Sensor Applications

A Novel Hybrid TDMA-DDMA Approach for Imaging Automotive Radar Systems

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Abstract—In this paper, we propose a novel hybrid time-division multiple access (TDMA) and doppler-division multiple acess (DDMA) model for cascaded radar systems, targeting high-resolution automotive radar applications. By leveraging the Texas instruments AWR2243 radar sensor, configured in a cascaded multiple-input multiple-output (MIMO) arrangement, we demonstrate the advantages of combining TDMA and DDMA for enhanced performance in both velocity resolution and range accuracy. Conventional TDMA and DDMA approaches suffer from inherent trade-offs between maximum unambiguous velocity, Doppler resolution, and frame rate. Our hybrid method dynamically toggle between TDMA and DDMA activation patterns, achieving a balance between these metrics. Through theoretical analysis and experimental validation, we show that our model improves Doppler resolution while maintaining a competitive frame rate and range resolution. The proposed hybrid solution is particularly advantageous for scenarios where both high velocity measurements and high angular resolution are critical, such as in advanced driver-assistance systems (ADAS) and autonomous driving. This approach provides a flexible and efficient means of optimizing radar performance without compromising key system parameters, as supported by our experimental results and theoretical calculations.

Index Terms—FMCW Radar, High-Resolution Radar, Antenna Activation, TDMA-DDMA, Radar Sensing.

I. INTRODUCTION

Frequency-modulated continuous wave (FMCW) radar systems have become an integral part of modern automotive sensing applications due to their ability to deliver precise range, velocity, and angular resolution for multiple targets simultaneously [1], [2]. With advancements in multiple-input multiple-output (MIMO) techniques, radar systems now exploit the benefits of virtual arrays, significantly enhancing spatial resolution by using a combination of fewer physical antennas [3], [4]. Despite these advancements, there are still inherent challenges when using traditional time division multiple access (TDMA) and doppler division multiple access (DDMA) methods, particularly when applied to large cascaded systems like the Texas instruments (TI) AWR2243 [5], [6].

In TDMA-based systems, each transmit antenna is sequentially activated to maintain orthogonality between the transmitted signals, thereby constructing a virtual antenna array [7]. While this approach effectively improves angular resolution, the sequential nature of transmission increases the overall frame time, leading to reduced update rates, which can be detrimental in fast-moving environments [2]. Moreover, longer transmission times reduce the maximum unambiguous velocity that can be measured, as the system becomes more susceptible to Doppler aliasing [8].

Besides, DDMA mitigates the time-based limitations by differentiating signals through distinct Doppler frequencies, allowing multiple transmit antennas to be active simultaneously [9]. However, as the number of antennas increases, Doppler ambiguities can arise, limiting velocity resolution and creating challenges in handling multiple fast-moving targets [10]. Additionally, DDMA's simultaneous activation of multiple antennas can introduce cross-talk between Tx channels and degrade the overall system's performance if not carefully managed [9].

To address the limitations of conventional TDMA and DDMA techniques, we propose a novel hybrid antenna activation scheme that combines their respective strengths. This method, implemented on a cascaded AWR2243 radar platform [6], divides the physical antenna array into two groups. Each group utilizes DDMA for simultaneous transmissions to maximize the number of virtual elements within the group. The groups are then time-separated via TDMA, allowing data from each group to be coherently combined to form an extended virtual antenna array. This approach enhances angular resolution and extends the spatial aperture while maintaining the inherent Doppler resolution determined by the total measurement time. Each DDMA transmission within a TDMA slot retains unique velocity information, allowing effective velocity estimation. However, relying solely on DDMA for velocity estimation is challenging due to Doppler ambiguities, reduced coherent integration time, and coupling between angular and velocity measurements. Our proposed method achieves a balance between transmission time and virtual channel density that is specifically tailored to maximize system performance under practical constraints. This balance ensures high frame update rates, improved spatial resolution, and accurate velocity estimation. By combining the complementary strengths of TDMA and DDMA, the method leverages the trade-off between achieving high angular resolution (through increased virtual channels) and maintaining sufficient coherent integration time for accurate Doppler velocity estimation.

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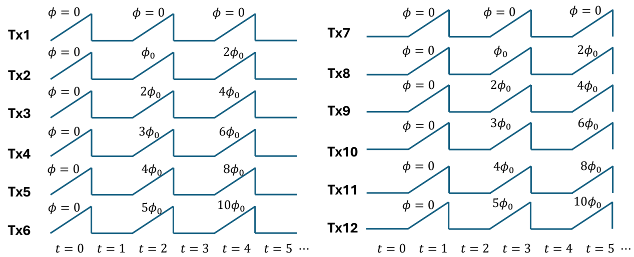


Fig. 1: TDMA and DDMA groups are used in the hybrid approach. The frequency varies over time for each of the 12 transmitters (Tx), with phase shifts between chirps for the same transmitter noted. Both groups start simultaneously, but their activation alternates.

These improvements are demonstrated in comparison to systems using only TDMA or only DDMA, showing enhanced performance by addressing limitations inherent to each technique [11].

This paper outlines the development and field validation of this hybrid TDMA-DDMA activation scheme. Through theoretical analysis, we demonstrate that our proposed method achieves superior performance compared to pure TDMA or DDMA approaches. Especially, in scenarios requiring both high-resolution imaging and fast frame updates.

The main contributions of this paper are as follows: (1) Introduces a hybrid antenna activation scheme that combines TDMA and DDMA strengths by dividing the antenna array into two groups, each transmitting simultaneously with DDMA and time-separated via TDMA. (2) Proposes an end-to-end signal processing pipeline for the newly introduced activation scheme to generate high-resolution point cloud. (3) The hybrid method optimizes the use of transmission time by leveraging the complementary strengths of TDMA and DDMA. While maintaining a fixed number of chirps per transmit antenna to ensure a specific Doppler resolution, the method enables more efficient use of available time slots, allowing for more frequent data refresh and improved real-time tracking of fast-moving targets. (4) The proposed system reduces Doppler ambiguities through DDMA, enabling more precise velocity estimation while maintaining the inherent velocity resolution defined by the total measurement time.

II. SYSTEM DESIGN

A. Hybrid TDMA-DDMA Antenna Activation Method

The key idea of our hybrid approach is to divide the transmit antennas into two groups, with each group being activated simultaneously using DDMA as shown in Figure 1. A time-division separation is introduced between the two groups to avoid interference between the transmissions. By employing this strategy, we achieve a balance between high angular resolution, efficient transmission times, and robust velocity discrimination.

In our implementation using the TI AWR2243 radar, which supports 12 transmit antennas and 16 receive antennas, the 12 transmit antennas are divided into two groups, each with 6 antennas:

- Group 1: $\{Tx_1 - Tx_6\}$
- Group 2: $\{Tx_7 - Tx_{12}\}$

In the first step of the transmission cycle, Group 1 is activated using DDMA. Each of the 6 antennas in this group transmits simultaneously, but the signals are differentiated using distinct Doppler shifts. The Doppler signature for each antenna in the group is defined by a unique phase shift, calculated as:

$$\phi_i = (i-1) \cdot \frac{2\pi}{8}, \quad \text{for } i = 1, 2, \ldots, 6$$

where ϕ_i is the phase shift for antenna i; for example, Tx_1 has a phase shift of 0 and Tx_2 has a phase shift of $\phi_0 = \frac{2\pi}{8}$ and so on.

After the transmission from Group 1 is completed, a time separation is introduced before Group 2 is activated. This time separation follows the principles of TDMA and ensures that the signals from Group 1 and Group 2 do not overlap, avoiding interference. After the time delay, Group 2 is activated using DDMA, following a similar pattern to Group 1. The phase shifts for Group 2 are given by:

$$\phi_i = (i-7) \cdot \frac{2\pi}{8}, \quad \text{for } i = 7, 8, \ldots, 12$$

This hybrid approach allows us to benefit from both TDMA and DDMA simultaneously. By activating multiple antennas within each group using DDMA, we reduce the total transmission time compared to the TDMA approach, preserving the radar's update rate and enabling the detection of high-velocity objects. At the same time, TDMA simplifies the construction of the virtual array by ensuring signal orthogonality between the two groups, which enhances the angular resolution in practical implementations. Although DDMA could theoretically achieve comparable angular resolution by carefully adjusting phase increments for multiple simultaneous transmitters, this introduces significant phase ambiguities and increased signal processing complexity, particularly in cascaded radar systems. These challenges limit the practicality of the DDMA in many automotive radar scenarios, highlighting the value of our hybrid method.

This combination of TDMA and DDMA balances the trade-offs between spatial and velocity resolution. The system achieves high angular resolution by leveraging the expanded virtual array created by TDMA, while DDMA ensures efficient use of transmission time and enables better discrimination of target velocities. The resulting radar system can detect targets with high resolution in both angular and Doppler domains, while ensuring accurate velocity estimation. This makes it highly suitable for automotive applications such as autonomous driving, where real-time performance and precise target detection are critical.

B. Proposed Signal Processing Pipeline

The proposed hybrid TDMA-DDMA radar signal processing pipeline is shown in Figure 2 and includes the following steps:

1) **Input Data ($N_s \times N_c \times N_{ch}$)**: The input data comprises radar returns from multiple samples (N_s), chirps (N_c), and channels (N_{ch}). A typical input size is $512 \times 512 \times 32$, with each channel corresponding to a receiver element in the radar array. The data undergoes several processing stages to extract valuable target information.
2) **Range FFT (RFFT)**: RFFT is applied along the range axis to transform the time-domain signals into the range domain. After this transformation, the data becomes $N_R \times N_c \times N_{ch}$, where N_R represents the range bins (e.g., $512 \times 512 \times 32$).
3) **Doppler FFT (DFFT)**: DFFT is performed along the Doppler axis to extract velocity information by measuring Doppler shifts

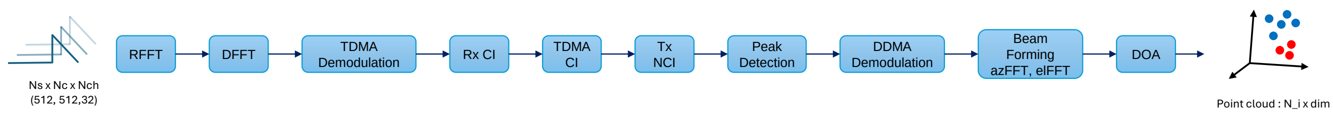


Fig. 2: Hybrid TDMA-DDMA implementation block diagram.

caused by moving targets. After this step, the data is formatted as $N_\mathrm{R} \times N_\mathrm{D} \times N_\mathrm{ch}$, where N_D denotes the Doppler bins (e.g., $512 \times 512 \times 32$).

4) **TDMA Demodulation**: TDMA demodulation separates the signals transmitted by different transmit antennas, which are assigned unique time slots. The output data has dimensions $N_\mathrm{R} \times N_\mathrm{D} \times N_\mathrm{ch} \times \mathrm{txG}$ (e.g., $512 \times 512 \times 16 \times 2$), where txG indicates two groups of transmit antennas.
5) **Receiver Coherent Integration (Rx CI)**: CI is performed on signals received from multiple channels, preserving phase information to enhance the signal-to-noise ratio (SNR) and improve the detection of weak targets. The output data format becomes $N_\mathrm{R} \times N_\mathrm{D} \times N_\mathrm{TxG}$ (e.g., $512 \times 512 \times 2$), where N_TxG represents transmit groups.
6) **TDMA Coherent Integration (CI)**: CI is also applied across the transmit channels following TDMA demodulation, further enhancing the SNR. The output data is reduced to $N_\mathrm{R} \times N_\mathrm{D}$ (e.g., 512×512), representing range-Doppler bins.
7) **Non-Coherent Integration (Tx NCI)**: NCI is performed across the transmit channels, where each channel corresponds to a specific section of the range-Doppler map derived from distinct transmit antenna activations. The magnitudes of these sections are combined without preserving phase information. This step improves detection by increasing SNR. The resulting data size is $N_R \times N_D$ (e.g., 512×64), with a reduced number of Doppler bins due to the combination process.
8) **Peak Detection**: A peak detection algorithm identifies significant signals representing potential targets. A binary mask is created to mark the detected peaks. The mask maintains the same size as the input data, $N_\mathrm{R} \times N_\mathrm{D}$ (e.g., 512×64), indicating the presence of targets in the range-Doppler plane.
9) **DDMA Demodulation**: DDMA demodulation separates the signals transmitted by different antennas based on Doppler shifts. The output format becomes $N_i \times N_\mathrm{ch}$ (e.g., $N_i \times 192$), where N_i represents the number of detected targets and N_ch is the number of channels.
10) **Beamforming (azFFT and elFFT)**: Azimuth and elevation beamforming are applied using azimuth FFT (azFFT) and elevation FFT (elFFT) to enable the estimation of azimuth and elevation of the targets. The resulting data is of size $N_i \times az \times el$ (e.g., $N_i \times 256 \times 12$), where 256 and 12 represent the number of azimuth and elevation steps, respectively, and azimuth and elevation information is processed for each detected target.
11) **Direction of Arrival (DoA) Peak Detection**: Direction of Arrival (DoA) peak detection identifies the precise azimuth and elevation angles of the detected targets, effectively reducing the output data to N_i, where each peak corresponds to one detected target. This provides 3D localization with output dimensions $N_i \times az \times el$ (e.g., $N_i \times 256 \times 12$).
12) **Point Cloud Construction**: A 3D point cloud is generated to represent the detected targets. Each point in the cloud corresponds to a detected object with attributes such as range, velocity, azimuth, and elevation. The point cloud has the format $N_i \times dim$, where $dim = 4$ corresponds to these four attributes.

C. KPIs for Each Antenna Activation Scheme

In the proposed models, several radar parameters remain common across TDMA, DDMA, and the hybrid approach, including the number of chirps, which is equal for all TXs. In contrast, derived parameters like Pulse Repetition Interval (PRI), velocity resolution, maximum velocity, unambiguous Doppler, Doppler resolution, and frame rate vary by modulation type, as given in Table 1.

T_PRI is defined as the time between the start points of consecutive chirps and includes the chirp duration (T_chirp), idle time (T_idle), and the ADC start time ($T_\mathrm{ADC\_start}$):

$$T_\mathrm{PRI} = T_\mathrm{chirp} + T_\mathrm{idle} + T_\mathrm{ADC\_start}$$

In the TDMA approach, the T_idle is longer due to the sequential activation of the antennas, resulting in a higher T_PRI. In contrast, DDMA reduces T_idle by simultaneously activating multiple antennas, leading to a shorter T_PRI. The hybrid model alternates between TDMA and DDMA patterns, achieving intermediate T_PRI values.

The velocity resolution (V_res) depends on the number of chirps per frame (N_chirps) and PRI. It is given by:

$$V_\mathrm{res} = \frac{\lambda}{2 N_\mathrm{chirps} T_\mathrm{PRI}}$$

where λ is the wavelength. A longer T_PRI in TDMA reduces V_res, resulting in improved velocity resolution, while the shorter T_PRI in DDMA increases V_res, allowing for higher frame rates. The hybrid approach offers a balance by leveraging both T_PRI and N_chirps, achieving a trade-off between velocity resolution and frame rate.

The maximum measurable velocity (V_max) is inversely related to the PRI and is calculated as:

$$V_\mathrm{max} = \frac{\lambda}{4 T_\mathrm{PRI}}$$

In the DDMA approach, the shorter T_PRI allows for a higher V_max, whereas TDMA's longer T_PRI limits V_max. The hybrid approach provides an intermediate maximum velocity, balancing between the two schemes.

Lastly, the frame length (T_frame) is given by the product of the number of chirps and the PRI:

$$T_\mathrm{frame} = N_\mathrm{chirps} \times T_\mathrm{PRI}$$

The hybrid approach achieves a balance between Doppler resolution, maximum measurable velocity, and frame update rates by leveraging the advantages of both TDMA and DDMA. While DDMA's shorter T_PRI allows for higher frame rates and maximum measurable velocity, TDMA provides better Doppler resolution due to its longer T_PRI. The hybrid model offers an intermediate solution, reducing T_frame compared to TDMA while maintaining sufficient Doppler resolution and ensuring higher frame update rates than pure TDMA. Key performance indicators (KPIs) are detailed in Table 1.

Table 1: Radar KPIs' comparison for TDMA, DDMA, and Hybrid Approach.

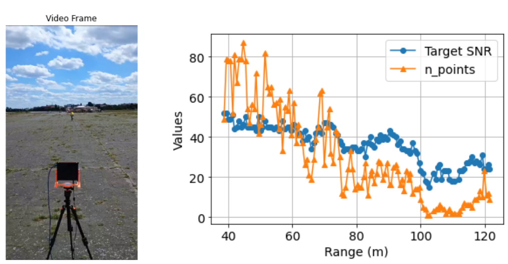
Parameter Type	Parameter	Unit	TDMA	DDMA	Hybrid
Common Parameters	Start Frequency f_{start}	GHz	76	76	76
	Bandwidth B	MHz	600	600	600
	Sampling Rate f_s	MHz	20	20	20
	Ramp Slope s	MHz/µs	23.44	23.44	23.44
	Chirp Duration T_{chirp}	µs	34.6	34.6	34.6
	Chirps/Frame N_{chirps}	-	512	512	512
	Samples	-	512	512	512
Derived Parameters	PRI T_{PRI}	µs	415.2	34.6	69.2
	Velocity Resolution V_{res}	m/s	0.00928	0.1114	0.0557
	Max Velocity V_{max}	m/s	2.38	28.51	14.30
	Max Unambiguous Doppler $f_{D,\text{max}}$	Hz	1204.57	14450.87	7236.41
	Doppler Resolution $f_{D,\text{res}}$	Hz	4.71	56.45	28.22

III. EXPERIMENTAL RESULTS

A. Field Measurements with The Pipeline

We designed and conducted several field experiments to assess the performance of the radar in terms of angle, range, and velocity. Fig. 3, demonstrate the successful implementation and evaluation of the proposed hybrid TDMA-DDMA activation scheme on the AWR2243 radar. Fig. 3(a) shows the setup where a bicycle moving away from the radar sensor from a starting distance of 10 meters to a final distance of 122 meters. This configuration allows us to evaluate the radar's performance across a wide range of distances for a moving weak target.

The Fig. 3(b) highlights the number of detected points for only bicycle and signal-to-noise ratio values (SNR) for the target across different frames or range. As the bicycle moves farther from the radar, the number of detected points decreases, which is expected as the radar's ability to detect an object degrades with range. However, the number of points remains sufficient for accurate detection, even at longer distances. This demonstrates the system's robustness in detecting objects across varying ranges. Similarly, as the target moves further away, the SNR values decrease; however, the proposed activation scheme ensures that the SNR remains sufficiently high for reliable detection over most of the range.



(a) (b)

Fig. 3: Hybrid activation measurement: (a) setup, (b) point cloud analysis showing target SNR and number of detections.

For the azimuth accuracy tests, we aimed to evaluate the radar module's azimuthal performance, targeting an accuracy of 1 degree around a 0-degree azimuthal orientation. During the tests, the radar was positioned on a calibrated rotating platform, directed at a 0 dBsm reflector placed 30 meters away. We incrementally varied the azimuthal angle of the radar's main beam in 1-degree steps within a ±5-degree range. To facilitate data analysis, a 2-meter 3D bounding box was placed around the region of interest in the radar's point cloud. The results of the azimuthal accuracy test are shown in Fig 4. The green lines in the figure indicate the acceptable range, specified as 0.9 degrees, while the red line represents zero error. It can be observed that the angle detection is nearly within the acceptable range in almost all cases, with a mean absolute error of 0.79 degrees and a standard deviation of 0.84 degrees. This deviation may stem from inaccuracies in the measurement setup.

Overall, these results validate the effectiveness of the proposed hybrid TDMA-DDMA activation method. The data shows a balanced performance in terms of both target detection and SNR maintenance across a wide range of distances, thereby confirming the suitability of our approach for real-world radar applications using the AWR2243.

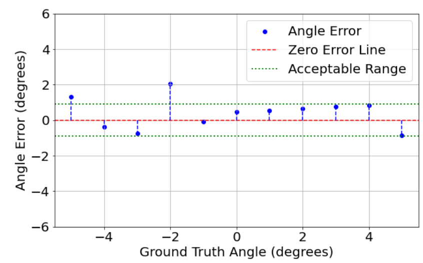


Fig. 4: Angular accuracy of the radar.

IV. CONCLUSION

Our proposed hybrid TDMA-DDMA scheme offers several key benefits for radar systems, particularly in automotive applications. 1) The hybrid approach results in a higher update rate, reducing the overall transmission time and enabling the radar to refresh data more frequently for real-time tracking of fast-moving targets. 2) Enhanced velocity estimation is achieved through DDMA's Doppler diversity, minimizing Doppler ambiguities and allowing for accurate velocity measurements. Finally, the combination of efficient transmission times and high-resolution detection ensures that the system achieves the desired frame rates required for automotive radar systems.

REFERENCES

[1] J. Hasch et al., "Millimeter-wave technology for automotive radar sensors in the 77 GHz frequency band," *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 3, pp. 845–860, 2012.

[2] S. M. Patole et al., "Automotive radars: A review of signal processing techniques," *IEEE Signal Process. Mag.*, vol. 34, no. 2, pp. 22–35, 2017.

[3] S. Tilli et al., "MIMO radar technology for automotive applications: Challenges and opportunities," *IEEE Sens. J.*, vol. 20, no. 23, pp. 14370–14380, 2020.

[4] M. Hanle et al., "MIMO radar technology for advanced driver assistance systems," *IEEE Int. Conf. Microwaves Commun. Antennas Electron. Syst. (COMCAS)*, 2018.

[5] Texas Instruments, "AWR2243: 76–81 GHz high-performance automotive radar sensor," Datasheet, [Online]. Available: https://www.ti.com/product/AWR2243.

[6] Texas Instruments, "Cascading radar systems: TIDEP-01012 reference design," [Online]. Available: https://www.ti.com/tool/TIDEP-01012.

[7] S. Gogineni, "FMCW Radar for Advanced Driver Assistance Systems," *IEEE Access*, vol. 7, pp. 88887-88894, 2019.

[8] Z. Li et al., "Advanced FMCW radar signal processing for automotive applications," *IEEE Trans. Veh. Technol.*, vol. 70, no. 3, pp. 2345-2355, 2021.

[9] J. Gao, "High-resolution automotive radar using DDMA," *IEEE Trans. Microw. Theory Techn.*, vol. 68, no. 10, pp. 4567–4575, 2020.

[10] Y. Li, et al., "Addressing the challenges of DDMA in automotive radar," *IEEE Access*, vol. 9, pp. 14678-14690, 2021.

[11] F. Xu et al., "Transmit beamspace DDMA based automotive MIMO radar.," *IEEE Transactions on Vehicular Technology*, vol. 71, no. 2, pp. 1669–1684, 2021.

[12] A. Kazemi et al., "Advanced radar signal processing using cascaded architectures for MIMO radar," *IEEE Sens. Lett.*, vol. 6, no. 1, pp. 76–82, 2022.