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Implementation of MIMO Beamforming on an OTS FMCW Automotive Radar

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Abstract: *Considering the real-time requirements for automotive scenario, a signal processing algorithm is developed using which, processing capability of the Texas Instruments (TI) AWR1642 chipset is presented for the first time as a W-band (77-81 GHz) MIMO-FMCW (multiple-input, multiple-output - frequency modulated continuous waveform) imaging radar with receiver beamforming. Post processing of raw ADC data obtained from the TI chip gives a range resolution of 4.1cm and an angular resolution of* 14.2°*, which are similar to those predicted by theoretical and simulation results in MATLAB.*

1. Introduction

An urban road environment is congested with close targets having different speeds, and radar cross sections (RCS), requiring an advanced radar with real-time sensing capability for precise target detection, tracking and recognition. Forthcoming autonomous vehicles therefore need high range-azimuth-Doppler resolution imaging radars which are low cost in mass manufacturing and have a small form-factor suitable for a proper mounting. Advances in digital technology are helping to solve these problems. Currently, the most advanced approach is to use multiple-input, multiple-output (MIMO) systems which, with $\mathrm{N_{Tx}}$ transmit elements and $\mathrm{N_{Rx}}$ receive elements can create a virtual array of $\mathrm{N_{Virtual}} = \mathrm{N_{Tx}} \cdot \mathrm{N_{Rx}}$ elements to achieve high angular resolution with a reduced number of physical elements [1]. At the same time, MIMO array has a better Doppler resolution in comparison with the scanning array due to longer dwell time. Another modern trend is to use digital beamforming (DBF) techniques at the receiver to narrow the beam towards target direction for precise angular information within the area illuminated by a wide transmit beam [2].

Several semiconductor manufacturers have introduced chipsets for automotive radar development, but there needs to be development of radar algorithms to use the raw information provided by these chipsets. This paper aims to develop an algorithm based on the digital beamforming at receiver side, which is implemented on the raw ADC data collected using an OTS (off-the-shelf) Texas Instruments (TI) AWR1642 chipset, that can form the hardware part of a $2\mathrm{T_x}$ and $4\mathrm{R_x}$ MIMO-FMCW (frequency modulated continuous waveform) radar, which has not been previously presented. The signal processing algorithm for the radar is based on 2D-FFT (fast Fourier transform) [3] and phase shift-and-sum beamformer [4]. The algorithm was initially simulated using MATLAB and later on, applied to the raw ADC data collected using the TI chipset and results were compared with the modelling prediction result.

In the following sections of the paper, first the description of MIMO beamforming, and the Texas Instruments hardware platform is presented, followed by the simulation, experimental setup and discussion of results along with an analysis of algorithm's real-time computational requirements.

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2. MIMO Beamforming Algorithm

To develop the signal processing algorithm, a uniform linear array (ULA) of 2 transmit elements with 2λ spacing, and 4 receive elements with $\lambda/2$ spacing as shown in Fig. 1a is considered. This combination of thin/ full array gives the two-way virtual array element spacing of $\lambda/2$. The phase difference between virtual array elements is given in Fig. 1b.

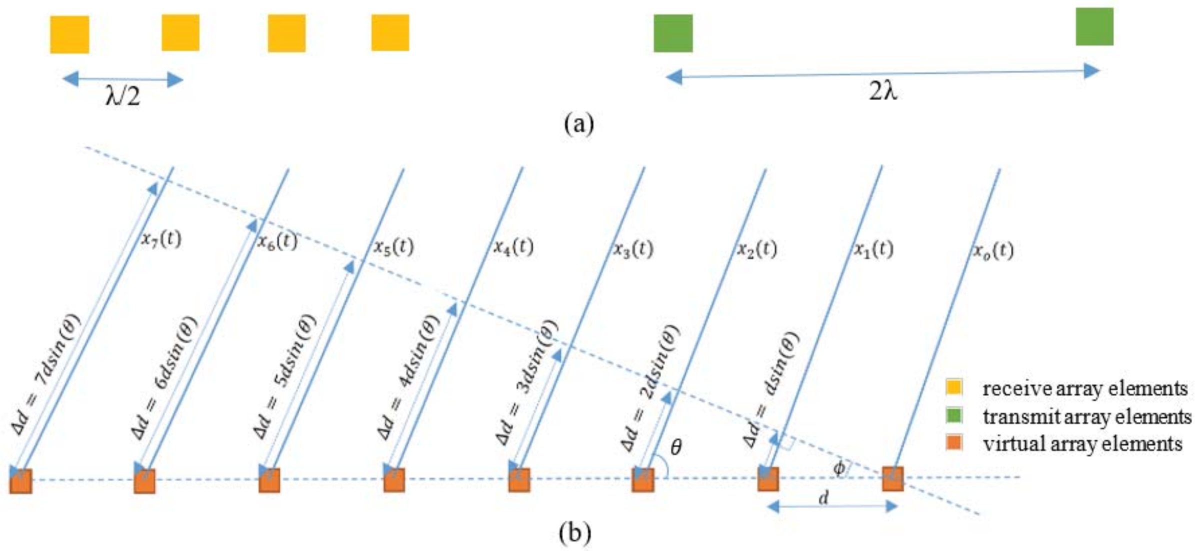
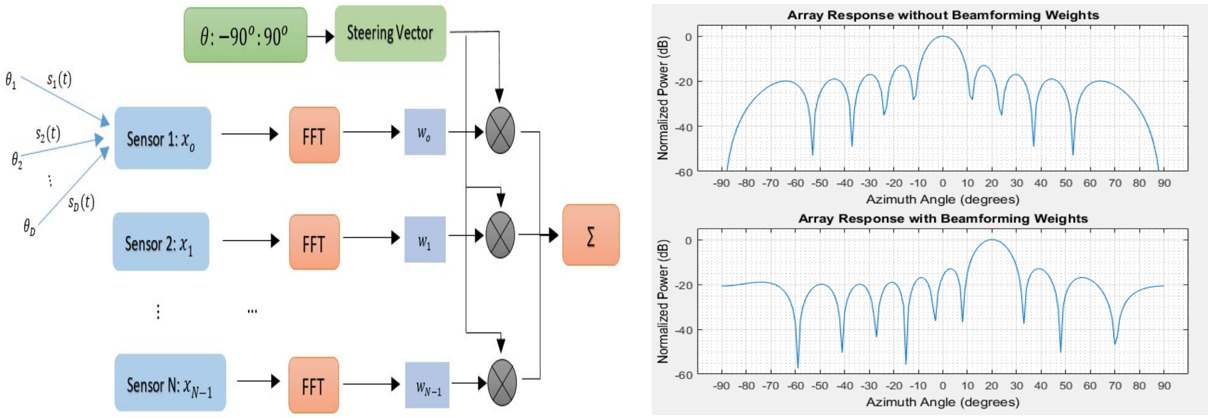


Figure 1. Array elements arrangement. (a) Spacing between the transmit and receive antenna elements (b) Phase difference between the virtual array elements formed by MIMO array.

Angular resolution (θ_{res}) of the beam is $\lambda/ND\cos(\theta)$ where, λ is the signal wavelength, N is the number of MIMO virtual array elements, which in this case is 8 elements, D is the virtual element spacing, and θ is the angle of arrival. With D= $\lambda/2$, and $\theta = 0^{\circ}$ (broadside beam), a beam width of 14° that is recommended for some short range automotive applications [5] is achieved with a virtual array of 8 elements formed from 6 physical elements, under the electromagnetic far field assumption.

An FFT based algorithm is developed in MATLAB where, first-FFT along each sweep gives the spectrum of beat signal to estimate range and second-FFT along the receiving channel gives the angular spectrum for each range to generate an azimuth-range plot. Azimuth angle is estimated from the signals' relative time delay between array elements which becomes a phase shift upon conversion to the frequency domain. Beamforming, which spatially filters the narrowband received signals by applying appropriate phase weights to array elements in order to steer the beam towards target(s) is implemented using a classical FFT based beamformer. This gives the target's azimuth with a wide angular resolution ($\approx 2/N$ radians) but with less computational load on the processor [6]. Angular information within this wide transmit beam is obtained by performing the conventional phase-shift receiver beamforming.

As demonstrated in Fig. 2a, each sensor collects signals from all directions followed by an FFT. These signals have different times of arrival at each array element. After down-conversion, a phase-shift beamformer compensates for these delays by applying a reverse delay to each sensor which steers the beam across desired direction. This delay is implemented by multiplication with a weight $W_i = e^{j\theta_i}$ so that the wave fronts arriving from target are aligned and then summed. The signal of each channel is then correlated with the ideal steering response for a wanted direction that is between -90° and 90° azimuth, which is the ideal field of view of radar. After summing up the signals, the beam is steered towards the wanted direction. Maximum correlated value gives angle of arrival. Output at any time is formed by linearly combining the signal from N sensors. An example of the simulated beamformed response, with and without beam steering towards target at 20° is shown in Fig. 2b.



(a) (b)

Figure 2. Receiver beamforming (a) Simulation steps for MIMO beamforming at receiver side. (b) Beamforming response with and without applying the beamforming weights with target towards 20° .

3. Hardware Platform and Tools

The hardware radar platform uses an AWR1642Boost board which contains the radar chipset. The board has a ULA of 2 transmit antennas, with 7.6mm spacing, and 4 receive antennas, with 1.9mm spacing, similar to the array for which signal processing algorithm was developed. Hardware tool-chain setup to capture raw-ADC data for post-processing consists of either a standalone AWR1642Boost board, or requires a combination of the AWR1642Boost board, mmWave-DevPack and TSW1400EVM, all from TI. TI's mmWave Sensing tool is used to calculate and verify the configuration parameters required to set up the radar.
When a standalone AWR1642Boost board is used to capture raw ADC data, only 768kB of data is stored in its internal L3 memory and transferred to host PC over the UART (universal asynchronous receiver-transmitter) interface. After setting up the configuration file in TI's Code Composer Studio (CCS) software and loading the firmware in the chipset, configuration parameters can be sent to the chip using either tera term or through a serial port via MATLAB. Once the L3 memory is updated with ADC samples, it is viewed and saved using CCS and post-processed in MATLAB through the developed algorithm. Due to limited L3 memory size (768kB) and UART speed (< 1 Mbps), the method although simple to implement, only saves ADC data for a single frame with chirp + interchirp time > 20us in the memory. Any other configuration parameters requiring greater memory or higher data transfer speed gives a failed configuration error.
Due to failed configurations with CCS, another software tool called Radar studio, which is specifically developed by TI to configure the AWR1642Boost board's frontend from PC, is used in this research to capture the raw ADC data for receiver beamforming. To use this tool the mmWave-DevPack, which provides interface for Radar Studio to configure the sensor, and the TSW1400EVM which collects raw-ADC Data from AWR1642Boost board, are integrated with the TI Boost board. This setup allows for real time data capture for up to 10s which is transferred to the PC over LVDS (low-voltage differential signalling) lines at a high data rate of 600Mbps. Raw ADC data is post processed on a host PC using the signal processing algorithm developed in MATLAB. The solution using Radar Studio is faster, robust, and allows flexibility to set the configuration parameters.

Table 1 shows the process for hardware configuration, raw ADC data capture, and post processing.

Table 1. Hardware setup, raw ADC data capture and beamforming via data post-processing using TI Chipset

No.	Process	Remarks
1	Hardware setup	AWR1642Boost board, mmWave-DevPack, and TSW1400EVM connected together
2	Flashing	AWR1642Boost board flashed using Uniflash
3	Firmware	Firmware loaded to TSW1400EVM and a 16-bit ADC selected for the processor using either MATLAB commands or HSDC Pro Tool developed by TI
4	Configuration	AWR1642Boost board configured for the TDM MIMO using either Radar Studio, or via MATLAB by establishing a connection between the board and Radar studio through LUA script
5	Raw ADC data	A .bin file is generated as a result of above process which contains the raw ADC data
6	Post Processing	• The .bin file called in MATLAB running on host PC • Raw ADC data samples arranged according to the set configuration parameters • Data post processing using FFT based algorithm in MATLAB
7	MIMO Beamforming	• Beamforming algorithm applied to the raw ADC data • Range and azimuth resolutions calculated and verified with the simulated results

4. Simulation Process

A simulation algorithm was developed for a target at 3m range, 20°azimuth, and 6.8 m^2 RCS, which is the same as the RCS of corner reflector used for the experimentation. To test the capabilities of TI chipset, static targets are considered, and elevation angle is assumed to be 0° which reduces the broadside angle to azimuth angle. Using a TDM-MIMO (time division multiplexing-MIMO) scheme, orthogonal frequency modulated continuous waveforms are transmitted through the transmit elements to form an unfocused transmit beam within an azimuth field of view (FOV) of $\pm 50^{\circ}$ which is the FOV supported by the TI chip. Each transmitter transmits for a chirp duration. At the receiver end, through developed MIMO beamforming algorithm, received signals are weighted and summed according to their angle of arrival to focus the receive beam towards the desired target.
The actual and computed simulation results of the target are shown in Table 2 which are determined from the simulation results given in Fig. 3. The target is identified with approximately 3% error in the range value and 1.1% error in the azimuth value.

Table 2. Actual and Computed parameters of the simulated point target in MATLAB

Actual Range	3m		Actual Azimuth	20°
Computed Range by signal processing algorithm	3.09m		Computed Azimuth by signal processing algorithm	20.22°
Percentage error	3%		Percentage error	1.1%

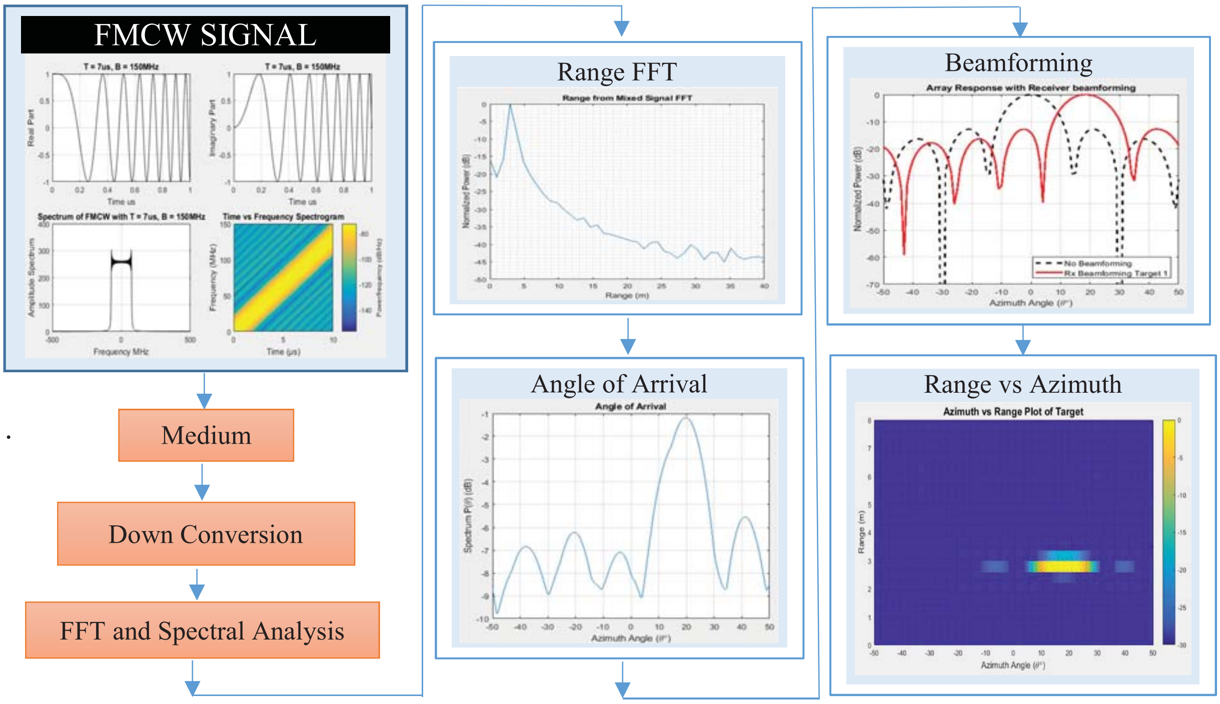


Figure 3. Simulation Results of MIMO-FMCW implementation in MATLAB with receiver beamforming

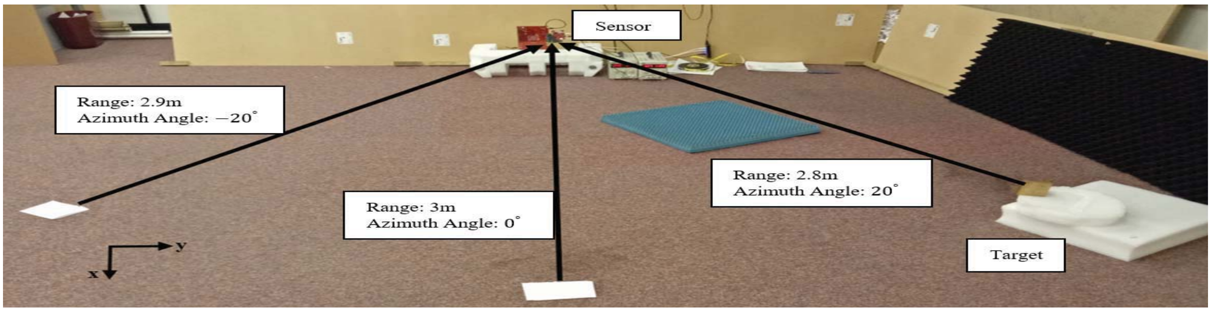
5. Radar Modelling and Experimental Validation

The real time experimentation was performed in a controlled indoor lab as shown in Fig. 4a, with a corner reflector placed approximately 3m from the radar sensor which is well enough in the electromagnetic far field (0.32m) of radar. The radar was configured for ultra short range radar (USRR) and short range radar (SRR) using parameters shown in Table 3.

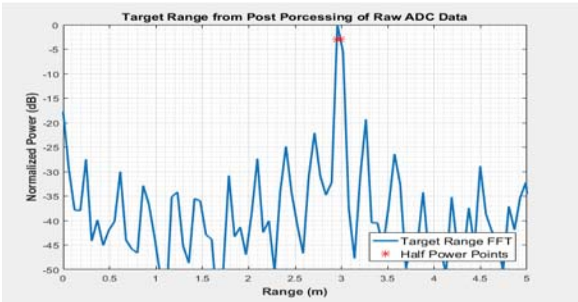
Table 3. USRR and SRR configuration parameters

	Ultra short range Radar (USRR)	**Short range Radar (SRR)**
Maximum Range	$R_{Max} = 3m$	$R_{Max} = 30m$
ADC Samples/ Chirp	4096	128
Sample Rate	2500 ksps	2000 ksps
ADC Sampling Time (ADC Samples per Chirp / Sample Rate)	1.6ms	64us
Slope ($\boldsymbol{\beta}$)	2.3174MHz/us	15.5MHz/us
Bandwidth (**ADC Sampling Time** $*$ $\boldsymbol{\beta}$)	3.7GHz	992MHz
Range Resolution ($\frac{\mathbf{c}}{\mathbf{2B}}$)	4cm	15.1cm

With the TI automotive sensor placed at (0,0,0), ADC samples were collected for three simulation scenarios mentioned in Table 4. As observed from the results in Fig. 4, an accurate estimation of range, and azimuth for the target used in experimentation is achieved. With 3.8GHz bandwidth for USRR application, Fig. 4b-4f shows the results obtained by performing MIMO signal post-processing in MATLAB. Range profile in Fig. 4b, gives the computed range resolution of approximately 4.1cm, which is similar to the one computed by theoretical result given in Table 3. Beamforming results for three scenarios in Fig. 4c-4e verifies the angular resolution to be 14.2° which is again comparable to that computed by theory for a virtual array of 8 elements. Range azimuth heatmap for reflector at 20° is given in Fig. 4f. The color scale is in dB with 0dB giving strongest value and the location of target.



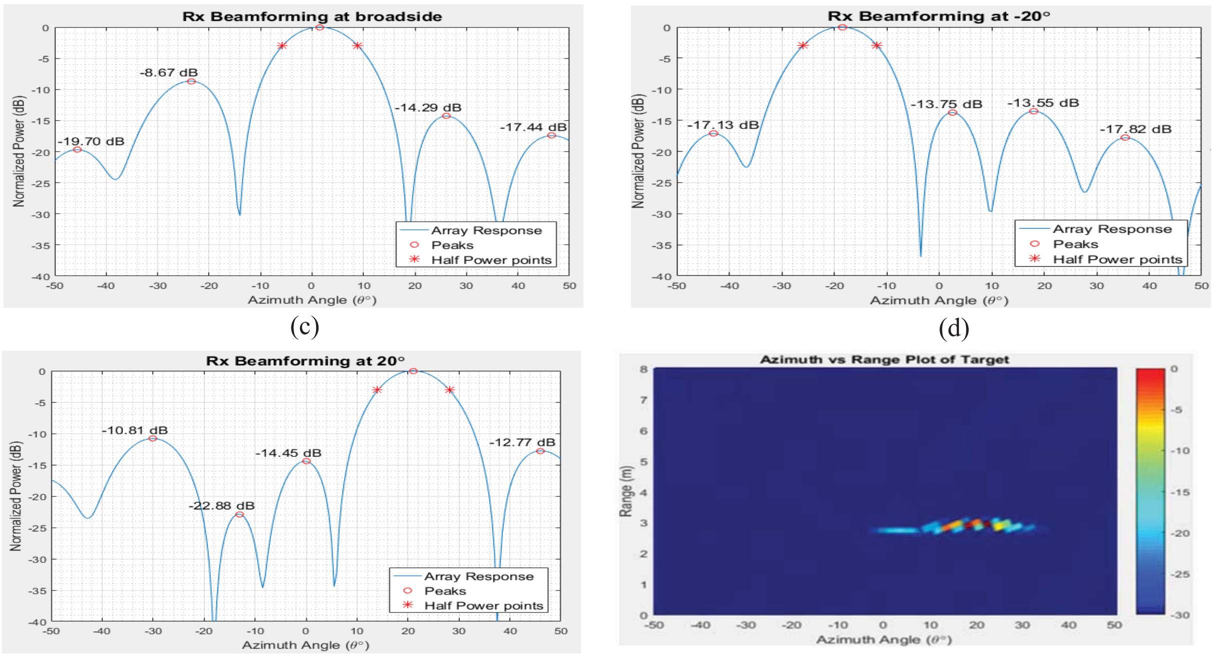
(a)



(b)

Table 4. Real time measurement scenario

Target	Range (m)	Azimuth (θ°)	RCS (m^2)
Scenario 1	3m	Broadside (0°)	6.8
Scenario 2	2.8m	20°	6.8
Scenario 3	2.9m	-20°	6.8



(e) (f)

Figure 4. Experimental setup and beamforming results. (a) Indoor setup for real time raw ADC data capture (b) Range Profile at zero Doppler. (c) Beamforming with corner reflector at broadside (d) Beamforming with corner reflector at -20°. (e) Beamforming with corner reflector at 20°. (f) Azimuth-Range Heat map with corner reflector at 20°.

6. Signal Flow Analysis for real-time Data Processing

For real time signal processing and beamforming, the TI chip needs to have enough computational power to process the consecutive radar chirps without any delays. Detailed signal flow analysis for real time processing of the USRR and SRR signal is discussed in Table 5. Total memory requirement for both applications is greater than the on-chip memory of 1.5MB

RAM in AWR1642 chip. Therefore, real time data processing with beamforming algorithm is not possible, and system is limited to the post-processing of raw-ADC data for beamforming.

Table 5. Signal flow analysis of USRR and SRR using AWR1642Boost board

	USRR	**SRR**
First FFT	4096	128
1st FFT computation time	1.63ms	64us
16-bit ADC used, 10 frames with 20 chirps per frame transmitted, complex output used for configuration		
Memory Requirement	10*20*4096*2*16 = 3276800 bytes	10*20*128*2*16= 102400 bytes
2nd FFT computed for each transmitting antenna has samples from first transmit antenna on 1st row, second transmit antenna on 2nd row, first transmit antenna on 3rd row and so on. Therefore, FFT is performed on samples from rows 1,3,...,19 for the first transmit antenna and 2,4,..,20 for the 2nd transmit antenna. Since the output of FFT is symmetric, it is enough to process the first $N_{1.FFT}/2$ columns [7].		
No. of 2nd FFT computations	2048*2 = 4096	64*2 = 128
2nd FFT	32	32
Total processing time	10*20*1.63ms = 326ms	10*20*64us = 12.8ms
2nd FFT computation time	326ms/4096 = 79.6us	12.8ms/128 = 100us
For each receiving antenna element		
Memory requirement	32*2048*2*16 = 262144bytes	32*64*2*16 = 8192bytes
Memory Requirement: 1 antenna	2*(3276800+262144*2)=7602176 bytes	2*(102400 +8192*2)= 237568 bytes
Memory Requirement $N_{Rx} = 4$	4*7602176 = 30408704 bytes	4*237568 = 950272 bytes
16-bit hex TI style which requires each value to be represented by 2 16-bit words is used.		
Total memory requirement	4*10*20*4096*2*16 = 104MB	4*10*20*128*2*16 = 3.27MB

7. Conclusion

In this paper, a complete cycle of radar development from raw-ADC data acquisition up to target detection with receiver beamforming is presented using the TI AWR1642 chipset. Ultra-wide-band signal gives range resolution of 4.1cm, whereas the MIMO beamforming technique provides 14.2° angular resolution using only 6 physical elements with 3% and 1.1% error in the range and azimuth values respectively. Real time processing with the beamforming algorithm is not possible with the TI chipset. The time required for FFT computation is the main bottleneck of this implementation and at the same time the subject for future work.
DCA1000, a new product launched by TI combines capabilities of both mmWave-DevPack and TSW1400EVM and uses Ethernet interface to transfer data directly to PC's hard disk at faster speed, without any time limitation and can later be integrated with AWR1642Boost board.

Acknowledgement

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