Real-Time Multiple Input Multiple Output (MIMO) Radar Using Software Defined Radio

Robert Gilpin[1,⋆], *Joey* Bray[1], and *Mostafa* Hefnawi[1]

[1] *Royal Military College of Canada, Electrical Engineering Department, Kingston, Ontario, Canada*

Abstract. In this paper, commercially-available software-defined radios (SDRs) are used to build a 64-channel, reconfigurable Active Electronically Scanned Arrays (AESA) radar operating in C-band (NATO G-band). The SDRs are used to design and implement a 3-dimensional multi-input and multi-output (MIMO) radar. The flexibility of the SDRs has been harnessed to evaluate the performance of a linear frequency modulated continuous wave (LFMCW) MIMO radar using three different methods of achieving the orthogonality, namely Time Division Multiplexing (TDM), Frequency Division Multiplexing (FDM), and Code Division Multiplexing (CDM). In addition, the radar's parameters are user-selectable and can be rapidly changed such that the radar can be used in different environments without requiring changes to the hardware. Measurements indicate that the radar is capable of detecting and localizing multiple targets in all 3-dimensions, including bearing, range, and Doppler. The MIMO radar operates in real-time, with a refresh rate of only 3 seconds. Experimental results are generated for the TDM mode of operation with further research reporting on the CDM and FDM modes of operation.

1 Introduction

A modern military radar provides situational awareness to the operator and the larger combat system in real time. The radar must be able to sense the entire environment to detect and track multiple targets. The faster a target can be detected and tracked, the more time the operator has to interpret the target and eliminate a threat, if required. As weapons, particularly missiles, continually increase in speed and improve in accuracy, an operator or anti-missile combat system needs as much time as possible to counter the threat posed [1].

Radars have traditionally consisted of customized equipment that cannot be easily reconfigured or modified. Although improvements to the radiofrequency front-end, such as the adoption of Active Electronically Scanned Arrays (AESA) have provided flexibility to the radar's beamforming, sector scans are often performed using conventional techniques in which a transmit beam is slowly steered through a sector to illuminate targets in a sequential manner, leaving the radar blind to threats when the transmit beam is pointed in other directions. Recent research in the field of communications has revealed a new scanning mode, known as the multiple input, multiple output (MIMO) mode. MIMO can be used by an AESA to illuminate the entire field of view (FOV) of the radar simultaneously, where beamforming is done in post-processing, thus providing uninterrupted situational awareness. However, the MIMO radar mode is more challenging to implement because of the added requirements of orthogonality between its channels, and because of the drastic increase in the required digital signal processing.

In this research, commercially available software-defined radios (SDRs) are used to build a 64-channel, reconfigurable AESA radar operating in C-band (NATO G-band). The SDRs are used to design and implement a 3-dimensional MIMO radar. For the first time, the flexibility of the SDRs have been harnessed to evaluate the performance of three different methods of achieving the orthogonality required for MIMO using a linear frequency modulated continuous waveform (FMCW). In addition, the radar's parameters are user-selectable and can be rapidly changed such that the radar can be used in different environments without requiring changes to the hardware.

This article provides a brief background section on radar basics and the concept of MIMO radar. Following the background, the MIMO radar design will be described. A selection of results is presented to emphasize the importance of MIMO radar research followed by potential areas for further research and a conclusion.

2 Background

2.1 Radar Basics

RAdio Detection And Ranging (RADAR) systems detect targets or objects by sending out high-frequency Electromagnetic (EM) waves that are reflected off the object and that propagate back to the radar to determine range, radial velocity and angle. A diagram showing the elements of a traditional, single source generic radar is shown in Fig. 1. The transmitter generates the radar waveform which

⋆e-mail: Robert.Gilpin@forces.gc.ca

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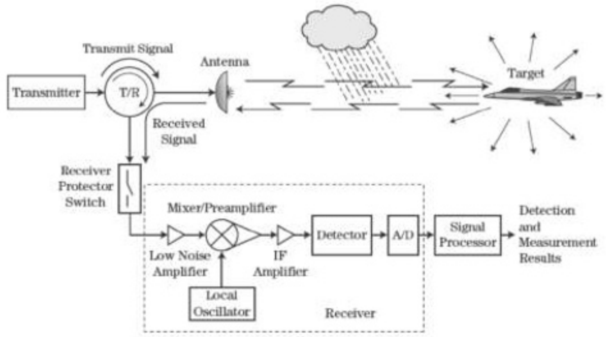

Figure 1. Basic elements of a radar including a target and atmospheric factors [2]

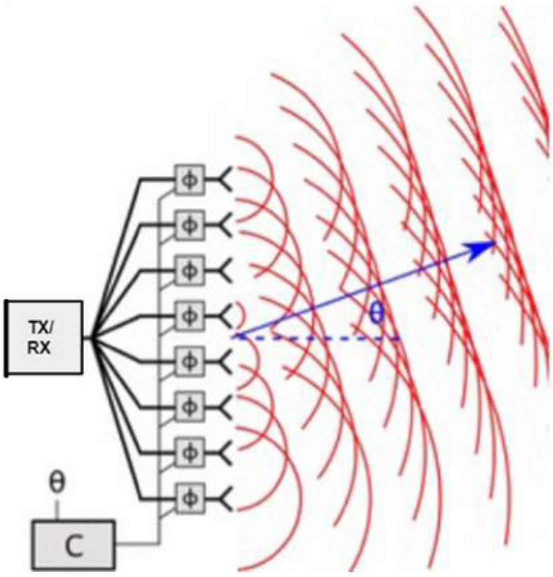

Figure 2. PESA radar architecture showing a single transmitter (TX), phase shifters (ϕ) being controlled by a computer system (C) with a desired transmit angle (θ). The red hemispherical lines show the direction of EM radiation [4]

is sent to the antenna (through a duplexer in some cases) and into free space. The EM wave travels to the target, is reflected and returns to the antenna. The signal from the antenna enters the receiver and is processed to determine the target range, velocity and azimuth [2].

2.2 MIMO Radar

The radar that has gained popularity due to its ability to scan a large FOV is the Phased Array Radar (PAR) [3]. To understand MIMO radar a brief description of PARs is required. First, a Passive Electronically Scanned Array (PESA) will be described followed by an Active Electronically Scanned Array (AESA) and finally a MIMO radar will be described.

Fig. 2 shows a traditional PAR known as a PESA. In the PESA, a single transmitter generates a high-powered signal that is transmitted through individual antenna elements. Each transmit element has an associated computer-

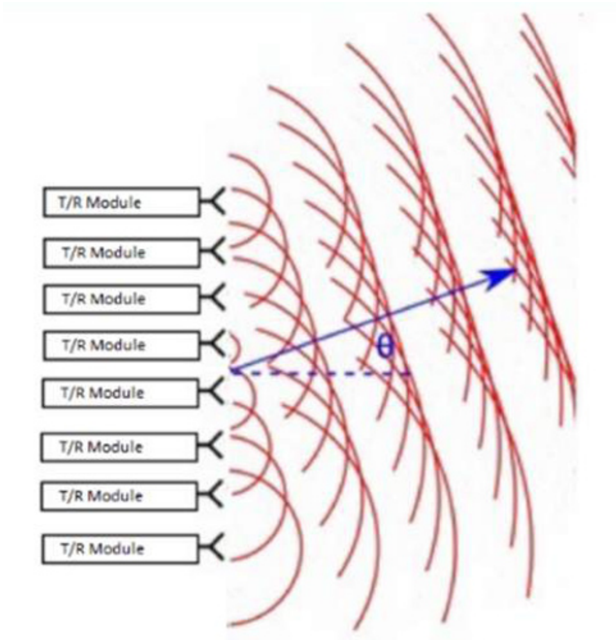

Figure 3. AESA radar architecture showing multiple T/R transmitting at a desired angle (θ). The red hemispherical lines show the direction of EM radiation [4]

controlled phase shifter (ϕ) that creates a directional beam by adding a phase shift to the signal from each element. The narrow beam is sequentially steered through the FOV by changing the phase at each element.

Fig. 3 displays the second generation of phased array radar, the AESA radar. This is the current technology used in modern radars like the AN/SPY family of PARs. Each element of the AESA is a Transmit Receive (TR) module which gives access to element control of the array. The AESA can create multiple beams using sub arrays which decreases the scan time of radar and allows the AESA to perform multiple functions at once, i.e. track while scan with multiple beams. Multiple beams allow for faster scanning however the radar requires time to scan the entire FOV [3].

Figure 4 shows an extension of the AESA known as MIMO radar. Rather than using sub arrays within the radar to form multiple beams like the AESA, each TR element acts independently, transmitting an orthogonal waveform. The transmit beams are wide, 180 degrees typically, and can illuminate the entire FOV with one sequences of pulses since there is no directivity on transmit, this is sometimes referred to as scan on receive [5].

To take advantage of MIMO technology the receiver must be able to separate the transmitted orthogonal signals on reception. This is done using Time Division Multiplexing (TDM), Frequency Division Multiplexing (FDM), or Code Division Multiplexing (CDM) [6]. For this paper only TDM will be discussed with FDM and CDM measurements happening in future publications.

In TDM each TR module transmits at a specified time interval ensuring the waveforms do not overlap. A figure representing TDM is shown in Fig. 5 with a FMCW chirp

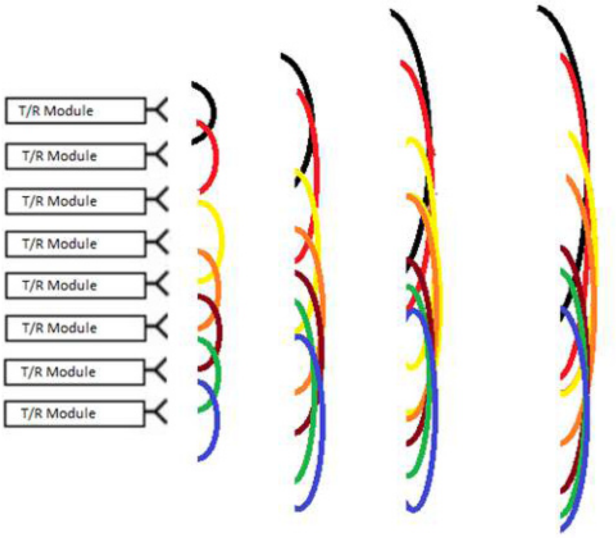

Figure 4. MIMO Radar (AESA - MIMO Mode) where each colour represents an orthogonal waveform transmitted from a TR Module

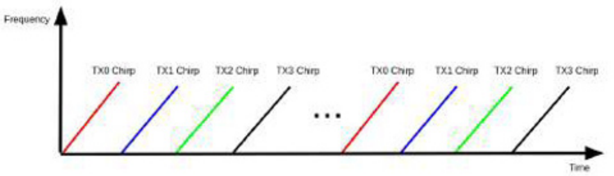

Figure 5. FMCW Signal using TDM, the TX indicates which TR module is transmitting

as the base waveform with 4 TR modules. Although easy to implement with perfect orthogonality between transmit channels, TDM is slow because each transmit element is given a place in time. This is not the case in FDM and CDM as those forms of multiplexing all signals are sent simultaneously. TDM servers as an excellent proof of concept before moving onto the mover complex multiplexing strategies.

3 MIMO Radar Design

With an understanding of PARs and MIMO radar theory the next section discuses the MIMO radar design. It describes the five phase process used to design and build an AESA radar capable of MIMO modes of operation.The design is broken down into five phases shown in Fig. 6.

In phase 0, the radar performance parameters are determined for a short-range surveillance AESA-MIMO radar using basic radar theory found in [2] or any other radar text book. To be able to test the radar in a lab environment two sets of requirements are created, a lab and a surveillance mode, shown in Table 1.

To obtain the required performance described in Table 1, Phase 1 of the design uses radar theory to determine the required specifications of the RF front and DSP algorithm

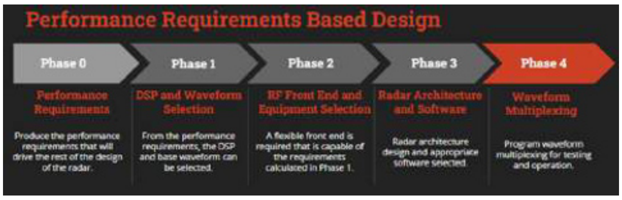

Figure 6. MIMO Radar Design Phases

Parameter	Symbol	Unit	Surveillance Mode	Lab Mode
Maximum Range	R_{max}	m	150	50
Range Resolution	R_{res}	m	0.75	0.75
Maximum Velocity	v_{max}	m/s	10	1.5
Minimum Velocity	v_{min}	m/s	-10	-1.5
Velocity Resolution	v_{res}	m/s	0.01	0.01
Angular Resolution	θ_{res}		2	2
Scanning Ability	N/A	N/A	Azimuth Only	Azimuth Only
MIMO Modes	n/a	n/a	CDM, TDM, FDM	CDM,TDM.FDM

Table 1. Radar Performance Requirements

Parameter	Surveilance Mode	Lab Mode
AESA Antenna Size (TX/TR)	8x8	8x8
Operating Frequency (f_0)	5 GHz	5 GHz
Bandwidth (B)	200 MHz	200 MHz
ADC Sampling Frequency ($f_{samp,min}$)	204 MHz	204 MHz
Coherent Operation Capable	Yes	Yes
Range Application	Medium = 150 m	Short = 50 m
Range Resolution	0.75 m	0.75 m

Table 2. MIMO Mode AESA Radar Minimum Performance Parameters

which are displayed in Table 2. Based on the DSP parameters and the short-range application, the FMCW waveform is selected as the base waveform.

Once the radar parameters from Phase 1 are calculated, Phase 2 of the design selects the RF and processing equipment for the radar. The cornerstone of the radar is the Ettus Research N-series (N321/N320) SDR [7]. Each radio has 2 transmit and 2 receive channels, each capable of 200 MHz of instantaneous bandwidth. To obtain the desired beamwidth of 2 degrees four SDRs were purchased to provide 8 transmit and 8 receive RF channels producing a 64 channel MIMO radar. Fig. 7 shows the 4 SDRs with associated cables and equipment. A 148-core host processor running Linus Mint and GNU Radio performs the required control and signal processing of the MIMO radar.

To construct the antenna array, the Tagolas 10 GHz ultra wideband antenna is selected. An antenna analysis was conducted in the anechoic chamber at the Royal Military College to ensure the individual antenna elements would meet the requirements of the MIMO radar antenna array.

Following the equipment selection, Phase 3 is the design of the MIMO radar architecture and software development in C and C++. A high-level diagram of the architecture is shown in Fig. 8. Moving right to left in Fig. 8, an 8 transmit by 8 receive antenna array is constructed using the Tagolas antenna elements. The next block to the left shows the MIMO radar hardware rack, consisting of

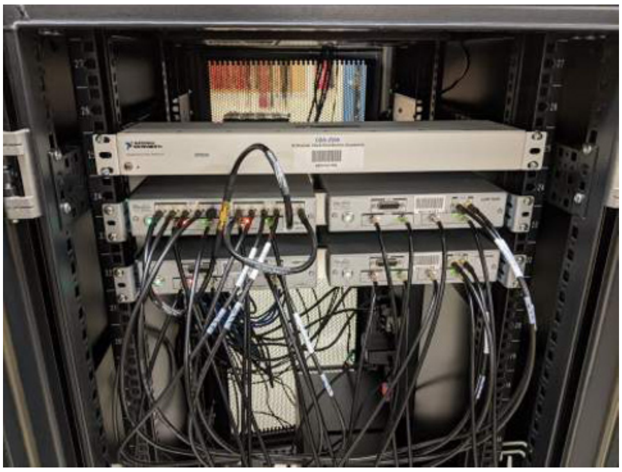

Figure 7. Four Ettus Research SDRs and a Clock Destitution Unit of the MIMO Radar

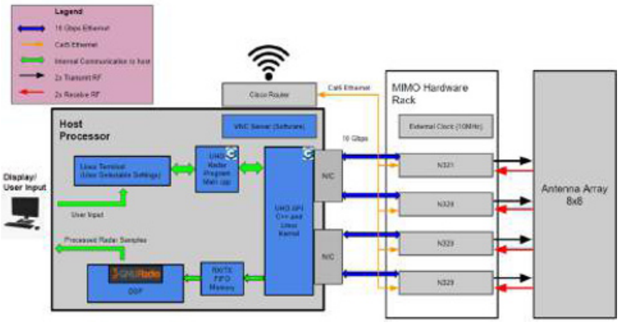

Figure 8. High level schematic of the MIMO radar, hardware components are grey and software components in blue

Figure 9. Photo of the final MIMO Radar during testing

the 4 Ettus research SDRs, and the clock distribution unit. The MIMO Radar Hardware rack is connected to the host processor. The host processor is running the main radar program and the DSP program used to process the radar data in real-time for display. Fig. 9 is a photograph of the MIMO radar.

4 Results

The performance of the multi-mode MIMO radar in terms of its ability to detect multiple targets in range, bearing, azimuth, and velocity, was tested in 2 different environments. The first environment was the lab environment. The second was the RMC Athletic Dome which provides a wide-open space to test the various parameters of the radar using humans as targets. The MIMO radar operates at a very low output power which ensured the safety of the personnel involved in all stages of testing. Several videos showing the radar in full operation can be found on YouTube at https://www.youtube.com/watch?v=eu5Wo0JYB3M&list=PL_lkRDKeAnhpYMzRbNTOyXM1O-xJ4aRwL or search YouTube for "Robert Gilpin MIMO Radar".

The first test environment was the lab, it provided an area to prove the operation of the MIMO radar during development and early radar operation. A target table was used to prove all three dimensions of operation: range, bearing, and velocity. In the lab it was clear that the MIMO Radar was fully operational in TDM mode. To gain better measurements in a less cluttered environment the Radar was moved to the RMC Athletic Dome. There were two main tests conducted in the RMC Dome: single target testing and multi-target testing.

4.1 Single Target Test

The single target consisted of a human starting right in front of the antenna array at 0 and then walking at a slow pace until the human was no longer visible on the MIMO radar display. The maximum range of the display is reached due to the SNR of the target dropping below the noise floor. The range, velocity, and bearing can be estimated in this single target test.

The TDM technique is used as a baseline to compare future radar performance techniques including CDM and FDM. Fig. 10 shows the target walking at $R = 5$ m with a velocity of $v = -1.2$ m/s at approximately -10 (right of boresite). In Fig. 10, the zero Doppler bin has been blanked in the range vs. velocity graph. However, the zero Doppler bin was not blanked in the range vs. bearing display. The zero Doppler bin was not blanked in range vs. bearing because that functionality is not possible with the DSP algorithm employed in GNU Radio. The maximum range observed was 21.75 m.

4.2 Multiple Target Identification

A radar must be able to detect several targets in the FOV simultaneously. The second test performed in the Dome was a 2 target in which test two humans start at zero range, walk at a normal pace, split apart after several steps, and then returning back to the starting point. This test is used to demonstrate the MIMO radar is able to detect multiple targets and separate them in bearing, velocity, and range.

The results from the TDM can be found in Fig. 12. The figure shows the point at which the two humans walking toward the radar are separated by a null in the bearing display.

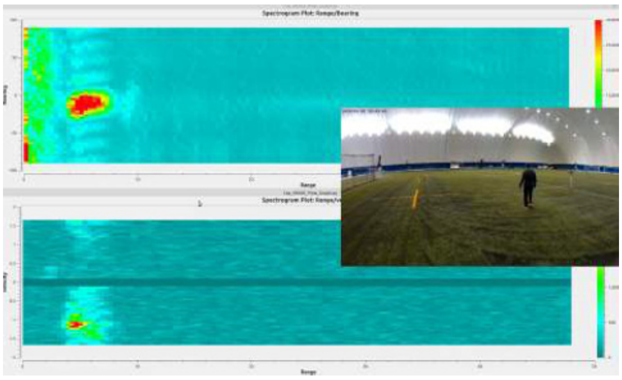

Figure 10. TDM MIMO mode real-time display of range vs. bearing on top, range vs. velocity on the bottom and an inserted photograph of the target and environment

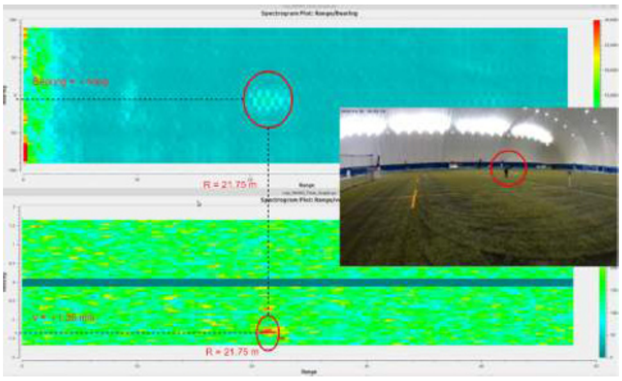

Figure 11. TDM MIMO radar real-time display showing the estimated maximum range of 21.75 m at a velocity of $v = -1.35$ m/s (opening)

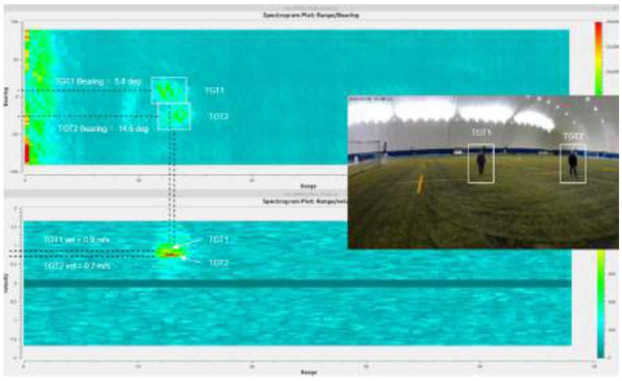

Figure 12. TDM MIMO radar real-time display, multi-target test, where TGT stands for target. TGT1 at a bearing of $\theta_{TGT1} = 5.8$, velocity of $v_{TGT1} = 0.9$ m/s and a range of $R_{TGT1} = 12.4$ m. TGT2 at a bearing of $\theta_{TGT2} = -14.5$, $v_{TGT2} = 0.7$ m/s and a range $R_{TGT1} = 12.6$ m

Both the single and multi-target tests are designed to prove functionality of the radar and not provide the full resolution and performance of the radar. Further research will implement a background subtraction algorithm and static testing will be conducted to provide a fully specified radar resolution cell.

5 Conclusion

This research aimed to do three things, all of which were demonstrated. The first was to create a AESA radar using SDRs capable of MIMO operation. Ettus Research SDRs were used to build a fully functional AESA Radar capable of MIMO operation using all three multiplexing techniques. The second aim was to ensure the signal processing remained real-time, which was demonstrated in all three test environments. The final aim of the research was to compare TDM, FDM and CDM modes which was completed in a multi-target environment.

This research has provided a basis for more work to continue in MIMO radar development in the radar community. It has demonstrated that modern SDRs can be used to build an AESA radar to allow for further development of multiplexing strategies for use in MIMO radar. Finally, this research has shown the advantages MIMO operation could bring to future radars for use in a military or civilian application.

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