Bluetooth Indoor Positioning

APAC RA | Nov 2022

Bluetooth Indoor Location - Target Markets and Use Cases

SMART RETAIL

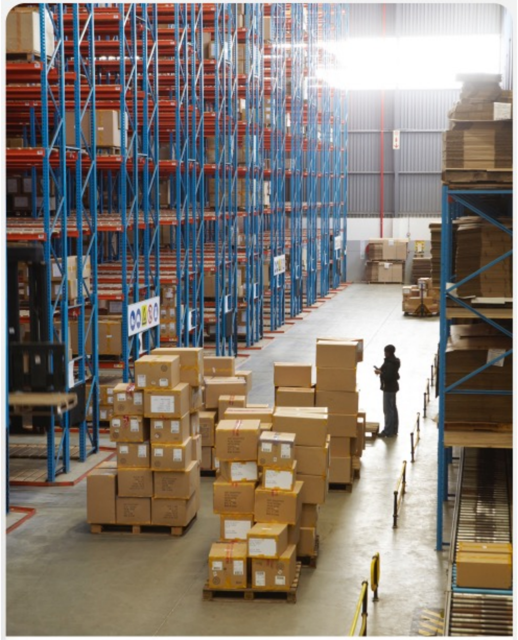
Store analytics
Supply chain optimization
Inventory optimization
Loss prevention

SMART HEALTHCARE

Equipment tracking
Staff & patient tracking
Hygiene compliancy
Social distancing

SMART BUILDINGS

Space optimization
Automated surveillance
Employee safety



SMART WAREHOUSES

Process optimization
Inventory management
Quality assurance

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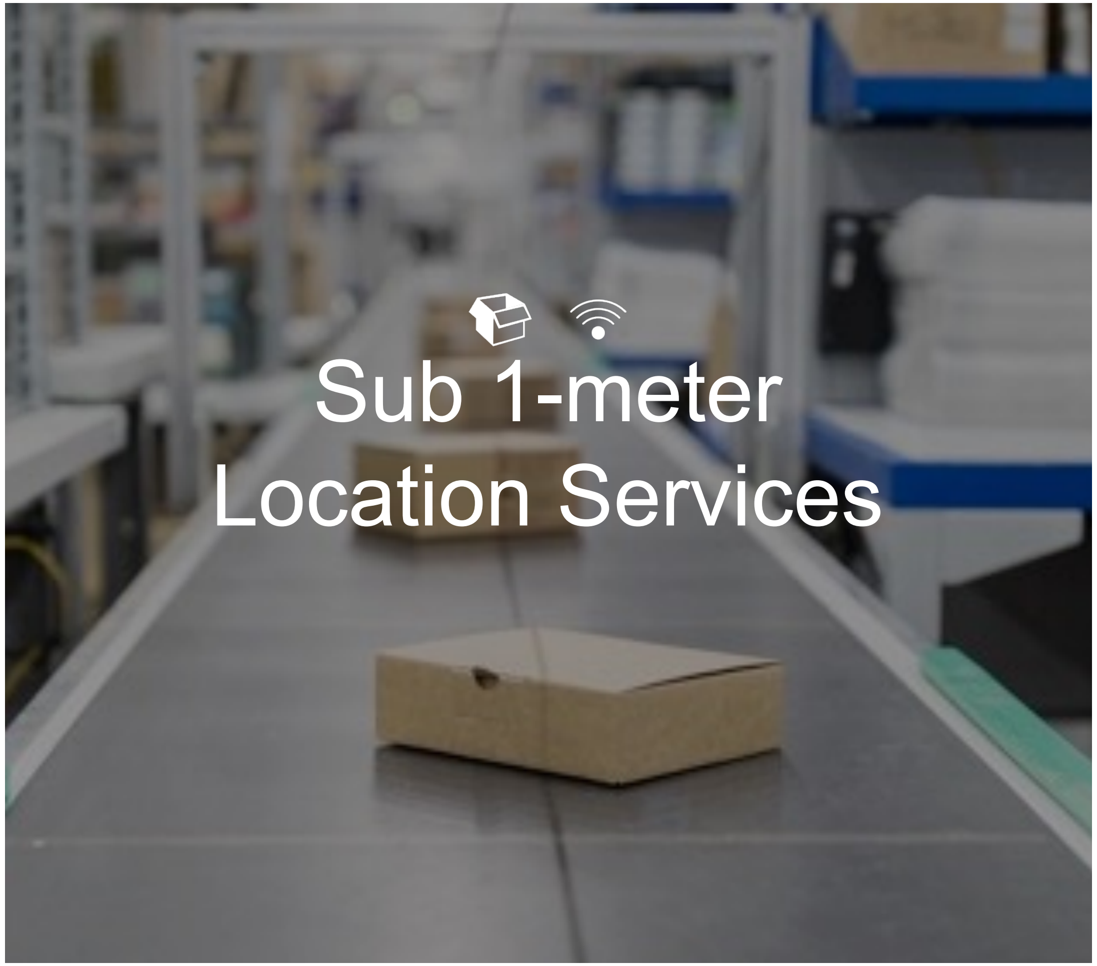
Why Bluetooth Direction Finding for Indoor Location Services?



- Bluetooth Direction Finding can deliver sub 1-meter accuracy for Indoor Location Services at reasonable infrastructure cost and complexity
- Bluetooth tags can operate 5-10 years on coin cell batteries
- The BoM of a Bluetooth tags can be reach <$1 in high volume
- Bluetooth also enables one or two-way data transfer
- Bluetooth tag functionality can be integrated as part of regular Bluetooth products like power tools, medical products, wearables etc. at no additional hardware cost

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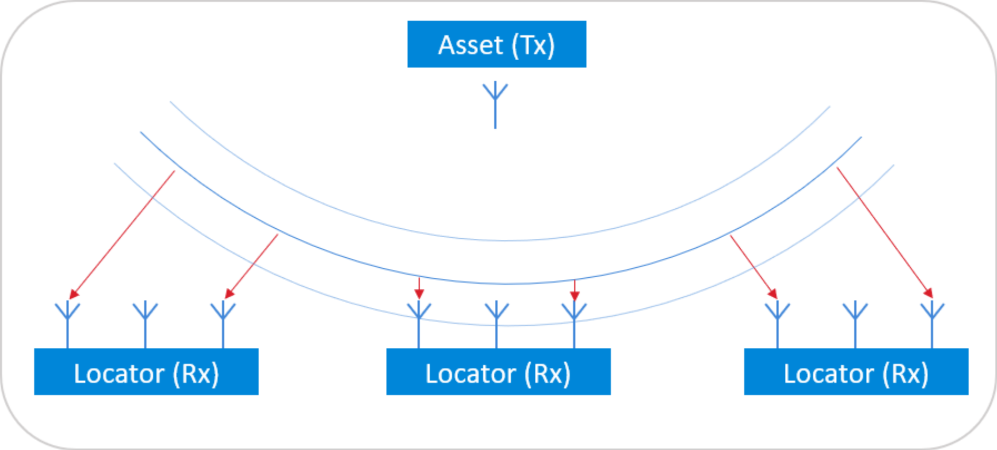
Agenda

- **Direction Finding Theory**
  - Angle of Arrival (AoA)
  - Angle of Departure (AoD)
- **Boosting AoA Scalability by Silicon Labs Enhanced mode**
  - Connection-Based
  - Connectionless
  - Silicon Labs Enhanced
- **Location Finding**
  - Interpreting IQ Samples
  - Angle estimation
  - Position calculation
- **Hardware Support**
  - Asset
  - Antenna Array Design
- **Demonstration**

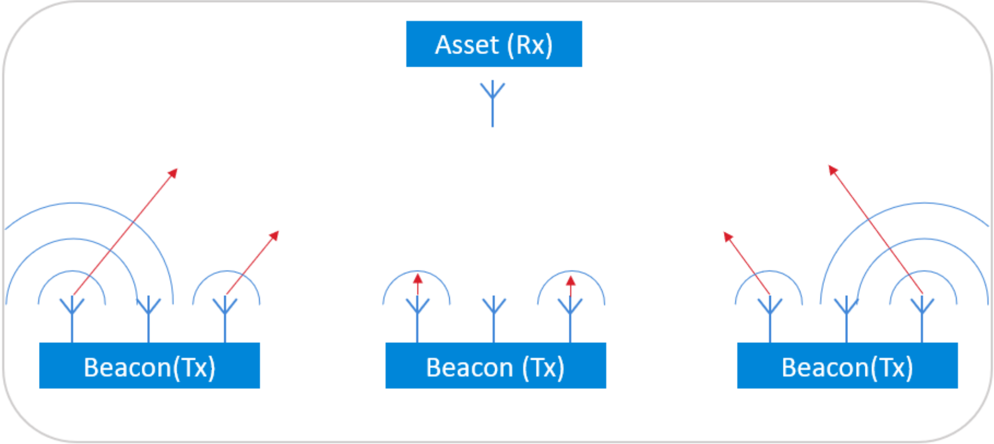
Direction Finding – AoA/AoD

Angle of Arrival (AoA)



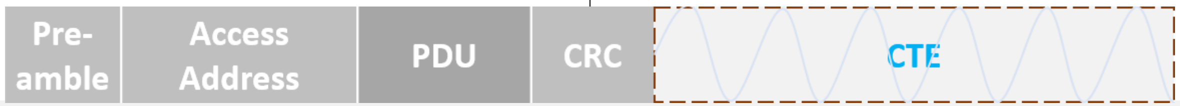
- Tag transmits signal
- Antenna array receives signal on different antennas and determines the direction of the tag

Angle of Departure (AoD)

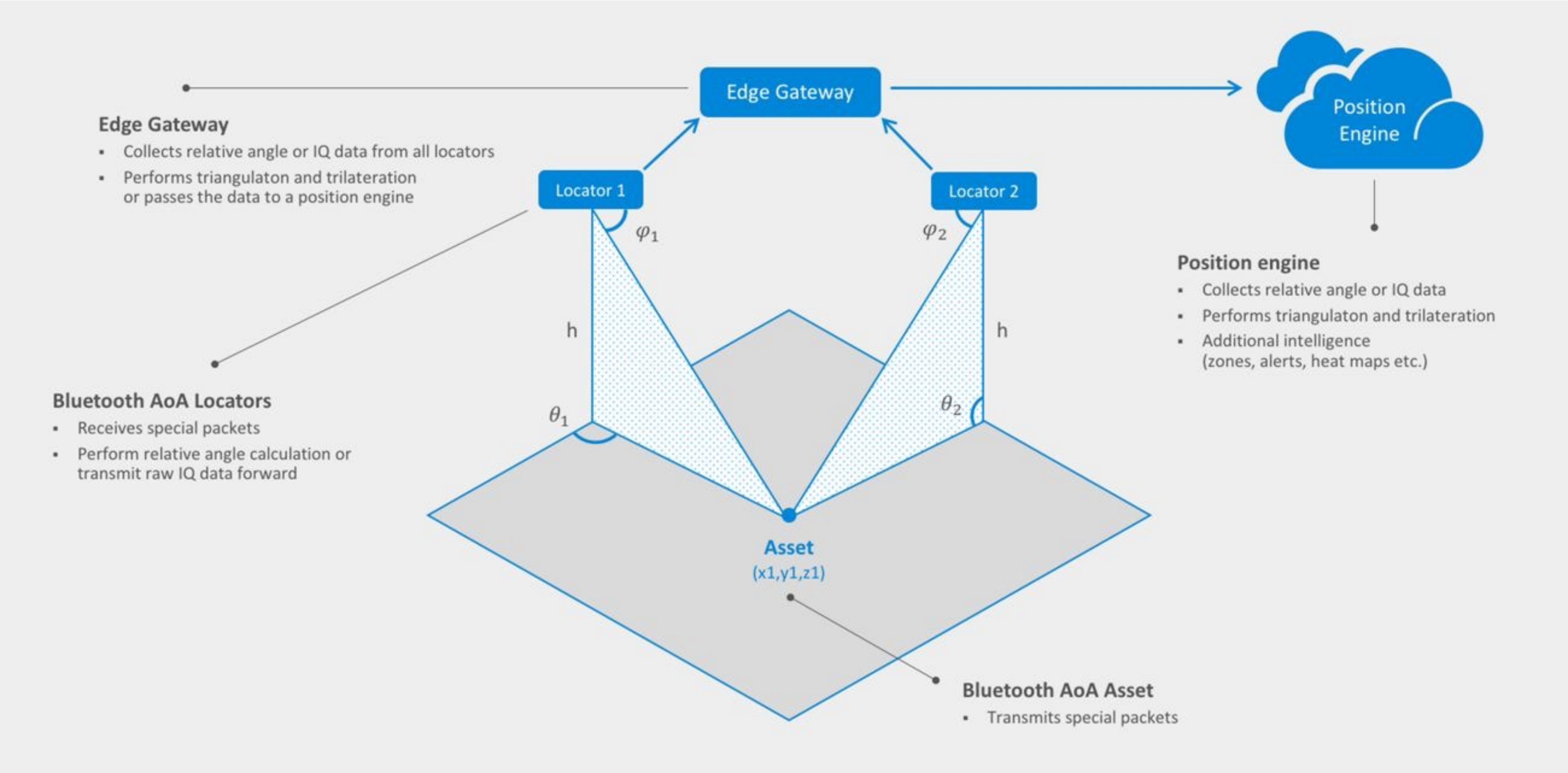


- Antenna arrays transmits signal on different antennas
- Tag receives signal and determines its own direction relative to the beacon(s)

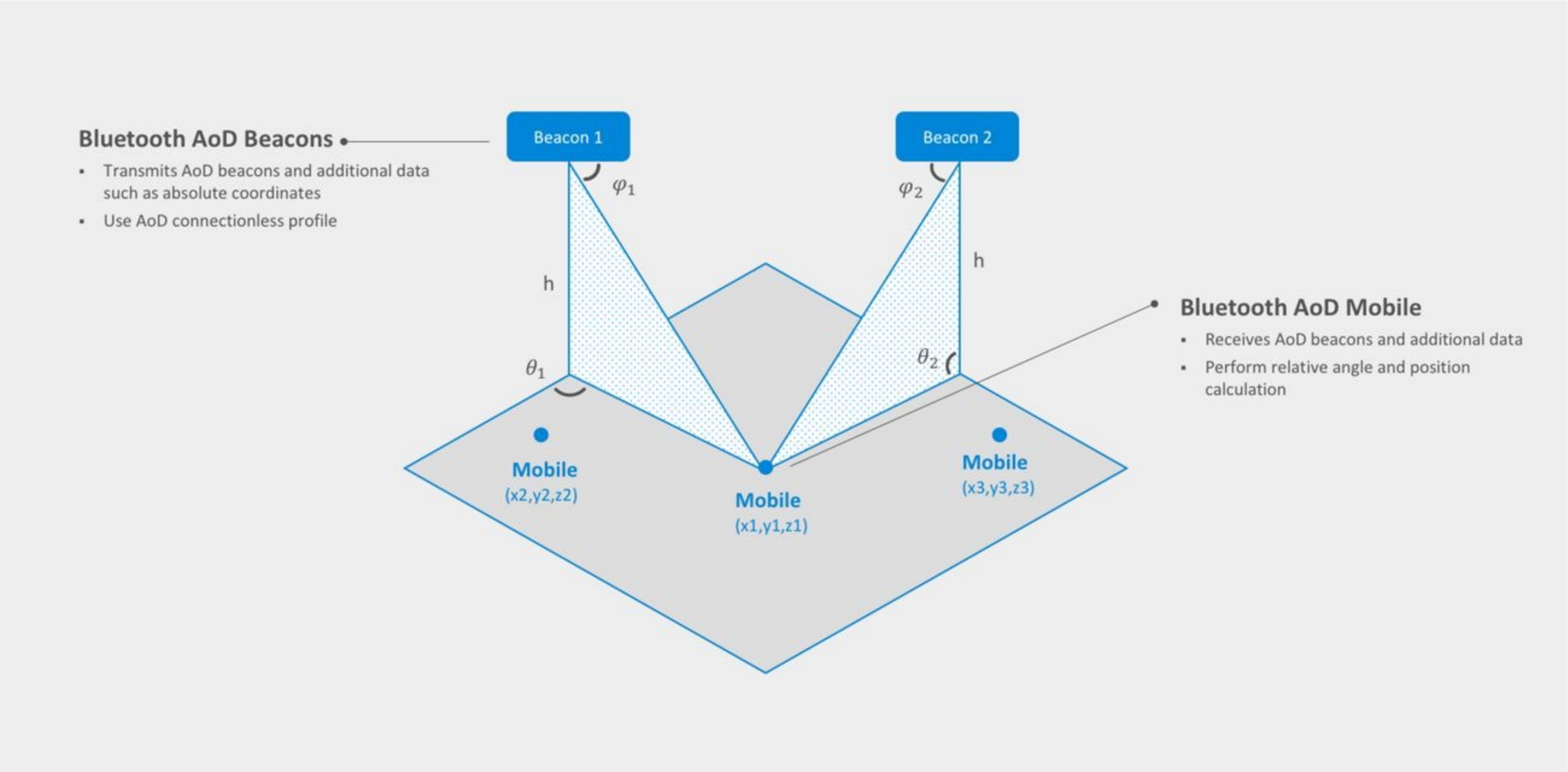
Constant Tone Extension (CTE) - unmodulated sin wave



Location Finding with AoA

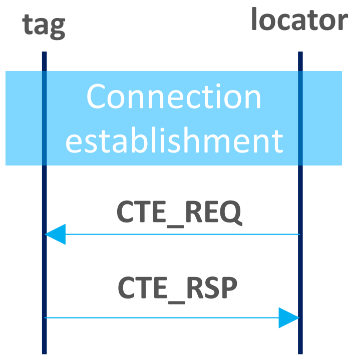


Location Finding with AoD – no example yet

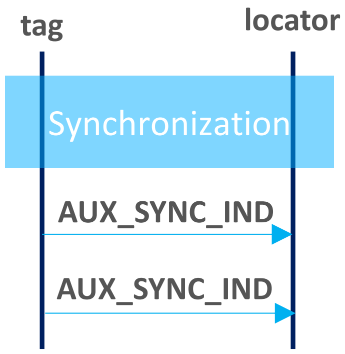


Connectionless vs Connection-Oriented Direction Finding

- **Bluetooth Core Specification v5.1 direction finding**
  - Connection-Based
    - Conveys the CTE using new LL_CTE_RSP packets that are sent over the connection in response to LL_CTE_REQ PDUs
  - Connectionless
    - Makes use of Bluetooth periodic advertising and the CTE is appended to otherwise standard ADV_EXT_IND PDUs.
- Both require RAM allocation on the locator to maintain the connections or synchronizations
- Limit the number of supported tags
- Also establishing connections or periodic advertising syncs can be time consuming for large number of assets



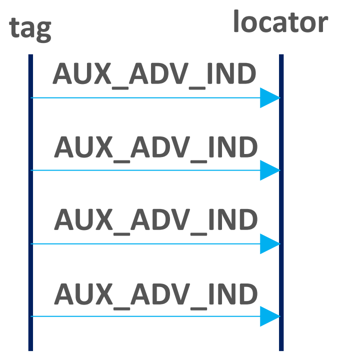
Bluetooth 5.1: Connection mode



Bluetooth 5.1: Connectionless mode

Silicon Labs Enhanced

- **Silicon Labs Enhanced CTE mode**
  - Sends CTEs in extended advertisements
  - Silicon Labs proprietary, can only be used with Silicon Labs locators.
  - Little RAM is needed in the locator and no time syncing is needed
  - CTE is transmitted on 37 data channels for maximizing spectrum usage
  - Tag implementation is very simple and low power
  - Up to hundreds of tags support.



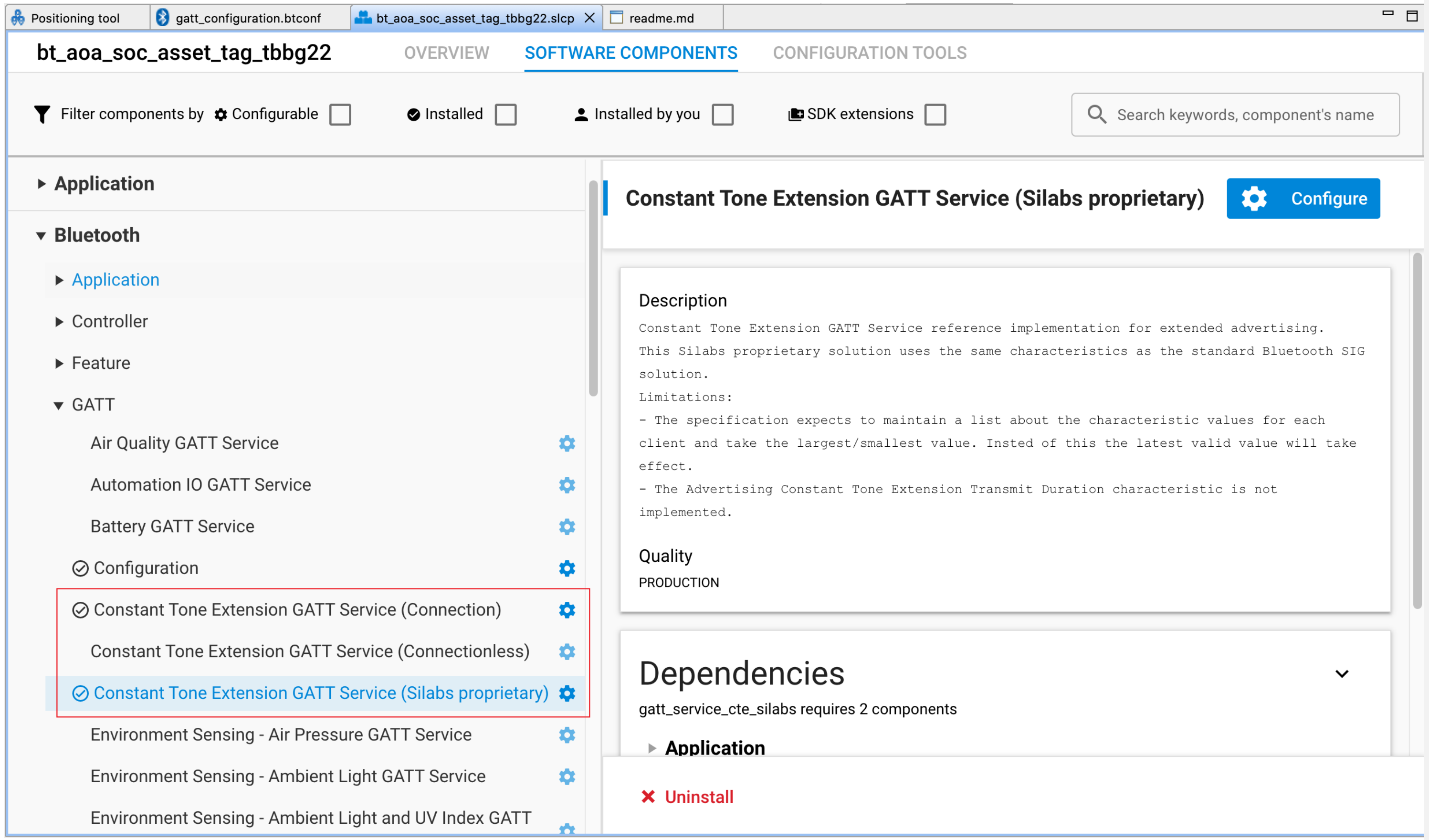
Silicon Labs enhanced mode

SDK Support - Software Components

- **Platform**
  |__Radio
  |__RAIL Utility, AoX
  - Used by the Bluetooth stack
  - Configure the antenna switch pins

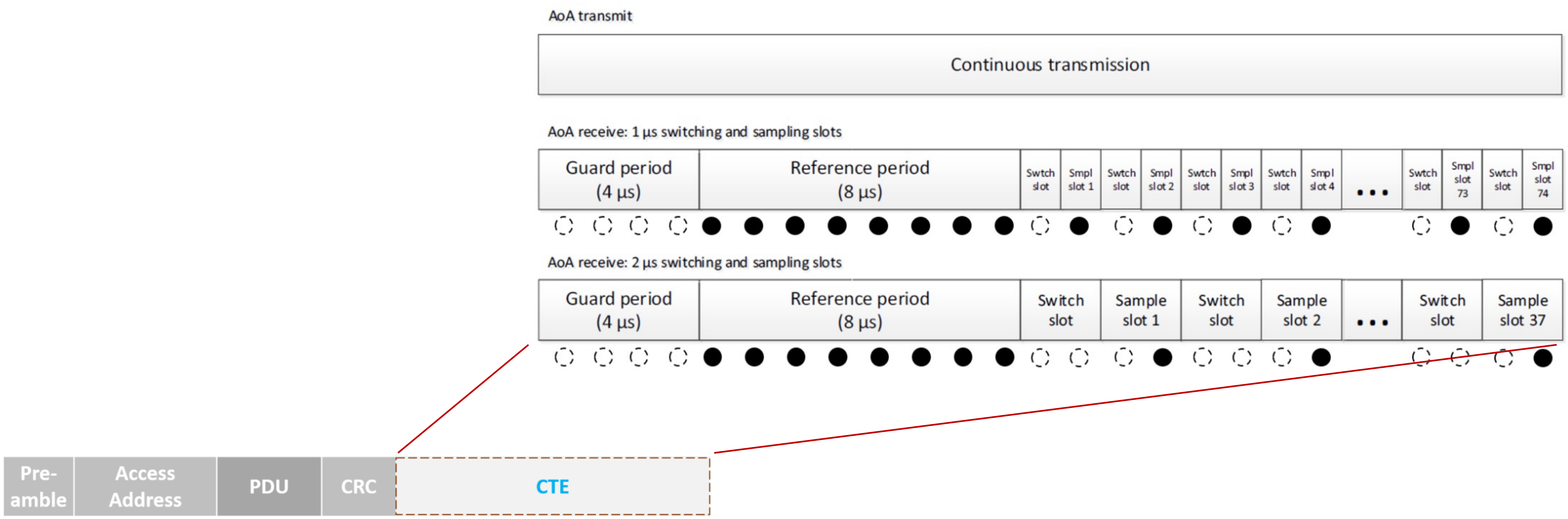
- **Bluetooth**
  |__Stack
  |__Direction Finding /
  - AoA Receiver
  - AoA Transmitter
  - AoD Receiver
  - AoD Transmitter

- **Bluetooth**
  |__GATT
  |__Constant Tone Extension GATT Service
  - Connection
  - Connectionless
  - Silabs proprietary



Interpreting IQ Samples

- The Constant Tone Extension is a simple continuous wave – with a variable length of 16 µs to 160 µs – it is divided into periods.
  - 4 µs of guard period
  - 8 µs of reference period
  - A sequence of alternating switch slots and sample slots, each either 1 µs or 2 µs long.



Interpreting IQ Samples

- Once a CTE has started, the radio starts sampling the In-phase (I) and Quadrature (Q) components of the baseband signal with its native sample rate.
- The samples are then downsampled to 1 sample/μs sample rate

```
Silabs IQ samples received.
IQ Sample of the received CTE packet:
        Address 0xc1:0xbd:0x31:0x14:0x2e:0x84
        Address Type: 0
        PHY: 1M PHY
        Channel: 25
        RSSI: -34
        rssi_antenna_id: 0
        cte_type: 0
        slot_durations: 1 us
        packet counter: 2166
        IQ sample, len 164, value: 0xb0 0x10 0xd 0x50 0x51 0xf8 0xfc 0xaf 0xaf 0x3 0x0 0x51 0x51 0x4 0xb 0xaf 0x1e 0x0 0xec 0x12
0xc1 0xe 0xe1 0xcd 0x2e 0xf5 0x2e 0x3 0xbe 0x28 0x6 0xf5 0xeb 0xd0 0x71 0xea 0x4 0x4e 0xf5 0xba 0x9 0xa9 0x6d 0xfb 0x23 0x6f 0x4f
 0xe5 0x3 0x1d 0xe8 0xef 0xe9 0xc7 0x2e 0xd8 0x12 0x2d 0x5 0x2d 0xcc 0xc6 0xd 0x5 0x2d 0xe3 0x27 0x6c 0xb5 0x13 0x42 0xe8 0x57 0x
f9 0x16 0x6b 0x98 0x38 0x27 0x4a 0xe4 0x8 0xc 0xe5 0x35 0xdf 0x31 0x24 0xd7 0x1b 0xd4 0xc 0x2d 0xc1 0xfe 0xd 0x25 0x26 0x9b 0x38
0xe3 0xb9 0x24 0x3c 0x16 0x54 0x9b 0x29 0xb4 0xa7 0xbf 0x35 0xf3 0xe6 0x1c 0x7 0x2b 0x2d 0xe6 0x37 0xe0 0xdc 0xed 0xd8 0x46 0x22
0xf2 0x0 0xe1 0x2b 0xb4 0xaa 0x3f 0xd4 0xcb 0x2e 0xb1 0x23 0xc4 0xa5 0x4c 0xa7 0xc1 0xc9 0x17 0xee 0xfe 0x1d 0xdb 0x32 0xc6 0xef
0x1d 0xd9 0x24 0xe5 0xe9 0x4a 0xfd 0xf2 0xd0 0xea 0x47 0xa2
```

Index	IQ			I	Q		ϕ = atan2($-Q$, I), In N	Phase (°)	Phase	Phase diff
1	-20			-20	33		-2.115660242	-121.22	238.78	
2	33			30	25		-0.694738276	-39.81	320.19	81.41
3	30			27	-26		0.766532477	43.92	43.92	-276.27
4	25			-22	-31		2.187987718	125.36	125.36	81.44
5	27			-33	19		-2.619189222	-150.07	209.93	84.57
6	-26			14	36		-1.199905038	-68.75	291.25	81.32
7	-22			37	-10		0.263963724	15.12	15.12	-276.13
8	-31			-5	-37		1.705117769	97.7	97.7	82.58
9	-33			17	46		-1.21679889	-69.72	290.28	192.58
10	19			-2	-61		1.603571471	91.88	91.88	-198.4
11	14			-58	0		3.141592654	180	180	88.12
12	36			-53	-5		3.047531419	174.61	174.61	-5.39
13	37			63	38		-0.542750498	-31.1	328.9	154.29
14	-10			-36	-90		1.951302704	111.8	111.8	-217.1
15	-5			-21	54		-1.941687616	-111.25	248.75	136.95

- The frequency of the CTE signal $f(CTE) = f_{\Delta} + f_{\text{offset}}$
  - $f_{\Delta} = 250kHz$
  - f_{offset} in the order of 10kHz
- Phase shift between two consecutive samples with 1-μs slot $\phi = 2\pi(f_{\Delta} + f_{\text{offset}})t \cong 2\pi \cdot 0.25 \cdot 1 = 90°$
- Taking the offset frequency into account, it might vary between 80°-100°.
- Retrieve the instantaneous phase of the signal with $\phi = atan2(-Q, I)$

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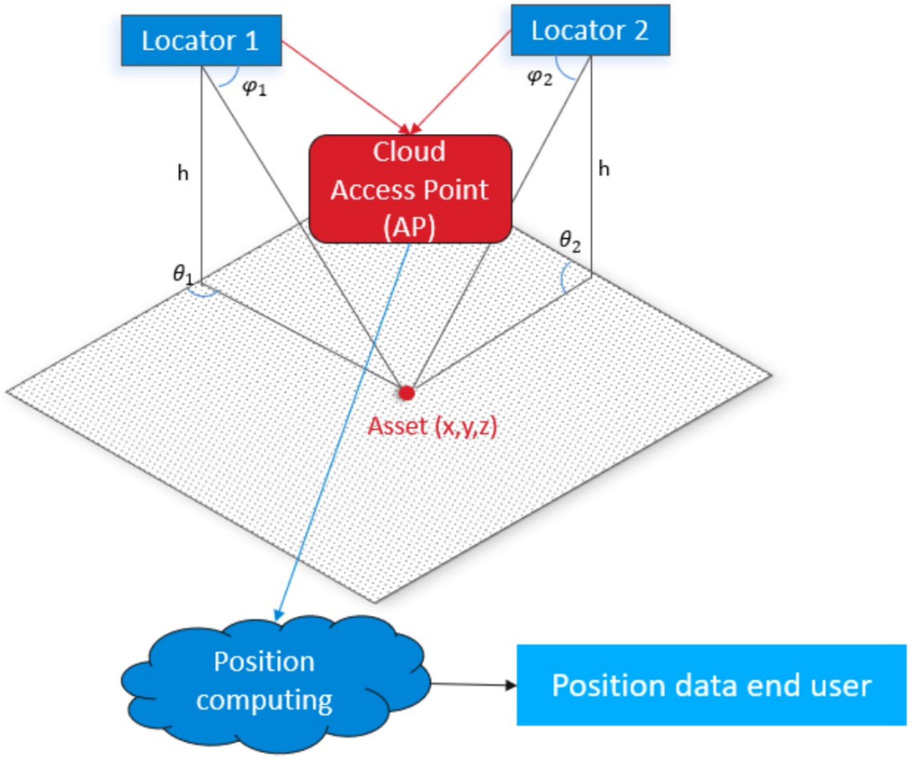
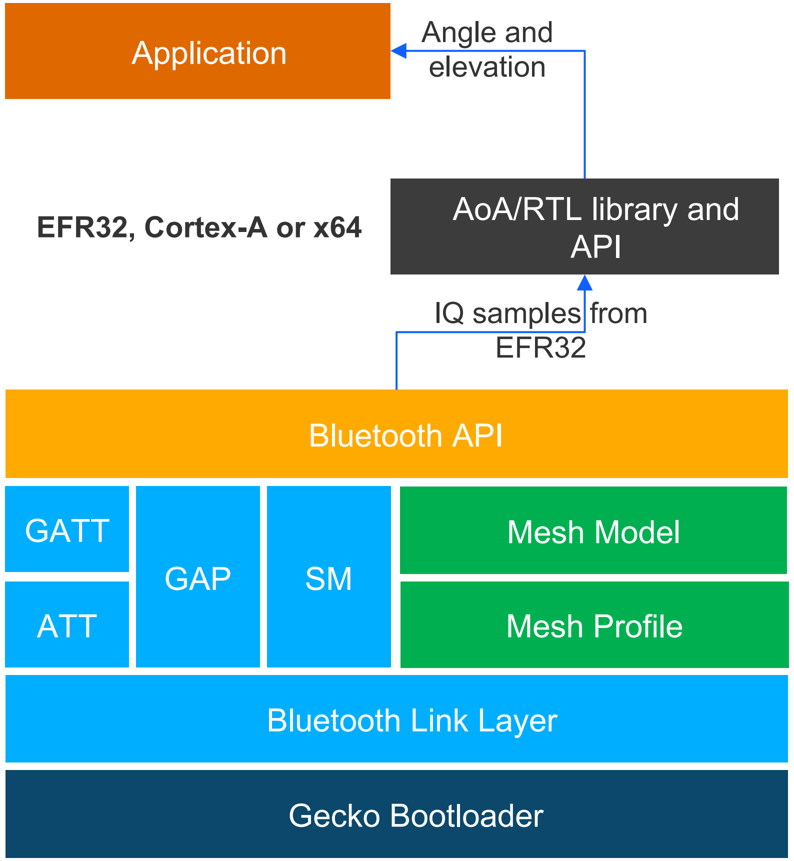
Location Finding



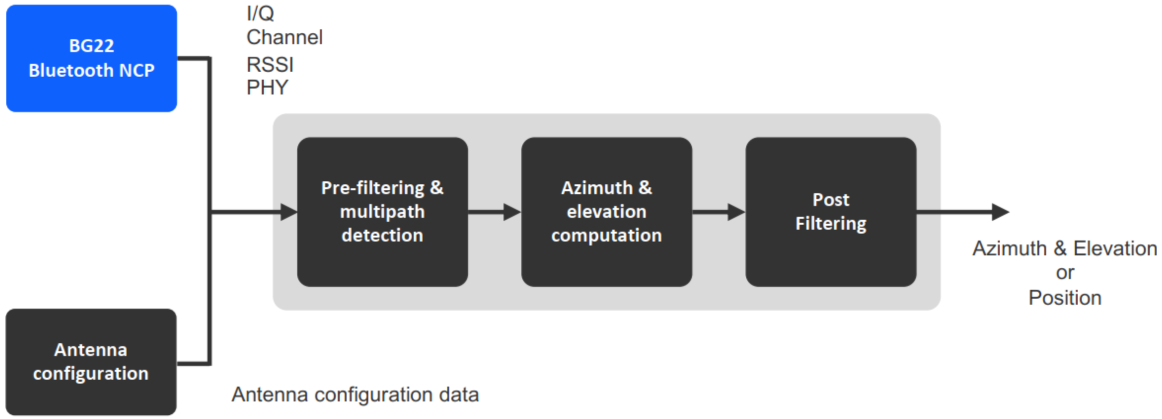
- One antenna array can provide the direction of the asset, but not its position.
- Multiple antenna arrays must be used for determining the position with triangulation.
- Triangulation can also be supplemented with trilateration.
  - Adding RSSI measurements to the direction estimations can further enhance the position estimation.

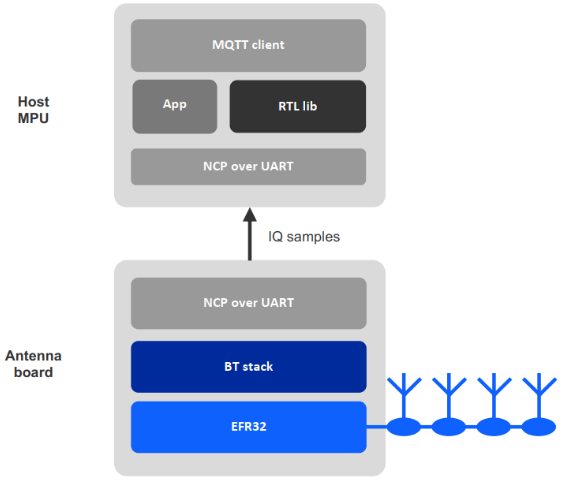
AoA Locators Software Architecture



- **Bluetooth software**
  - Connection-oriented and connectionsless AoA receive support
  - AoD Ready
  - RF switch control and IQ sampling with BG22 (Tested with Skyworks, pSemi and CoreHW RF switches)
  - Raw IQ data available via API
- **AoA/RTL library and API**
  - Converts raw IQ data to azimuth & elevation
    - Detects and filters out multipath
    - Detects and filters out CTE collisions
    - Angle and elevation filtering algorithms for different use cases (high accuracy, real time etc.)
  - Provides a developer API for configuration and data coversion
  - Signifanctly simplifies locator software development

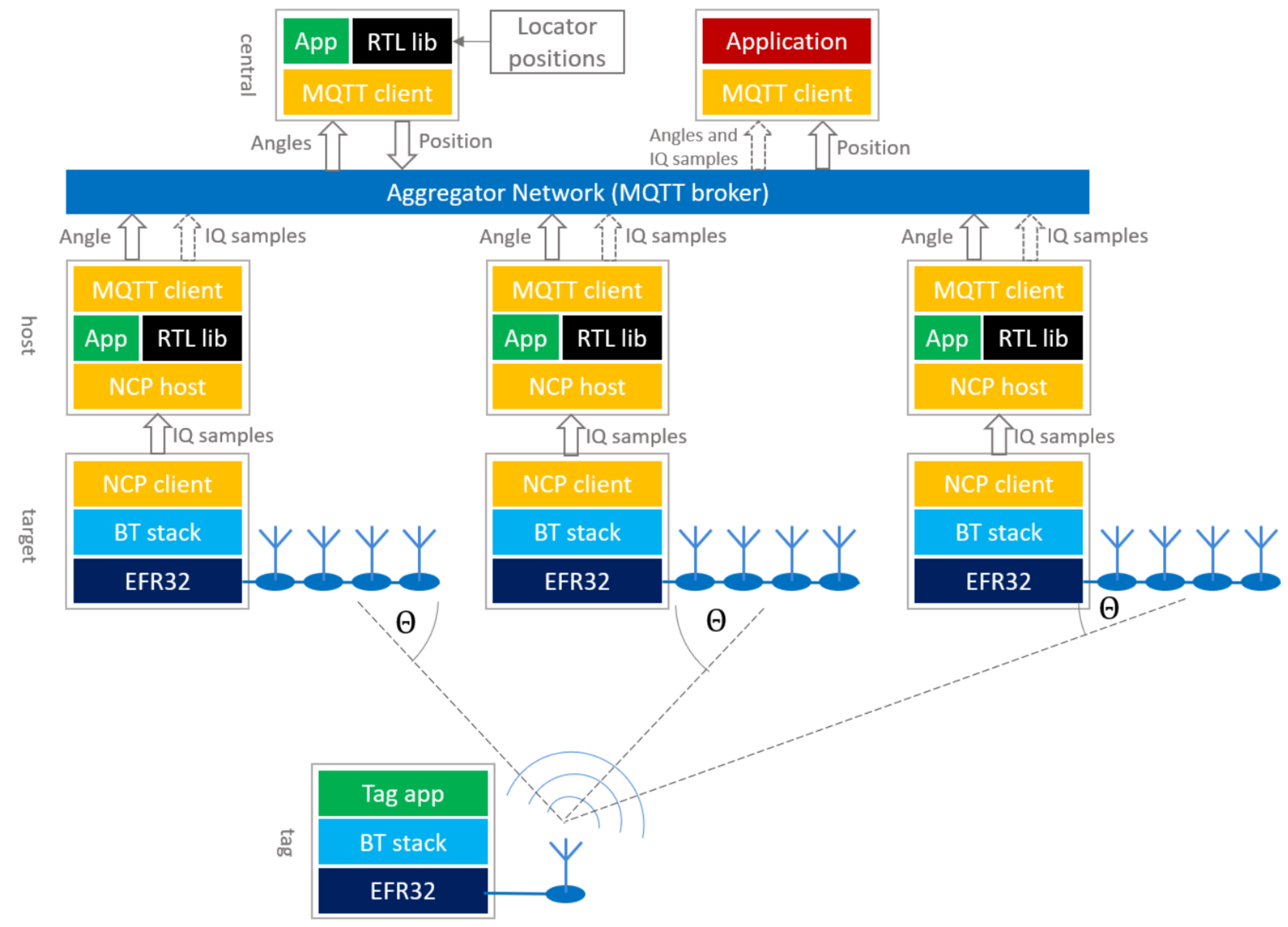
Silicon Labs Real Time Location (RTL) Library





- **RTL library**
  - Consumers antenna configuration and Bluetooth I/Q data
  - Performs multipath and other filtering operations
  - Computes and outputs azimuth and elevation
  - Can also compute and output position
- **Currently supported host platforms**
  - Cortex-A with Linux
  - x86 with Linux or Windows
  - Delivered as binary library
- **Documentation:**
  - https://docs.silabs.com/rtl-lib/latest/

AoA Position Engine Reference for RTLS



- **AoA position engine reference application**
  - Supports multiple AoA locators over USB or IP
  - Consumes I/Q or azimuth elevation data from
  - individual locators and computes positions
  - Shares data using MQTT
  - Incudes also a visualization components
  - Delivered as source code (except RTL and Bluetooth stack)
  - Modular, expandable and customizable
- **Platform independent**
  - x86 and Cortex-A support
  - Can be run on Windows and Linux
  - Components can be run centrally or distributed

Sample Applications

- **Studio Projects**
  - Bluetooth AoA - SoC Asset Tag
    - CTE transmitter
  - Bluetooth AoA - NCP locator (NCP target)
    - CTE receiver

- **Host Sample Apps**
  - bt_aoa_host_locator (NCP Host)
    - single AoA locator host for angle estimation
    - IQ samples → Angle of arrive (AoA)
  - bt_host_positioning
    - host app for position estimation using multiple locators
    - AoA → location
  - bt_host_positioning_gui
    - Python host app for the visualization of a multi-locator setup

BG22: Optimized for Asset Tags

Optimized

Secure Bluetooth 5.2 SoCs for High-Volume Products

Radio
Bluetooth 5.2
+6 dBm TX
AoA & AoD

Ultra-Low Power
3.6 mA RX current (1 Mbps GFSK)
4.1 mA TX current @ 0 dBm output
1.40 µA EM2 DeepSleep current
0.17 µA EM4 current

World Class Software
Bluetooth 5.2 Bluetooth mesh LPN Direction Finding

Compact Size
5x5 QFN40 (26 GPIO)
4x4 QFN32 (18 GPIO)
4x4 TQFN32 (18 GPIO)

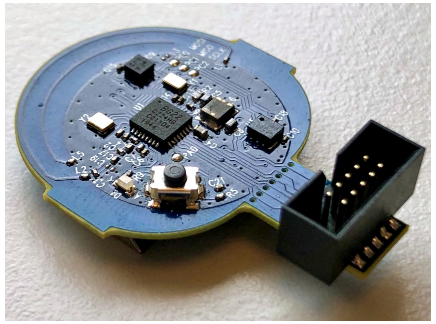
ARM Cortex-M33 with TrustZone
76.8 MHz with FPU and DSP
352/512kB of flash
32kB RAM

Peripherals Fit for Purpose
2x USART, 2x I2C, 2x PDM and GPIO
16-bit ADC
Built-in temperature sensor with +/- 1.5 °C
32kHz, 500ppm PLFRCO

Security
AES128/256,SHA-1, SHA-2 (256-bit)
ECC (up to 256-bit), ECDSA and ECDH
True Random Number Generator (TRNG)
Secure boot with RTSL
Secure debug with lock/unlock

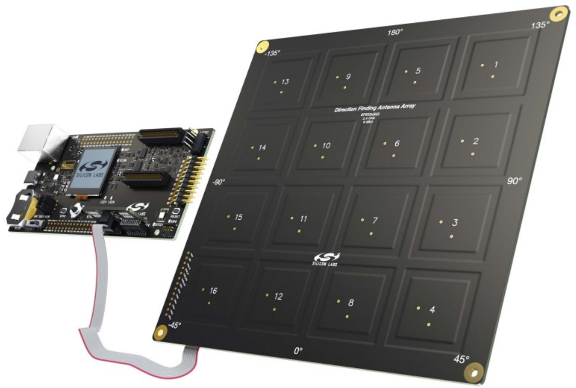
Hardware Support

- **BG22 tag reference design**
  - Size and cost optimized tag
  - 5–7-year lifetime with CR2032
- **Reference design files include**
  - Tag Reference Manual
  - PCB design files
  - Schematics
  - BOM
  - EFR32BG22_TAG_REF_DES_A01



- **BG22 Thunderboard Kit**
  - Low-cost development board x1
  - On-board debugger
  - Signal breakouts
  - On-board sensors
- **xG24 Dev Kit**
  - Low-cost development board
  - On-board debugger
  - Signal breakouts
  - On-board sensors
  - Hardware accelerator for AoA

- **Antenna Array Kits**
  - BG22 Direction Finding Radio Board
  - 1x antenna array board
- **BG22 Direction Finding Pro Kit**
  - 1x BRD4191A antenna array board
  - 1x BRD4002A wireless mainboard



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Antenna Reference Design

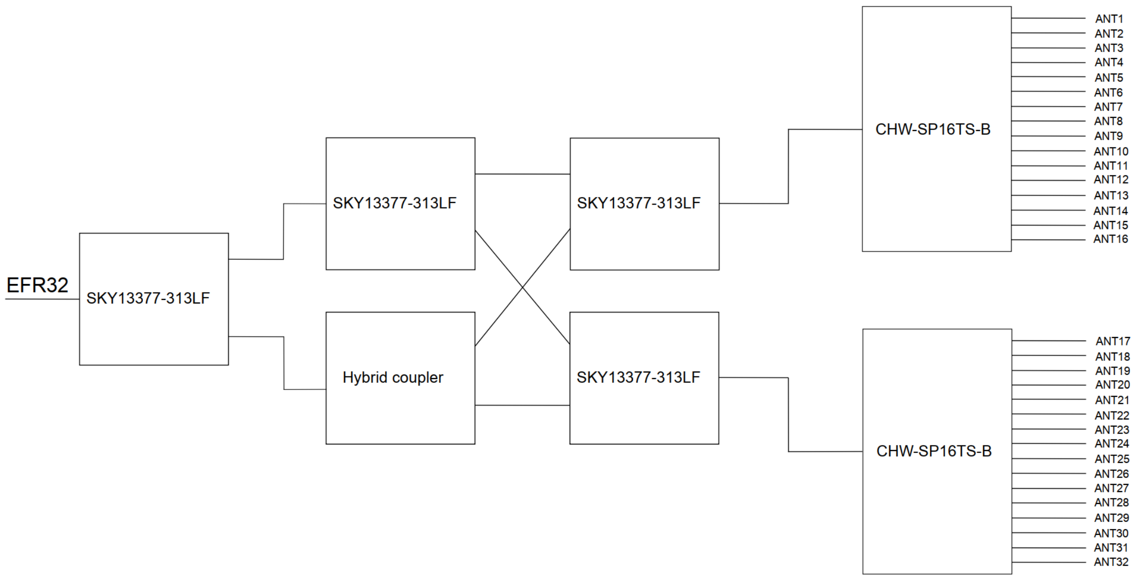
Front side

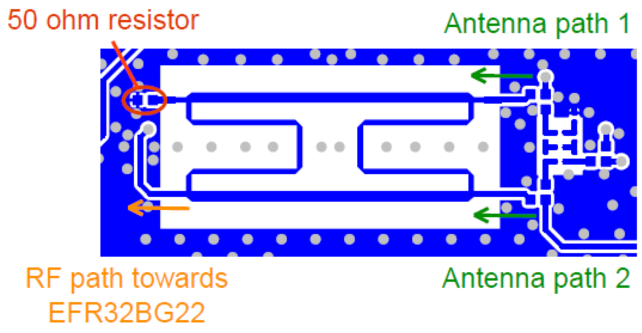
Back side

- 4x 4 antenna array
- 16 DP patch antenna elements
- 160 x 160mm
- 6-layer PCB
- Horizontal and Vertical polarized antennas at each location (i.e 4*4*2= 32 antennas in total).
- Two antennas (i.e 6 &13) can be driven in CP mode for accurate AGC value setting.
- Built-in BG22, CoreHW1010 and Skyworks RF switches
- BG22 provides IQ data over NCP
- BG22 can be replaced with BG24
- AoD beacon application can be also realized

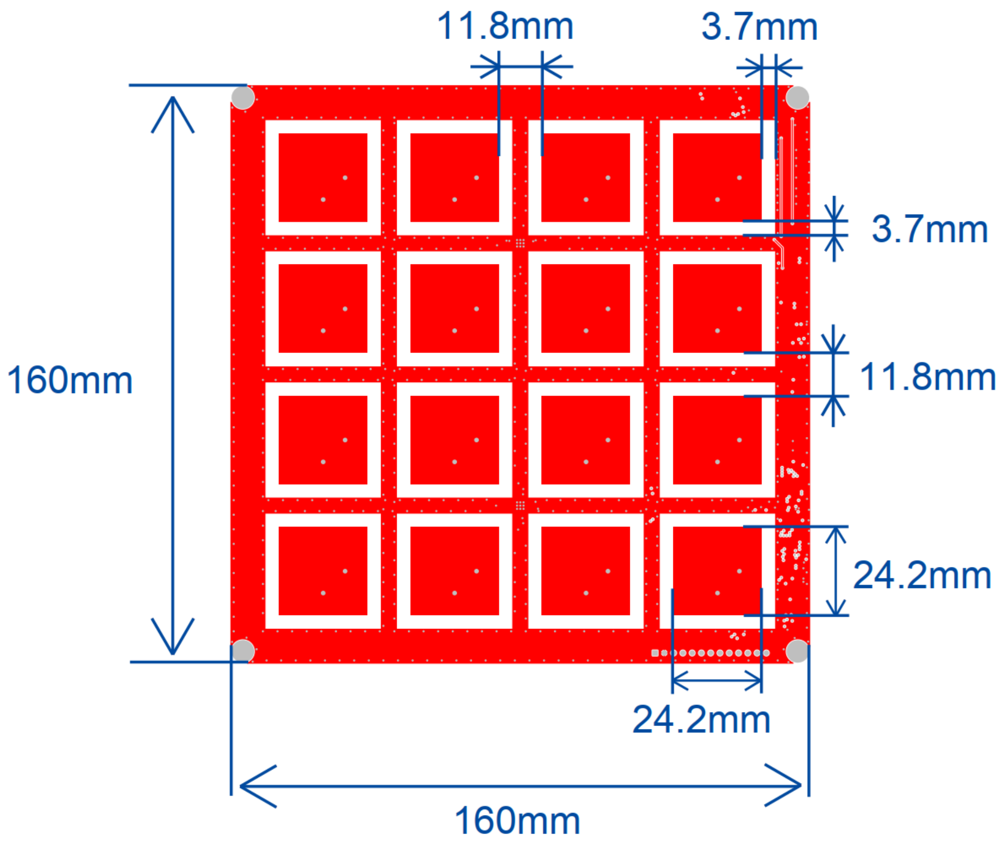
RF Switch structure

- The 32 ports of the antenna array are connected to the EFR32BG22 device using multiple RF switches





Properties of the 4x4 Antenna Array

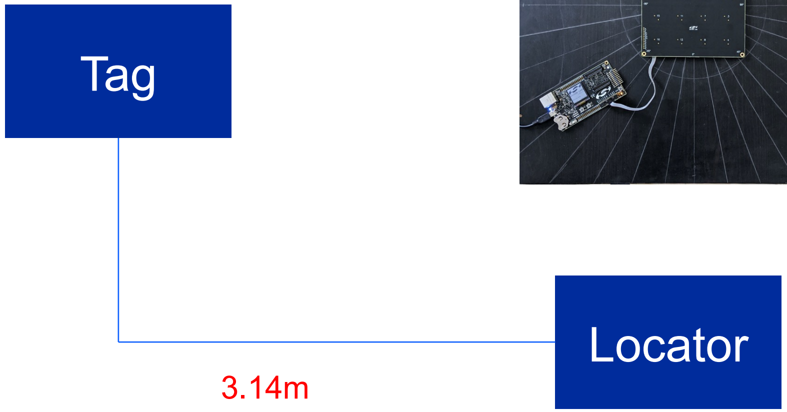


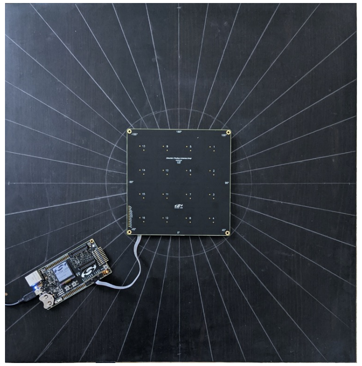
- **Silicon Labs recommends copying the antenna array structure from the reference design as is.**
  - Antenna building block dimensions
  - Single antenna dimensions
  - Distance between single antennas
  - RIS (Reactive Impedance Surface) dimensions
  - GND guard ring dimensions
  - Position of antenna feed points
  - Hybrid coupler dimensions
  - Coplanar transmission line lengths and widths
  - Stitching vias around the coplanar transmission lines
  - PCB dimensions (length, width, thickness)
  - PCB layer stack-up + laminate type + laminate construction

Performance Characteristics

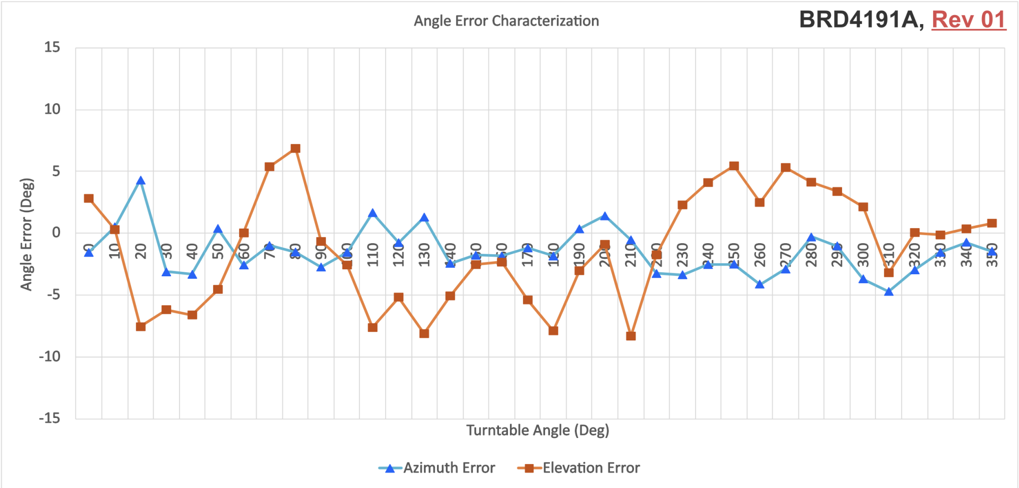
Azimuth & Elevation accuracy in a multipath environment

- Setup:
  - Tag: AoA Coin cell tag
  - Locator: BRD4191A, Rev 01
  - Locator on Turntable
  - Locator tag separation distance: 3.14 m
  - Tag height from floor: 2.69m
  - Locator height from floor: 0.46 m

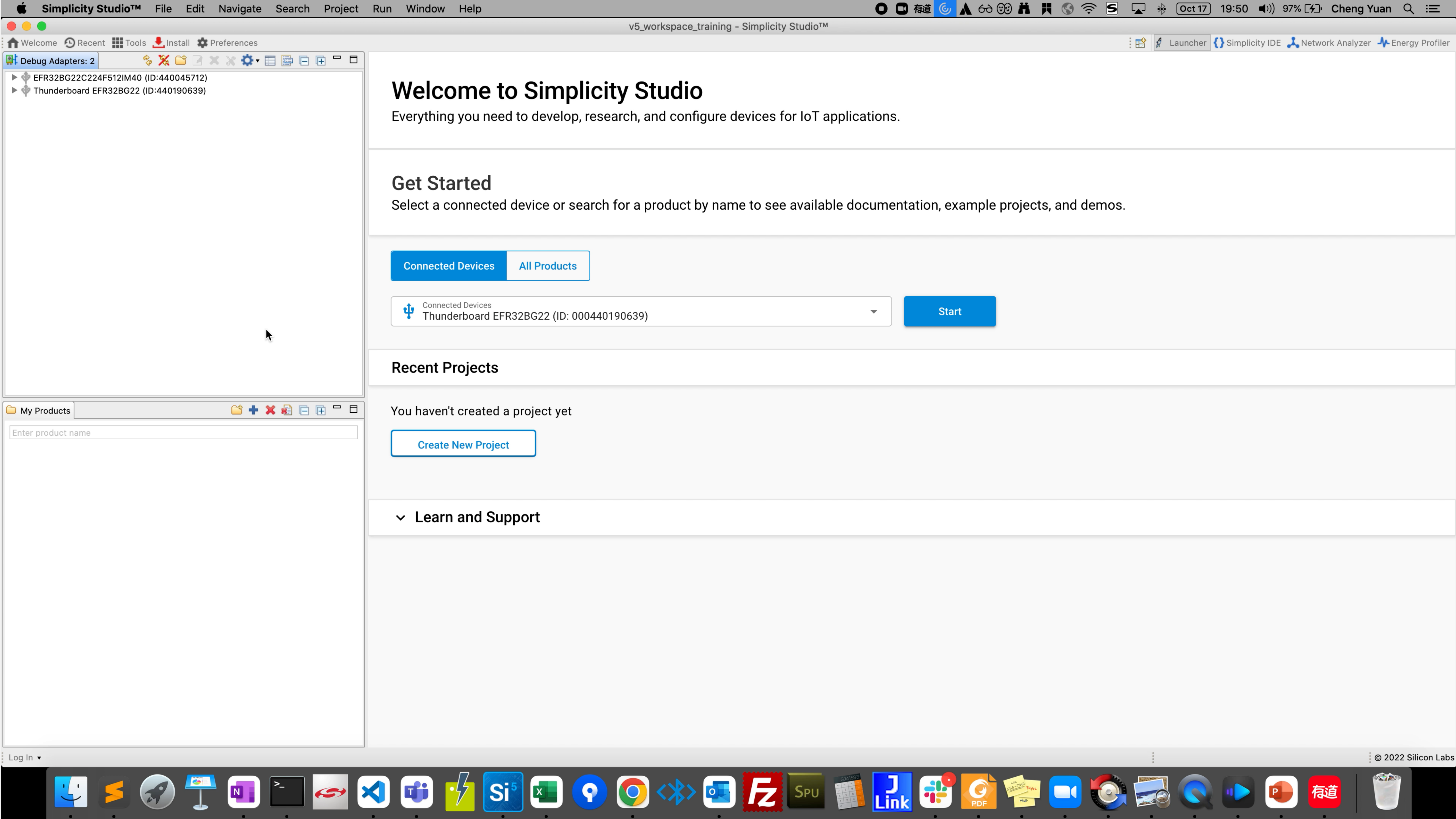




BRD4191A - Angle Error (without enclosure)



More test result can be found in AN1195



Simplicity Studio™ File Edit Navigate Search Project Run Window Help
Oct 17 19:50 97% Cheng Yuan
v5_workspace_training - Simplicity Studio™
Welcome Recent Tools Install Preferences
Launcher Simplicity IDE Network Analyzer Energy Profiler
Debug Adapters: 2
EFR32BG22C224F512IM40 (ID:440045712)
Thunderboard EFR32BG22 (ID:440190639)
My Products
Enter product name
Welcome to Simplicity Studio
Everything you need to develop, research, and configure devices for IoT applications.
Get Started
Select a connected device or search for a product by name to see available documentation, example projects, and demos.
Connected Devices
All Products
Connected Devices
Thunderboard EFR32BG22 (ID: 000440190639)
Start
Recent Projects
You haven't created a project yet
Create New Project
Learn and Support
Log In
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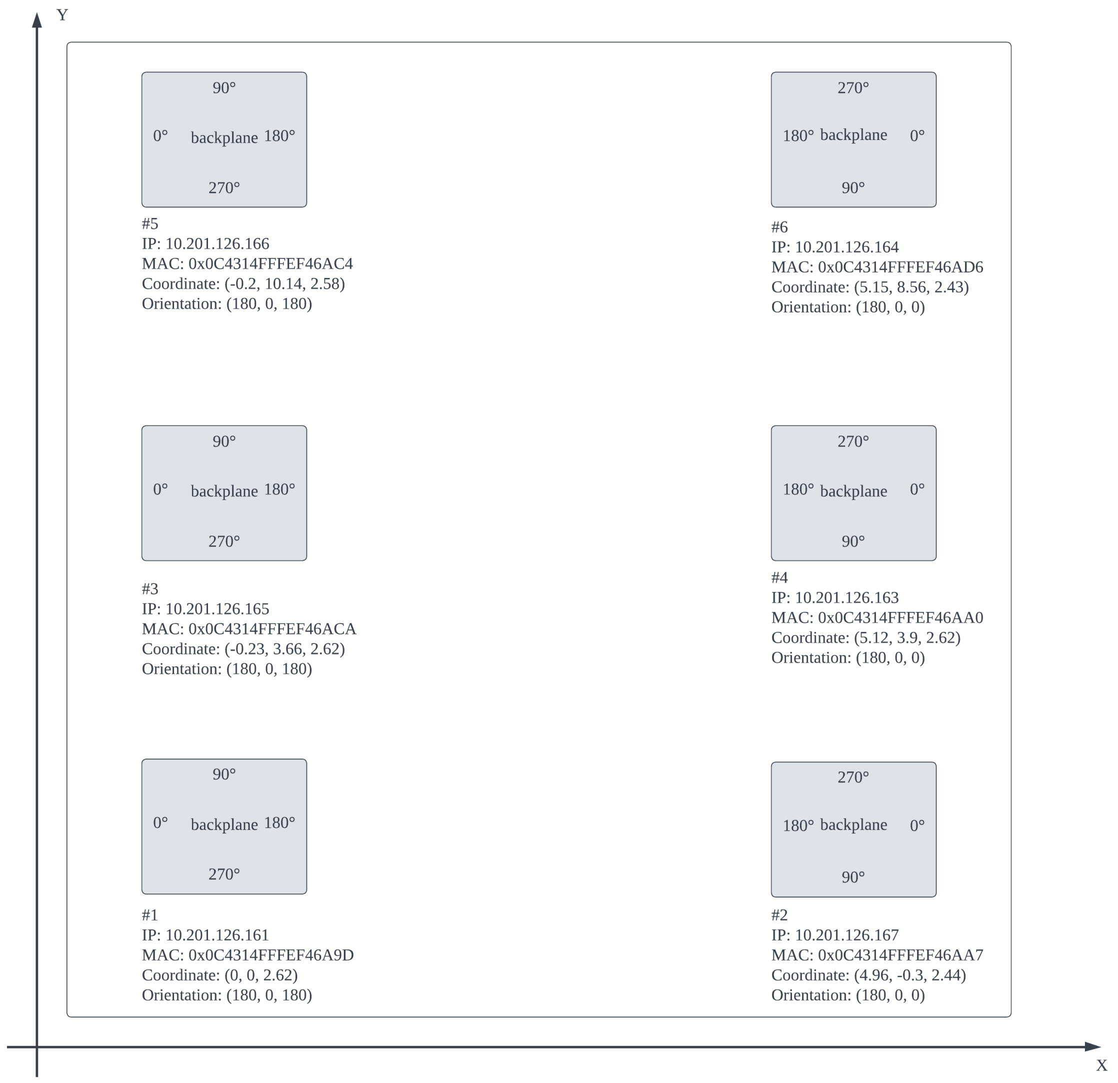
Testing Environment

Testing Environment



Environment:

- Location: Office environment, open space, lots of desks, shelves, and cubicles in the measurement area
- Locator height from floor: 2.5 m
- Tag height from floor: 1.5 m
- Testing range: 50 m2

Hardware

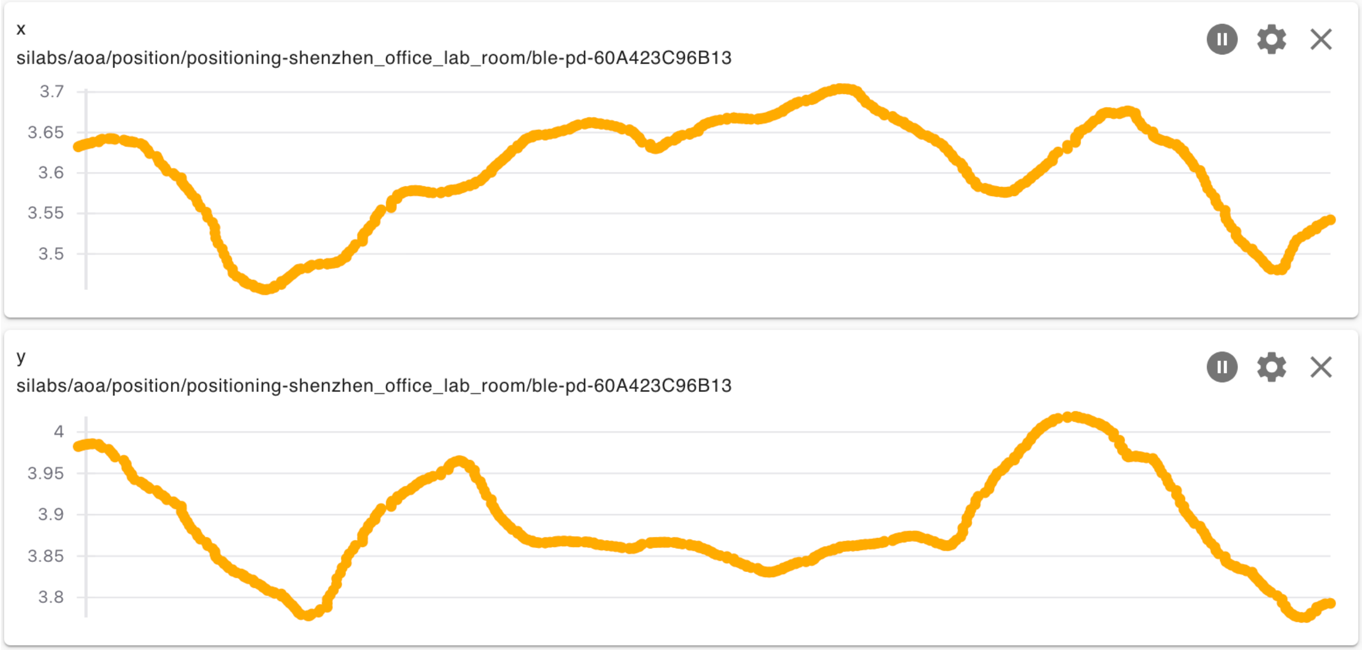
- 6 EFR32BG22 Direction Finding boards (BRD4191A)
- 1 Thunderboard BG22 (BRD4184A) or 1 Thunderboard xG24 (BRD2601B) or EFR32BG22 Tag Reference Design

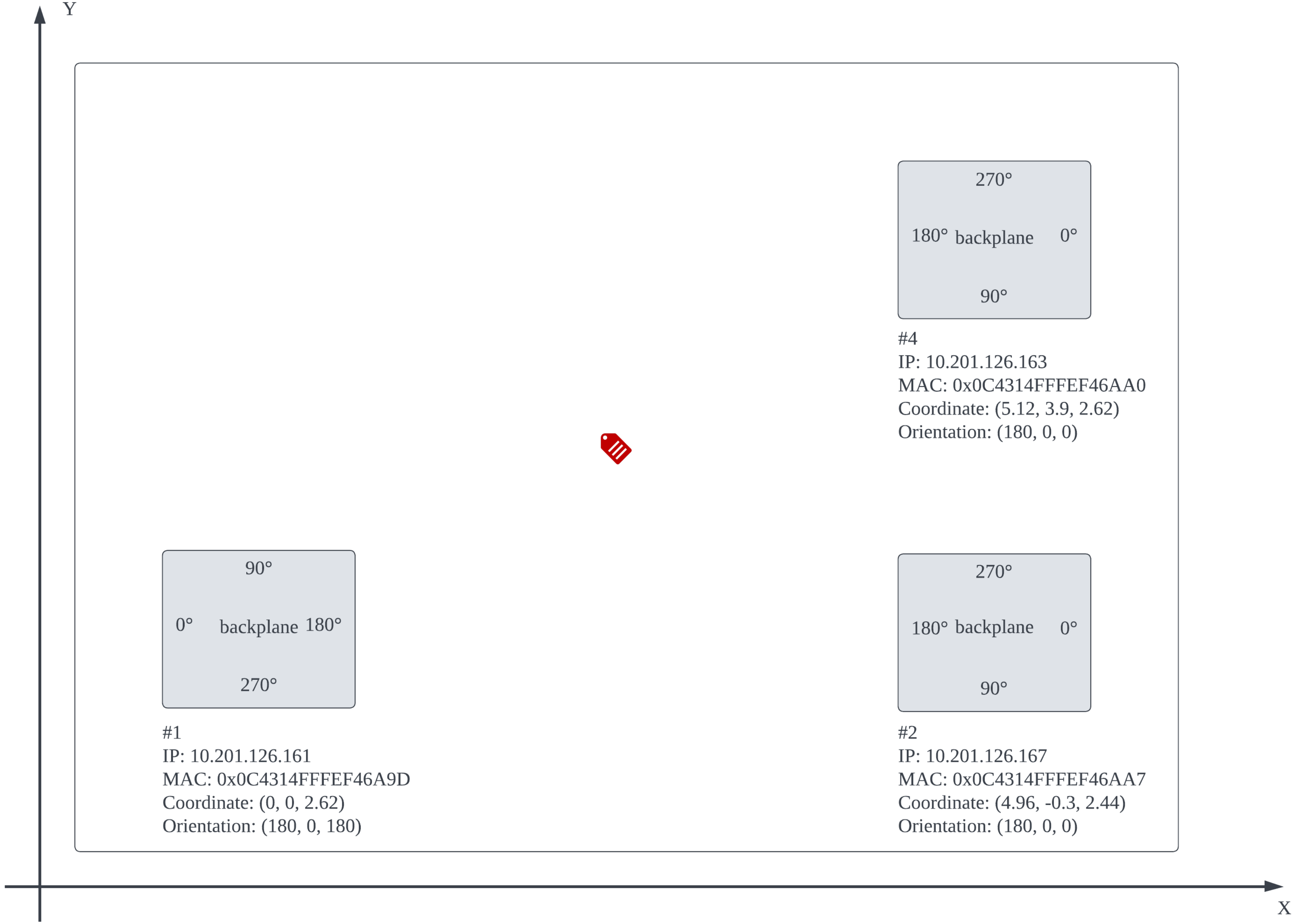
Software

- Simplicity Studio v5
- Gecko SDK Suite 4.1.0 or later

Test Result


Y
Tag
#2
(1.8, 7, 1.5)
Tag
#3
(3.5, 4, 1.5)
Tag
#1
(2.3, 2.7, 1.5)
X


x
silabs/aoa/position/positioning-shenzhen_office_lab_room/ble-pd-60A423C96B13
3.7
3.65
3.6
3.55
3.5
y
silabs/aoa/position/positioning-shenzhen_office_lab_room/ble-pd-60A423C96B13
4
3.95
3.9
3.85
3.8


Y
X
270°
180° backplane 0°
90°
#4
IP: 10.201.126.163
MAC: 0x0C4314FFFEF46AA0
Coordinate: (5.12, 3.9, 2.62)
Orientation: (180, 0, 0)
90°
0° backplane 180°
270°
#1
IP: 10.201.126.161
MAC: 0x0C4314FFFEF46A9D
Coordinate: (0, 0, 2.62)
Orientation: (180, 0, 180)
270°
180° backplane 0°
90°
#2
IP: 10.201.126.167
MAC: 0x0C4314FFFEF46AA7
Coordinate: (4.96, -0.3, 2.44)
Orientation: (180, 0, 0)

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Thank You!

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