# AN1493: Antenna Design Guidelines for BLE Channel Sounding

This application note provides antenna design guidelines for BLE Channel Sounding (CS) feature used for applications that require accurate distance measurement. The accuracy of distance measurement also depends on the antenna design and the most important antenna properties are discussed in this document which need considerations to help improve the distance estimation accuracy.

Besides the antenna properties, some other HW considerations are also being discussed. Board offset calibration is also needed on any custom HW which compensates out board design-specific differences, such as antenna, matching network, RF trace lengths, etc.

Further channel sounding related documentation and guidelines can be found under the link provided here: https://docs.silabs.com/rtl-lib/latest/rtl-lib-channel-sounding-fundamentals/.

**KEY FEATURES**

- Antenna properties affecting CS accuracy, such as group delay, radiation pattern, polarization are discussed.
- Custom board offset calibration considerations.
- Single- and multi-antenna solutions.
- Test data provided with Silicon Labs reference designs.
- Other HW considerations.
- Dual-antenna example shown.

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# 1. Introduction

The goal of Bluetooth Ranging technology is to measure the distance between two devices using Bluetooth. It is based on the BLE Channel Sounding feature. It is released as part of the BLE Specification 6.0 by the SIG: https://www.bluetooth.com/specifications/specs/core-specification-6-0/

This method provides an accurate way to calculate the distance in the simplest way by sending packets or unmodulated carriers between two devices on normal Bluetooth. No additional complex antenna arrays are needed, and the calculations can be implemented in low-cost MCUs while maintaining low power consumption. There are two main measurement methods: the phase-based ranging (PBR), and the round trip time (RTT) measurement. Currently, Silicon Labs channel sounding solution is supported only on the EFR32xG24 device.

For distance measurement, two devices are used, an Initiator and a Reflector. The description of these measurement methods are discussed in more detail in the Bluetooth LE Channel Sounding Fundamentals guide: https://docs.silabs.com/rtl-lib/latest/rtl-lib-channel-sounding-fundamentals/.

## 1.1 HW Support

Bluetooth ranging is supported on the EFR32MG24 SoC. The required crystal frequency reference is 40 MHz.

The Bluetooth Core Spec requires that channel sounding implementations refer their measurements to their antenna port. This allows the system to be interoperable without concern for the circuit delays of implementations. Referring the PCT to the antenna is done by rotating complex numbers to compensate for the group delay. Extra delay is equivalent to extra distance and affects the accuracy of the system. The delays can be separated into the internal radio group delay and the board and antenna group delay.

The internal radio group delay is the delay from the RF and digital filter circuits. Silicon Labs has compensated for the variation of this delay over RF gain. This is automatically applied, and no further compensation is needed. However, the calibration of group delays due to the RF matching network, PCB traces, and antenna design should be performed per board design. Constant offset in the board and antenna group delay can be calibrated out with an API command. The wireless distance offset calibration is discussed in this document in detail in 4. Calibration of Silicon Labs Distance Ranging.

This application note focuses on the antenna design recommendations to achieve the best possible accuracy in distance estimation.

# 2. Antenna Requirements

## 2.1 Group Delay

This section explains the impact of antenna linearity (i.e., antenna group delay) to the accuracy of CS-based distance estimation. This document does not set strict requirements for antenna design for CS use cases, nor does it specify exact requirements for the antenna's group delay. Instead, this document explains how the group delay of an antenna affects the accuracy of distance estimation using CS.

Measuring the group delay of an antenna requires state of the art 3D antenna test chamber. However, for a typical case, measurement of antenna group delay is not necessary as the antennas typically easily meet the group delay requirements to achieve ±0.5 m accuracy in an anechoic chamber.

The following equations describe the group delay definition and its calculations, where Φ is the phase in radian, *f* is the frequency in GHz, *R* is the distance in m, while *c* is the speed of light in m/ns.

$$Group\ Delay\ (GD) = -\frac{\Delta\phi}{\Delta\omega} = \frac{\phi_1 - \phi_2}{2\pi(f_1 - f_2)}$$

$$R = c * GD \qquad (c = 0.299792458\text{m/ns})$$

The accuracy of distance estimation using CS is affected by the following:

- Multipath propagation
- Polarization of antennas
- Obstacles within line of sight (diffraction)
- Radiation pattern (nulls in particular)
- Background RF noise (e.g., Wi-Fi)
- Linearity of antennas (i.e., group delay flatness of the antennas)
- Signal-to-noise ratio

The group delay of an antenna varies depending on radiation pattern and direction. Calculating the group delay at given distances will give a specification for the antenna linearity. The group delay translates directly to distance with the formula R=c*GD. Thus, the GD stability requirement for the antenna can be calculated. Linear phase response of an antenna ensures flat group delay, which is desired.

For example, if ±0.5 m accuracy is required, then the group delay variations of the antenna must be less than GD=R/c= 1 m/ 0.299792458 m/ns = 3.3 ns

In practice, since the accuracy of distance estimation depends on multipath environment, it is good to make sure the antenna group delay stability is far less than the desired CS accuracy.

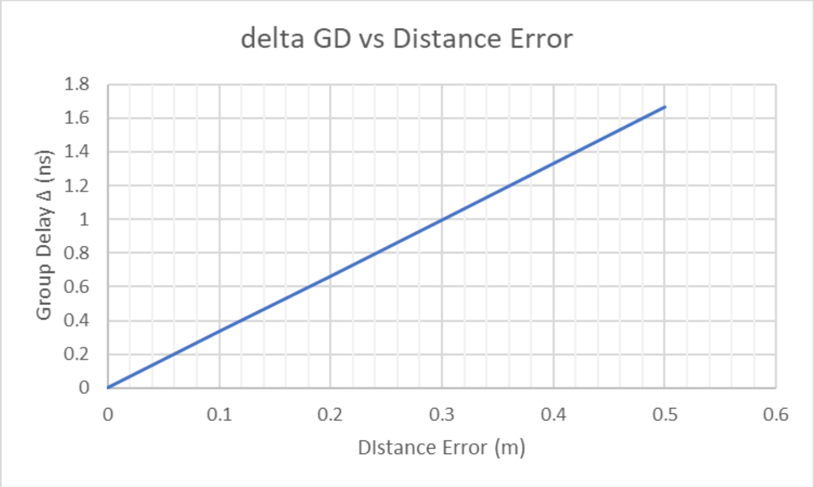


**Figure 2.1. Group Delay Variation versus Distance Estimation Error**

Constant offset in the antenna group delay can be calibrated out with an API command. Flat group delay across the Bluetooth band will be converted directly to distance according to the formula R = c * GD.

For example, 1 ns variations in GD will convert to 0.3 m variations in distance and 2 ns variation will convert to 0.6 m variations in distance.

If the GD has a linear slope > 1ns across the Bluetooth band, it will cause noise to the distance readings. Non-linear group delay is not a problem as long as the group delay remains within 1ns across the full 2.4 GHz BLE band.

While these recommendations are provided to help optimize antenna design, simulations and testing have shown that acceptable CS performance can be achieved with a variety of antenna designs, even when faced with sub-optimal system constraints and conditions.

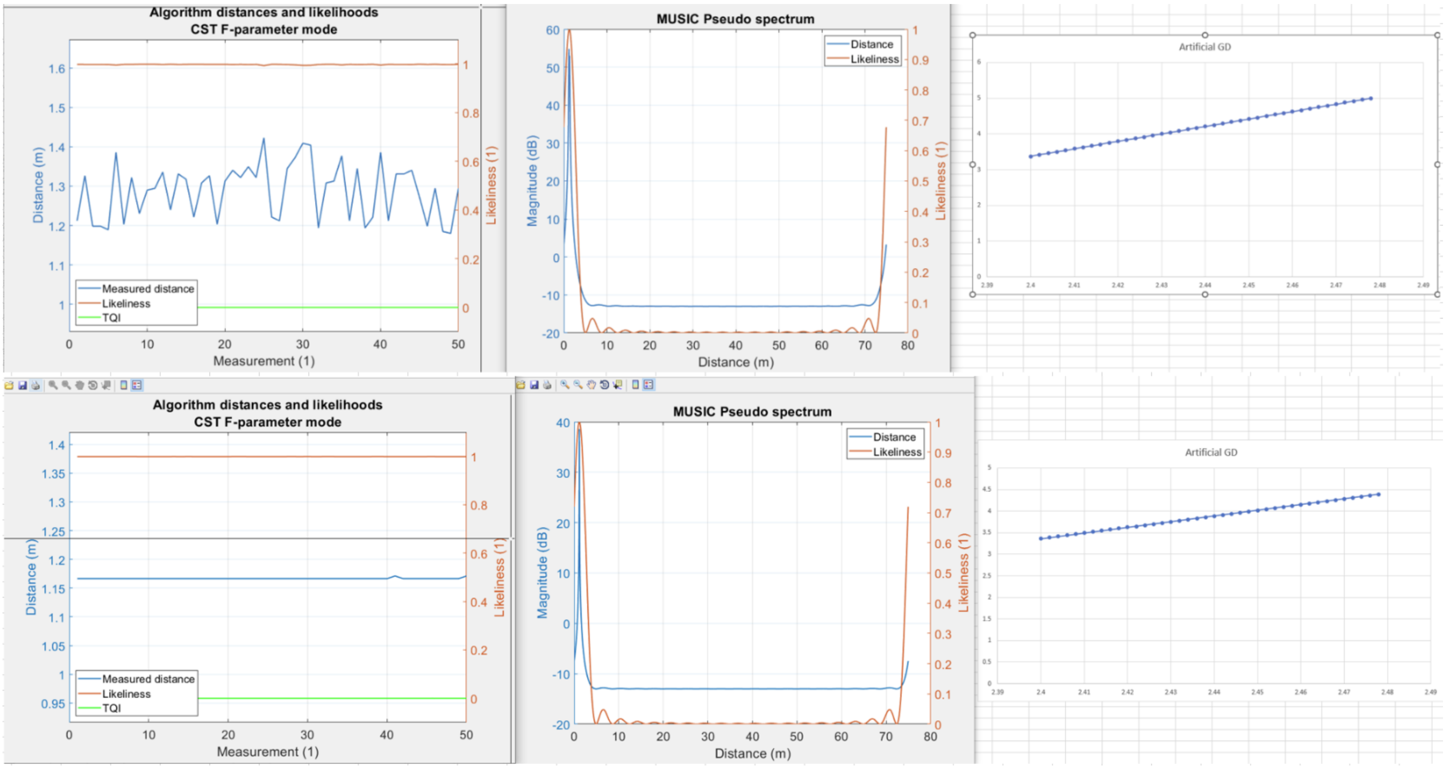


**Figure 2.2. Impact of Linear Group Delay Slope**

If the antenna has slope in group delay larger than 1ns across the full BLE band, it will be seen as noise kind of variation in the accuracy.

The recommendation for the maximum antenna group delay variation across the full 2.4 GHz BLE band is 1 ns, while the constant group delay offset due to the PCB traces, matching network and antenna is being calibrated out by an API command. In general, any well-designed single antenna satisfies the necessary group delay requirements for channel sounding applications, since in most cases the group delay across the given impedance bandwidth is flat enough for linear antennas and the group delay variation remains within 1 ns.

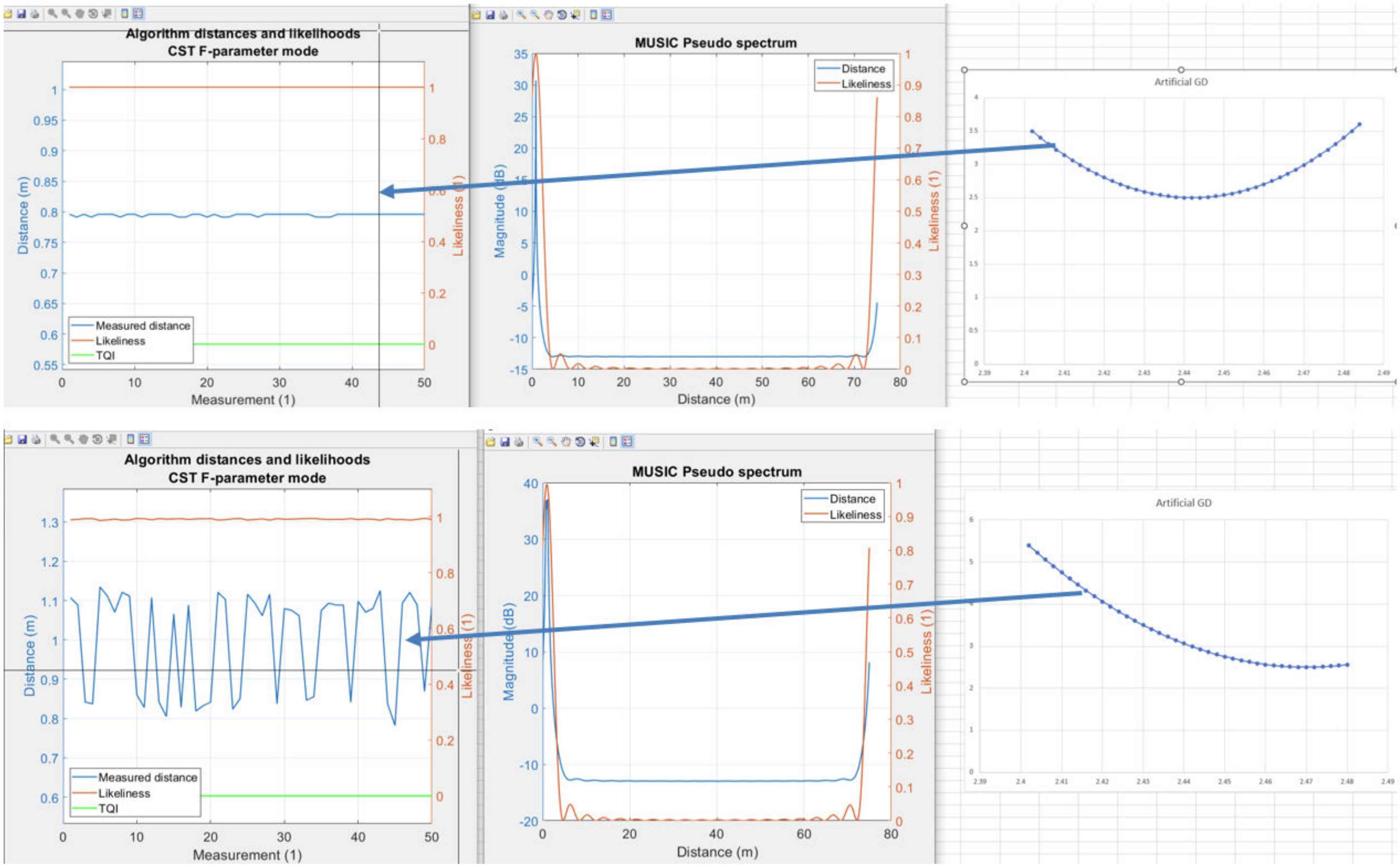


**Figure 2.3. Effect of Non-Linear Antenna Group Delay**

If the antenna has non-linear group delay without sudden/sharp changes and less than 1 ns slope across the Bluetooth band, the accuracy will remain good.

## 2.2 Radiation Pattern

The following points summarize the requirements on the antenna radiation pattern:

- Good SNR is essential for good CS accuracy.
- The antenna must generally have good radiation efficiency to help achieve good SNR.
- When the direction of distance measurement is arbitrary, the antenna should have low directivity with high efficiency.
- Nulls (≥ -15 dBc) in the radiation pattern are known to cause outliers and recommended to avoid nulls in the radiation pattern. Nulls tend to have non-linear response (i.e., group delay variation) which is undesired.

Typically, the antenna group delay is not a problem for CS and in most cases measuring or analyzing the group delay is not needed to achieve good accuracy.

- Normal antenna with a good impedance match has by nature a flat group delay.
- Different antennas can have different initial offset in the group delay resulting to an offset in CS accuracy accordingly. However, this can be compensated easily by the SW.

The antenna group delay can be analyzed either by simulation or by measurements. The figures below show typical antenna group delay measured in an anechoic chamber.

- The outliers are due to cross polarized situation, which means the receiving antenna is on horizontal polarization while the transmitting antenna is on vertical polarization.
- Excluding the outliers due to cross polarization, the antenna easily meets the requirement of < 1 ns group delay.

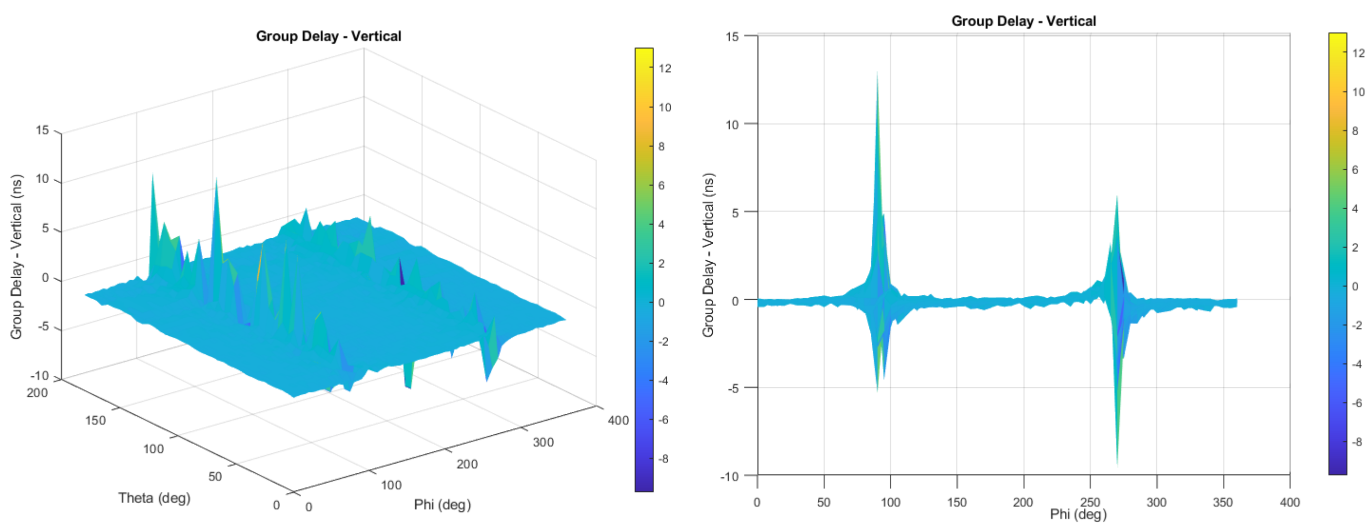


**Figure 2.4. Typical Antenna Group Delay**

## 2.3 Multi-Antenna Support and Recommendations

In general, any well-designed single antenna satisfies all the necessary requirements for channel sounding (Bluetooth ranging), including antenna efficiency, group delay (<1 ns) or radiation pattern (avoid nulls, ≥ -15 dBc). So, designing an antenna for channel sounding does not require anything else than what any normal antenna requires.

Real world measurements are showing that the orientation of the antenna can have significant impact to the accuracy. This in turn suggests that antenna diversity has good potential to remove outliers and enhance the accuracy of CS significantly.

The antenna must be well-matched to the RF-FE path (typically to 50 ohms), and it is good to have high radiation efficiency. However, high distance accuracy cannot be achieved with a single antenna. High accuracy will require more than 1 antenna path. Single antenna can be accurate in certain cases if the position of the products is fixed, but if the position (physical orientation) of the product is not fixed then good accuracy will always require more than 1 antenna path. This is because of the possible nulls in the radiation patterns and/or antenna polarization differences, similarly to antenna diversity use-cases and applications.

Most important is to have two antennas at least at one side, either initiator or reflector. Having two antennas on both ends is the best.

- Single antenna path (with one antenna on both initiator and reflector ends) will cause several meters wrong results depending on orientation of the product. In some orientation the distance might be correct, but on another there will be large offset.
- Four antenna paths (with two antennas on both initiator and reflector sides) will remove the problem of having different results on different positions and it will stabilize the results so that the CS returns stable and accurate distance.
- Two antenna paths (with one antenna on one side and two antennas on the other end) are sufficient for many use cases, but there is possibility that in some orientations both antenna paths will result wrong distance. Basically, compared to 4 paths, it is just more likely to have wrong distance and compared to 1 antenna path it is more likely to have correct distance.

Silicon Labs recommends designing more antenna paths for channel sounding applications to improve the distance estimation accuracy. The general recommendations for dual-antenna designs are as follows:

- Use 50-ohm terminated RF switch to select between antennas. Ensure to provide the possible best isolation between the two onboard antenna paths.
- Have the antennas in different polarization and orientation to improve the polarization diversity. This also helps improve the CS accuracy when the orientation/position of either the locator or initiator changes. Polarization diversity is one of the most important features that is required for high CS accuracy and more important than the spatial diversity discussed in the next bullet point below. This helps place the null points of the two antennas on opposite direction as well which can help eliminate outliers. Figure 2.5 Polarization Diversity Highlights on a board design example on page 9 below highlights the polarization diversity on a board design example.
- The ideal distance between the antennas is recommended to be minimum of quarter-wavelength of ~3 cm (up to maximum half-wavelength) to improve the spatial diversity (if it cannot be achieved in space constrained designs, then maximize the antenna distance). This helps improve the accuracy of CS in a multi-path environment. This spatial diversity is a nice-to-have requirement, but not mandatory.
- Chip antennas can also be used, but it is not always possible to achieve good polarization diversity with monopole type chip antennas due to their own nature. Therefore, ground radiating loop type chip antennas are recommended to achieve good polarization diversity.

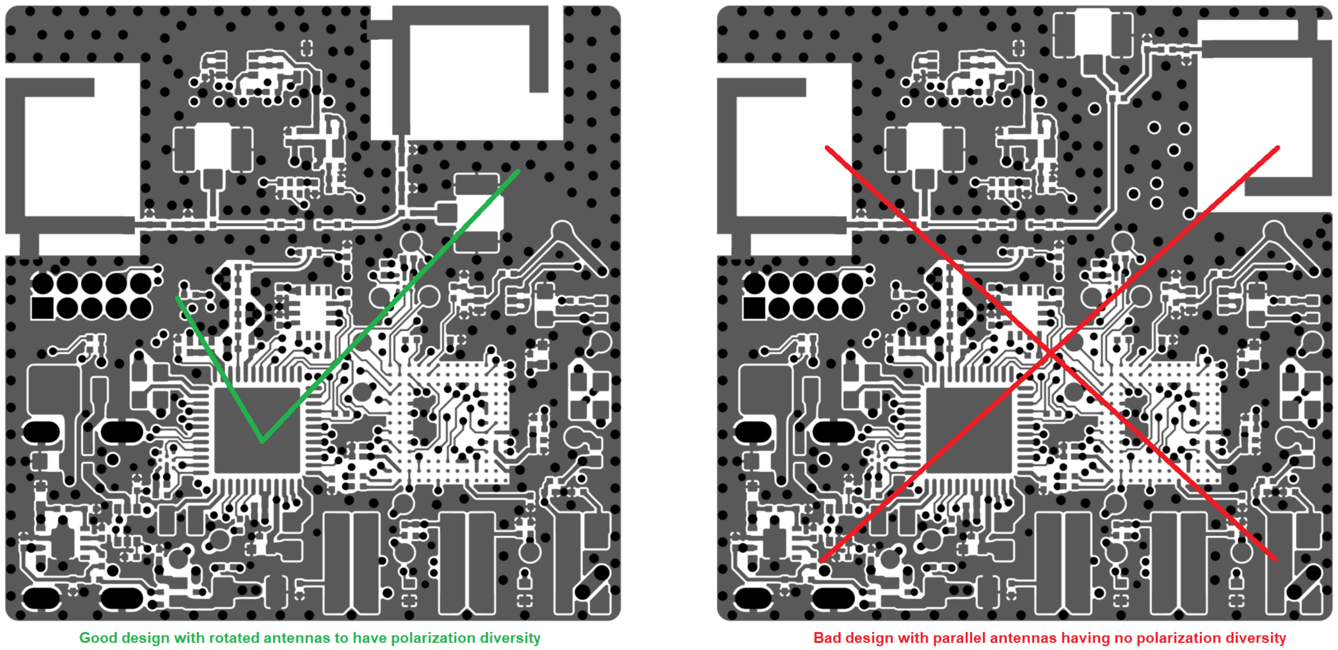


**Figure 2.5. Polarization Diversity Highlights on a board design example**

## 3. Dual Antenna Examples

Silicon Labs provides reference design of BRD2606A having dual-antenna on board with two antenna paths for BLE CS applications.

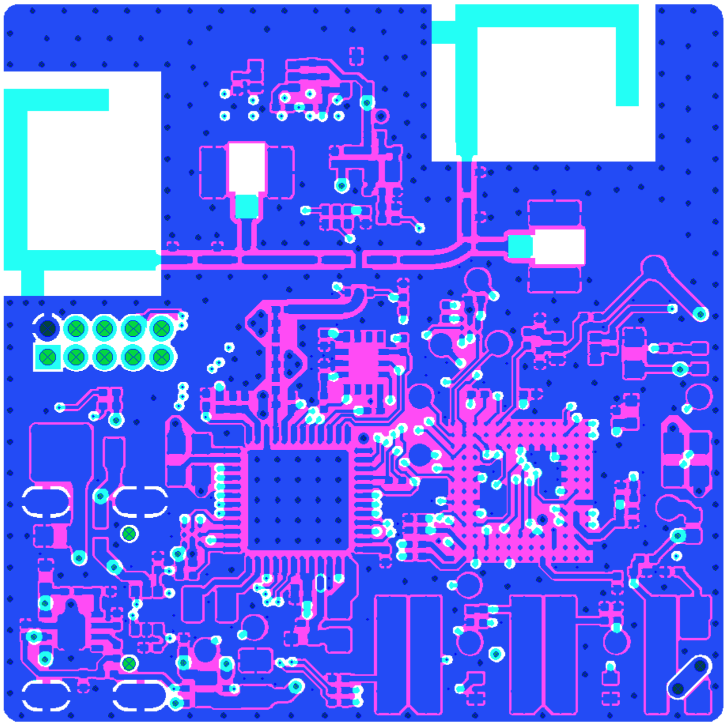

**Figure 3.1. Top Layout of BRD2606A Reference Design with Dual Diversity Antenna**

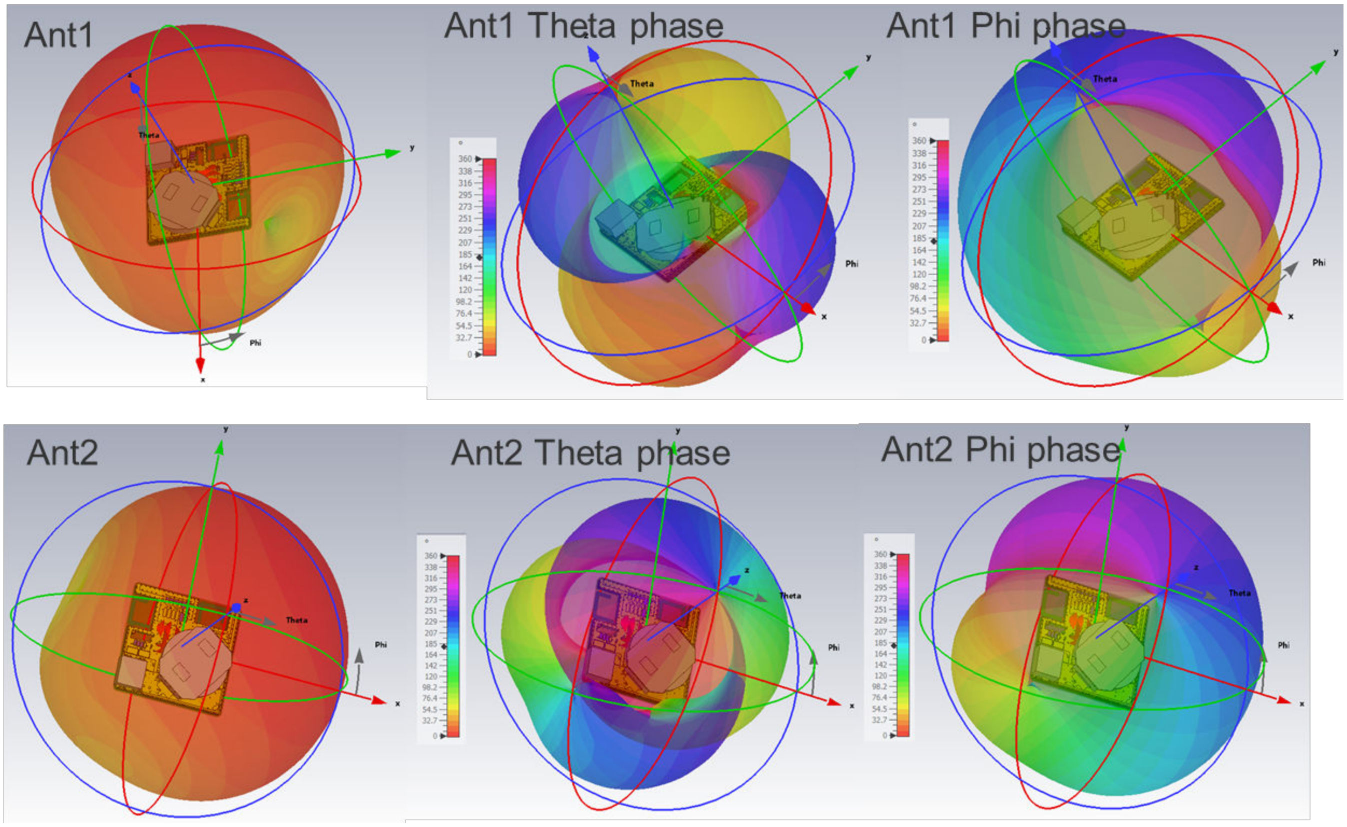


**Figure 3.2. Simulated Antenna Patterns of BRD2606A Reference Design**

The following test results (with PBR measurement method) demonstrate how the polarization diversity with the dual-antenna reference design of BRD2606A improves the channel sounding accuracy compared to board designs with single antenna path, while the DUT is also being rotated (and can also make it possible to use even in body blocking cases).

The tests are done in an office environment which is possibly the most difficult environment for CS testing, especially compared to cases where clear LOS is available with less reflections, (e.g., in a parking lot). The test results of the dual-antenna solution with four antenna paths using switch (“AntSwitch” in the label name) show good CS accuracy. The tests are performed in both co- and cross-polarization (shown in the figures below as "Co-pol" and "X-pol", respectively) between the initiator and reflector (both ends use BRD2606A reference boards, and the results are calculated from the full set of 2x2 antenna paths measurements, providing a 4-antenna paths test). The single-antenna path solutions are also shown, where the results are logged separately in each combination between the two antennas of both initiator and reflector devices. The initiator was placed in a fixed position with horizontal polarization, i.e. board plane was set horizontal. The reflector was placed at the given 3 or 11 m distance, and it was rotated by 45 degree steps. The tests were done with having the reflector in both horizontal (reflector board set to horizontal, co-polarization) and vertical (reflector board set to vertical, cross- or X-polarization) polarizations. The measurements in each position were averaged across 50 CS tests. The test results are shown in Figure 3.3 and Figure 3.4 below where the small horizontal red line is the 20-80% percentile average, the orange region of test results falls below the median, and the grey area of test results falls above the median of the total 50 tests. The 20-80% percentile average is 3.07 m and 11.1 m with the antenna switch, co-polarized case, testing at 3 m and 11 m, respectively. Single antenna cases utilize one antenna path, while the dual antenna cases have four antenna paths tested.

The tests are performed with FW SiSDK 2024.12.0. The board offsets including the antennas of the BRD2606A board are 56 cm and 67 cm (ANT1 and ANT2 paths, respectively, and being compensated out in the SW).

For conducted tests, the BRD2606A board offset without the antennas at the u.FL connector is 25 cm.

The dual-antenna switch-less solution, where a resistive combiner is applied to split the antennas, is also possible and saves BOM cost but its CS accuracy falls between the single-antenna and dual-antenna with RF switch solutions.

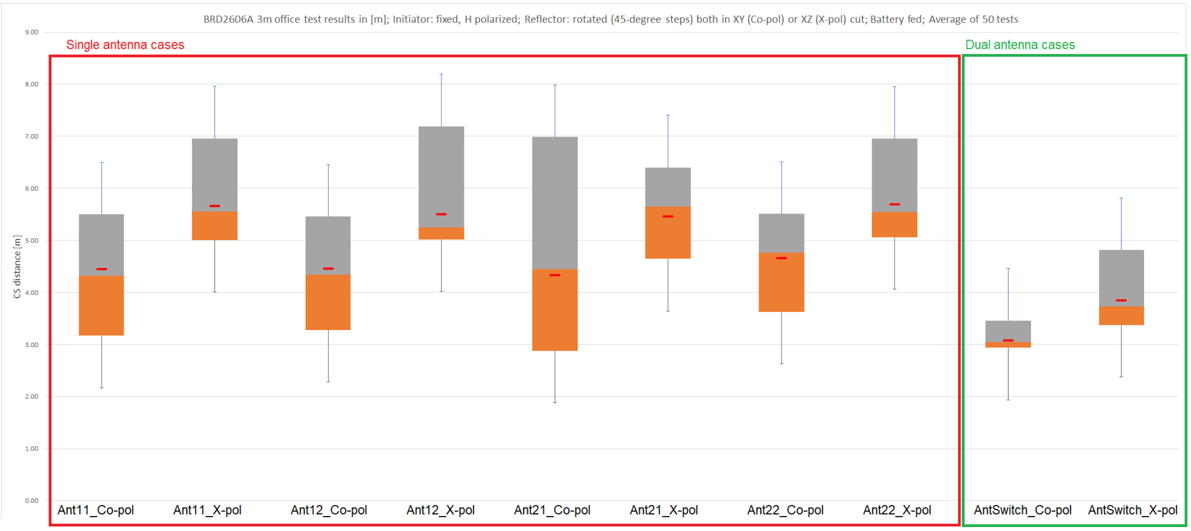


**Figure 3.3. Single Antenna with 1 Path vs. Dual-Antenna with 4 Paths CS Office Test Results at 3 m Distance**

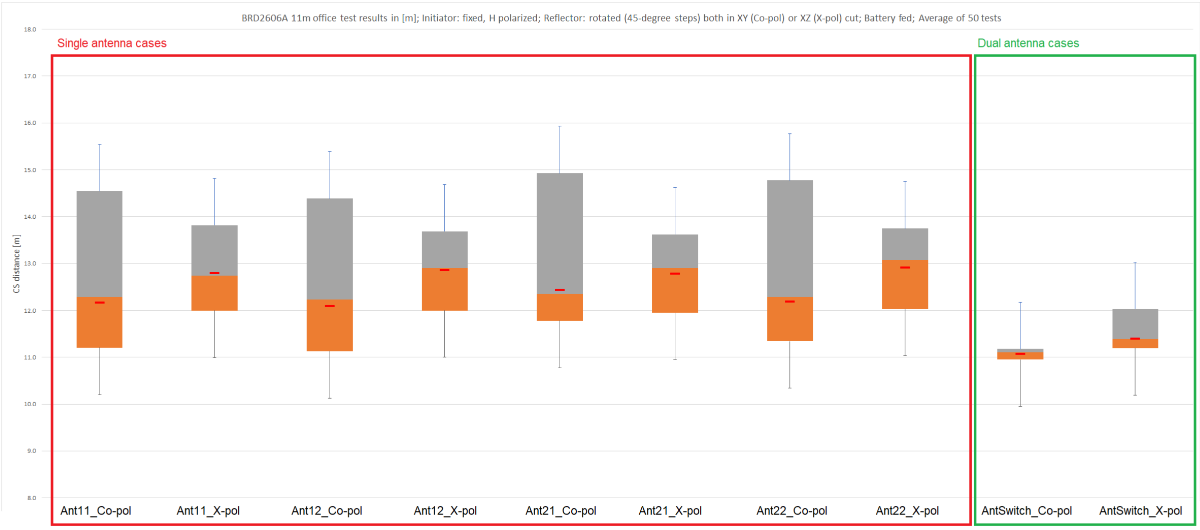


**Figure 3.4. Single Antenna with 1 Path vs. Dual-Antenna with 4 Paths CS Office Test Results at 11 m Distance**

Figure 3.3 and Figure 3.4 above show the comparison test results when using 1-antenna path (single antenna cases) and 4-antenna paths (dual antenna cases). The 1-antenna path tests are done between two single antennas of the BRD2606A reference design, while the 4-antenna paths tests are performed between the full set of 2x2 antennas of the BRD2606A boards. Figure 3.5 below shows an additional test comparison between the 2-antenna paths and 4-antenna paths tests. In the 2-antenna paths measurements, the initiator uses a single antenna of the BRD2606A board, while the reflector utilizes both antennas with an RF switch. The tests are also done in an office environment at the distance of 10 m. The X axis is the number of CS events, the series traces represent the different orientations/cuts of the DUT, while it is also being rotated by 45-degree steps.

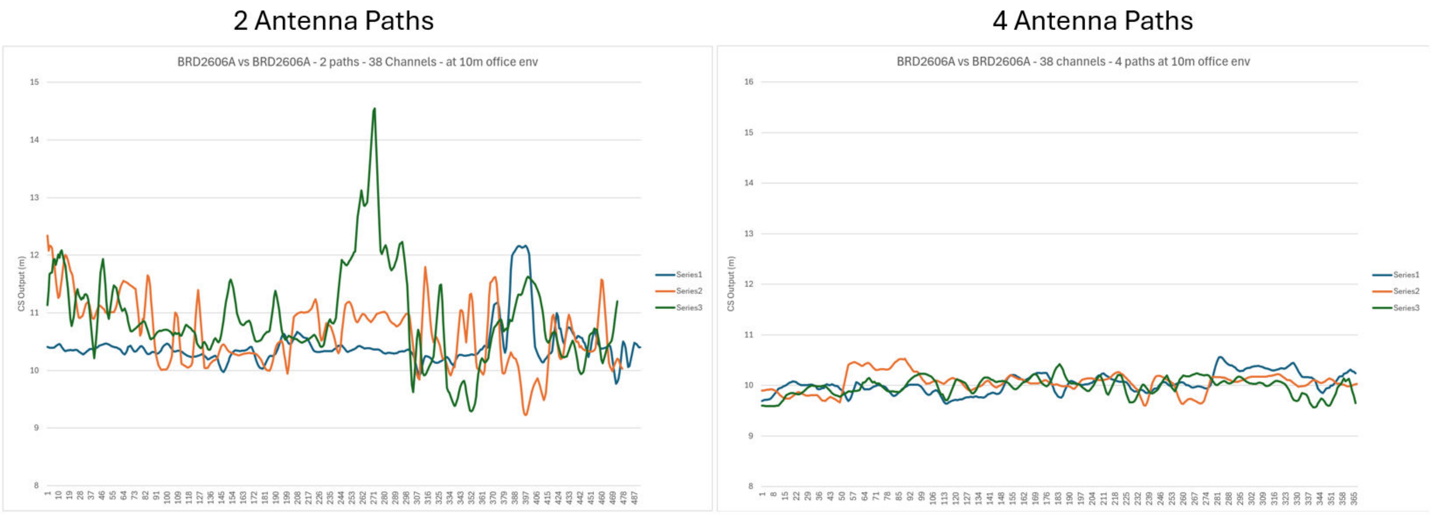


**Figure 3.5. 2- vs. 4-antenna Paths CS Office Test Results at 10 m Distance**

The following table summarizes the measurement errors, processing time, and power consumption for the 2- and 4-antenna paths tests when also using a different number of test channels. Depending on the multi-path environment, the practical RF range for CS testing with the PBR method is around 30 m for 36 channels and 100 m when testing across 72 channels. The RTT method has less accuracy compared to the PBR, but has higher achievable practical RF range.

| Absolute Error (m) | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 90% percentile | 95% percentile | Error Mean | Error std | Processing Time @ 80 MHz (ms) | Total RF Airtime (ms) | Consumption/Measurement (nAh) (excluding processing) |
| **72Ch, 4 Paths** | 0.41 | 0.53 | 0.11 | 0.22 | 185 | 41 | 166 |
| **36Ch, 4 Paths** | 0.34 | 0.4 | 0.02 | 0.21 | 45 | 22 | 99 |

| Absolute Error (m) | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 90% percen-tile | 95% percen-tile | Error Mean | Error std | Processing Time @ 80 MHz (ms) | Total RF Airtime (ms) | Consumption/Measure-ment (nAh) (excluding processing) |
| **72Ch, 2 Paths** | 1.31 | 1.74 | 0.59 | 0.61 | 90 | 35 | 127 |
| **36Ch, 2 Paths** | 1.3 | 1.54 | 0.48 | 0.55 | 20 | 19 | 82 |

# 4. Calibration of Silicon Labs Distance Ranging

This section discusses the theory and procedure of calibrating a Silicon Labs channel sounding SoC for accurate distance ranging. A wireless calibration should be performed per board design. Antenna recommendations should be adhered to.

The Bluetooth Core Spec requires that channel sounding implementations refer their measurements to their antenna port. This allows the system to be interoperable without concern for the circuit delays of implementations. Referring the PCT to the antenna is done by rotating complex numbers to compensate for the group delay. Extra delay is equivalent to extra distance and affects the accuracy of the system. The delays can be separated into the internal radio group delay and the board and antenna group delay.

The internal radio group delay is the delay from the RF and digital filter circuits. Silicon Labs has compensated for the variation of this delay over RF gain. This is automatically applied, and no further compensation is needed.

The board delay can be further divided into the delay from the matching network and delay from traces or cabling. The recommended matching network for the EFR32xG24 was simulated over its component tolerances. The notes below the figure show that, while there is a phase shift, the group delay remains relatively constant. Further analysis shows that the component tolerance should contribute only up to ±0.05 m.

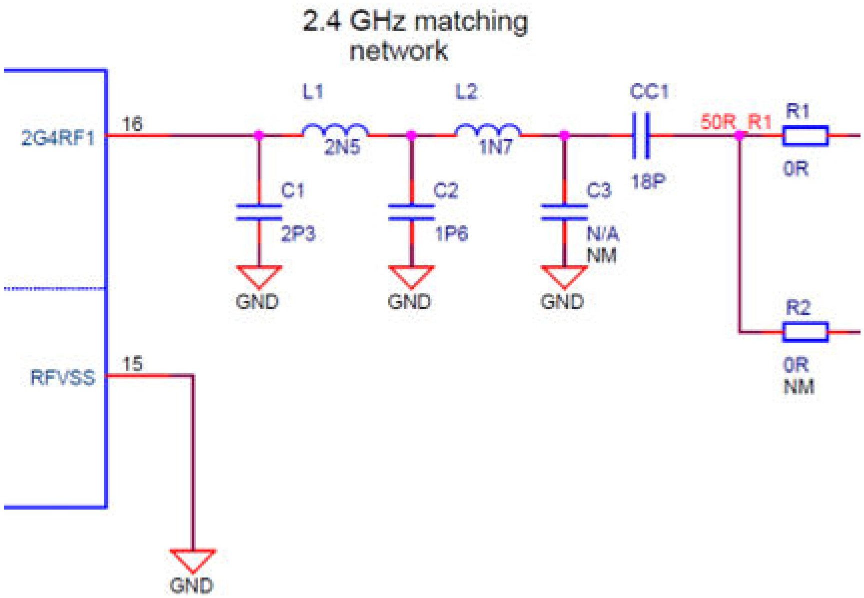


**Figure 4.1. EFR32xG24 RF Matching Network**

- C1: 2.3 pF ±0.05 pF Murata GRM0335C1H2R3WA01
- L1: 2.5 nH ±0.05 nH Murata LQP03HQ2N5W02
- C2: 1.6 pF ±0.05 pF Murata GRM0335C1H1R6WA01
- L2: 1.7 nH ±0.05 nH Murata LQP03HQ1N7W02
- C3: No population
- CC1: 18 pF ±2% Murata GJM0335C1E180GB01

The traces and cabling delay consists of the propagation through the RF traces and coaxial cable if an off-board antenna is used. Direct measurement of these delays is not necessary, as the delays are additive and are captured in the wireless calibration. The speed of propagation through these materials is slower than the speed of light in a vacuum. This ratio is the velocity factor and varies widely from 0.6–0.9 depending on the construction and geometry. This explains why when inserting a cable of physical length L, the measured distance will shift by L/VF. For designs with multiple antenna paths, the calibration should be run once per antenna path.

The last component is the antenna contributing delay. The plot below shows the group delay over azimuth for a printed inverted F antenna. With a group delay of 1–1.5 ns, the antennas are contributing approximately 0.75 m of offset. Due to the antenna distance offset, Silicon Labs recommends a wireless distance offset calibration, as a cabled test will not include this significant offset.

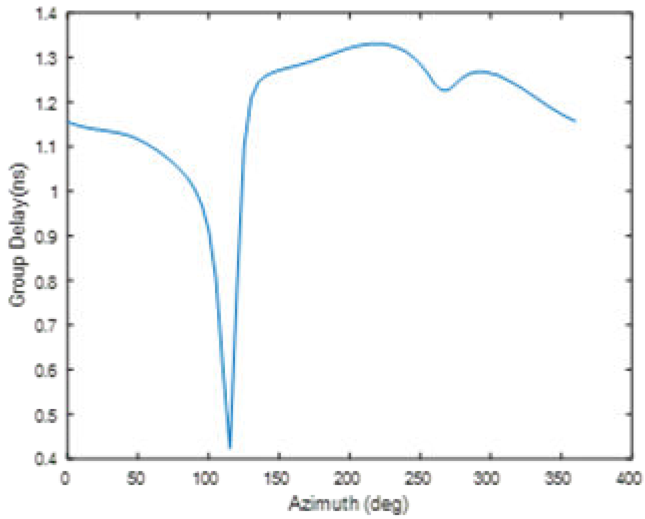


**Figure 4.2. Typical Printed Inverted-F Antenna Group Delay**

### 4.1 Calibration Procedure

To get a comprehensive metric on the accuracy (and to calibrate for optimum overall accuracy), the ranging error should be tested at 5 or more different distances and preferably in at least 8 different directions (every 45°) at each distance. This is because the performance could depend on the direction (especially, in single antenna configurations) and there could be outlier data points in (for example, the antenna null directions).

Board designs utilizing multiple antennas with unknown antenna path offsets require calibration on each antenna and the calibration must be done between two identical board antennas, that is, between ANT1-ANT1 of each board, and then between ANT2-ANT2 of each board, etc. That way, the antenna board offset for each antenna is the half of the total offset in the setup of the given antenna path tests (similar to antenna gain tests of an unknown antenna).

The calibration can also be done between a known and unknown board design. That way, the board offset can also be calculated for the unknown device by knowing the total offset of the setup from the tests.

Below you can find guidelines for the testing in multiple directions:

**Test setup and configuration:**

- For the calibration, use two identical devices: one configured as initiator, the other one configured as reflector.
- T_PM = 20 maximum measurement time and at least two mode0 steps should be configured.
- Have the entire channel sweep contained in a single subevent (default configuration for the provided sample application).
- The devices should be elevated off the ground by at least 1 m.
- Make sure that there is a clear line of sight between the two devices and avoid any objects (especially metallic ones) in close proximity to the devices and in the propagation zone (see to Fresnel Zones for additional details on this) to minimize multi path propagation. It might be a good idea to perform the calibration in an outdoor environment for this reason.
- Also, make sure that the test environment has no interference in the 2.4 GHz band (e.g., from nearby Wi-Fi access points or stations).

**Calibration Procedure:**

1. Prepare two devices (A and B) for wireless distance measurements.
2. Place device A on a turntable. The rotation axis should be representative for the expected direction variation of the application. For example, for devices mounted on ceilings, the device should be placed in the same orientation as if it was placed on a ceiling (facing down) and rotated around the axis perpendicular to the ground. Ideally, Device B should be oriented in such a way that its antenna max direction is facing Device A (if the antenna radiation pattern is available). See the figure below.
3. Follow the Configuration Options section of the Developer's guide: https://docs.silabs.com/rtl-lib/latest/rtl-lib-channel-sounding-dev-guide/05-sample-applications#configuration-options
4. Run the measurements and algorithm for 100 distance measurements. Record the median of the distribution.
5. Repeat for at least 5 different distances between 1 and 20 m. Perform the test in 8 different directions (every 45°) by rotating Device A at each distance.
6. Get the median of all angle test results and calculate a linear regression of the expected distance vs measured distance. The distance offset is the y-intercept.
7. Set the distance offset calibration to half of the distance offset. Reflash the devices.
8. Repeat step 4 and 5 making measurements.
9. Verify the distance error is centered around zero.

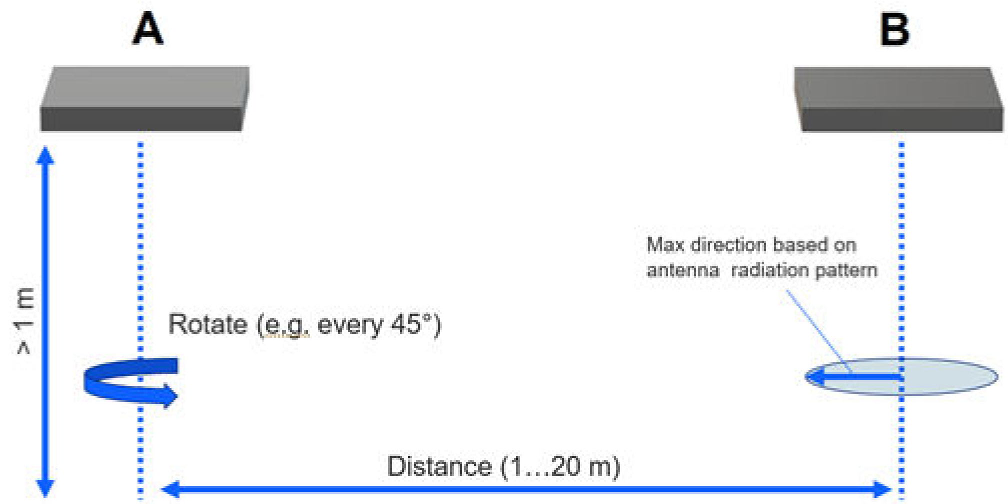


**Figure 4.3. Board-offset Calibration Test Setup**

# 5. Revision History

**Revision 0.3**

March, 2025

Following are the updates:

- Updated: 2.3 Multi-Antenna Support and Recommendations.
- Updated: 3. Dual Antenna Examples.

**Revision 0.2**

November, 2024

Following are the updates:

- Minor editorial updates.
- Test results are updated in 3. Dual Antenna Examples.

**Revision 0.1**

December, 2021

Initial release.

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