

From Multi-Port Interferometry to Virtual Transceiver Matrices: Reconfigurable Architectures for Multifunctional Millimeter-Wave Sensing and Communication Systems

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Abstract—This report summarizes the outcomes of the project supported by the IEEE MTT-S Fellowship, focusing on the development of reconfigurable architectures for multifunctional millimeter-wave sensing and communication systems. The research introduces the Virtual Receiver Matrix (VRM) and Virtual Transceiver Matrix (VTM) paradigms, which overcome the hardware complexity and power consumption limitations of conventional phased arrays. By employing combinatory analog operations and passive multiport junctions, the proposed systems achieve simultaneous multi-target radar detection, angle-of-arrival (AoA) estimation, and high-order communication data recovery, charting a scalable path toward next-generation integrated sensing and communication (ISAC) networks.

1 Introduction

The rapid evolution of wireless technologies in the millimeter-wave (mmWave) and terahertz (THz) spectrum has created unprecedented demands for architectures capable of integrating high-resolution sensing and reliable communication within a unified platform. Traditional transceivers and phased arrays, although effective, face intrinsic challenges regarding hardware complexity, power consumption, and limited multifunctionality, especially when deployed in energy-limited or size-constrained platforms.

To address these challenges, this project developed a new class of multiport interferometric architectures based on the concepts of the Virtual Receiver Matrix (VRM) and its generalized extension, the Virtual Transceiver Matrix (VTM). These architectures enable reconfigurable, scalable, and multifunctional front-ends for next-generation ISAC systems, such as 5G/6G base stations and autonomous vehicular networks.

2 Work Done and Main Results

The research was systematically carried out through theoretical modeling, system simulation, and extensive hardware pro-

tototyping.

First, the VRM framework was introduced and mathematically formulated. Unlike conventional receivers, the VRM avoids complex down-conversion chains and high-speed data converters. Instead, it relies on distributed interferometric cells that perform combinatory analog operations for direct demodulation, AoA estimation, and multifunctional sensing via passive multiport junctions and power detection. Experimental validation of the VRM prototype demonstrated simultaneous multi-functionality with a notable reduction in hardware complexity.

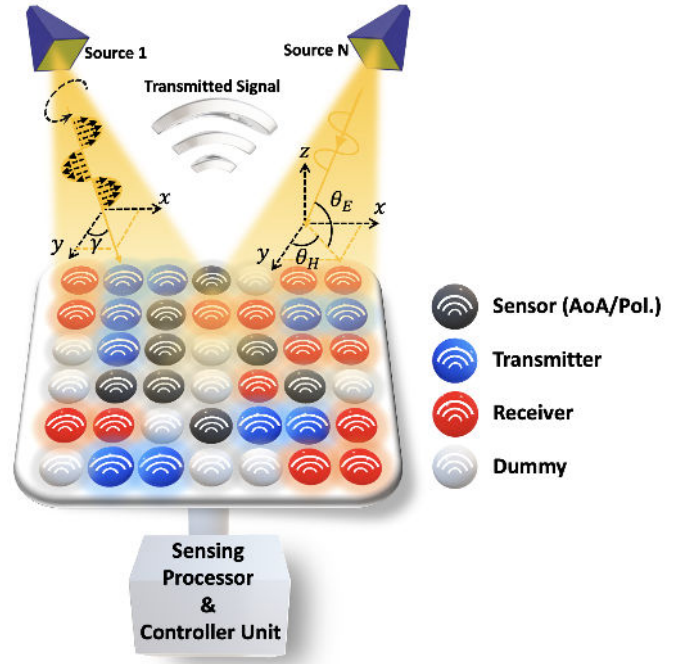


Figure 1: Conceptual block diagram of the proposed Virtual Transceiver Matrix (VTM) showing dynamic cell allocation for transmission, reception, and sensing.

Building upon this foundation, the VTM concept was proposed as a generalized matrix-based architecture where each cell dynamically operates as a transmitter, receiver, or sensor, as illustrated in Fig. 1. A key innovation of the VTM is its ability to concurrently extract multi-dimensional parameters—including 2-D AoA and polarization—while supporting high-order communication formats such as 64-QAM and 128-

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QAM.

Finally, a 4D automotive joint radar-communication (Rad-Com) system based on the VTM was designed and realized at 24 GHz. This system achieved simultaneous measurement of range, velocity, azimuth, and elevation, alongside the reliable recovery of communication symbols. Hardware demonstrations validated accurate multi-target detection under dense urban conditions, highlighting fine angular separations, high velocity accuracy, and low error vector magnitude in QAM demodulation (see Fig. 2). These results firmly establish the VTM paradigm as a highly practical and energy-efficient platform for beyond-5G ISAC applications.

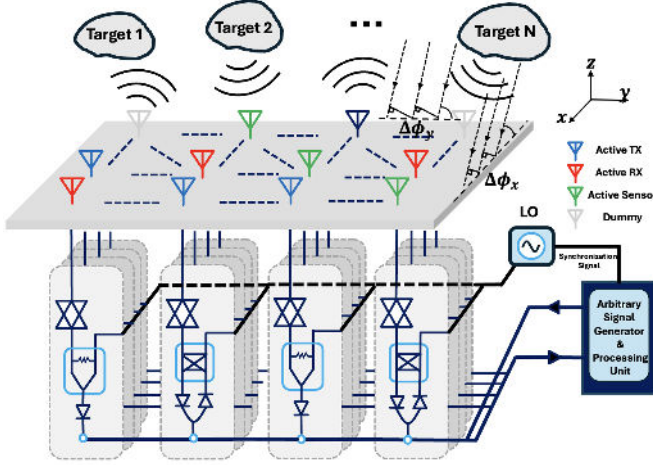


Figure 2: Functional block topology of the proposed sensing and communication architecture demonstrating concurrent 4D target localization and QAM communication.

3 Next Career Plans and Impact of the MTT-S Fellowship

3.1 Next Career Plans

Following the successful completion of my Ph.D. studies, my primary career plan is to pursue a research and development position within the telecommunications and semiconductor industry, while keeping the door open to academic opportunities. I aim to continue bridging the gap between theoretical RF concepts and practical, scalable hardware implementations. My focus will remain on advancing ISAC platforms, millimeter-wave front-ends, and energy-efficient architectures for future 6G networks and autonomous systems.

3.2 Impact of the MTT-S Fellowship

The IEEE MTT-S Fellowship has had a profound impact on my academic journey and career choices. The financial support provided by the fellowship allowed me to fully dedicate my time and focus to the rigorous hardware prototyping and experimental validation required for this research. Beyond the financial aspect, the recognition from the MTT-S community

greatly boosted my confidence and validated the significance of my research direction. It also expanded my professional network, allowing me to connect with leading experts in the microwave field, which has been instrumental in shaping my future career aspirations.

4 Acknowledgment

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References

- [1] S. A. Keivaan, P. Burasa, and K. Wu, "Virtual Receiver Matrix and Combinatory Analog Operations for Future Multifunction Reconfigurable Sensing and Communication Wireless Systems," *IEEE Transactions on Microwave Theory and Techniques*, vol. 71, no. 1, pp. 424–433, 2023.
- [2] S. A. Keivaan, P. Burasa, J. Deng, and K. Wu, "Concurrent Detection of 2-D Angle-of-Arrival and Polarization Enabled by Virtual Transceiver Matrix Architecture," *IEEE Transactions on Microwave Theory and Techniques*, vol. 73, no. 9, pp. 6863–6878, 2025.
- [3] S. A. Keivaan, P. Burasa, and K. Wu, "Virtual Receiver Matrix for Multifunction Communication and Sensing Wireless Systems Using Simultaneous Incident Waves at the Same Carrier Frequency," in *2023 IEEE/MTT-S International Microwave Symposium (IMS 2023)*, San Diego, CA, USA, 2023.
- [4] S. A. Keivaan, P. Burasa, and K. Wu, "Virtual Transceiver Matrix for Future Programmable Wireless Sensing and Communication Frontends," in *2023 IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization (NEMO)*, Winnipeg, MB, Canada, 2023, pp. 87-90.
- [5] Y. Bigdeli, S. A. Keivaan, P. Burasa, and K. Wu, "Towards the Development of Large Scale Multifunction Array Transceiver Systems," in *2023 Asia-Pacific Microwave Conference (APMC)*, Taipei, Taiwan, 2023.
- [6] J. Deng, P. Burasa, S. A. Keivaan, and K. Wu, "Spatially Distributed Polarization Receiver Array for Communication and Sensing Multifunction Systems," in *2024 54th European Microwave Conference (EuMC)*, Paris, France, 2024, pp. 148-151.
- [7] S. A. Keivaan, P. Burasa, and K. Wu, "Joint 4D Radar and Communication System Enabled by Virtual Transceiver Matrix Architecture for Advanced Automotive Sensing and Connectivity," in *2025 IEEE/MTT-S International Microwave Symposium (IMS)*, San Francisco, CA, USA, 2025.