qorvo

AoA Design Guide

APS330

Application Note

1 Introduction

Angle of Arrival (AoA) is a micro-location technology that determines the location of a tag relative to a node by measuring both angular position and distance. The angle is determined by detecting the phase difference between signals received from the tag by two separate antennas in the node.

Using an array of two receiver antennas, the location of a transmitter can be estimated by calculating the AoA through the Phase Difference of Arrival (PDoA) between the two receiving antennas. This is done in conjunction with time-of-flight measurements to determine the distance.

Careful consideration should be given to the design of the physical antenna array for products using AoA technology. Once built, characterization data from precisely measured PDoA on the product can be processed and used in the product's embedded firmware as a look-up table. This approach maximizes the overall performance of products using Qorvo AoA technology.

This application note provides guidance on antenna design, measurement, and data processing techniques for successful AoA product design.

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2 AoA Antenna Array Design

This section highlights considerations for the design of an AoA antenna array for optimum system performance. Measurements are given in terms of wavelength, λ, at the center frequency of the desired UWB channel.

2.1 Phase Difference Between Two Receiving Antennas

In Figure 1, an incident pulse from transmitter, Tx, is received by two antenna elements in the receiver, Rx, array. The range *r* is calculated from the time of flight of the pulse, and the path difference *p* can be calculated from the difference in phase between the two elements. From those, the x-y coordinates of Tx can be determined.

For a spacing of λ/2, the phase difference of arrival is between -180° and +180° for incident angles *Φ* between -90° and +90°.

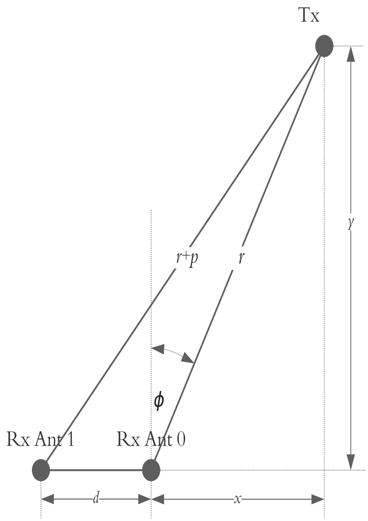

Figure 1. Tx signal is received by an Rx array of two antennas

2.2 Element Spacing

The spacing *d* between the two array elements is an important factor for the accuracy and resolution that can be achieved by the system. Figure 2 relates the PDoA to the AoA of the incident pulse.

In the ideal case (- - -), the antennas are spaced half a wavelength apart and the PDoA ranges from -180° to +180° for the -90° to +90° incident angle. If the antennas are spaced closer at 0.3λ (—), resolution is lost as the maximum PDoA range is reduced to ±108°.

If the antennas are spaced further apart at 0.6λ (—), as the phase wraps around continuously, there is ambiguity for measurements of less than -180° or more than +180° phase difference. If the AoA is changed gradually to higher angles, the PDoA will cross this discontinuity and appear to 'wrap' to the other side. This effect is highly undesirable, and the antenna design must ensure that the total range on the vertical axis is less than 360°.

The recommended antenna element spacing is 0.45λ (—), to account for phase measurement errors and noise, and to avoid PDoA wrapping without sacrificing too much resolution. The Qorvo Jolie-AoA antenna has optimal spacing for channel 9, but also supports channel 5.

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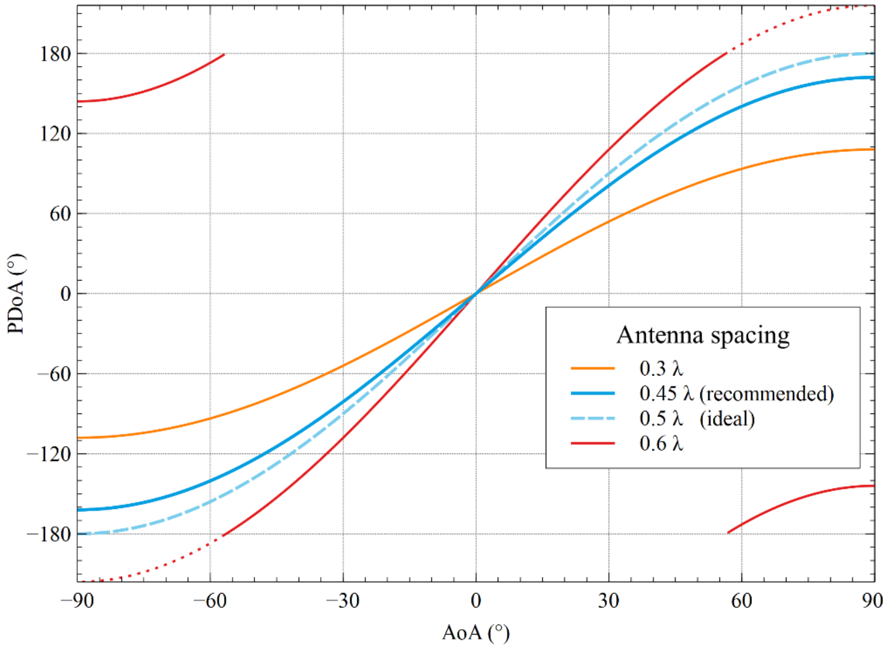

Figure 2. PDoA as a function of AoA for various antenna spacings.

2.3 Feed Lines

The feed lines between the chip and antennas should ideally be of equal length and as short as possible. It is recommended to print the antenna array on the same PCB as the chip or use SMA connectors with short microstrip lines near the chip as done in Qorvo's QM33120DK1 evaluation kit.

If flexible coax cables are used, tolerances in length, bend radius of the cable and vibrations can introduce a phase error that needs to be calibrated out for each device. It is recommended to fix coaxial cables in position on the device to minimize these effects.

Care should be taken to avoid discontinuities, impedance steps and coupling in the RF path which can lead to undesired reflections or radiation.

2.4 Antenna Types and Specification

The type of antenna element to choose depends on the desired application. Patch or directional antenna elements cover a hemisphere in front of the antenna PCB and are typically used in wall or ceiling-mounted applications.

If monopole antennas are used, there will be ambiguity regarding which side of the array the received pulse came from ('y' in Figure 1 can be positive or negative). This ambiguity needs to be resolved by other sensor data, such as an accelerometer, or the device should be positioned to make it impossible for the signal to have come from the -y direction.

The antenna elements should be well-matched in the desired frequency band, efficient, and capable of radiating a UWB pulse with low phase variation (group delay < 100 ps). Mutual coupling between the elements should be minimized, with at least 20 dB isolation recommended between each antenna.

If the array is integrated within a device, the effect of the material covering the antenna should be considered at the design stage. The array should have an unobstructed 'view' of the desired sector in front of the device.

For best results, the polarization of the AoA antenna should match the polarization of the tag antenna.

If possible, it is recommended to perform a full electromagnetic simulation of the AoA antenna, including the effects of external components and enclosures. Important parameters to simulate include gain, directivity, polarization, radiation pattern, isolation, and phase response in the azimuth plane, as well as phase response in planes away from azimuth.

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3 Angle Of Arrival Calculation

The stages of numerical processing in determining angular position are outlined in Figure 3 below. A raw PDoA result comes from the transceiver, which is then converted to a corresponding angle via a pre-characterized look-up table.

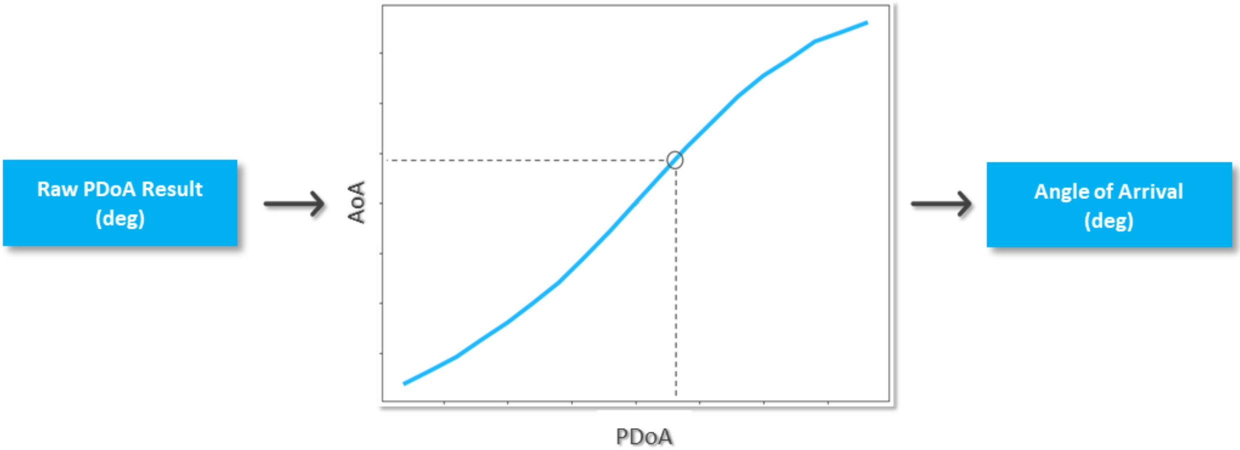

Figure 3. AoA calculation Process via Look-Up Table

4 Making Accurate PDoA Measurements

The PDoA measurement procedure involves establishing a two-way ranging (TWR) link between a tag and a node and plotting reported phase difference versus actual angle, as the node is rotated on a turntable. To maximize performance in the final product, the measurements should be set up as accurately as possible.

4.1 Hardware Setup

In this example, a QM33120WDK1 kit is shown, with QM33110 and QM33120 boards mounted to Nordic nRF52840-DK development boards. The QM33110 shield has Jolie-Omni antenna connected, while the QM33120 EVB has Jolie-AoA antenna connected. To avoid crosstalk, the Jolie-AoA antennas are mounted with the direction of propagation facing towards the bottom of the PCB (opposite side of the QM33120 device). Both boards are programmed with the latest QM33_SDK_V1.0 firmware image, provided by Qorvo. More details on this and getting started can be found in the Quick Start Guide in the SDK package.

Figure 4. QM33110 board with omni-directional antenna and QM33120 board with AoA antenna

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Once the boards are programmed, ranging can be started between the two devices. Examining the output logs should show ranging information including distance, AoA and PDoA. Example output is shown below.

Once the boards are programmed, ranging can be started between the two devices. Examining the output logs should show ranging information including distance, AoA and PDoA. Example output is shown below.

```
# Ranging Diag. Report 2:
    Message id:    RangingResponse
    Action:        Rx
    Antenna_set:   0
    Nbr of fields: 2
    # Frame Status Report:
        is processing ok  : 1
        is wifi activated : 0
    # AoA Report on axis 0:
        TDoA:     0.0322265625
        PDoA:     120.72365147292993 deg
        AoA:      51.19488953025478  deg
        AoA FOM:  215 %
        AoA Type: XAxis
```

To ensure the PDoA measurement is output in the logs, the diagnostics need to be enabled when calling the ranging scripts by adding the following arguments:

→ `run_fira_twr -p COMxx --en-diag --diag-fields “aoa”`

4.2 Measurement Setup

It is recommended to test using an anechoic chamber, to avoid reflections that could cause errors in the PDoA readings. The AoA node device is placed on a turntable and the tag device is mounted on a tripod. A laptop is used for coordinating the ranging exchanges between tag and node and for controlling the turntable. Place the tag device directly in front of the node with both the node and tag antenna at the same height.

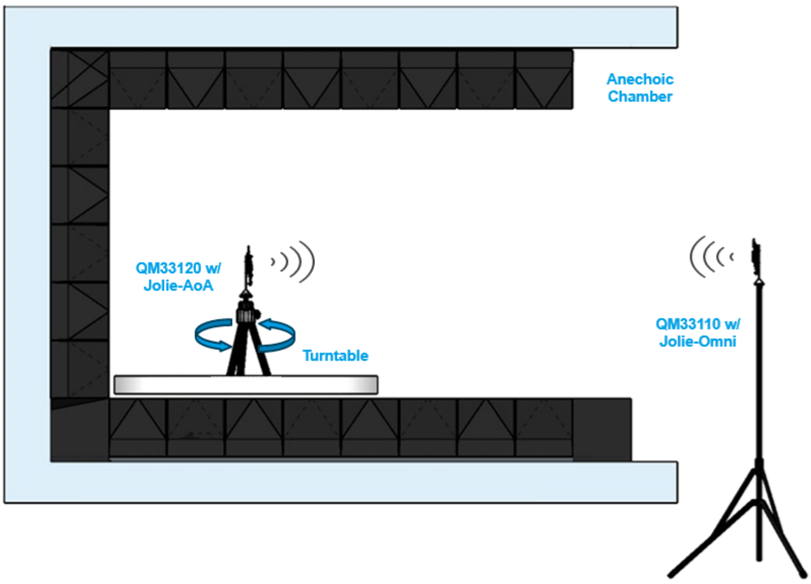

Figure 5. AoA node device is placed on turntable inside an anechoic chamber

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4.2.1.1 Precision Alignment in the Setup

To ensure the best AoA performance in the final RTLS system, great care should be taken to ensure that the measurement procedure is as accurate and repeatable as possible.

4.2.1.2 Relative Positioning of Node and Tag Antennas

The midpoint of the node's antenna array should be directly in-line with the turntable's axis of rotation (Figure 6). At the zero-degree position, the tag antenna should be perfectly normal to the midpoint of the node's antenna array (Figure 7).

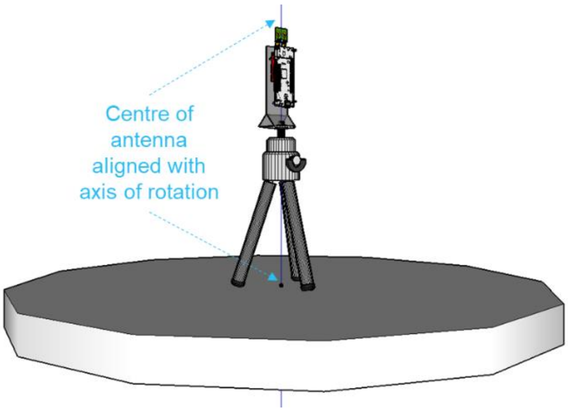

Figure 6. Centre of PDoA antenna array aligned with axis of rotation

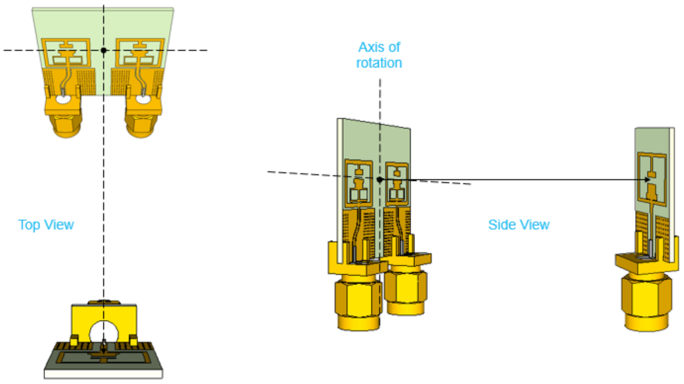

Figure 7. Align centre of node antenna with centre of tag antenna

4.2.1.3 Levelling Node Antenna Array

It is also important to ensure that the X and Z axes of the PDoA antenna array are parallel with the ground and the y-axis is perpendicular. You can do this by using a spirit level placed against the antenna and adjusting the position slightly if needed.

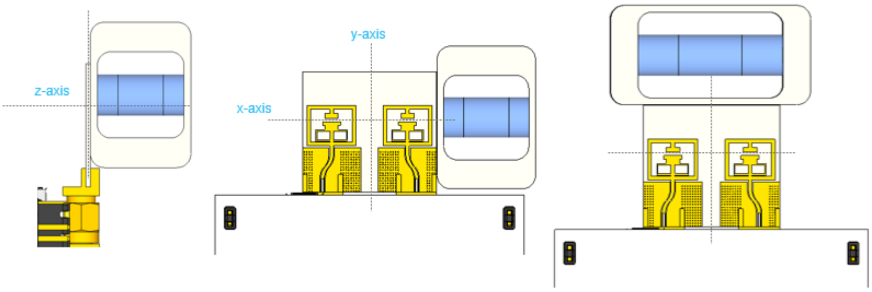

Figure 8. Correct levelling of antenna array

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4.3 Measurement Procedure

Once the boards are aligned in the 0° position, the process of gathering data can begin. This involves rotating the AoA board to a starting position of -90° and logging TWR data at incremental step sizes, such as 5° or 10°, until the +90° position is reached. It is recommended to record approximately 250 ranging data points at each angle to obtain a good statistical average. Save the data logs in separate files for each turntable step. If 5° steps are used, there should be 37 log files, and if 10° steps are used, there should be 19 log files. These log files can be processed to generate graphs, providing a visual indication of PDoA performance.

4.4 Graphing the Raw PDoA Characteristic

The raw data should be reviewed by plotting the mean, as well as individual PDoA data points against the actual AoA angle. In the saved log files, the PDoA report is found in the “Ranging Diag. Report section”.

```
# Ranging Diag. Report 2:
    Message id:    RangingResponse
    Action:        Rx
    Antenna_set:   0
    Nbr of fields: 2
    # Frame Status Report:
        is processing ok  : 1
        is wifi activated : 0
    # AoA Report on axis 0:
        TDoA:     0.0322265625
        PDoA:     120.72365147292993 deg
        AoA:      51.19488953025478  deg
        AoA FOM:  215 %
        AoA Type: XAxis
```

Figure 9. Example PDoA result from log file

Figure 10 shows the 500 individual PDoA results (grey dots) and mean (blue line) for each angle.

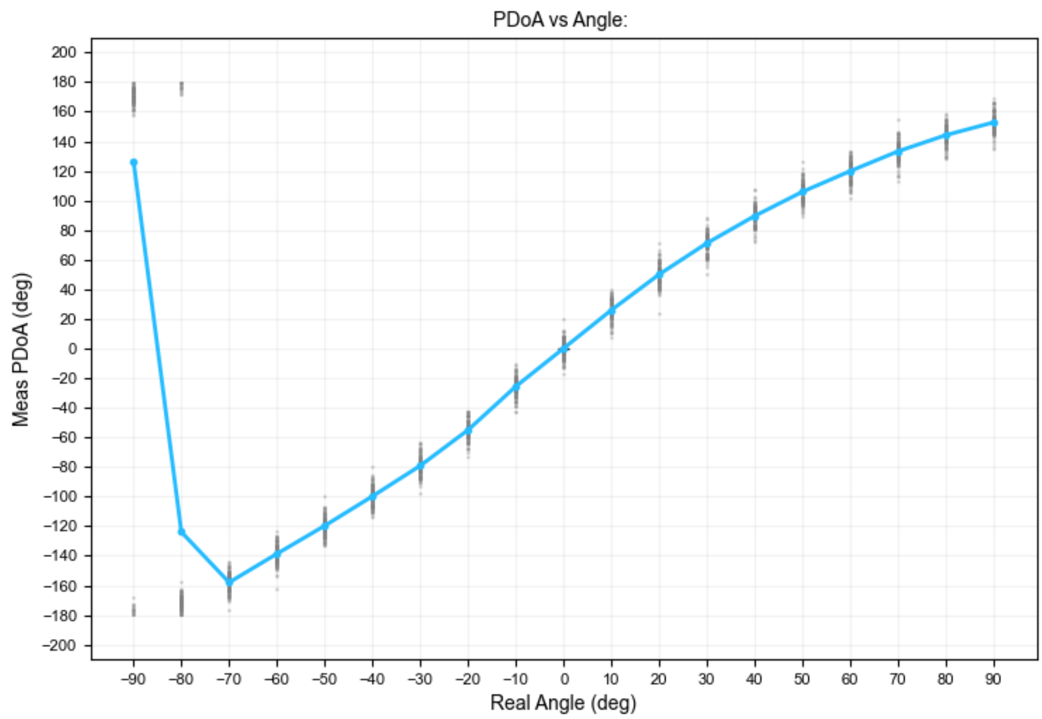

Figure 10. Jolie-AoA PDoA Measurement Curve on Channel 9

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5 Offset Calibration and Data Processing

5.1 Calibrating PDoA Offset

In the raw PDoA plot shown in Figure 11, a distinctive phase wrapping effect is observed, where individual PDoA results (grey dots) can exceed the ±180° boundaries on the Y-axis, especially near the ±90° angles.

When the device is initially set up at the 0-degree position, with the antenna facing the tag device, an offset in the PDoA measurement may be present, or the mean PDoA measured at 0 degrees may not equal zero. This could result from slight misplacement of the antenna during setup. In such cases, ensure precise antenna positioning. An inherent offset may also arise from the PDoA antenna array design, mismatched RF trace lengths on the PCB, or phase/signal propagation delay differences between RF paths in silicon.

To obtain an accurate mean or average, it is recommended to measure a large number of samples in the 0-degree position. The PDoA offset can be adjusted by setting the PDoA offset configuration value [ant_pair0.ch5.pdoa.offset, ant_pair0.ch9.pdoa.offset] using the “set_cal” function or in the calibration file using the “load_cal” function. PDoA offset configuration value must be converted from degrees to fixed point q11 format before using set_cal or load_cal. In mass production factory testing, calibrating the PDoA offset for each product may be necessary. More details can be found in APS312. [1]

5.2 PDoA Interval Shift

The wrapping effect in the PDoA curve is usually asymmetric; the positive end may exhibit more wrapping than the negative end, or vice versa. In real-world applications, it is desirable to minimize the severity of PDoA wrapping at extreme angles on either side of the antenna array and distribute the likelihood of wrapping equally. This can be achieved by processing the raw PDoA results with a PDoA interval shift.

In Figure 12, the left-hand raw PDoA curve shows wrapping at the negative end and none at the positive end. The PDoA interval shift value is determined by adjusting the wrapping boundaries on the 'Meas PDoA' axis to redistribute some wrapping to the positive end, balancing it on both sides. In this example, a PDoA shift value of '-17' changes the boundaries from -180, 180 to -197, 163, as shown in the right-hand curve, balancing the wrapping between extreme positive and negative angles.

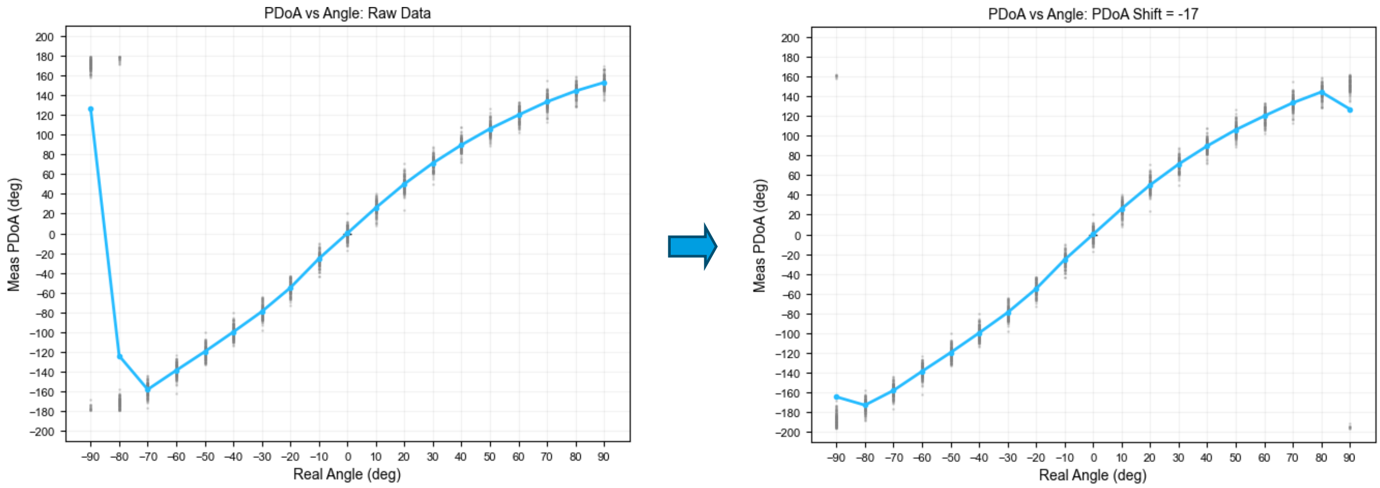

Figure 11. PDoA curves with offset calibration (left) and PDoA interval shift (right)

The PDoA results in the right-hand graph are generated using the Python equation below, with the 'pdoa_shift', set to -17:

```
new_pdoa = (raw_pdoa − pdoa_shift + 540) % 360 − 180 + pdoa_shift
```

Once a suitable pdoa_shift value is found, update the device configuration by modifying the "pdoa.interval_shift" configuration key using the set_cal or load_cal functions. When using set_cal/load_cal, the pdoa interval shift value needs to be converted from degrees to fixed point q11 format.

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5.3 The Unwrapped PDoA Curve

For creating the look-up table, the PDoA curve must have wrapping removed. In the raw PDoA curve, such as the left-hand curve in

Figure 11, wrapping occurs when results fall outside the [-180, 180] boundaries. Unwrapping can be achieved by deducting 360° from those results. The unwrapped curve is shown in the right-hand plot in Figure 12.

```
unwrapped_pdoa = (raw_pdoa − (2*angle) + 180) % 360 − 180 + (2*angle)
```

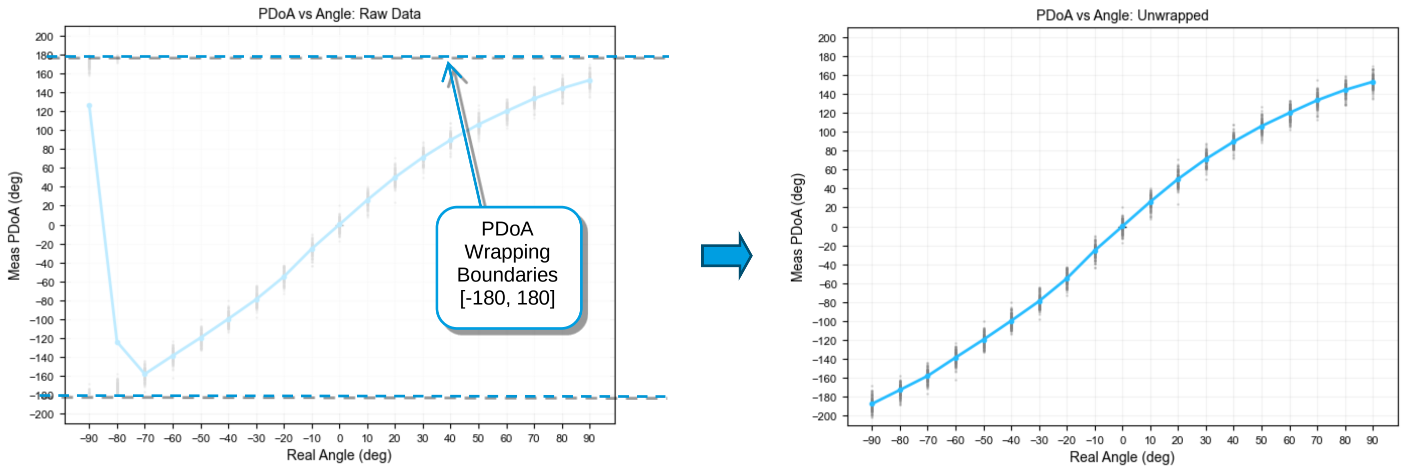

Figure 12. Unwrapping the PDoA curve

Another approach to "unwrapping" is using the concept of "circular mean" or "angular mean." This method is useful for periodic data, like angles, where the mean is calculated by considering each data point as a vector on a unit circle. This ensures an accurate representation of the central tendency, even when data wraps around.

It's worth noting that unwrapping can also be performed on the PDoA-shifted curve to achieve the same final unwrapped curve. The original PDoA data remains unchanged during the shifting process; instead, the PDoA wrapping boundaries are modified. The shift value of '-17' changes the boundaries from -180, 180 to -197, 163. Wrapped PDoA results below the lower boundary have 360° deducted, and those above the upper boundary have 360° added.

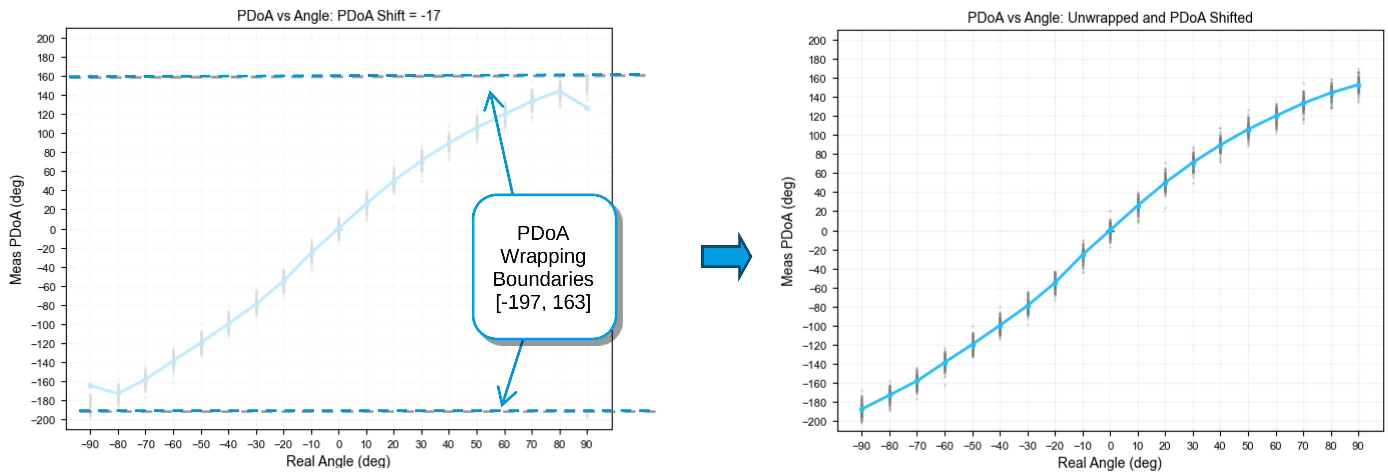

Figure 13. Unwrapping of the PDoA-shifted curve

6 Summary of Steps in Creating PDoA-to-AoA Look-Up Table

The flowchart in Figure 14 below summarizes the steps in creating the path difference look-up table.
Note: It is recommended to calibrate clock frequency offset and transmit power before calibrating PDoA performance.[1]

Step 1: Measure PDoA on your Product
- Setup devices precisely in anechoic chamber.
- Calibrate the PDoA offset.
- Measure and plot the PDoA vs. AoA curve.

↓

Step 2: Tune PDoA-Shift for Best User Experience
- Find interval shift value and wrapping boundaries that give equal wrapping at both angle extremes.
- Update PDoA shift in configuration file.
- Equal likelihood of PDoA wrapping at extreme angles on either side improves user experience.

↓

Step 3: Unwrap PDoA Curve
- Translate wrapped results past wrapping boundaries to get continuous PDoA vs. AoA curve.

↓

Step 4: Create Look-Up Table
- Use Python script (Appendix B) to generate LUT from these inputs:
  - List of AoA angles.
  - List of mean unwrapped PDoA results for each angle.

↓

Step 5: Use LUT in Application Firmware
- Update LUT in configuration.
- Angle result is derived from this.

Figure 14. Steps in creating look-up table

7 Conclusion

This application note serves as a guide to maximizing AoA performance by highlighting important design aspects of the antenna array and presenting approaches in measurement, calibration and data manipulation to accommodate any Qorvo-based PDoA end-product. Example formulas and programming code are also provided to ease the process for designers.

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References

[1] APS312 Production Tests for DW3000-Based Products

Abbreviations

AoA	Angle of Arrival
CFO	Carrier Frequency Offset
DUT	Device Under Test
LUT	Look Up Table
PDoA	Phase Difference of Arrival
ppm	parts per million
TWR	Two Way Ranging

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Document History

Version	Date	Section	Changes
A	April 2022		Initial release.
B	December 2024		Updated for SDK version 1.0.1 Updated AoA derivation process and diagrams Updated photos with QM33120DK1 Updated illustrations with Jolie359 AoA antenna Updated ranging output to match QM33 SDK v1.0 Updated code to generate AoA LUT (Appendix A) Updated template formatting Added appendix B

Appendix A: Look-Up Table Generator Script

The Python function in Figure 15 makes the process easier for customers by providing some sample data so that the LUT for your PDoA implementation can be generated.

The function `generate_LUT(mean_pdoa, angles)` takes in 2 parameters and outputs the look-up table for PDoA to AoA.

```
import numpy
import matplotlib.pyplot as plt

def generate_LUT(mean_pdoa, angles):
    np.set_printoptions(suppress=True, precision=3, linewidth=2000)

    mean_pdoa = np.array(mean_pdoa)
    plt.plot(angles, mean_pdoa, 'o')

    aoa_short = np.linspace(angles[0], angles[-1], 31)
    pdoa_short = [np.interp(a, angles, mean_pdoa) for a in np.linspace(angles[0], angles[-1], 31)]
    plt.plot(aoa_short, pdoa_short, 'o')

    aoa_optim = [-90, -73, -65, -57, -51, -45, -40, -35, -30, -25, -20, -15, -11, -8, -4, -0, 4, 8, 11, 15,
                 20, 25, 30, 35, 40, 45, 51, 57, 65, 73, 90]

    pdoa_optim = [np.interp(a, angles, mean_pdoa) for a in aoa_optim]
    plt.plot(aoa_optim, pdoa_optim, 'x--')

    plt.show()

    aoa_rads = np.array([np.radians(a) for a in aoa_optim])
    mean_pdoa_rads = np.array([np.radians(p) for p in pdoa_optim])

    PDOA_LUT = [(mean_pdoa_rads[a], aoa_rads[a]) for a in range(len(aoa_rads))]

    print('\n---- Copy output below into calibration file ----\n')
    space = ' ' * 17

    print(f'"PDOA_LUT_1_05" : [[{PDOA_LUT[0][0]:.6f}, {PDOA_LUT[0][1]:.6f}],', end='\n')
    [print(f'{space}[{n[0]:.6f}, {n[1]:.6f}],') for n in PDOA_LUT[1:-1]]
    print(f'{space}[{PDOA_LUT[-1][0]:.6f}, {PDOA_LUT[-1][1]:.6f}]\n]\n')

    print('--------------\n')

    print('setcal pdoa_lut0.data ', end='')
    [print(f'{n[0]:.4f} {n[1]:.4f} ', end='') for n in PDOA_LUT[:]]
    print('\n\n')

if __name__ == '__main__':
    mean_pdoa = [-187.48, -172.84, -157.976, -138.648, -119.712, -99.784, -79.144, -55.04, -25.624, 0.12,
                 25.976, 50.056, 71.176, 89.544, 105.904, 119.88, 133.216, 144.152, 152.768]
    angles = np.arange(-90, 100, 10)
    generate_LUT(mean_pdoa, angles)
```

Figure 15. Python Script to Generate PDoA-to-AoA LUT

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Appendix B: Look-Up Table Formats

The format of the LUT in *source code* files is radians converted to q11 fixed point format. A direct PDoA to AoA conversion table is implemented, consisting of an array 31x2 elements. First element in each pair is PDoA value and second element is AoA value.

```
pdoa_lut_entry default_lut_ch9_jolie[L1_CONFIG_PDOA_LUT_MAX] = {
    /* clang-format off */
    {0xe4e0, 0xf36f},
    {0xe59a, 0xf445},
    {0xe66b, 0xf51c},
    …
    …
    {0x161f, 0x0ae4},
    {0x16c3, 0x0bbb},
    {0x1725, 0x0c91}
    /* clang-format on */
};
```

Figure 16. LUT implementation in source files: …\Src\Boards\Src\nRF52840DK\platform_l1_config.c

In the calibration files provided in *uwb_qorvo_tools* folder, the LUT is implemented in radians floating point format:

```
   "PDOA_LUT_1_CH9" : [
      [-3.3905, -1.5708],
      [-3.2998, -1.4661],
      [-3.1978, -1.3614],
       …
       …
      [2.7652, 1.3614],
      [2.8451, 1.4661],
      [2.8932, 1.5708]]
```

Figure 17. LUT implementation in calibration files: …\scripts\device\load_cal\calib_files\QM33120WDK1\jolie_aoa.json

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