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IEEE 802.15.4 IR-UWB: A Technology Precisely Positioned for Adoption

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(Invited Paper)

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ABSTRACT This paper provides an overview of impulse radio ultra-wideband (IR-UWB), focusing on the low data rate version standardized in IEEE Std 802.15.4. It reviews the current state of standards-based IR-UWB adoption, including use cases targeted by industry alliances. Next, the fundamentals of IR-UWB signaling and key characteristics enabling accurate localization are summarized. Recent enhancements to IEEE Std 802.15.4 related to ranging, sensing, and data communication with IR-UWB are highlighted. Emerging application scenarios in digital vehicle access, indoor navigation, and vital sign monitoring, among others, are presented as indicators for future UWB proliferation, followed by an outlook on ongoing IEEE standardization efforts. Finally, the ability of IR-UWB's low transmit power levels to enable spectral coexistence is discussed in the context of creating new sharing paradigms for congested midband spectrum.

INDEX TERMS Impulse radio, range finding, ultra-wideband technology, wireless communication, wireless sensing, location services, low latency communications, spatial reuse, spectral reuse, positive coexistence.

I. INTRODUCTION

Ultra-Wideband (UWB) is a technology that has been around for decades and has seen a major uptake in large volumes in the last 5 years. Regulators have allowed for the use of this technology in unlicensed spectrum both globally and regionally around the world. Impulse radio (IR)-UWB, and in particular as specified in IEEE Std 802.15.4 [1], has grown rapidly in adoption over the past several years with significant traction in the consumer, commercial, industrial and automotive spaces. This paper explains IR-UWB as specified in IEEE Std 802.15.4, including its current state, a technology overview/foundation, what to expect next, and current regulatory concerns and challenges. The primary focus of this paper is the high rate pulse repetition frequency (HRP) variant defined in IEEE Std 802.15.4, that is being predominantly adopted by the automotive and consumer industries. We provide an overview of the current state of IR-UWB adoption and industry ecosystem, an overview of current technology. We then look at the future of UWB, with applications being developed and deployed at the time of this writing. We also discuss some regulatory concerns related to UWB spectrum and sharing of spectrum.

II. CURRENT STATE OF IR-UWB

Before giving a current state of IR-UWB, it's helpful first to review a brief history of the evolution of IR-UWB in IEEE Std 802.15.4, see also Fig. 1. The IEEE Std 802.15.4a amendment [2] first introduced IR-UWB into the standard, published in 2007. That amendment defines the use of an IR-UWB Physical Layer (PHY) operating at frequencies of 3 GHz to 5 GHz, 6 GHz to 10 GHz, and less than 1 GHz. The amendment defines UWB channels of nominally 500 MHz bandwidth and 1.3 GHz bandwidth. The UWB PHY supports an over-the-air mandatory data rate of 851 kb/s with optional data rates of 110kb/s, 6.81 Mb/s, and 27.24 Mb/s.

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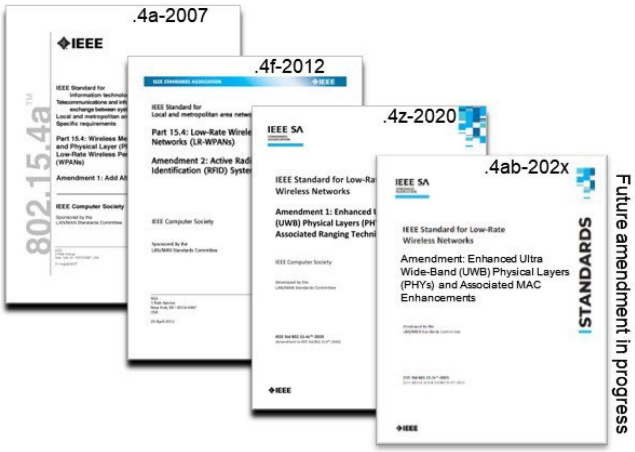

FIGURE 1. Evolution of UWB in 802.15.4.

The IEEE Std 802.15.4f amendment published in 2012 [3] introduces two new PHYs, a minimum shift keying (MSK) PHY and a low rate pulse repetition frequency (LRP) UWB PHY. The LRP UWB PHY supported data rates from 31.25 kb/s to 1 Mb/s. This amendment targeted enhancing capabilities to support radio frequency identification (RFID) and real-time location services (RTLS).

The IEEE Std 802.15.4z amendment [4] in 2020 introduces concepts to enhance the UWB PHYs with additional coding options and improvements to increase the integrity and accuracy of ranging measurements and support control of time-of-flight ranging procedures and ranging-related information exchange between the participating ranging devices. The enhancements in this amendment were defined to meet the needs of a wide set of applications where the integrity and accuracy of distance measurement were important.

The IEEE P802.15.4ab amendment project [5], currently under development, introduces further enhancements to build on the IEEE Std 802.15.4z amendment. Goals for this project include aligning the standard with leading consortia/market needs. Dozens of participants from industry-leading companies are contributing to and collaborating on this effort. Enhancements being worked on in this amendment include the following:

Ranging
- Link budget improvements
- Improvements to accuracy, precision and reliability

Sensing
- Pulse shape improvements
- Channel impulse response reporting to support multi-static sensing
- Better support for presence detection, environment mapping and other uses

Data
- Higher data rates for shorter transmission duration and power savings
- Channel coding and packet format improvements for robustness

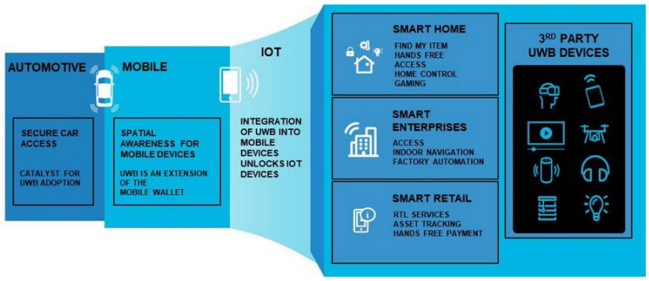

FIGURE 2. Consumer evolution of UWB adoption (figure courtesy of NXP).

- Additional options for even greater power savings
- Protocol enhancements to support very low latency, low energy communications

Interference mitigation techniques to support
- Greater device density
- Coexistence in the presence of other users

A. GENERAL ADOPTION PROGRESSION OVER TIME

The applications of IR-UWB technology continue to grow. Initially used in industrial spaces such as asset and equipment inventory and tracking, this was followed by use in commercial spaces where IR-UWB is used for applications such as pallet tracking. IR-UWB is now increasingly being adopted for consumer markets, starting with automotive and mobile handsets, with expansion into the Internet of Things (IoT), which includes smart homes, smart enterprises, smart retail, and 3rd party UWB devices (see also Fig. 2).

B. CONSORTIA AND USE CASE ADOPTION

Several industry consortiums have adopted the IR-UWB technology defined in IEEE Std 802.15.4 for use in their standards. Some of the more notable consortia include the following:

Omlox
- Omlox [6] is most notable for its use in asset tracking, particularly pallet tracking. It has the potential to take advantage of work currently being done in IEEE Std 802.15.4.

CCC
- The Car Connectivity Consortium (CCC) [7] is well known for its standardization of wireless entry into automobiles (digital key). Its 3rd generation protocol relies heavily on the IR-UWB technology developed in IEEE Std 802.15.4. CCC is working on fully releasing its 3.0 Specification, including Certification for UWB support.

FiRa Consortium
- The Fine Ranging (FiRa) Consortium [8] has and continues to define use cases (see Fig. 3) and develop technical specifications to support those use cases, exploiting the benefits of the IR-UWB technology defined in IEEE Std 802.15.4. FiRa has recently been working on additional profiles along with multiple ranging techniques to support various use cases.

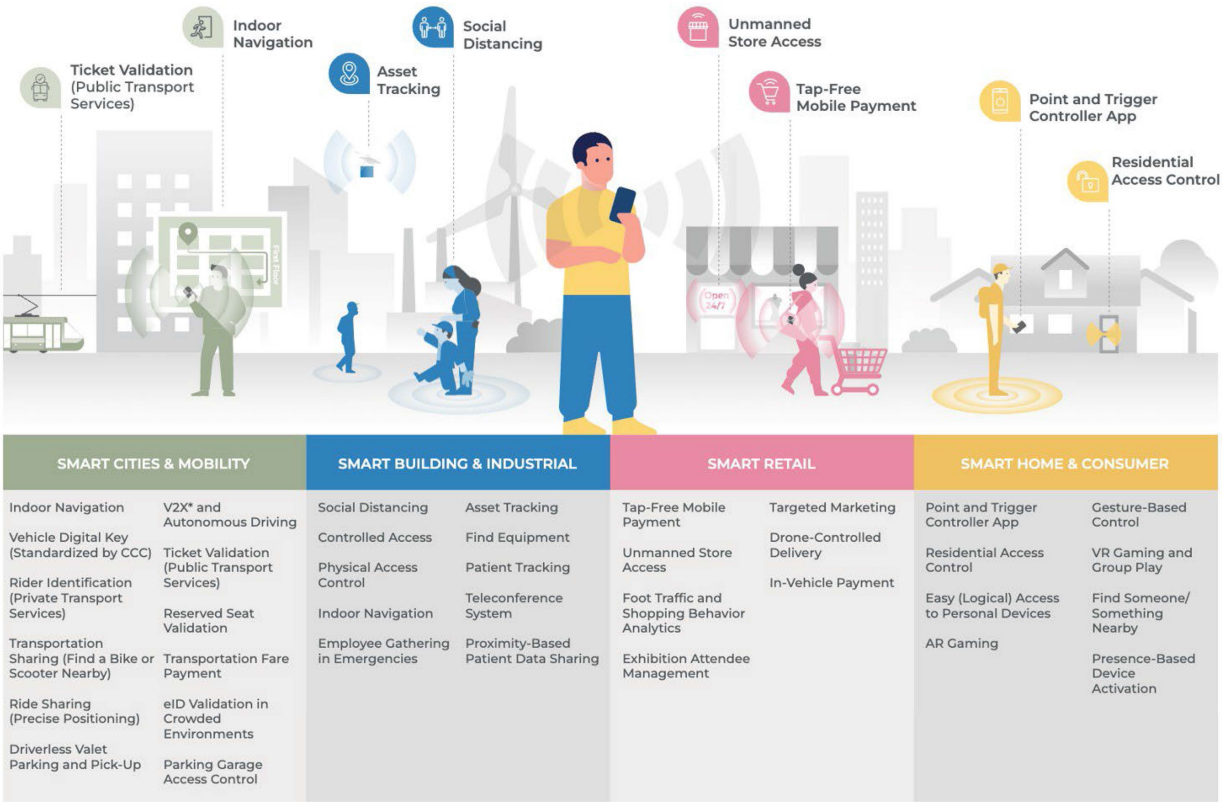

FIGURE 3. **UWB application use cases (figure courtesy of FiRa).**

CSA - Aliro

- Aliro [9] is a standard under development in the Connectivity Standards Alliance (CSA) aimed at transforming how users unlock doors or other entry points using their mobile device or wearable – targeting single-family homes, multi-family homes, commercial and enterprise spaces. The Aliro Specification is targeting release in the 2025 timeframe.

UWB Alliance

- The UWB Alliance [10] proactively shapes US and international UWB spectrum management and rule-making, actively working with many member companies and collaborating with several consortiums listed here. The Alliance promotes spectrum sharing through positive coexistence, conducting studies, and developing and sharing information on effective coexistence strategies.

AES

- In response to growing industry interest and activities around UWB technology for audio applications, the Audio Engineering Society is developing a new standard for UWB high-resolution, low-latency audio interface. The AES Standards group, SC-02-02-B [11], is under the Working Group on Digital Audio Interfacing. The standard will enable leveraging the expertise and standards of AES into a broad range of audio applications. The group is basing the UWB air interface defined in IEEE Std 802.15.4.

III. TECHNOLOGY OVERVIEW

A. UWB REGULATORY DEFINITION

In 2002, the Federal Communications Commission (FCC) in the US was the first administration to issue UWB regulations [12]. Those regulations allowed unlicensed transmissions between 3.1 and 10.6 GHz provided that the signal occupied a 10 dB bandwidth larger than 500 MHz, or had a fractional bandwidth (B_{frac}) of at least 20%:

$$B_{frac} = \frac{B}{f_c}$$

where B is the occupied bandwidth, and f_c is the center frequency.

When first envisioned for commercial application, there was no available unlicensed frequency band with 500 MHz of contiguous spectrum in the midband frequency range. To prevent interference with the incumbent spectrum licensees, the regulations limit UWB operation to a very low mean power spectral density (PSD) of −41.3 dBm/MHz, equivalent to the limit for unintentional radiation of 500 microvolts/meter measured at 3 meters. Since this is a mean power spectral density limit, interference from very short, infrequent, high-powered pulses could still occur. The regulations also include a peak power limit of 0 dBm per 50 MHz to prevent that.

These constraints represent a defining characteristic of UWB technology. As shown in Table 1 and illustrated in Fig. 4, UWB operates at orders of magnitude below the power levels permitted for other conventional radio signals such as

TABLE 1. Typical Power Limits

Technology	Global Frequency Bands	Typical Regulatory Power Limits		
		Power Spectral Density (PSD)	PSD, mW	Peak power, mW
Bluetooth, RLAN	2.4 GHz	8 dBm/3 kHz	6.31	1000
RLAN	5 GHz, Lower 6 GHz Low power indoor (LPI)	5 dBm/MHz	3.16	1000
UWB	6 GHz to 8.5 GHz	-41 dBm/MHz	0.000079	1

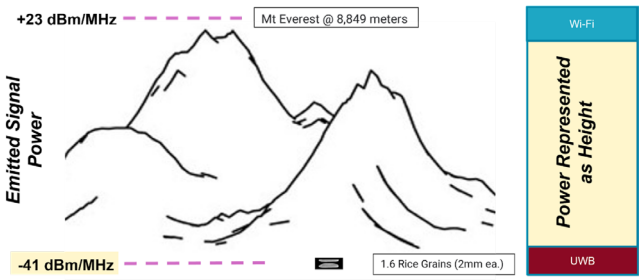

FIGURE 4. Comparison of UWB and Wi-Fi power spectral density.

Bluetooth and Radio Local Area Network (RLAN) under current North American regulations.

In addition to being non-interfering, UWB also operates on a non-protected basis, meaning that it cannot claim protection from harmful interference from other spectrum users. UWB also operates on an unlicensed basis, like Wi-Fi and Bluetooth, so there is no need for expensive spectrum licenses to deploy an ultra-wideband system.

Most countries have since introduced UWB regulations. While variations exist, they all share the unlicensed operation on a non-protected, non-interfering basis and mandate that a certain minimum bandwidth is occupied. While there are differences, there is great similarity in rules worldwide, facilitating a common design that can readily address global requirements.

B. IMPULSE RADIO UWB (IR-UWB)

This paper focuses on the Impulse Radio Ultra-wideband (IR-UWB) technique. The primary characteristic of impulse radio signaling is that it comprises a sequence of discrete pulses rather than a continuous signal. This is illustrated in Fig. 5. The occupied bandwidth is inversely proportional to the duration of the pulse, which for IR-UWB is typically in the order of a nanosecond.

1) RANGING ACCURACY AND MULTIPATH PERFORMANCE

The large bandwidth of UWB allows for short pulses with steep rising and falling edges. These allow ranging systems

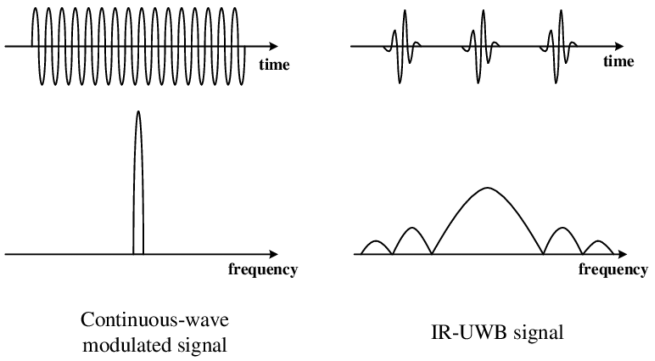

FIGURE 5. Simplified depiction of a continuous vs. IR-UWB signal.

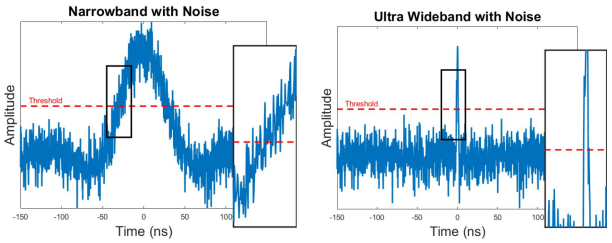

FIGURE 6. Illustration how noise affects time of arrival estimation for narrowband and ultra-wideband signals.

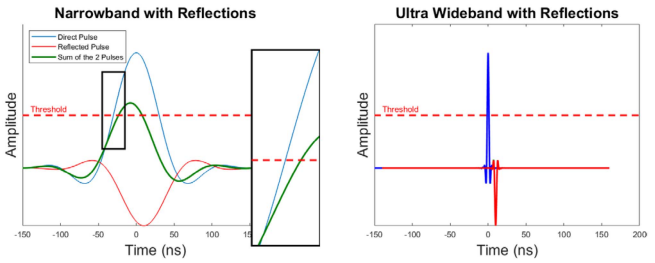

FIGURE 7. Illustration how multipath reflections affect time of arrival estimation for narrowband and ultra-wideband signals.

to accurately detect the signal's arrival time in noise and multipath conditions, as mathematically expressed by the Cramer-Rao lower bound[1] [13].

This can be intuitively shown by Fig. 6. The time axes are scaled such that the ultra-wideband signal has 25 times more bandwidth than the narrowband signal, e.g., 20 and 500 MHz, respectively. The noise power in both subplots is the same. Finding the time of arrival is shown conceptually as comparing to a threshold. While the noise adds uncertainty about when the threshold is crossed in the narrowband case, the steep rising edge dramatically reduces that uncertainty in the ultra-wideband signal case.

The advantages extend to multipath environments as well. Fig. 7 shows how multipath gives rise to overlapping pulses for the narrowband signal, leading to a change in the slope of

[1]The Cramer-Rao Lower Bound sets a lower bound on the mean-squared-error of an unbiased estimator as a function of signal-to-noise ratio (SNR).

the rising edge depending on the phase relationship between the two overlapping pulses. In contrast, the ultra-wideband signal's steep rising and falling edges allow both pulses to be resolved individually.

Unlike narrowband communication systems that can suffer from multipath fading, ultra-wideband systems combine the energy from the various multipath components, resulting in higher signal energy at the receiver, making the link more robust. While the slope change makes the time of arrival estimation for the narrowband system more difficult, the ultra-wideband system does not suffer from this complication.

These characteristics directly translate to practical ranging performance. Ultra-wideband, therefore, enables accurate ranging with centimeter accuracy. The simple structure of an IR-UWB signal enables low-cost and very low-energy consumption implementations.

2) TRANSMITTER DESIGN AND MODULATION

Due to the inherently low transmit power, the transmitter design tends to be relatively straightforward. Modulation is mainly time-based, with variations on on-off keying and position modulation. Some simple binary phase shift keying could also be employed if coherent receivers are used.

In both cases, the amplitude does not encode information, so linearity in the analog chain is not critical. In IEEE Std 802.15.4 [1], the UWB modulation orders (bits per symbol) are 1 or 2, with specified pulse position, pulse polarity, and on-off keying modulations. A wide range of data rates are possible. Most recently, the focus has been on moderate rates, from below 1 Mbit/sec to around 100 Mbit/sec.

3) RECEIVER DETECTION METHODS

The transmitter simplicity shifts complexity to the receiver side, where several detection approaches are available. There are multiple ways to detect a pulse in the receiver, with performance tradeoffs.

The simplest method is energy detection, integrating over the expected pulse duration; this technique is called noncoherent reception. A coherent receiver implementation uses energy level and phase information for the highest accuracy in determining range. This can be thought of as comparing a color image to a black-and-white image: the coherent receiver can recover more of the information in the signal, as illustrated in Fig. 8 . Information can be encoded so that either reception method works.

4) SIGNAL INTEGRATION AND SYNCHRONIZATION

Detection is based upon integrating energy from multiple pulses to extract the very low power signal from the channel's noise. To meet peak power and mean power spectral density limits, and to avoid inter-pulse interference from multipath, pulses are spread out in time, producing a relatively low signal duty cycle.

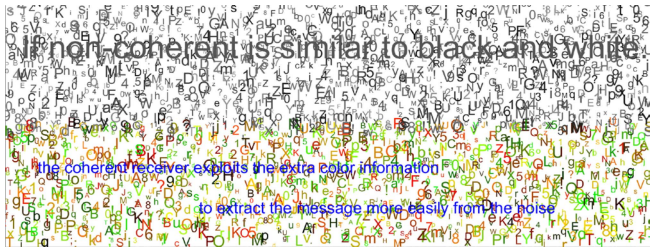

FIGURE 8. Illustration comparing coherent and noncoherent receivers to black and white versus color pictures.

FIGURE 9. Hands-free access can use UWB to protect against relay attacks.

To be able to perform this integration, especially when done coherently, the timing references in the transmitter and receiver need to be close enough together such that the receiver window remains aligned with the energy of the pulse. Initial synchronization is achieved via a preamble sequence that is relatively long compared with the overall packet duration. Synchronization patterns are chosen to be recognized by the receiver, which is looking for this known pattern.

Additionally, a receiver may implement a means to estimate the timing offset and drift relative to the transmitter to improve the duration with which it remains "close enough" and thus increase the packet size that can be received.

5) ENERGY EFFICIENCY BENEFITS

These simpler modulation and detection schemes have significant practical benefits beyond just technical performance. This can enable lower energy consumption than conventional radios. Compared with complex modulations such as high order quadrature amplitude modulation (QAM) combined with

orthogonal frequency-division multiplexing (OFDM), it can be orders of magnitude less energy needed [21].

An implementation currently available for computer-human interface devices and high-definition audio using IR-UWB and non-coherent reception modes has achieved nearly $1/10^{th}$ the energy use as commonly used wireless technology, with higher performance (in these specific uses) [22].

6) INTERFERENCE MANAGEMENT AND COEXISTENCE

While UWB's low power nature creates challenges for receiver sensitivity, several design approaches can address these concerns. Highly sensitive receiver design can present conflicts with the underlay nature of UWB. Receiver designs must provide robustness to interference at every stage of the received signal chain.

Good selectivity in the radio frequency (RF) front end is required to minimize the interference energy from signals outside the UWB channel. Performance can be further enhanced with baseband filtering, using information about the expected signal.

Beyond hardware design, protocol-level solutions also help. Channel access protocols can be used to detect the presence of potential interference and reduce transmit collisions. Another mitigation that can be used is to employ multiple UWB channels so as to avoid or offset the UWB center frequency from potentially interfering systems. Several of these techniques are addressed in the ongoing work of the task group working on the IEEE P802.15.4ab amendment project, as discussed later in this paper.

The combined characteristics of IR-UWB are also very favorable for operating many devices, both UWB and other services, in the same space without interfering. This makes UWB ideal for mixed-technology coexistence. These combined characteristics have made UWB a preferred choice for several key vehicle applications.

C. IR-UWB IN IEEE STD 802.15.4

1) STANDARDIZATION FRAMEWORK

Within IEEE 802, impulse radio physical layer and medium access control provisions are standardized in Working Group 802.15 and published in IEEE Std 802.15.4 and its amendments.

To enable interoperability, the standard defines reference pulse shapes. Transmitters are required to generate pulses that fit certain masks or correlate highly with the reference shape. This ensures receivers can be designed to receive transmissions from different vendors. The spectral mask is given in 16.4.5 of IEEE Std 802.15.4 [1].

2) PACKET STRUCTURE AND SYNCHRONIZATION

The basic packet configuration consists of a synchronization header with repetitions of a preamble symbol followed by a start of frame delimiter (SFD). This structure serves multiple purposes for the receiver.

The repeating preamble symbols allow the receivers to detect incoming transmissions, adjust front-end configurations like gain control, and estimate the carrier frequency offset. Since the energy per individual preamble symbol might be below the noise floor, the receiver is expected to integrate the energy of several preamble symbols. The standard specifies clock offset accuracy to ensure the sampling points don't drift too far during this integration.

Once synchronization is established, the SFD signals the end of the repeating preamble sequence to the receiver such that it can prepare for the reception of the remainder of the packet.

3) PREAMBLE DESIGN AND RANGING

The HRP PHY preamble symbols are ternary Ipatov sequences with perfect periodic autocorrelation irrespective of whether they are received coherently or non-coherently. The perfect periodic autocorrelation properties allow the receiver to estimate the channel impulse response, which is used to support ranging functionality.

However, since the symbols are repeating, the ranging result could easily be tampered with. A malicious person could, for example, use a delay line with a length slightly shorter than the symbol period to insert a false correlation peak just before the direct channel response, which is likely to reduce the estimated distance.

To address this vulnerability, the IEEE Std 802.15.4z amendment added a scrambled timestamp sequence (STS) [4]. This pseudorandom sequence, based on a key that only the transmitter and receiver should know, enables secure channel impulse response estimation and authenticated ranging.

4) DATA TRANSMISSION AND ERROR PROTECTION

Following the synchronization phase, the packet transitions to data transmission. The SFD or STS are followed by a PHY header (PHR), informing the receiver about the format and duration of the payload data coming. Most PHYs protect the header content against errors using a Hamming-based single error correction, double error detection code.

The payload itself supports flexible configuration options. Various payload modulation formats are available based on combinations and variations of position modulation and binary phase or frequency shift keying. Different data rates and noise and interference robustness are achieved by varying the number of active pulses per symbol.

Further phase scrambling is used to whiten the spectrum of the transmitted signal. Forward error correction can consist of convolutional and/or Reed-Solomon based encoding.

5) INTERFERENCE AVOIDANCE

To allow the UWB transceivers to avoid interference, the standard provides several center frequencies and has provisions for performing clear channel assessments. The channel definitions are given in clause 16.4.1 and table 16-27 of the standard [1].

IV. LOOKING FORWARD – WHERE IS UWB GOING NEXT?

A. EXPANSION OF RANGING USE CASES

The IEEE Std 802.15.4z amendment for ultra-wideband defines new wireless capabilities that enable precise ranging and localization between devices with accuracy as high as 10 cm. This includes secure ranging techniques that allow encrypted distance measurements between trusted devices. Various industry alliances and manufacturers are increasingly adopting these capabilities for emerging applications.

1) DIGITAL VEHICLE ACCESS WITH THE IEEE STD 802.15.4Z AMENDMENT

In the automotive domain, the Car Connectivity Consortium, comprising vehicle manufacturers and smartphone vendors, has developed the Digital Key specification (CCC DK 3.0) that allows drivers' smartphones to securely access and start vehicles using high integrity, accurate UWB ranging to verify proximity [14]. Here, the standard defines wireless connectivity to ensure the phone is next to the vehicle before unlocking, with encryption to prevent relay attacks. This digital key technology, running as a mobile phone application, is expected to replace physical keys in the near future as it enables easy sharing of virtual keys and revocation of access [14].

2) EVOLUTION TO HANDS-FREE ACCESS CONTROL

Building on the secure ranging foundations, applications of the IEEE Std 802.15.4z amendment are expanding beyond vehicles into generalized hands-free access control systems. Industry alliances like the Fine Ranging Consortium and the Connectivity Standards Alliance are working to standardize and certify the interoperability of hands-free access to buildings and/or rooms based on proximity detection, as illustrated in Fig. 9. The ultra-wideband sensors verify that the person is physically present next to an access point before allowing entry [15].

3) HANDS-FREE AUTHENTICATION

The capabilities unlocked by the IEEE Std 802.15.4z amendment can continue evolving to enable presence-based hands-free experiences like automatically logging in to computers when the user approaches or pre-approving high-value payments when a customer is detected to be present in retail outlets, hotels, and rental stations. As costs lower and standardization improves, such ambient user experiences can leverage secure ranging to authorize privileged actions only when appropriate proximity is verified via UWB [16].

4) BUILDING ON THE MOBILE PLATFORM

With UWB hardware integration into smartphones based on interoperable IEEE and FiRa standards, precise indoor location is now a widely accessible commodity that opens up new application possibilities. In the near term, the availability of precision location determination is being used to power accurate indoor navigation in venues like airports, malls, and hospitals. This augments Global Positioning System (GPS), which is only available outdoors, as well as provides significantly finer resolution than GPS signals (centimeters compared to meters).

Precision location knowledge further enables innovative controls and interfaces like point-and-control, where touchscreens can change functionality depending on which device the smartphone is pointing at within the room based on UWB ranging measurements. Early applications include contextual controls for smart home devices, interactive screens, and digital signage that adjusts content based on who is standing where.

As UWB adoption spreads, standards like the IEEE Std 802.15.4z amendment mature to ensure interoperability across smartphone vendors, and costs continue to decrease, the possibilities are abundant for startups and enterprises to leverage precise positioning in creative ways yet to be discovered.

B. SENSING BREAKTHROUGH

The short pulse duration used by IR-UWB is useful for measuring the impulse response of the RF channel, which varies based on physical conditions in the area of the transmitter and receiver, such as the presence of people. Furthermore, the impulse response varies based on the type of object present so that a child can be differentiated from a bag of groceries, for example.

Ultra-wideband radar technology has evolved from its initial applications in professional and industrial imaging of structures and materials. Similar to ranging, a shift towards widespread consumer use is about to happen. The fine resolution capability of UWB, with its large bandwidth, now lends itself to the accurate detection of minute motions associated with vital signs, motion analysis, and occupancy.

1) SENSING VITAL SIGNS

UWB sensing systems are now being applied for contactless monitoring of vital signs such as breathing and heart rate with medical-grade accuracy [17]. These are combined with motion detection for sleep analysis and baby monitoring applications. Similar technology is used to provide senior independent and assisted living and used in clinical care settings. In consumer applications, these sensors start to be integrated into laptops to provide wake-up functionality [18].

2) CHILD PRESENCE DETECTION

A key upcoming application is child presence detection in vehicles using UWB to prevent hot car deaths, see Fig. 10. UWB sensors placed in seats can reliably detect children left accidentally in seats by monitoring breathing and movements. Such systems can extend to become part of digital vehicle access platforms by combining secure ranging for keys with child presence alerts [19].

FIGURE 10. UWB radar technology will be used in child presence detection applications.

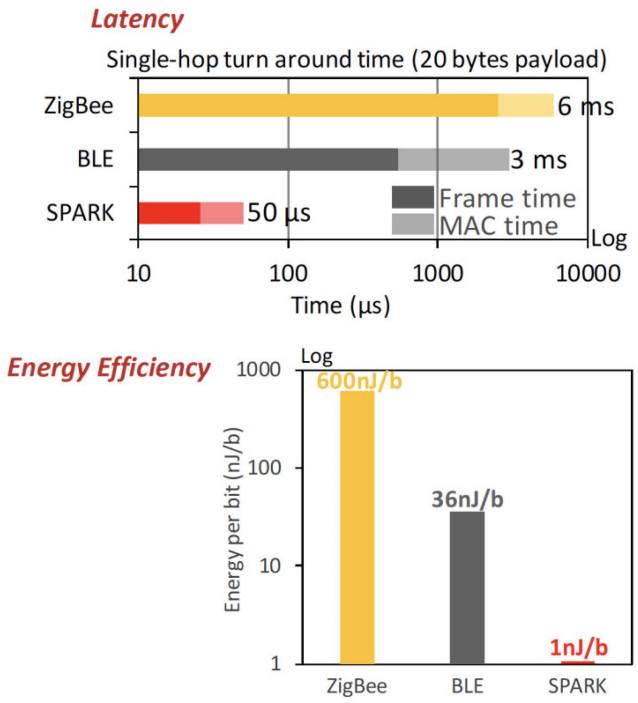

FIGURE 11. Comparison of UWB latency and energy efficiency for streaming [23].

3) AUTOMOTIVE USE CASES

The use of UWB as radar is also finding automotive applications like guiding wireless charging alignment between electric vehicles and charging pads by monitoring distance. It further assists self-driving vehicles by imaging the environment for reliable object detection complementary to LiDAR and cameras. UWB installed on cars can also be used for high-accuracy positioning and mapping.

C. RETURN OF COMMUNICATION APPLICATIONS

Ultra-wideband technology initially generated interest for high-throughput wireless communication links in the 2000s era. Despite limited adoption then, UWB is being re-evaluated given its ability to provide low latency, higher capacity connections compared to prevailing narrowband radios like Bluetooth Low Energy (BLE) but at similar power budgets.

1) HIGH-FIDELITY WIRELESS AUDIO

UWB is able to offer cable-like quality for next-generation wireless lossless multi-channel audio streaming. The robustness in multipath environments makes it particularly well-suited for vehicle cabins. Using power consumption levels like BLE, UWB is able to provide higher throughput at lower latency (see Fig. 11). AES is currently developing an interoperability standard to provide lossless audio streaming using UWB.

2) MULTI-LINK CONNECTIONS FOR EXTENDED REALITY

Another developing use case exploits UWB's concurrency to maintain multiple links with low latency guarantees simultaneously. This aids extended reality scenarios using multiple accessories that require a reliable, high-performance wireless backbone for streaming telemetry, tracking data between multi-node AR/VR rigs, and edge computing resources at scale [20].

D. STANDARDIZATION – IEEE P802.154AB AMENDMENT PROJECT AND BEYOND

1) OVERVIEW OF THE AMENDMENT PROJECT

While much of the current uptake of UWB is based on the IEEE Std 802.15.4z amendment, the 802.15 standardization working group is developing the next-generation UWB standard. This is underway in the IEEE P802.15.4ab amendment project to further enhance the Ultra-Wideband physical layers (PHYs) and medium access control (MAC) sublayer.

2) ENHANCED RANGING CAPABILITIES

Predictably, some of the effort focuses on the ranging capabilities of UWB.

a) Multi-millisecond ranging: A multi-millisecond extension will improve the link budget of ranging operations. Since the regulations limit the energy that can be transmitted per millisecond, this technique combines several fragments transmitted in different milliseconds to improve the link budget.

The fragments themselves could consist of scrambled timestamp sequences if security is a concern or of complementary set based ranging sequences otherwise. This approach also can improve coexistence by reducing the duration of a given transmission, providing more space between fragments.

b) Narrowband companion PHY: A tightly coupled narrowband companion PHY simplifies frequency offset synchronization. At the MAC level, this is reflected in the 'mirroring channel' provisions, where the narrowband radio is used for the discovery and control of the UWB radio.

This companion approach addresses a fundamental challenge in UWB receiver design. Since the UWB signal is transmitted at such low power, the receiver's complexity stems from detecting such a weak signal buried below the noise floor. Narrowband assist helps by mandating that the narrowband and ultra-wideband signals are derived from the same frequency source, such that the UWB radio can use the more efficient coherent detection once it is informed over the narrowband channel that a ranging packet is coming.

Using the narrowband assist radio also simplifies discovery of devices, making initial connection establishment more efficient.

c) Sensing support: For the first time, the standard will also include provisions to support sensing. This represents a significant expansion of its capabilities beyond ranging and communication.

Here, the pseudo-random scrambled time-stamp sequences from the IEEE Std 802.15.4z amendment are replaced by sensing segments consisting of Ipatov sequences.

While only the first path is important for ranging, sensing information could be located anywhere in the channel impulse response. The standard, therefore, specifies a Kaiser based reference pulse without post-cursors to minimize interference between the pulses.

At the MAC level, provisions for reporting the channel impulse response or extracted sensing features are also included.

3) DATA COMMUNICATION ENHANCEMENTS

Beyond ranging and sensing, optimizations for data communications are being added to address diverse application needs.

a) High-rate extension: One enhancement extends the data rates of the current HRP PHY by shrinking the number of pulses per symbol and increases the resistance to noise by including the Low-Density Parity-Check (LDPC) coding scheme used in 802.11n but without the puncturing. This PHY aims to provide data rates up to almost 125 Mbps.

b) Energy-optimized PHY: Another enhancement provides a PHY optimized for extremely low energy consumption, enabling either coherent or non-coherent detection and usable with inexpensive, less stringent timing references. While the maximum data rate is more moderate, about 20 Mbps, power-optimized implementations are able to reach 1 nJ/bit.

4) IMPROVED CHANNEL ACCESS

To complement these physical layer improvements, the MAC layer is also being enhanced. A proposed spectrum sensing based deferral scheme replaces the classical channel access with exponential back-off in listen before talk with a linear back-off and adds a fallback to Aloha limit channel access latency.

V. SPECTRUM CONCERNS

A. THE VALUE OF EXTREMELY LOW TX POWER

1) SPECTRUM IS A LIMITED RESOURCE

Spectrum is a resource that exists in limited quantities. While innovation continues to expand the usability of RF spectrum to ever higher frequencies, there are practical reasons why what we call "midband", generally considered below 15 GHz, is in high demand.

This creates increasing pressure as more and more users are trying to work in the same or nearly the same frequency ranges.

Historically, spectrum management has relied on two primary approaches. Traditional models of managing spectrum include exclusive use via licensing and sharing via licensed exempt users who contend for use.

In recent decades, other models of sharing have come into use that allow a degree of combining licensed and unlicensed access: methods that generally rely on coordination through a centralized database and spectrum access system that identifies when unlicensed users may (or may not) have access to frequency ranges used by licensed or priority services.

For unlicensed spectrum, effective sharing requires different strategies. The most common means of "sharing" in unlicensed bands is through avoidance, either via coordination or other means, such as sensing the desired channel for interfering signals.

The implicit assumption is that two transmitters using the spectrum will result in failure of both transmissions. This creates an interference footprint – an area around the transmitter in which it will disrupt communications other than the desired link.

This concept is especially important when Wi-Fi and UWB are sharing a frequency band. Since Wi-Fi transmissions are generally at a much higher power level, the interference footprint considerations become critical for ensuring both technologies can operate effectively in the same spectrum.

2) A NEW PARADIGM FOR SHARING

The good coexistence and extremely low transmit power provide for very high spectral and spatial reuse. This results in high efficiency when considering the total value from each MHz – more than just bits per second.

With UWB technologies, the extremely low power levels result in very small impact footprints. In general, a UWB transmitter will have zero impact on other technologies more than a few cm distant as the extremely low TX power, typically −41.3 dBm/MHz, quickly falls below the receiver's desired signal level and sensitivity.

For reference, this is at (or below) an energy level, which is allowed as unintentional radiation from electronic devices (e.g., anything with a processor or digital logic). This makes UWB an extremely good neighbor, as it hardly, if ever, is noticeable.

A concrete example illustrates this minimal footprint. UWB operating at −41.3 dBm/MHz would appear in a 20 MHz

Wi-Fi channel as a signal at −28.3 dBm. Assuming a free space path loss of 70 dB at 10 meters for 6 GHz operation, the UWB signal would be received at −98.3 dBm by the Wi-Fi system, only 3 dB above the thermal noise limit.

UWB achieves operation at such low TX powers by using wide bandwidth and sensitive receivers. In contrast, TX power levels used by other wireless technologies are much higher. For example, a Wi-Fi link may be at 100000 to 1000000 times higher power. A mobile base station can be higher still, several more orders of magnitude.

Higher power means larger impact areas that are inherently less capable of sharing. This fundamental difference in power levels has significant implications for spectrum utilization.

The extremely low interference footprint allows UWB to recycle spectrum: UWB can underlay other services – operating simultaneously with other services without impacts. This also means that UWB can support a much higher density of users because many more users can be operating simultaneously.

The high spectral reuse inherent in extremely low TX power is augmented by an important characteristic of UWB signal design. With the most popular UWB signal design, simultaneous transmission does not lead to transmission failure. This fundamentally changes the assumptions regarding the sharing of the spectrum.

This enables a new paradigm for sharing in which simultaneous use of the channel is possible. Sharing through coexistence can increase overall capacity and realize value for spectrum resources. Combined, this means more devices and more diverse uses of the spectrum are possible.

However, coexistence presents challenges when technologies with vastly different power levels share spectrum. Higher power signals occupy (and can block) the channel over large areas. When operating in the presence of transmitters using substantially higher TX power levels, as noted above, Sensitive receivers such as UWB may be overwhelmed (saturated) by those massively powered signals. This further degrades the potential for sharing.

Expanding the use of very and extremely low-power radio systems can dramatically increase spectrum reuse and result in greater value per MHz of spectrum. Expanding sharing is essential as the need increases for more and more users in the midband.

Enabling greater use of UWB technologies and adopting techniques in using conventional radios to reduce their impact area and magnitude will greatly improve sharing. This approach offers a practical path toward more efficient spectrum utilization in increasingly crowded frequency bands.

B. UWB REGULATORY EVOLUTION AND HARMONIZATION

1) THE GROWING MATURITY OF UWB TECHNOLOGY

Over the past five years, the use of UWB has expanded rapidly, as has awareness of its capabilities. However, UWB has been in commercial operation for over two decades, and there is a significant body of experience upon which we can draw.

Applications for UWB have changed significantly since the first rulemaking in 2002. The range of applications is diverse, and continues to expand. Experience has also shown that the potential for UWB to cause interference is far less than was assumed two decades ago. These factors have led to a need to update regulations worldwide to enable an even greater diversity of applications.

2) THE CHALLENGE OF REGULATORY FRAGMENTATION

One of the challenges today is that regulations vary greatly around the world. The range of frequencies available and other technical characteristics differ across regions. This adds both cost and complexity to developing products for consumer markets.

Harmonization can reduce costs significantly by allowing common designs to be deployed in many markets worldwide. This will increase availability and consumer choice, bringing the technology's many benefits to more people.

3) KEY AREAS FOR REGULATORY UPDATES

Drawing on two decades of operational experience, several specific regulatory improvements have emerged as priorities. These updates would enable broader deployment while maintaining the interference-free operation that UWB has demonstrated.

a) Outdoor operation and fixed infrastructure: In applications such as precise location and secure entry, one device in the link may be non-mobile, i.e., installed at a fixed location. In such deployments, many small portable UWB devices communicate with one or more fixed devices.

Examples include door locks and "anchors" – fixed devices used in location networks that can support many use cases, such as smart parking in parking lots and along streets, smart traffic management in cities, and many others. In many regions, current rules do not differentiate between tower-mounted transmitters and external antennas on small devices near the ground.

These rules were originally put in place to avoid interference with sensitive systems where a tower mounted transmitter could operate in the exclusion zone of the protected system. This regulatory framework does not reflect the reality of today's low-power, ground-level UWB deployments.

b) Transmit-only devices: Some regional regulations were driven by the desire to prevent wasteful use of the underlay spectrum. For example, requiring two-way communication so that a transmitter would cease operation if there were no receiving devices (and thus no point in transmitting).

Experience has shown, however, that there are legitimate applications where transmit-only devices make sense, and other techniques mitigate any risk of the spectrum waste. Examples include very low-cost location tags that transmit very little data infrequently. These devices provide valuable functionality while maintaining minimal spectrum impact.

c) Vehicular applications: Another area where harmonization would be valuable is in vehicular deployments. Some regulations are unclear on what is required for UWB to be used in and around vehicles.

Clarification and harmonization will decrease the complexity and cost of certifying products and allow consistent performance across markets. This would allow a UWB-enabled digital key to be used in multiple, if not global, markets without requiring region-specific implementations.

d) Indoor location services: A very popular use of UWB is for precise location indoors. UWB provides centimeter resolution ranging/location accuracy, which enables many things such as navigation in large warehouses, stores, malls and similar venues.

When covering large areas, which are often unfriendly to radio signal propagation, a modest increase in TX power can be very helpful. Recent EU updates have enabled a 10 dB increase (to −31 dBm/MHz) for such applications. Adopting this power level globally will extend these benefits to more people and enable more robust indoor location systems worldwide.

VI. CONCLUSION

In this paper we have provided a comprehensive summary of the current state of IR-UWB and the standards that are enabling continued mass market adoption. IR-UWB technology has matured over decades of engineering innovation to provide communication, fine-ranging, and sensing capabilities that unlock new application possibilities like hands-free access control, precise indoor navigation, and low energy, low latency communications. With recent standardization activities in IEEE Std 802.15.4 to enhance security, data rates, and use cases, IR-UWB adoption is rapidly accelerating, as evidenced by proliferation in domains spanning consumer, automotive to industrial IoT.

As costs reduce further and new startups leverage its advantages, IR-UWB's full potential will emerge. The ultra-low transmit power levels open up new models for wireless coexistence that will relieve congestion issues in midband spectrum, thereby enabling support for massive device densities. Academic-industry collaboration will push the limits of IR-UWB sensing capabilities. As standardization keeps pace with silicon improvements, this technology will transform experiences across healthcare, retail, transportation, and smart spaces in the coming years through precise, energy-efficient, and scalable implementations.

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REFERENCES

[1] *IEEE Standard for Low-Rate Wireless Networks*, IEEE Standard 802.15.4-2024 (Revision of IEEE Standard 802.15.4-2020, 2024, doi: 10.1109/IEEESTD.2020.9144691.
[2] *IEEE Standard for Information technology– Local and metropolitan area networks– Specific requirements– Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs): Amendment 1: Add Alternate PHYs*, IEEE Standard 802.15.4a-2007 (Amendment to IEEE Standard 802.15.4-2006), 2007, doi: 10.1109/IEEESTD.2007.4299496.
[3] *IEEE Standard for Local and metropolitan area networks– Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs) Amendment 2: Active Radio Frequency Identification (RFID) System Physical Layer (PHY)*, IEEE Standard 802.15.4f-2012 (Amendment to IEEE Standard 802.15.4-2011), 2012, doi: 10.1109/IEEESTD.2012.6188488.
[4] *IEEE Standard for Low-Rate Wireless Networks–Amendment 1: Enhanced Ultra Wideband (UWB) Physical Layers (PHYs) and Associated Ranging Techniques*, IEEE Standard 802.15.4z-2020 (Amendment to IEEE Standard 802.15.4-2020), 2020, doi: 10.1109/IEEESTD.2020.9179124.
[5] IEEE 802.15 WSN^{TM} Task Group 4ab (TG4ab) 802.15.4 UWB Next Generation, (n.d.). [Online]. Available: https://www.ieee802.org/15/pub/TG4ab.html
[6] Omlox, (n.d.). [Online]. Available: https://omlox.com/
[7] Car Connectivity Consortium, (n.d.). [Online]. Available: https://carconnectivity.org/
[8] FiRa Consortium, (n.d.). [Online]. Available: https://www.firaconsortium.org/
[9] CSA Aliro, (n.d.). [Online]. Available: https://csa-iot.org/all-solutions/aliro/
[10] UWB Alliance, (n.d.). [Online]. Available: https://uwballiance.org/
[11] Audio Engineering Society, (n.d.). [Online]. Available: https://www.aes.org/standards/blog/2023/10/new-task-group-for-uwb
[12] Revision of Part 15 of the Commission's Rules Regarding Ultra WideBand Transmission Systems, Federal Communications Commission, 2002, [Online]. Available: https://www.fcc.gov/document/revision-part-15-commissions-rules-regarding-ultra-wideband-7
[13] J. Hamie et al., "On the cramer-rao lower bounds of ranging based on IR-UWB TOA estimation in wireless body area networks," in *Proc. 9th IFIP Int. Conf. New Technol., Mobility Secur.*, 2018, pp. 1–4, doi: 10.1109/NTMS.2018.8328708.
[14] CCC Digital Key – The Future of Vehicle Access, Car Connectivity Consortium, 2022. [Online]. Available: https://carconnectivity.org/wp-content/uploads/2022/12/CCC_Digital_Key_Whitepaper_Approved_v2-1.pdf
[15] H. Pirch and F. Leong, "Introduction to impulse radio UWB seamless access systems," in *Proc. Fraunhofer SIT ID:SMART Workshop*, 2020, pp. 19–20.
[16] (n.d.). [Online]. Available: https://www.firaconsortium.com/discover/use-cases/smart-home-consumer
[17] M. S. Raheel et al., "Breathing and heartrate monitoring system using IR-UWB Radar," in *Proc. 13th Int. Conf. Signal Process. Commun. Syst.*, 2019, pp. 1–5, doi: 10.1109/ICSPCS47537.2019.9008755.
[18] Novelda, "Redefining how we interact with the objects around us," (n.d.). [Online]. Available: https://novelda.com/solutions
[19] M. Robaszkiewicz, "Saving lives when temperatures rise, In-cabin UWB radar to ensure everyone's out of a parked car," *NXP Whitepaper*, 2022. [Online]. Available: https://www.nxp.com/docs/en/white-paper/RADAR-CHILD-DETECTION-WP.pdf
[20] ETSI TR 103 750 V1.1.1 (2023-04), System Reference document (SRdoc); Short Range Devices (SRD) using Ultra Wide Band (UWB); Technical characteristics for UWB operation in the frequency band between 8,5 GHz to 10,6 GHz, Apr. 2023. [Online]. Available: https://www.etsi.org/deliver/etsi_tr/103700_103799/103750/01.01.01_60/tr_103750v010101p.pdf
[21] M. Ghavami, L. B. Michael, and R. Kohno, *Ultra Wideband Signals and Systems in Communication Engineering*, 2nd ed. Hoboken, NJ, USA: Wiley, 2007.
[22] "SPARK microsystems' SR1120 UWB transceiver outperforms bluetooth by 40X for wireless data throughput," 2025.
[23] J. Martins, "Spark microsystems shows way-forward for wireless audio over UWB," 2022.

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