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Target Characterization Using MIMO Radar

Samarendra Nath Sur[1],
Soumyasree Bera[1],
Subhankar Shome[1],
Rabindranath Bera[1]
and Bansibadan Maji[2]

[1]Department of Electronics and Communication Engineering, Sikkim Manipal Institute of Technology, Sikkim Manipal University, Gangtok, 737102, Sikkim, India.

[2]Department of Electronics and Communication Engineering, National Institute of Technology, Durgapur, 713209, West Bengal, India.

E-mail: samar.sur@gmail.com

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Abstract

The exploitation of coherency gain and diversity gain to improve the MIMO system performance is a burning research topic. This paper is to examine the performance analysis of MIMO radar by utilizing the above-said gains. The authors have analyzed the performance of the MIMO radar, in terms of mathematical modeling, considering the probability of detection and post-processing SNR, with respect to changes in the diversity order. Furthermore, this paper also deals with the practical implementation and analysis of the said system, demonstrating the range imaging and RCS pattern of a known standard target.

Keywords
MIMO, Probability of detection, SNR, Radar, SDR.

Multiple input multiple output (MIMO) radar draws the attention of the researchers at the background of MIMO communication. Detection, target characterization and tracking are the basic functions of a radar system. But environmental conditions (multipath, clutter) and a low signal-to-noise ratio (SNR) put lots of challenges among many challenges faced by any radar system (Godrich et al., 2009, 2010; Chiriac and Haimovich, 2010).

In MIMO radar, targets are probed with multiple, simultaneous waveforms, relying on the characteristic of the transmitted waveform, and joint signal processing of the target return signal using multiple receive antennas. MIMO radar utilizes a large number of degrees of freedom to boost the system performance over the conventional radar. MIMO radar systems may have collocated (Li and Stoica, 2007) or distributed (Fishler et al., 2004; Haimovich et al., 2008) antenna configuration. In the studies of Li and Stoica (2007), Guerci et al. (2008), Grossi et al. (2010), Jin et al. (2010), De Maio and Lops (2007), theoretical investigations about the MIMO radar system have been presented. In the studies of Deng (2012) and Li et al. (2017), the use of different orthogonal waveforms for implementing the MIMO radar system showed significant performance improvement in finding the direction of arrival (DOA) and estimation of Doppler shifts. Sammartino et al. (2012) addressed the issue of phase discontinuity in MIMO radar systems both theoretically and practically. The performance of some typical realistic MIMO radar waveforms is evaluated and compared for a co-located MIMO radar configuration in the study of Sun et al. (2016).

Contributions of this study are listed as follows:

1. This paper deals with the development and analysis of the software-defined radio-based (SDR) radar system for the target aspect angle pattern characterization. Aspect angle measurement is one of the important radar parameters considered for target characterization.
2. Authors apply the concept of the spread spectrum for developing the radar system. It is well known that the spread spectrum coded system possesses a low probability of intercept (LPI).

Thus, it will make the radar system more superior. The spread spectrum system requires proper choice of waveform. Hence, the design of proper waveform is being considered and analyzed on the basis of the parameters like range resolution, side lobe level, Doppler resolution, Doppler side lobe level, etc.

3. Furthermore, the development of the distributed MIMO system is considered due to its advantage of improving the resolution of the target detection over other available antenna configuration systems. Here, the signals returned from target are processed coherently, which requires proper phase synchronizing.
4. Then a hybrid spread spectrum with the MIMO architecture radar system is developed and its performance is analyzed on the basis of simulation. In the simulation, the probability of detection and post-processing SNR levels of the signals have been analyzed and compared with respect to the change in the number of antennas.
5. The developed radar system is then implemented on both single antenna-based stand-alone instrumentation system and multi antenna-based SDR platform. The testing is done over the open range so as to reflect the system performance under jamming and fading channel condition. The system's performance is analyzed on the basis of target characterization (i.e. aspect angle pattern) of a known standard target like flat plate.

The rest of the paper is organized as follows. Section "Mathematical model" represents a mathematical analysis of the probability of detection and post-processing SNR for MIMO radar. Section "Simulation results" represents the simulated results, which include the comparison of the probability of detection and post-processing SNR for MIMO radar with the change in transmitter and receiver antennas. The next section "Hardware results" produces the hardware implementation of the single input single output (SISO) radar system and MIMO radar. Section "Conclusion" concludes the paper.

Mathematical model

Let us consider the radar detection problem at the delay τ as follows (Levanon, 1998; Eran Fishler et al., 2006):

- H_0: Fall detection.
- H_1: Target detected.

Based on the Neyman–Pearson sense, the optimal detector likelihood ratio test (LRT) can be given as (Trees, 1968) follows:

$$T = \log \frac{f\left(r\left(t\right)\middle|H_1\right)}{f\left(r\left(t\right)\middle|H_0\right)} \begin{matrix} < H_1 \\ > H_0 \end{matrix} \delta_{th}, \tag{1}$$

where $f(r(t)|H_0)$ and $f(r(t)|H_1)$ are the probability density function of observation corresponding to the radar detection hypotheses and δ_{th} is a threshold, which is governed by the probability of false alarm. Here, the received signal model is represented by $r(t)$.

For the analysis purpose, in this paper we have considered M and N number of transmitter and receiver antennas. Let x be the output of matched filter banks. Then, the optimal detector is given by the following:

$$T = \|x\|^2 \begin{matrix} < H_1 \\ > H_0 \end{matrix} \delta_{th}. \tag{2}$$

Discussion on probability of detection

Now for the MIMO system, the distribution of the test statistic (Levanon, 1998; Eran Fishler et al., 2006) can be represented as follows:

$$\|x\|^2 \sim \begin{cases} \dfrac{\sigma_n^2}{2} X^2_{(2MN)} & H_0 \\ \left(\dfrac{E}{2M} + \dfrac{\sigma_n^2}{2}\right) X^2_{(2MN)} & H_1 \end{cases}, \tag{3}$$

where $x^2_{(d)}$ denotes a χ^2 random variable having d degrees of freedom, E is the total transmitted energy and σ_n^2 is the noise level per receive element.

The probability of false alarm can be expressed as follows:

$$\begin{aligned} P_{rFA} &= \Pr\left(T > \delta_{th}\middle|H_0\right) \\ &= \Pr\left(\frac{\sigma_n^2}{2} X^2_{2MN} > \delta\right) = \Pr\left(X^2_{2Mn} > \frac{2\delta_{th}}{\sigma_n^2}\right). \end{aligned} \tag{4}$$

The probability of detection is given by the following:

$$\begin{aligned} Pr_D &= \Pr\left(T > \delta_{th}\middle|H_1\right) = Pr\left(\left(\frac{E}{2M} + \frac{\sigma_n^2}{2}\right) X^2_{2MN} > \delta_{th}\right) \\ &= 1 - F_{X^2_{2M}}\left(\frac{2\delta_{th}}{\frac{E}{M} + \sigma_n^2}\right) = 1 - F_{X^2_{2MN}}\left(\frac{\sigma_n^2}{\frac{E}{M} + \sigma_n^2} F^{-1}_{X^2_{2MN}}\left(1 - Pr_{FA}\right)\right). \end{aligned} \tag{5}$$

Discussion on output SNR

As in the study of Trees (1968), the detector's output SNR (β) is defined as follows:

$$\beta = \frac{\left|E\left(T|H_0\right) - E\left(T|H_1\right)\right|^2}{\frac{1}{2}\left[Var\left(T|H_0\right) + Var\left(T|H_1\right)\right]}. \quad (6)$$

For MIMO radar, $(T/H_0) = NM(\sigma_n)^2$ and:

$$E\left(T/H_1\right) = MN\left(\sigma_n^2 + \frac{E}{M}\right) = MN\sigma_n^2 + EN.$$

And also:

$$Var\left(T/H_0\right) = MN\left(\sigma_n^2\right)^2 = NM\sigma_n^4$$

and:

$$\begin{aligned} Var\left(T/H_1\right) &= MN\left\{\left(\sigma_n^2 + \frac{E}{M}\right)^2\right\} \\ &= MN\left(\sigma_n^4 + \frac{E^2}{M^2} + 2.\sigma_n^2\frac{E}{M}\right). \end{aligned} \quad (7)$$

Therefore, using Equation (5), the output SNR level can be calculated as follows:

$$\begin{aligned} \beta_{MIMO} &= \frac{\left|E\left(T/H_0\right) - E\left(T/H_1\right)\right|^2}{\frac{1}{2}\left[Var\left(T/H_0\right) + Var\left(T/H_1\right)\right]} \\ &= \frac{(EN)^2}{\frac{1}{2}\left[2MN\sigma_n^4 + \left(E^2/M^2\right) + 2\left(\sigma_n^2 E/M\right)\right]}, \\ &= \frac{\rho^2 N}{M\left(1 + \left(\rho^2/2M^2\right) + \left(\rho/M\right)\right)} \end{aligned} \quad (8)$$

where the SNR is denoted by ρ as the ratio between the total transmitted energy and the noise level per receive element and can be defined as $\rho = E/\sigma_n^2$.

Simulation results

In this section, we consider different configurations of the MIMO system to analyze the system performance. All the simulation results have been done using MATLAB software. Here, the probability of the detection (P_d) and the output signal SNR after the MIMO signal processing have been studied.

Figures 1 and 2 show the performance of a MIMO radar with the change in the number of antennas in the transmitter and receiver section. As shown in the figure, there is an improvement in the radar performance with the increase in the number of the antennas. To simulate the result of Figure 1, the authors have taken the probability of false alarm (Pfa) = 10e−6. For quantitatively analyzing the result as in Figure 1, let us consider that the required SNR for the SISO system is 18 dB. Similarly, the required SNR for the MIMO system having configuration 2 × 2, 4 × 4x, 8 × 8 is 12.3 dB, 9.8 dB, 8 dB, respectively. This indicates the tremendous performance improvement due to the increase in the number of antennas. The same is true for the post-processing SNR for the MIMO system as indicated in Figure 2.

Therefore, from these two numerical results, one can conclude that diversity order plays an important role in enhancing the performance of a MIMO system. MIMO radar exploits the target angular spread to combat target fading. MIMO radar observes a different aspect of the target, enabling the MIMO

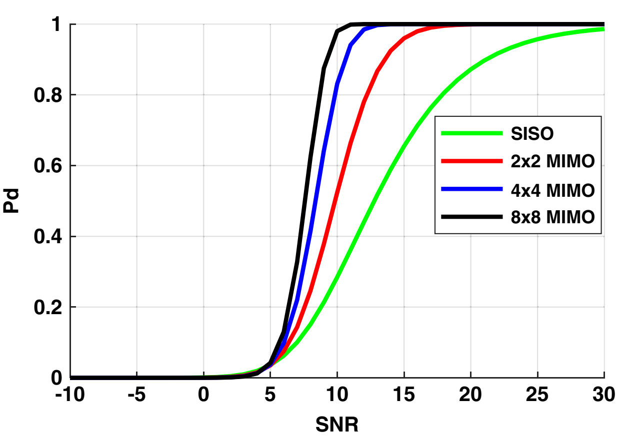

Figure 1: MIMO radar probability of detection variations with respect to the antenna variation.

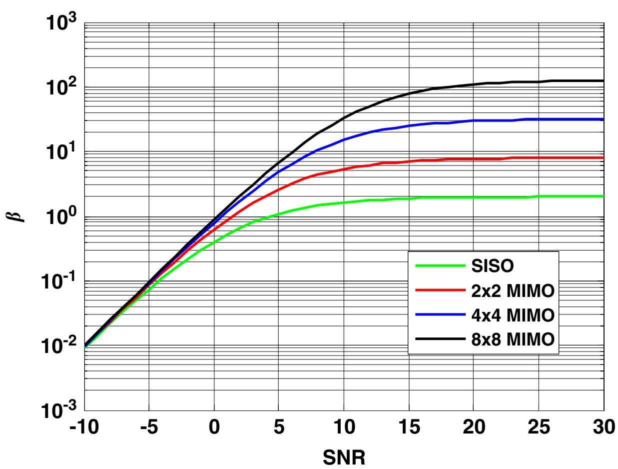

Figure 2: MIMO radar output SNR variations with respect to the antenna variation.

radar to exploit spatial diversity to overcome target fading. The diversity order is directly proportional to the number of the antennas and the same is visible here in the results.

It is reasonable to point out that although MIMO radar offers many advantages, but from the point of view of the implementation, MIMO radar is considerably more complex and costly than the monostatic radar. Therefore, this puts some limitations on the number of antennas that can be used.

Hardware results

The authors have taken the double-folded approach for the development of the radar setup. First, the authors have taken stand-alone hardware such as arbitrary waveform generator (AWG), vector signal analyzer (VSA) for the design of the transmitter and receiver section. And the vector signal generator (VSG) is used as RF frequency generator. Second, after parameter finalization through the rigorous experimentation, the total system has been realized in the miniaturized version using the SDR platform with multiple antennas.

Single antenna-based radar development

In the stand-alone approach as in Figure 3, as the baseband signal generator, AWG has been used to generate P4 coded signal with 5 MHz bandwidth. The authors have used 70 MHz as the IF frequency. The VSA used in this experiment has 14 bits resolution and it can support the maximum sampling rate up to 250 MHz. Now higher IF leads to the increased possibilities of the clock jitter. As our system is based on the correlation processing, proper synchronization is very much required, and therefore we cannot afford the clock jitter. However, very low IF makes the system more susceptible to electromagnetic noise. This leads to the choice of IF frequency as 70 MHz. Also, the authors want to have a flexibility of having the baseband signal bandwidth up to 100 MHz and this is one of the reasons for choosing IF frequency as 70 MHz. However, here we have taken a signal bandwidth of 5 MHz only.

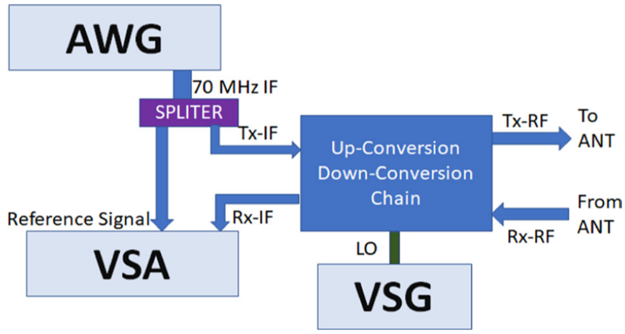

Figure 3: Radar setup with stand-alone instruments.

The baseband signal has the following specifications: No. of bits: 25 bits P4 code; Duty cycle: 35%; Ton = 5 micro sec; Toff = 9.28 micro sec. Then the IF signal is upconverted to the RF frequencies (0.3–3.0 GHz) by using a vector signal generator (VSG) as RF frequency generator. For the transmission and reception, Horn antenna has been used. The target under the test (TUT) is placed on a three-axis rotating pylon. At the receiver side, all the radar signal processing algorithms have been performed in VSA. Here, the authors have used two-channel VSA; one channel is used to take the reference signal and another channel is used for the received signal. In VSA, with the help of the correlation processing between

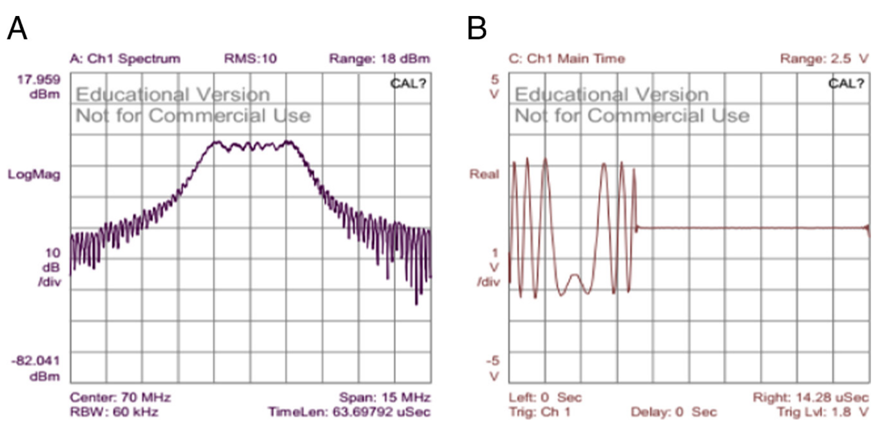

Figure 4: (A) Spectrum of the reference signal at VSA; (B) reference signal at VSA.

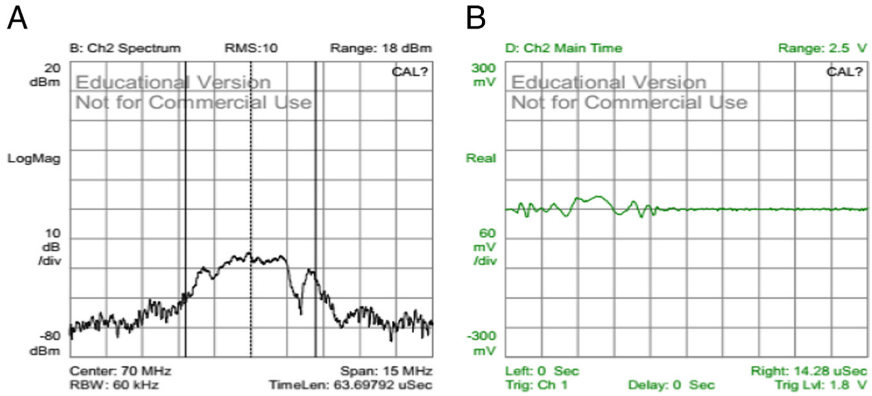

Figure 5: (A) Spectrum of the received signal at VSA; (B) received signal at VSA.

the received and reference signal, the target detection has been carried out. The entire system is designed in LabView platform.

As a part of system validation, initially, only the range imaging has been considered. As we know that the range resolution depends on the signal bandwidth, here, we have considered a swept bandwidth of 1 GHz for having the resolution of 0.15 meter. Now, to have the swept bandwidth of 1 GHz, we have swept the RF frequency from 1.5 GHz to 2.5 GHz. For the experimentation purpose, the target is kept at a distance of 162 meters. The Tx and Rx antenna height is 18 feet and Pylon height is 16.5 feet.

Figures 4 and 5 represent the signals at the VSA end. These received and reference signals are used for the correlation processing for target detection. Figure 4 represents the reference signal taken directly from the AWG. Figure 5 represents the received signal. The multipath effect of the channel is clearly visible in Figure 5 and is also visible in the range imaging as presented in Figure 7.

Figure 6A shows the test bed for radar measurements. As it is clearly shown in the figure, the test bed is surrounded by trees and these are responsible for the unwanted reflection. These reflections produce multipath dispersion over the actual target response. And that puts lots of challenges for the radar designer. Now, with the spread spectrum radar and with swept bandwidth of 1 GHz, a target can be precisely located, and thereby pinpoint characterization of the target is possible under such severe channel condition. To analyze the performance of the radar, a standard flat plate has been used as shown in Figure 6B.

Figure 7 shows the radar performance in terms of range imaging. Here, a single flat plate of dimension

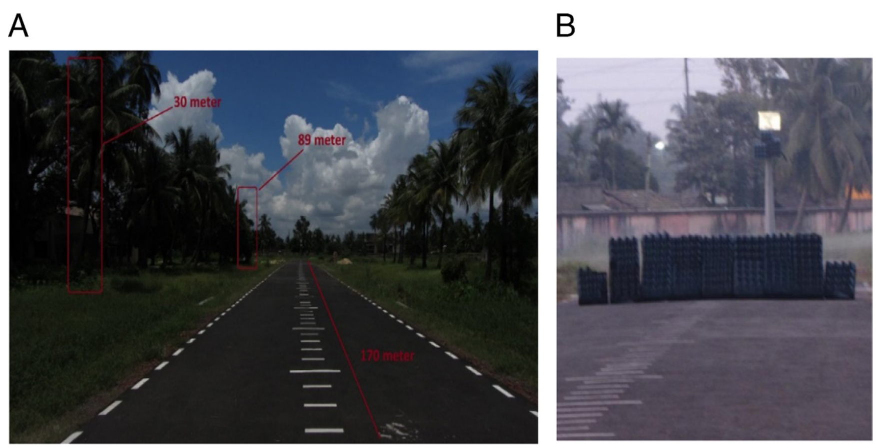

Figure 6: (A) Radar test range; (B) flat plate (target) placed over Pylon.

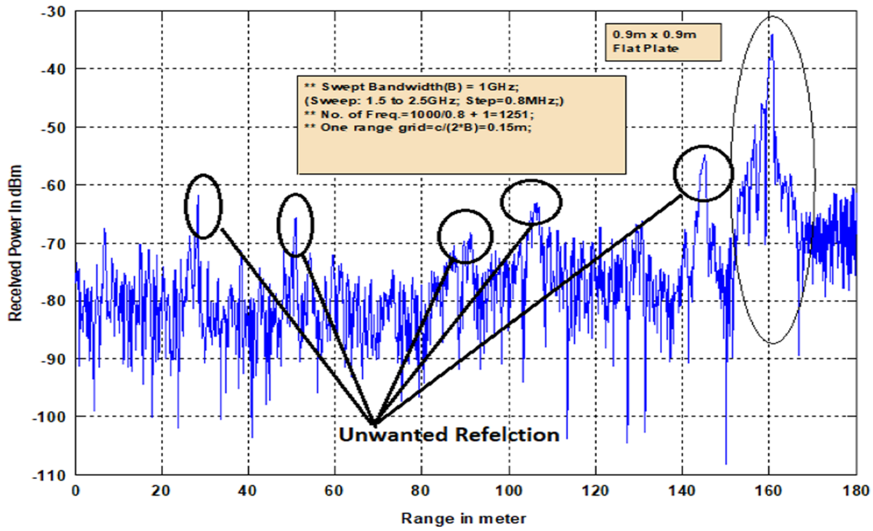

Figure 7: Range measurement.

0.9 m × 0.9 m has been put over the pylon for the detection purpose as shown in Figure 6B. Then the range imaging has been carried over a swept bandwidth of 1 GHz. As shown in the figure, along with the desired target peak, there are some additional peaks throughout the test range, which are due to nearby obstacles such as trees and boundary walls (as in Figure 6). The objective of these experiments is to analyze the detectability performance of the radar system and also accurately point out the target location under severe multipath channel condition. These experiments help us during the characterization of the target through the aspect angle pattern.

As mentioned in the introduction section, MIMO exploits the spatial diversity to combat the channel fading effect, thereby enhancing the system performance. Therefore, as its extension, the authors have implemented the MIMO radar and the performance of the same has been tested in the same open range, as presented in the next section.

MIMO radar development

Here, as reconfigurable hardware, Wireless-Access Research Platform (WARP) SDR is used, which has a Xilinx Xilinx Virtex-6 LX240T FPGA along with 2 Radio daughter Cards. Dual-band RF option (2,400–2,500 MHz, 4,900–5,875 MHz) is available, and 2.4 GHz is selected as the carrier frequency for this radar development. The maximum available RF bandwidth is 40 MHz. Available TX power is 30 dB and the Rx gains' control range is 93 dB. This board can be interfaced with Laptop using a LAN protocol. The baseband P4 code generation, data transmission, data reception and WARP board control code are written in MATLAB. And after receiving the signal, all the receiver signal processing algorithms have been performed in the MATLAB environment (Fig. 8).

Here, the authors have used two SDR platforms in order to design a 2 × 2 MIMO system; one SDR platform has been used to design the transmitter section with two transmitting antennas, and the other one is used to design two channel MIMO radar signal processing. At the receiver side, two signals are coherently added and then passed through the correlation processing for the detection and characterization purpose. A typical radar setup with the SDR kits is shown below. As in the figure, we have used two horn antennas (frequency of operation: 1.7 GHz–2.7 GHz) both at the transmitter and the receiver section (Fig. 9).

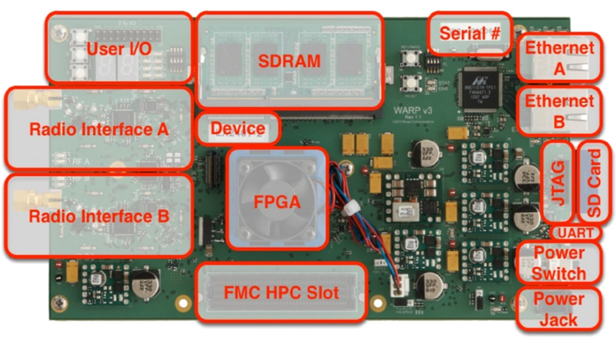

Figure 8: WARP SDR hardware platform (http://warpproject.org/trac/wiki/GettingStarted/WARPv3/Hardware).

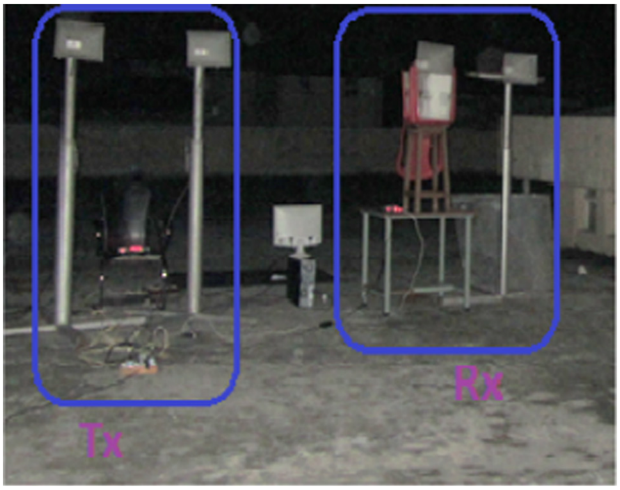

Figure 9: 2 × 2 MIMO radar setup.

Figure 10A, B represents the transmitted and received signal at the transmitter section SDR and the receiver section SDR platform, respectively. It is basically a 25 bits P4 coded signal. After the reception of the reflected signal, it has been passed through the correlation processing for the detection purpose. After the successful detection of the target, the correlation peak values are plotted against the azimuth rotational angle of the target to get the aspect angle pattern of the desired target. The same procedure has been followed to have the result as in Figure 11.

Figure 11 shows the flat plate pattern using 2 × 2 MIMO radar. Here, in this experiment, 0.98 m × 0.68 m flat plate has been used as target. The RF frequency for this experiment is kept fixed at 2.4 GHz. The above figure depicts that the experimental result is able to achieve almost the same main lobe beam width as per the theoretical calculation. This shows almost

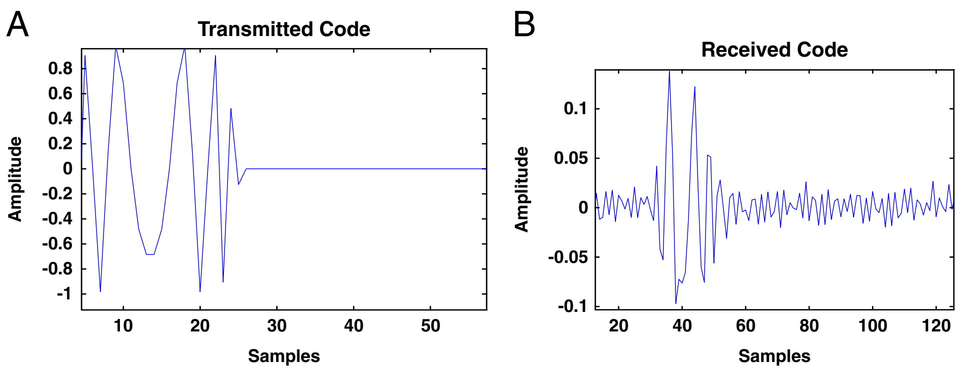

Figure 10: (A) Transmitted signal from SDR platform; (B) received signal at the SDR platform.

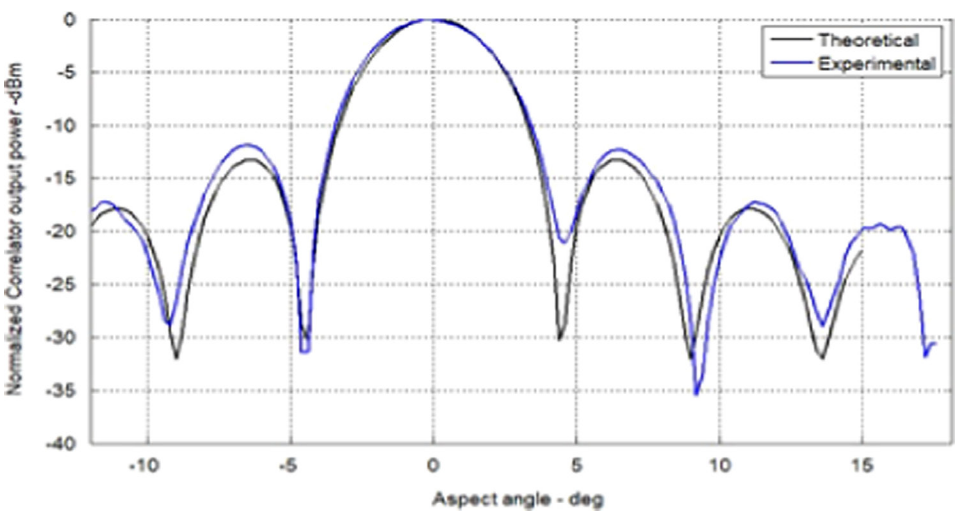

Figure 11: Target characterization using 2 × 2 MIMO radar.

equal performance of the MIMO radar system with respect to the theoretical calculation. One important observation is that there is a slight deviation in null formation in the pattern, which is due to the multipath fading effect. This can be improved if we increase the number of antennas, which is the future work corresponding to this project.

Conclusion

This paper deals with the development of the MIMO radar. As presented here, the diversity order increases with the increase in the number of antennas, and this leads to an increase in the probability of detection and also the post-processing SNR level of the received signal. Therefore, one can conclude that MIMO radar significantly improves radar performance. In order to have an intuitive aspect of the performance of the MIMO radar, the experimental result has been presented in terms of the flat plate pattern, where the experimental pattern is nearly identical to the theoretical pattern.

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