WiP paper: UWB-based Integrated Sensing and Communication (ISAC) for Robotic Applications

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ABSTRACT

Integrated sensing and communication (ISAC) (sometimes also referred to as joint communication and sensing (JC&S)) is the trend toward integrating both sensing and communication functionalities into a single radio transceiver. Ultra-wideband (UWB) is a prime candidate for such a use case since its large bandwidth is suitable for high-throughput communication, accurate positioning, and fine resolution radar-based sensing. This paper showcases a real-life demonstrator capable of UWB-based ISAC and explores future challenges toward further integration of sensing and communication into single-chip ISAC solutions where multiple functionalities (communication, localization and radar) are simultaneously derived from packet transmissions. The demonstrator features a fixed single anchor node with a custom antenna array and mobile tag mounted on a robot. The antenna array on the anchor node calculates distance and angle-of-arrival estimation for the robot's 2D localization (MAE: 35 cm). Simultaneously, the robot uses the reflections of these packets to detect nearby objects with an accuracy of up to 23 cm and to communicate reliably with the anchor. Our innovative approach reduces deployment costs, enables multi-service offerings, and incorporates advanced antennas to improve performance in challenging conditions. Five key areas for future research are identified and further discussed in the paper: 1) antenna design, 2) pulse and waveform design, 3) software algorithms, 4) evaluation metrics, and 5) standardization.

CCS CONCEPTS

• **Computer systems organization → Sensor networks**; *Embedded software*; Robotic autonomy.

KEYWORDS

Integrated Sensing & Communication, ISAC, Joint Sensing & Communication, JSAC, Ultra-wideband, UWB, Robotics

1 INTRODUCTION AND VISION

Wireless communication technologies like Wi-Fi, Bluetooth, cellular networks, and satellite systems have been firmly integrated into our daily lives. Beyond communication, electromagnetic waves can also gather information from the environment. Wireless sensing systems analyze changes in signal properties like amplitude, phase, or frequency—to detect movement, presence, proximity, and environmental factors such as temperature or humidity. One prominent example is radar, which emits radio waves and analyzes their reflections to detect objects, allowing to measure their distance, speed, and other characteristics. Another important application of wireless sensing is localization, which involves determining the position of objects or individuals within a defined area. Through techniques such as multilateration or fingerprinting, wireless signals are utilized to estimate the location of devices or assets.

Wireless communication and wireless sensing are considered separately as their performance is measured differently and sometimes their radio configuration parameters are opposite. For example, in wireless communication, all propagation paths can be leveraged to improve performance while in sensing mainly the reflected paths from the objects of interest are desired. **The concept of ISAC is to merge multiple functionalities (communication and sensing), either by (i) using the same radio platform for both services sequentially or (ii) even reusing the same transmitted wireless signals for multiple purposes simultaneously**. The first option allows optimization of the radio settings (like pulse shape and transmission settings) for each specific service, but the second option, (which is realized in our demo) is more spectrum and energy-efficient. However, both options require the availability of a radio platform with hardware characteristics that are suitable for both applications (e.g. an omnidirectional radiation patterns for communication versus a more directional antenna for sensing). In both cases, a significant cost reductions can be achieved by using ISAC, as fewer hardware components need to be deployed.

UWB is a highly promising candidate technology for ISAC. The high-resolution timestamps enable excellent clock synchronization between two devices which is essential for distributed sensing applications. Owing to the short pulses of UWB, a distinction can be made between the direct path and reflected paths, making it well-suited for ISAC applications. Moreover, the high carrier frequency and wide bandwidths of UWB increase the data rate. Despite these facts, actual implementations of UWB-based ISAC are only recently gaining attention. Previous work on UWB ISAC mainly studied the technology's theoretical background, feasibility and limits. In [38], the limits of ISAC and sensing-only systems are presented as Cramer-Rao bound (CRB). In [19], UWB communication signals are also used for fall detection. Such sensing-only systems can even detect 4 mm chest movements from heartbeats, though this requires high-bandwidth chips. For ISAC, accuracy often focuses on spectral efficiency. In [26], the Simultaneous Ranging and Communication (SRAC) technique piggybacks ranging information on existing communication traffic, reducing network traffic by 40% without losing accuracy. Similarly, [2] introduces

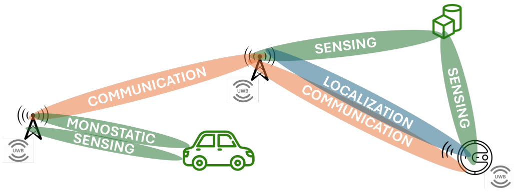

Figure 1: In ISAC systems, communication infrastructure is used for communication between nodes, localization, and (mono-/bi-)static radar sensing. Reflections on objects without UWB capabilities (green) can be used to gain more insights on the environment.

a MAC protocol that integrates positioning and communication using UWB transceivers, collecting position data with minimal energy consumption while maintaining network performance. Several theoretical works focus on the design of novel physical layers that are better suited for both communication and sensing [21, 35]. However, none of these papers present initial results on realistic experiments with both sensing and communication, nor do they discuss practical implementation and standardization steps needed for experimental research.

To remedy these shortcomings, the main contributions of this work in progress paper are as follows:

- We provide a brief overview of advances for UWB in ISAC applications and their use cases.
- We present a novel proof-of-concept (POC) implementation of a robotic application that simultaneously realizes three distinct functions: localization, sensing, and communication. To the best of our knowledge, this is the first experimental evaluation of UWB-based ISAC concepts.
- We present challenges and clear guidelines for the development of future UWB ISAC systems.

This paper is structured as follows: in Section 2, a proof-of-concept demonstration is presented. The next steps and challenges for UWB ISAC based on this POC are discussed in Section 3. The paper concludes in Section 4.

2 UWB ISAC PROOF-OF-CONCEPT DEMONSTRATOR

The feasibility of UWB for localization systems has been widely acknowledged and intensively studied. In addition, papers on UWB radar or UWB communication have been published. However, the simultaneous combination of all three application domains has never been demonstrated. In this POC, an autonomous robot use case is realized. The front of the robot uses UWB radar for object detection [32]. This radar measures distances to obstacles, aiding in collision avoidance, landmark-based localization, and UWB-based SLAM navigation. Simultanuously, the same packets are used to localize the robot from a single anchor combining two-way-ranging (TWR) and angle-of-arrival (AoA) [24]. Finally, the object detection results are communicated to this anchor over the same UWB link.

In Figure 2, the tag and receiver at the robot are shown. For the POC, three DW3000-based UWB hardware devices are used: (i) one fixed dual-antenna infrastructure anchor node that can determine the position of all nearby robots. (ii) One omnidirectional antenna on the mobile robotic platform for communication and (iii) one front-facing directional receiving antenna at the robot for object detection. In the next parts of this section, we will first discuss the technical details of this ISAC realization. Afterward, we will evaluate the performance of the different domains.

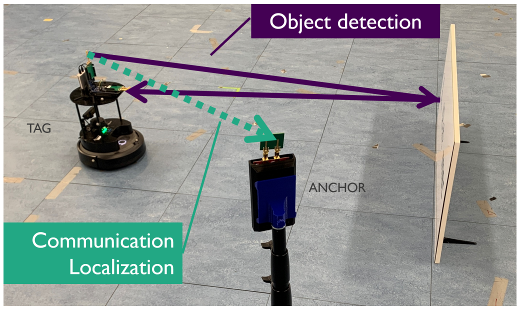

Figure 2: The tag is mounted on a robotic platform and communicates with the anchor. Simultaneously, an object next to the anchor node is detected by its reflection at the tag.

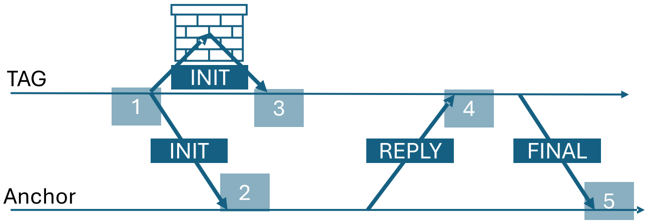

Figure 3: In the demonstrator, three packets are exchanged between tag and anchor. The INIT packet is used for object detection, as part of the two-way ranging for localization and as communication packet.

Sensing, localization, and communication are all realized with only three UWB packets transmitted between the tag and the fixed anchor. For localization, double sided two-way-ranging (DS-TWR) is a technique that requires three packets to be transmitted for a single distance estimation. However, by reusing these packets in the POC, no additional packets need to be transmitted to achieve both sensing (object detection) and communication of the sensing and localization data, thereby improving efficient spectrum usage. The packet exchange is shown in Figure 3. The following steps are executed:

1. The tag initiates a TWR sequence by sending an *INIT* packet to the anchor. This packet is broadcast to both the fixed anchor node and the receiver at the robot to optimize the efficiency of the system fully.
2. The fixed anchor receives and decodes the *INIT* packet. The anchor sends a *REPLY* packet after a predetermined reply time, allowing the tag to activate its radio at the correct moment, thereby conserving power. The anchor logs the time of the *INIT* (RX) and *REPLY* (TX) packets.

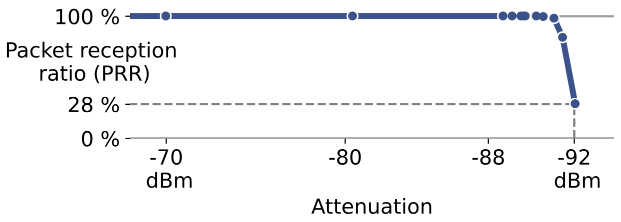

Figure 4: The UWB communication is stable and robust up to receive powers of -92 dBm. This corresponds to a maximal range of approximately 27 m.

(3) **Simultaneously**, the receiver at the robot receives the same *INIT* packet. The channel impulse response (CIR) and multipath components (MPC) of this packet are analyzed. Based on the highest reflection peak, an object in front of the robot is detected.

(4) Afterwards, the tag receives the *REPLY* packet in the TWR exchange and prepares the *FINAL* packet. In this packet, the tag adds the timing information from the tag (TX *INIT*, RX *REPLY*, and TX *FINAL*) and sensing information from the detected object to the payload.

(5) Finally, the anchor receives the *FINAL* packet and calculates the distance to the tag based on the three timestamps from the tag and his three timestamps. Additionally, the angle of the last packet is determined using PDoA which is possible due to the two antennas at the anchor node. Lastly, the anchor decodes the sensor information.

The evaluation of this POC has been performed in an industrial indoor environment [14] in an area of 25 m^2 for more than 10 minutes.

Firstly, the **communication** of the link between tag and anchor is stable with near 100% packet reception rate (PRR) for receive powers up to -90.6 dBm. In Figure 4, the measured PRR for different measured received power levels is depicted. These power levels can be converted into distances based on link budget calculations and depend on the environment, UWB frequency and transmitted power level. In line-of-sight (LOS) conditions, this corresponds to 27 m range.

Secondly, the single anchor **localization** reaches a mean absolute error (MAE) of 34.71 cm. Detailed results of the accuracy can be found in Figure 5. The robustness of the localization can be showed by the 75, 90 and 95th percentile errors at 42.3, 91.1 and 110.4 cm respectively.

Thirdly, the **sensing** part of the POC detects a metal plate of 0.36 m^2 within 4 m in front of it in 98.95 % of the time, and this with a mean absolute error of only 23 cm. Only 10 % of the estimations differ more than 45.4 cm from the true distance, 5 % of the estimated detections are further than 69.7 cm away from the true distance to the object. For the detection, 10 CIRs are averaged with the ACIR method presented in [32], resulting in a detection latency of less than 0.33 seconds. The object detection accuracy is given in Figure 6.

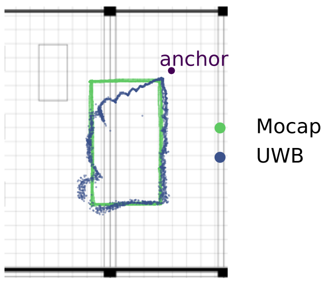

Figure 5: The single anchor localization is very accurate (MAE lower than 20cm) in a field-of-view up to +60 degrees. Outside these zones, the accuracy drops.

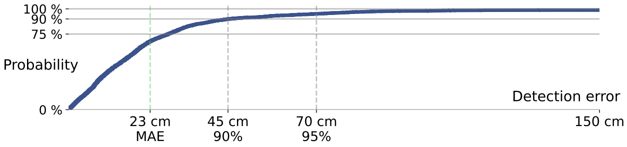

Figure 6: The cumulative distribution function of the object detection error for detecting a metal object while varying their separation between 60 and 400 cm.

3 NEXT STEPS TOWARDS AN INTEGRATED SOLUTION

Our current POC demonstrator still utilizes multiple separate antenna units, rather than consisting of a fully integrated radio. The next sections outline the required optimizations for the antenna design, pulse and waveform design, software algorithms, evaluation metrics and standardization to integrate all functionality in a single transceiver.

For an integrated solution, an important difference is the choice between co-design and co-existence of the envisioned system. For example, co-existence allows waveforms and antennas to be optimized for either sensing or communication in a specific prevailing environmental context. In contrast, co-design allows simultaneous reuse of waveforms and antennas for multiple purposes, thus showcasing superior spectral efficiency. The signal processing optimizations can thus be co-optimized in collaboration with pulse shape modifications to permit optimal reception of the signal.

3.1 Antenna design

The design of novel UWB multi-antenna systems will be crucial for ISAC to (1) enhance data rates by leveraging beamforming and Multiple-Input Multiple-Output (MIMO) techniques, (2) improve positioning accuracy and reliability while reducing the number of anchor nodes (e.g. through angle-of-arrival estimation), and (3) providing higher resolution to enable multi-target sensing and/or multi-person vital sign monitoring. Although many multi-antenna

UWB systems have been proposed, high-performance antenna arrays for UWB are complex due to their large bandwidth requirements and are hence typically bulky, involve advanced fabrication technology, and hinder compact integration with active electronics. In contrast, UWB array designs that prioritize compactness and cost, often utilize lower-performing antennas, which are prone to detuning in real-life use-cases [13, 24] and suffer from a limited field-of-view (FOV). Hence, there is a need for a holistic design strategy, innovative antenna topologies and novel fabrication techniques to reconcile high performance with a compact size, facilitate mass manufacturing at low cost, enable scaling to large arrays, and maintain integrated performance in real-life conditions.

Potential solutions: First, there is a need for **miniaturized and high-performing antennas**. UWB antennas such as planar monopoles [13], Vivaldi [6], horn [5], and sinuous antennas already support wide impedance bandwidths and cover multiple UWB channels. Yet, to enable integration in a wide variety of array architectures, this large bandwidth should be achieved within $\lambda/2 \times \lambda/2$ footprints, while mutual coupling should be minimized. Moreover, high efficiency is crucial to maximize range and reduce power consumption, thereby extending battery life. Recently, two promising technology platforms have emerged, exceeding 90% efficiencies in compact footprints by either eliminating dielectric losses, leading to so-called Air-Filled Substrate-Integrated-Waveguide (AFSIW) systems [10], or by reducing conductor losses through Dielectric Resonator Antenna (DRA) technology [20]. Additionally, the pulse-based nature of IR-UWB systems imposes a set of stringent time-domain design requirements, urging the need for tight antenna-IC co-integration and system-level co-design to minimize orientation-specific pulse distortion and phase-center variation [4].

Second, **monostatic or colocated transmit/receive (TX/RX) configurations with shared-aperture in-band full-duplex operation** have the potential to reduce overall system size and cost, while boosting the spectral efficiency. Yet, they require extremely high isolation over a wide bandwidth [3]. Thereto, novel wideband Self-Interference Cancellation (SIC) techniques should be conceived in the propagation (antenna), analog (chip) and digital (processing) domains to enhance RX sensitivity. Among these, SIC in the propagation domain is particularly crucial, as it enhances signal quality and system performance by mitigating interference early on, reducing the complexity of subsequent analog and digital stages. Innovative decoupling structures and metamaterials, such as Electromagnetic band-gap (EBG) or Defected Ground Structure (DGS) [36], as well as arrays with parasitic elements [20], must be developed and optimized for wideband SIC in a compact footprint.

Third, **multi-polarization and polarization-reconfigurable antenna systems** provide several benefits, such as polarization diversity and spatial multiplexing for reliable communication and increased channel capacity, robust single-anchor localization with joint distance and AoA estimation with pose estimation [30], and spatial filtering of multipath components to improve target detection. Multi-mode [36] and polarization-reconfigurable [17] antennas have been conceived, but a compact form factor that is suited for array deployment, while providing a pure polarization over a wide FOV and over a large bandwidth remains challenging.

Finally, **advanced array configurations** have shown their potential to enhance radar systems through super-resolution techniques, or reducing the antenna element count while maintaining performance through array sparsification [39]. Moreover, three-dimensional conformal antenna arrays enable sectorization and a wider FOV, ultimately providing 360-degree coverage [28]. These configurations pose their own challenges, including the design of compact and efficient feeding networks, and ensuring reliable, low-cost and mass-manufacturable fabrication that can withstand temperature variations and vibrations in challenging real-life industrial environments.

3.2 Pulse shape and waveform design

UWB systems leverage bursts of (sub)nanosecond pulses, which are defined by the IEEE 802.15.4z-2020 standard. From a localization and ranging perspective, the adopted signal pulse should be as short as possible to (1) improve the precision of the measured time-of-arrival (ToA), and to (2) distinguish the direct path from the multipath signals. Yet, the aim for short pulses should be balanced against spectrum usage [12]. Moreover, to manage interference between users, the spectrum is divided into channels, further constraining pulse shapes as (1) the transmitter must adhere to a spectral mask to avoid interference with users in adjacent channels [1] and (2) the receiver must be equipped with a channel filter to mitigate signal interference from neighboring channels. As such, the current standard [1] specifies a time-domain mask to limit the amplitude of the main lobe and the sidelobes, and a transmit spectrum mask to limit the Power Spectral Density (PSD), with options for choosing a symmetrical or a monotonic pulse [1] and with recommended pulse shape envelopes [7], avoiding interference, ensuring interoperability, and maximizing localization performance. However, recent studies, where common UWB waveforms are used, show the importance of **pulse optimization for both localization and sensing**. Therefore, a novel and more optimized waveform for ranging and sensing is necessary to boost the accuracy of sensing applications, enabling presence detection [18], vital sign monitoring [9], and environment mapping [22], while ensuring backward compatibility with 802.15.4z devices.

Potential solutions: In [25], an asymmetric pulse with a steep leading edge is proposed to improve close-in multipath robustness by using an anti-phase precursor with the opposite carrier phase. Measurements show the improved precision of a receiver's ToA difference measurement in a test experiment. It is also found that the optimal pulse shape for sensing applications typically differs from that employed for ranging purposes as the latter focuses on accurately measuring the timestamp of the earliest path, while the former focuses on measuring the parameters of the reflected path [16]. Yet, as long as the specifications described in the standard are met, the exact pulse shape and the transmitter/receiver circuitry can be freely optimized by the system and product developers for maximum performance in the target application (localization or sensing), while minimizing power consumption and cost [29].

In the expected release of IEEE 802.15.4ab, planned for 2025, a new unified pulse shape is expected to enable joint communication, localization, radar and sensing applications in one packet [15]. In this release, a more restrictive additional time-domain mask will be proposed to minimize both precursors and postcursors, as required for UWB sensing, and also comply with the time-domain mask defined in the IEEE 802.15.4z-2020 standard.

Finally, **hardware/algorithm co-optimization** will become essential to translate the physical layer innovations in Section 3.1 to interoperable high-performance and multi-function UWB systems. Next-generation UWB systems will therefore require simultaneous optimization in the frequency, time and spatial domains to guarantee optimal system-level performance, such as low pulse distortion and minimal phase-center variation [23]. This system-level optimization process is becoming more challenging for future generation ISAC UWB systems due to the increasing number of antenna elements and the evolution towards higher levels of integration, fueled by the roll-out of the Internet-of-Things and Industry 4.0.

3.3 Software algorithms

Currently, most UWB software algorithm aim to improve localization accuracy only. First, ranging accuracy is improved through software algorithms that optimize calibration, LOS/NLOS detection, and ML error mitigation. Second, the estimation of the location can be improved using filters [33]. Advanced filtering algorithms like Kalman, extended Kalman, and particle filters estimate the location. Combining techniques such as AoA with TWR or time-difference-of-arrival (TDoA) also improves accuracy. A third possible improvement is the anchor placement which influences the localization results as well and can be assessed with the dilution of precision (DOP). On the other hand, software algorithms for sensing applications exploit information in the CIR to detect objects or analyze vital signs. In [32], the resolution of the CIR is increased by aligning and combining different CIRs. Other sensing software algorithms include constant false alarm rate (CFAR) [34], clutter removal [37], and CLEAN [27].

Potential solutions: To integrate both applications in the same device, they need to interact. For sensing applications, IQ samples (CIRs) are desired. Collecting this information lowers communication and localization update rates, but integrating these functions on the same device allows localization algorithms to use object detection data to improve accuracy. Room information is used in [11, 31] to localize based on reflected signals. Applications such as smart home systems, enlarge the number of connected devices, enabling mesh networks installed in lights or switches to communicate wirelessly information through buildings. This communication can be used in ISAC UWB systems to detect and monitor people in different rooms. New opportunities emerge within the automotive industry: UWB transceivers integrated into cars for secure unlocking can be used to add safety in low-visibility scenarios.

3.4 Evaluation metrics

Separate UWB applications each use their own evaluation metrics. Applications such as object and presence detection, environmental mapping, and vital sign monitoring are evaluated using metrics like L1 error, detection rate, and accuracy. Localization is mainly evaluated by accuracy (e.g., MAE/RMSE), often achieving sub-10 cm precision. Communication focuses on throughput, latency, SNR, and BER. Since many of these different metrics are coupled, most ISAC systems are Pareto inefficient: no metric can be improved without worsening another. This raises the question: how can different ISAC systems objectively be compared with each other.

Potential solutions: One option is to define ISAC as a subset of a major research domain (communication, sensing or localization) and to express ISAC gains as the spectral efficiency gained by combining both options instead of performing both operations sequentially. This method however does not express the potential performance drops of the ISAC system due to made trade-offs. For this reason, evaluation metric can be expanded with secondary metrics (power consumption of the tags or the anchor nodes, device cost, scalability, privacy and security,...). These secondary metrics are important for system designers to design and adapt UWB infrastructure.

An alternative approach is to define use-case-specific reference scenarios across various application domains. Such a standard typically includes (1) reference datasets and test environments, (2) benchmark metrics, and (3) a benchmarking process. This method was previously suggested in standards like ISO/IEC CD 21134 for localization systems. In these systems, a similar challenge arises where the primary metric (accuracy) can often be artificially enhanced at the expense of degrading secondary metrics (such as anchor density, etc.). Since benchmarks can be application specific, specific ISAC implementations will favor one of the domains. This favoritism can be incorporated into the weights of the different individual metrics. Several applications will only use sensing to improve communication and the communication evaluation will mostly define the metric. Some metrics such as latency and signal-to-noise ratio (SNR) are important for all applications and can always be considered.

3.5 Standardization

All current UWB standards focus on interoperability for ranging and communication. UWB sensing devices are limited to proprietary closed solutions. The first UWB PHY was introduced in the IEEE 802.15.4a-2007 amendment which defines UWB communication with low data rates. In the IEEE 802.15.4f-2012 , a LRP PHY was added to the standard. The original UWB PHY is renamed to HRP PHY in the 802.15.4-2015 standard . A new amendment to the IEEE 802.15.4z-2020 standard was released, enhancing both LRP and HRP PHYs. A task group is defining a new amendment to the standard, which will be named IEEE 802.15.4ab , focusing on enhancing the current HRP PHY and adding sensing capabilities. Other standards involved with UWB are the Car Connectivity Consortium [7], FiRa consortium [8], Apple's Nearby interaction framework [8] and more general localization standards such as the Omlox standard.

Potential solutions The challenge to integrate sensing in different applications is expected to be partly mitigated by the new IEEE 802.15.4ab standard. This standard aims to introduce packet structures focused on sensing applications, explore mechanisms for streaming audio and/or video (low latency, high data rate) and improvements in scalability and accuracy improvements.

4 CONCLUSIONS

Integrating sensing into communications systems will be a major step in wireless communication. For UWB integrated sensing and communication (ISAC), a first demonstrator is showcased and evaluated. In this demonstrator, we combine sensing (object detection and localization) with communication. We showed a regular TWR packet exchange with added functionality. Objects in front of the robotic platform are detected up to 23 cm accurately by receiving the INIT packet again at the tag. The angle information is collected at the fixed single multi-antenna anchor node for the FINAL UWB packet, permitting localization up to 34.71 cm accurately. Finally, the CIR for object detection is transmitted in the payload of the FINAL packet, showing a robust high throughput communication link between tag and anchor. Finally, to further miniaturize the solutions into an overall single integrated hardware device, five major challenges for UWB ISAC are identified and are thoroughly discussed in this paper, focusing on antenna design, pulse and waveform design, algorithms, evaluations metrics and standardization.

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