Design Guide: TIDEP-01040

Wafer Chip-Scale Package 60GHz mmWave Sensor Reference Design for Industrial Applications

Description

This reference design targets applications requiring smaller form factor and low-power consumption. The design is based on TI's IWRL6432W, 60GHz mmWave radar device and uses a four-layer PCB stack-up with FR408HR material from Isola®. The reference design also has a smaller form-factor counterpart without debug and evaluation interfaces.

Resources

TIDEP-01040	Design Folder
IWRL6432W	Product Folder
TPS6285020MDRLR	Product Folder

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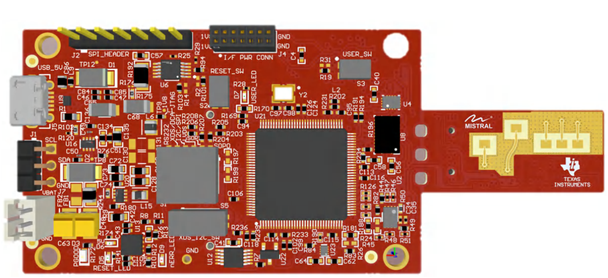
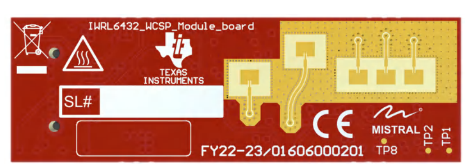
Features

- Single 1.8V power rail
- FR408HR based four-layer PCB stack up
- Design dimensions:
  - IWRL6432W reference design: 89mm × 37mm
  - IWRL6432W small form-factor reference design: 12.6mm × 39mm
- Low-power, low-cost 60GHz mmWave sensor using the IWRL6432W
- Communication interfaces: UART, SPI, I2C, and RS232
  - Reference design has XDS110 debug probe and 60pin header for LVDS data capture
- Antenna features:
  - Single element patch antenna array
  - 120° field of view
  - Angular resolution of 23° in azimuth plane and 58° in elevation plane
  - Human detection up to 15 meters at boresight
  - 4GHz bandwidth

Applications

- Personal electronics
- PC and notebooks
- Television
- Building automation
- Lighting





1 System Description

Industrial applications equipped with radar in industrial building automation, parking area automation, personal electronics, lighting and other end equipment provide quality of life and safety benefits for day-to-day living.

Frequency-modulated continuous-wave (FMCW) radars allow accurate measurement of range, angular resolution, and relative velocity. Because of the usefulness, radars are widely used for presence detection, motion detection, tracking, and many other applications. An important advantage of radars over camera and light-detection-and ranging (lidar)-based systems is that radars are relatively immune to environmental conditions (such as the effects of dust and smoke). FMCW radars can work in complete darkness and also in bright light environments since radars are not affected by glare.

This reference design uses a wafer chip-scale package (WCSP) single chip with a package size of 4.89mm × 4.5mm, bill-of-material (BOM) optimized, small-scale, 60GHz mmWave design. This design is easy to integrate because of the simplified schematic and small four-layer layout. The antenna was developed on the bottom-layer of the PCB, whereas, the mmWave device resides on the top-layer. This provides even smaller form factor. The antenna provides ±60° field of view in azimuth and elevation planes. The reference design has the XDS110 (UART and JTAG) debug probe and 60-pin connector for high-speed LVDS data capture (with onboard differential LVDS drivers), for evaluation purposes. The reference design also has a small form factor counterpart without the additional debug and evaluation interfaces.

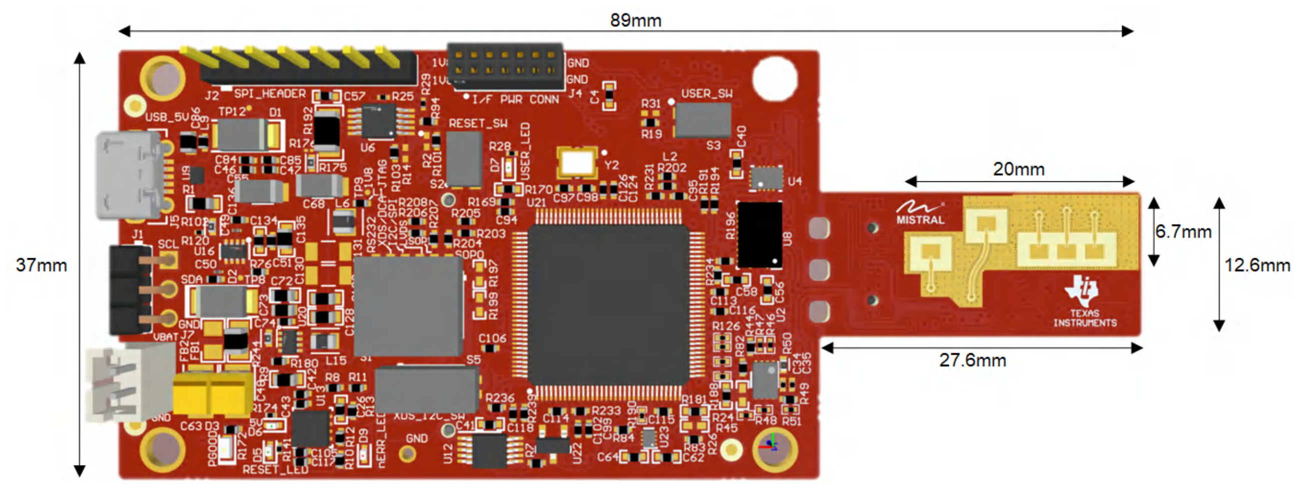


Figure 1-1. IWRL6432W Reference Design Dimensions

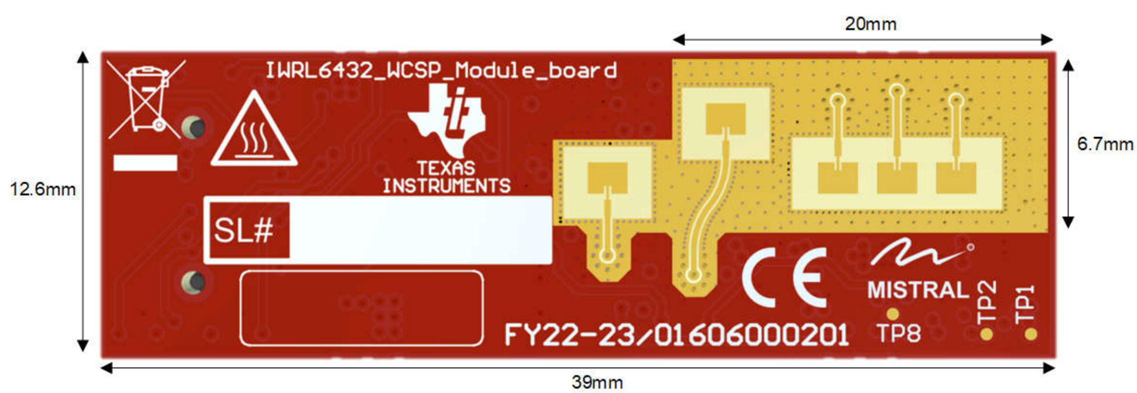


Figure 1-2. Small Form Factor Reference Design Dimensions

2 System Overview

2.1 Block Diagram

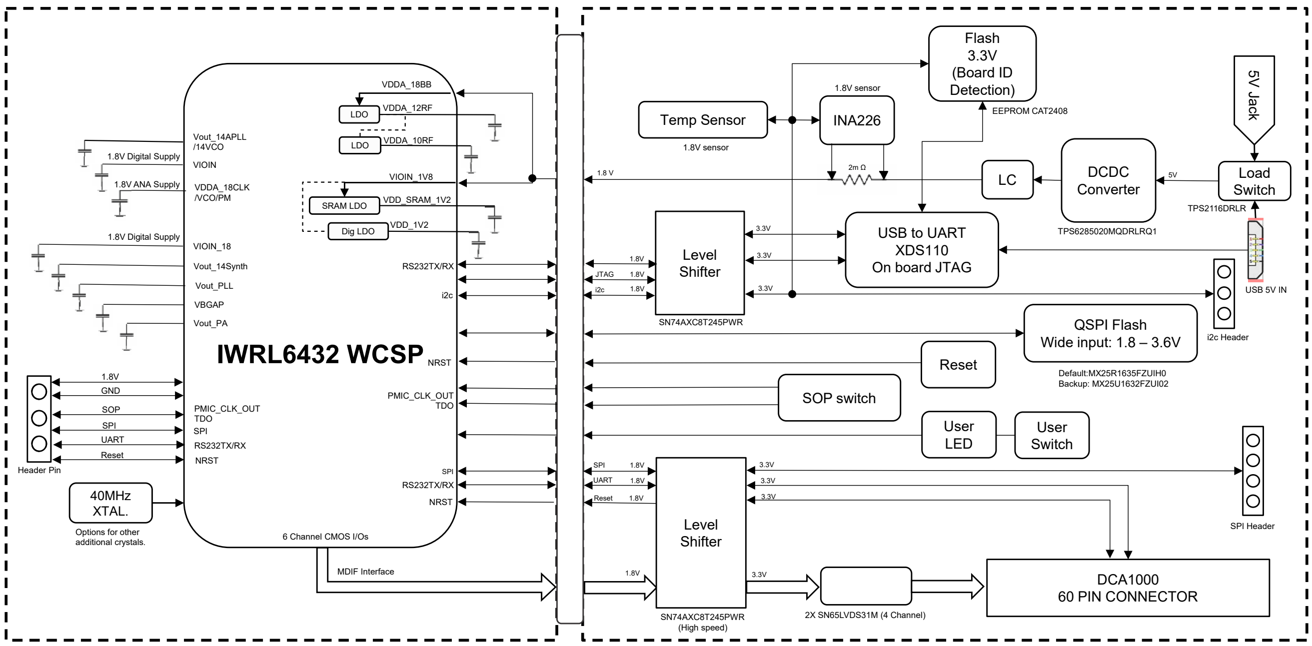


Figure 2-1. IWRL6432W Reference Design Functional Block Diagram

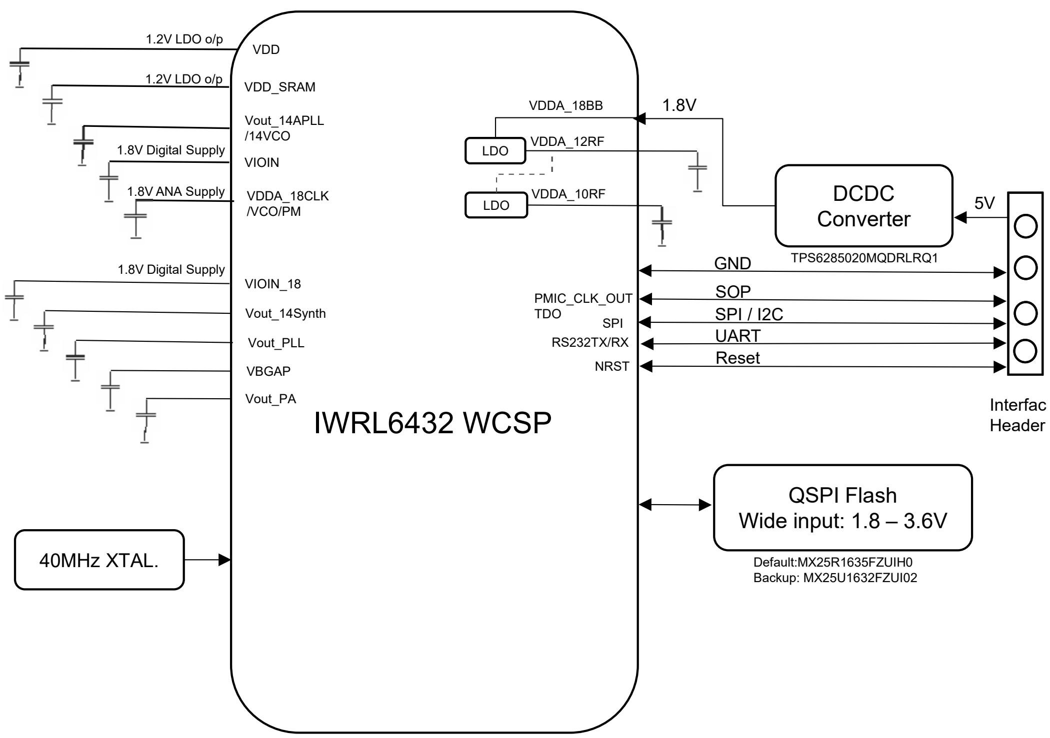


Figure 2-2. IWRL6432W Small Form-Factor Reference Design

2.2 Design Considerations

This reference design is developed to target applications that require lower power consumption, reduced BOM cost, as well as smaller sensor size. Following are the main design considerations:

- **Low power consumption**
  The design consumes less power for applications like motion and presence detection, gesture recognition.
- **Low cost**
  The design has a reduced BOM cost.
- **Small overall size**
  The reference design has a small form factor to allow the same to be placed into space constrained environments such as TVs, monitors, and digital picture frames. In these and similar end equipment, the radar often needs to be placed in the bezel region. Therefore, the antenna region must be optimized to fit into an area which can now easily be less then 2 cm in width.
- **Antenna Field of View (FoV) and angle resolution**
  The antenna design has a wide FoV and a good angular resolution that helps covering larger areas.

2.2.1 Reference Design Features

The reference design uses the single-rail, BOM-optimized topology of the IWRL6432W. The design includes a quad serial peripheral interface (QSPI) flash to store the application programs, a 40MHz XTAL as a clock source and an antenna array of two transmitters and three receivers along with the radar device. The reference design also provides onboard power distribution from USB power along with an XDS110 debug probe and LVDS interfaces. The reference design has onboard level shifters to shift the IO voltage from device IO voltage 1.8V to 3.3V for host communication.

The small form-factor counterpart of the IWRL6432W reference design only features the radar device functioning in single-rail BOM-optimized topology, a 40MHz crystal as clock source, a QSPI flash and an antenna array of two transmitters and three receivers. The small form-factor reference design has a 14-pin connector for external power supply and communication interfaces. SPI, I2C and RS232 communication interfaces are available for the small form-factor reference design.

Note

The small form-factor reference design takes a 5V external supply. The device operates in single-rail 1.8V supply generated from 5V external supply in an onboard DCDC regulator. The IO level of the device is set to 1.8V. Therefore, for external communication or host communication, the IO voltage level needs to be matched.

Table 2-1 states the high-level description of the reference design board features along with the elementary components.

Table 2-1. Reference Design Board Features

FEATURE	DESCRIPTION
IWRL6432W	Single-chip radar transceiver with an integrated local oscillator, with 3 RX and 2 TX, low power, low cost
2-TX and 3-RX antennas	Single-element patch antenna with 120° FoV
Azimuth array	The antenna design forms a 5-element virtual array which allows 23° angular resolution
Elevation array	2-element virtual array – enabling 58-degree angular resolution
Clock source	40MHz crystal oscillator
QSPI Flash	Ultra-low power, 80MHz, 16Mbit flash memory
Serial peripherals	SPI, I2C, UART
Evaluation options (for reference design only)	XDS110, LVDS

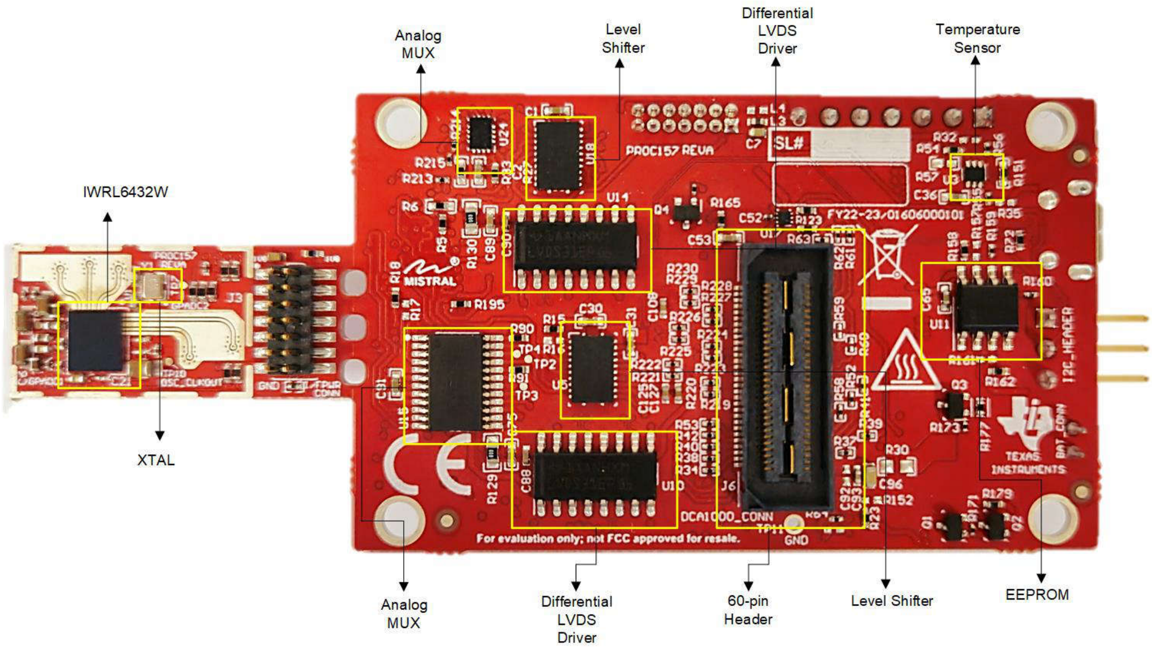


Figure 2-3. IWRL6432W Reference Design Mark-up: Top

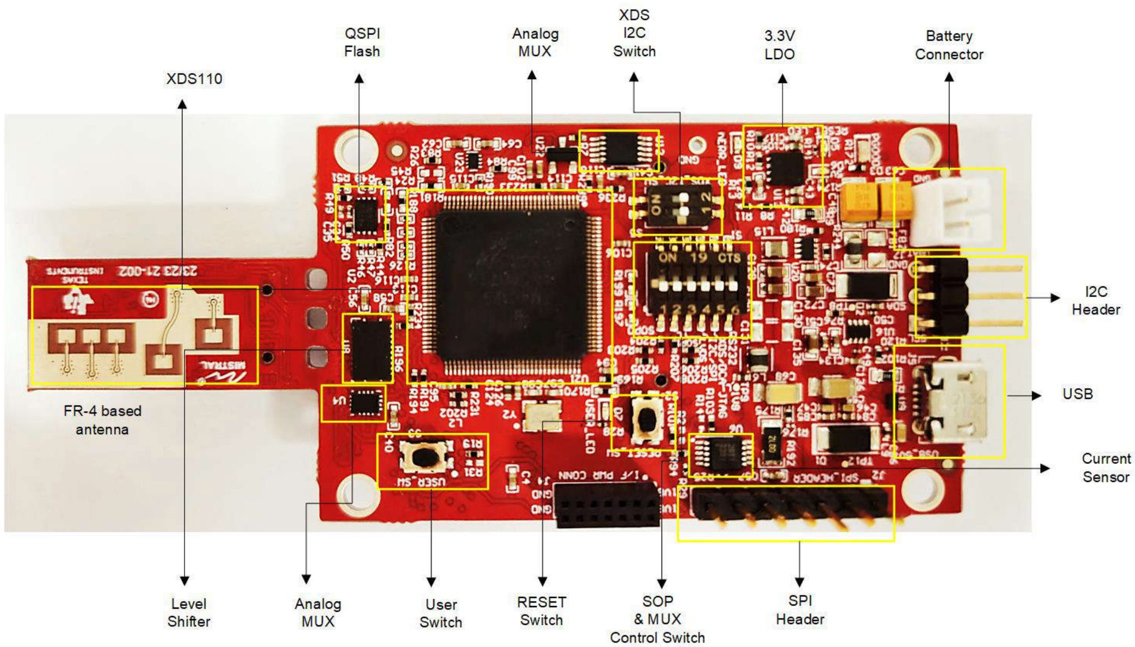


Figure 2-4. IWRL6432W Reference Design Mark-up: Bottom

2.2.2 Switch Settings

Switch-1 (S1) controls the device sense-on-power (SOP) and MUX for different communication interface. The following tables explain the switch positions and the respective controls.

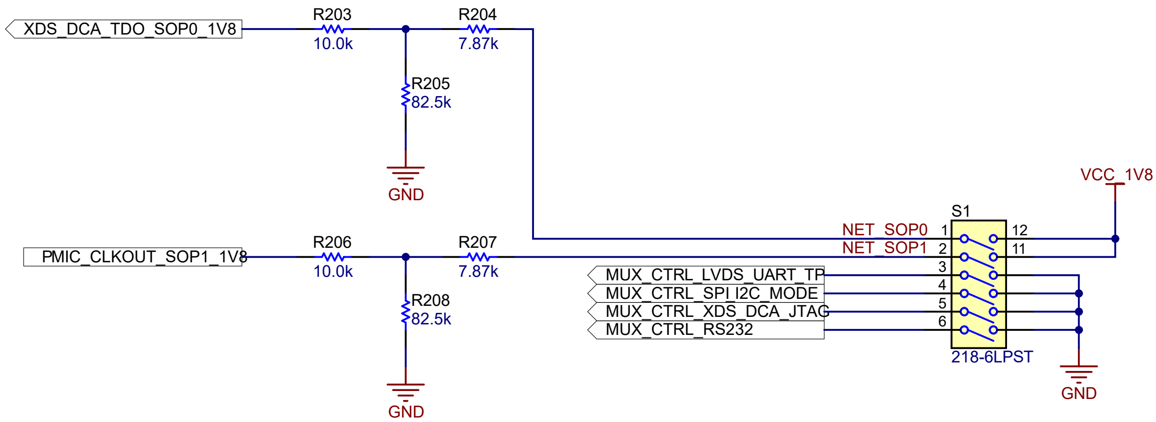


Figure 2-5. Switch-1 (S1)

Table 2-2. SOP Configuration

SOP MODE	DEVICE FUNCTION	SOP1 (S1.2)	SOP0 (S1.1)
SOP_MODE1	Device management mode, QSPI Flashing mode	0	0
SOP_MODE2	Application mode, Functional mode	0	1
SOP_MODE4	Debug mode, mmWave studio connectivity mode	1	1

Table 2-3. MUX Table

SWITCH	SWITCH POSITION OFF	SWITCH POSITION ON
S1.3	LVDS	XDS_UARTA, NERROR_LED, WATCH_DOG_TP, RTC_CLK_IN_TP, HOST_CLK_TP
S1.4	I2C, REG_MODE, USER_LED_SW	SPI, HOST_INTR
S1.5	XDS_JTAG	DCA_JTAG
S1.6	XDS_RS232	DCA_RS232

2.3 Highlighted Products

2.3.1 IWRL6432W

The *IWRL6432W* is TI's low-power, low-cost radar that offers industry-leading radio-frequency (RF) performance. The IWRL6432W is an integrated single chip, low-power, frequency modulated continuous wave (FMCW) radar sensor capable of operating in the 57GHz to 63.9GHz frequency band. The device is built with TI's low-power 45nm RF complementary metal-oxide semiconductor (CMOS) process and enables unprecedented levels of integration in an extremely small form factor. The device has three receivers and two transmitters with binary phase modulation for MIMO radar, TX beamforming applications as well as programmable transmitter power back off support.

The single-chip radar transceiver comes with an integrated Arm® Cortex® M4F at 160MHz, an ARM Cortex M3F at 80MHz and a Radar Hardware Accelerator (HWA) at 80MHz for radar processing. The device supports intermediate frequency (IF) bandwidths up to 5MHz.

The IWRL6432W is designed for low-power, self-monitored, ultra-accurate radar systems in the industrial (and personal electronics) space for applications such as building or factory automation, commercial or residential security, personal electronics, presence or motion detection, and gesture detection or recognition for human machine interfaces (HMI).

2.3.2 Crystal

The Diodes Incorporated® FW4000044Q quartz crystal ceramic surface mount device is used as the 40MHz clock source. The crystal has a ±10ppm frequency tolerance, load capacitance of 8pF and ESR of 50Ω.

2.3.3 TPS6285020M – 1.8V DC/DC Regulator

The TPS6285020M is TI's 2A (continuous), high efficiency, synchronous step-down, fixed 1.8V output DC/DC converter which is used in this reference design to supply the 1.8V rail.

The peak current requirement from the 1.8V rail of the device needs to be met. See also the *peak current requirement per voltage rail* section in the IWRL6432 WCSP Single-Chip 57 to 64GHz Industrial Radar Sensor data sheet, for additional details. Along with the current requirement, the DC/DC regulator needs to have *forced PWM mode* (or auto mode of switching) and *spread spectrum clocking (SSC)* features.

Note

If overall system power consumption needs to be optimized in device's deep sleep conditions where typically light load conditions are followed, auto mode of switching can be enabled. In this mode, depending on light load conditions PFM mode of switching is enabled to reduce power consumption of the DC regulator. Auto mode and forced PWM switching mode can be altered using the MODE pin of the DC regulator. The MODE pin of the DC/DC regulator can be controlled by the device through a GPIO in a way that the DC/DC regulator switches between auto mode and forced PWM mode depending on the deep sleep entry and exit of the device. See also *Enabling PFM Mode for DCDC Converter*.

2.3.4 QSPI Flash Memory

The reference design uses the Macronix® MX25R1635FZUIH0 device; a low-cost and low-power 16Mbit flash memory. The flash supports a wide range of input voltage of 1.65V to 3.6V to support both of the 3.3V and 1.8V IO voltages of the device.

Because the device works in 1.8V single-rail power topology in this reference design, the Macronix® MX25U1632FZUI02, operating in 1.65V to 2.0V can also be used.

Note

See the *Flash Variants Supported by the mmWave Sensor* application report for the flash-variant compatibility.

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3 System Design Theory

3.1 Antenna

The reference design uses a single-element patch antenna for the three receiver and two transmitter antennas. The reference design has one TX antenna placed λ/2 below the other TX antenna in the elevation plane and 2 × λ/2 apart in the azimuth plane. All the RX antennas are kept in the same plane with λ/2 distance between RX1 and RX2 and RX2 and RX3.

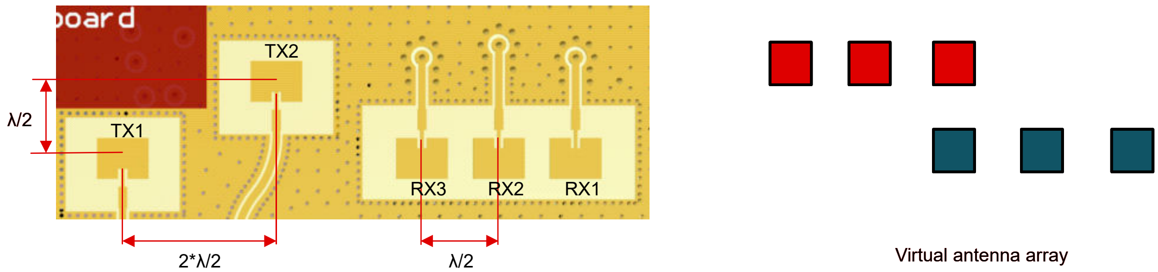

Figure 3-1. Virtual Antenna Array

To save the overall space, the FR4-based antenna is located on the opposite side (backside) of the PCB from the IWRL6432W chip

The RX antennas are upside down compared to the TX antennas. Therefore, the virtual antenna array is also turned upside down after deriving the location of the virtual antennas in the given position.

Corresponding antenna geometry CLI command is:

antGeometryCfg 1 2 1 1 1 0 0 4 0 3 0 2 2.5 2.5

Note

1. This command line is necessary to add within any configuration, before sending the same to device, otherwise the angle of arrival calculated by the processing chain can be erroneous.
2. See the MMWAVE-L-SDK documentation (tuning guide) for more details about this CLI command.

Figure 3-2 depicts the antenna gain plot for different frequencies across azimuth and elevation angles.

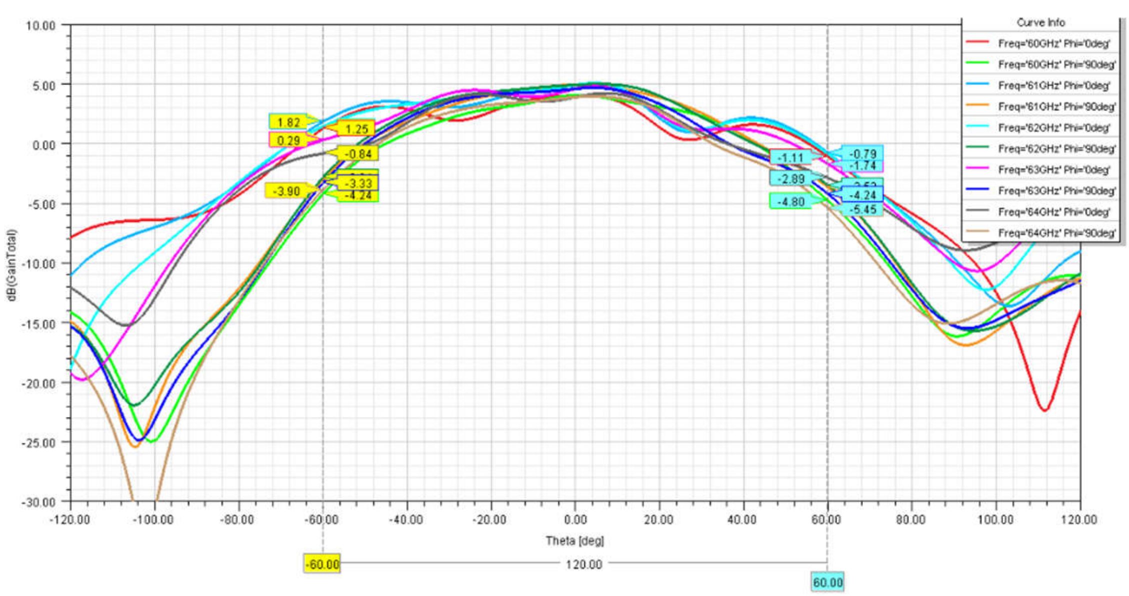

Figure 3-2. Antenna Gain Plot

3.1.1 Range and Phase Compensation

The range bias and phase error needs to be compensated for different antenna designs using the compRangeBiasAndRxChanPhase command. There are default values incorporated in the demonstration configurations present in the MMWAVE-L-SDK (version 5.5.3.0 and above).

If the antennas are flipped, the range bias and phase compensation API needs to be used to correct the phase. The procedure for this is explained in the MMWAVE-L-SDK.

Note

The range bias and phase compensation is necessary to be done after manufacturing; otherwise, the range and angle of arrival calculated by the processing chain can be erroneous.

3.1.2 Chirp Configuration

The chirp properties can be altered depending on the application requirement using the different commands in the configuration file. A few determining factors for a particular chirp profile are: maximum detection distance requirement, power consumption, and performance. For more information on chirp configuration, see the *Programming Chirp Parameters in TI Radar Devices* and *MIMO Radar* application reports.

3.2 PCB

The reference design uses a four-layer stack-up for the PCB. The antenna resides on the bottom layer (Lyr 4) of the PCB. The top layer along with the bottom layer has FR408HR dielectric material. Because both the layers contribute in the grounded coplanar waveguide (GCPW) transmission lines, the stack-up, especially the dielectric for both of these layers is critical for good antenna performance. The following are a few critical properties of the dielectric for both of these layers:

1. The dielectric has 2 × 1067 (dual ply) spread glass construction
2. The thickness of the dielectric is 5mils (127µm), this thickness value is adjusted for impedance matching
3. The Dk value of the dielectric is 3.3 at 60GHz
4. This is core material

Note

- The dielectric thickness must not be altered because this can cause impedance mismatch and more reflection of the radiated power.
- Prepreg material must not be used for the antenna layers.

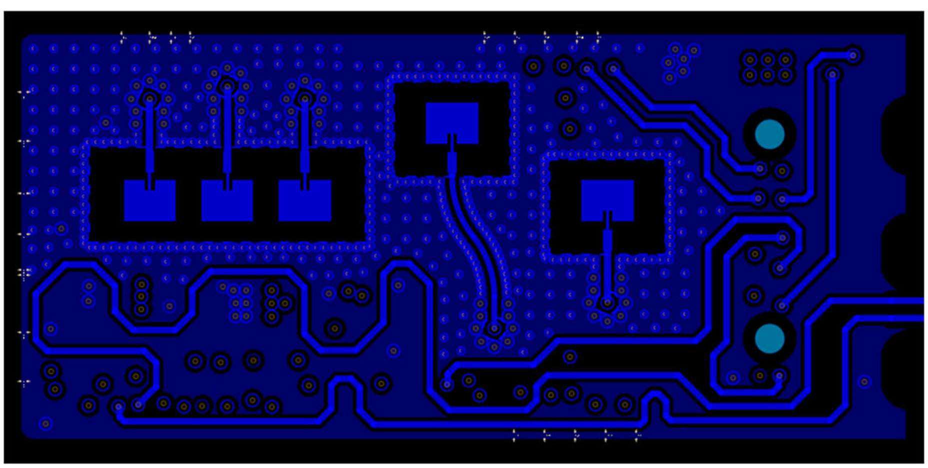

Figure 3-3. Antenna on the Bottom Layer

Grounded coplanar waveguide (GCPW) transmission lines are used to carry the RF signals to the antenna. Following are some critical considerations for the antenna layer and the ground layer followed by the antenna layer:

1. Finished copper thickness on the antenna layer is 40µm
2. Ground plane (below the antenna plane, Layer 2) thickness is 1oz (0.5oz can also be used if 1oz is not available).
3. The copper is very low profile (VLP) or better for reduced surface roughness
4. PCB surface finish is OSP or immersion silver

Note

Electroless Nickel Immersion Gold (ENIG) surface finish is *not* recommended because this can potentially cause higher insertion losses for the mmWave frequency range.

The overall PCB thickness of the reference design is 1.17mm.

Figure 3-4 shows the stack-up details.

STACKUP REPORT

Part Number: IWRL6432W EVM & MODULE
Program: N/A

Target Thickness: 47.000 (± 10%) Over mask on plated copper
Total Thickness: 45.898

Lyr	Lyr Type	Image	Foil Wt	Thk (mil)	Cu Thk (mil)	Er	Generic Name	Construction	Material Family
tsmp				0.400		3.9			
1 2	Sig Sig		0.5 1	5.000	1.600 1.150	3.18	Core 0.130 mm H/1	2x1067	FR408HR
				5.597		3.24 3.24	1080 1080		FR408HR FR408HR
3 4	Sig Sig		1 1	5.000	1.150 1.150	3.49	Core 0.130 mm 1/1	2116	FR408HR
				3.826		3.03 3.03	106 106		FR408HR FR408HR
5 6	Sig Sig		1 1	5.000	1.150 1.150	3.49	Core 0.130 mm 1/1	2116	FR408HR
				5.574		3.24 3.24	1080 1080		FR408HR FR408HR
7 8	Pln Sig		1 0.5	5.000	1.150 1.600	3.18	Core 0.130 mm H/1	2x1067	FR408HR
bsmp				0.400		3.9			

Figure 3-4. Design Stack-Up

Note

1. Use the TI stack-up as manufactured. If a different stack-up is desired, 3D electromagnetic solvers are recommended and antenna optimization needs to be done.
2. The Er values mentioned in the stack-up are of lower frequency and are not optimized for 60GHz. Also, depending on different types of construction, the value can alter a little.

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4 Hardware, Software, Testing Requirements, and Test Results

4.1 Hardware Requirements

4.1.1 Reference Design

The reference design can be powered up and communicated to the host through USB. The onboard XDS110 debug probe and 60-pin connector for high-speed LVDS are provided for evaluation purposes.

Note

The reference design can also be powered up with a 5V battery through the J7 connector. In that case, the PR1 pin of the power load switch U16 needs to be pulled low to bypass the VBAT_IN to VCC_IN.

4.1.2 Small Form-Factor Reference Design

The small form-factor reference design has a 14-pin connector.

Table 4-1. Small Form-Factor Reference Design Pin Description

PIN NUMBER	PIN NAME	FUNCTIONALITY
1 (J3A)	VCC_5V	5V power supply
2 (J3B)	VCC_5V	5V power supply
3 (J3A)	RS232_TX_1V8	UART B (RS232) TX
4 (J3B)	SPI_MISO_REG_MODE_1V8	SPI MISO signal
5 (J3A)	SPI_CS_I2C_SDA_1V8	SPI chip select, SDA of I2C
6 (J3B)	GPIO2_1V8	GPIO
7 (J3A)	SPI_CLK_I2C_SCL_1V8	SPI clock, SCL of I2C
8 (J3B)	TDO_SOP0_1V8	SOP0 control
9 (J3A)	RS232_RX_1V8	UART B (RS232) RX
10 (J3B)	SPI_MOSI_1V8	SPI MOSO signal
11 (J3A)	HOST_INTR_GPIO_1V8	GPIO
12 (J3B)	RADAR_NRST_1V8	NRESET control pin
13 (J3A)	GND	Ground
14 (J3B)	GND	Ground

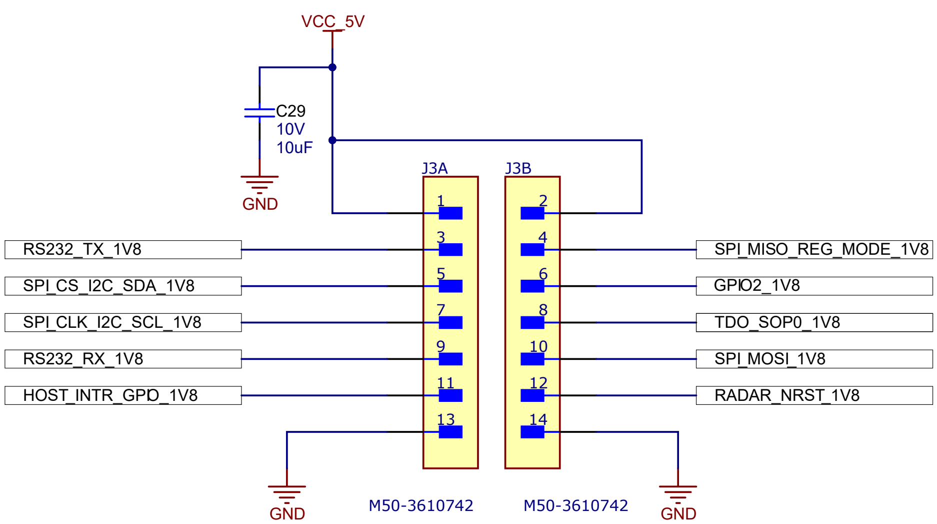

Figure 4-1. Pin Description

The small form-factor reference design takes in 5V power. However, the IO voltage level is 1.8V, because the device operates in a single 1.8V supply. Match the IO voltage on the host side, .

The small form-factor reference design can be connected to host the PC using a LaunchPad™ Development Kit.

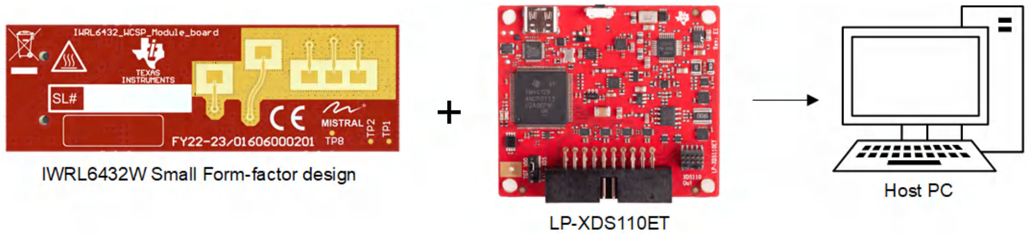

Figure 4-2. Connection to Host PC Options

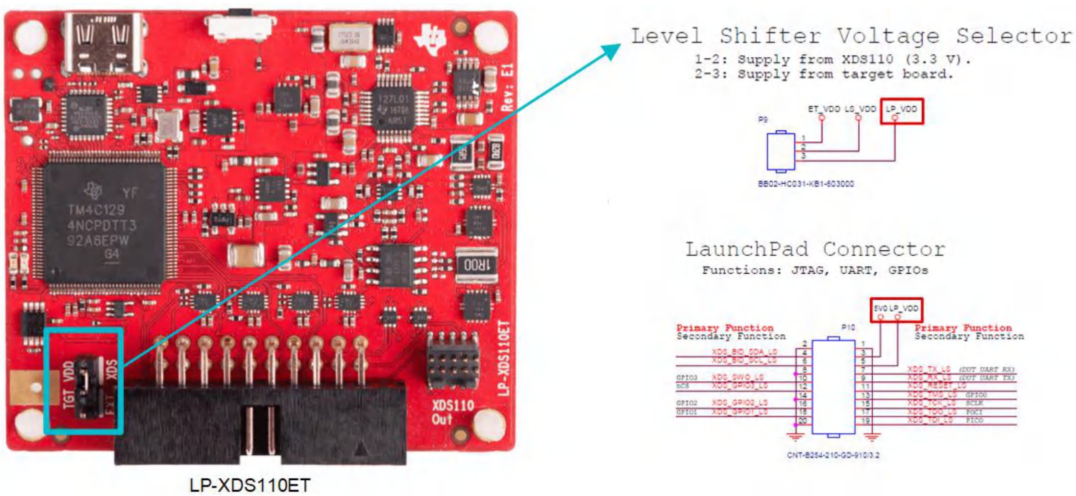

Figure 4-3. LaunchPad™ Development Kit Connection

The LP-XDS110ET LaunchPad development kit can be used to connect the small form-factor reference design to the host PC. Consider the following points for this connection:

1. The reference design can be powered directly by feeding the design with the 5V supply from the LaunchPad development kit.
2. The reference design has 1.8V IO. However, the LaunchPad development kit has a default of 3.3V IO (P9 jumper position 1-2). To modify the LaunchPad development kit IO, position the P9 jumper to 2-3 (see Figure 4-3) to have the IO voltage from the target board.
3. Connect 1.8V (reference design IO voltage) to pin 5 (LP_VDD) of P10 in the LaunchPad development kit to modify the LaunchPad development kit IO voltage to 1.8V.

The small form factor reference design uses 1.27mm pitch pins to reduce the form factor. However, 2.54mm pitch jumpers are needed to connect to most USB-to-UART adapters. Because of this, a pitch converter DR127D254P20F was used to connect with the USB bridges.

Figure 4-4 depicts this connection:

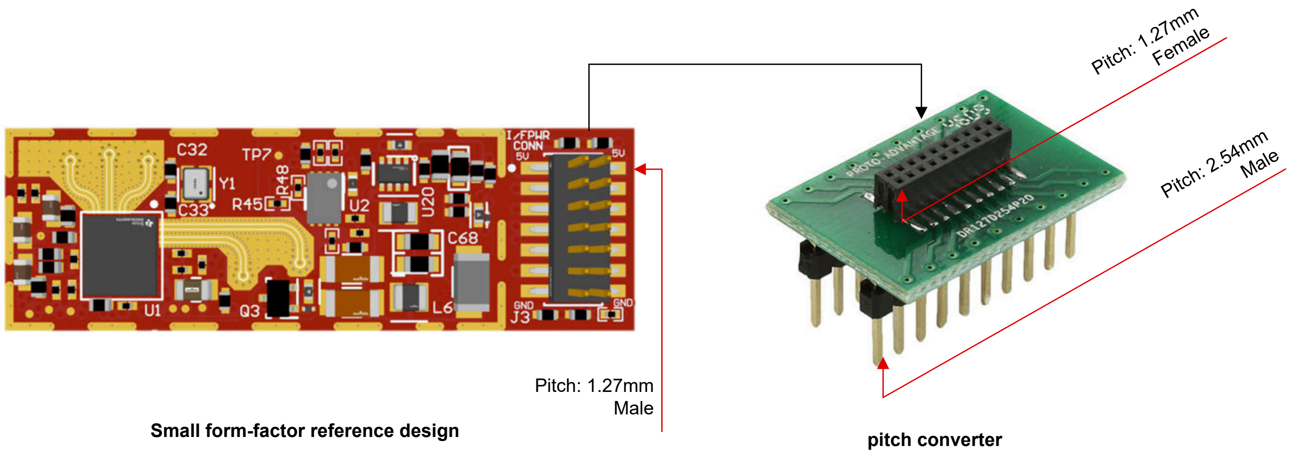

Figure 4-4. Use of Pitch Converter

In this procedure, the reference design is mated to the pitch converter. The 2.54mm pitch male headers from the other side of the pitch converter were used to make the connection. The following list includes a few cautionary items to consider while establishing the connection.

In this connection, jumper wires:

1. Need to support the maximum peak current requirement for the power pins (5V), for example 200mA to 300mA
2. Are of smaller and equal length without introducing large DCR to compromise data transfer speeds to lose information
3. Need to have a small IR drop and inductance to prevent ringing on supply and GND

4.2 Software Requirements

The reference design can be programed using *UniFlash flash programming tool*. MMWAVE-L-SDK5.5.3.0 and above versions have IWRL6432W support. The pedestrian detection testings were performed using the MMWAVE-L-SDK5.5.3.0.

4.3 Test Setup

The sensor was placed in an open space for testing. The detection of human presence at 15m in boresight was captured in this test. Using MATLAB®, TI analyzed the antenna radiation pattern and angle error across the FoV with data collected from the anechoic chamber. The following tests are demonstrated here:

1. Human presence detection at 15m (boresight)
2. Antenna radiation pattern
3. Angle error across FoV

4.4 Test Results

4.4.1 Human Detection at 15 Meters in Boresight

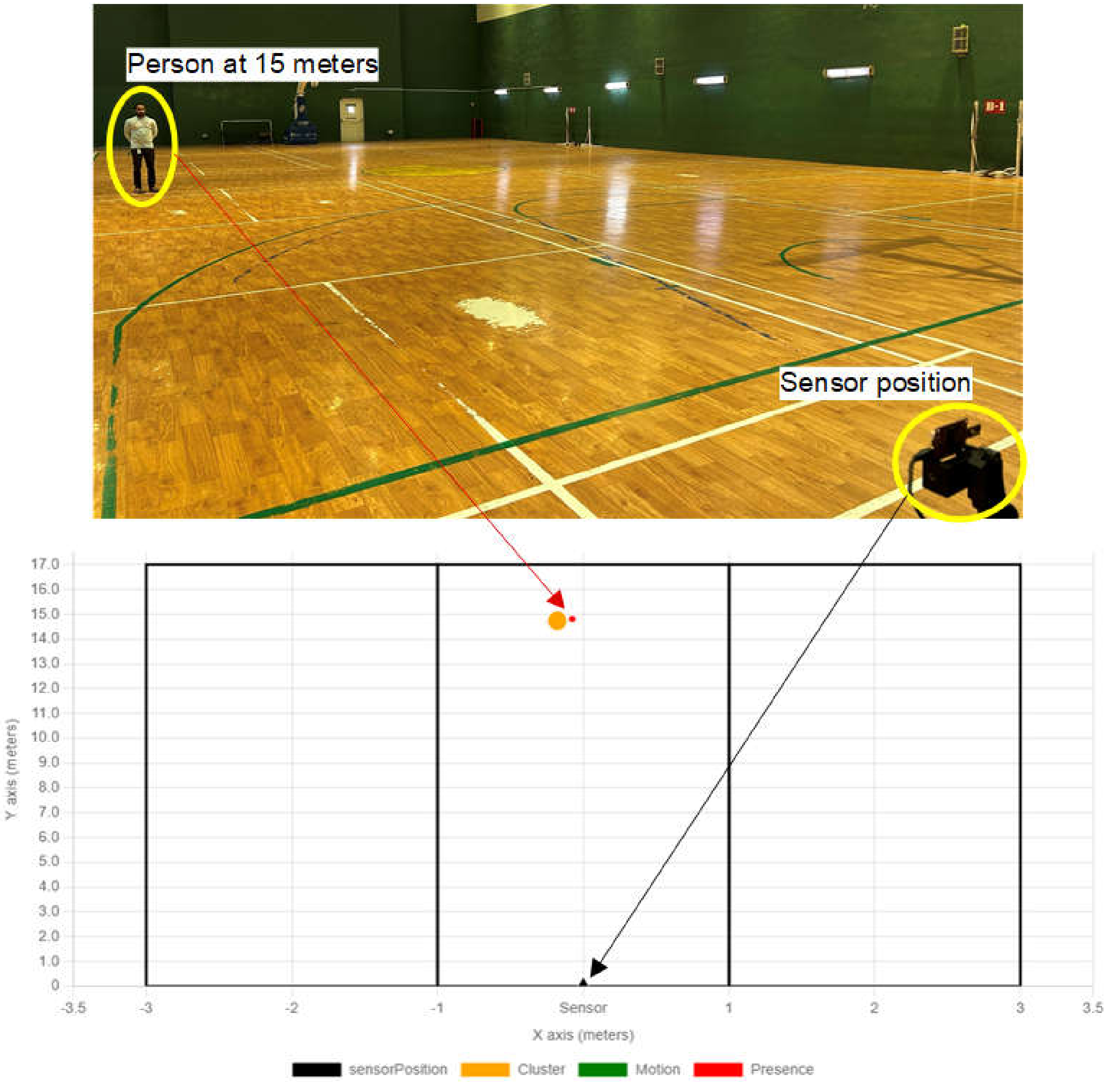

Figure 4-5. Test Result: People Detection at 15 Meters

4.4.2 Antenna Radiation Plots

Antenna radiation pattern and angle error across FoV were processed in MATLAB with the raw data collected from the anechoic chamber.

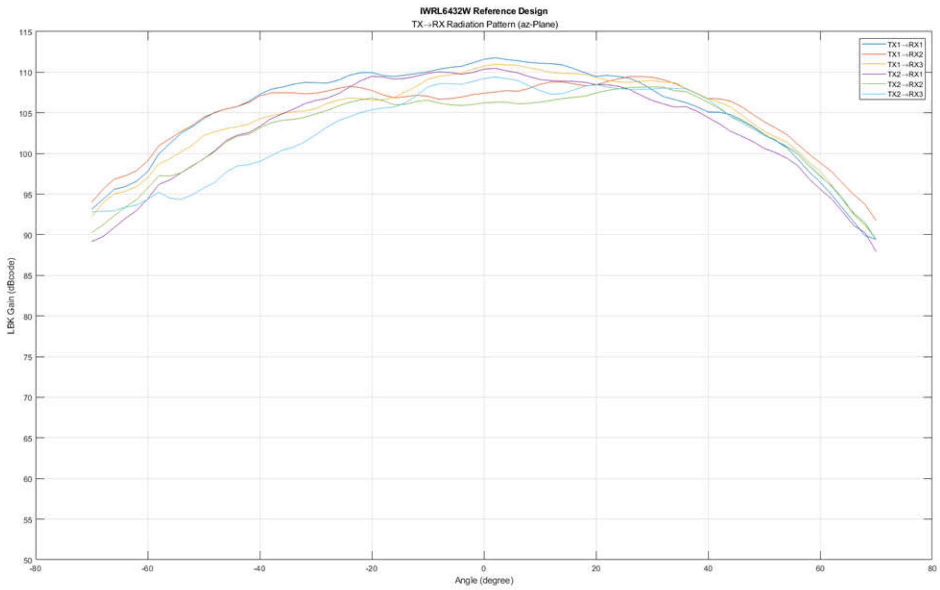

Figure 4-6. Measured Radiation Pattern (Azimuth)

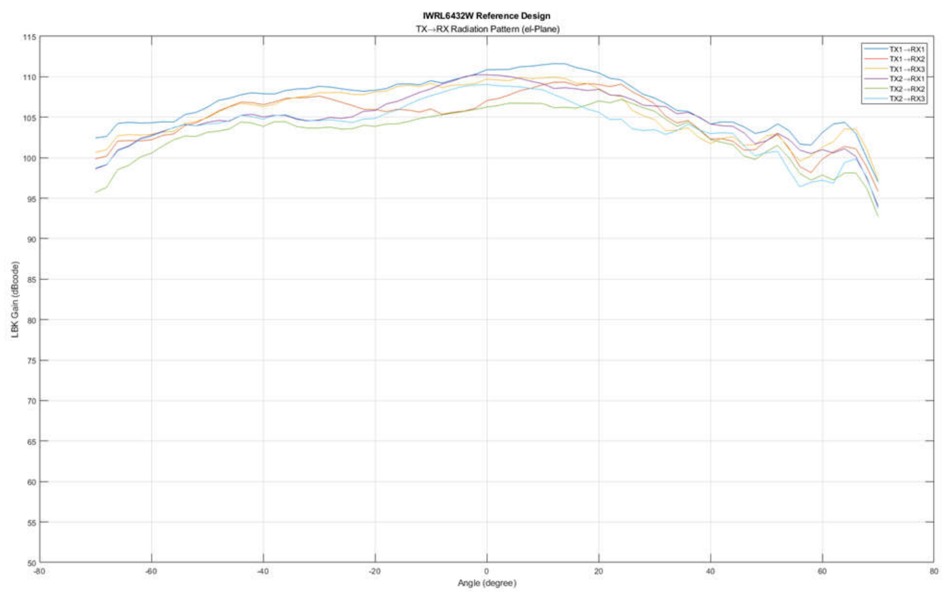

Figure 4-7. Measured Radiation Pattern (Elevation)

4.4.3 Angle Estimation Accuracy

To estimate the angle, boresight phase calibration is done first. This helps reducing the angle estimation error. In the complete FoV sweep, the angle estimation error found is within ±10 degrees.

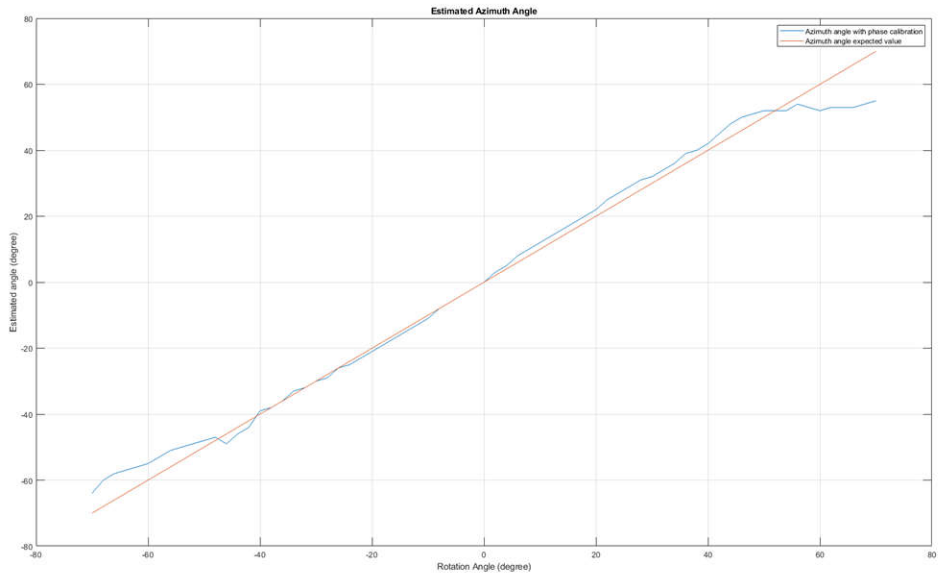

Figure 4-8. Azimuth Angle Estimation

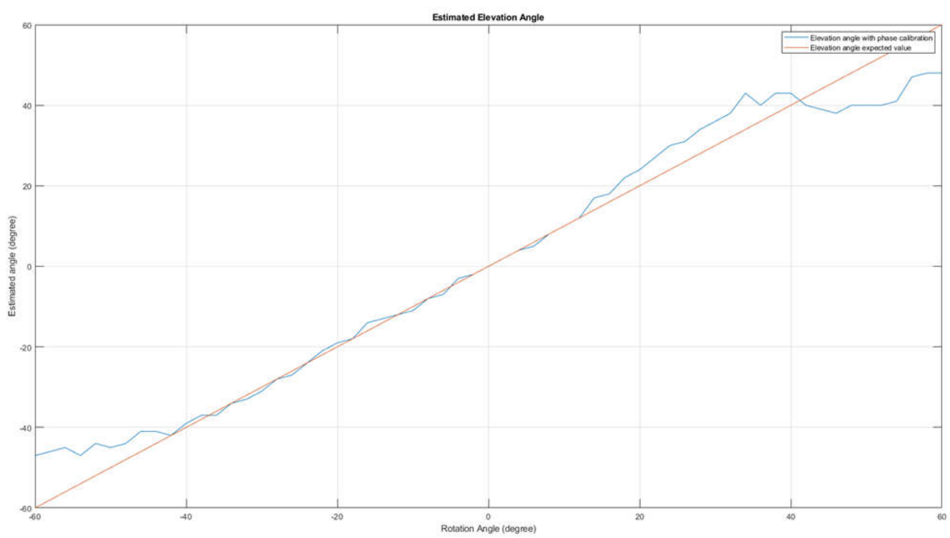

Figure 4-9. Elevation Angle Estimation

5 Design and Documentation Support

5.1 Design Files

5.1.1 Schematics

To download the schematics, see the design files at TIDEP-01040.

5.1.2 BOM

To download the bill of materials (BOM), see the design files at TIDEP-01040.

5.2 Tools and Software

Tools

CCS Studio — Code Composer Studio is an integrated development environment (IDE) for TI's microcontrollers and processors. The tool comprises a suite of tools used to develop and debug embedded applications. Code Composer Studio is available for download across Microsoft® Windows®, Linux®, and macOS® desktops. The tool can also be used in the cloud by visiting the TI Developer Zone.

Software

UniFlash — UniFlash is a software tool for programming on-chip flash on TI microcontrollers and wireless connectivity devices and onboard flash for TI processors. UniFlash provides both graphical and command-line interfaces.

5.3 Documentation Support

1. Texas Instruments, *IWRL6432 WCSP Single-Chip 57- to 64GHz Industrial Radar Sensor Data Sheet*

5.4 Support Resources

TI E2E™ support forums are an engineer's go-to source for fast, verified answers and design help — straight from the experts. Search existing answers or ask your own question to get the quick design help you need.

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SWARNENDU CHATTOPADHYAY is a Hardware Applications Engineer in the Industrial Radar team. Swarnendu has a Master's degree in VLSI Design from the Indian Institute of Engineering Science and Technology. Swarnendu began his career at Texas Instruments in 2023. He develops hardware for mmWave sensors and works closely with customers to help integrate mmWave radar sensors into designs and overcome design challenges seamlessly.

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