

BLE-203

Accurate Distance Estimation Using Channel Sounding



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Channel Sounding Overview

Channel Sounding Overview

Measure distance between two devices using

- Phase-based Ranging (PBR)
- Round Trip Time (RTT)

RTT and PBR operates across 2.4 GHz band

- Standard specifies up to 72 channels
- Random hopping pattern

Connection-Oriented 2-way ranging with two roles

- Initiator: device that wishes to calculate distance from itself to another device
- Reflector: device responding to initiator

Supports up to 4 antenna paths between devices

- 8 possible antenna combinations

Multiple security features included in the standard

Can be combined with Angle of Arrival / Departure (AoA/AoD)

- Enables position estimation with single initiator/reflector pair

Bluetooth SIG Specification

- Channel Sounding specification
<https://www.bluetooth.com/channel-sounding-tech-overview/>

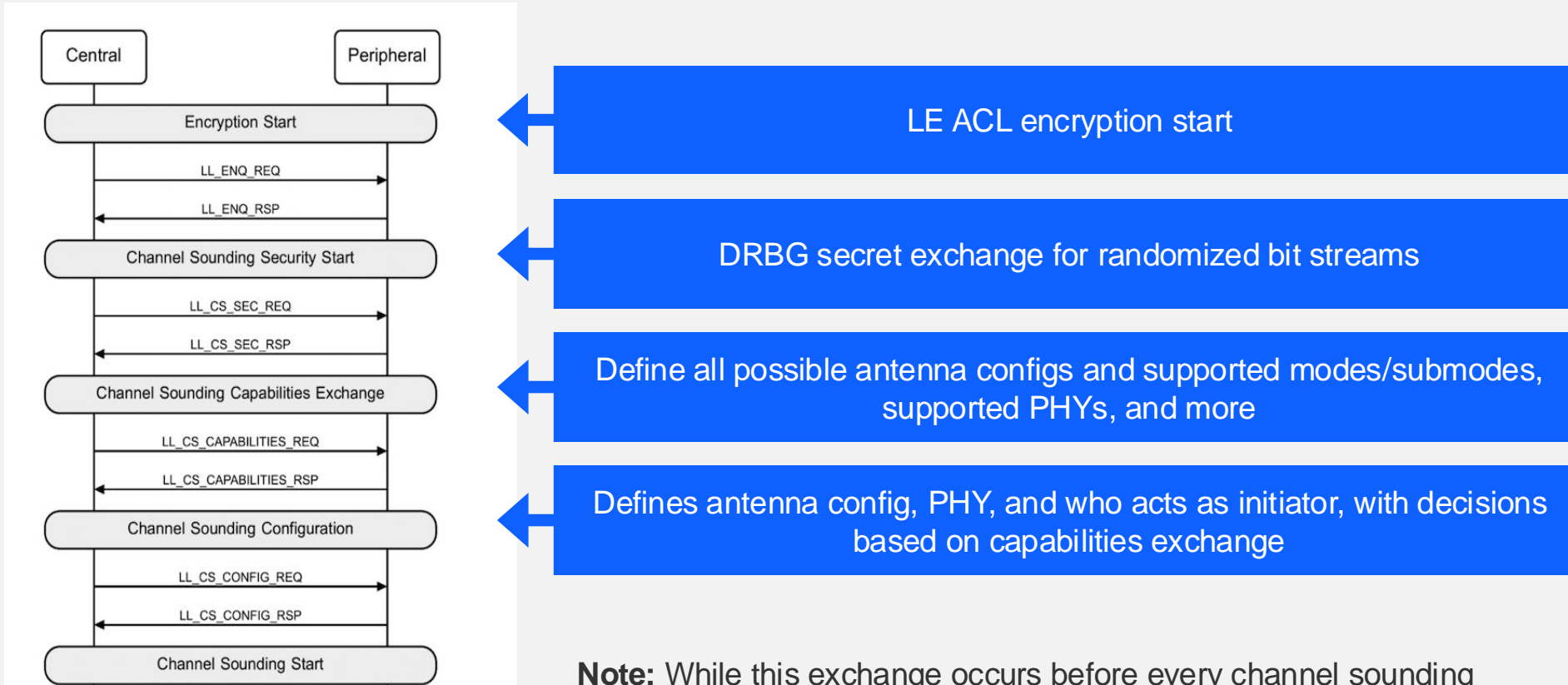
What's included in the spec:

- RF and link layer timing and functional requirements
- Mandatory vs. optional features and modes
- Guidance on antenna configurations and security features

What's not included in the spec:

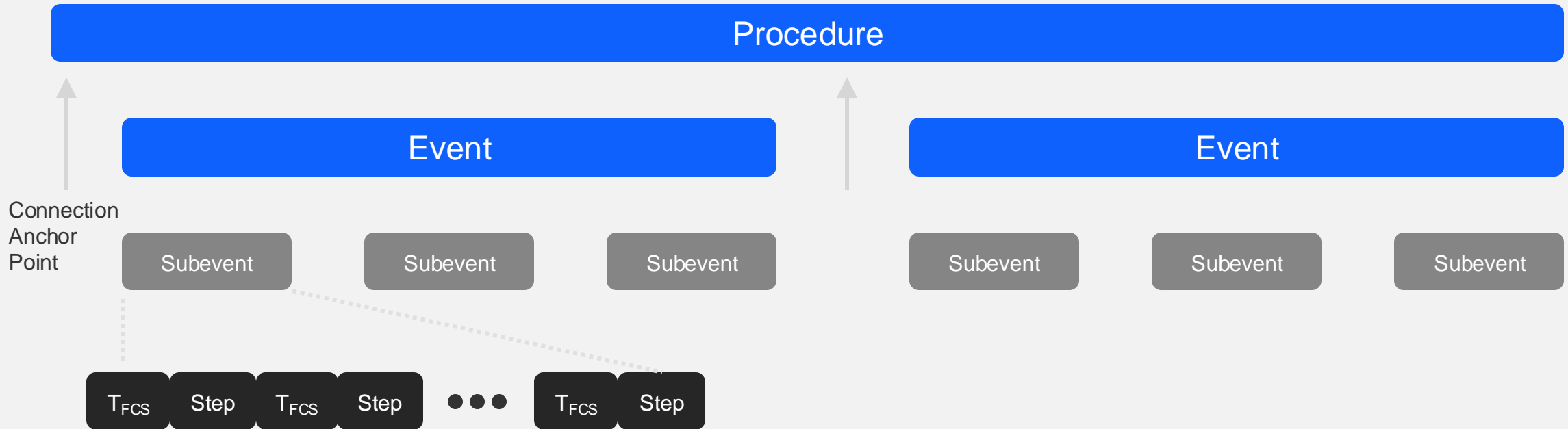
- Distance measurement algorithm recommendations and optimizations

Channel Sounding setup between central and peripheral



Note: While this exchange occurs before every channel sounding procedure start, some of these steps can be skipped during setup if information has been cached previously

Channel Sounding Procedure -> Events -> Subevents -> Steps



Procedures, composed of **events**, can span multiple connection intervals

Subevents are required to complete within single connection interval

Steps correspond to setup, PBR, or RTT ranging, defined as **4 modes**

Channel Sounding Step Modes

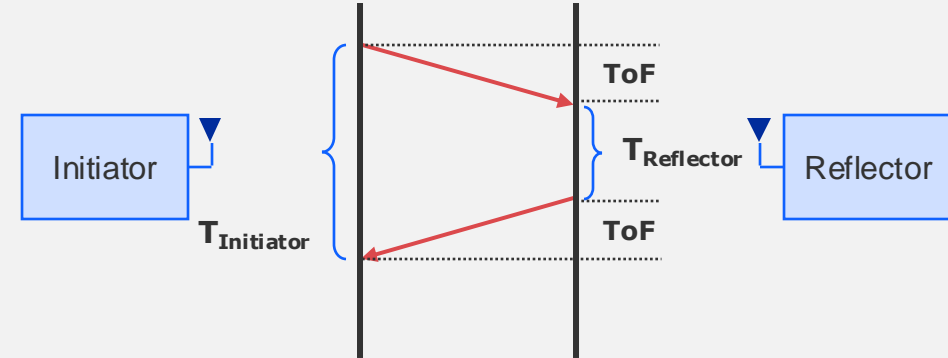
Mode-0: Calibration

Compensates for clock drift and frequency offset

Results in fractional frequency offset table

Required

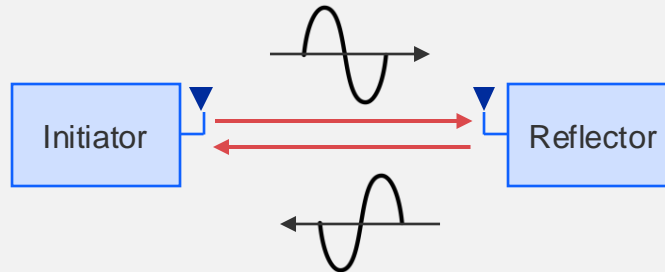
Mode-1: Round trip time



- CS SYNC packets exchanged between initiator and reflector

Required

Mode-2: Phase based ranging



- CS Tone exchanged between initiator and reflector
- Each antenna path exercised in each step

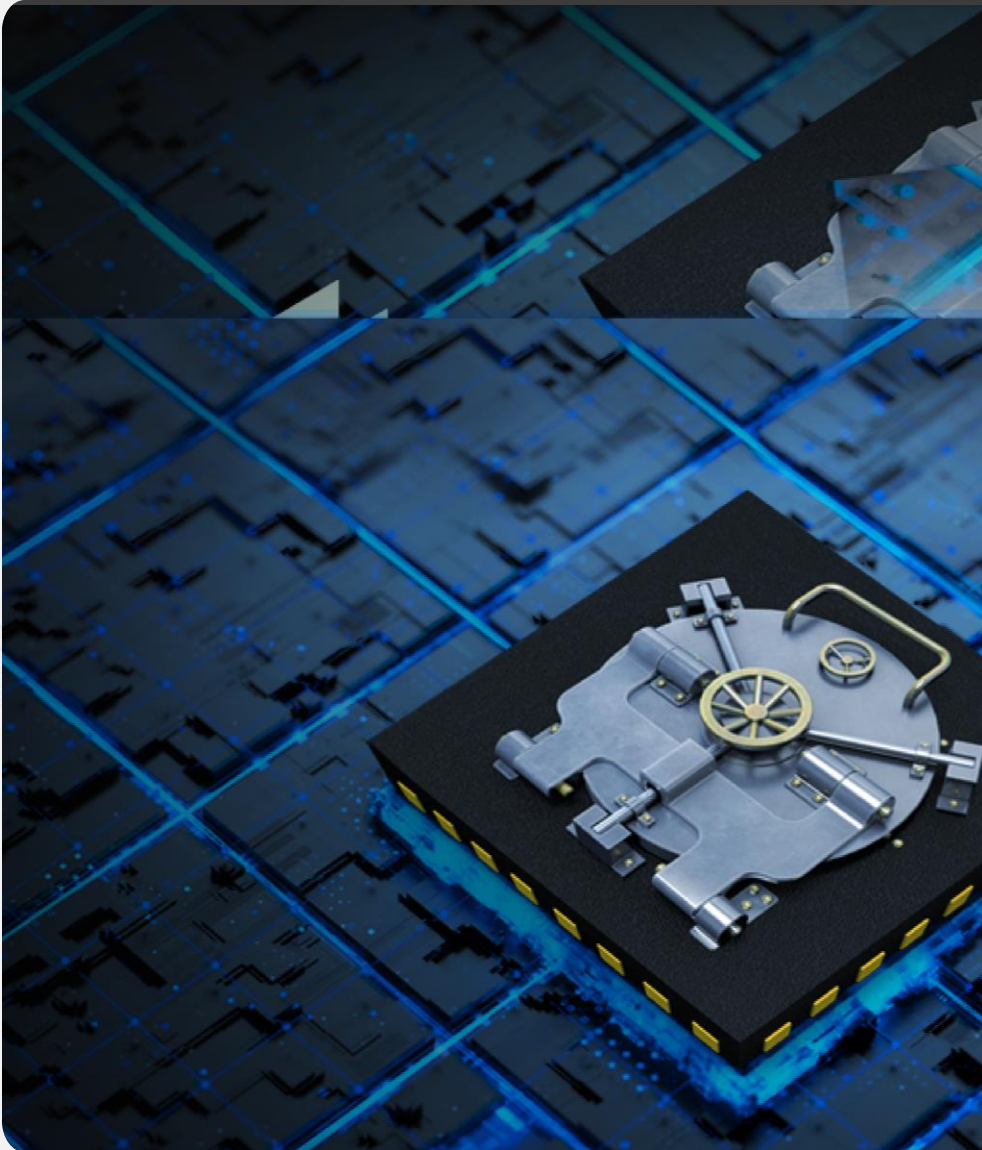
Required

Mode-3: PBR+RTT

- Combined PBR and RTT in each step
- RTT distance measurement can be cross-checked with PBR results
- Provides higher security as a mismatch in distance estimation can indicate relay attack

Optional

Channel Sounding Security Features



Potential vulnerabilities

- Spoofing
- Man in the middle (MITM) or relay attacks

Deterministic random bit generator (DRBG)

- Initialized during security start data exchange
- Scrambles bit sequences between initiator and reflector
- Randomizes payloads in tone extensions, antenna path selection, and more

Cross-checking PBR with RTT

- Can be done in Mode 1 steps with mode 2 as submode or using Mode 3
- Mismatch in distance estimation indicates relay attack

Normalized Attack Detector Metric (NADM)

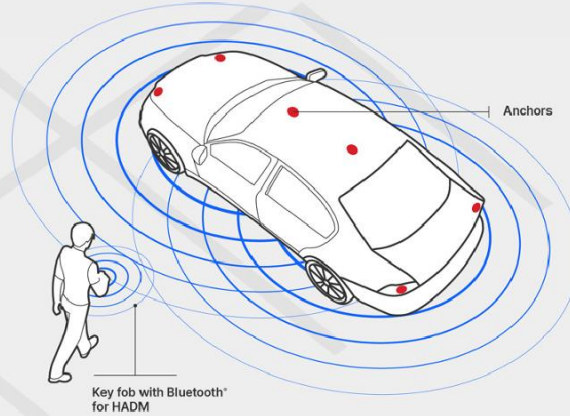
- Detects unexpected bit transitions or phase changes in received signals
- Standard does not include implementation requirements,
- Prescribes scale for how anomalies are classified
- Optional feature

Bluetooth® LE Location Services Comparison

	RSSI	Angle of Arrival	Channel Sounding
Localization metric	Resolve distance estimation from transmitter signal strength	Resolve relative angle between two points	Resolve distance between two points using time of flight and phase-based ranging
Antenna requirements	Single antenna	Multi-antenna required by spec	Multi-antenna not required, but useful for optimal position resolution
Bluetooth® LE connectivity	Connection-oriented and connectionless	Connection-oriented and connectionless	Connection-oriented
Performance metrics	+/- 5 m, high susceptibility to multipath interference	+/- 3 degrees accuracy – azimuth +/- 5 degrees accuracy – elevation	+/- .3 m < 5m with PBR ranging +/- 0.5 m > 5m with PBR ranging
Solution advantages	<ul style="list-style-type: none"> Ubiquitous support for RSSI measurements in existing Bluetooth LE products 	<ul style="list-style-type: none"> Scalable solution for real time position tracking Supports 5-10 year battery life 	<ul style="list-style-type: none"> Small form factor with flexible antenna design Feature-add for security by proximity

Channel Sounding Applications

Channel Sounding for Geo-Fencing Applications



Unlock on Approach:

- Remote Keyless Entry
 - Zonal detection through ranging for secure vehicle access
 - User enhancement with wake/welcome response
- Proximity-based locking and unlocking
 - Automatic door lock & unlock at a certain distance from it

Loss Prevention

- Retail theft prevention
 - Tracks the location of high-value items within the store and triggers alarms if they are moved outside designated areas.
- Geofenced Notifications for Unauthorized Movement
 - Sends alerts upon detection of unauthorized movement or movement of goods outside a certain defined boundary.



Channel Sounding in an Indoor Facility

Access Control

- Restrict access to unauthorized personnel
- Send alerts to local servers/cloud if anyone dwells in the area for too long

Entry access

Authenticate and grant access to authorized workers when they approach the door



Asset management

- Coarse localization of inventory inside the facility
- Increase worker efficiency

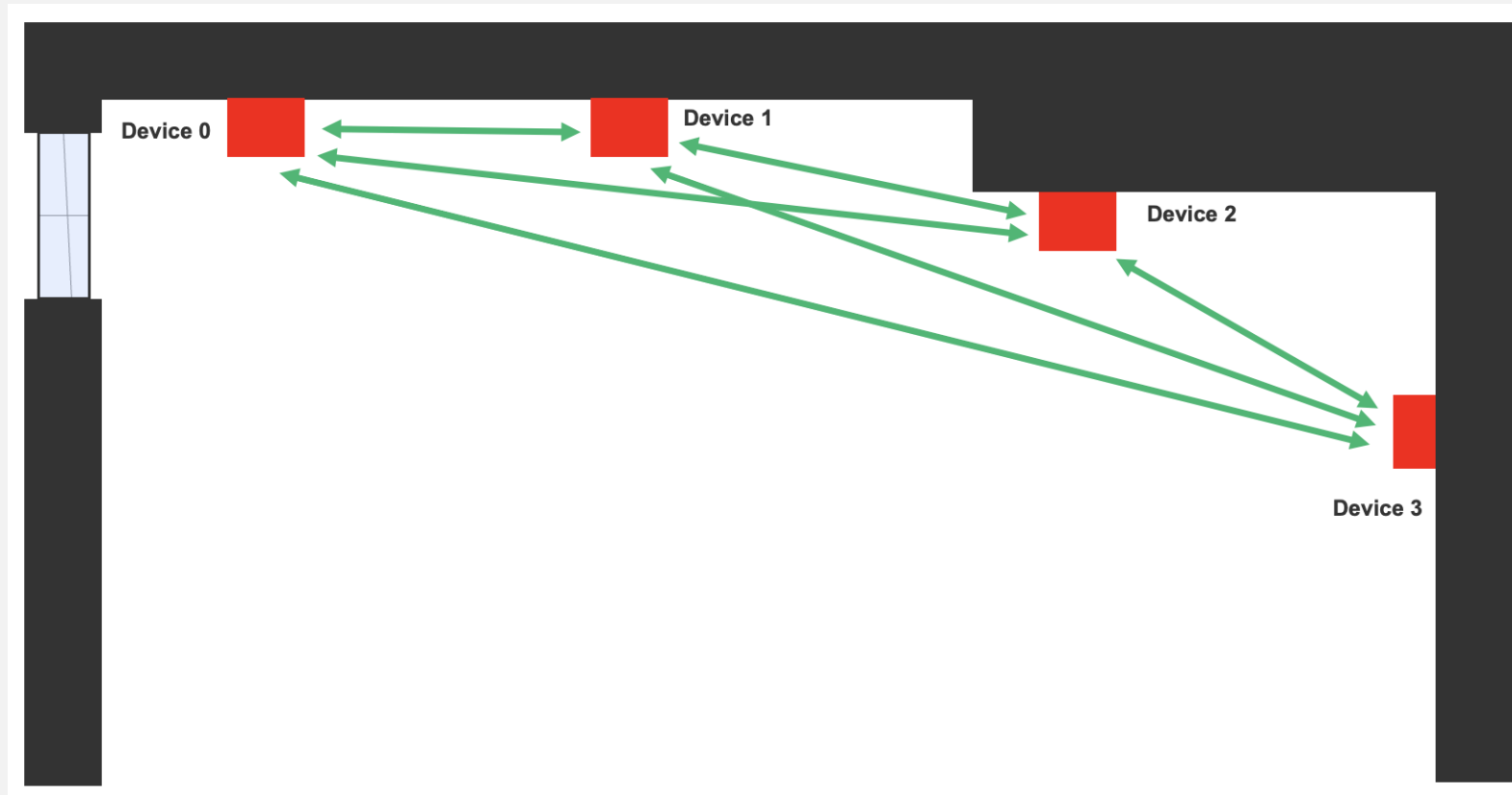
Distance Measurement Demo



Distance Measurement Demo



Channel Sounding for Static Device Positioning



- Enables device positioning for static devices like luminaries or access points.
- The devices act as initiators and reflectors to calculate the distance from each other to create a geometric map.

Static Device Positioning Demo



Static Device Positioning



Performance

Performance in Indoor Office Environment



- **Ceiling rail infrastructure**

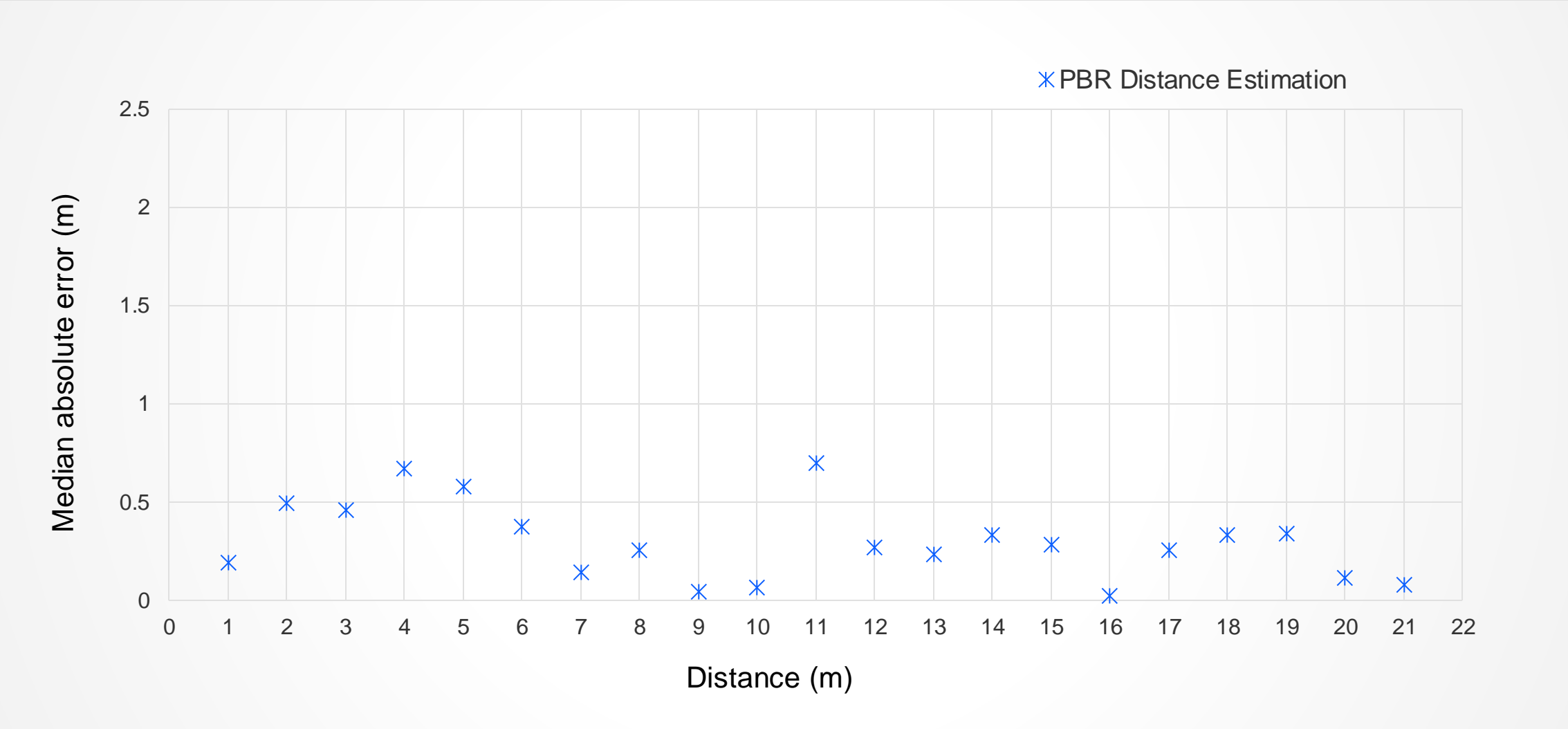
- Internal test environment
- Multiple stationary EFR32 devices placed at different locations
- Mobile EFR32 device for controlled measurements (repeatability)

- **Challenges - heavy multi-path in an indoor office setting**

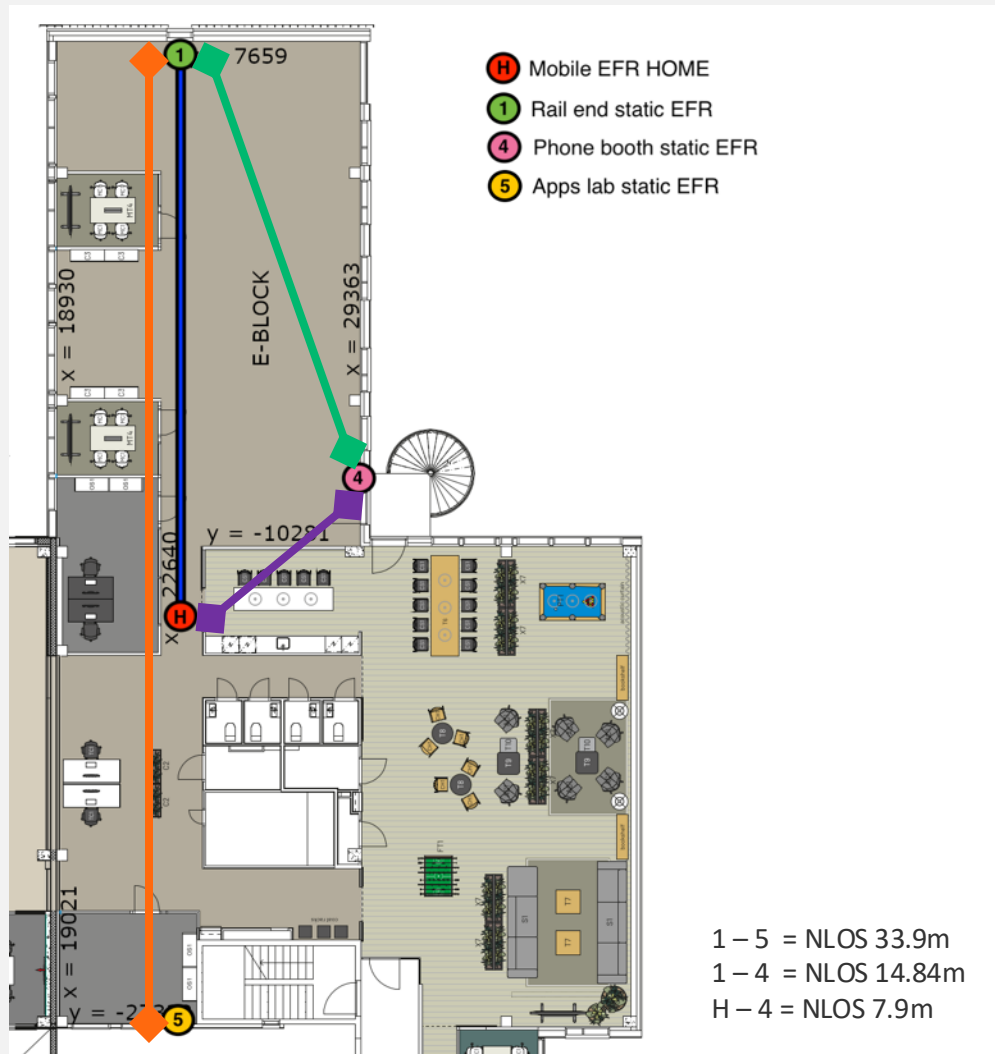
- **Statistical analysis**

- Static measurements at multiple distances up to 30 meters
- Hundreds of measurements per distance to determine min/max, mean, median, std, absolute error

Indoor Performance Result – Line of Sight



Indoor Performance Result – Non-Line of Sight



Nodes	Distance	Obstacles	Error
■ 1 & 5	33.9m	Walls	+/- 0.3 m
■ 1 & 4	14.84m	Cubicles	+/- 0.2 m
■ H & 4	7.9m	Walls, Kitchen	+/- 0.5 m

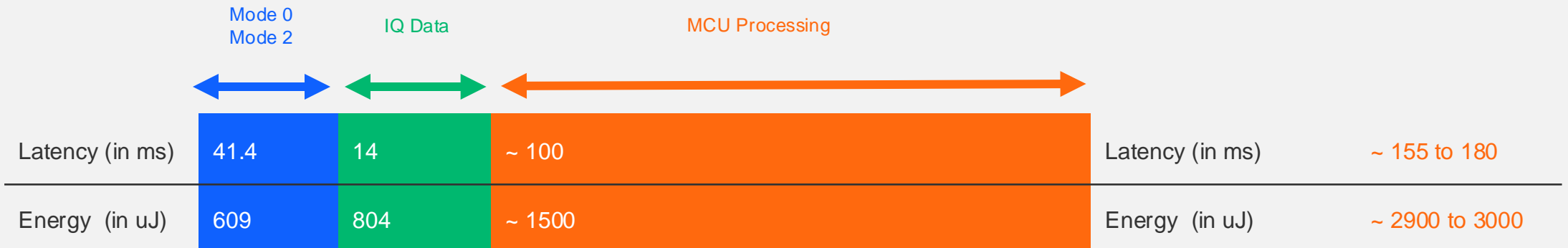
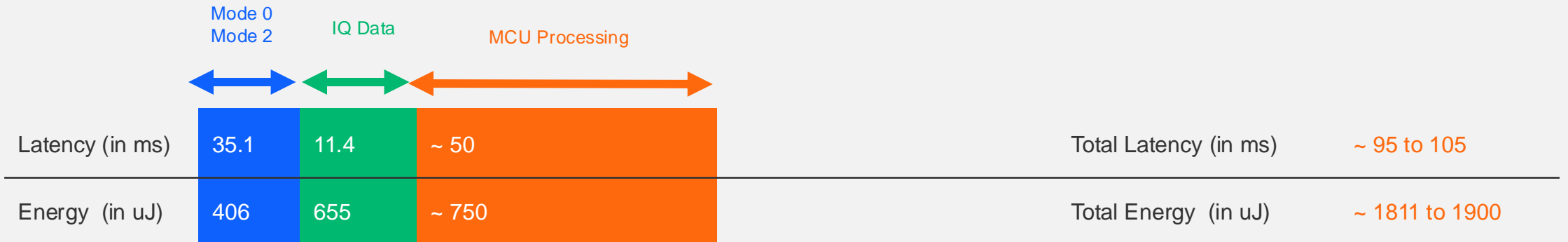
■ NLOS performance indoors

- Setup in office space with nodes on the ceiling
- Nodes face various obstacles: walls, kitchen, office cubicles
- Utilizes antenna diversity and intra-event antenna switching
- Dual-antenna solution ensures robust accuracy

Single antenna vs Dual antenna

	Single Antenna (4198A)	Dual Antenna (2606A)
Accuracy	Less accurate due to fewer antenna paths and limited multipath information.	More accurate with better spatial resolution and enhanced multipath resolution.
Power Consumption	Lower power consumption. Power numbers - TBD	Higher power consumption. Power numbers - TBD
Antenna Diversity	No antenna diversity, which can affect signal robustness.	Offers antenna diversity, which improves signal quality and robustness.
Reliability	Reliable in simpler environments.	Very reliable in complex environments with high multipath.
Use Cases	Suitable for basic Channel Sounding applications.	Ideal for advanced applications requiring precise channel estimation.

Single antenna vs Dual antenna



Silicon Labs Offerings

BG24: Optimized for Battery Powered, Channel Sounding-enabled IoT Devices



- 5x5 QFN40 (26 GPIO), AEC-Q100
- 6x6 QFN48 (32 GPIO), AEC-Q100
- 3.1x3.0 WLCSP42

DIFFERENTIATED FEATURES

Ultra small form-factor

- 3.1 x 3.0 WLCSP package

+20 dBm output power

- Eliminates need for external power amplify

AI/ML accelerator

- Accelerates inferencing while reducing power consumption

Secure Vault High

- Protects data and device from local and remote attacks

20-bit ADC

- 16-bit ENOB for advance sensing

Improved Coexistence

- Ideal for gateways and hubs

PLFRCO

- Eliminates need for 32 kHz crystal

DEVICE SPECIFICATIONS

High Performance Radio

- Up to +19.5 dBm TX
- -97.6 dBm RX @ BLE 1 Mbps

Efficient ARM® Cortex®-M33

- Up to 78 MHz
- 1536kB Flash, 256kB RAM

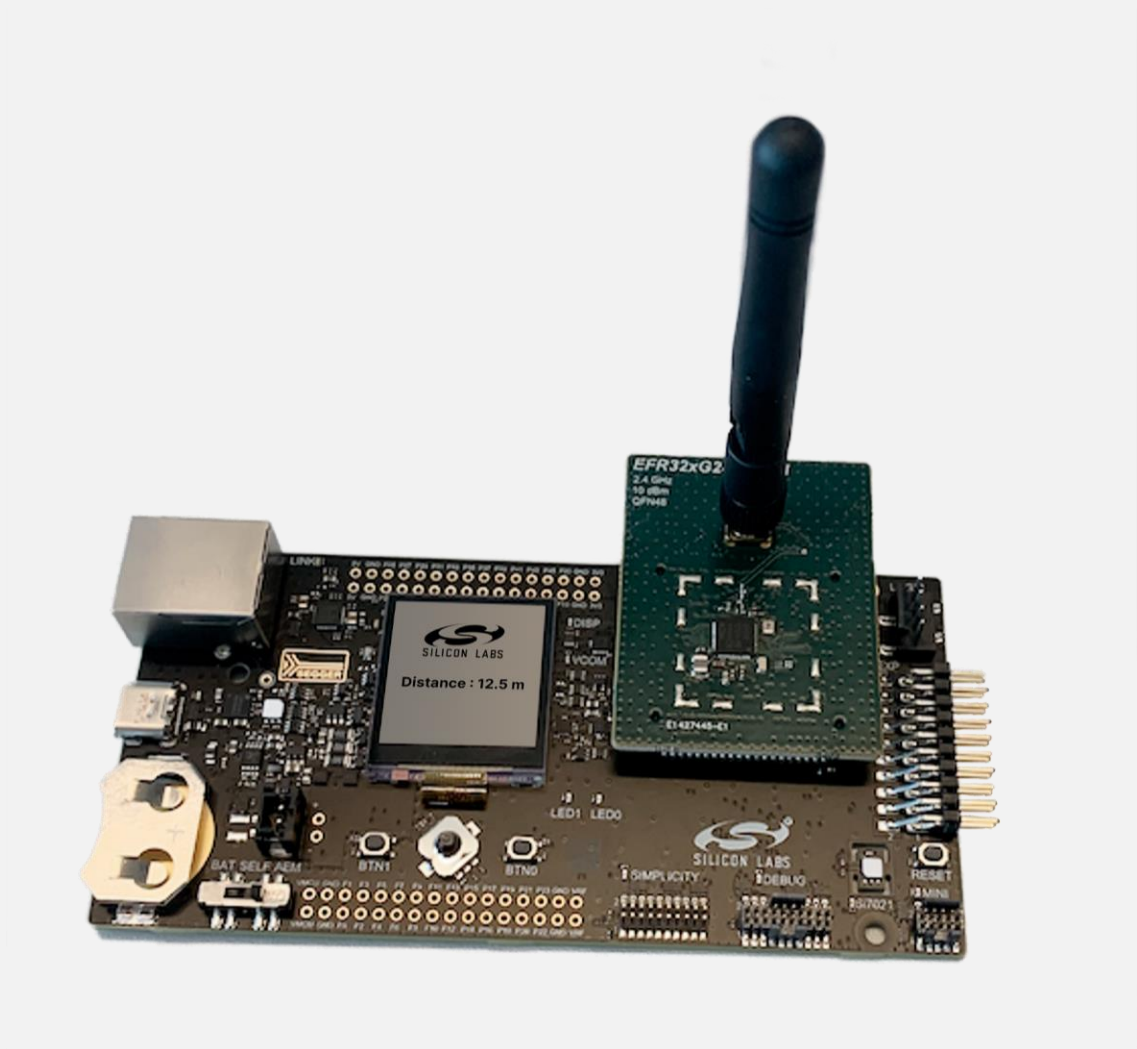
Low Power

- 49.1 μ A/MHz (CoreMark)
- 5.0 mA TX @ 0 dBm
- 5.1 mA RX (802.15.4)
- 4.4 mA RX (BLE 1 Mbps)
- 1.3 μ A EM2 sleep

Multiple protocol support

- Bluetooth 5.4 (1M/2M/LR), Bluetooth mesh, Proprietary 2.4 GHz

Single-Antenna Channel Sounding Board



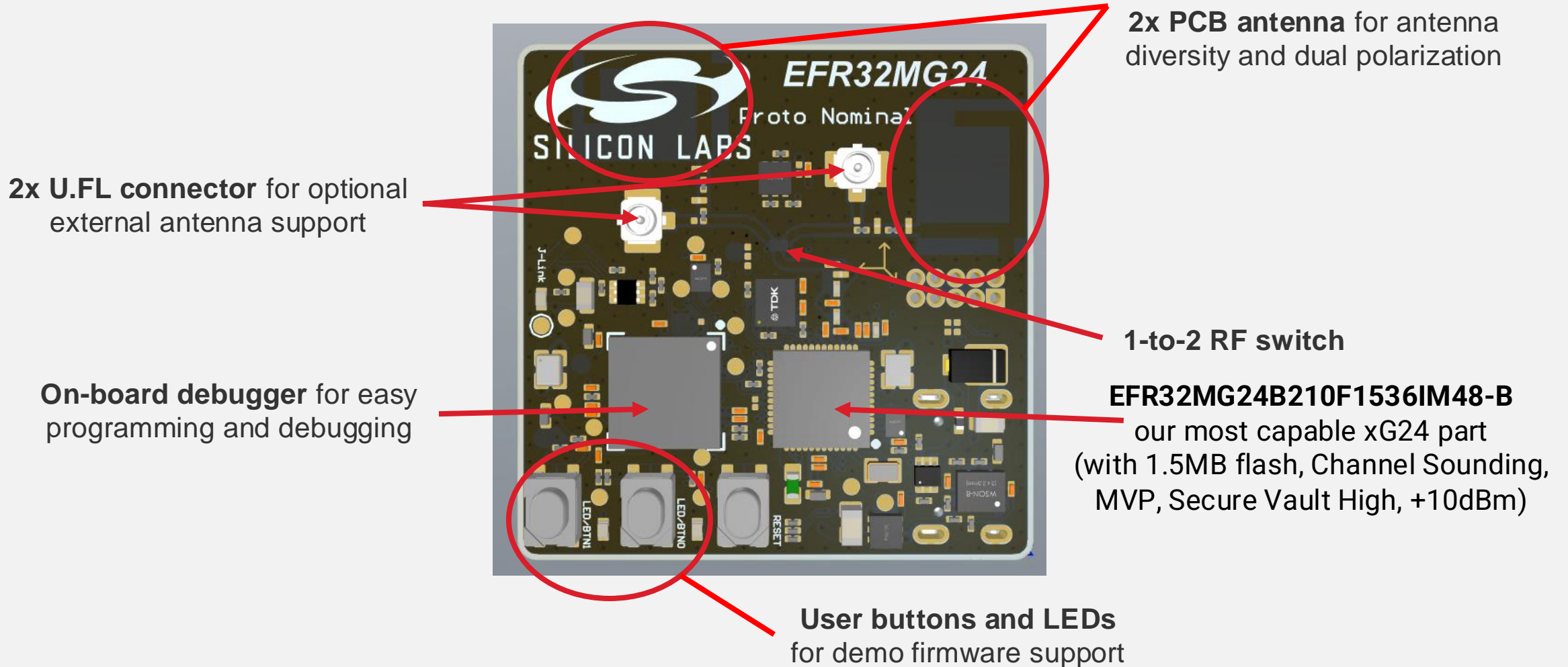
Channel Sounding evaluation using Ranging Kit

- EFR32xG24 Pro Kit with external antenna
- Full featured development option leveraging WPK features
- AEC-Q100 Compliant
- SoC/NCP Sample Apps
 - Initiator and Reflector examples supported
- Ranging Library
 - Process IQ samples, post-filtering, and compute distance using configurable algorithm

Optimized antenna designs

- EFR32xG24 reference designs with optimized PCB antenna solutions for indoor location systems

Dual-Antenna Channel Sounding board - front



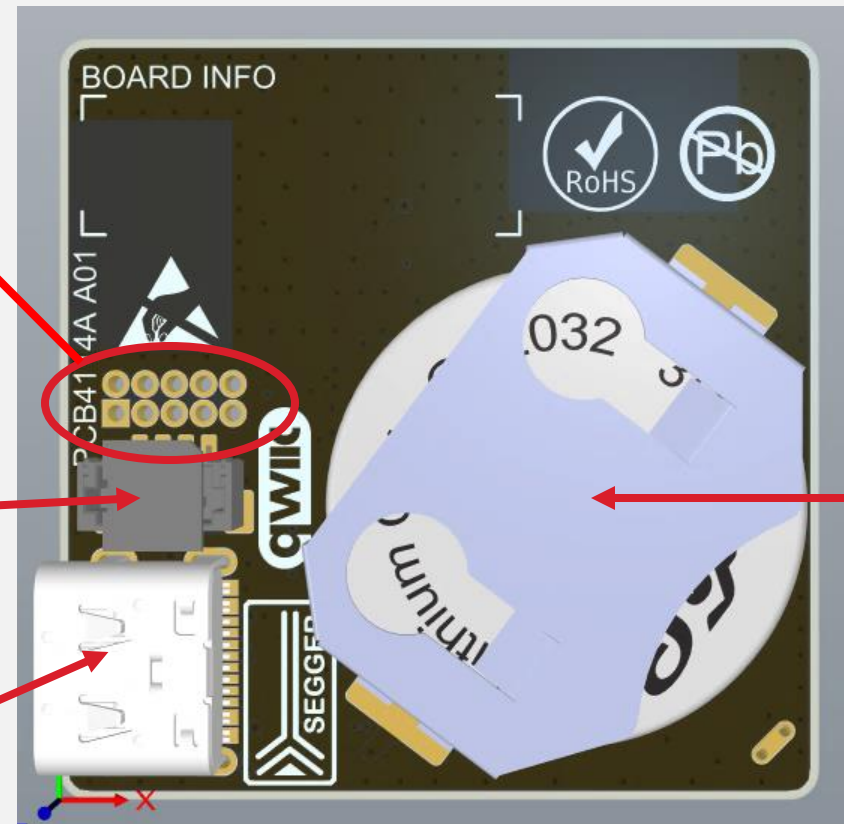
Dual antenna Channel Sounding board - back

← 33x33mm overall size →

Mini Simplicity header for Wireless Main Board connectivity. Provides Advanced Energy Monitoring and Packet Trace Interface options.

Qwiic connector for extendibility

USB-C connector for easy PC connectivity. Provides both debugger and virtual UART interfaces



← CR2032 for portability →

Visualizer Tool



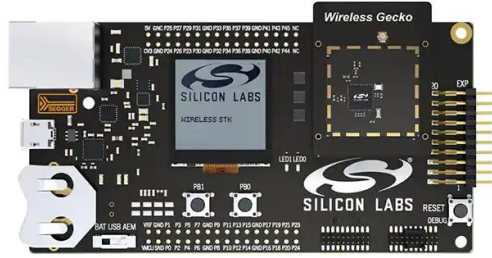
Visualizer Tool displays real-time data

- Channel sounding data with RSSI readings for comparison
- Interfaces with Channel Sounding-enabled EVKs

Upcoming features

- Data logging
- Confidence metric display
- Channel map selection

Silicon Labs Channel Sounding – Complete Offering



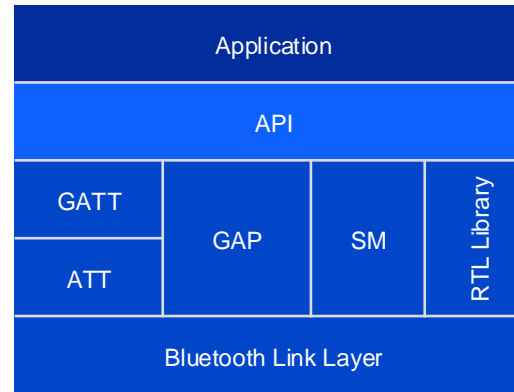
DEVELOPMENT KITS

BRD4198A with Single Antenna

Wireless Pro Kit

EFR32MG24 + 10dBm OPN

BRD2606A with Dual Antennas



STACK SOFTWARE

In-house developed stack

Supports Bluetooth 6.0 features +
Channel Sounding

New and improved Ranging features



DEVELOPMENT TOOLS

Real-time visualization tool

PBR, RTT modes

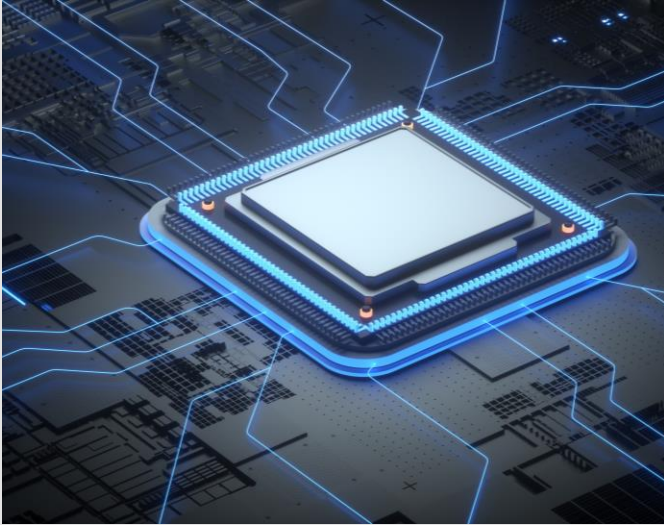
CS Sample projects

CS Analyzer + Energy Profiler +

Network Analyzer

App note + Salesforce Support

Learn More About Silicon Labs Channel Sounding



GETTING STARTED

Channel Sounding Kits Available at:

[Visit site](#)

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