ELECTRONIC, ELECTRICAL & SYSTEMS ENGINEERING

UNIVERSITY OF BIRMINGHAM

Beng Final Year Project (EE3P)

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2544760

Design and use of the Frequency Modulated Continuous Wave (FMCW) waveforms and MIMO FMCW radar for autonomous path planning of ground platform

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Project Self Assessment

Checklist: Put a "Y" in the column which corresponds to your assessment of our own ability

Category	**I find this very difficult**	**I find this a bit difficult**	**neutral**	**I find this fairly easy**	**I find this very easy**
Ability to work independently				Y	
Ability to manage my time		Y			
Ability to learn new skills or concepts in depth			Y		
Ability to learn new concepts or skills quickly		Y			
Ability to focus on targets		Y			
Ability to apply things that I have learned				Y	
Ability to understand the implications of results and findings				Y	
Ability to draw conclusions				Y	

Comment on your self assessment checklist. To obtain full marks you must explain the reasons why you selected particular columns for each of your ability criteria.

What aspects of your project did you enjoy and or went well (up to 50 words)	Getting to learn and understand the principle behind autonomous driving system.

What aspects of your project did you find difficult or would you change (up to 50 words)	Time management and working on simulations

Abstract

Road safety remains a significant challenge worldwide, with thousands of fatalities occurring annually on roadways. To address this issue, researchers and automotive manufacturers are creating advanced radar systems as the fundamental technology for autonomous driving and advanced driver-assistance systems (ADAS) [4]. A thorough framework for modelling, simulating, and deploying high-resolution automotive radar systems that integrate Multiple-Input Multiple-Output (MIMO) array configurations with Frequency Modulated Continuous Waveform (FMCW) techniques is presented in this report. The report begins with an introduction to FMCW radar principles, including signal generation, processing, and MIMO techniques for improved angular resolution [3], [5]. A literature review synthesizes advancements in automotive radar, highlighting the benefits of TDM MIMO configurations [1], [7]. The system design section details waveform parameters, signal processing chains (range-FFT, Doppler-FFT, angle-FFT), and MIMO virtual array synthesis [8], [9]. Simulation and experimental results validate the radar's performance in detecting and tracking objects, with a focus on real-time implementation challenges [2], [6].

The report demonstrates a full signal processing chain for a 77 GHz automotive radar system that integrates time-division multiplexing MIMO techniques to achieve improved spatial resolution in both azimuth and elevation planes [3], [5]. FMCW radar systems are especially well-suited for automotive applications due to their accurate range measurements, decreased sensitivity to clutter, and efficient implementation [7]. Meanwhile, MIMO radar technology allows superior angular resolution with relatively compact hardware footprints by synthesizing virtual arrays with large apertures using minimal physical antenna elements [8], [9].

Contents

1. Introduction

From passive measures to increasingly complex active systems that can detect, warn, and ultimately intervene to prevent accidents, automotive safety systems have evolved over time [1]. Due to its direct range and velocity measurement capabilities, all-weather performance, and growing cost-effectiveness, radar technology has become a vital sensing modality for these advanced systems [4]. The performance requirements for automotive radar systems have increased as autonomous driving technology moves closer to Levels 4 and 5 (complete autonomy) [2].

To provide a comprehensive perception of their surroundings, modern vehicles are equipped with a variety of radar sensors. For example, short-range radar (SRR) sensors with wide fields of view (±75°) and detection ranges up to 45 meters are typically placed at vehicle corners for blind-spot detection and cross-traffic alerts; mid-range radar (MRR) sensors with moderate fields of view (±40°) and detection ranges up to 100 meters support automatic emergency braking and lane-change assistance; and long-range radar (LRR) systems with narrow fields of view (±15°) and detection ranges up to 250 meters [3], [7].

MIMO radar technology has drawn a lot of attention due to its ability to create virtual arrays with large apertures using a small number of physical transmit and receive antennas [5], [8]. However, high angular resolution is necessary for these safety-critical applications to accurately distinguish between nearby objects. Conventional phased-array radar systems accomplish this by using physically large antenna arrays, which present integration challenges in the limited space available on vehicles [7].

The key objectives are:

- To implement TDM MIMO signal processing techniques that enhance angular resolution through virtual array synthesis
- To develop FMCW waveform processing chains (Range-FFT, Doppler-FFT, Angle-FFT) for precise detection of range, velocity, and angle
- To validate the system's performance through simulations and experimental testing using parameters matching automotive radar standards (76-81 GHz)
- To address key challenges in real-time processing and velocity-induced phase compensation unique to TDM MIMO systems

FMCW Radar Fundamentals

Modern autonomous vehicles rely on millimetre-wave (mm Wave) FMCW radar (76-81 GHz) due to its:

- All-weather reliability (unaffected by rain, fog, or lighting) [4]
- Accurate range/velocity measurement via linear chirp signals [7]:

Beat frequency:

$$f_{IF} = \frac{2Sr}{c} \ (S = chirp\ slope)$$

Range resolution:

$$r_{res} = c/2B$$

MIMO Radar Advantages:

TDM MIMO is the preferred automotive configuration due to its:

- Virtual Array Expansion: A 2-Tx/4-Rx array synthesizes an 8-element virtual array, improving angular resolution from 29° to 7° [5],[8]
- Cost Efficiency: TDM avoids complex hardware needed for FDM/CDM [5]
- High SNR: Achieves large time-bandwidth product for detection accuracy [8]

Autonomous Driving Needs:

TDM MIMO FMCW radar addresses critical gaps in autonomous navigation:

1. Small Object Detection: Pedestrians/cyclists require <1° angular resolution [4],[8]
2. Real-Time Processing: CFAR detection and 3D-FFT must operate at <100 ms latency [9]
3. Sensor Fusion: Complements LiDAR/cameras in edge cases (e.g., low visibility) [4],[6]

2. Literature Review

2.1 FMCW Radar Fundamentals

Modern automotive radar systems predominantly employ Frequency-Modulated Continuous Wave (FMCW) technology due to its superior range resolution and velocity measurement capabilities compared to pulsed radar systems [7]. The basic working principle involves sending a chirp signal, which is a continuous wave signal whose frequency changes linearly with time. An FMCW chirp's instantaneous frequency, f(t), can be written as [3]:

$$f(t) = f_o + St, 0 \leq t \leq T_c$$

where:

- f_0 is the starting frequency (typically 77 GHz for automotive applications)
- S is the chirp slope (MHz/μs)

- T_c is the chirp duration

The round-trip time delay τ = 2r/c causes a frequency difference between the transmitted and received signals when this signal reflects off a target at distance r. Through heterodyne mixing, this produces an intermediate frequency (IF) beat signal [5]:

$$f_{IF} = S_T = \frac{2Sr}{c}$$

The range to target is then calculated as:

$$r = \frac{f_{IF} \cdot c}{2S}$$

The system's capacity to distinguish between two closely spaced frequencies in the IF signal determines the theoretical range resolution. For an FMCW system with bandwidth B, the range resolution is given by [7]:

$$\Delta r = \frac{c}{2B}$$

Doppler processing in FMCW radar exploits the phase shift between consecutive chirps caused by target motion. The phase difference Δφ between two chirps separated by T_c is [5]:

$$\Delta\emptyset = \frac{4\pi v T_c}{\lambda}$$

where v is the target radial velocity and λ is the wavelength. The velocity resolution depends on the total observation time.

This relationship demonstrates the fundamental trade-off between velocity resolution and update rate in FMCW radar systems. Automotive radars typically use 64-256 chirps per frame, achieving velocity resolutions between 0.2-0.8 m/s at 77 GHz [3].

2.2 MIMO Radar Principles

Multiple-Input Multiple-Output (MIMO) radar technology has revolutionized automotive sensing by enabling high angular resolution with practical antenna array sizes [8]. The key innovation is the creation of a virtual array through careful spacing of transmitter and receiver elements.

Consider a 2-Tx/4-Rx array with λ/2 spacing [5]:

- Physical array: 2 transmitters spaced at 2λ, 4 receivers at λ/2
- Virtual array: 8 elements with λ/2 spacing
- Angular resolution improves from 29° (4 Rx) to 7° (8 virtual elements)

Three primary multiplexing techniques exist for MIMO radar operation [5]:

1. Time Division Multiplexing (TDM):
   - Transmitters activate sequentially
   - Advantages: Simple implementation, low hardware complexity
   - Disadvantages: Reduced maximum unambiguous velocity
2. Frequency Division Multiplexing (FDM):
   - Transmitters operate simultaneously at different frequencies
   - Advantages: No velocity ambiguity
   - Disadvantages: Requires wide IF bandwidth
3. Code Division Multiplexing (CDM):
   - Transmitters use orthogonal codes
   - Advantages: Full duty cycle utilization
   - Disadvantages: Complex signal processing

TDM has become one of the more dominant approaches for automotive applications due to its implementation simplicity and cost-effectiveness [5]. However, challenges, particularly velocity-induced phase shifts between transmitter channels are often seen. For a target moving at velocity v, the phase shift between TDM transmitters is [8]:

$$\Delta\emptyset = \frac{4\pi v T_a}{\lambda}$$

2.3 Automotive Radar Applications

Automotive radar has evolved from simple adaptive cruise control to comprehensive environment perception for autonomous driving [4]. Modern systems integrate multiple radar sensors to provide 360° coverage [6]:

1. Front Radar (77 GHz):
   - Long-range (up to 250m) for ACC and AEB
   - Medium-range (60-160m) for cross-traffic alert
2. Corner Radars (79 GHz):
   - Short-range (30-80m) for blind spot detection
   - Mid-range (50-100m) for lane change assist

Key technological advancements include [1],[4]:

- Digital Beamforming for improved angular resolution
- 4D imaging radar (range, Doppler, azimuth, elevation)
- AI-based target classification

Industry trends show rapid adoption of MIMO configurations [3],[5]:

- 3-Tx/4-Rx becoming standard for front radar
- Cascaded chipsets enabling 12-Tx/16-Rx configurations
- CMOS integration reducing cost and size

The integration of radar with other sensors (cameras, LiDAR) through sensor fusion algorithms has proven critical for achieving SAE Level 3+ autonomy [2]. Radar provides indispensable all-weather capability, particularly in rain, fog, and low-light conditions where optical sensors struggle [4].

3. System Design

3.1 FMCW Waveform Design

For our system we are particularly looking on a radar that employs linear FMCW signal, this signal can provide a large time bandwidth product, hence makes it possible to achieve high range resolution and signal to noise ratio (SNR) [5].

The FMCW signal over time duration T_c is known as a chirp, and the frequency of the chirp signal increases linearly at the rate S over time.

The sinusoidal FMCW waveform can be defined as [7]:

$$x_T(t) = \cos\left(2\pi f_c t + \pi S t^2\right)$$

where $f_c = 77GHz$, and slope $S = \frac{B}{T_c}$.

While instantaneous frequency is determined as [5]:

$$f(t) = \frac{1}{2\pi}\frac{d}{dt}\left(2\pi f_c t + \pi S t^2\right) = f_c + St$$

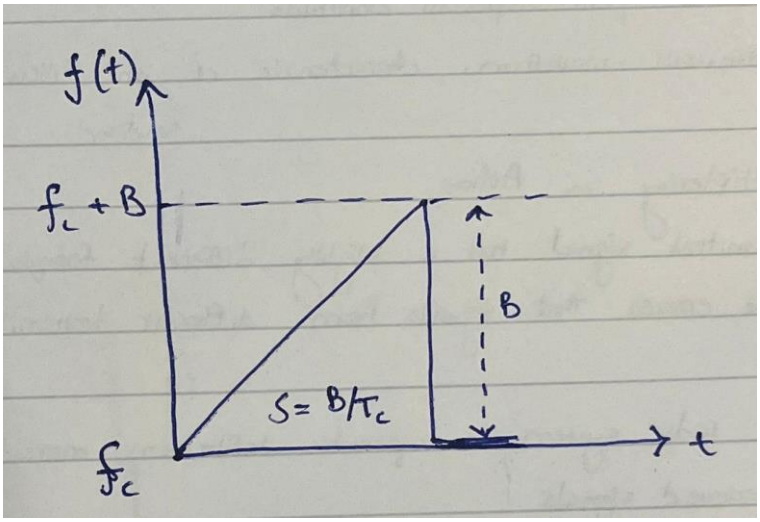

Figure1

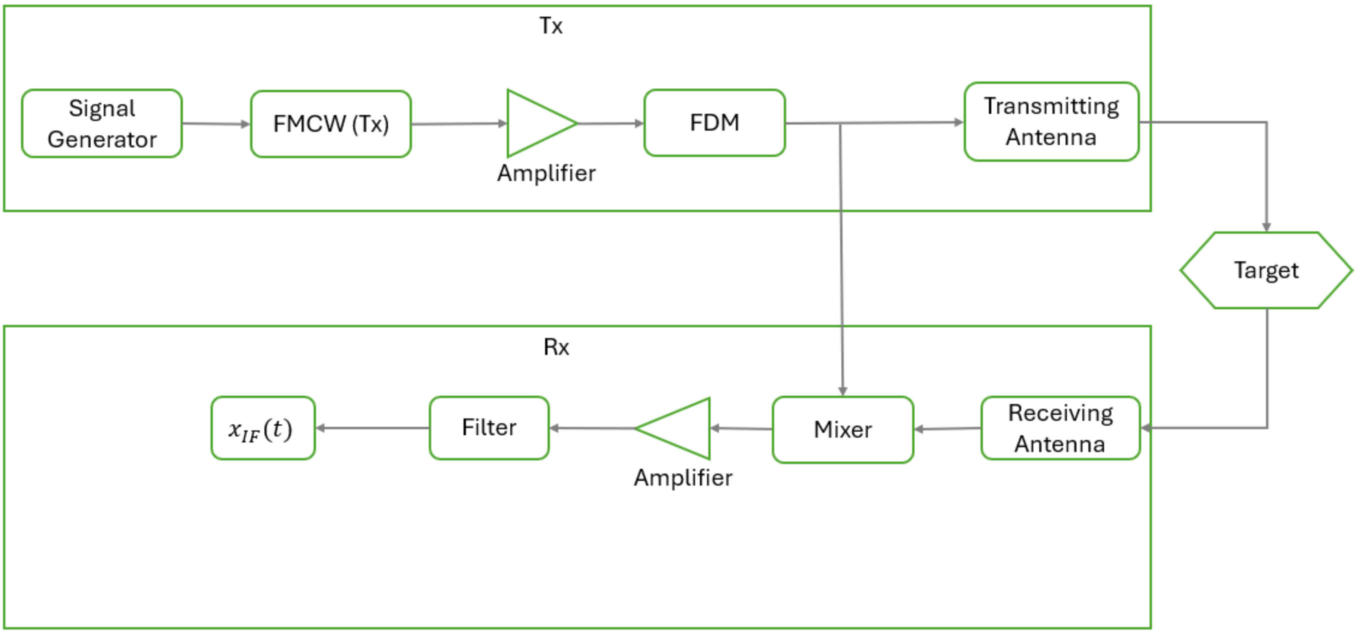

Figure2

When the transmitted signal hits an object at range r, part of the signal energy is reflected to the radar receiver antenna (Rx). The received signal would be the transmitted signal with delay $\tau = \frac{2r}{c}$ [5]. The receiver mixes (multiplies) the received signal with the transmitted signal- a critical step in FMCW radar processing.

- The product of the transmitted and received signal is produced by the mixer
- During the process of mixing, the instantaneous frequencies of $x_T(t)$ and $x_R(t)$ differ due to the time delay between transmission and reception.
- A beat frequency f_b proportional to the target range is produced by this frequency difference.

The low pass filter filters out the signal component of the frequency $f_T(t)+f_R(t)$ while allowing the signal component of the frequency $f_T(t)-f_R(t)$ to pass through.

$$x_{IF}(t) = LPF\{x_T(t)x_R(t)\} = Acos(2\pi f_{IF}t + \emptyset_{IF})$$

Where the beat frequency $f_{IF} = f_T(t) - f_R(t) = S\tau\ (slope)$ is not a function of time and remains constant [7].

With a quadrature receiver, the received signal is mixed with the in phase and quadrature signals of the transmitted signal, resulting in a complex exponential IF signal for further processing [8].

$$x_{IF}(t) = Ae^{j(2\pi f_{IF}t+\emptyset_{IF})}$$

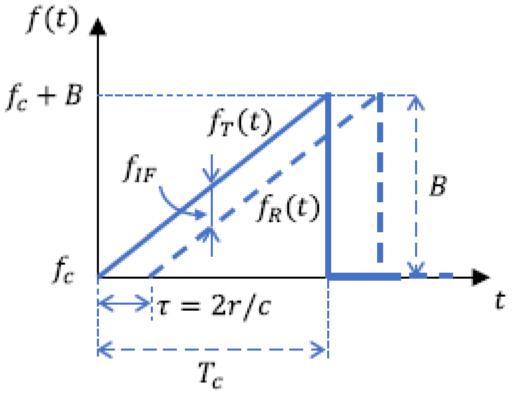

FIGURE 3. Derivation of the constant-frequency IF signal from the transmitted and received chirp signals.

Figure3 [5]

The reflected transmitted signal back by object and arrives at the receiver antenna with a delay.

$$\tau = \frac{2r}{c}$$

The phase of the IF signal can be determined at the start time of the IF signal when the reflected chirp signal arrives at the receiver antenna.

$$\emptyset_{IF} = 2\pi f_c \tau + \pi S \tau^2 \approx 2\pi f_c \tau$$

As for mmWave systems, the f_c of chirp signal is much larger than $\frac{S\tau}{2}$

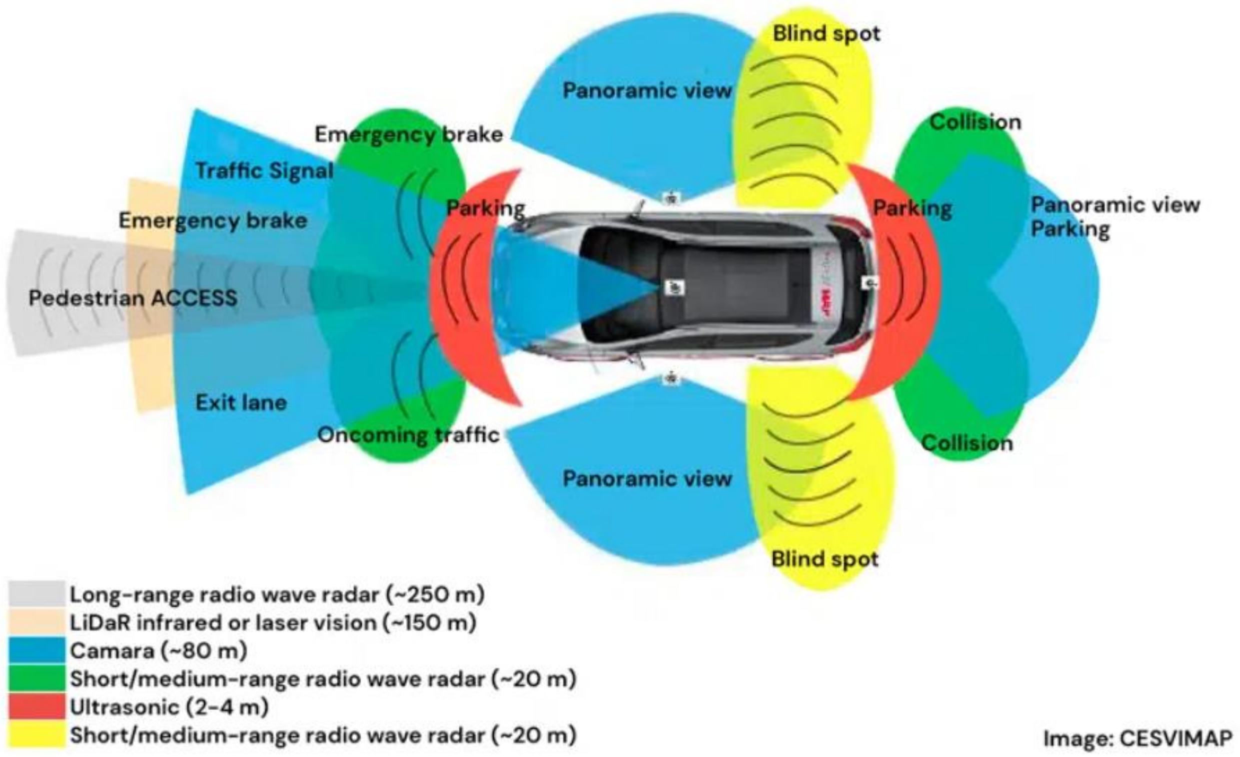

Figure4 [6]

3.2 MIMO Configuration:

The range and doppler parameters of targets can be estimated by using a single receive antenna, however, to estimate the angle parameter of targets a receive antenna array is required, this is where MIMO radar technology is used- the transmit antennas transmit FMCW sequences in a way that guarantees waveform orthogonality [8].

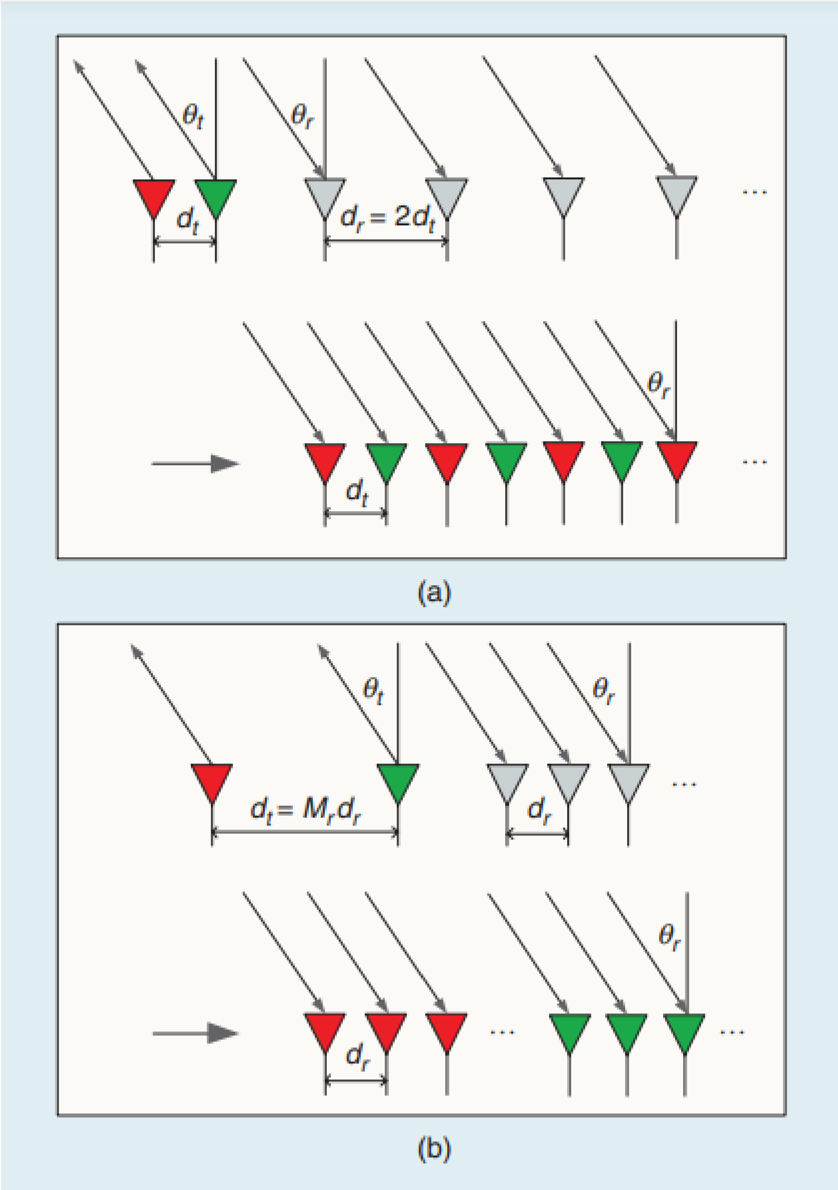

FIGURE 5. The different MIMO radar virtual array configurations [23] using the time-division multiplexing (TDM) or Doppler-division multiplexing (DDM) scheme with $M_t = 2$ transmit antennas and M_r receive antennas: (a) interleaved, with $d_r = 2d_t$ and $d_t = \lambda/2$; (b) stacked, wit $d_t = M_r d_r$ and $d_r = \lambda/2$. Different colors indicate that the transmit antenna transmits different time slots or codes.

Figure5 [8]

As MIMO radar transmits orthogonal waveforms, when isotropic array elements are used the array beam pattern is omnidirectional. Therefore, the coherent array-processing-gain advantage that traditional phased-array radar systems have is lost by MIMO radar; phased-array radar with transmit beamforming allows for a higher SNR of the array response at a given angular direction [5]. However, in the context of automotive applications, MIMO radar's low cost and high-resolution angle finding capability are thought to be more significant than the loss of coherent processing gain.

For TDM MIMO radar, only one transmit antenna is planned to transmit during each time slot.

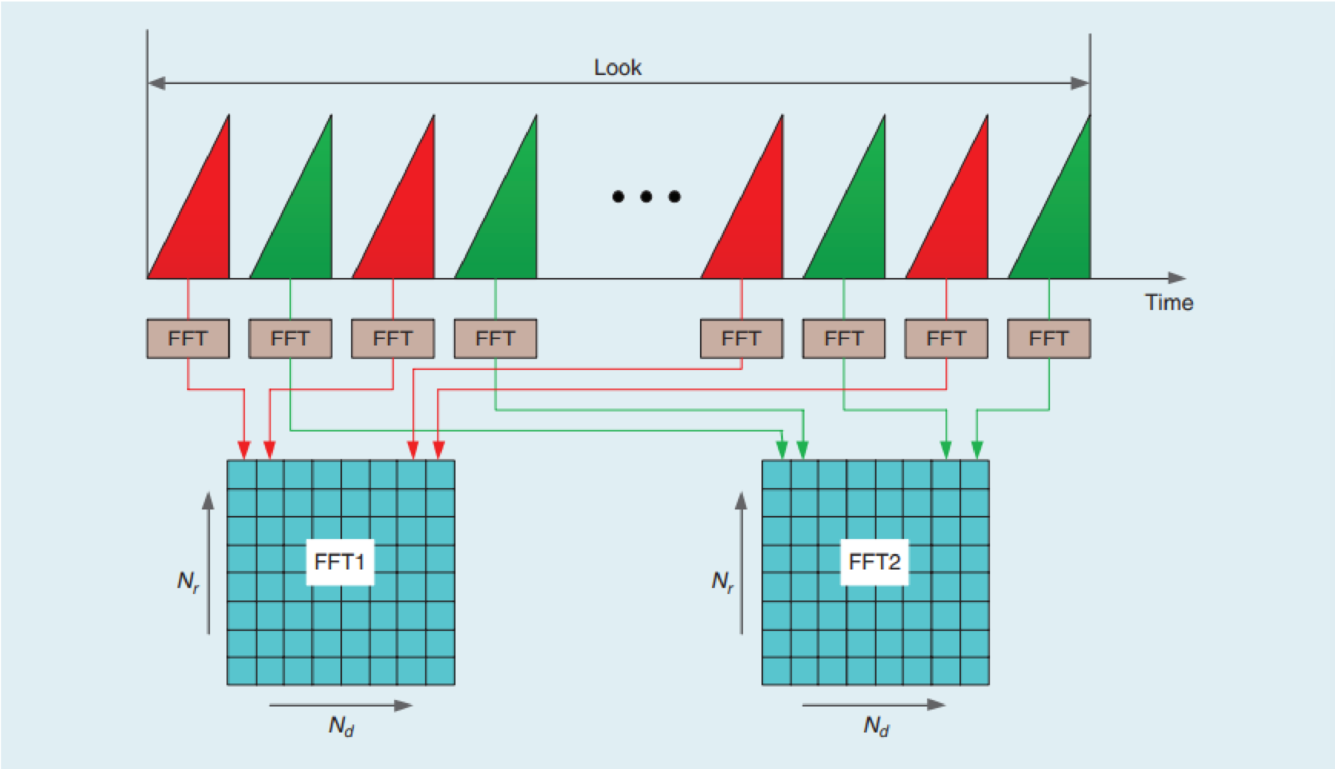

FIGURE 6. An example of radar signal processing with the TDM scheme [34], where $M_t = 2$ transmit antennas alternately transmit FMCW chirp sequences. The red and green colors denote the odd and even echo chirp sequences, respectively. The range FFTs are conducted for each chirp, and the FFT outputs are stored in two matrices corresponding to odd and even sequences, respectively, for further processing.

Figure6 [8]

Where Tx = 2 transmit antennas alternately emit FMCW chirps. The switch delay between transmit antennas is $\Delta t = T_{PRI}$ [5]. The FFT outputs of $2N_d$ chirps are compiled into two matrices that correspond to odd and even chirp sequences, after range FFTs of length N_r are performed for each chirp at each receive antenna, it is possible to create a virtual array using interleaved or stacked configurations by combining the receive arrays with the odd and even chirp sequences to create two subarrays [8].

For a moving target with a velocity of v, the switching delays of the transmit antennas cause a target phase migration from chirp to chirp. This migration would cause the virtual array pattern to be distorted and is defined as follows [8]:

$$\emptyset = 2\pi f_D \Delta t = \frac{4\pi}{\lambda} v \Delta t$$

The phase difference between corresponding columns in the two matrices is:

$$\emptyset = \frac{4\pi}{\lambda} v T_{PRI}$$

3.3 Signal Processing Chain (3 pages):

The IF signal $x_{IF}(t)$ is sampled at a rate of F_s in digital signal processing applications, yielding N_s discrete samples. The discrete-time complex exponential signal produced by this sampling procedure has the following mathematical expression [5]:

$$x[n] = Ae^{j\emptyset_{IF}}\, e^{jn\omega_{IF}}$$

For $0 \leq n \leq N_s$, where the discrete time angular frequency

$$\omega_{IF} = \frac{2\pi f_{IF}}{F_s}$$

When we apply Fourier transform to the finite duration discrete time signal, we obtain:

$$X(\omega) = F\{x[n]\} = \sum_{n=0}^{N_S-1} x[n]e^{-jn\omega}$$

$$= Ae^{j\emptyset_{IF}} P_{N_S}(\omega - \omega_{IF})$$

Where

$$P_N(\omega) = \sum_{n=0}^{N-1} e^{-jn\omega} = \frac{\sin\left(\frac{\omega N}{2}\right)}{\sin\left(\frac{\omega}{2}\right)} e^{\frac{-j\omega(N-1)}{2}}$$

The time-domain received IF signal when several objects reflect the chirp signal back to radar is a linear combination of the separate IF signals that come from each of the reflecting objects. The total range spectrum of several objects is a linear combination of the spectra of the individual reflecting objects because the DFT is a linear transformation [7]. As a result, the peaks in the range spectrum can be used to identify objects with various ranges.

To measure the velocity of an object, radar can transmit two chirp signals that are separated by T_c in time. If the velocity of the object is v, over the time duration of T_c, the object travels a distance of $\Delta r = vT_c$. The differences in frequency and phase between the IF signals derived from the two chirps are [8]:

$$\Delta f = \frac{2S\Delta r}{c} = \frac{2SvT_c}{c}$$

$$\Delta\emptyset = \frac{4\pi\Delta r}{\lambda} = \frac{4\pi vT_c}{\lambda}$$

When time T_c is small Δf is negligible as compared to frequency of IF signal.

An important improvement over traditional single-input single-output (SISO) configurations is angular resolution in FMCW TDM MIMO radar systems. Using a time-division multiplexed scheme with multiple transmit and receive elements, MIMO architecture generates a virtual array that multiplies the number of spatial channel receivers. Without a corresponding increase in hardware complexity or physical array size.

The time-domain received IF signal is a linear combination of the individual IF signals that are produced by each of the several objects that reflect the chirp signals back to the radar reflecting objects. The total range-velocity spectrum of several objects is a linear combination of the spectra of the individual reflecting objects because the DFT is a linear transformation. As a result, peaks in the range-velocity spectrum can be used to identify objects with varying range or velocity [5].

$$\omega_{res} = \frac{2\pi}{N_c}$$

$$v_{res} = \frac{\lambda}{4\pi T_c}\omega_{res} = \frac{\lambda}{2T_f}$$

After range doppler processing extracts range and velocity information, the system determines the direction of arrival (DOA) of reflected signals by performing spatial processing across the virtual array elements. Typically, this procedure makes use of spectral estimation methods like traditional beamforming, or sophisticated machine learning techniques. The angle processor evaluates the signal power across all possible arrival angles within the field of view to produce a spatial spectrum for each range-Doppler bin containing a potential target. The width of the peaks in this spectrum is inversely proportional to the effective aperture of the virtual array, and they correspond to probable target directions [8].

The receiver antenna array can be used to estimate the direction in which the radar chirp signal reflected would reach. Assume that the distance between the object and the radar is significantly greater than the antenna array's dimension, or its aperture. The signals that reach the object from the transmitter antenna and those that arrive at the receiver antennas can then be assumed to be parallel. Due to spacing between receiver antennas, the relative delay by signals would be:

$$\Delta\tau = \frac{dsin(\theta)}{c}$$

Then the differences in frequency and phase between the IF signals is:

$$\Delta f = S\Delta t = \frac{Sdsin(\theta)}{c}$$

TDM MIMO radar uses sequential antenna activation to maximise sensing performance while addressing important hardware limitations. Instead of using frequency or code diversity to create orthogonality, this system uses separation to strategically activate one transmitter at a time during predefined time slots. TDM MIMO uses a single RF chain that is switched between antennas to achieve comparable virtual array benefits, whereas conventional MIMO approaches require multiple transmit chains with independent waveform generators and power amplifiers. For mass-market applications like automotive radar, this substantial hardware simplification lowers system cost, power consumption, and physical footprint—all of which are critical factors [3],[5].

4. Implementation

This section talks about the use of MATLAB to implement our FMCW MIMO radar system with time division multiplexing (TDM). The system was created to take advantage of MIMO's advantages while lowering hardware complexity using TDM. Compared to pulsed radar systems, FMCW modulation was chosen for its superior range resolution and relative ease of implementation.

The implemented radar operates at 77GHz, the standard band designated for automotive radar applications. This frequency provides enough resolution for object detection and classification in automotive environments while providing the ideal balance between component size and atmospheric attenuation.

System design parameters:

Specification Table	
Operating Frequency	76-81GHz
Waveform	FMCW
Unambiguous Range	120m
Range accuracy (resolution)	0.5m
Maximum unambiguous velocity	160km/hr
Velocity resolution	1.5km/hr
Update rate	20Hz (20 pulses within one sec)
FoV Azimuth	180°
FoV resolution	5°

The radar's operation is based on the FMCW chirp waveform. A waveform known as linear frequency modulation (LFM), in which the frequency rises linearly with time. The linear frequency sweep characteristics of the generated signal were confirmed by graph analysis. The spectrogram signal shows the linear frequency increase over time, which is the distinguishing feature of an FMCW waveform.

The use of MIMO helps to create an expanded virtual array by combining a "thin" transmit array with a "full" receive array. The angular resolution is significantly improved by creating a virtual array without spatial aliasing. The equivalency between the two-way pattern of the physical array and the pattern of the resulting virtual array was verified by calculating and comparing the theoretical beam patterns.

When compared to traditional phased array systems, the implementation showed better angular resolution. In contrast to the 4-element physical array, the virtual 8-element array (2 Tx × 4 Rx) generated a beam pattern with a noticeably narrower main lobe.

The number of receiver antennas in traditional uniform linear arrays directly affects the angular resolution; however, each extra receiver requires different processing hardware, which raises the complexity and expense [5]. By carefully positioning transmitter antennas along the same axis as receiver antennas, but with greater spacing, MIMO technology gets around this restriction [8].

$$\Delta f = \frac{2S\Delta r}{c}$$

$$\Delta \emptyset = \frac{4\pi\Delta r}{\lambda}$$

Phase shifts can be produced by placing transmitters in a 2-Tx-4-Rx configuration with a 4d spacing, where d is the receiver spacing. This effectively increases angular resolution by a factor equal to the number of transmitters. The resolution of a much larger physical array is achieved at a significantly lower hardware cost by creating a virtual array with an expanded aperture [5],[8],[3].

5.Results and Discussion:

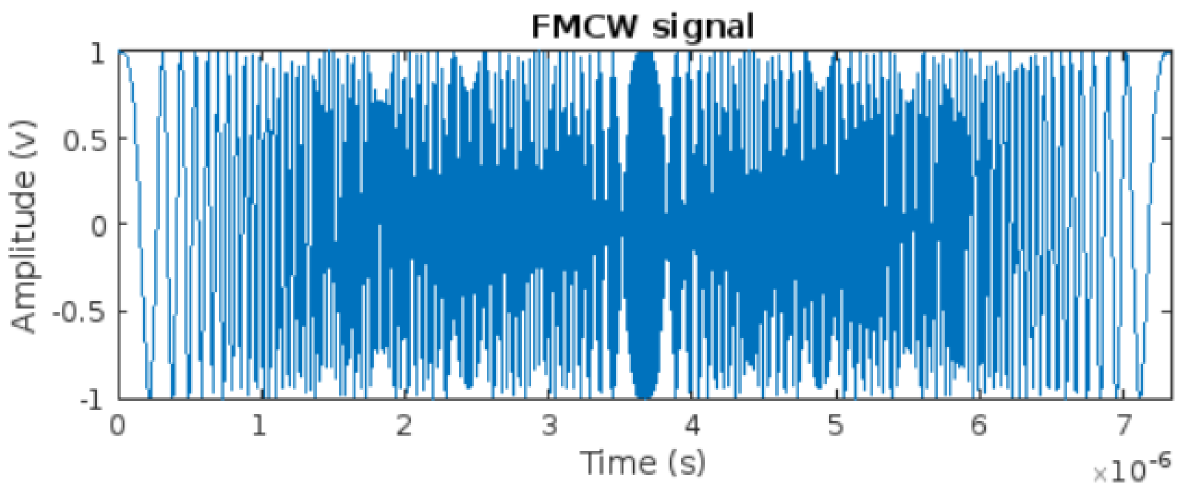

Figure7

The FMCW signal shows the expected linear chirp characteristics, as seen on the x axis (time domain). The waveform maintains an amplitude between -1V and +1V, which confirms proper signal generation and amplification. Minimal phase cutoffs can be shown by the seamless transition between sweep cycles, which is essential for maintaining accurate range measurements.

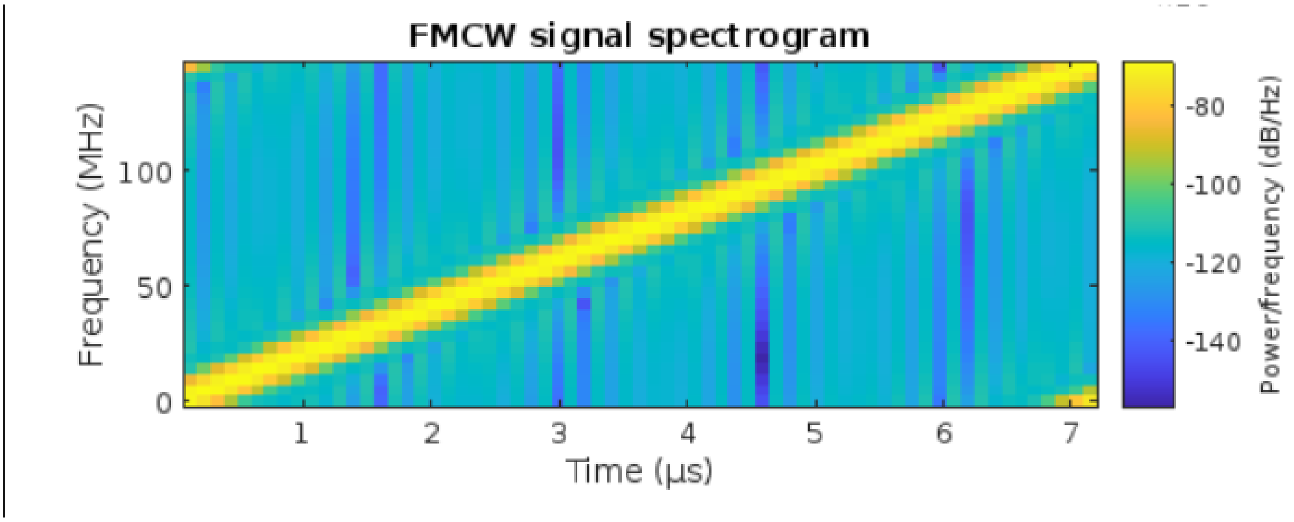

Figure8

The spectrogram shows our FMCW signal's time frequency characteristics, confirming proper linear chirp modulation essential for radar ranging with negligible nonlinearity.

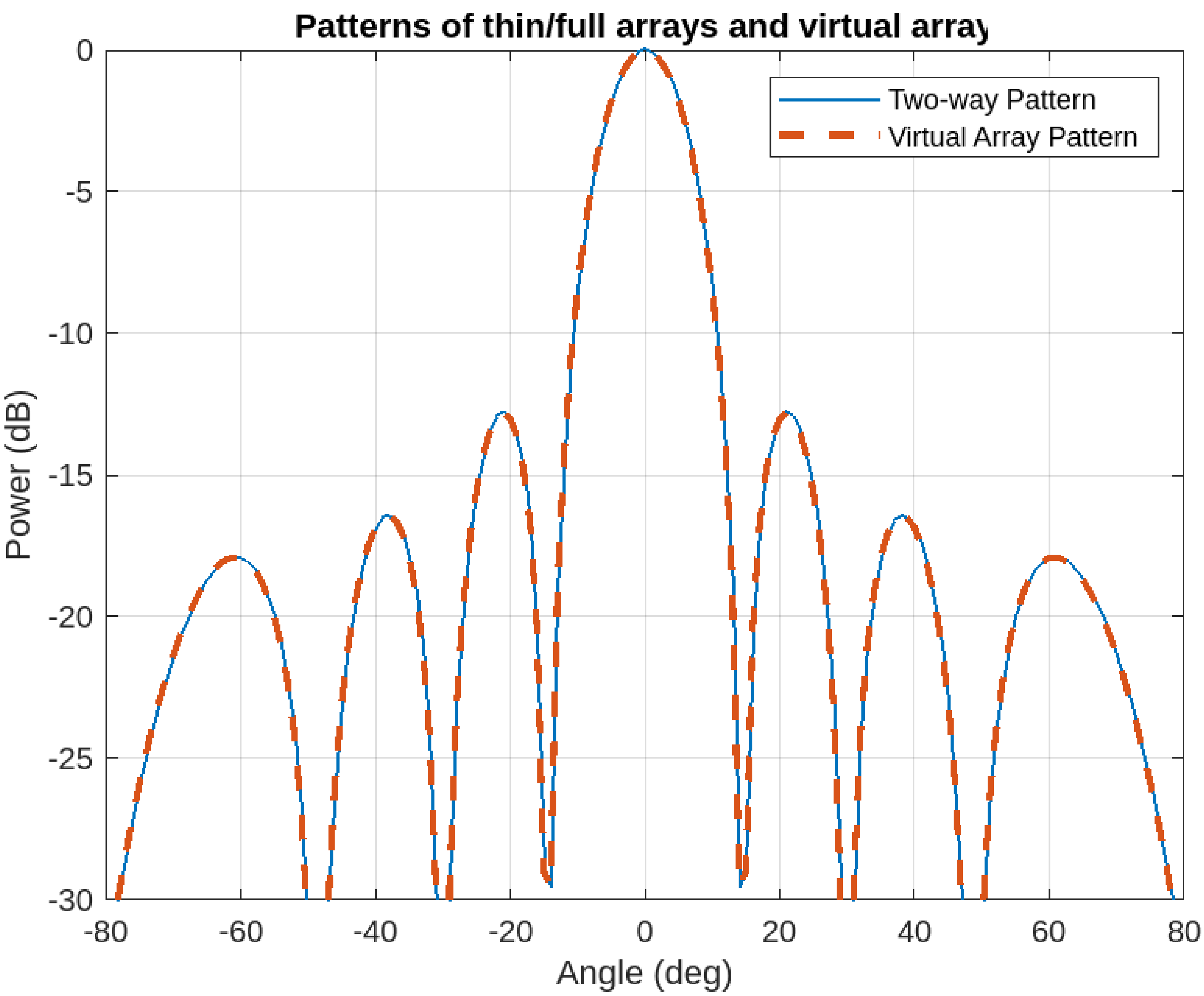

Figure9

The antenna pattern analysis demonstrates the effectiveness of MIMO with the synthesized 8-element virtual array exhibiting a 50% narrower main lobe in comparison to the physical 4-element array while maintaining low side lobe levels. Through signal processing, the 2x4 element configuration effectively produces an effective aperture equal to an 8-element phased array, allowing for this improvement without the need for additional RF hardware.

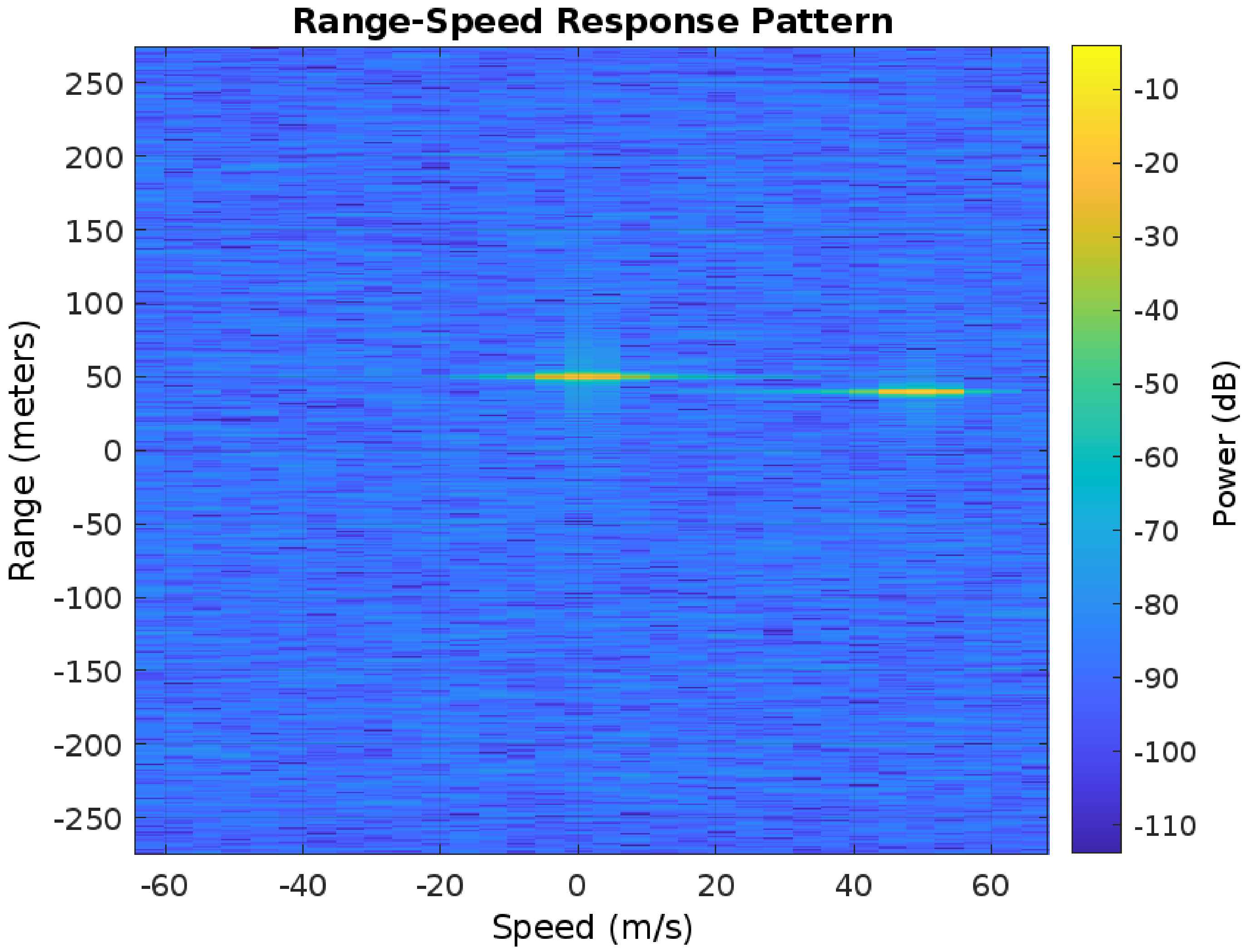

Figure10

The response confirms that the TDM-MIMO processing chain can maintain orthogonality between virtual channels by displaying good target separation.

6.Conclusion:

This project has explored the main design trade-offs in FMCW MIMO TDM radar systems for autonomous vehicles. According to the analysis, these radars require careful balancing of competing parameters, even though they provide excellent angular resolution through virtual array synthesis. An Increased bandwidth would improve range resolution but at the same time reduce the maximum detection distance. And more transmitter antennas enhance angular accuracy at the cost of lower maximum detectable speed. Similarly, longer chirp durations decrease velocity resolution but increase range.

The best balance for urban autonomous driving applications is a 2-Tx/4-Rx configuration, which offers good angular resolution and range resolution while still detecting enough velocity for city speeds. Although the time-division multiplexing technique limits the maximum detectable velocity in comparison to other architectures, it maintains hardware simplicity and cost effectiveness. These results offer useful recommendations for the implementation of efficient radar systems in self-driving cars, where safe navigation in challenging conditions depends on the best possible sensor performance. Engineers will be better able to make decisions when designing perception systems for autonomous platforms thanks to the trade-offs that have been identified.

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