Trilogy 1: Bluetooth Channel Sounding — The Foundations —

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Date:	2026-07-01
Document Revision:	1.0

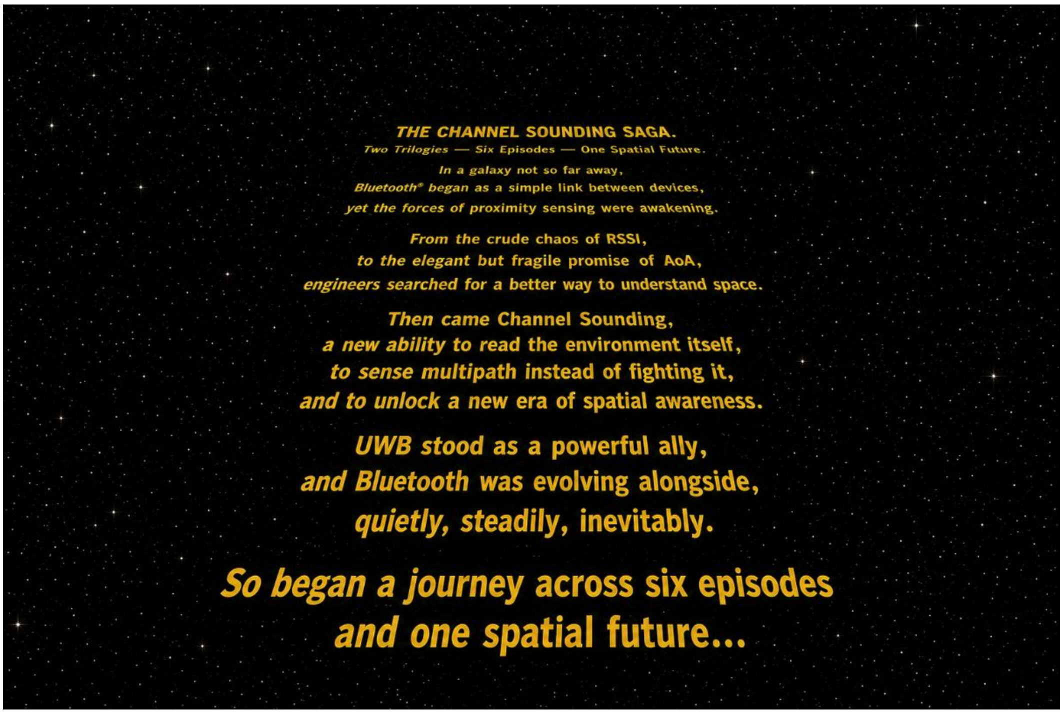
Content

1 Introduction

Bluetooth® has evolved far beyond its origins as a cable-replacement radio. Over the past decade, Bluetooth LE has taken on a new role as a sensing modality capable of real spatial awareness. This shift emerged through a sequence of breakthroughs in measurement, signal processing, and antenna design.

Trilogy 1 captures that progression. It explains how multipath transitioned from a source of error to a source of information, how timing and impulse responses reveal structure in the environment, and why antenna geometry is essential for robust spatial performance.

This whitepaper consolidates the first trilogy into a single, offline resource. It is designed for engineers, product teams, and ecosystem partners who want a clear, technically grounded understanding of how Bluetooth Channel Sounding works and why it matters.



2 Episode I — A New Hope for Spatial Awareness

Bluetooth began its life as a simple cable-replacement technology. A way to connect headsets, keyboards, and sensors. A workhorse radio, not a spatial instrument. Yet over the past decade, something unexpected happened: Bluetooth began learning to sense. Not all at once. Not cleanly. Not without missteps. But steadily, and inevitably. This is the story of that evolution.

2.1 From RSSI: The Blaster Era

RSSI was Bluetooth's first attempt at proximity. It was noisy, unstable, and easily fooled by walls, bodies, and multipath. It was a blaster, crude, imprecise, and impossible to aim. But it was a start. RSSI taught the industry two important lessons: proximity matters, and we needed something far better.

2.2 To AoA: Lightsaber Training Begins

Angle of Arrival (AoA) was the next leap. It introduced geometry, phase, and antenna arrays. It promised direction, not just distance. AoA was elegant in theory but fragile in practice: calibration drift, multipath distortion, large arrays, sensitivity to placement, and real-world environments that refused to behave. AoA was like early lightsaber training, powerful but difficult to master. Still, it pushed the industry forward. It showed that Bluetooth could do more.

2.3 Then Came Channel Sounding: Use the Force

Channel Sounding changed everything. Instead of fighting multipath, it embraced it. Instead of guessing distance from signal strength, it measured the structure of the channel itself. Instead of relying on a single angle, it extracted the full Channel Impulse Response (CIR), the fingerprint of the environment. This was the moment Bluetooth stopped being a radio and started becoming a sensor. Channel Sounding is the use-the-force moment: it sees the environment, it reads reflections, it understands space, it unlocks accuracy, and it works in real-world environments, not just labs. This is the foundation of modern Bluetooth spatial awareness.

2.4 UWB: A Powerful Tool in the Toolbox

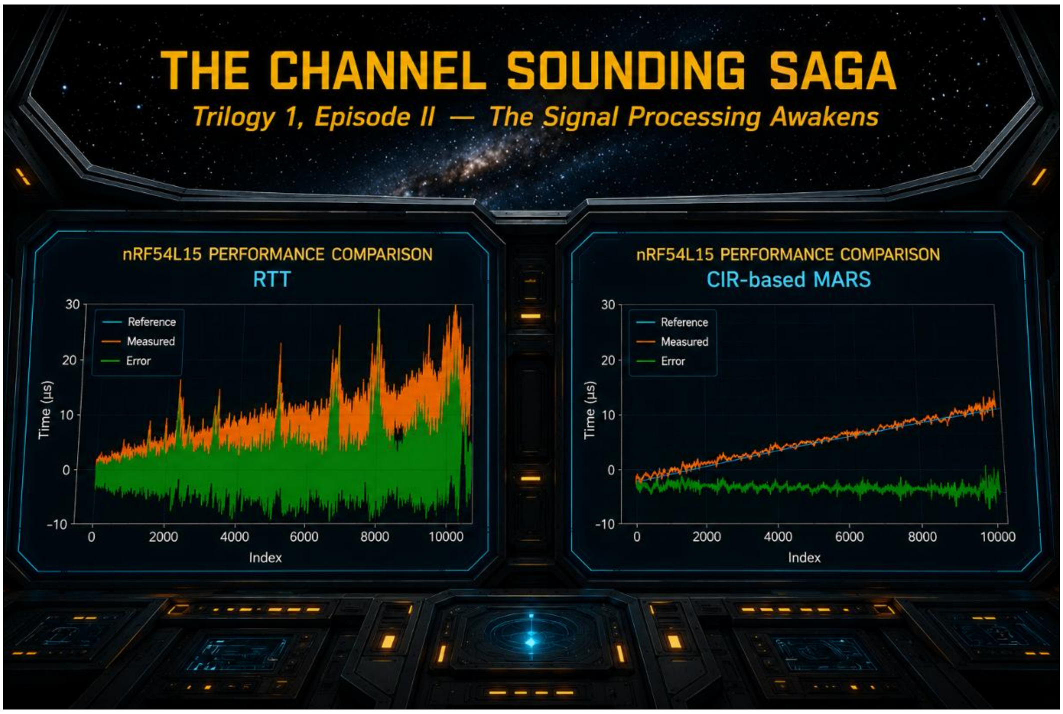
UWB has long been the benchmark for precision ranging. It remains a powerful ally in the spatial ecosystem. Bluetooth was evolving alongside it, quietly, steadily, inevitably. The future is not UWB or Bluetooth. It is UWB and Bluetooth, each serving different roles, each strengthening the other, each expanding the spatial landscape. Channel Sounding is Bluetooth's contribution to that future.

2.5 Why This Matters Now

Bluetooth is everywhere: phones, laptops, tags, wearables, sensors, industrial devices, and consumer electronics. Billions of devices, already deployed, are now gaining the ability to understand space. This is the inflection point. The moment the industry shifts from connectivity to awareness, from links to location, from radios to sensors. It all begins with Channel Sounding.

2.6 What Comes Next

Episode I sets the stage. The evolution. The awakening. The new hope. But the real power of Channel Sounding emerges in the next chapter.
Up next: Episode II — The Signal Processing Awakens. RTT, PBR, CIR, and the algorithms that make spatial awareness real. The Force is strong with this one.



3 Episode II — The Signal Processing Awakens

Bluetooth's journey toward spatial awareness did not begin with antennas or geometry. It began with signal processing. Long before Channel Sounding became a headline feature, engineers were searching for ways to extract more meaning from the radio itself. They pushed past simple strength measurements and into the structure of the signal, looking for timing, patterns, and reflections that could reveal distance more reliably. This is where the awakening truly began, in 2013. The earliest experiments showed that Bluetooth signals contained far more structure than anyone expected.

3.1 RTT: The First Step Toward Time

Round Trip Time was the earliest attempt to measure distance through timing. A device would send a packet, wait for a response, and measure how long the exchange took. The idea was simple, but Bluetooth's architecture made it difficult. Processing delays, scheduling uncertainty, and radio turnaround times introduced errors that could not be calibrated out. RTT showed that timing mattered, but it also showed that timing alone was not enough. It marked the moment when Bluetooth stopped looking only at signal strength and started looking at time, which remains important today, just not sufficient.

3.2 PBR: A Better Way to Measure Delay

Phase Based Ranging refined the idea. Instead of relying on a single timing exchange, PBR used known sequences and phase measurements across different frequencies in the Bluetooth band to characterize the RF channel between two devices more accurately. This reduced some of the uncertainty that limited RTT and brought Bluetooth closer to practical distance measurement. PBR was a meaningful step forward because it introduced structure and discipline into the measurement process. It showed that Bluetooth signals contained more information than previously assumed. But PBR still lived in the frequency domain: it could measure the channel, not fully interpret it. In real environments, multipath, reflections, and frequency-selective fading still made it difficult to separate the direct path from everything else, which limited consistency and prevented PBR alone from delivering robust spatial awareness.

3.3 CIR: A Better Way to Understand Multipath

The Channel Impulse Response is where the awakening becomes unmistakable. If PBR characterizes the channel in the frequency domain, CIR is its time-domain representation: it describes how an impulse would propagate through that channel. This is where signal processing truly awakens. The phase relationships can be measured, but CIR must be extracted and interpreted through signal processing. Once that happens, every reflection, every path, and every interaction between the signal and the environment becomes visible. CIR is the fingerprint of the space between two devices. It reveals not only how far the signal traveled, but how it traveled. This is the foundation of Channel Sounding. It is the moment Bluetooth transitions from estimating distance to understanding the environment. CIR is the signal processing breakthrough that makes spatial awareness possible.

3.4 Why CIR Matters

CIR transforms the problem. With RSSI, the question was how strong the signal is. With AoA, the question was where the signal appears to come from. With CIR, the question becomes what the environment looks like. This shift is profound. It enables ranging in real-world environments, not just controlled spaces. It allows Bluetooth to use multipath instead of being defeated by it. Instead of collapsing everything into a single noisy value, CIR exposes the structure of the channel so algorithms can identify likely direct-path components, distinguish strong reflections, and make robust distance estimates even in dense multipath conditions. It provides raw I and Q data for algorithms that can extract distance with accuracy in the 20 cm +/- range. CIR is the engine behind modern Bluetooth spatial sensing.

3.5 Metirionic's Role in the Awakening

While the Bluetooth ecosystem explored timing and delay, Metirionic focused on the deeper structure of the signal. The company built tools, algorithms, and measurement techniques that made CIR practical, reliable, and deployable. This work did not happen overnight. It took years of engineering, testing, and refinement. But it laid the groundwork for what Bluetooth Channel Sounding would eventually become. The signal processing awakening was not just a theoretical milestone. It was a practical one, shaped by real engineering and real systems.

3.6 From Research to Tools and Services

Metirionic's evaluation application gives engineers the ability to visualize both sides of the channel: signal vector magnitude and phase over frequency, and the resulting CIR in the time domain. It lets users inspect reflections, compare channel behavior across setups, and understand how the RF environment shapes ranging performance in real-world conditions. It turns abstract signal processing into something tangible and measurable. Alongside this, Metirionic's engineering services support customers through proof-of-concept development, methodical testing in wired, anechoic, indoor, test-track, and outdoor environments, and performance validation at the product and system level. These capabilities help bridge the gap between theory and deployment, making Channel Sounding accessible to companies building next-generation spatial systems and helping teams reach useful results faster, with fewer blind iterations.

3.7 What Comes Next

Episode II reveals the foundation beneath Channel Sounding. Timing. Delay. Structure. Reflection. The awakening of signal processing. But the story is not complete. Spatial awareness requires more than signal structure. It requires geometry. It requires antennas. It requires the ability to understand not only how far, but from where.

Up next: Episode III - Return of the Antennas. Single, dual, and quad configurations, and why geometry matters more than most people realize.

4 Episode III — Return of the Antennas

Bluetooth Channel Sounding is built on signal processing, but signal processing alone does not deliver reliable spatial awareness. The radio still has to interact with the physical world, and that interaction is governed by antennas. Antennas shape how energy radiates, how reflections form, how nulls appear, and how much of the Channel Impulse Response can actually be trusted. Episode III is where antennas return to center stage, and where geometry starts to matter as much as algorithms.

4.1 Single Antenna: The Limits of Simplicity

Early Channel Sounding experiments often began with a single antenna. In ideal conditions, that can work surprisingly well. On a bare PCB with a clean ground plane and few mechanical constraints, radiation patterns can remain stable and group delay variation can stay low enough for useful ranging. But products do not live on bare PCBs. Housings, batteries, displays, cables, nearby metal, and high-permittivity plastics all change antenna behavior. Resonances shift, patterns distort, and non-linear group delay variation can appear across the band. Those effects may be tolerable for communication, but they become a direct source of ranging error for Channel Sounding. A single antenna is simple, but it cannot avoid nulls, cannot cover every device orientation equally well, and cannot provide the consistency that robust spatial systems require.

4.2 Dual Antennas: Diversity Makes Ranging Practical

The first real breakthrough comes with diversity. Two antennas do not create more spectrum, but they do create another view of the channel. Where one antenna falls into a deep fade, the other may still see a cleaner direct path. Where one antenna is distorted by orientation or nearby materials, the other may remain more stable. That matters because Channel Sounding depends on extracting useful structure from the channel, not just on receiving enough energy to stay connected.
This is why dual-antenna systems are such an important step. They reduce the chance that a single bad radiation null or local integration problem dominates the entire measurement. They make CIR

extraction more stable, reduce outliers, and improve robustness in non-line-of-sight and orientation-sensitive situations. In practice, this is often the point where Channel Sounding starts to move from an interesting lab capability toward something a product team can trust.

4.3 Geometry Turns Ranging into Spatial Awareness

Once multiple antennas are available, the next question is not only how many, but where they are placed and how the system uses them. Geometry is what turns antenna diversity into spatial awareness. Different antenna placements create different observations of the same propagation environment, and those observations can be fused to improve both robustness and directional understanding.

This is why asymmetric architectures are so practical. In many real systems, the infrastructure side can carry more RF complexity than the mobile side. A door lock, anchor, gateway, or access point can support multiple antennas and switching, while the phone, tag, or wearable stays simpler and lower power. That balance is attractive because it moves cost and complexity to the fixed device while still allowing the system to gather multiple spatial observations during the same Channel Sounding procedure.

Different layouts serve different goals. A 1x4 linear array is useful when bearing resolution matters on the infrastructure side. A 2x2 layout can provide more balanced angular coverage. A 1x2 setup is a compact compromise when space is limited. A 2x4 interaction becomes relevant when both sides contribute some diversity. These geometries do not change the underlying Channel Sounding procedure, but they strongly influence angular resolution, calibration stability, and how reliably the system can separate a likely direct path from reflections.

With four antennas, the system gains enough spatial structure to do more than stabilize distance. It can begin to estimate bearing by comparing how the channel evolves across antenna positions. That does not happen automatically. The array must be physically stable, the switching path must be well controlled, and phase behavior across the antennas must remain consistent enough to interpret. But when those conditions are met, geometry stops being an implementation detail and becomes the enabler of true spatial awareness. This is also the direction Metirionic has demonstrated publicly, including at Embedded World 2026.

Antenna spacing is critical for achieving reliable phase diversity. For Bluetooth Channel Sounding, the industry baseline is $\lambda/4$ spacing, approximately 3 cm at 2.4 GHz. Metirionic supports customers in evaluating these tradeoffs and selecting optimal configurations for distance and angle estimation. Our test environments, including anechoic chambers, attenuation labs, indoor tracks, and outdoor setups, allow us to validate antenna and ranging performance under controlled and real-world conditions.

4.4 Why Integration Matters More Than the Datasheet

Antenna performance on a development board does not predict antenna performance in a finished product. This is one of the easiest mistakes to make and one of the most expensive to discover late. A design can look strong in communication metrics such as efficiency or gain yet still behave poorly for Channel Sounding once it is integrated into a real mechanical environment.

The reason is that Channel Sounding is unusually sensitive to phase behavior, group delay variation, and radiation-pattern stability across the band. Displays, batteries, metal structures, plastics, and packaging constraints can all introduce behavior that is acceptable for connectivity but damaging for ranging. Deep nulls, detuning, mode changes, and unexpected delay variation can produce unstable results even when the link budget appears healthy. That is why final product integration has to be evaluated through simulation, lab measurement, and real-world testing rather than assumed from component-level performance. It is also why collaboration across the ecosystem matters, from antenna specialists such as Radientum to module suppliers such as Ezurio.

4.5 Metirionic's Contribution to Antenna-Aware Systems

Metirionic's work in Channel Sounding has focused on making these effects visible and actionable. The evaluation application helps engineers inspect channel behavior across antennas, compare how different RF paths behave, and identify where integration is introducing instability into the measurement. The engineering work around it supports antenna selection, switching strategy, calibration, and validation across wired, anechoic, indoor, outdoor, and application-specific environments.

That matters because antenna decisions are not isolated RF choices. They affect system architecture, industrial design, validation effort, deployment risk, and ultimately time to market. The practical lesson of Episode III is simple: if Episode II showed that signal processing awakened the channel, Episode III shows that antennas determine whether that insight survives contact with the real-world.

4.6 What Comes Next

Episode III shows that antennas are not accessories. They are part of the sensing system itself. They determine how reliably Channel Sounding performs, how robust the measurements remain across orientations and environments, and whether a product can progress from basic ranging to useful spatial awareness.

But antennas alone are still not enough. Real systems have to remain stable while devices move, users rotate, and environments change. That is where radio measurements have to be fused with motion and context.

Up next: Episode IV - Sensor Fusion Strikes Back. How IMUs, motion models, and environmental context help stabilize spatial awareness in the real-world.

5 Conclusion — The Foundations Are Set

Trilogy 1 establishes the essential building blocks of Bluetooth Channel Sounding. The historical evolution, the signal processing core, and the antenna and geometry layer together form a complete foundation for spatial awareness.

This is also where the Metirionic message becomes clear. Channel Sounding is not just a set of concepts. It is a deployable capability. The techniques described in this trilogy are already being used to build real systems, and Metirionic provides the tools, algorithms, and engineering support needed to bring these ideas into production.

Our work spans the full chain:

- Channel Sounding algorithms
- Measurement and evaluation tools
- Integration support for industrial and embedded devices
- Performance optimization for real-world environments

Trilogy 1 outlines the foundations. Metirionic helps customers build what comes next. This includes the industry's first demonstration of simultaneous distance and angle estimation using Bluetooth Channel Sounding, announced and shown publicly in March 2026 during Embedded World Germany, which marked a turning point in the commercial viability of spatially aware Bluetooth systems.

6 Looking Ahead: Trilogy 2 — Sensor Fusion Strikes Back

The next arc moves beyond radio alone. Trilogy 2 will explore how Channel Sounding combines with motion, context, and stability to create robust, deployable spatial systems. It will also highlight the growing ecosystem of partners working to commercialize these capabilities.

This is where the technology transitions from breakthrough to product.

About Metirionic

Metirionic develops signal processing algorithmic solutions for mobile and IoT applications, along with evaluation tools and engineering services that help customers accelerate development, validate performance, and bring next-generation wireless products to market. The company's expertise includes advanced distance and angle-estimation techniques for Bluetooth and other short-range wireless systems, supporting industrial, consumer, and IoT applications. More info at https://metirionic.com.