

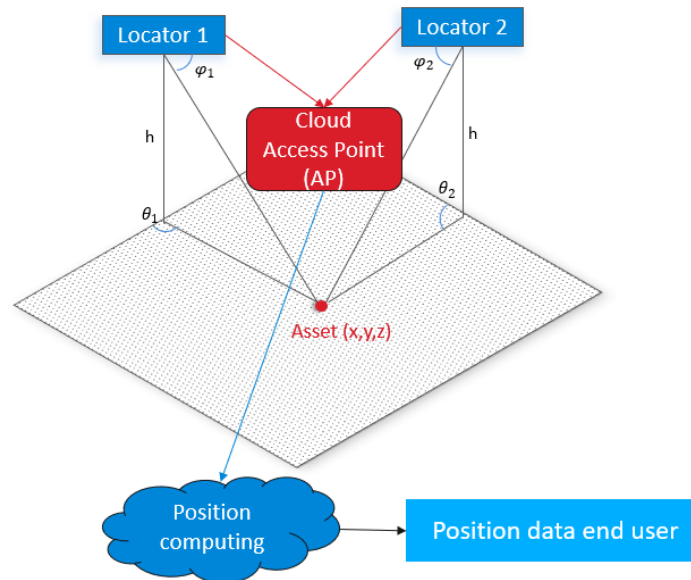
QSG175: Silicon Labs Direction Finding Solution Quick-Start Guide



Bluetooth version 5.1 introduced support for Direction Finding to provide a standard protocol for radio-based Real Time Locating Systems (RTLS). Silicon Labs not only supports this feature in its Bluetooth stack, but it also provides a reference implementation of a Real Time Locating System running over Bluetooth. This guide walks through the offered solution to help anyone get started with Direction Finding.

KEY POINTS

- Stack support for Direction Finding
- RTL library
- Architecture
- Demos and Examples



1 Introduction

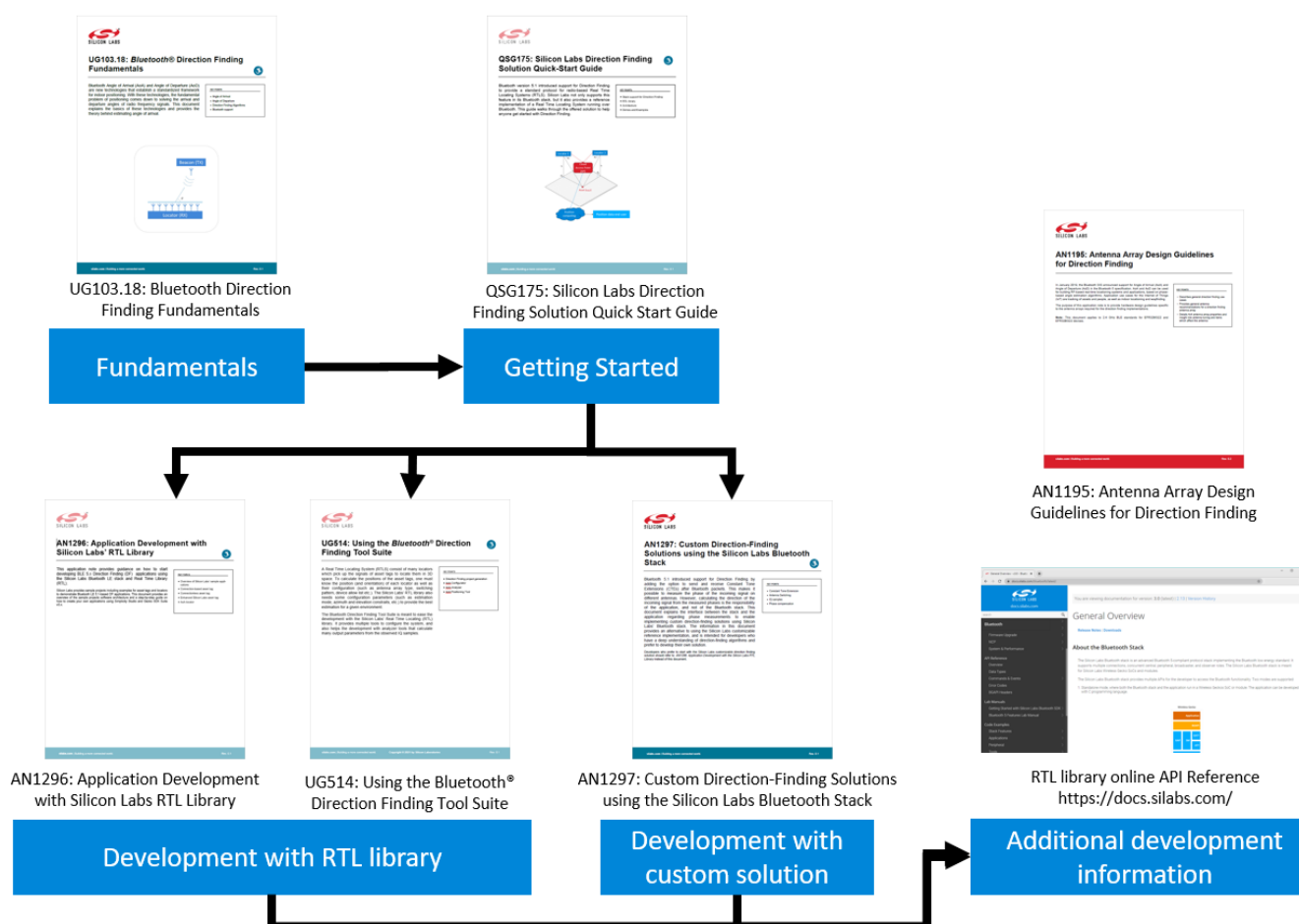
Bluetooth 5.1 introduced support for Direction Finding by adding the option to send and receive Constant Tone Extensions (CTEs) after Bluetooth packets. This makes it possible to do phase measurements on antenna arrays and ultimately to determine the direction of an incoming signal. To learn more about the theory of Direction Finding, that is how to determine the direction of incoming signals, see *UG103.18: Bluetooth® Direction Finding Fundamentals*. Readers of this document should be familiar with the basics and terms of Direction Finding.

Beginning with Bluetooth SDK v3.1, Silicon Labs' Bluetooth stack supports CTE transmitting and receiving features on selected devices and can take phase measurements on the incoming signal as specified by the Bluetooth standard. Note, however, that the determination of the angle of incidence from the phase measurements is outside of the scope of the standard and must be implemented in the application. To reduce the Time to Market for its customers, Silicon Labs also offers a reference implementation of a Bluetooth-based Real Time Locating System (RTL), which provides both an out-of-box experience to evaluate the solution and a flexible framework that makes it possible for everyone to create their own RTLs. To get started with the reference implementation, refer to *AN1296: Application Development with Silicon Labs' RTL Library*. To find the API Reference Manual for the RTL library, visit <https://docs.silabs.com/>. The link for the RTL library is under the Bluetooth section. To learn about the Simplicity Studio tools supporting Direction Finding, see *UG514: Using the Bluetooth® Direction Finding Tool Suite*.

It is of course also possible for anyone to use their own direction-finding algorithm on top of the Bluetooth stack. This requires deep knowledge in Direction Finding but enables even more flexibility. If you choose this approach, see *AN1297: Custom Direction-Finding Solutions using Silicon Labs' Bluetooth Stack*.

The Silicon Labs Direction Finding solution is part of the Bluetooth SDK. If you are not yet familiar with the Silicon Labs Bluetooth SDK, start with the following document: [QSG169: Bluetooth® SDK v3.x Quick-Start Guide](#).

Finally, either you use Silicon Labs' Direction Finding board or your own design. *AN1195: Antenna Array Design Guidelines for Direction Finding* provides you with useful information regarding antenna design. It also provides accuracy measurement results of the RTL library used with Silicon Labs' Direction Finding board.



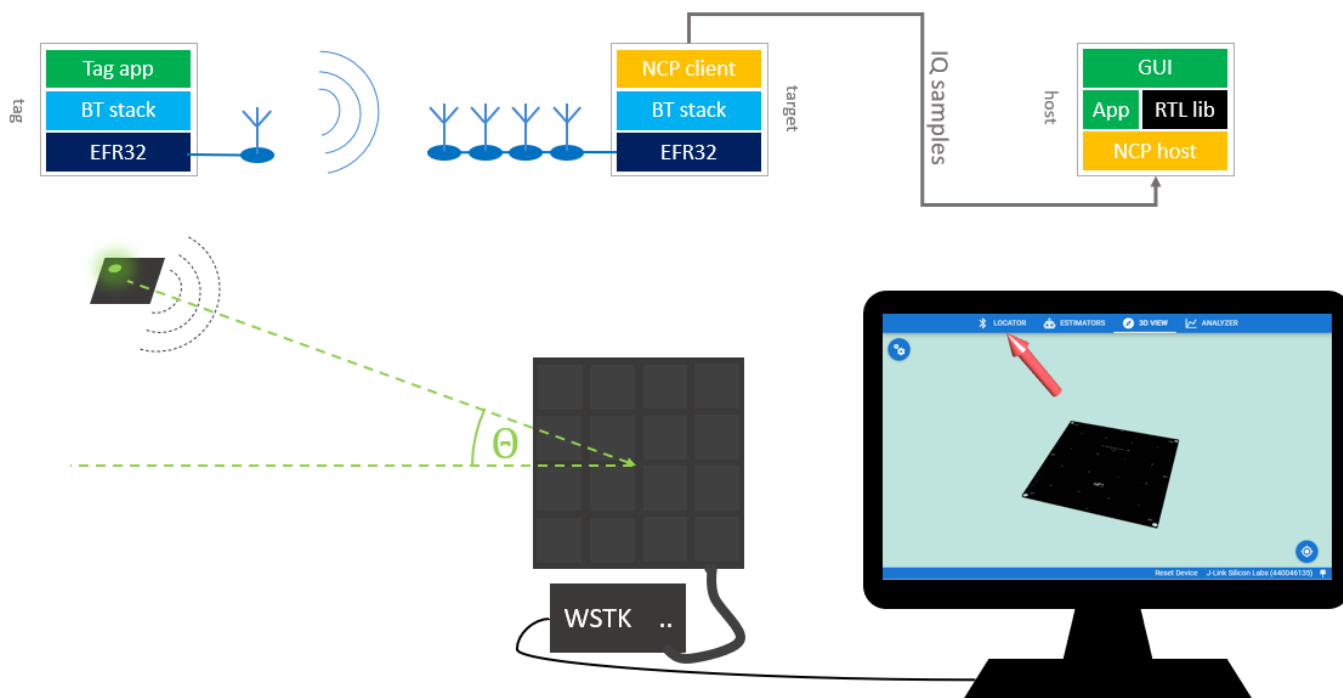
2 Demos and Examples

Silicon Labs provides both hardware and software solutions to make the evaluation of the Direction Finding solution quick and easy. Using a Direction Finding radio board along with a Wireless Starter Kit (WSTK) as a locator, and a Thunderboard BG22 as a tag, you can easily set up our demo environment, which shows you the capabilities of Bluetooth-based Direction Finding.

To get started with Bluetooth demo software, you should have downloaded Simplicity Studio 5 (SSv5) and the Bluetooth SDK v3.x or later as described in the [Simplicity Studio 5 User's Guide](#), available online and through the SSv5 help menu. The Bluetooth SDK comes with some prebuilt demos that can be flashed to your EFR32 device and tested with the appropriate tool as described in this section. If you are new to Silicon Labs' Direction Finding solution, it is worth starting with setting up this demo.

2.1 Demo

- The demo comprises three demo applications:
- The **Bluetooth AoA – SoC Asset Tag** demo app is a prebuilt version of the sample app with the same name, and it is to be run on the tag that you want to follow.
- The **Bluetooth AoA – NCP Locator** demo app is a prebuilt version of the sample app with the same name, and it is to be run on the antenna array board (Direction Finding board).
- The **AoA Analyzer** tool is a Java based application, built into Simplicity Studio 5, that showcases the angle estimation skills of the RTL library in a graphical user interface. It is intended for demo and evaluation purposes and follows a simple architecture as shown in the following figure:

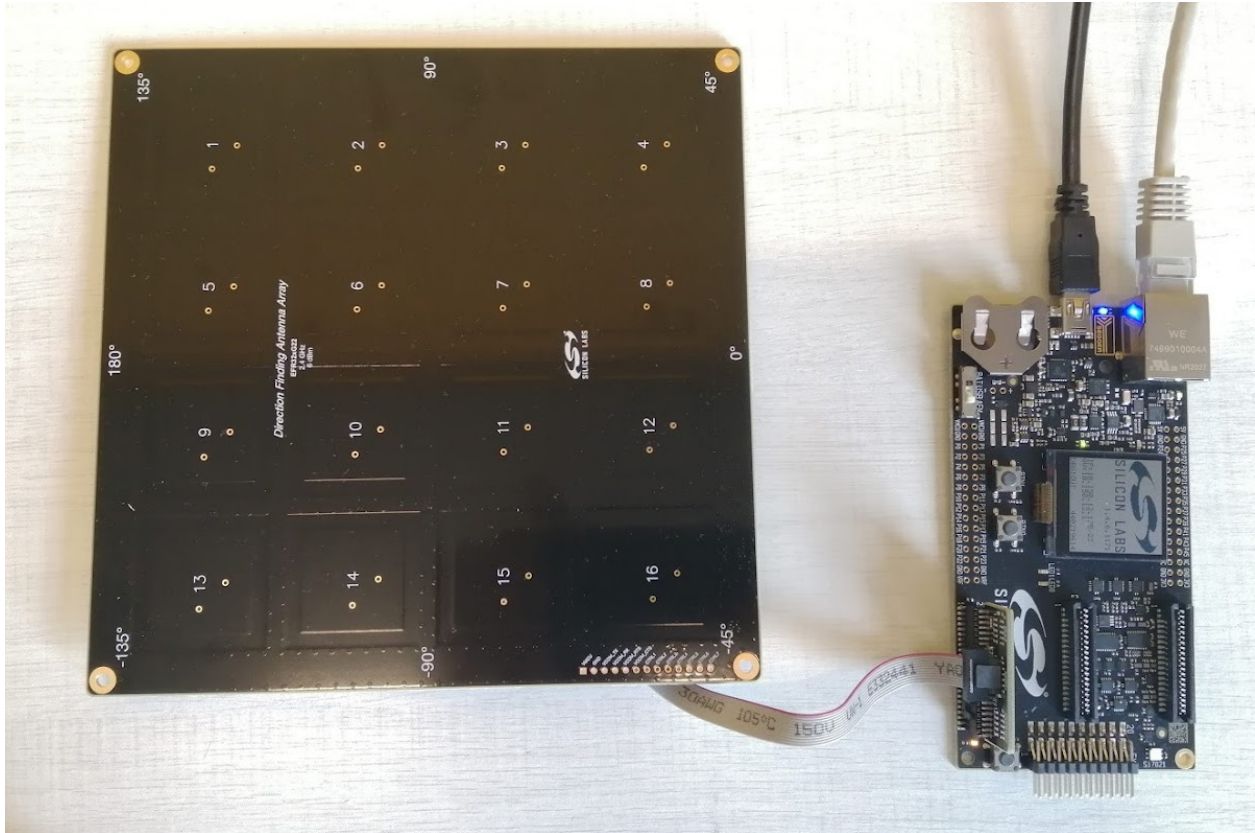


- Running the demo requires the following devices:
 - An EFR32xG22 or an EFR32xG24 radio board, preferably a Thunderboard BG22
 - A BRD4191A antenna array board with a WSTK Mainboard and with a Debug Adapter board
 - A PC running Simplicity Studio 5 with Gecko SDK Suite v4.1.0 or later

2.1.1 Set Up the Antenna Array Board

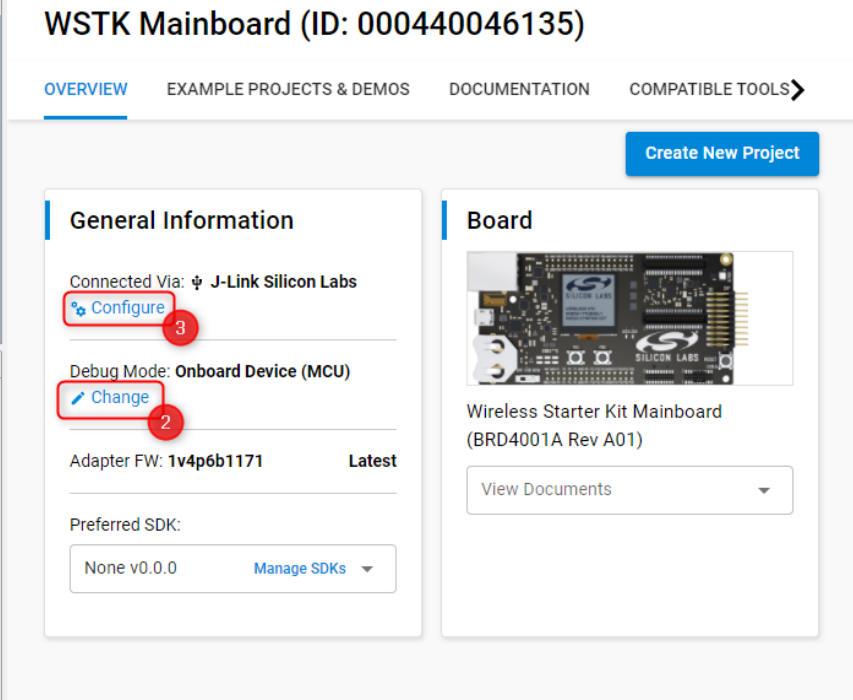
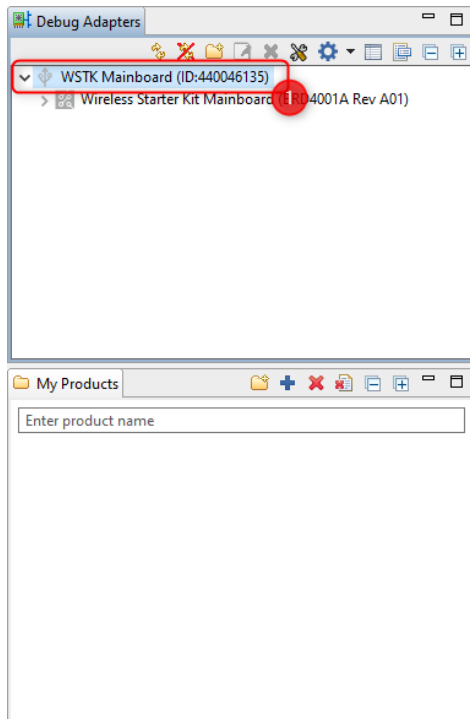
To set up the demo, first connect the antenna array board and install the proper firmware on it.

1. Attach the Antenna Array board to the Mainboard using the Debug Adapter board and a ribbon cable as shown in the following figure. The Antenna Array board uses the Mini Simplicity+ connector (MINI+) to communicate with the Mainboard. **Note:** The MINI+ connector is located on the back of the Antenna Array board. Flip the board after attaching the cable so that the antennas face upward.

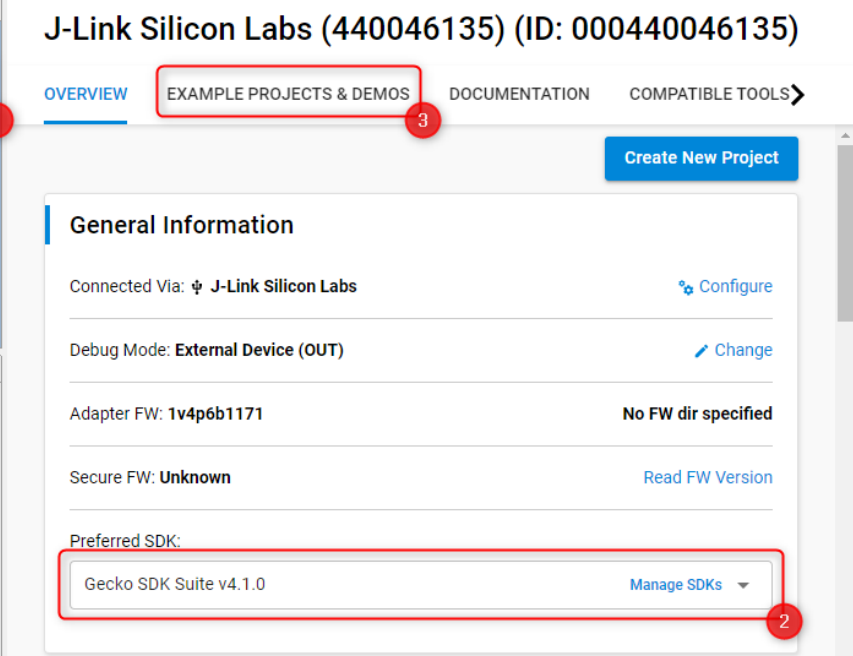
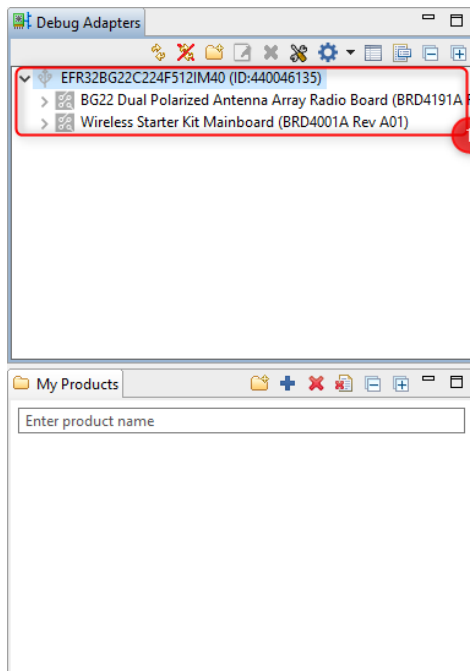


2. Connect the mainboard to a PC using an USB cable or via Ethernet. **Note:** A USB connection is required, even if Ethernet is used for communication, to power the board. Do not use a coin cell battery for this use case.
3. Make sure that the switch on the mainboard is set to 'AEM'.
4. Start Simplicity Studio 5.

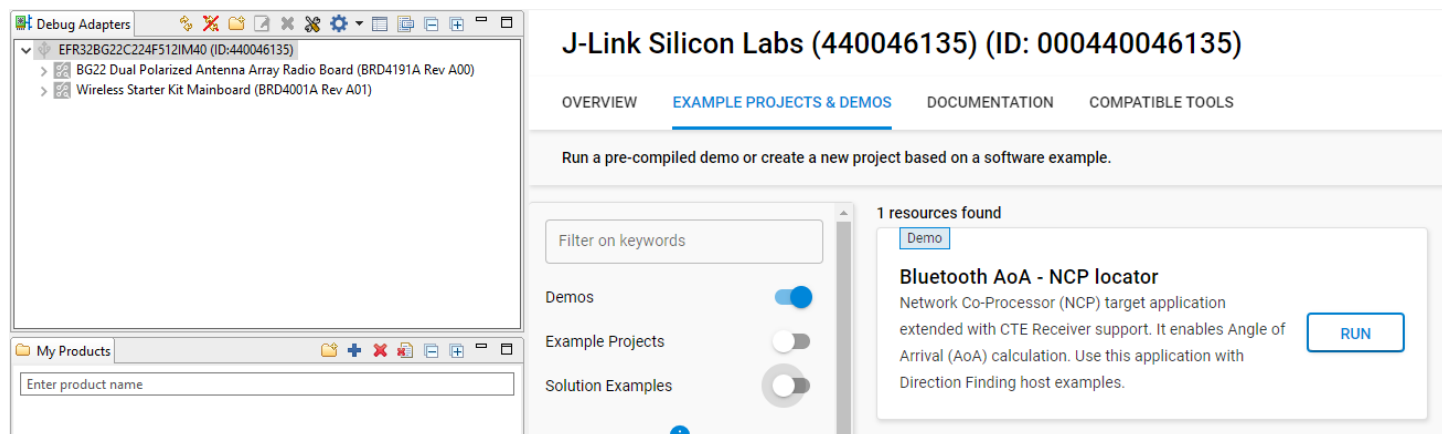
5. Since the Antenna Array board is attached via the external debug connector of the mainboard, the board is not automatically recognized. You must configure the mainboard into external debug mode.
 1. In the Simplicity Studio 5 Launcher perspective's Debug Adapters view, click the board to select it.
 2. In the Launcher perspective's Overview tab, on the General Information card, click **Change** next to **Debug Mode**. In the Device Configuration's Adapter Configuration tab, change the **Debug Mode** setting from 'MCU' to 'OUT' and click **OK**.
 3. On the General Information card, click **Configure** next to **Connected via**. In the Device Configuration's Device Hardware tab, start typing "antenna array" into the **Boards** input field and select 'BG22 Dual Polarized Antenna Array Radio Board (BRD4191A)' from the list. Click **OK**.



6. Select the configured Antenna Array board in the Debug Adapters view and make sure that Gecko SDK Suite v4.1 (or later) is selected as Preferred SDK. Go to the **Example Projects & Demos** tab.



7. Filter for demos only and find the **Bluetooth AoA – NCP Locator** demo.



8. Click **RUN** to download and run the demo on your board. (Note: the demo also includes a bootloader. If you build the AoA locator application from source, a bootloader must also be flashed to the device.)

2.1.2 Set Up the Tag

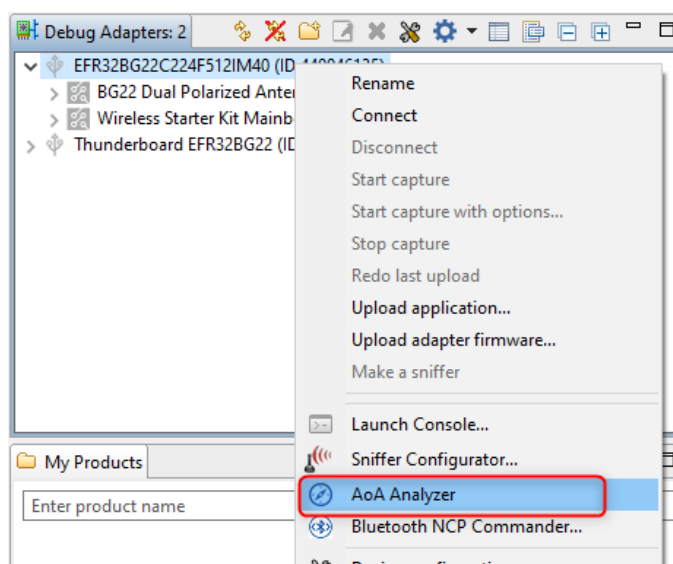
Next, install software on the board with an EFR32xG22 or EFR32xG24 part (the tag). **Note:** A precompiled demo is only available for the Thunderboard BG22. For other boards, build the example project with the same name, and flash it to the device along with a bootloader. These instructions are for the Thunderboard BG22.

1. Connect a Thunderboard BG22 to the PC.
2. Select the board in the Debug Adapters view, and make sure that Gecko SDK Suite v4.1 (or later) is selected as Preferred SDK.
3. Go to the Example Projects & Demos tab, filter for Bluetooth technology type and find the **Bluetooth AoA – SoC Asset Tag** demo.
4. If this is a new Thunderboard, push its reset button. On some boards the factory default firmware puts the device into EM4 sleep mode after 30 seconds, so the device must be restarted before the programmer can load the demo.
5. Click **RUN** to download and run the demo.

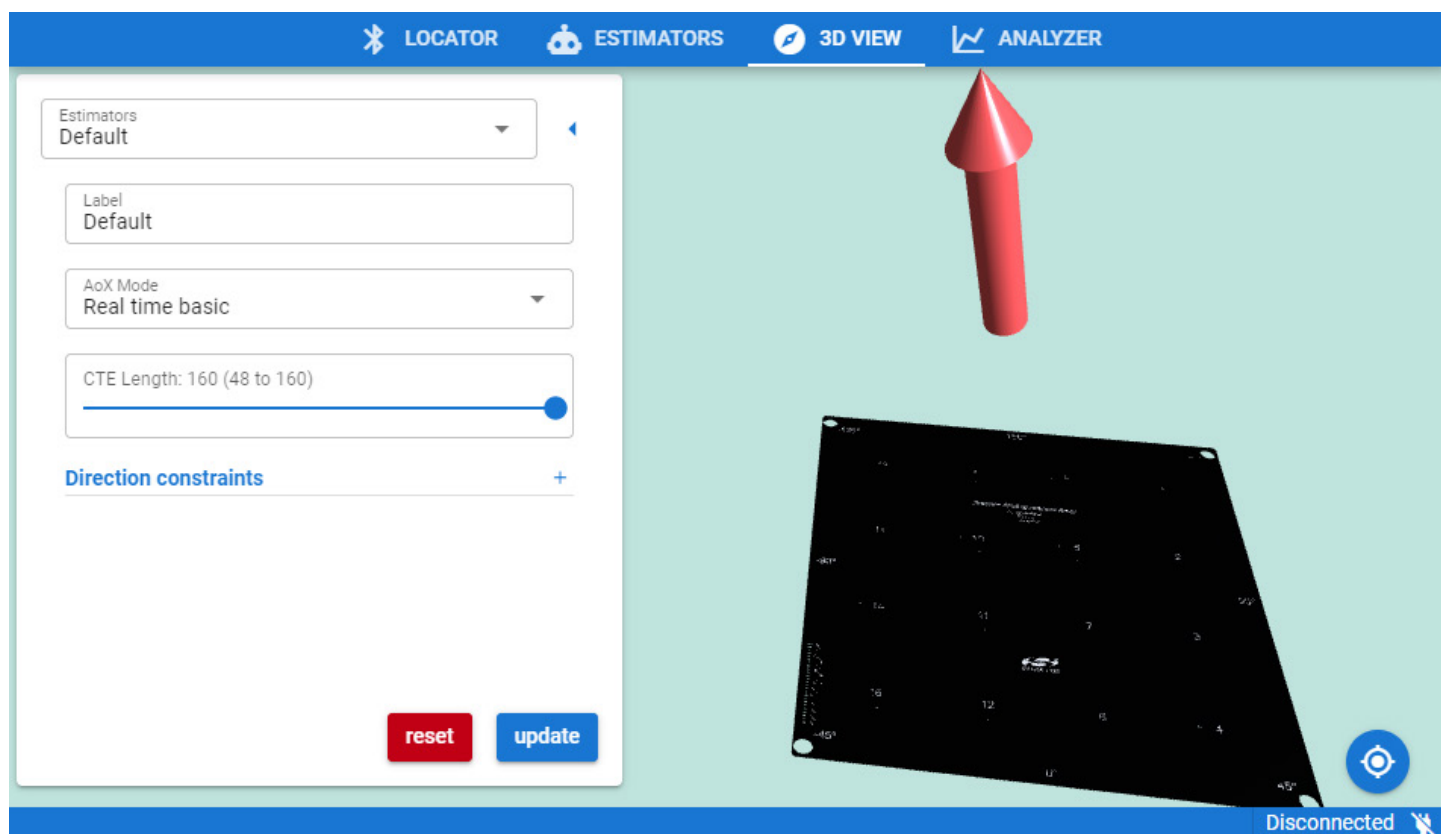
2.1.3 Start the AoA Analyzer Tool

Finally, start the AoA Analyzer tool in Simplicity Studio 5.

1. In the Launcher perspective's Debug Adapters view, right-click the antenna array board (Direction Finding board).
2. Select AoA Analyzer in the context menu. The tool is also available through the Tools menu in the Simplicity Studio toolbar.



3. The analyzer opens, connects to the antenna array board, finds the asset tag near you, and displays its direction relative to the antenna array board.
4. Move around the scene with your mouse to get a better view on the board.
5. Move the tag around, and see the right arrow following your movement:



6. Expand the Assets window in the lower right to see more information about the assets.
7. In the Settings window you can experiment with the AoX Mode. Different AoX modes provide different latency and different accuracy of the angle estimation.
8. The application supports multiple tags, so if the **Bluetooth AoA – SoC Asset Tag** application is flashed to multiple devices, the AoA Analyzer will display each direction with multiple arrows.

If the AoA Analyzer gets stuck after starting, try resetting the board. If that does not solve the problem:

1. In Simplicity Studio's Debug Adapters view, right-click the antenna array board.
2. Select **Connect**.
3. Right-click the device again and select **Launch Console**.
4. Select the admin tab.
5. Check the serial vcom settings with the command

```
serial vcom
```

6. Change the serial vcom settings to use CTS handshake mode

```
serial vcom config handshake cts
```

7. Now re-try running AoA Analyzer. If it still does not work, upgrade the WSTK to the latest firmware version through the update functionality on the Launcher perspective's Overview tab.

2.2 Application Examples

As part of its reference RTLS implementations, Silicon Labs provides multiple sample apps that demonstrate the usage of the CTE Transmitter and CTE Receiver features and of the RTL library.

While the Demo is focusing on Angle of Arrival calculation only, the sample apps demonstrate both Angle of Arrival calculation and position estimation, using multiple locators.

The sample apps follow the software architecture shows in section [4.1 Overview](#):

- The **Bluetooth AoA – SoC Asset Tag** sample app running on the *tag* demonstrates the CTE Transmitter feature.
- The **Bluetooth AoA – NCP Locator** sample app running on the antenna array board (*target*) is a modified version of the **Bluetooth - NCP** example supporting the CTE receiver feature.
- The **bt_aoa_host_locator** host sample app running on the *host* demonstrates the CTE Receiver feature and the use of the angle estimation feature of the RTL library. It uses the same application logic as the AoA Analyzer used in the demo setup.
- The **bt_host_positioning** host sample app running on the *central* device demonstrates the position estimation feature of the RTL library.
- The **bt_host_positioning_gui** python script running on the *central* device visualizes the positions of the tags as calculated by the positioning app.
- For detailed description of the sample apps, see *AN1296: Application Development with Silicon Labs' RTL Library*.

2.3 Tools

Since setting up a full RTL system with multiple locators is not easy, Simplicity Studio also provides a set of tools that helps the developer. The tools can be used for:

- Configuring the parameters of the individual locators and of the whole system,
- Running 3D demos (Angle of Arrival and Positioning),
- Analyzing the incoming and processed data.

To learn more about the tools, see *UG514: Using the Bluetooth® Direction Finding Tool Suite*.

3 Bluetooth Stack and SDK Support

3.1 CTE Transmitter and Receiver

To support Direction Finding, Bluetooth 5.1 introduced the concept of Constant Tone Extension (CTE). CTE, as its name suggests, extends the Bluetooth packets with a constant tone, that is with a continuous phase, constant amplitude and constant frequency signal, sent immediately after the CRC of the Bluetooth packet. The length of this extension varies between 16 μ s – 160 μ s. This signal can be used on the receiver side to measure the phase of the incoming signal on multiple antennas.



Figure 2-1. Bluetooth Package with CTE

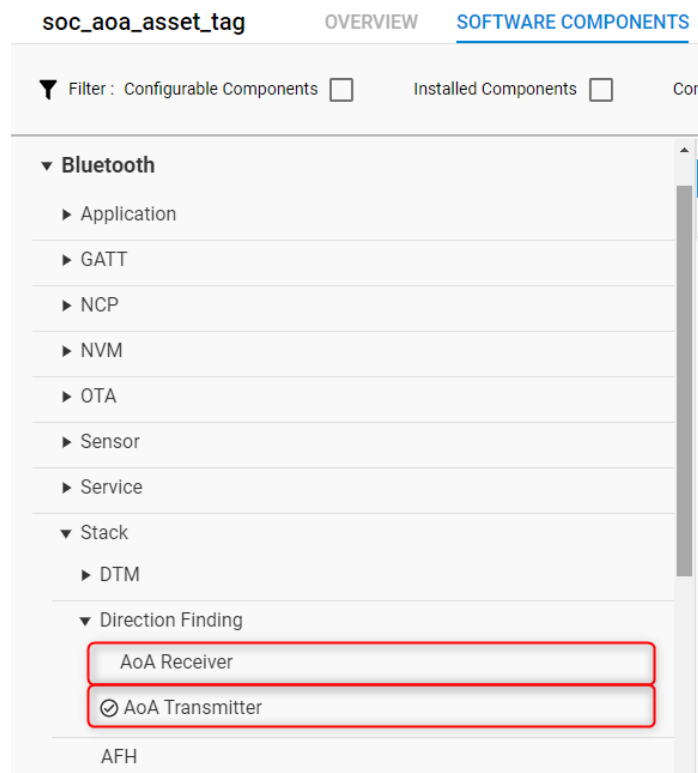
To learn more about CTE, see the Technical Overview of Bluetooth Direction Finding published by the Bluetooth SIG: <https://www.bluetooth.com/bluetooth-resources/bluetooth-direction-finding/> and *Bluetooth Core Specification v5.1* or later.

CTEs can be sent:

- Over Bluetooth connections using the Link Layer Constant Tone Extension Request procedure (**connection-oriented mode**).
- In periodic advertisements, if the CTEInfo field is present (**connectionless mode**).

Additionally, Silicon Labs provide a proprietary solution to send CTEs in extended advertisements (**Silicon Labs enhanced mode**), which makes Real Time Locating Systems more scalable. This solution is highly recommended in a use case with hundreds of tags, as it is stateless, in contrast to connections and periodic advertisement synchronizations which need to store sync information for each tag and do not scale well.

To be able to send or receive CTEs, the **CTE Transmitter** and **CTE Receiver** software components must be installed in your Bluetooth project, respectively.



These components initialize the `cte_transmitter` and `cte_receiver` BGAPI classes, and make it possible to use the associated APIs:

<https://docs.silabs.com/bluetooth/3.1/group-si-bt-cte-transmitter>,

<https://docs.silabs.com/bluetooth/3.1/group-si-bt-cte-receiver>.

Note: The CTE Transmitter feature is available on all EFR32xG22 and EFR32xG24 devices, including SoCs and modules. The CTE Receiver feature is available only on part numbers marked with “Direction Finding” protocol stack support in the datasheet.

EFR32BG22C224F512GM32-C	<ul style="list-style-type: none"> • Bluetooth 5.2 • Direction finding • Proprietary 	6 dBm	76.8 MHz	Precision	512	32	18	QFN32	-40 to 85 °C
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Typically a device is either in CTE transmitter or in CTE receiver mode, but not both. Install the corresponding software component on each device.

To enable CTE responses on a connection, use the API `sl_bt_cte_transmitter_enable_connection_cte()` on the CTE transmitter side. To send a CTE request from the receiver to the transmitter, use the API `sl_bt_cte_receiver_enable_connection_cte()` on the receiver side. If CTE responses are enabled on the transmitter side, the Bluetooth stack will automatically respond to each CTE request with a CTE response.

To transmit CTEs in periodic advertisements, first start a periodic advertiser on the transmitter side (install the Periodic Advertising software component and use the corresponding Bluetooth APIs), and then use the `sl_bt_cte_transmitter_enable_connectionless_cte()` API to add CTE to the existing advertiser. To start listening to CTEs attached to periodic advertisements, first establish a periodic synchronization on the receiver side (install the Periodic Advertising Synchronization software component and use the corresponding APIs), and then use the `sl_bt_cte_receiver_enable_connectionless_cte()` API to enable CTE reception on the established synchronization.

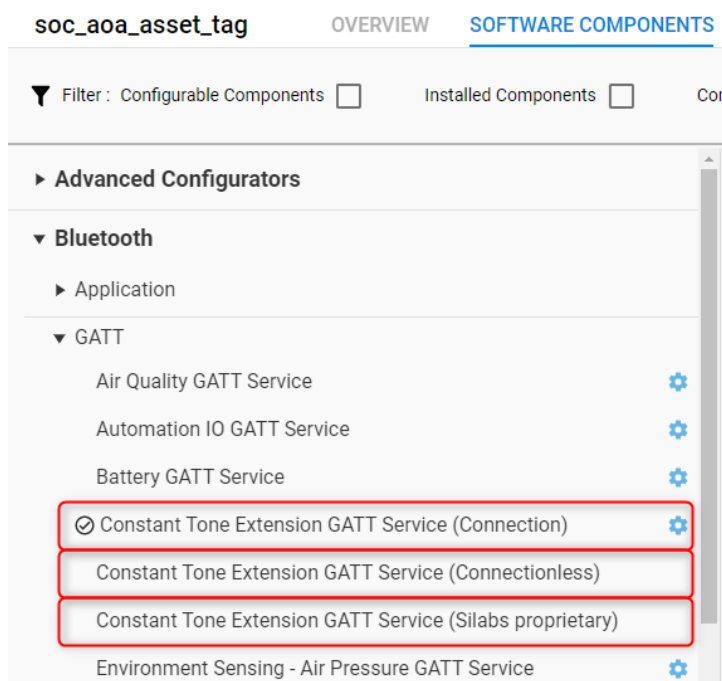
To transmit CTEs in Silicon Labs proprietary extended advertisements, first start a (regular) extended advertisement on the transmitter side, and then use the API `sl_bt_cte_transmitter_enable_silabs_cte()` to add CTE to the advertiser. To start listening to CTEs attached to Silicon Labs proprietary extended advertisements, first start (regular) scanning on the receiver side and then use the API `sl_bt_cte_receiver_enable_silabs_cte()`.

Every time a CTE is received on the receiver side, the signal is automatically sampled by the Bluetooth stack and an IQ report event is generated by the Bluetooth stack. If you choose to use the reference RTL implementation of Silicon Labs, you do not have to care about these events. The IQ samples are forwarded to the RTL library, which then calculates the Angle of Arrival for you. If you choose to process the IQ samples with your application, find more details about IQ samples in *AN1297: Custom Direction-Finding Solutions using Silicon Labs' Bluetooth Stack*.

3.2 GATT Services

CTEs have parameters such as length, slot duration, and how often they should be sent. To make their configuration easy, the Bluetooth SDK adds support for CTE configuration via the GATT database. This is especially useful in AoA mode on the asset tags (CTE transmitters).

There are three CTE configuration services corresponding to the three CTE transmit mode (connection-oriented, connectionless, Silicon Labs enhanced mode). To add these services to your project, install the corresponding software component:



The software components will not only add the service to the GATT database, but they will also take care of enabling, disabling and configuring CTEs when the characteristics of the CTE service are written from a remote device. Note that the Connection oriented service must always be installed when using any of the three software components. Connectionless and Silicon Labs enhanced services cannot be installed at the same time.

3.3 Antenna Switching

Determining the direction of the Bluetooth signal is not possible without one device having an antenna array. As described in *UG103.18: Bluetooth® Direction Finding Fundamentals*, in Angle of Arrival (AoA) mode the receiver must have an antenna array, while in Angle of Departure (AoD) mode the transmitter must have an antenna array. In AoA mode the antennas must be switched during CTE reception, while in AoD mode the antennas must be switched during AoA transmission. The Bluetooth stack supports both AoA and AoD mode, and it controls antenna switches automatically during CTE transmission or reception. If you use Silicon Labs' antenna array boards, you do not have to care about switching pin configuration and antenna switching patterns, since they are implemented in the sample apps. If you use a custom antenna array, details about the configuration are in *AN1297: Custom Direction-Finding Solutions using Silicon Labs' Bluetooth Stack*.

4 Real-Time Location (RTL) Library

4.1 Overview

Estimating the Angle of Arrival (AoA) or Angle of Departure (AoD) from IQ samples is not trivial, especially in a real environment full of reflections. To ease the burden for developers and to speed up time-to-market, Silicon Labs provides a Real Time Locating library (RTL lib), which processes the IQ samples received from the Bluetooth stack, implements multipath detection and azimuth and elevation calculation, and exposes the data to the application via an open API.

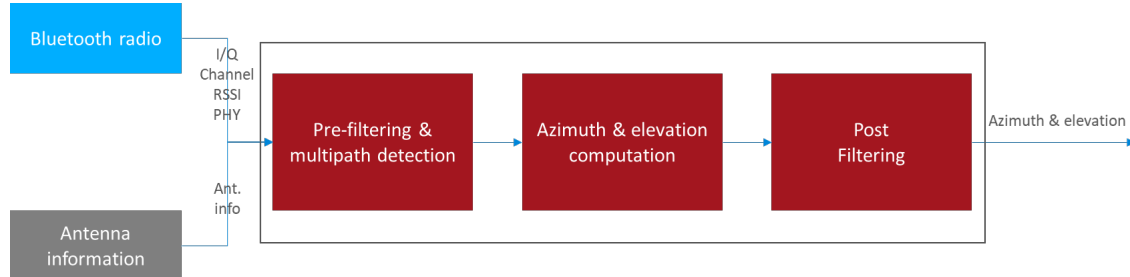


Figure 3-1: Silicon Labs RTL Library Providing Azimuth and Elevation

Furthermore, the library is also able to estimate the location of a tracked asset in a multi-locator scenario using triangulation, where multiple locators receive CTEs from the same asset tag, provided that the library knows the position of each locator. In this case the positions of the locators and the estimated angles (AoA) serve as the input, and the estimated location is the output.

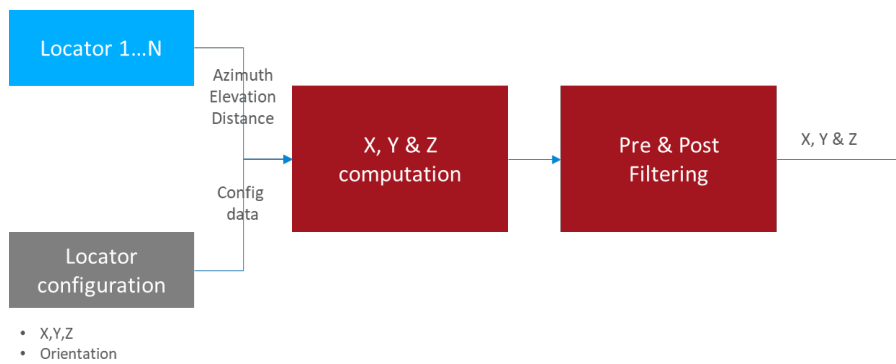
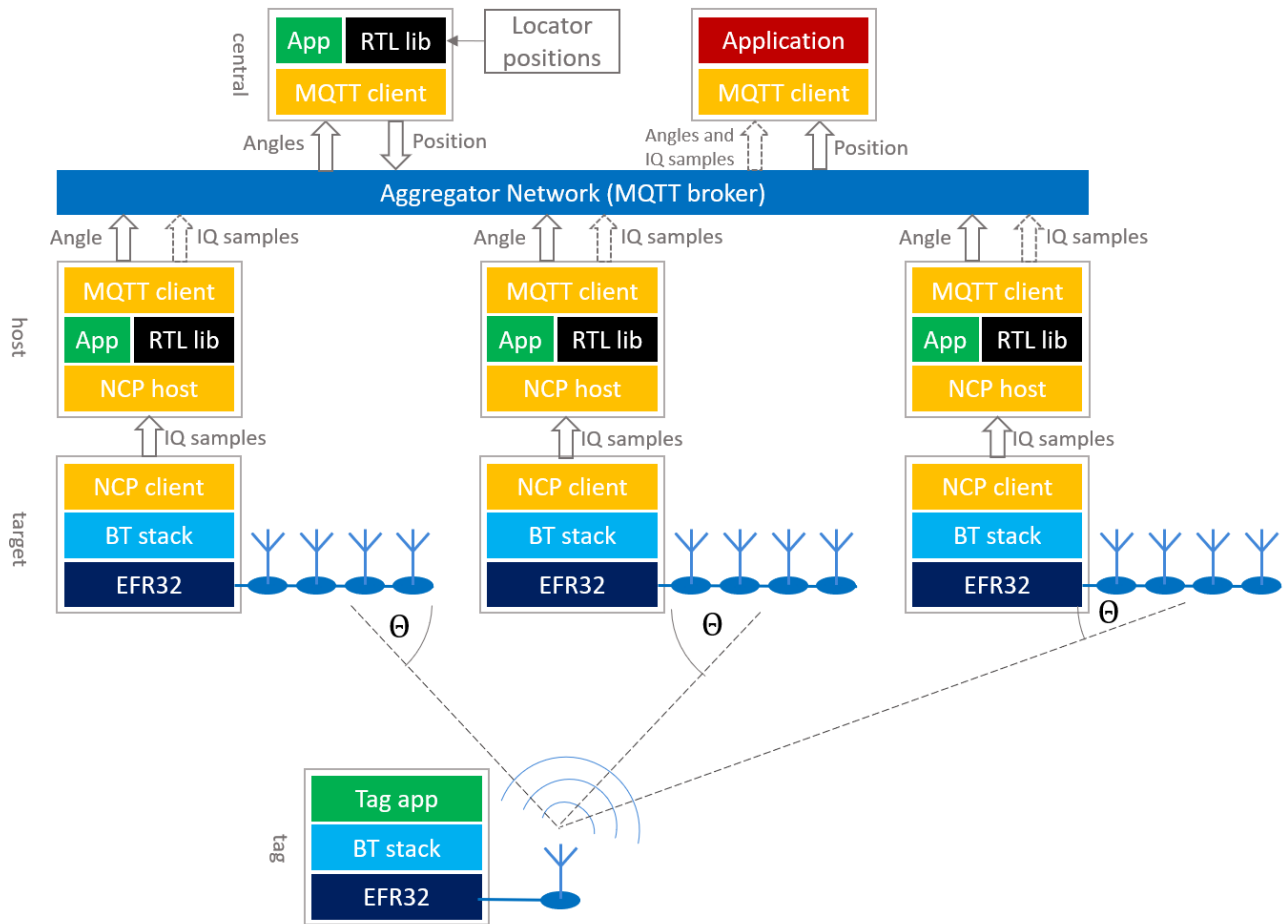


Figure 3-2: Silicon Labs RTL Library Providing X, Y and Z

Once the positions are estimated it is up to the user's application how to process the data. The general architecture of an RTLS using Silicon Labs RTL library looks like this:



All AoA-related sample apps in the Bluetooth SDK are created so that they support this model. To learn more about the sample apps, see *AN1296: Application Development with Silicon Labs' RTL Library*.

Note that on the Locator side the devices work in a Network Co-Processor (NCP) mode, that is, the stack runs on the EFR32 chip, but the application runs on a host computer. Currently, due to the limited computational capacity of the EFR32 chips, only NCP mode is supported, that is the RTL library cannot be used on the chip. To learn more about NCP mode, see *AN1259: Using the v3.x Silicon Labs Bluetooth® Stack in Network Co-Processor Mode*.

The locators can connect to the central PC in many ways. Silicon Labs' reference implementation uses MQTT to collect angle data from locators, since it gives the flexibility to run the host sample apps on a distributed network as well as on a single PC using localhost, but other implementations can be used as well.

The RTL library provides the following features:

Feature	Value and Comments
Direction Finding Method	AoA
# of tags supported	infinite (lib needs to be initialized for each, and physical channel puts a limitation on this)
# of locators supported	infinite (lib needs to be initialized for each)
Antenna arrays supported	BG22 Dual Polarized Antenna Array Radio Board (BRD4191A), EFR32BG22 Direction Finding Radio Board (BRD4185A), CoreHW PCB4 and PCB8 Antenna Array boards

Feature	Value and Comments
Modes of operation	Single shot / Real time, Fast response / Basic / High accuracy Azimuth & elevation / Azimuth only
Supported platforms	Windows x64, Ubuntu x64, Raspbian (Cortex A), Darwin x64

The RTL library is provided as a single static library for each supported platform. The library can be found in the Gecko SDK suite under:

- GSDK 3.x: `C:\SiliconLabs\SimplicityStudio\v5\developer\sdk\gecko_sdk_suite\v3.1\util\silicon_labs\aox`
- GSDK 4.0 and higher: `C:\Users\<username>\SimplicityStudio\SDKs\gecko_sdk_util\silicon_labs\aox`

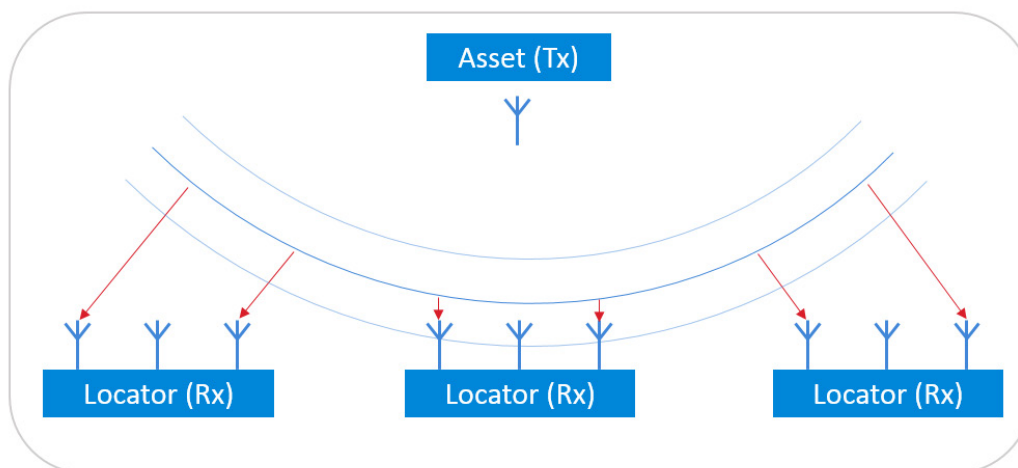
The library has three API classes:

- **Angle of Arrival / Departure** (`sl_rtl_aox_`): API used for AoA/AoD estimation from IQ samples. (Currently only AoA is supported.)
- **Location Finding** (`sl_rtl_loc_`): API used for location estimation (x, y, z coordinates) from AoA/AoD.
- **Utility Functionality** (`sl_rtl_util_`): API grouping utility functions that may be useful during AoA/AoD/location estimation

Inside the Angle of Arrival / Departure and Utility Functionality classes an **IQ Sample Quality Analysis** API is also available to provide analytical measurements of different kind of errors in the system.

4.2 Angle of Arrival / Departure

There are two Bluetooth based direction-finding methods: Angle of Arrival (AoA) estimation and Angle of Departure (AoD) estimation. Currently the RTL library supports AoA mode only. In this mode, the transmitter transmits a constant tone on a single antenna, and the receiver receives this signal on multiple antennas. Based on their spatial situation, the receiver antennas will receive the same signal with different phase offsets, from which the direction of the incoming signal can be estimated.



While it is easy to estimate the Angle of Arrival in an environment free of noise and reflections, it can get quite challenging in a noisy real-world environment with a lot of reflections. To mitigate the effects of reflections, the RTL library uses different methods, such as spatial and temporal filtering, averaging over multiple frequencies, and so on.

4.2.1 Antenna Configuration

The estimator algorithm must know the exact position of each antenna in the array, and the phase of the incoming signal for each antenna. Currently the RTL library only supports some antenna array boards with pre-defined antenna positions. When running the RTL library, the antenna array board must be specified so that the library knows which predefined values to use. Custom antenna array configuration is not yet available. The default antenna array board set in the sample applications is BRD4191A.

4.2.2 Angle Estimation Modes

The library provides different modes for different use cases:

One Shot / Real Time modes

In “one shot” mode the angles are always calculated from the latest measurements without any a priori knowledge or assumptions about the direction of the transmitter. On the other hand, in the “real time” mode the library keeps account of the latest angle estimation and tries to find the transmitter in the vicinity of the last direction.

Fast Response / Basic / High Accuracy modes:

In “fast response” mode the estimator uses fewer measurements to provide one estimation. This results in a fast response but can result in a poor accuracy. On the contrary, “high accuracy” mode uses more measurements, which results in higher latency, but much better accuracy. Basic mode is a trade-off between fast response and high accuracy. For details see the *RTL API Reference*.

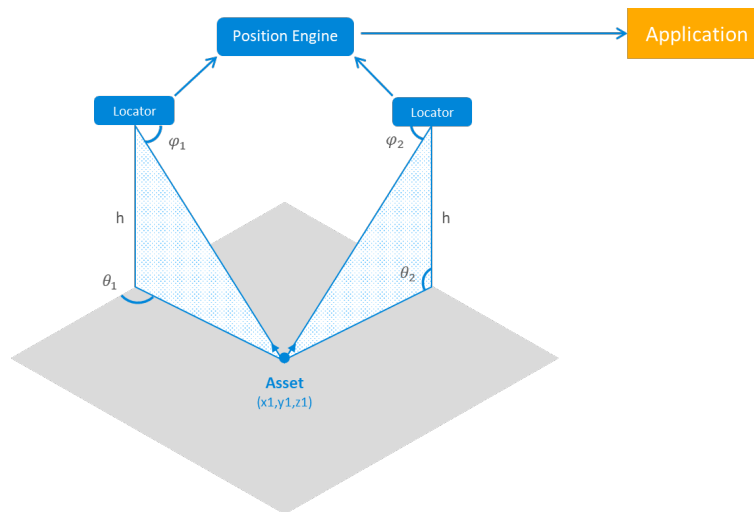
Azimuth & Elevation / Azimuth Only modes:

By default the RTL library calculates both azimuth and elevation angles. In some use cases, however, it is enough to calculate the azimuth angle. “Azimuth only” mode results in faster calculation.

These modes are used together to give a single AoA mode that can be set when initializing the library. For details see the *RTL API Reference*.

4.3 Location Finding (Positioning)

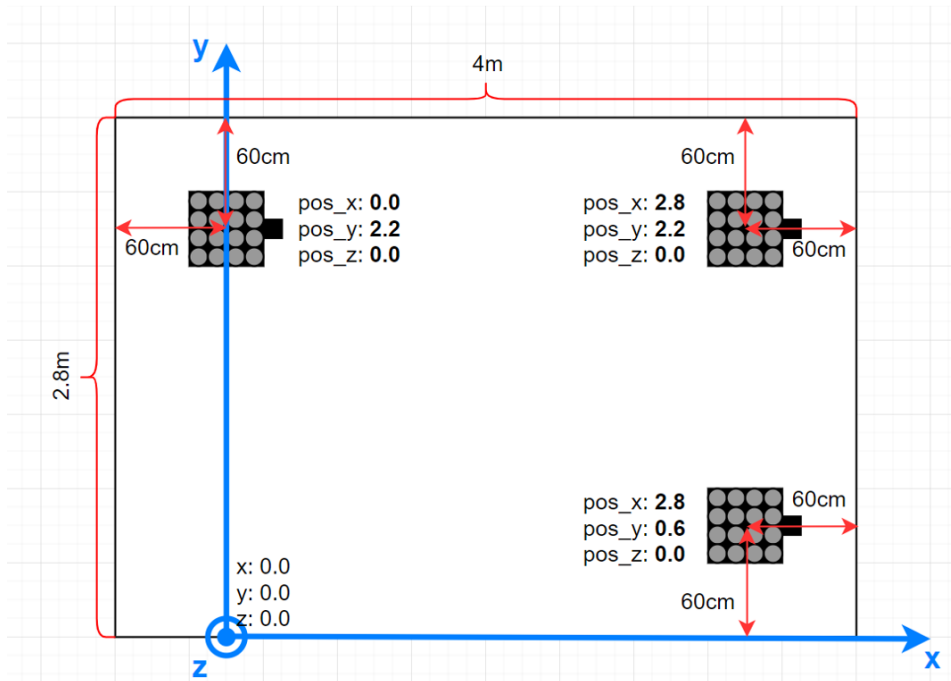
If there are multiple fixed-position locators that can calculate the direction of the transmitter (asset tag), the position of the asset tag can be calculated from the angles using triangulation. Beside Angle of Arrival estimation the RTL library also provides location finding functionality. Once the library learns the position of and gathers the angles from each locator it can provide a position estimation for asset tags. Just as for AoA estimation, challenges introduced by the reflective and noisy environment are addressed.



4.3.1 Locator Configuration

In order to calculate the position of the asset tags (transmitters), the RTL library must learn both the position and the orientation of each locator relative to a local coordinate system. The choice of the local coordinate system is arbitrary, the only constraint being that it must

be right-handed Cartesian (so that if x is pointing right, y is pointing up, as on the following image), and the unit of distance must be meter. The position of each locator board must be understood as the position of the center of the antenna array – relative to the origin.



The position and orientation of each locator can be provided to the RTL library using the RTL API, but the *bt_host_positioning* sample app also makes it possible to describe the configuration of each locator in a single config file using JSON format. For more details see *AN1296: Application Development with Silicon Labs' RTL Library* and *UG514: Using the Bluetooth® Direction Finding Tool Suite*.

4.3.2 Location Finding Modes

The RTL library supports two location-finding modes: two-dimensional and three-dimensional. In three-dimensional mode x, y and z coordinates of the tag are calculated from the azimuth and elevation angles. In two-dimensional mode, the z coordinate of the tag is fixed (this fixed value must be provided to the library using the RTL API *sl_rtl_loc_set_target_parameter*) and x and y coordinates are calculated.

4.4 IQ Sample Quality Analysis

Errors from multiple sources can affect the quality of the received IQ samples. In a real-life environment, some phenomena are considered as normal and not errors, but can also corrupt the perceived IQ data. The most notable example of this is the multipath propagation, which twists the perceived magnitude and phase of the IQ sample data. Its extent depends on the particular antenna location in the array as well as the position and the angle of the followed tag related to the locator antenna array.

The possible sources for the perceived noise may include the following:

- Radio receiver analog noise
- Quantization noise from the sampling
- Leaking signals from the surrounding channels folding into the band of interest
- Sampling jitter that translates into noise
- Other radio protocols operating on the same band
- Cosmic background noise
- And so on

In other words, there are a plenty of sources for signal noise even in relatively good conditions.

As well as the calculation of Angle of Arrival and position estimations, the RTL library also provides functionality called IQ sample quality analysis to help the developer find the root cause of angle estimation issues by analyzing statistical properties of the IQ samples.

4.4.1 Description of Operation

The IQ sample quality analysis tool may be used to further investigate what could be the source of observed problems in the AoA/AoD angle values. If the calculated angles seem to be good and the position values calculated from these are within the expected range, investigating the quality analysis figures may not be of use.

The IQ sample quality analysis measures a few statistical key figures from the samples and presents them per antenna element level. These include:

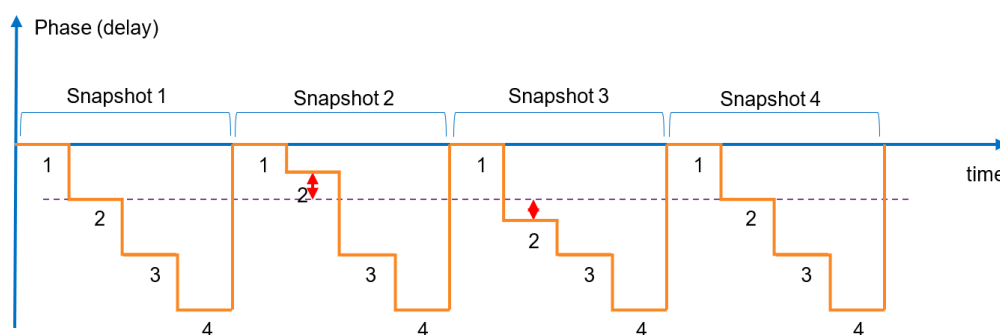
- Antenna's signal level (in dB), average over snapshots in the same radio packet
- Antenna's signal to noise ratio (SNR), noise measured as a level variation between antenna's samples in the packet
- Phase value: antenna's unrotated average phase value, in radians (relative to the delay between antenna elements in the array)
- Phase jitter: antenna's unrotated phase variation, in radians

A few common, or not antenna related, values are included for a packet:

- The radio channel the packet was sent on
- Apparent supplemental tone frequency, in Hz
- Reference period signal to noise and distortion ratio (SNDR)

If enabled, the IQ sample quality analysis code detects some predefined conditions and raises a warning flag for each in case the limits were exceeded. These limits are defined inside the RTL library and are subject to change without further notice. The limits are chosen such that warning flags should not be raised in normal conditions but only occasionally. However, since every environment is different the actual number of warnings may vary from system to system. These flags are shown to the user as bits in a bitmask output of the overall status query function. Further information can be then queried using the detail query functions. The API allows querying details for the latest packet received, or for the latest packet using a specified radio channel.

The following figure shows an example phase signal of a 1 x 4 antenna array. The signal is otherwise ideal, but some exaggerated error is seen in the detected phase (=delay) values for the second antenna in the array during the snapshots 2 and 3. The amplitude graph also resembles a step function, but unlike the phase signal, the amplitude value does not change the same way along the angle the signal is arriving on. In real life the change from an antenna to next does not take place immediately but there is a transfer period during which the signal settles. This is affected by the radio system and filtering.



4.4.2 Some Interpretation Examples

Here are some practical examples of what can be learned from the quality figures in different situations:

- The figures seem mostly good, but some channels have a high amount of noise.
 → *These radio channels may be occupied by some other system.*
- Some antennas show much lower amplitude levels. The amount of reduction, and also the antennas on which this is seen, changes along the position of the followed tag.
 → *Radio signal reflects from the surfaces of the surrounding space causing interference with the received signal (called multipath propagation).*
- Some antenna values show a lot of noise or the phase value is not changing relative to the tag movement as it does for other antennas
 → *The antenna board may be defective, preventing it from receiving the signal from one or more antennas.*
- All the antennas' phase values are the same
 → *The tag is directly above the antenna board at a 90° elevation angle.*
 → *The antenna board may be defective and is not switching at all.*

- Reference period SNDR value is bad
→ *The whole packet may be corrupted because of some other system's disturbance.*

4.4.3 Usage

The IQ sample quality analysis tool is available through the Angle of Arrival/Departure API class of the RTL lib. See the functions starting with `sl_rtl_aox_iq_sample_qa_` in the API Reference. For a reference implementation of the usage of IQ sample quality analysis see the `aoa_locator` host sample app in the Bluetooth SDK.

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