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.

Accurate Bluetooth Ranging user guide linked below under https://docs.silabs.com/ provides some further information and details on accurate Bluetooth ranging and, on its measurement, and calibration methods.

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.

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/channel-sounding-cr-pr/

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 EFR32MG24 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 Accurate Bluetooth Ranging user guide under https://docs.silabs.com/.

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 detail in section "Calibration of Silicon Labs Distance Ranging" in the Accurate Bluetooth Ranging user's guide under https://docs.silabs.com/.

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.

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

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

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.

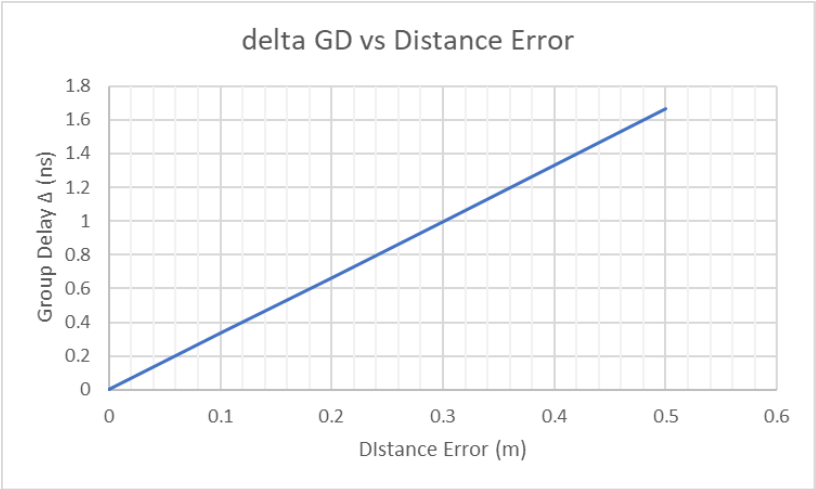

Figure 2.1. Group Delay Variation versus Distance Estimation Error

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.

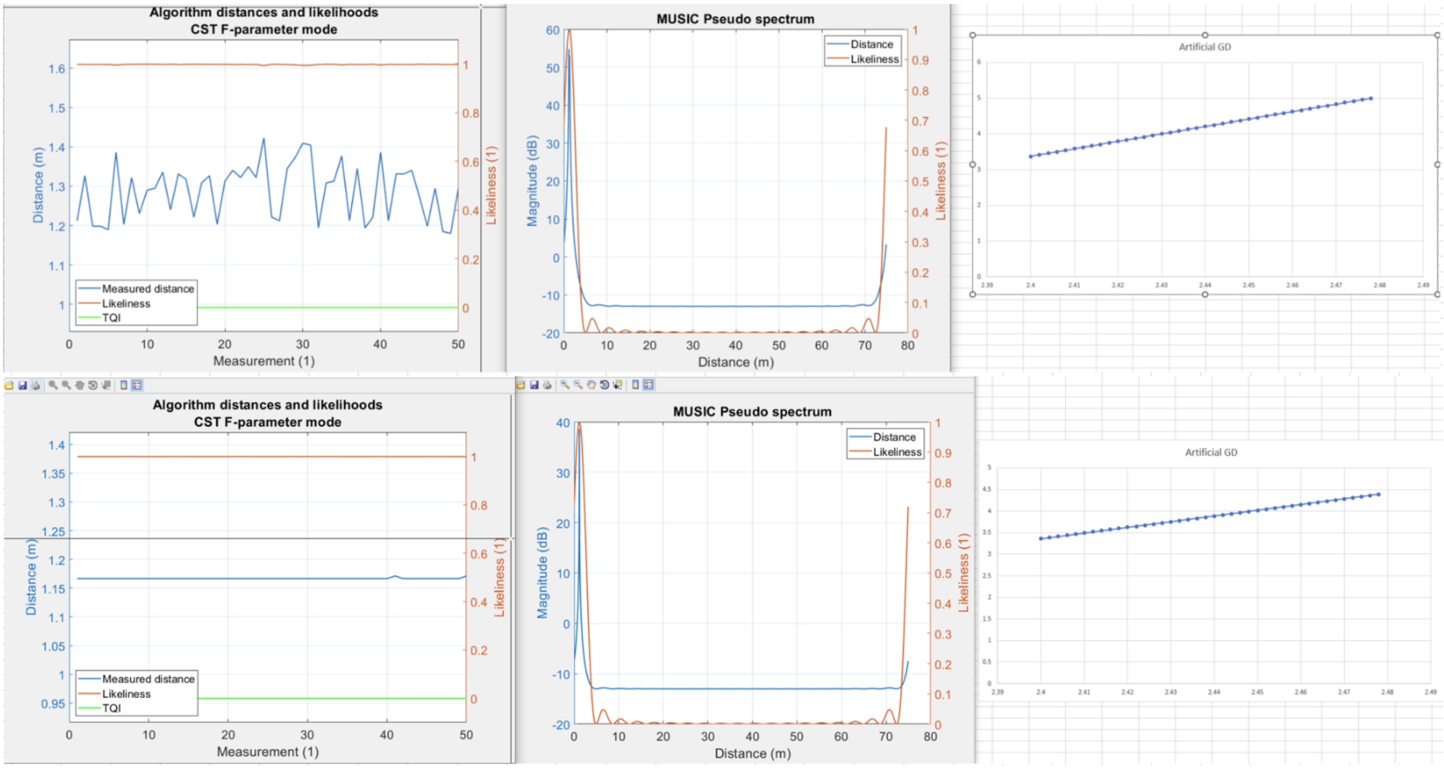

Figure 2.2. Impact of Linear Group Delay Slope

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.

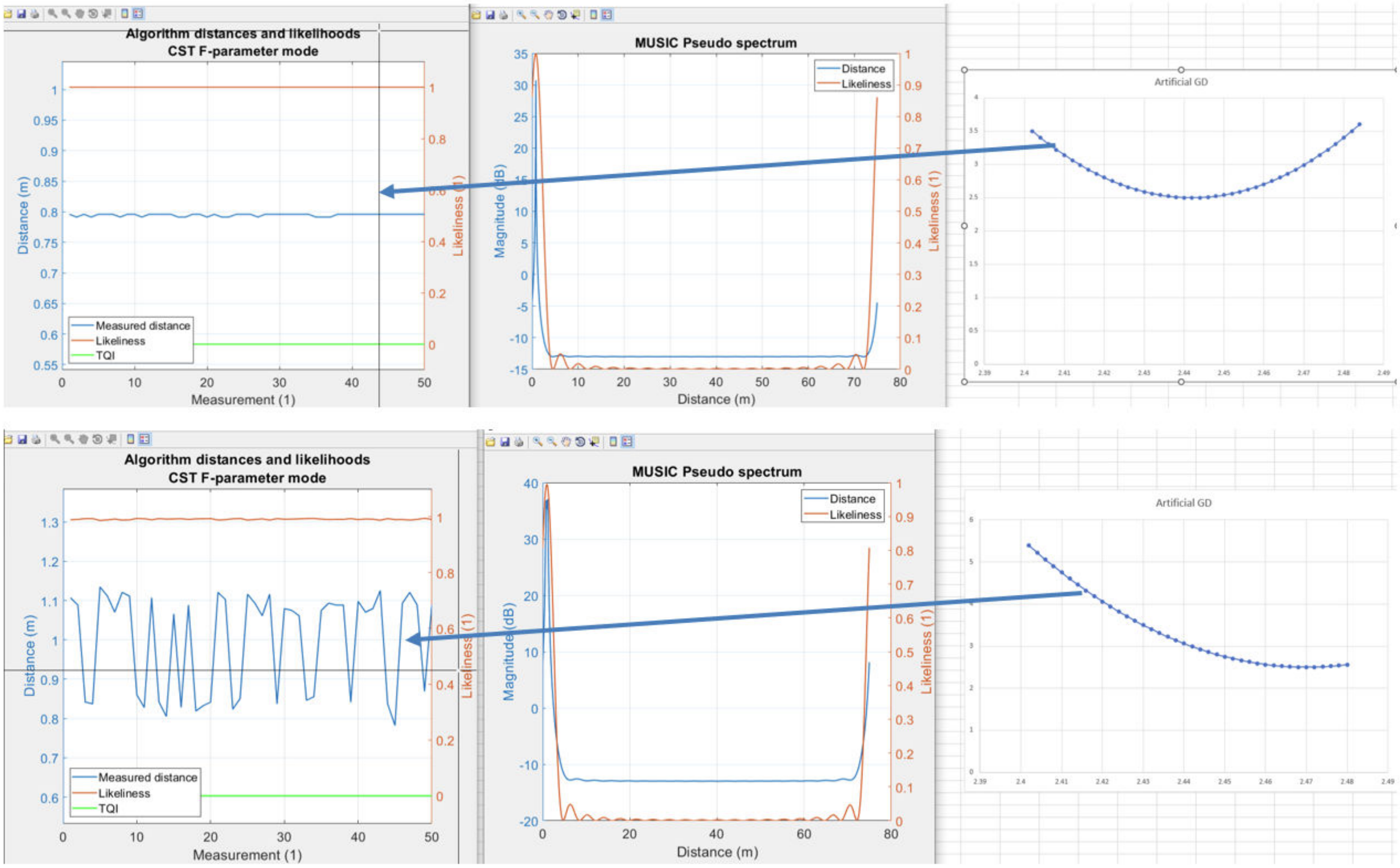

Figure 2.3. Effect of Non-Linear Antenna Group Delay

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.

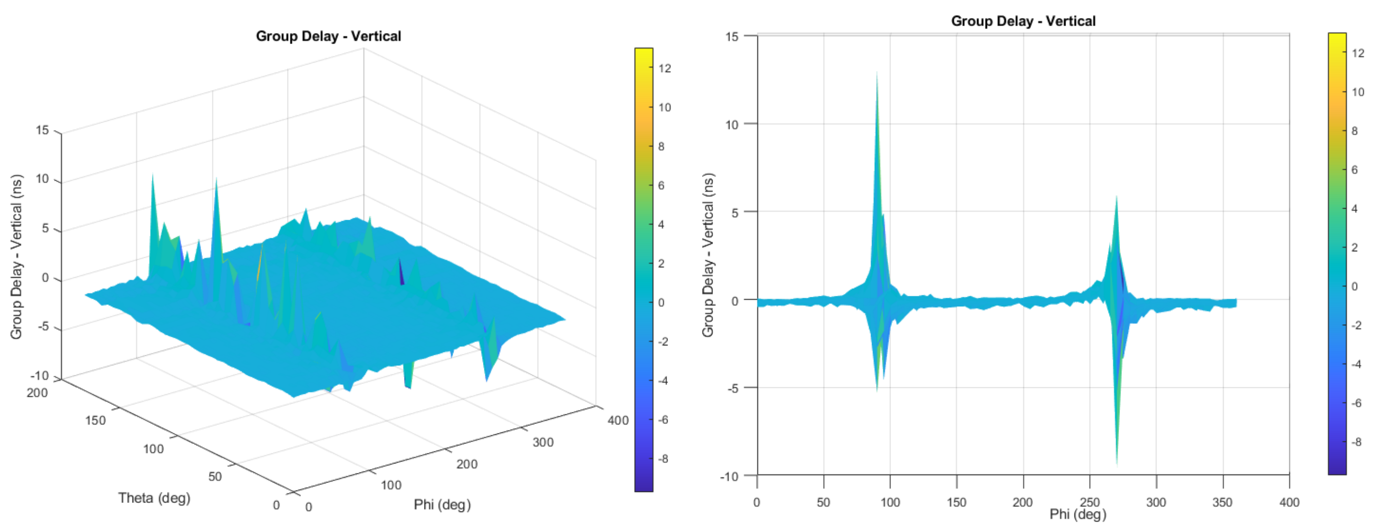

Figure 2.4. Typical Antenna Group Delay

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 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 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 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.
- 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.
- 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.
- 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.

3. Dual Antenna Examples

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

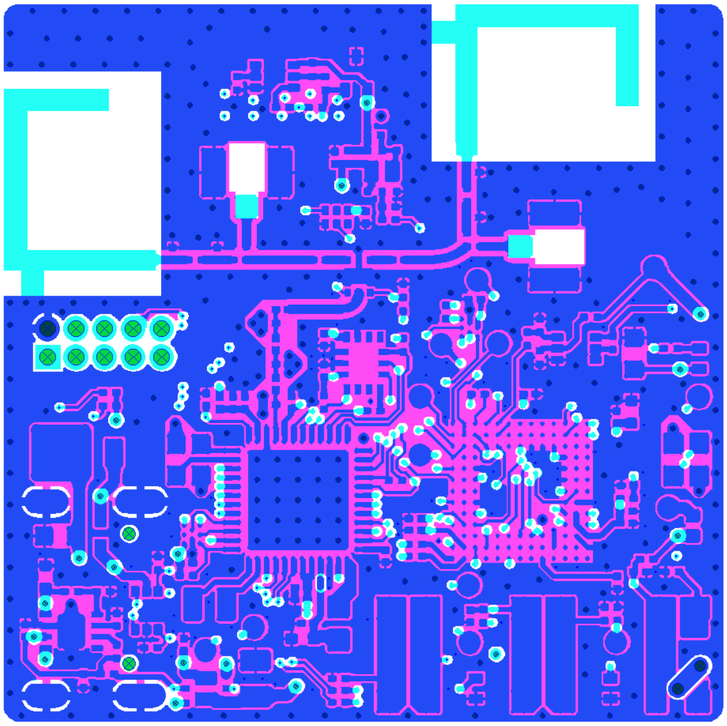

Figure 3.1. Top Layout of BRD2606A Reference Design with Dual Diversity Antenna

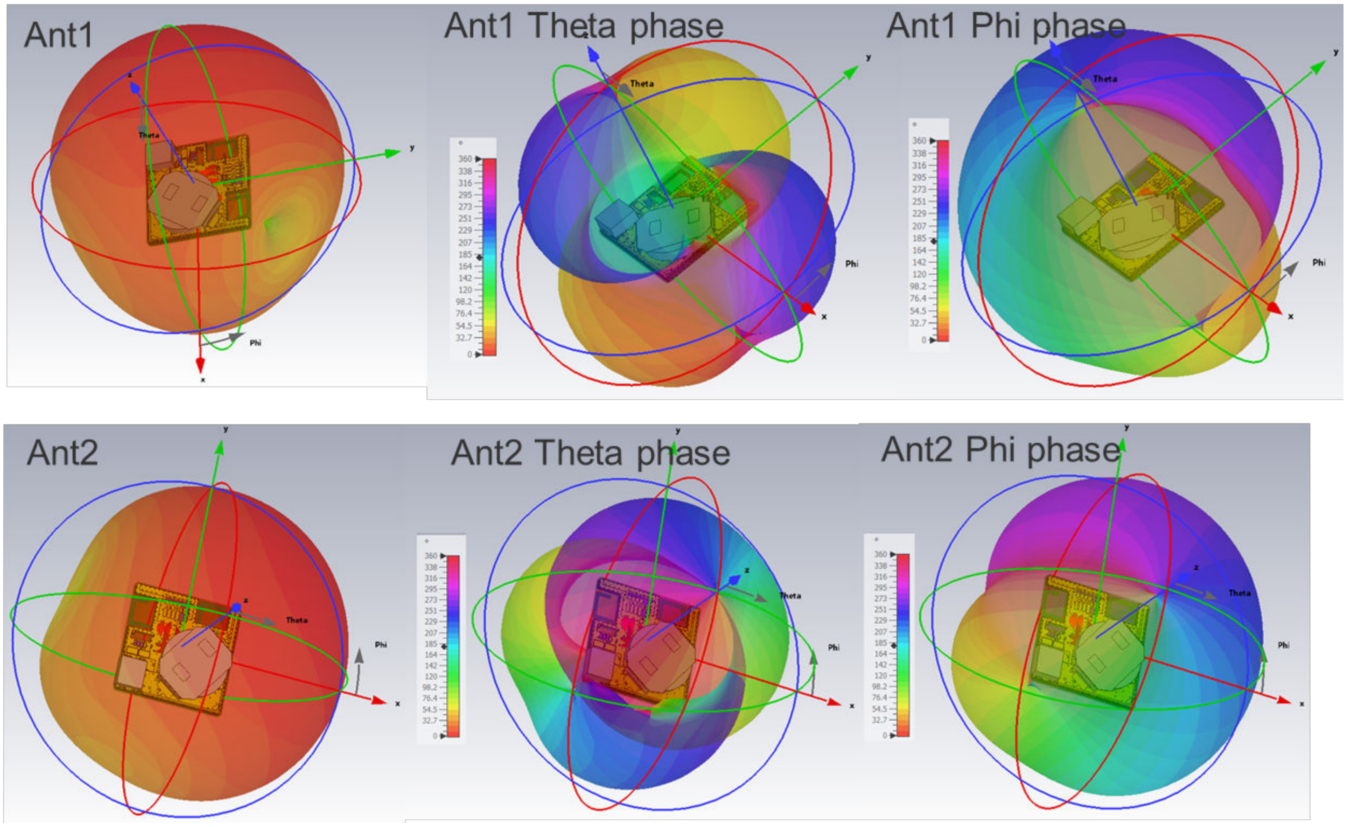

Figure 3.2. Simulated Antenna Patterns of BRD2606A Reference Design

The following test results 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 basically the possible 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 two antenna paths using switch (“AntSW” in the label name) show good CS accuracy. The switch-less solution, where a resistive combiner is applied to split the antennas, has worse CS accuracy but saves BOM cost and is still better compared to the single-antenna cases with a single antenna path.

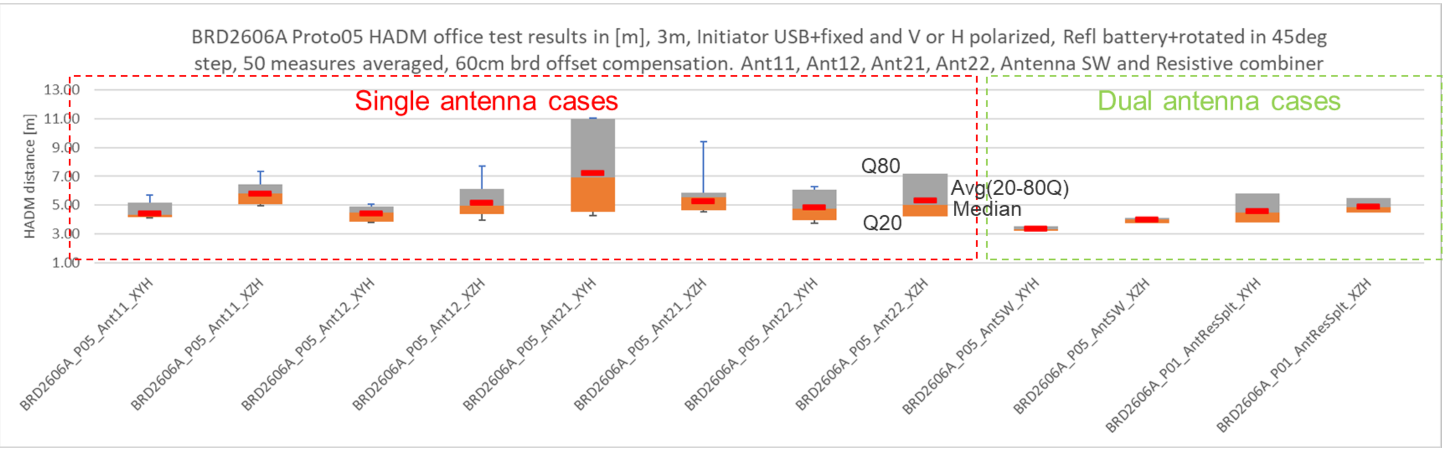

Figure 3.3. Single Antenna vs. BRD2606A with Dual-Antenna CS Office Test Results at 3 m Distance

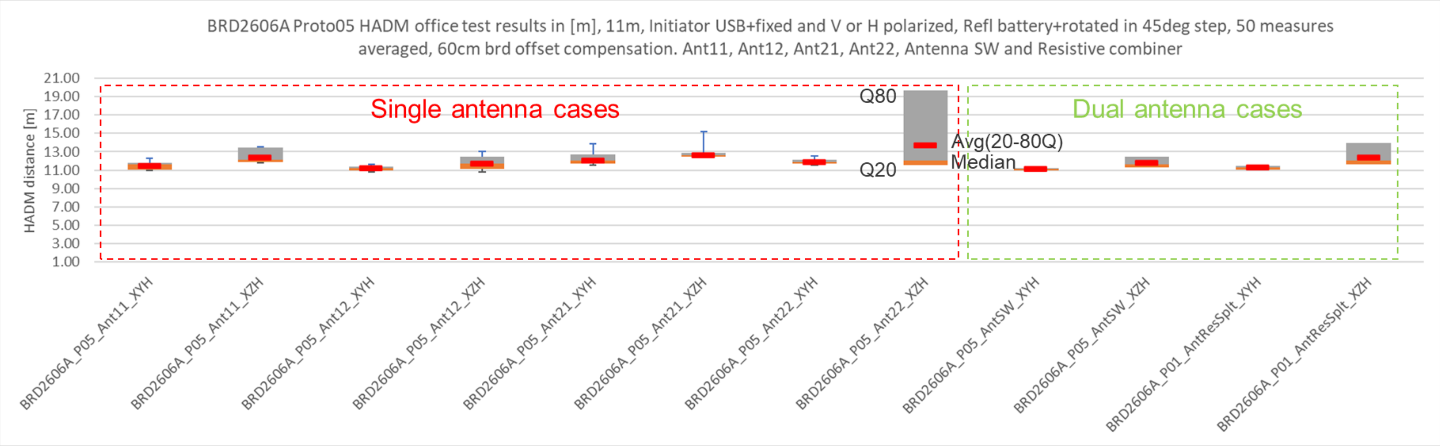

Figure 3.4. Single Antenna vs. BRD2606A with Dual-Antenna CS Office Test Results at 11 m Distance

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