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High-Resolution Target Detection in TDMA-MIMO FMCW Millimeter-Wave Radar Systems

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كشف الأهداف بدقة عالية في أنظمة الرادار ذات الموجات المليمترية *FMCW* بتقنية *TDMA-MIMO*

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Abstract:
This paper discusses the integration of Time Division Multiple Access (TDMA) with MIMO (Multiple Input Multiple Output) techniques in FMCW millimeter wave (mm-Wave) radar systems for high-resolution target detection and imaging. Through the proposed TDMA-MIMO, we demonstrate that the system can form a virtual antenna array, which significantly improves the angular resolution in range, and Doppler-azimuth-elevation domains. Challenges, including side lobe artifacts, phase errors, and Doppler ambiguity, are mitigated through advanced signal processing methodologies, specifically employing Iterative Peak Component Elimination (IPCE) and Constant False Alarm Rate (CFAR) algorithms. From the experiments carried out, the radar is shown to be able to resolve targets with the use of IQ signal analyses, range-azimuth spectrum imaging, and range-Doppler distribution mapping. moving target detection was accomplished using adaptive thresholding and non-coherent accumulation techniques, showcasing the effectiveness of the proposed framework. These advancements illustrate the system's potential use in scenarios that require precise spatial and velocity parameter estimation, such as security monitoring or aircraft tracking.

Keywords: TDMA-MIMO Radar, FMCW Millimeter-Wave Radar, Virtual Antenna Array, Iterative Peak Component Elimination (IPCE), Constant False Alarm Rate (CFAR), Doppler Ambiguity Resolution, Range-Azimuth Spectrum, Phase Error Mitigation, Non-Coherent Accumulation.

الملخص
في هذه الورقة البحثية، نركز على دمج تقنية الوصول المتعدد بتقسيم الزمن (*TDMA*) مع تقنيات *MIMO* (مدخلات متعددة ومخرجات متعددة) في أنظمة رادار الموجات المليمترية *FMCW* (موجات المليمتر) للكشف عن الأهداف وتصويرها بدقة عالية. يُظهر تصميم *TDMA-MIMO* أن النظام قادر على تكوين مصفوفة هوائيات افتراضية تُحسّن بشكل كبير الدقة الزاوية في نطاقات المدى-دوبلر-السمت-الارتفاع. تُعالج تقنيات معالجة الإشارات المتطورة، مثل تشوهات الفصوص الجانبية وأخطاء الطور وغموض دوبلر، حيث أظهرت التجارب التي أُجريت قدرة الرادار على تحديد الأهداف باستخدام تحليلات إشارات *IQ*، وتصوير طيف المدى-السمت، ورسم خرائط توزيع المدى-دوبلر. تم الكشف عن الأهداف المتحركة باستخدام تقنيات العتبة التكيفية والتراكم غير المتماسك، مما يُظهر فعالية الإطار المقترح وتوضح هذه التطورات إمكانية استخدام الأنظمة في السيناريوهات التي تتطلب تقديرًا دقيقًا للمعلمات المكانية والسرعة مثل مراقبة الأمن أو تتبع الطائرات.

الكلمات المفتاحية: رادار *TDMA-MIMO*، رادار الموجة المليمترية *FMCW*، مجموعة الهوائيات الافتراضية، إزالة مكون الذروة التكراري (*IPCE*)، معدل الإنذار الكاذب الثابت (*CFAR*)، حل غموض دوبلر، طيف النطاق والسمت، تخفيف خطأ الطور، التراكم غير المتماسك.

Introduction

Millimeter-wave (mm-wave) radar systems are used for target detection and imaging, including the security system of aircraft and others, utilizing TDMA and MIMO techniques. These systems use sophisticated signal processing techniques to improve detection performance and mitigate problems due to Doppler confusion and energy defocus. Detecting High Resolution Images: TDMA-MIMO mm wave radars have high angular resolution, which is useful for security monitoring. When MIMO is employed, the virtual array of the antenna increases, resulting in improved target resolution in the domain of range-Doppler-azimuth-elevation.[1][2][3]. New algorithms, such as Iterative Peak Component Elimination (IPCE), have been developed for dealing with side lobe effect complications when attempting to extract targets from the angular spectrum. These algorithm developments improve the target detection and tracking capabilities of radars. [2]. Employing TDMA enhances the efficiency and cost-effectiveness of the radar's hardware system. However, there are still problems to solve regarding the optimization of the interface between the array configurations and the chipsets to reduce losses and phase deviations [4]. It is critical to monitor the performance of the radar systems continuously, particularly for displacement measurement and target detection accuracy. Research indicates that parameters such as target range distance and angle of arrival are some of the most impactful regarding the performance results [5]. Incorporating a TDMA-MIMO architecture with a millimeter wave radar entails correcting phase error and velocity ambiguity issues. Using sophisticated signal processing methods and strong algorithms enables these systems to provide sharp detection and precise parameter estimation, which is extremely useful for safety and security systems applications.

II. Theoretical Background

a. Radar Operation

FMCW radar uses a continuous wave (CW) signal whose frequency is linearly modulated over time, typically as a "chirp" (e.g., increasing frequency). The transmitted signal reflects off-targets, and the received signal is mixed with the transmitted signal to produce a beat frequency. This beat frequency encodes target range and velocity. The radar consists of an antenna, a duplexer, a transmitter, and a receiver in Figure 1. Since the same antenna is used for both transmitted and reflected waves, this system is known as monostatic radar [1].

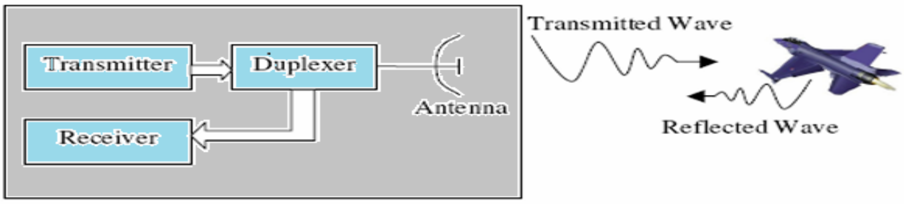

Figure 1 Simple monostatic radar configuration

When there is an item present, the incident waves are absorbed by it as they move through open space. After that, the item reradiates the surrounding waves. A portion of this reradiated wave makes a reflected wave back to the antenna. The duplexer directs the wave that is reflected at the antenna toward the receiver [7].

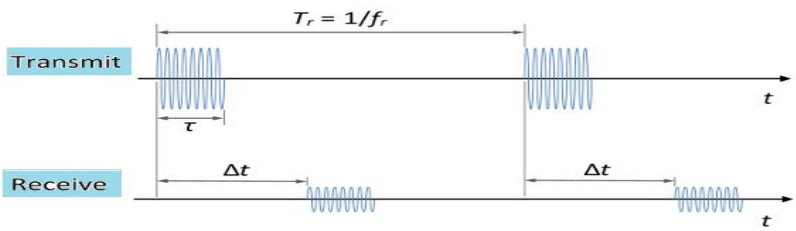

Figure 2 Signal waveforms in pulse-modulated radar. The delay and received power are related to the range of objects.

Radio waves travel to object over R distance and backscatter to radar again over R distance with the speed c. Hence the distance R is given by the equation:

$$R = \frac{\tau \times c}{2} \quad (1)$$

$R =$ the distance to the target object, $\tau =$ the time it takes for the radar signal to travel to the object and back, $c =$ the speed of light.

b. Operation of FM-CW Radar

FM-CW radar uses frequency-modulated continuous waves (not pulsed) and belongs to the CW radar subclass. Unlike basic CW radars (limited to velocity detection via Doppler), FM-CW also measures target range. The Doppler effect causes frequency shifts when the radar and object move relative to each other. Assume the wavelength of the transmitted wave is λ and the range from radar to object is R, then the total phase difference φ between the transmitted and the received waves is given by 4πR / λ. In the case of relative motion, R and φ change with time. This change is expressed with angular frequency as follows **:**

$$w_d = \frac{d\emptyset}{dt} = \frac{4\pi}{\lambda}\frac{dR}{dt} = \frac{4\pi V_r}{\lambda} \qquad (2)$$

Equation (3) describes the relationship between the radial velocity V_r of an object relative to a radar system and the resulting Doppler frequency f_d observed by the radar. The equation is given as: where V_r is the radial velocity of object with respect to radar. If $f_0$is the frequency of oscillation of radar then Doppler frequency is:

$$f_d = \frac{2V_r f_0}{c} \qquad (3)$$

where V_r is the radial velocity of object with respect to radar. If $f_0$is the frequency of oscillation of radar.

In FM-CW radars, frequency-modulated continuous waves are transmitted such that stationary targets reflect signals back that possess a frequency shift due to modulation delay. The radar mixes received and transmitted waves producing a beat signal that contains information about target speed and range. This system enables the simultaneous measurement of velocity and distance. A simplified block diagram of this system is illustrated in Figure 2.

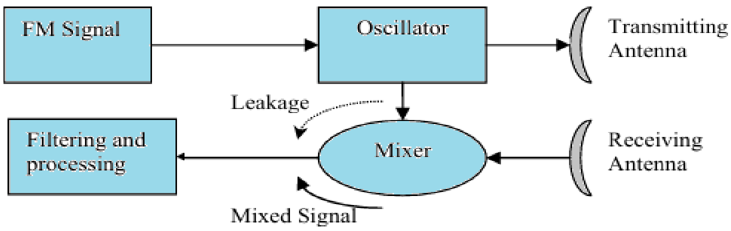

Figure 3 Block diagram of a simple FM-CW radar**.**

Equation (4) describes a general form of a transmitted FM (Frequency Modulated) continuous wave (CW) radar signal. The equation is given as:

$$s_r(t) = Acos(\theta_t(t)) \qquad (4)$$

Equation (5) describes the received radar signal $s_r(t)$ after it has interacted with an object and is given as:

$$s_r(t) = A_r(t-\tau)cos(\theta_t(t-\tau) + \emptyset_0) \qquad (5)$$

In (5) A_r denotes the amplitude of the received signal in relation with delay τ, in order to reflect the effect of many different scatterers from different ranges.

$\emptyset_0$ is the phase difference due to reflection. The mixed signal $s_m(t)$ is obtained from multiplication of (4) and (5) as:

$$s_m(t) = A_m(t,\tau)cos(\emptyset_d(t) - \theta_t(t-\tau)) - \emptyset_0) + A_l U_d(t) \qquad (6)$$

where ($\emptyset_d$ is phase and $U_d(t)$ is the amplitude of the leakage signal from the transmitter and $A_l$is the leakage gain.

In (6), the first term carries the information about the range and the relative speed of object. The second term is an unwanted signal and it is one of the major problems in range determination [6] [8].

c. **Multiple-Input Multiple-Output MIMO**

Time Division Multiplexing Multiple-Input Multiple-Output (TDM MIMO) is a widely used technique in radar systems as figure (4), particularly in Frequency-Modulated Continuous-Wave (FMCW) radars, to separate signals transmitted from multiple transmit (TX) antennas by allocating distinct time slots for each antenna's transmission within a frame. This temporal orthogonality allows the receiver (RX) antennas to distinguish signals from different TX antennas effectively [9].

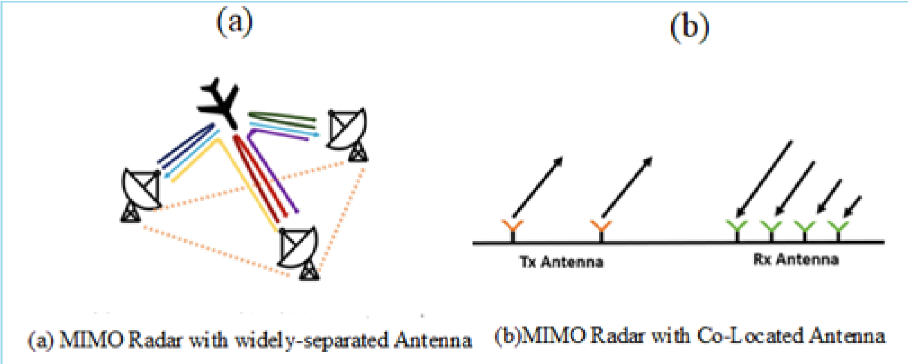

Figure 4 (a)MIMO Radar with widely-separated Antenna and (b)MIMO Radar with Co-Located Antenna.

- **Basic Principles to TDM –MIMO**

  - Each TX antenna transmits an orthogonal FMCW waveform in its dedicated time slot Utilizes frequency-modulated signals to measure the range and velocity of targets. The precise distance measurements can be obtained because the frequency of the transmitted signal is continuously varied [10][11].
  - The RX antennas pick up all TX antenna echoes, while the signals associated with every TX antenna are separated because of time multiplexing.[10].
  - The measurements from all TX-RX pairs are combined to form a virtual array, which has a larger aperture and thus higher angular resolution than the physical array alone. Because TDM transmits sequentially, the transmit pattern is broad without beamforming, allowing simultaneous illumination of the entire field of view (FOV). The receive array then performs beamforming to resolve target directions [12][10].
  - Signal processing involves applying 2D FFTs (range-Doppler processing) for each TX-RX pair to generate range-Doppler maps, which are then combined non coherently for target detection. The angle of arrival (direction) is estimated via angle FFT on detected peaks after Doppler correction [12].
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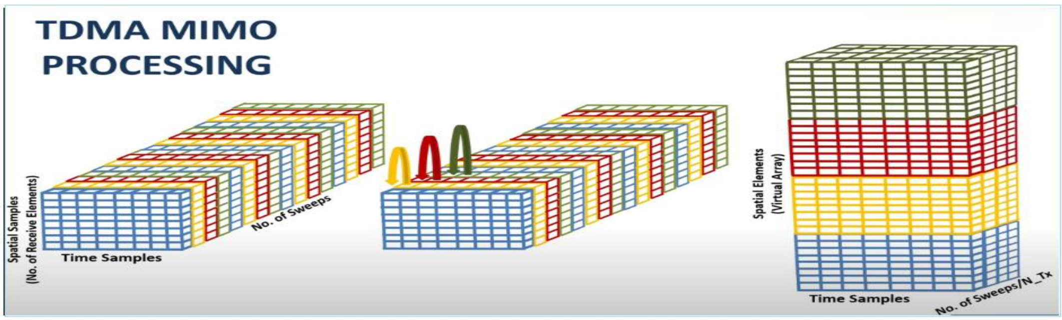

Figure 5 TDMA-MIMO Processing: Spatial and Temporal Sampling Framework.

Table 1 IPCE Algorithm vs. Traditional Methods.

Novel Aspect	Description
MIMO Virtual Array Integration	Optimized for TDMA-MIMO virtual arrays while preserving spatial coherence and attenuating side lobes due to sparse spatial sampling.
Adaptive Iteration with CFAR	During the suppression process of the side lobe using CFAR, the detection threshold is adaptively adjusted, so that the number of false alarms is reduced and the sensitivity of the weak target is maintained.
Phase Error Mitigation	Compensates for phase errors due to TDMA switching by iterative phase misalignment calibration during peak cancellation.
Doppler-Aware Processing	Suppresses the side lobes effectively in the Doppler-azimuth domain for high-speed targets
Scalable Non-Coherent Accumulation	It increases the SNR by combining non-coherently received radar frames while keeping detection performance consistent with varying observation times.

III. Methodology

The methodology for high-resolution target detection in the TDMA-MIMO FMCW millimeter-wave radar system is structured as follows:

1. **System Architecture and Virtual Array Formation**
The system employs a TDMA-MIMO architecture, where multiple transmit (TX) antennas sequentially emit orthogonal FMCW chirps in distinct time slots. This time separation guarantees that signals are orthogonal at RX antennas, allowing the echoes from each TX-RX pair to be decoded coherently. The signals from all TX-RX pairs are combined to synthesize a virtual array and a larger aperture size. The virtual array has NT × NR elements, leading to large angular resolutions in azimuth and elevation dimensions. The spatial sampling scheme (Figure 5) demonstrates how temporal and spatial diversity is utilized to acquire fine structure images.

2. **Signal Acquisition and Preprocessing**
ADC Data Generation: The radar captures raw ADC data from reflected signals, which includes in-phase (I) and quadrature (Q) components (Figure 6 Dual-channel IQ sampled signals are used, which retain the phase and amplitude information, and are necessary for estimation of the range and velocity.

- Range FFT: a 1-D Fast Fourier Transform (FFT) is performed along the ADC samples to separate targets in the range domain. The range resolution ΔR is given by the system bandwidth B:
$\Delta R = c/(2B)$ (7)
- Doppler FFT: A second FFT across consecutive chirps extracts Doppler shifts, enabling velocity estimation. The Doppler resolution Δv is given by:
$\Delta \boldsymbol{v} = \frac{\boldsymbol{\lambda}}{2\boldsymbol{T_F}}$ (8)
where λ is the wavelength and $\boldsymbol{T_F}$ is the total time of a frame.

3. **Range-Azimuth Spectrum Generation**
A 2-D (range and azimuth) range-azimuth spectrum is formed by spatial processing (Figure 8):

- MUSIC algorithm: It uses MUSIC for the super-resolution angle-of-arrival (AoA) estimation to separate closely spaced targets.
• Virtual Array Beamforming: With the virtually composed array, high resolution of azimuth angle estimation can be achieved through the application of FFT or subspace-based methods in the antenna domain.

4. **Target Detection and Parameter Constant False Alarm Rate (CFAR) Detection:** A CFAR algorithm processes measurements (Figure 10) that automatically adjust the threshold for the measured power level to avoid false alarms from the background noise. Guard and reference cells are also designed to provide an appropriate trade-off between sensitivity and false alarm rate.

- **Iterative Peak Component Elimination (IPCE):** This reduces the impact of side lobe interference by identifying and suppressing dominant peaks in the angular spectrum, iteratively enhancing the detection performance.

- To increase the signal-to-noise ratio (SNR) and improve speed estimates, Multiple frame Doppler maps are added.

By analyzing the (IQ) signal in (Figure 6), range-azimuth imaging (Figure 8), and CFAR detection (Figure 10), we found this methodology ensures precise spatial and velocity parameter estimation, demonstrating robustness in complex multi-target environments

IV. Experimental Results and Discussion

Figure 6 provides a dual-channel comparison of the in-phase (I) and quadrature (Q) components of the radar signal. I and Q Signals Sinusoidal: waves 90° out of phase, used to preserve both amplitude and phase information for target detection. Shows how the radar processes I/Q signals to resolve target characteristics.

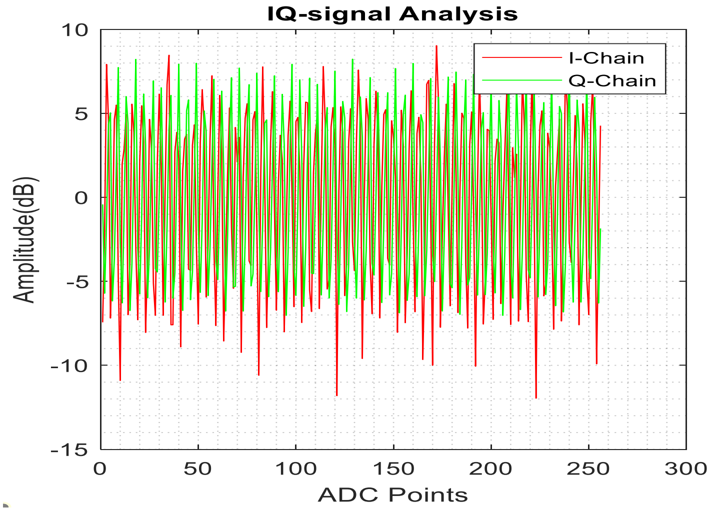

Figure 6 IQ-signal Analysis.

Figure 7. provides a Target Distance Distribution that displays a signal amplitude (dB) concerning target range (in meters). Detected targets show up as peaks at certain distances. Free-space path loss results in an amplitude decrement with distance. Illustrates the radar's capability to detect targets at different distances where stronger reflections (closeness of targets) result in taller peaks, and the strongest demonstrably signify the greatest detection values.

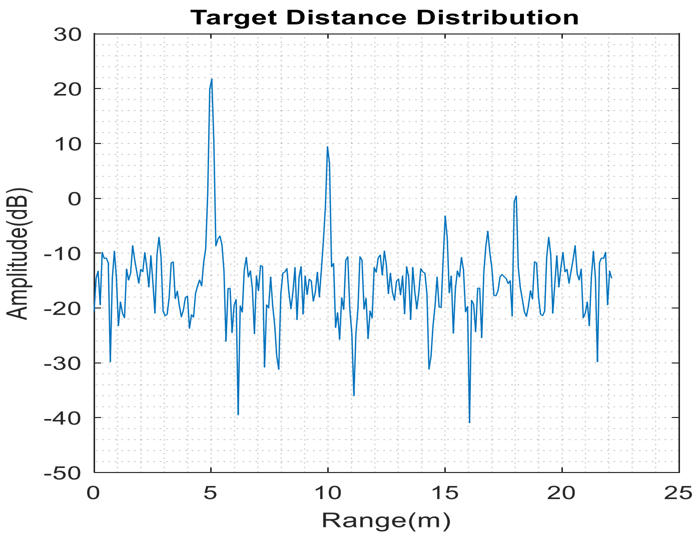

Figure 7 Target Distance Distribution.

Figure 8 Range-Azimuth Spectrum provides range (meters) on one axis and azimuth angle (degrees) on the other. Bright spots (high intensity) indicate detected targets at specific range-azimuth coordinates. The azimuth axis shows angular resolution, while the range axis is linear. Clusters of peaks suggest multiple targets at the same distance but positioned around different angles. The figure captures the effectiveness of the radar in resolving the spatial distribution of the targets.

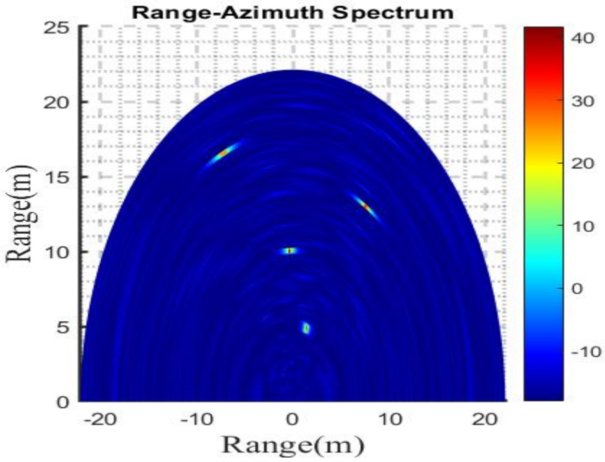

Figure 8 Range-Azimuth Spectrum.

Figure 9 provides a Target range-Doppler distribution, where a visualization range (meters) is provided on one axis and Doppler frequency (velocity) on the other. Clear indications of targets within a specific range and speed are visible in the form of bright dots.

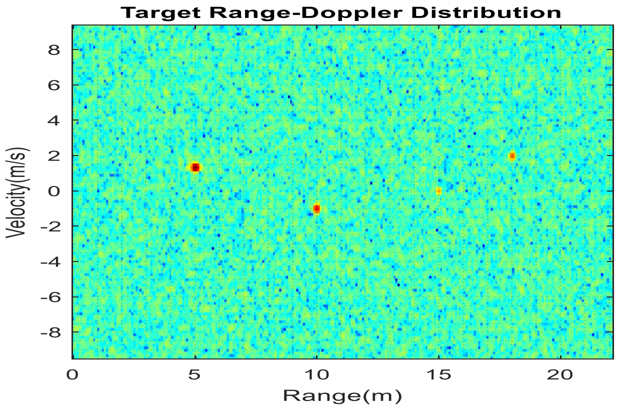

Figure 9 Target Range-Doppler Distribution.

Figure 10 provides the target CFAR Detection Result. detected targets after applying the Constant False Alarm Rate (CFAR) algorithm. Threshold lines suppress noise and clutter while highlighting valid targets. Detected targets are marked as peaks above the adaptive threshold. Demonstrates how CFAR improves detection reliability by reducing false alarms in varying noise environments.

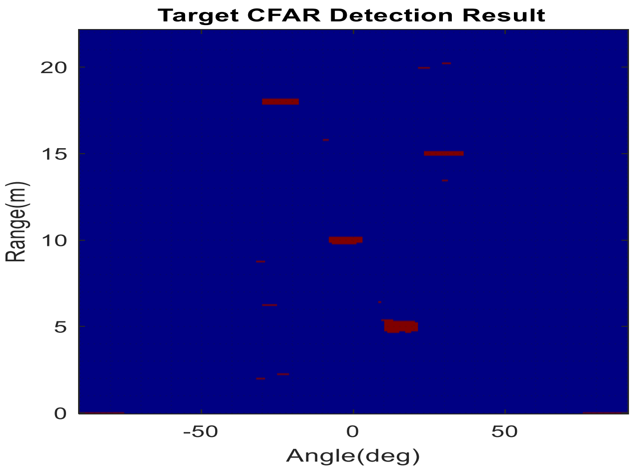

Figure 10 Target CFAR Detection Result.

Conclusion

The study demonstrates the achievement of high-precision target detection and parameter estimation using a TDMA-MIMO FMCW millimetre wave radar system. The system integrates the TDMA technique with MIMO to suppress side lobes through IPCE and 2D-FFT-based range-Doppler processing, which mimics a virtual antenna array, significantly improving the angular resolution in the pseudo range-Doppler-azimuth domains. The results of the experiment confirm the system's efficacy in resolving targets with high precision via IQ signal evaluation, range-azimuth spectral analysis, and Doppler map distribution assessment defined by spatial decorrelation filtering. Constant false alarm rate CFAR detection integrated in contrast enhances mistake-free target detection, while non-coherent accumulation increases estimation of target velocity. All of these contributions highlight the system's effectiveness in scenarios requiring the extraction of spatial and velocity parameters in real time, like in the case of security surveillance or aircraft detection. where provides a scalable solution for future enhancements in radar imaging and multi-target tracking.

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