure 4). Strategically placed anchors can report different ranges and vectors to a tagged object, locating them in two- and three-dimensional space with great accuracy.

Figure 4. UWB's greater range and accuracy enable micro-location with fewer components, reducing infrastructure.



A UWB Ecosystem to Support Industry and Beyond

The FiRa (fine ranging) Consortium (**www.firaconsortium.org**) defines specifications and provides certifications for UWB devices. The consortium supports the enabling of the UWB ecosystem and interoperability between UWB and other technologies to enable micro-location services for industry and consumers.

The upcoming new FiRa standard (FiRa 2.0) opens the door to greater applicability for micro-location using UWB. It includes specific functionalities that target industrial applications. It will help enable greater interoperability between consumer and industrial devices (UWB is already deployed in modern smartphones). And it is seen as the first step toward including UWB in large-scale, real-time location systems (RTLS), enabling indoor and sub-meter accuracy in mapping services, such as Google Maps.

While FiRa 2.0 will help enable new use cases, the ecosystem anticipates a breakthrough of DL-TDoA solutions. These solutions will enable micro-location navigation indoors with privacy as only the mobile device will know its own position. Such services will soon become available to UWB-enabled smartphones. The deployment of relevant UWB DL-TDoA will be up to the OEMs of infrastructure devices, such as access points that combine UWB anchors with Wi-Fi access points. But also, lighting and other fixed power devices that can be installed in public or private facilities could trigger DL-TDoA and activate when a UWB-enabled device is nearby.

You can learn more about UWB in other articles in this document and on the FiRa website. UWB solutions are already being deployed in a variety of use cases. The following describes some of these.

European League of Football

A football (soccer in the U.S.) field is typically 105 by 68 meters (115 by 74.4 yards). That is 7,140 square meters (nearly 8,540 square yards). Sports stadiums often do not have a roof. This makes placement of UWB anchors other than around the field impractical. **Noccela**, a micro-location solution provider, developed a UWB ranging solution using both TWR and TDoA ranging methods. Their solution can cover up to 500 square meters (nearly 600 square yards) per anchor with as fine as two-centimeter (0.8 inch) accuracy of objects moving at up to 60 km/h (over 37 mph). Using UWB, they can cover a soccer field with 16 anchors, strategically placed around the field perimeter while delivering high, 3D positional accuracy.

Used in athletics with sports analytics software, micro-location allows teams to optimize performance. But for the European League of Football (ELF), the solution was instrumental in Europe during the pandemic to keep teams playing. While Covid-19 was raging and before the wide availability of vaccines, players and coaches in the ELF still had work to do. But they needed a way to practice in proximity with other players and team personnel while tracking both social distancing and contact among members. Without the granularity of tracking of individuals, a breakout of Covid-19 could shut down an entire season.

The UWB-based micro-location solution offered point-to-point tracking to upload member tag positions through anchors. The tracking software then recorded where attendees (tags) were at any time. If a case of the disease was reported amongst the team, managers would know immediately all potentially affected members and isolate them without shutting down.

VELUX Modular Skylights

VELUX Modular Skylights are manufactured in Ostbrirk Denmark. When the company wanted to modernize operations and digitalize the manufacturing process across 2,304 square meters (2,756 square yards) in their production sites, they implemented a digital twin of the factory floor utilizing **Sewio's** RTLS solution. The digital twin would monitor, track, trace and analyze their entire manufacturing workflow. A critical input to the data was RTLS tracking of people and machines, which included forklifts and automated worktables (AGVs) that moved the work in process (WIP) through the work site and adjusted to accommodate each worker's height.

The solution incorporated 12 UWB anchors and 59 UWB tags to track objects. For each step in the manufacturing process, the AGV delivers the WIP to a station, where a skilled worker performs the necessary task. The RTLS identifies the nearest worker and adjusts to the appropriate height, creating an ergonomic and safe work environment. If a worker is not present, the system alerts the nearest skilled worker to complete the task. Data from the movement of materials and personnel is processed to provide managers with the real-time information they need to understand the productivity of the plant. The data is also used to manage machine maintenance. With the UWB-based RTLS in place, VELUX Modular Skylights was able to:

- Increase productivity by 10 percent through better shop-floor management.
- Boost performance on maintenance activities by 50 percent.
- Decrease WIP by 10 percent.

SEG Automotive

SEG Automotive manufactures motors and starters for nearly every automotive manufacturer in the world. The company's manufacturing floor and warehouse are in two buildings with a ten-minute truck drive to deliver raw materials from the warehouse to the manufacturing facility. Picking orders were fulfilled manually using a just-in-time process. Manual operations were prone to errors, costly in terms of person-hours, and delayed data entry to the ERP systems, which limited visibility of inventory and handling.

SEG Automotive wanted to replace the manual process with a fully digital, real-time asset booking and tracking system. A key challenge was the closeness of the truck gates. Ensuring materials were delivered to the correct gate required an accuracy of 30 cm.

The deployment of **Sewio's** RTLS took only four months and required 40 anchors across 2,000 square meters (2,392 square feet) and 600 tags to track metal pallets. After integrating the UWB-based RTLS with the existing data tracking and analysis system, SEG automotive achieved the following:

- Eliminated human picking errors.
- Shortened lead times by 50 percent.
- Moved 15 percent of employees to less routine work.
- Continuous track and trace of material as it moved throughout the warehouse.
- Easy scalability to track more objects as needed and expand to the manufacturing site.

Budweiser Budvar Brewery

While shipping its beer to 76 countries around the world, Budweiser Budvar brews its beer in only one city in the world – České Budějovice (Budweis) in the Czech Republic. Producing ten different kinds of beer with dozens of languages on labels created 360 combinations of products to distribute. The warehouse stored over 20,000 pallets of two different sizes of containers, some inside and some in an outdoor facility.

They had managed their inventories using a passive RFID system with RFID anchors on the forklifts and up to 10 tags per tracking position, which were located only inside the warehouse. The legacy solution presented reliability problems, was costly to maintain and scale, caused operational inefficiencies, and did not always provide true location of the goods. Without accurate, real-time tracking, they could not utilize up-to-the-second data for spaghetti diagrams, heat maps and other analytics.

Installing **Sewio's** UWB-based RTLS system took only a month to install, plus another six months to integrate with the rest of their ERP systems. To cover 15,000 square meters (17,940 square yards) for both inside and outside warehouse facilities, they deployed 70 anchors and equipped 15 forklifts with tags that provided 30 cm positional accuracy. The installation and integration resulted in the following:

- 19 percent better uptime compared to the legacy RFID system.
- 19 percent better warehouse utilization.

UWB technology enables delivering the highest accuracy of micro-location services to industry. The technology is already being deployed across multiple industries with significant benefits to business operations. The ecosystem of UWB technology and solution providers, working with FiRa, are paving the way for innovative micro-location services to come.