UWB AoA Antenna Fundamentals

APH511

Application Note

1 Introduction

This Application Note provides answers to commonly asked questions on antennas for angle of arrival (AoA) applications with Qorvo DW3000 or QM33 UWB chips. An array of two antennas is required to measure the direction of a UWB pulse approaching the receiver. A phase measurement is obtained from each antenna and the phase difference between the two antennas is used to calculate the AoA. The accuracy of these measurements depends on the design of the antenna array. This document gives guidelines for the specifications of the antennas and RF layout considerations.

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2 Basic Principle of AoA Estimation

An incident pulse from a transmitter (Tx) is received by two antenna elements in a receiving array (Rx). The range r is calculated from the time of flight of the pulse. The angle of arrival Φ can be calculated from the difference in phase between the two elements. With the angle and range, the x-y coordinates of Tx can be determined.

A geometric representation for the AoA setup is shown in Figure 1. For a spacing d of λ/2, the phase difference of arrival is between -180° and +180° for incident angles Φ between -90° and +90°. At Φ=0° the Tx antenna is normal to the Rx array and the phase difference is 0°.

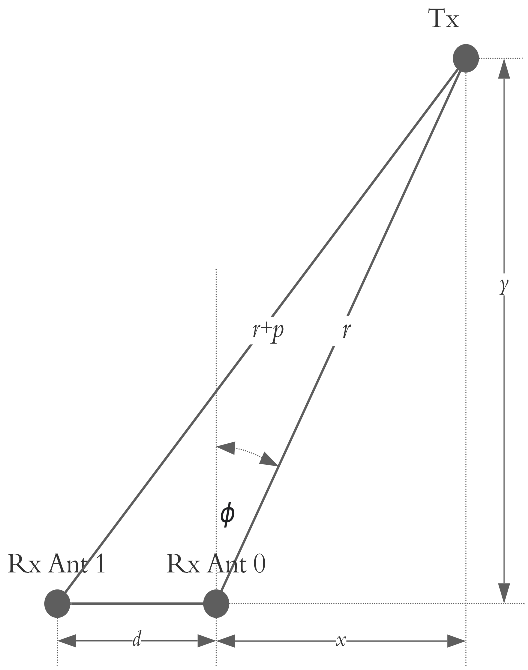

Figure 1. A Tx signal is received by an Rx array of two antennas.

3 Element Spacing

The spacing d between the phase centers of the two array elements is an important factor for the accuracy and resolution that can be achieved by the system. In this application note, when expressing a distance in wavelength, we consider the free space wavelength at the center frequency of the respective UWB channels 5 or 9 as supported by DW3000 or QM33 chips. Figure 2 relates the phase difference between the antennas (PDoA) to the angle of arrival (AoA) of the incident pulse.

In the ideal case (- - -), the antennas are spaced half a wavelength apart at the center frequency 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 'jump' 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 jumping without sacrificing too much resolution.

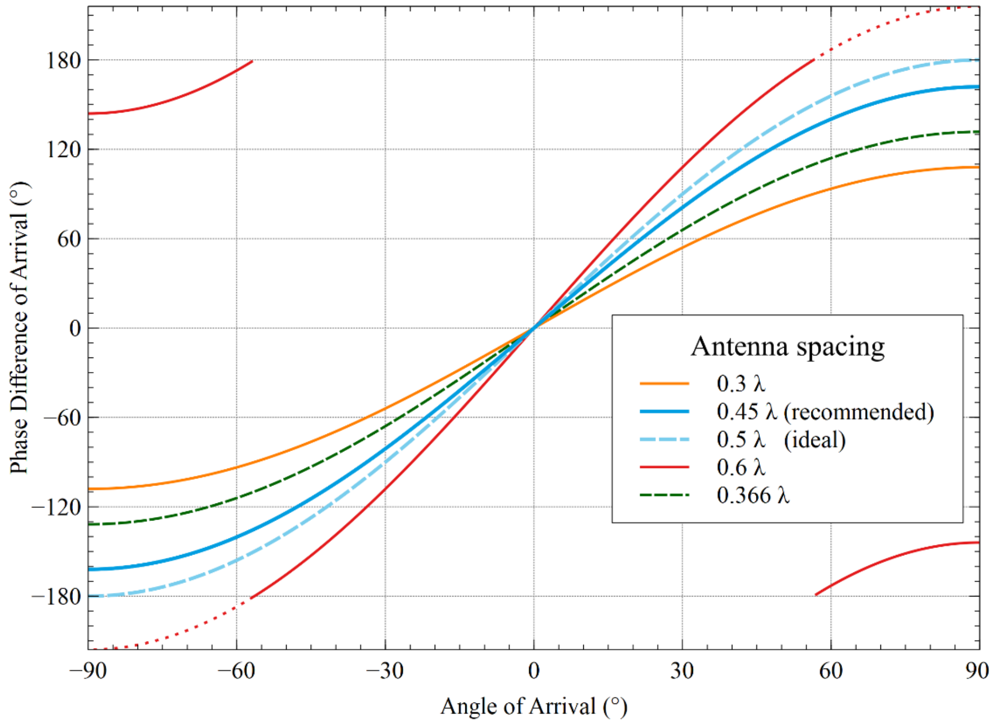

Figure 2: PDoA as a function of AoA for various antenna spacings

For dual band antennas covering e.g. channels 5 and 9, the spacing can only be ideal for one channel. In this case the antennas should be spaced for the higher frequency channel 9 (—) so the fraction of λ is smaller for the lower frequency channel 5 (- - -). Otherwise there will be phase wrapping at the higher frequency channel. These values are guidelines only. Actual spacing should be checked in simulation by subtracting the farfield phase patterns of both elements and confirming no phase wrapping occurs over the desired aperture angles.

4 Antenna Types

The type of antenna element to choose depends on the desired application. Patch antenna elements cover a hemisphere in front of the antenna PCB and are typically used in wall- or ceiling mounted applications. Monopole antennas are omni-directional and can achieve coverage in 360 degrees.

If off-the-shelf antenna elements are used, a matching network is often required. Such antennas are typically characterized on large evaluation boards to achieve advertised performance, which can differ significantly when implemented on smaller devices. Care should be taken that matching components don't introduce pulse distortion.

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

5 Front-Back Ambiguity

With raw PDoA measurements, there can be ambiguity as to which side of the array the received pulse came from. For the scenario in Figure 1, The position of the Tx node can be symmetric around the x axis, thus y can be positive or negative and give the same phase difference. Resolving or mitigating this ambiguity needs to be considered at the application design stage.

With directive antennas, the ambiguity may be resolved by the received signal strength where lower power is received from the back.

Other sensor data, from an accelerometer or gyroscope can help to resolve the ambiguity. When the antenna array turns counter clockwise, incident angles Φ will increase for positive y (front), but decrease for negative y (back).

A third antenna can be used perpendicular to the array, connected by a switch, forming a second antenna pair with one of the original antennas. This would allow a second PDoA measurement in the perpendicular plane to resolve the ambiguity.

If the application allows, the device can be placed in such a way to make it impossible for the signal to have come from the back direction.

6 Antenna Design Specification

6.1 Impedance Matching

The antenna elements should be well matched with S11 in the desired channel ideally below -10 dB, but -6 dB at the edges can be acceptable. The bandwidth should be at least 500 MHz centered around each desired channel frequency. When designing the antennas, any connectors or cables should be included and modelled as accurately as possible to ensure those parts or transitions do not introduce impedance mismatch. For integrated antennas, the full device ground plane and housing needs to be considered at the design stage.

6.1 Phase Variation / Group Delay

The antennas should exhibit a low phase variation with angle and frequency. Sudden variation in phase, e.g. at a sharp resonance, can distort the UWB pulse and lead to inaccurate measurements.

Phase variation is commonly expressed in terms of group delay. Group delay is the negative derivative of phase with respect to frequency. It is recommended to minimize group delay variation to <100 ps within the 500 MHz band over the useful orientation angle. At the speed of light the signal travels approximately 30 mm in 100 ps. Therefore, any variation in antenna group delay due to a change in antenna orientation will cause some reduction in the time of flight calculation accuracy.

6.2 Mutual Coupling / Isolation

Mutual coupling between the elements in the Rx array will depend on antenna type and surrounding components. For example, at $\lambda/2$ monopole antennas will couple more than patch antennas. Techniques to mitigate coupling include isolators, ground plane slots or metamaterial features between the antennas.

For best performance for PDoA, we specify isolation of at least 25 dB.

7 PCB Layout Considerations

7.1 Feed Lines

The characteristic impedance of the RF pins on DW3000 or QM33 chips is 50Ω and antenna feed lines should be of the same impedance. Controlled impedance lines should be specified in the PCB design, and the PCB vendor will bias the line widths to achieve the target impedance during fabrication to account for normal process variations. The feed lines between the chip and antennas should ideally be of similar length and as short as possible. It is not necessary for the lines to be exactly the same length, a calibration measurement at Φ=0° can be used to obtain a PDoA offset value which is used to correct subsequent PDoA measurements.

The RF traces should be routed so as to minimize coupling with other RF, control, and DC traces as this can lead to impedance mismatch, distortion in the UWB pulse or EMC issues. This can be achieved by placing co-planar ground on each side of microstrip traces and using via stitching along the traces. Ensure there is an unbroken ground path beneath transmission lines so that current paths in the RF track and ground plane beneath it are of matching lengths.

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 the Qorvo QM33120WEVB evaluation kit.

Changes in direction of the RF traces should be gradual. It is best to use smooth curves, 90° bends should be avoided.

7.2 RF Cables

Micro coax cables should ideally be avoided as they can exhibit unpredictable phase variation when bending. They can have poor length tolerance which will require per-device calibration to compensate for. A typical 1.13 mm diameter micro coax cable will have a phase shift of 11.4° at 6.5 GHz (Channel 5) and 14.1° at 8 GHz (Channel 9) per 1 mm length difference.

7.3 Other Components in the RF Path

7.3.1 Vias

Vias in the RF path to change layers should ideally be avoided because they can introduce mismatch, reflections and scattering. A via is essentially two 90° bends in the z direction. If vias are used they must be designed carefully to avoid problems.

7.3.2 Matching Networks

It is best to design the antenna elements to be inherently matched to 50Ω and avoid the need for and expense of matching networks. Matching networks can introduce resonances that lead to phase variation (see below). Every additional component will introduce tolerance.

If components are used, they should be placed as close as possible to the circuit element / antenna to be matched. Series components should be placed directly on the line and parallel components should be placed directly across the CPW gap. Ideally the component footprint matches the dimensions of the RF trace without the need for larger landing pattern. This avoids creating unintentional stubs or discontinuities in the RF traces.

7.3.3 Band Pass Filters

Band pass filters are used to suppress interference from adjacent frequency channels (e.g. WiFi) or harmonics. Using a filter will add insertion loss to the RF path. A filter can also introduce phase non-linearity and thus group delay variation as discussed in section 4 above.

Qorvo uses the Murata LFB217G35CFHE826 on QM33120WEVB evaluation board. This is a good choice for Channel 9 with 66 ps group delay variation between 7.75 GHz and 8.25 GHz.

The group delay contributions of the filter and antenna will superimpose and the total variation should be taken into account to estimate the expected ranging error.

When discrete filters are used, layout guidelines for the filter should be followed.

7.3.4 PA / LNA

When PA and/or LNA amplifiers are used, models with integrated bypass switches should be chosen to avoid the need for discrete switches. Qorvo QM14070 PA and QM14068 LNA are recommended options for UWB operation. Layout guidelines for the components should be followed.

References

[1] DW3000 Data Sheet
[2] QM33120W Data Sheet
[3] APH301 Hardware design guide for DW3000 and QM33000 series ICs

Abbreviations

AoA Angle of Arrival
CPW Co-planar Wave Guide
EMC Electromagnetic Compatibility
FR4 Flame Retardant (fiberglass reinforced epoxy laminates) grade 4
IC Integrated Circuit
LNA Low Noise Amplifier
PA Power Amplifier
PCB Printed Circuit Board
PDoA Phase Difference of Arrival
RF Radio Frequency

Important Notices

Document History

Rev	Date	Section	Changes
1.0	28 Sept 2023		Initial release
1.1	13 Nov 2024		Scheduled update. Added section on front-back ambiguity.