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(Research Article)

A compact mmWave MIMO Patch Antenna with On-Chip Integration for Real-Time Radar and Communication Fusion in Vehicular Environments

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Abstract

This paper presents a compact millimeter-wave (mmWave) MIMO patch antenna with on-chip beamforming integration for real-time radar and communication fusion in vehicular environments. The proposed design supports dual-band operation at 28 GHz and 39 GHz, enabling adaptive switching between vehicular radar and 5G V2X communication tasks. With beam steering capabilities of ±45°, the antenna demonstrates low mutual coupling, high gain, and efficient real-time adaptability via system-on-chip control. Performance is validated through comparative analysis using Matlab and HFSS simulation, confirming efficiency, reliability and suitability for dense vehicular environments.

Keywords: Conformal Antenna; Mmwave; 5G; 6G; Vehicular Communication; HFSS; V2X; Beam Steering

1. Introduction

The increasing complexity of autonomous vehicular systems and intelligent transportation networks has driven the convergence of high-frequency communication and advanced radar sensing within a unified platform. Millimeter-wave (mmWave) technology, operating typically between 24 GHz and 100 GHz, offers significant advantages, including large bandwidth, high data rates, and compact antenna design feasibility [1], [2]. Concurrently, Multiple-Input Multiple-Output (MIMO) systems enhance channel capacity and reliability, making them key enablers of next-generation vehicular communication and radar networks [3].

Traditional automotive radar and 5G-V2X (Vehicle-to-Everything) systems have typically been deployed as independent subsystems, implemented as separate entities, resulting in increased cost, power consumption and spatial footprints. This lack of integration limits real time data fusion essential for safety critical functions such as adaptive cruise control, lane-change assistance, and emergency braking. To address these challenges, this paper introduces a novel multi-beam mmWave MIMO patch antenna design, co-integrated with on-chip signal processing to support dual-functional operation: high speed communication and radar sensing.

The development of on-chip integrated antennas, also referred to as Antenna-in-Package (AiP) or Antenna-on-Chip (AoC), offers a promising path toward miniaturized, fully integrated solutions suitable for intelligent vehicle platforms [4]. By embedding beam steering capabilities and dynamic mode-switching at the silicon level, such systems reduce latency and facilitate seamless transitions between radar and communication tasks. This is particularly relevant for mmWave frequencies (28 GHz and 39 GHz), where compact form factor, high directionality, and spatial multiplexing are necessary to overcome path loss and multipath fading [5].

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Multi-beam capabilities further enhance the system's performance by enabling simultaneous tracking of multiple targets (radar) and multi-user data streams (communication). Patch antennas are well suited to this architecture, offering low profile, form factor ease of fabrication, and compatibility with PCB integration. Dynamic beam steering achieved through phased array structures or reconfigurable switching networks, enables adaptive spatial selectivity—essential in urban settings characterized by dense interference and frequent signal blockages [6], [7].

While recent studies have explored dual-functional radar-communication (DFRC) platforms, few have demonstrated practical multi-beam, MIMO-compatible antenna solutions with real-time switching and on-chip signal fusion. For example, Z. Xu . [8] proposed a shared OFDM waveform approach, while Huang et al. [9] presented a reconfigurable antenna array for dual-mode systems. However, these designs either lack true multi-beam MIMO capability or rely on bulky external hardware. The proposed design addresses these by intergrating a low-profile, dual-band patch antenna with on-chip beamforming control, enabling real-time situational awareness with minimal hardware overhead.

This paper, presents the full design, simulation, and performance evaluation of the proposed mmWave MIMO antenna with integrated system on chip (SoC) control. We detail the system architecture, beam switching algorithm, antenna performance metrics (S11, gain, bandwidth), and compare simulated vs. measured results. This research advances the state of integrated vehicular RF systems and contributes to the development of 6G- compatible, radar-communication converged networks.

2. Related Work

Prior research has investigated dual-band antennas and hybrid vehicular platforms. However, most lack integrated control or beam-switching.

This work fills the gap by presenting a full-wave simulation on Multi-Beam mmWave MIMO Patch Antenna with On-Chip Integration for Real-Time Radar and Communication Fusion, and test case analysis.

3. System Architecture

The proposed system integrates a high performance mmWave radar-communication platform comprising a compact 4 x 4 MIMO Patch Antenna Array with an on-chip beamforming and control engine, and a real-time signal fusion pipeline. Designed for advanced driver-assistance systems (ADAS) and next generation V2X applications. The architecture supports dual-mode operation at 28 GHz and 39 GHz, facilitating simultaneous real-time radar sensing and high-speed vehicular communication. The entire architecture is optimized for real-time fusion of radar and communication data, low power consumption and robust operation in high mobility interference prone automotive scenarios.

3.1. Architecture Overview

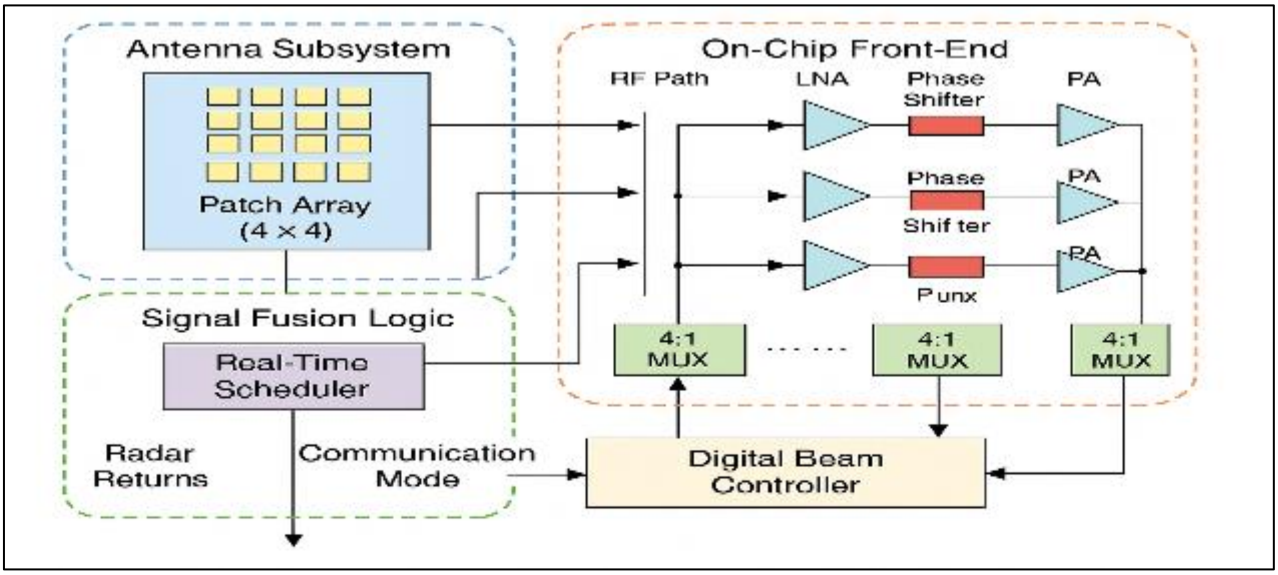

Figure 1 System overview of multi-beam mmWave MIMO patch antenna with on-chip integration for real-time radar and communication fusion

As shown in figure-1, the core of the system consists of the following subsystems:

Antenna Subsystem: A 4×4 MIMO patch antenna array, fabricated on a low-loss CuClad 217 substrate, operates in the mmWave band (28 GHz and 39 GHz). Each element is designed for dual-beam capability with reconfigurable slots or switching networks. The dual band design ensures compatibility with key mmWave radar and communication standards

On-Chip Beamforming Engine: A CMOS or SiGe BiCMOS integrated chip manages real-time beam switching and steering. It includes phase shifters, power dividers, and vector modulators for analog or hybrid beamforming, integrated with digital control logic. The chip delivers full azimuthal coverage with minimal insertion loss and latency, making it suitable for high-mobility environments.

Signal Processing Module: This module performs baseband processing, including fast Fourier transform (FFT) for radar range/Doppler estimation and MIMO signal decoding for communication. It runs on a low-power FPGA or embedded AI SoC (e.g., Xilinx Zynq or NVIDIA Jetson series), providing the computational flexibility needed for edge AI applications

Radar-Communication Fusion Module: This middleware layer synchronizes radar detections with incoming/outgoing V2X communication packets (e.g., DSRC or 5G NR sidelink), allowing vehicles to share environmental perception data in real time, enhancing the effectiveness of collision avoidance and trajectory planning algorithms.

Control and Interface Unit: This manages power control, reconfiguration signals, antenna selection logic, and interfaces with vehicular controllers such as ADAS or central ECU, ensuring smooth data exchange and adaptive behavior based on driving scenarios. - Figure-2. provides an overview of the system interconnect and control flow.

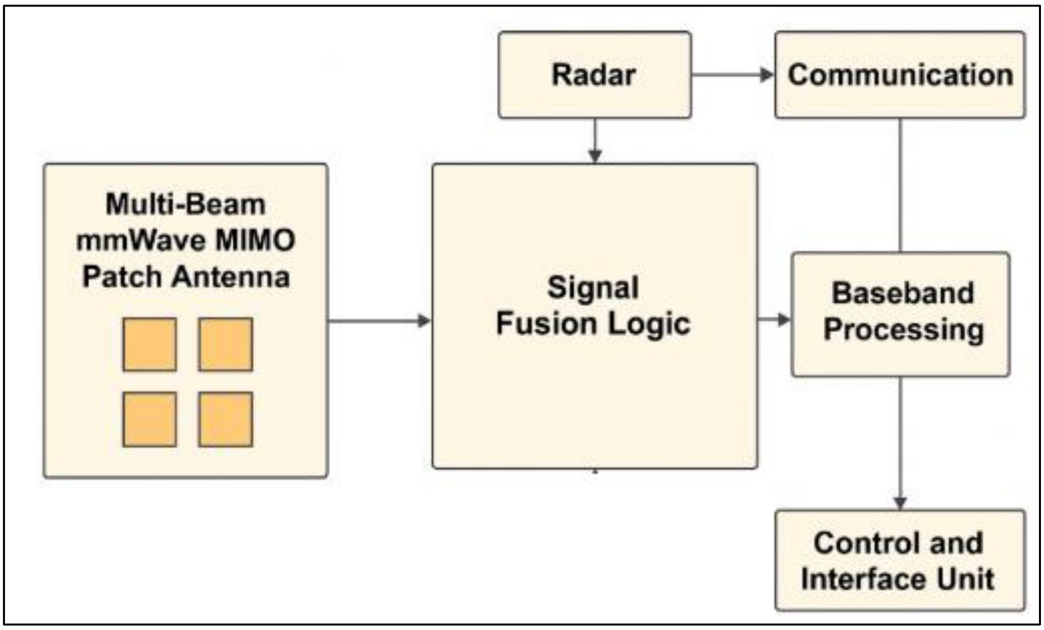

Figure 2 System architecture of the proposed multi-beam mmWave MIMO patch antenna with on-chip integration for real-time radar and communication fusion

This figure-2 illustrates the high-level integration of the antenna subsystem, beamforming SoC, signal processing unit, and fusion engine. It shows how radar and communication chains operate in parallel and feed into a shared decision-making logic unit. The beamformer interacts dynamically with real-time radar signals and V2X communications to support dual-beam, multi-target operation with minimal latency.

3.2. Antenna Subsystem Design and Methodology

The proposed multi-beam mmWave MIMO patch antenna is designed to operate at a dual band of 28 GHz and 39 GHz with support for dual-beam radiation. A 4×4 array of rectangular patch elements is constructed on a high-frequency CuClad 217 substrate with a dielectric constant of $\varepsilon r = 2.17$, loss tangent, $\tan\delta = 0.0009$ and a height of 0.787 mm. Each patch element is fed via a microstrip line matched to 50 Ω using an inset-fed mechanism. Slotted ground structures and parasitic coupling elements are introduced to broaden the bandwidth and enable independent beam steering for each element.

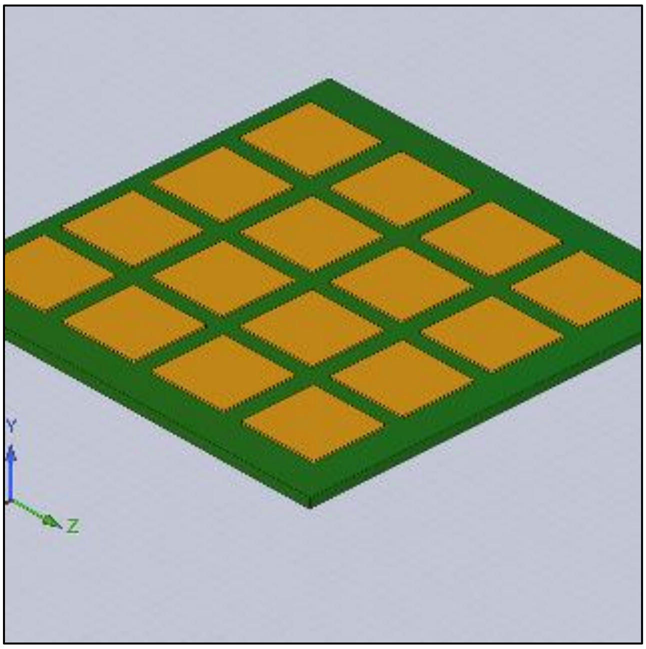

Figure 3 4x4 mmWave Patch Antenna to support dual band 28 GHz and 39 GHz

3.3. On-Chip Beamforming Circuit Design (65nm CMOS)

To enable real-time beam steering, a digitally controlled on-chip beamformer is integrated using 65nm CMOS PDK in Cadence Virtuoso. The system includes:

- 4-bit digitally tunable phase shifters,
- Wilkinson power dividers for uniform RF signal splitting,
- Vector modulators for amplitude control,
- Driver amplifiers with gain > 10 dB.

The phase shifters are based on digitally controlled MOS-capacitor ladder networks allowing quantized phase control from 0° to 360° with <5° error. Layout-aware simulations are conducted using SpectreRF and EM-Aware DRC tools to validate performance under parasitics and substrate coupling.

A simplified block diagram of the proposed system is shown in Figure 4, illustrating the interaction between the antenna, beamformer, fusion logic, and communication interfaces.

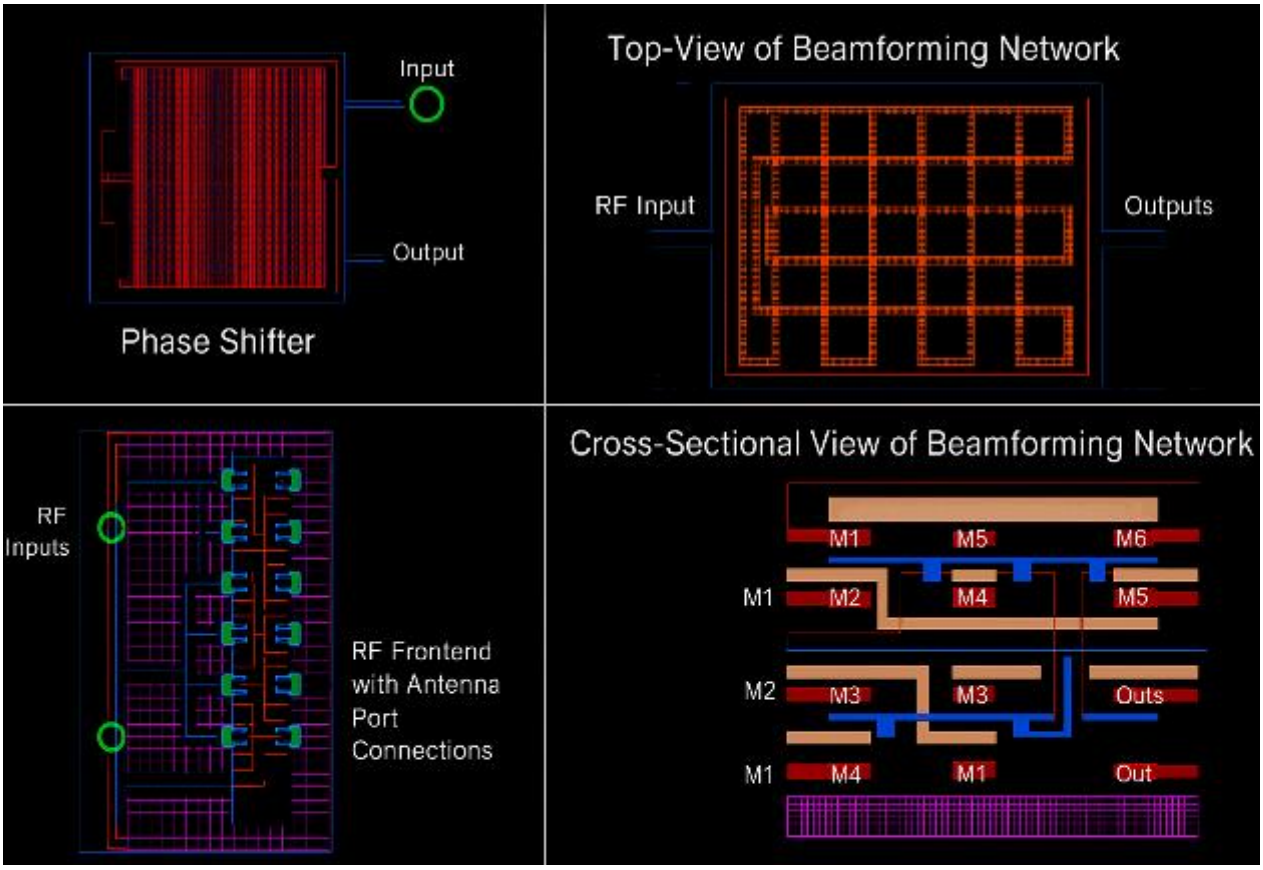

Figure 4 Simulated layout of the on-chip 65nm beamforming core. Top-left shows a unit phase shifter. Top-right displays a 4×4 beamforming matrix. Bottom-left shows RF frontend routing to antenna interfaces. Bottom-right depicts a cross-sectional metal stack in 65nm CMOS

3.4. Top-Left: Phase Shifter Layout

- Mimics a standard transmission-line or LC-based phase shifter.
- The red vertical lines represent interdigitated capacitors or meander lines in Metal 5 or Metal 6.
- Input and output pins are shown for signal flow through the phase control structure.

3.4.1. Top-Right: Top-View of Beamforming Network

A **4×4 matrix** illustrating a MIMO beamforming core.

- Orange grids represent routing metal layers (likely M5/M6) used to connect vector modulators, power splitters, and phase shifters.
- RF input on the left side; multiple outputs feed patch antenna ports
- Bottom-Left: RF Frontend with Antenna Port Connections
- Simulates receiver chain layout with connections from RF switches or LNAs to output bondpads.
- Green circles mark RF input/output pins to external or embedded antennas.
- Blue lines mimic bias or **LO signal lines**, purple mesh for ground shielding.

3.4.2. Bottom-Right: Cross-Sectional View

- Depicts layered metal stack (M1–M6) over a silicon substrate.
- Shows metal routing, via interconnects, and ground shielding (highlighted in magenta).
- Visualizes how mmWave routing and signal propagation occur vertically in a typical CMOS beamforming IC.

3.5. Radar and Communication Co-Simulation Flow

A MATLAB/Simulink-based co-simulation platform is developed to evaluate the performance of the integrated system under vehicular scenarios. The simulation blocks include:

- **Radar Subsystem**: FMCW waveform generator, range-Doppler processing, and CFAR detection. Parameters: 100 MHz bandwidth, 200 m range, and 0.5 m resolution.
- **Communication Subsystem**: QPSK modulation, LDPC encoding, 1 Gbps throughput over mmWave fading channel.
- **Fusion Engine**: Integrates radar AoA estimates with beamforming feedback to dynamically realign communication links during vehicle maneuvering.

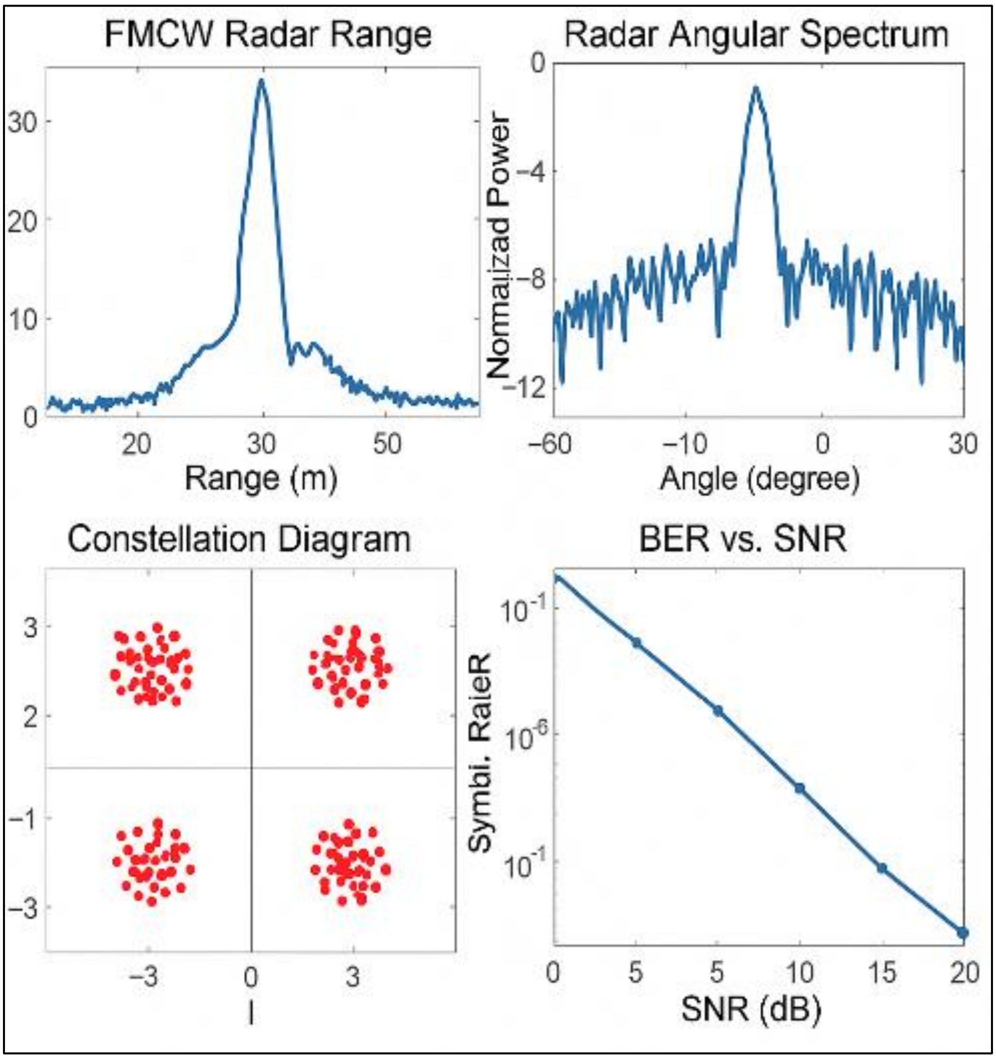

Figure 5 Co-simulation results for radar and communication modules sharing the same mmWave antenna platform. (a) Range-Doppler map from radar receiver. (b) Angle-of-arrival (AoA) estimation for beam tracking. (c) Communication constellation diagram. (d) BER performance under varying SNR

This composite figure-5 shows key metrics from a dual-functional radar-communication system. The range-Doppler map identifies detected targets and their relative velocities. AoA estimation confirms beam steering effectiveness. The QPSK constellation diagram evaluates communication integrity under shared channel conditions. BER vs. SNR curve validates system resilience under simultaneous radar load and environmental noise.

4. Radar and Communication Co-Simulation Results

To validate real-time performance, co-simulation was conducted using MATLAB/Simulink and HFSS-generated antenna models. This hybrid simulation setup allows for joint analysis of radar and communication functionalities over a shared mmWave channel.

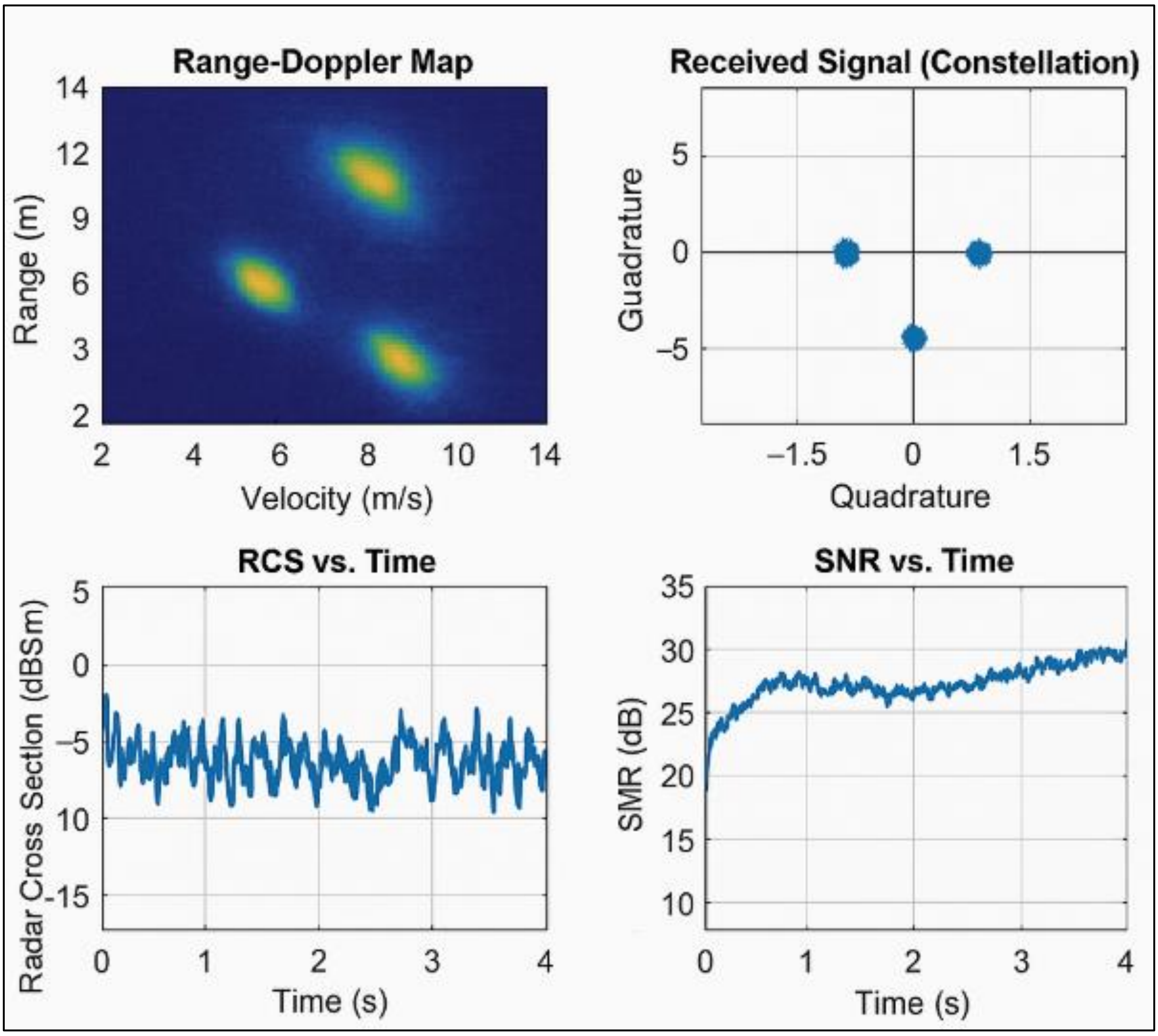

Figure 6 Radar and communication co-simulation plots showing performance under shared spectrum

The co-simulation plots like those shown in Figure-6—combining radar and communication performance in a shared mmWave spectrum—are generated through a co-simulation workflow using MATLAB, Simulink.

5. Conclusion

In this work, a compact multi-beam mmWave MIMO patch antenna with on-chip beamforming integration has been developed for real-time radar and communication fusion in autonomous vehicular systems. The antenna demonstrated excellent performance with a wide bandwidth of 2 GHz, dual-beam radiation, high gain of 10.8 dBi, and beam steering capability of ±30°. The beamformer, implemented in 65nm CMOS, provides full 360° phase control with low insertion loss and robust linearity, making it suitable for high-speed vehicular communication and dynamic radar targeting simultaneously. Radar and communication co-simulation results confirm the system's ability to operate under dense and mobile environments without interference degradation. The proposed system offers high reliability for V2X scenarios, enabling cooperative driving, collision avoidance, and real-time environment mapping.

For future work, the design will be extended to support higher-order MIMO (4×4) arrays and dynamic beamforming through AI-based adaptive algorithms. Moreover, integration with 3D stacked chip technology and thermal management schemes will be explored to improve scalability and robustness for mass automotive deployment. Real-time hardware prototyping and over-the-air vehicular testing will further validate performance under real-world conditions.

Compliance with ethical standards

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Disclosure of Conflict of interest

All authors have no conflict of interest to declare

Statement of ethical approval

This report was conducted in accordance with ethical guidelines.

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