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Disturbances of Time Measurement in UWB Localization Systems - Comparison of Protective Mechanisms in DW1000 and DW3000 Modules*

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Abstract

This study investigates the application potential of the DW1000 and DW3000 UWB transceiver platforms in the design of high-accuracy indoor positioning systems. As industrial environments increasingly adopt cyber-physical automation, indoor localization technologies are evolving into critical components of intelligent manufacturing and warehouse management infrastructures. Accurate position tracking of mobile platforms—such as autonomous transportation units and robotic systems—is now a fundamental requirement for modern production and logistics environments. Ensuring precise spatial awareness enables robust automation, enhances operational safety, and facilitates data-driven optimization consistent with Industry 4.0 objectives.

Keywords: UWB, indoor positioning systems.

Introduction

Analyzing the technological progress that has taken place over the past several years—across virtually every area of life—it can be stated that we are already witnessing a genuine technological revolution. This trend also applies to the specialized domain of indoor positioning systems (IPS). These systems are becoming key components of intelligent building infrastructures, particularly in highly specific environments such as large warehouse facilities and industrial production halls. Challenges related to indoor positioning arise mainly from two fundamental factors. The first concerns the limited propagation of radio waves caused by the materials used in building construction. For this reason, widely known satellite-based positioning systems such as GPS (Global Positioning System) or GLONASS (Globalnaja Nawigacjonnaja Satelitarnaja Sistemma, Russian) cannot be effectively utilized indoors. It is also worth noting that propagation issues affect other radio communication technologies used inside buildings. The second crucial aspect is that indoor positioning systems must provide high accuracy and reliability, and most importantly, real-time operation. These requirements are essential to ensure the safe and efficient functioning of industrial and logistics processes within enclosed and dynamically changing environments.

Currently, a variety of technologies are used to develop indoor positioning systems, including Wi-Fi, Bluetooth Low Energy (BLE), RFID, optical systems, inertial sensors, and ultra-wideband (UWB) signals. Each of these

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solutions exhibits distinct propagation characteristics, infrastructure costs, and positioning accuracy levels, ranging from several meters in mass-market systems (e.g., Wi-Fi) to even a few centimeters in high-precision UWB-based systems (Zafari et al., 2019, Youssef and Ashok, 2005). Furthermore, hybrid techniques are gaining increasing importance, wherein multiple sensing modalities are combined (e.g., UWB with IMU sensors or BLE with vision-based methods), enabling enhanced resilience to noise, multipath effects, and temporary signal loss (He and Chan, 2016).

Considering the performance requirements imposed on indoor positioning technologies, Ultra-Wideband clearly stands out as one of the most precise and robust solutions for localization in dynamic indoor environments. Owing to its wide bandwidth, high temporal resolution, and resistance to signal reflections, UWB forms the foundation of modern IPS implementations in high-reliability industrial applications as well as in next-generation consumer devices (Qorvo, 2021, 2018).

The section entitled UWB Systems presents key information concerning Ultra-Wideband technology. The subsequent part of the paper discusses issues related to electromagnetic wave propagation in environments intended for the deployment of indoor localization systems. This is followed by an evaluation of the feasibility of employing the DW1000 and DW3000 chipsets for the development of indoor positioning solutions. Finally, recommendations of the Authors regarding the DW1000 and DW3000 platforms are provided.

UWB systes

UWB technology differs from other wireless systems (such as WiFi or Bluetooth) by its ability to operate with very short-duration signals (on the order of nanoseconds) and a wide frequency band. This unique feature allows precise discrimination of individual signal propagation paths, which is the basis for accurate distance measurements. One of the commonly used distance measurement methods in UWB systems is Two-Way Ranging (TWR). In its basic Single-Sided TWR form, (presented in Figure 1) the procedure is as follows:

1. The initiating device (Initiator) sends a data the poll packet to the responding device (Responder).

2. The Responder, after receiving the packet, waits a known (or predetermined, or its value is sent in the message), fixed processing time (T3 - T2) and sends back a response packet.

3. Knowing the exact time of sending the poll (T1), the time of receiving the response (T4) and the Responder's processing time, the Initiator can compute the total round-trip signal time:

$$T_{ToF} = \frac{(T_4 - T_1) - (T_3 - T_2)}{2} \quad (1)$$

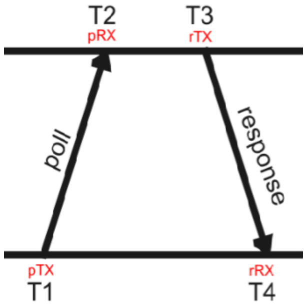

Figure 1. Two Way Ranging Single-Sided

This method is precise only if the initiator knows its clock offset relative to the responder’s clock. For that reason Double-Sided TWR became initially much more popular. It proceeds as follows:

1. Initiator sends a poll message.

2. Responder replies with a response message.

3. Initiator sends a final message.

4. Knowing the processing times, which are either predefined or included in messages, the responder computes the clock offset and, using this value, calculates the time of flight and thus the distance between initiator and responder:

$$T_{ToF} = \frac{(T_4 - T_1) - (T_3 - T_2) + (T_6 - T_3) - (T_5 - T_4)}{4} \tag{2}$$

Thanks to this method, the system is resistant to inaccuracies and clock drift in individual devices. The final object position is usually determined by trilateration using distance measurements to at least three fixed Anchors whose locations are known and constant.

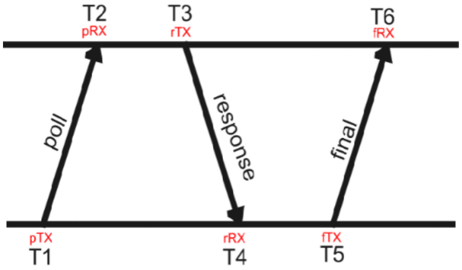

Figure 2. Two Way Ranging Double-Sided

The accuracy of localization in UWB systems is inseparably linked to the precision of the measured Time of Flight (ToF). This dependence is described by the fundamental physical formula:

latex: $d = c \cdot t$ (3)

where:

d – travelled distance [m],

c – speed of light in vacuum (≈ 299 792 458 m/s),

t – signal propagation time [s].

To illustrate how critical time measurement is, consider a simple example. A timing error of just one nanosecond (1 ns = 10^{-9} s) results in a distance error:

$$\Delta d = 299\,792\,458 \frac{\mathrm{m}}{\mathrm{s}} \cdot 10^{-9}\,\mathrm{s} \approx 0.3\mathrm{m} = 30\ \mathrm{cm} \tag{4}$$

Such an error is at the edge of acceptability for many applications requiring precise localization. In practice these errors accumulate and stem from many factors, such as thermal noise in electronic circuits, inaccuracies of crystal oscillators in UWB modules, quantization errors in signal sampling or—most relevant here—propagation conditions, especially LOS (Line-of-Sight) and NLOS (Non-Line-of-Sight) phenomena.

An error in a single distance measurement, even if small, propagates to the final result. In trilateration, errors in distance measurements to different anchors cause the circles (in 2D) or spheres (in 3D) defined by those distances not to intersect at a single point, creating an error region. The larger the distance measurement error, the larger this region becomes, directly degrading the accuracy and reliability of the localization system, as illustrated in Figure 3.

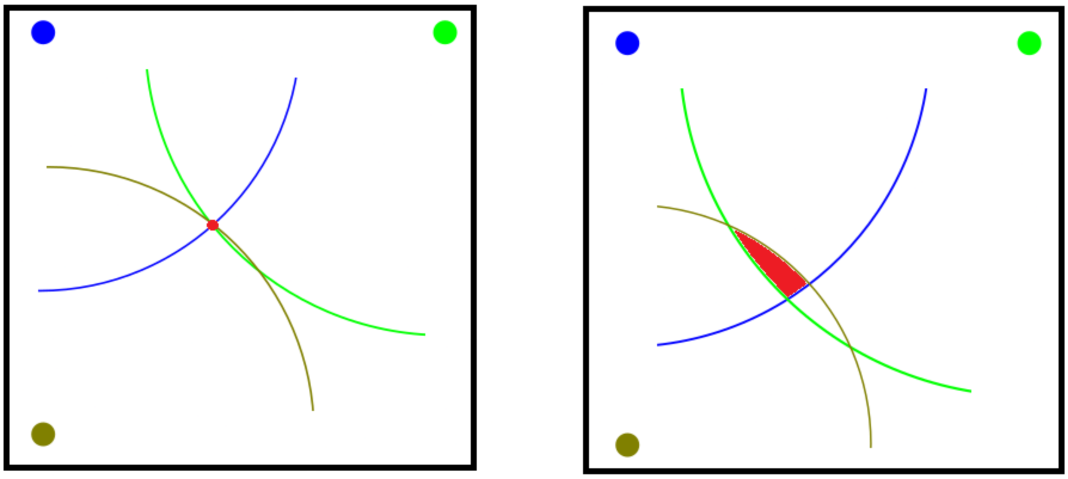

Figure 3. TWR in UWB systems a) Ideal TWR giving an exact point on the plane b) TWR with errors giving the space where the point should be located.

The aim of this article is to analyze sources of time measurement errors in popular UWB modules— Qorvo DW1000 and the newer DW3000. The work focuses on comparing built-in protective mechanisms such as the first-path CIR (Channel Impulse Response) estimation algorithm and the novel STS (Scrambled Timestamp Sequence) mechanism which aim to minimize the influence of adverse propagation conditions on final localization accuracy.

Line-of-Sight and Non-Line-of-Sight conditions

Line-of-Sight (LOS) conditions occur when there is an unobstructed path between the transmitting and receiving antennas. This is the ideal scenario where the received signal consists of a direct path—the shortest path that arrives earliest—and multipath reflections that arrive later and are usually much weaker than the direct path. In ideal LOS conditions, the Channel Impulse Response (CIR) is characterized by a distinct sharp peak at the very beginning corresponding to the direct path. Subsequent smaller peaks represent multipath reflections. The combination of these two phenomena is presented in Figure 4. The ToF estimation algorithm in UWB modules (DW1000 and DW3000) is designed to identify this earliest, highest peak as the start point of the measurement. Although LOS conditions are optimal, small measurement errors can still occur due to thermal noise in the receiver chain, which can cause slight shifts in peak detection or clock inaccuracies that affect subsequent calculations. These errors are random and typically much smaller than errors occurring in NLOS conditions, so we will not discuss them further here.

Non-Line-of-Sight (NLOS) conditions arise when the direct propagation path is blocked by a material obstacle such as walls, doors, furniture or even the human body. In this case the signal reaches the receiver solely via reflections from surrounding surfaces or by penetrating the object. Note that multipath reflections are present even when LOS exists—whenever there are objects nearby that can reflect the signal, for example floors, walls or ceilings. When the direct path is absent, the CIR's first detectable peak no longer corresponds to the direct path (which is strongly attenuated or absent), but to the earliest reflected path. Moreover, this peak is usually much weaker (lower amplitude) due to attenuation through the obstacle and broader in time, which makes precise detection of its maximum more difficult. As a result, the ToF estimation algorithm may mistakenly identify a delayed and attenuated peak as the direct path, leading to significant overestimation of distance. NLOS error can be not only large but also systematic, which makes it particularly hard to compensate with simple filtering methods. Detecting and mitigating NLOS errors effectively remains one of the biggest challenges for UWB indoor localization designers and is a major driver for developing advanced protective mechanisms in newer modules such as the DW3000.

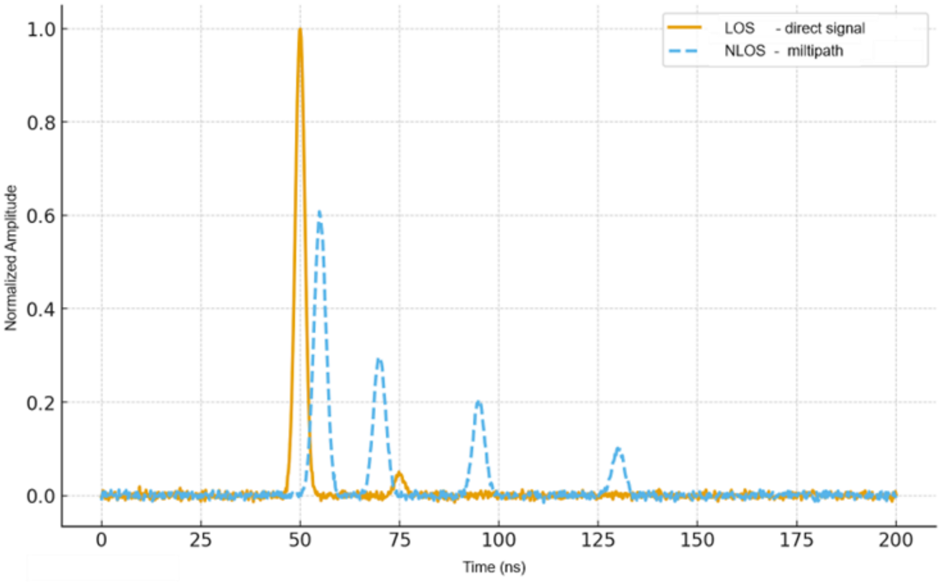

Figure 4. CIR simulation for LOS and NLOS signals

As a result, algorithms and hardware improvements that can detect or reduce NLOS-induced errors are critical for robust positioning.

Impact of multipath on false RMARKER detection

In UWB systems such as Qorvo (formerly Decawave) DW3000 or DW1000 family chips, the RMARKER (Ranging Marker) serves as the time reference indicating the exact instant of detection of the start of a received message. Physically, RMARKER latches the receiver's internal time counter at the moment the SFD detector recognizes the characteristic bit sequence that initiates the PHY header (PHR). The message diagram with SFD and RMARKER position is shown in Figure 5. During reception, after detecting the preamble, a matched-filter (correlation) procedure is performed between the incoming signal and a local SFD pattern. The receiver shifts a correlation window in time and computes the correlation value for successive offsets. When the correlation exceeds a detection threshold, the SFD is considered detected and RMARKER is generated. RMARKER is then used as a reference for subsequent ToF calculations and frame synchronization. To limit false detections, receivers also use quality metrics such as First Path Power, signal-to-noise ratio and temporal consistency of successive correlation samples. However, in severe multipath environments the classical correlation threshold may be insufficient.

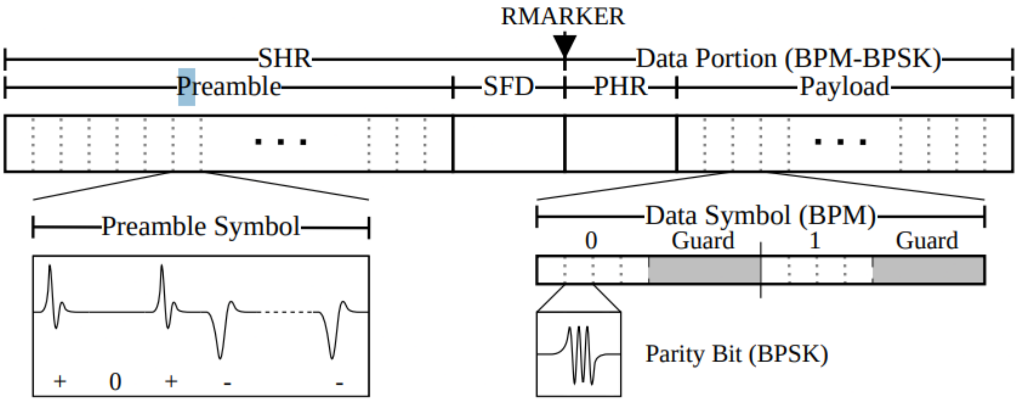

Figure 5. Structure of a UWB frame (Schuh et al., 2024)

In real industrial applications UWB systems often operate in environments with strong reflections (long narrow corridors, tunnels, racking in warehouses or halls filled with metal structures). In such spaces a single UWB pulse is reflected many times, and many copies of the signal arrive at the receiving antenna with different delays and amplitudes. The receiver interprets these as multiple multipath components. Normally reflected paths arrive later than the LOS path, which usually leads to overestimation of distance. However, in multipath-rich environments with strong nearby reflections it is possible for the receiver to latch RMARKER prematurely. This occurs when a strong echo or the superposition of multiple reflections forms a fragment that correlates sufficiently well with the local SFD pattern; the correlation threshold is exceeded before the true SFD from an LOS signal appears, and the device erroneously interprets this as the frame start. In that case RMARKER corresponds to an earlier time, making computed ToF shorter than actual and thus underestimating the distance—sometimes by as much as half. Another cause can be overlapping UWB transmissions in the channel which together form a temporary structure resembling a preamble or SFD (Schuh et al., 2024). This phenomenon can cause erroneous SFD detection even when a valid packet was sent. Studies have observed that false RMARKER detection occurs more frequently than data errors (Schuh et al., 2024), because SFD detection happens at the analog-digital correlation stage before higher-layer error-correction and CRC checks are available.

Laboratory measurements and DW3000 documentation (Qorvo, 2024) show that false RMARKER latching mainly occurs with low-quality STS and low preamble quality when a high-energy peak appears in the CIR before the correct first LOS path. These errors are not detected by classic CRC checks because they happen at the frame detection layer, not data. Practically, this problem can be mitigated by using mechanisms implemented in newer UWB modules.

Channel Impulse Response analysis in UWB transceivers series DW1000 and DW3000

The DW1000 was a pioneering solution that provided raw Channel Impulse Response (CIR) data to developers, enabling implementation of advanced positioning algorithms. CIR acquisition in the DW1000 (Qorvo, 2018) relies on a specialized hardware block called an accumulator. After receiving and demodulating the preamble (SHR - Synchronization Header), used for synchronization, the DW1000 starts sampling the signal at the ADC input. Sampling is done at approximately 1 GHz. Each sample is a complex number with in-phase (I) and quadrature (Q) components, preserving full amplitude and phase information at each time point. Samples are stored sequentially in the CIR accumulator, which in DW1000 holds 1016 complex samples (Qorvo, 2018). Each sample corresponds to a time interval of roughly 1 ns. An internal Leading Edge Detection (LDE) algorithm analyzes the stored CIR to find the index corresponding to the start of the LOS signal, which is crucial for precise RMARKER generation. Additionally, by reading appropriate registers the user can access raw and processed CIR data such as: raw CIR, first path index, amplitudes of key samples and quality indicators.

The DW3000, as a successor to the DW1000, retains the basic CIR acquisition architecture while introducing improvements that increase reliability, security and functionality. The DW3000 (Qorvo, 2021) still uses an accumulator to store raw complex I/Q samples forming the CIR. Key enhancements concern the interpretation and processing of these data to determine timestamps and additional information—primarily by determining timing based on correlation with STS. In DW3000 STS frames according to IEEE 802.15.4z (IEEE, 2020) are supported; although CIR memory still stores the raw channel profile, the method of timestamp extraction fundamentally changed. Instead of leading-edge detection on the preamble, the receiver hardware correlates the received signal (stored in CIR as discrete representation) with the expected STS sequence. The maximum of this correlation indicates the precise reception time, providing more reliable first-path detection (Qorvo, 2021). Secondly, DW3000 adds support for PDoA (Phase Difference of Arrival). Some modules in the DW3000 family support multiple antennas; the device can operate on two separate CIRs and compute hardware-level phase differences (PDoA) between them (Qorvo, 2021a).

Scrambled Timestamp Sequence. Increased security and reliability.

The introduction of STS in IEEE 802.15.4z (IEEE, 2020) and its implementation in DW3000 represents a fundamental change in timestamping, improving both security and measurement reliability.

STS uses a dynamically generated pseudorandom pulse sequence based on a shared secret (cryptographic key) and a varying initialization vector (Qorvo, 2019). Physically, CIR acquisition remains unchanged—raw I/Q samples containing both the preamble (SHR) and the STS sequence distorted by the radio channel are still collected in the accumulator.

However, the interpretation of this data is fundamentally different. Instead of searching for an amplitude edge in the preamble (as in non-STS mode), the receiver performs a cross-correlation between the raw received signal stored in CIR and a locally generated ideal STS template. The time index where the correlation function reaches its maximum with high confidence indicates when the received, channel-distorted STS sequence best matches the expected pattern. This index becomes the basis for precise timestamping. The difference in the result of determining the Timestamp certainty with and without STS is presented in Figure 6. This operation is implemented in dedicated hardware—the STS correlator block described in the DW3000 documentation (Qorvo, 2021; Qorvo, 2019).

DW3000 not only provides a final timestamp but also metadata describing the quality of correlation (Qorvo, 2021) such as ACC_QUAL registers which quantify the quality of the found correlation peak, accumulated STS quality and STS key. High values indicate a clean, strong and unambiguous signal, typically characteristic of LOS conditions; in NLOS it may differ.

Using these data enables significant improvement in system performance and security. The dynamic STS protects against replay attacks. It increases robustness to interference: correlation over a long sequence yields processing gain, making measurements more resistant to noise. Analysis of the STS quality indicator is a powerful tool to identify measurements affected by NLOS. The system can in real time reject or downweight measurements with low ACC_QUAL, leading to much more accurate position estimates.

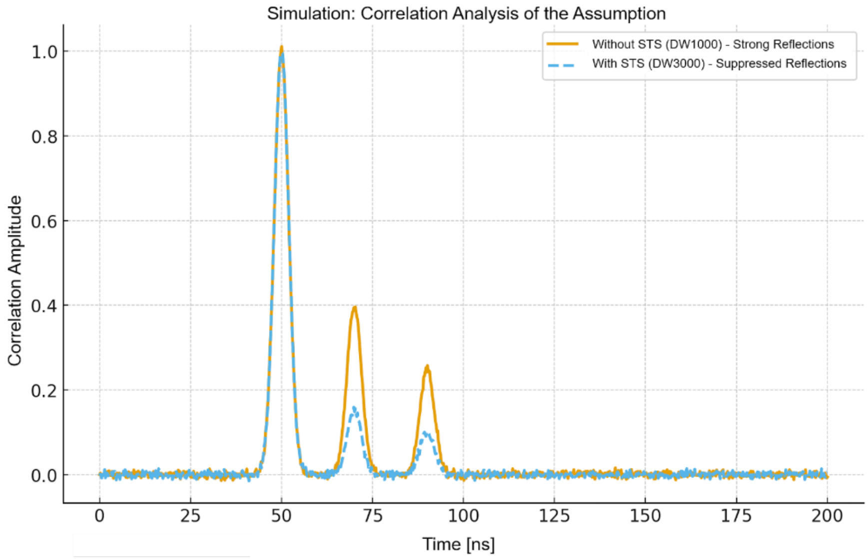

Figure 6. Simulation: correlation analysis assumption

Conclusions and design recommendations

Analyses confirm that ToF measurement accuracy in UWB systems largely depends on the quality of first-path detection and the receiver's robustness against multipath. Both the DW1000 and the newer DW3000 use CIR data for RMARKER generation, but their timestamp computation and protection mechanisms differ significantly.

The DW1000, relying on an LDE algorithm, performs well in LOS but shows significant errors in NLOS and highly reflective environments. This is because the highest peak in the CIR does not always correspond to the true first path, and the lack of detection-quality metrics prevents programmatic rejection of erroneous measurements. As a result, the system may overestimate distance by tens of centimeters or in some cases severely underestimate it.

The DW3000 introduces a new timestamping method based on STS correlation. Correlation with a dynamic STS sequence allows accurate reception time detection and provides high resistance to interference, echoes and multipath. Availability of quality registers (ACC_QUAL) enables direct assessment of detection correctness. Therefore, the DW3000 is substantially less prone to false RMARKER latching than its predecessor.

In highly reflective environments such as corridors, tunnels or warehouse racking, there is an increased risk of false SFD detection which leads to premature RMARKER generation and underestimation of measured distance. This effect was observed particularly when multiple reflections with similar delays overlap in the channel or when neighboring UWB transmitters concurrently send signals. The STS mechanism considerably reduces this effect but does not eliminate it entirely; however it allows for assessment of RMARKER recognition quality.

Based on the analysis of both chips, the following design recommendations can be made:

Transmission parameters: In multipath-rich environments, use longer preambles (e.g., 1024 or longer) to improve correlation accuracy and reduce false SFD detection. Avoid excessive transmit power in enclosed metallic spaces, as it amplifies reflections and can cause premature RMARKER. Also choose frequency channels with low interference.

Measurement quality assessment: For DW3000 inspect ACC_QUAL registers. Low ACC_QUAL values may indicate poor correlation and false RMARKER. For DW1000, analyze the CIR profile and compare first-path amplitude with later peaks to detect reflections dominating the direct signal.

Filtering and data verification: Measurements of low quality should be downweighted or rejected. In RTLS systems use filtering and outlier rejection algorithms. For moving tags, applying Kalman filters (Qorvo, 2021; Jiménez and Seco, 2021) is beneficial.

System diagnostics and testing: During design and commissioning, log raw CIR data in different propagation conditions. This allows observing how first-path detection behaves and tuning detection thresholds. Tests should include LOS, NLOS and highly reflective environments like warehouses and industrial halls.

System architecture planning: To increase localization reliability use a larger number of anchors to eliminate erroneous ranges through redundancy. In dense-node systems avoid simultaneous transmissions on the same channels or implement dynamic time-slot scheduling.

In summary, STS in DW3000 chips significantly improves UWB measurement resilience against multipath and complex propagation conditions. Nevertheless, even with modern protection mechanisms, careful system design, correct selection of physical transmission parameters and measurement quality control at hardware and software levels remain crucial. Only the combination of these elements yields stable and repeatable time measurement accuracy required for real-time precise localization applications.

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