ACCURATE RANGING WITH

BLUETOOTH® CHANNEL SOUNDING:

TECHNICAL INSIGHTS AND PRACTICAL APPLICATIONS

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Table of Contents

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EXECUTIVE SUMMARY

Bluetooth Channel Sounding, introduced in the Bluetooth 6.0 Core Specification, enables centimeter-level distance measurement using standard Bluetooth Low Energy radios. Achieving this level of accuracy requires careful attention to antenna design, calibration, and integration - not just firmware updates. In addition to antenna optimization, signal processing plays a vital role in turning channel sounding data into accurate distance information. Advanced algorithms are required to separate direct and reflected paths, mitigate multipath effects, and ensure consistent accuracy across environments.

This whitepaper outlines the key technical requirements, practical design considerations, and real-world lessons learned to help product companies add precise ranging to their Bluetooth devices with minimal hardware changes. By following these guidelines, developers can unlock new use cases and ensure reliable, accurate performance in real-world deployments.

INTRODUCTION

Bluetooth® technology has powered wireless connectivity in consumer and industrial products for over two decades. Until now, distance estimation (ranging) between two Bluetooth Low Energy (BLE) devices was limited to coarse received-signal-strength indication (RSSI) or angle-of-arrival (AoA/AoD) techniques that required complex antenna arrays and significant design changes. The new Channel Sounding feature in Bluetooth Core Specification 6.0 changes this by enabling sub-meter, often centimeter-level, distance accuracy using standard Bluetooth LE radios and cost-effective hardware.

This breakthrough in precise ranging opens up a variety of high-value applications for existing Bluetooth product makers, including:

- Precise access and digital keys that only unlock when the user is truly within reach, eliminating relay attacks.
- Indoor asset tracking and real-time-location systems (RTLS) with room-level granularity-achieved using the same radios already present in smartphones, wearables, tags and gateways.
- Context-aware peripherals (mice, keyboards, AR/VR accessories) that automatically connect or sleep based on spatial proximity, extending battery life.
- Industrial automation & logistics where knowing that a pallet is 1 m away-rather than "somewhere nearby"-reduces errors and improves safety.

Most of the improvements are done in firmware, but accurate ranging now depends directly on antenna performance and calibration. This white paper explains the new Channel Sounding specification, practical antenna design guidelines (single and multi-element), and integration lessons learned, so you can add accurate ranging to your products–quickly and cost-effectively.

Key takeaway:
If your existing Bluetooth design is able to accommodate a second antenna feed along with a cost-effective RF switch, it is possible to achieve centimeter-level ranging accuracy without the need for specialised silicon or millimetre-wave hardware.

BT CHANNEL SOUNDINGS SPECIFICATION

6.0 Core Specification Overview

Bluetooth Core Spec 6.0 introduces Channel Sounding (CS) as an optional feature for Bluetooth LE devices. In each ranging session two devices are involved:

- Initiator (I): starts the procedure and calculates distance.
- Reflector (R): responds with continues wave signals so the initiator can measure phase and magnitude or the round-trip time.

Two ranging methods are defined:

- Phase-Based Ranging (PBR): Measures the phase change of multi-tone carriers sent across multiple channels; this allows for high precision (~10–30 cm line-of-sight) but can be ambiguous at longer distances.
- Round-Trip Time (RTT): Measures the time for a packet to travel to the reflector and back; this is less precise (~2–3 m) but avoids ambiguity and can help with security (anti-relay).

These methods can be combined for better accuracy and robustness.

Antenna Paths & Switching

To combat nulls in the radiation pattern and improve polarization diversity, the spec allows up to four RF paths per device pair, selected via the Antenna Switching (AntSW) field embedded in each CS packet. Paths are sounded sequentially inside the same CS procedure so the Initiator can pick the "best-quality" antenna pair – or fuse multiple results for higher resilience.

- Minimum recommended spacing: $\geq \lambda/4 \approx 31$ mm at 2.44 GHz.
- Orthogonal polarizations (e.g. monopole + loop) further reduce deep-fade probability.
- Group delay between paths must be stable; constant offset is calibrated out.

Calibration & Error Budget

The spec mandates that ranging values be referenced to the antenna port. Consequently, board-level delays introduced by RF traces, matching networks and the antenna itself must be compensated. Most vendors, including Silicon Labs (EFR32MG24) and Nordic (nRF54L series), expose simple API hooks to write a Board Offset Calibration (BOC) value obtained either from fixture-based phase sweep or over-the-air two-way calibration.

Rule of thumb:
keep residual, un-calibrated group-delay variations < 1 ns across the entire 80 MHz BLE band-equivalent to ±30 cm ranging error.

Performance Snapshot

Line-of-sight (office): <u>Figure 1</u> illustrates a Cumulative Distribution Function (CDF) of the distance errors measured in 10cm steps along a 12m track showing just how accurate the solution is. Here, the x-axis represents the error in meters, while the y-axis indicates the probability. One sigma (68% of all errors) corresponds to an error smaller than 0.65 meters (~2 feet), shown by the orange line. Meanwhile, two sigma (95% of all errors) highlights that errors were smaller than 1.25 meters (~4 feet), shown by the green line.

Non-Line-of-Sight (NLoS) with human body blocking: dual-antenna diversity reduces outliers > 5m by 90% compared to a single antenna.
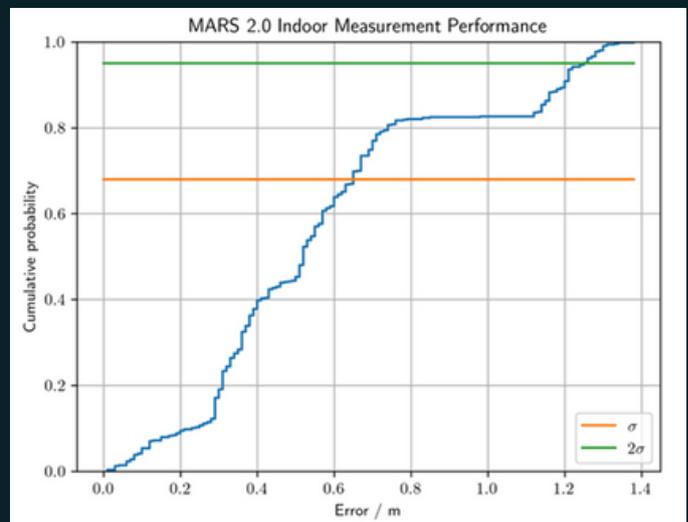
Figure 1:

Figure 1: Cumulative Distribution Function of the measured distance errors.

ANTENNA DESIGN

Single antenna

Typical performance metrics for antennas using BLE communication are their efficiency and realized gain. However, for channel sounding, the group delay variation as a figure-of-merit becomes critical. Group delay is defined as the derivate of the signal phase with respect to the frequency as shown in Equation (1):

$$\tau_g(\omega) = -\frac{d\varphi(\omega)}{d\omega}, \quad (1)$$

where τ_g is the group delay, expressed typically in nanoseconds (ns), ω denotes the angular frequency $2\pi f$, and φ is the (unwrapped) phase response of the system at the given frequency f.

Already simple RF-traces do introduce group delay to the system, since the change in signal phase is not constant over the frequency band but rather linear. Same applies to the typical antennas, and their group delay performance can be analyzed through the phase response of the far-field radiation patterns. The variation in the group delay over the frequency band will remain small, especially in passive systems, as long as the radiation pattern remains stable over the observed band.

Nulls in the radiation pattern are particularly problematic, as they often correspond to sharp, non-linear group delay spikes and large ranging errors. It is extremely difficult to avoid nulls forming with small form-factor devices. Additionally, even antennas with good efficiency and gain may exhibit unacceptable group delay variation if the propagation mode changes within the BLE band or if integrated poorly within the product. The reason is that the phase response of the antenna does not remain linear over the frequency band when the propagating mode changes.

The change in propagating mode can be especially problematic with some Commercial-Of-The-Shelf (COTS) antenna solutions. While they can work well enough for communication purposes, it does not indicate that the COTS antenna solution can work for Channel Sounding. Furthermore, COTS antennas cannot be easily modified, which is often needed to make the antenna perform well in both application scenarios.

Multiple antennas

Single antenna cannot achieve perfect isotropic radiation or polarization coverage. Hence, multiple antennas are often required to ensure consistent, accurate ranging in all device orientations and environments. They can help to cover wider area, and this can help to mitigate the group delay variations as the system becomes more resilient to the single antenna variations.

Key recommendations for multi-antenna channel sounding:
- Antenna Diversity: Use antennas that are physically separated (preferably $\lambda/4 \approx 31$ mm at 2.44 GHz) and/or have different polarization (e.g., monopole plus loop), which helps to reduce correlation and provides independent information streams from each antenna.
- Group Delay Variation: While absolute group delay offsets between antennas (due to different feed lengths or matching) can be calibrated out, group delay variation across frequency is what matters for accuracy.
- Null Compensation: The primary benefit of multiple antennas is resilience–if one antenna suffers a deep null in a particular direction, another can compensate, reducing the risk of large errors or outliers.
- Integration: Identical antennas can be used if integrated wisely; however, ensuring low envelope correlation coefficient (ECC) between them is desirable, as with MIMO (Multiple-Input, Multiple-Output) systems in communications.

Great improvement can be already obtained with two antennas. Properly implemented, a dual-antenna system can dramatically reduce outliers and improve robustness against multipath, obstructions, and device orientation. For best results, combine simulation, measurement, and real-world testing during product integration.

PRODUCT INTEGRATION

Integration Challenges

Many antennas that perform well on bare PCBs fail to meet group delay and efficiency requirements when integrated into real products. Integrating antennas into real-world devices introduces significant challenges beyond what is encountered at the PCB prototyping stage. The performance of antennas can be heavily degraded by the device's mechanical housing, metallic components such as display backplates or batteries, and plastics with high permittivity. These environmental factors can detune the antenna, change its radiation pattern, and–critically for channel sounding–cause large, non-linear variations in group delay.

For Bluetooth channel sounding applications, the most critical parameters impacted by integration are:

- Resonant frequencies: Often shifted due to nearby materials or mechanical constraints.
- System total efficiency: Metallic components like batteries and displays can cause non-radiating resonances in the structure that decrease the total efficiency.
- Radiation pattern and gain: Can be altered by device shape, placement, and internal components.
- Group delay variation: Integration can introduce sharp, non-linear changes, severely affecting ranging accuracy–even if matching and efficiency remain high.

It is essential to evaluate antenna performance in the final mechanical environment through both simulation and real-world measurements. Relying only on datasheets or performance measured on bare PCBs can lead to significant surprises during system integration.

Case Study: Antenna Performance in Real Devices

To highlight these integration effects, we examined a two-antenna system across three stages of product development:

1. Standard Antennas on Bare PCB:

Figure 2 shows our example case of a two-antenna system on a bare PCB. Inverted-F antennas (IFA) designed for the 2.4–2.5 GHz band, placed on an 80x40 mm² ground plane, perform well in terms of matching, efficiency, and group delay when evaluated without any device mechanics. These results are presented in Figures 5 and 6 for matching and efficiency, and Figure 7 for gain and group delay. The group delay variation for the standard antenna without the device mechanics is below the target level of 1 ns in practically every direction, meaning that accuracy should be very high and the second antenna might not even be needed.
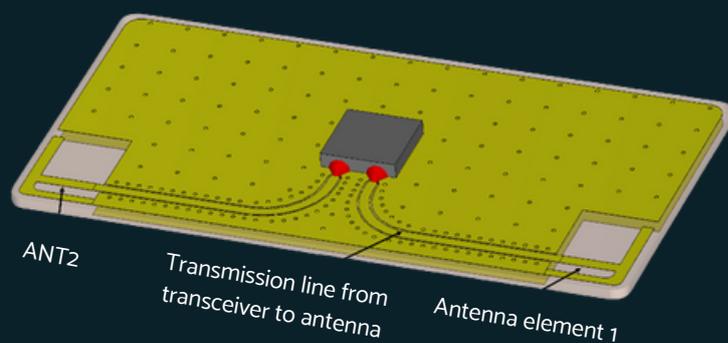
Figure 2:

Figure 2: Standard antennas without device mechanics.

2. Standard Antennas with Device Mechanics:

Introducing typical product components, including ABS plastic housing, a display with a metallic backplate and glass panel, and a battery beneath the PCB, causes significant changes. Our example case for this is shown in Figure 3. Antenna matching degrades (Figure 5), total efficiency drops by more than 3 dB (Figure 6), and, most importantly, group delay variation increases substantially across many directions as can be seen from the results of Figure 8.

Large regions of the radiation pattern show excessive group delay, making these antennas unsuitable for accurate channel sounding, despite still performing "well enough" for communication. Moreover, large group delay variation appears in the same angular regions for both antennas. This means that utilizing two antennas does not provide the wanted improvement in the accuracy of the channel sounding system.
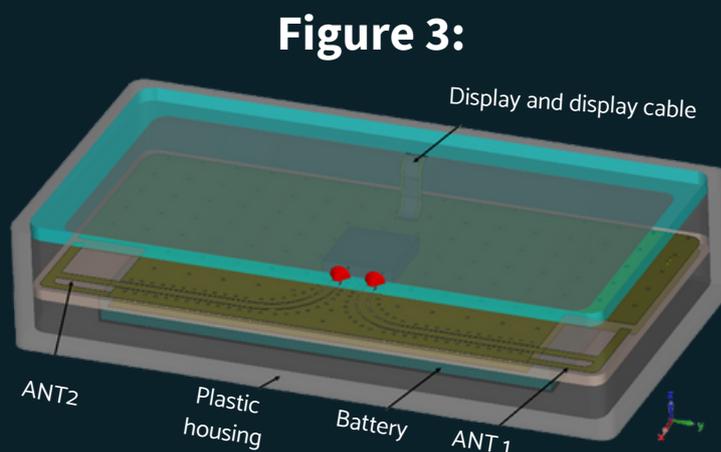
Figure 3:

Figure 3: Standard antennas with device mechanics.

3. Custom Antennas Optimized for the Device:

1.By redesigning the antennas specifically for the integrated environment (including additional grounding for the display), both matching and group delay variation are restored to near-ideal levels, with only ~0.5-1 dB lower efficiency than when the device mechanics are not included. The device with the custom antennas is shown in Figure 4 and the corresponding matching, efficiency, and group delay results in Figures 5 and 6, and 9. With the single custom antennas, there are only a few directions that have large variation in the group delay. Yet, these regions with possibly limited channel sounding performance do not overlap for the two custom antennas.

A comparison of the group delay variation seen in Figure 10 demonstrates the significant improvement offered by proper antenna design and integration compared to using standard antenna without properly integrating them into the final product. The custom antennas keep group delay variation below the critical 1 ns threshold in all directions, ensuring robust and accurate ranging.
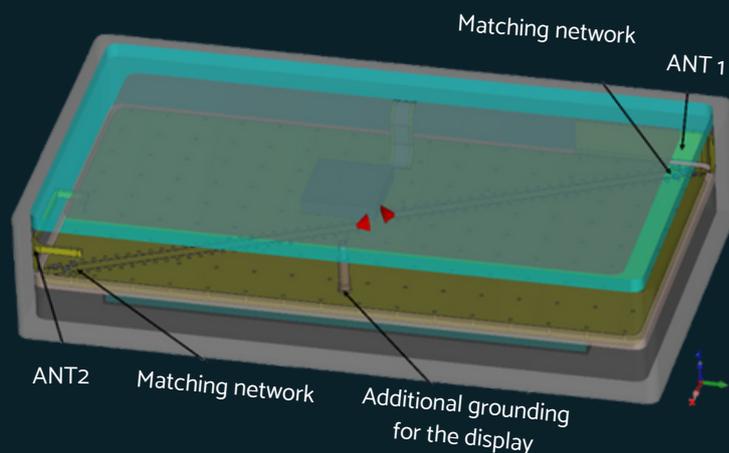
Figure 4:

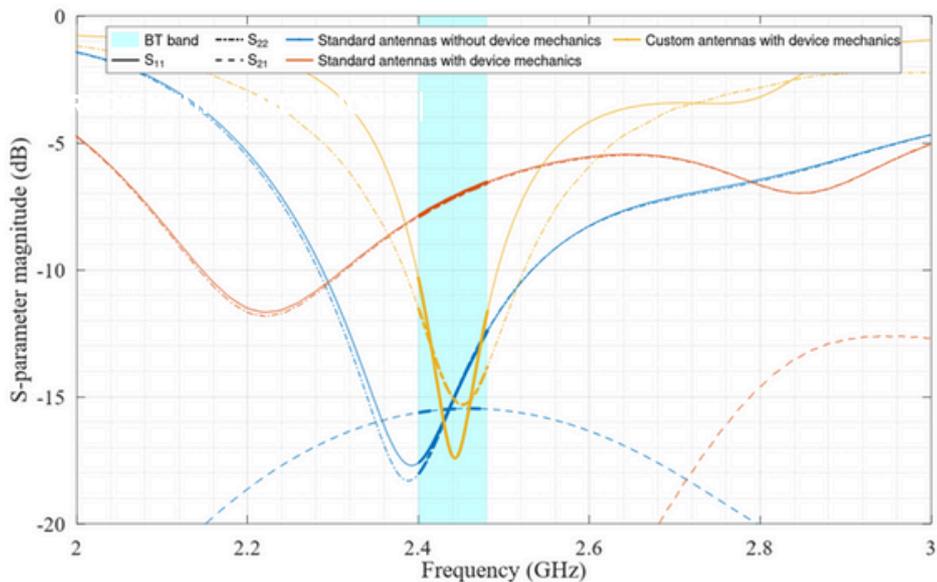Figure 4: Custom antennas with device mechanics.

Figure 5:

Figure 5: Antenna reflection and coupling
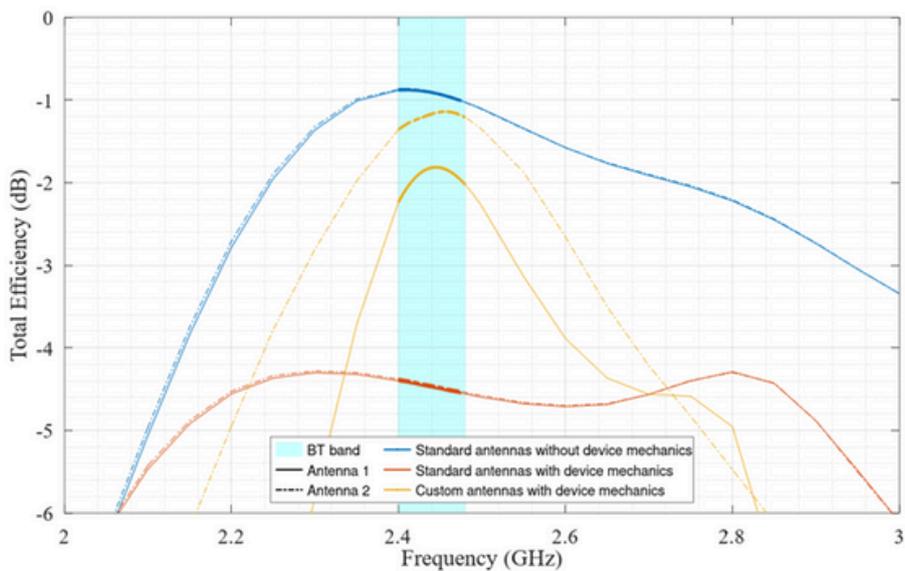coefficients for the three dual-antenna systems.

Figure 6:

Figure 6: Antenna total efficiencies for the three
dual-antenna systems.
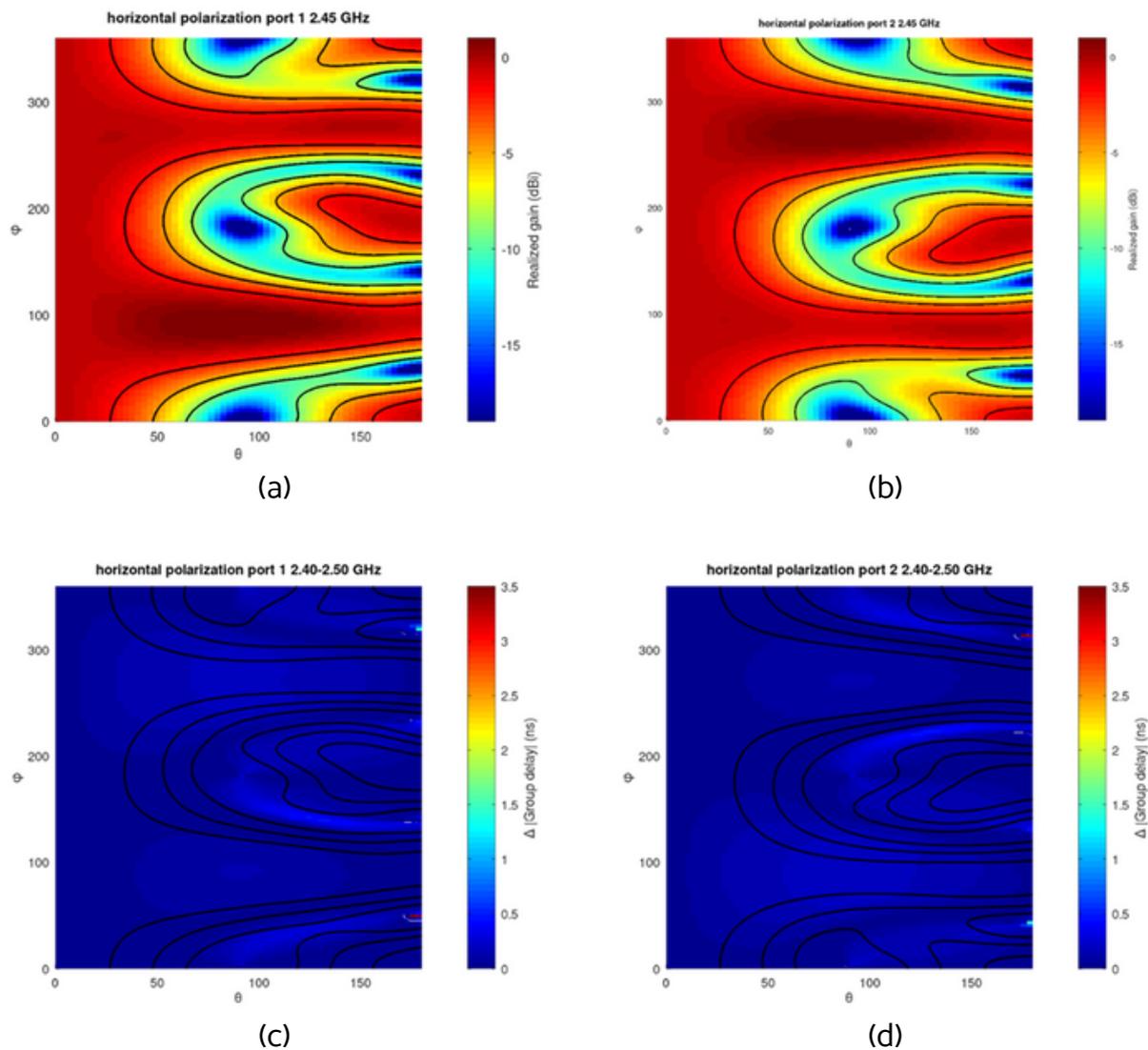
Figure 7:

(a)

(b)

(c)

(d)

Figure 7: Realized gain patterns (a)-(b) and group delay variations (c)-(d) for the 2.4-2.5 GHz band for the standard antenna without the device mechanics. Note that group delay variation is very low for both antennas and channel sounding works well in this ideal case.
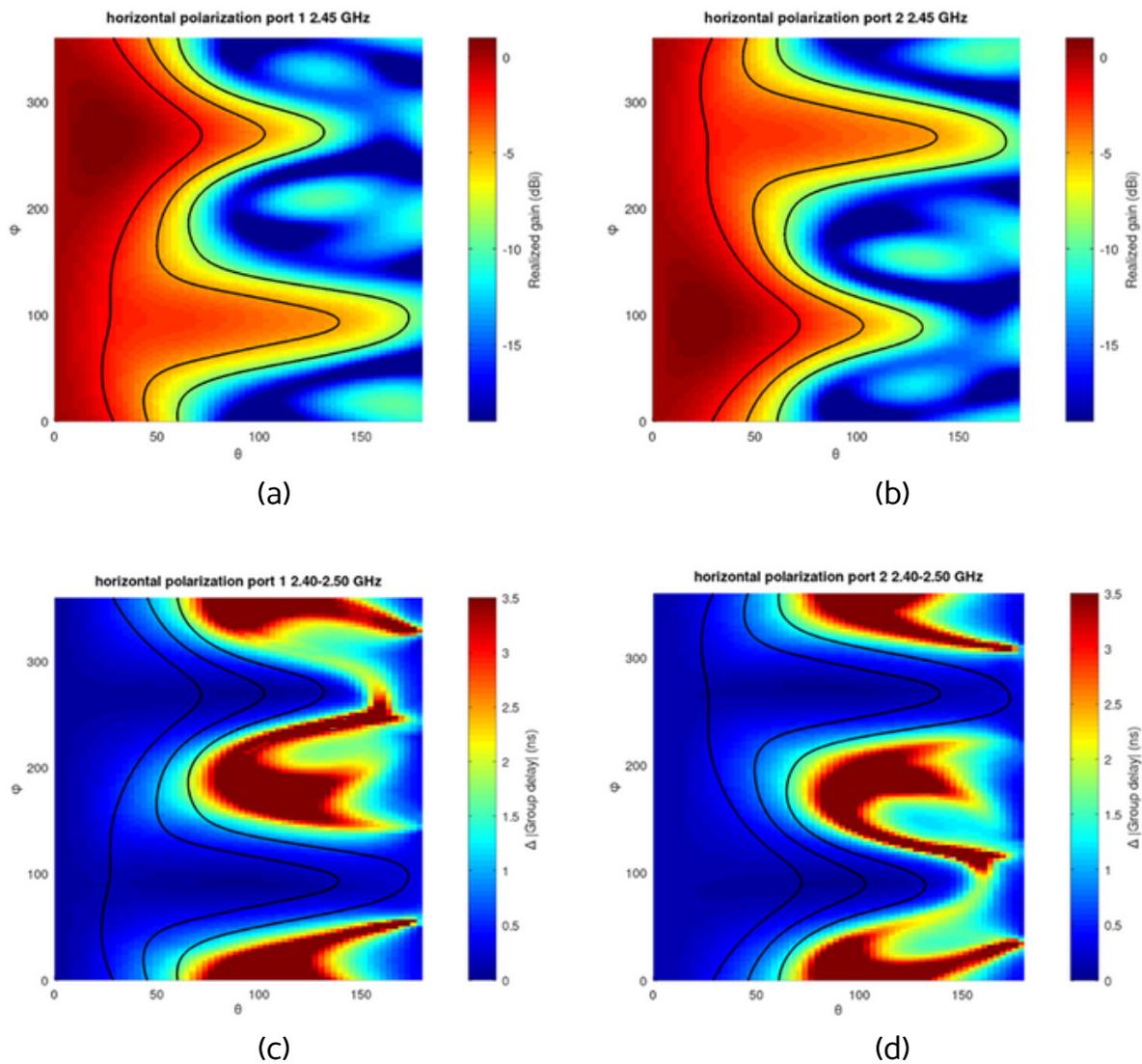
Figure 8:

Figure 8: Realized gain patterns (a)-(b) and group delay variations (c)-(d) for the 2.4-2.5 GHz band for both ports of the standard antenna with the device mechanics. Note that there are multiple overlapping regions with large group delay variation leading to ranging errors. These regions typically compare to the low gain regions (nulls).
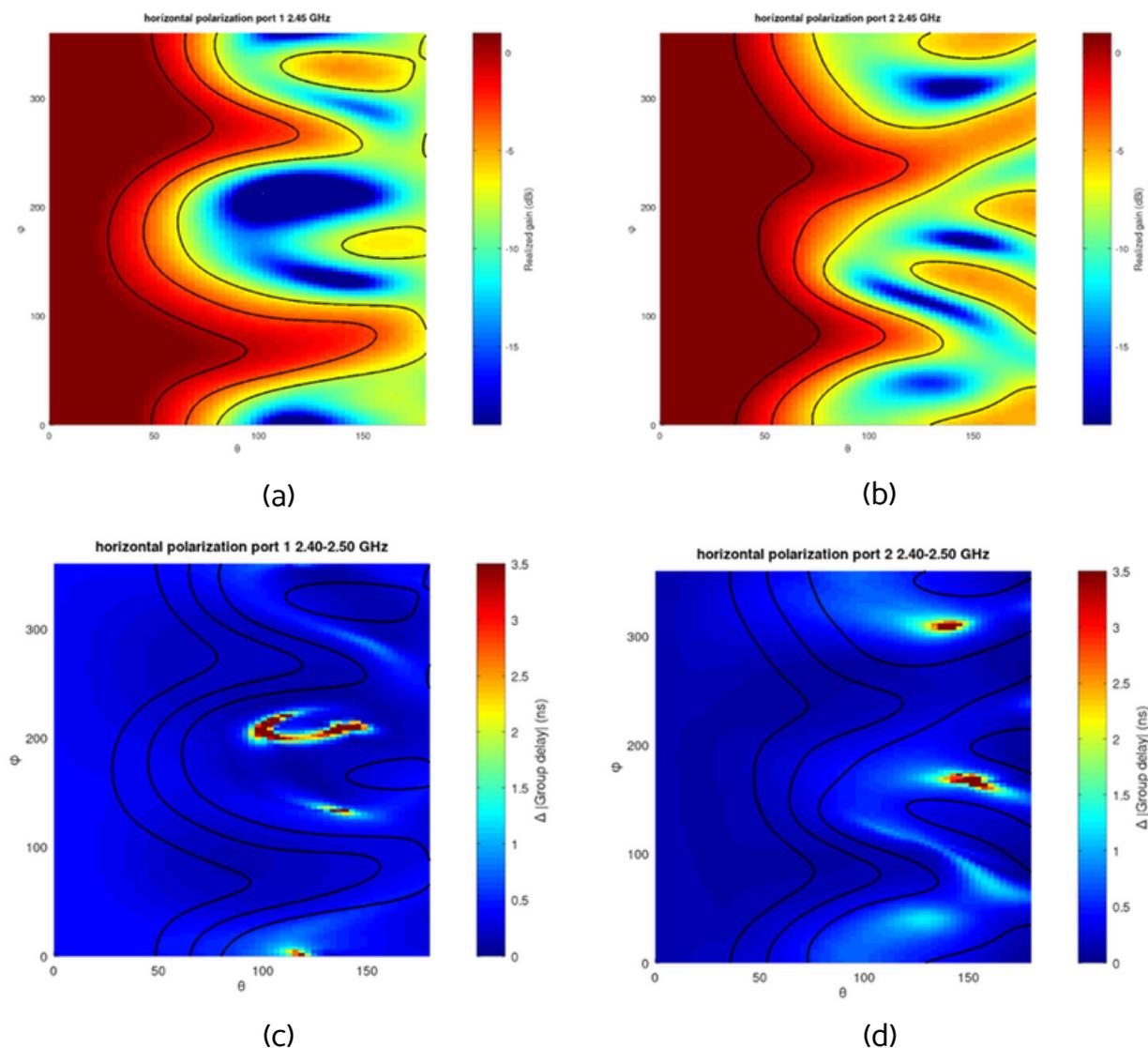
Figure 9:

(a)

(b)

(c)

(d)

Figure 9: Realized gain patterns (a)-(b) and group delays (c)-(d) for the 2.4-2.5 GHz band for custom antennas with the device mechanics. Note that the large regions of the group delay variation are few, and they are not overlapping between the antennas.
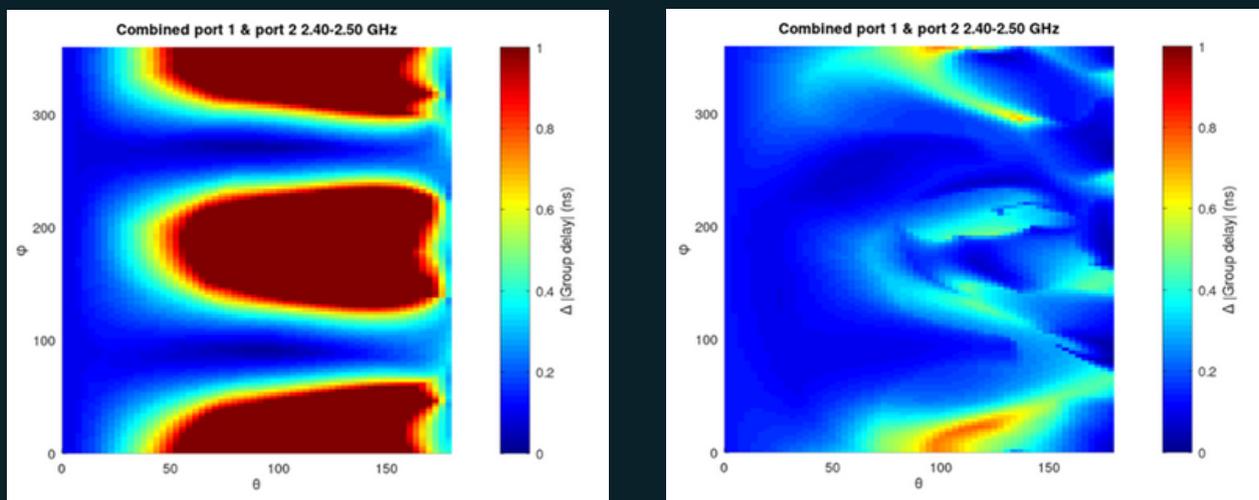
Figure 10:

Figure 10: Combined group delay variation when both antennas are considered for (a) standard antennas with device mechanics and (b) custom antennas with device mechanics. Note that the custom antennas have significantly lower group delay variation in all directions, ensuring precise and robust ranging.

Key finding:

Even if an antenna meets conventional communication metrics after integration, its group delay variation can still be unacceptable for channel sounding purposes. For many cases, better than -5 dB antenna total efficiency is more than enough to get the required range of the wireless link for Bluetooth devices. However, they are not suitable for Channel Sounding purposes when fully integrated device is considered. Only through simulation and testing in the final mechanical environment can true performance be ensured.

Key Lessons Learned &
Best Practices

- Always evaluate antennas in the final integrated product, not just in isolation or on development boards.
- Prioritize group delay variation as a design target, alongside efficiency and impedance matching.
- Custom antenna designs are often needed to maintain performance in mechanically complex devices.
- Component placement (battery, display, housing material, and other major elements) must be considered early in the design process to avoid costly redesigns.

Final board-level calibration is essential after integration to compensate for all mechanical and electrical offsets introduced by the complete product assembly.

Conclusion

Bluetooth Channel Sounding, introduced with Bluetooth 6.0, provides a foundation for centimeter-level distance measurement for a wide variety of devices. Realizing the full potential of this technology requires more than simply updating firmware or adding new hardware features, it calls for a holistic approach that addresses both advanced signal processing and careful antenna design.

Combining advanced signal processing and optimized antenna design enables developers to deliver reliable and precise results in real-world environments. Metirionic's Advanced Ranging Stack (MARS) addresses the signal processing side of this challenge by providing multipath-resilient algorithms for Bluetooth® Channel Sounding. Robust algorithms are essential to compensate for multipath effects, hardware non-idealities, and to enable full use of the new features offered by the latest Bluetooth specification.

At the same time, the accuracy and reliability of channel sounding depend fundamentally on the quality of the antenna system and its integration. Radientum's expertise ensures that antennas are optimized for low group delay variation, minimal nulls, and real-world performance in the final product, addressing challenges that often go unseen in standard development processes. Together, these technologies enable a practical path toward reliable, accurate, and production-ready Bluetooth ranging solutions.

If you are planning to integrate Bluetooth Channel Sounding into your device and want to ensure best-in-class ranging performance, we invite you to contact Metirionic and Radientum for tailored support and proven solutions.

Metirionic GmbH, headquartered in Dresden, Germany, specializes in advanced wireless positioning and ranging solutions. Since its founding in 2013, the company has focused on delivering proprietary and standard-compliant software technologies for distance measurement, positioning, and Real-Time Locating Systems (RTLS) applications, leveraging Bluetooth®, IEEE 802.15.4, and Ultra-Wideband (UWB) radios.

Building on these foundations, Metirionic focuses on advanced signal processing to improve ranging precision and robustness. Its Metirionic Advanced Ranging Stack (MARS) enhances Bluetooth® Channel Sounding with multipath-resilient algorithms, providing reliable and accurate distance estimation even in complex environments. MARS operates across various platforms, including Nordic's nRF54L15, external MCUs, and host PCs.

Metirionic also provides comprehensive engineering services, including firmware stack optimization and tailored integration support, guiding clients from specification and development to product launch. Their technology has been successfully applied in diverse scenarios, from indoor navigation for firefighters to industrial automation use cases, demonstrating robust performance even in challenging environments like tunnels and dense forests.

Radientum Oy, based in Finland, offers engineering services and consultancy with specialized proficiency in antenna, RF, and EMC/EMI disciplines. Founded in 2015, the company has assisted over 300 clients by providing solutions covering a broad range of technologies, including NFC, Bluetooth, UWB, LTE/5G, and 79GHz radar.

Radientum's service delivery is structured into three distinct models. Firstly, turnkey development projects encompass comprehensive antenna design, from initial concept simulation through to validated prototyping. Secondly, testing assignments are undertaken to measure, troubleshoot, and optimize existing antenna, RF, or electronic designs. The third model involves supplying consultants who utilize advanced tools and facilities, integrating fully with the client's development teams.

The firm excels in developing complex multi-antenna systems, miniaturized products featuring antennas designed for limited spaces, and wearable technologies, where antenna performance is significantly influenced by interaction with the human or animal body in real-world scenarios.

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