Design of Flexible MIMO Radar Sensors to Improve Angle Estimation

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***Abstract*—This report summarizes the research project "Design of flexible MIMO radar sensors to improve angle estimation," conducted as part of the Fellowship 2024. The goal was to design and evaluate a radar system for angle estimation with limited resources. The proposed concept utilizes frequency-dependent beam squint effects in a SISO radar system's transmit antenna to extract precise angular information. It includes simulations for range-Doppler analysis, leading to specific antenna requirements. A specialized 60 GHz leaky-wave antenna was designed, fabricated, and measured. Additionally, a digital signal processing concept was introduced as a basis for system evaluations.**

Project Description and Research Outcome

I. Introduction

The precise estimation of target angles is a key challenge in modern radar systems. Traditional (Multiple Input Multiple Output) MIMO approaches, which utilize multiple antenna elements, often come with high hardware complexity and increased power consumption. This report presents an innovative concept that achieves angle estimation in a (Single Input Single Output) SISO system by exploiting frequency-dependent beam squint effects. The overall system includes a simulation-based methodology for generating dynamic beam steering, the derivation of antenna requirements, the development of a leaky-wave antenna design, and a digital signal processing concept.

II. Overall Concept

Typically, beam squint generation and angular separation in radar systems rely on multiple antennas to evaluate the angle-dependent phase shifts of received signals. In this concept, however, this effect is realized using a simple SISO radar system. A 60 GHz FMCW radar chip is employed, featuring a single transmit and receive antenna. The static receiving antenna maintains a constant, frequency-independent main lobe, while the specially modified transmitting antenna generates a frequency-dependent beam squint—meaning the main lobe shifts across the frequency range. This frequency-dependent shift enables the differentiation of targets that are identical in range and velocity by analyzing variations in backscatter signal strength at different angles. [1]

A. Concept Simulation

A simulation framework was developed based on the generation of an FMCW signal that is transmitted over a discretized frequency scale. In each frequency segment, the transmitting antenna is rotated by a fixed angle (e.g., 2° per segment), resulting in a continuous scan of the radiation pattern.

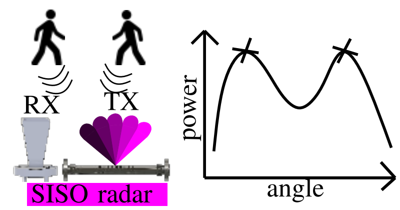

Fig. 1. Overall system concept.

B. Simulation Analysis

During the simulation process, the FMCW signal in each frequency segment is transformed into range-Doppler plots using a Fast Fourier Transform (FFT). A Constant False Alarm Rate (CFAR) detector is then applied to identify significant peaks. These peaks are combined across the entire scan range to form a power curve, where the maximum signal level consistently correlates with the optimal beam direction. The resulting power curve enables precise determination of the target angles.

C. Derivation of Antenna Requirements

The simulation results indicate that a large and precise beam squint is essential to differentiate target angles even when range and Doppler data are identical. Additionally, sufficient bandwidth must be maintained to avoid excessive degradation of range resolution. This trade-off leads to specific antenna design requirements: the beam squint should range between 40° and 55° within a frequency range of 55 GHz to 65 GHz, ensuring both accurate angular separation and precise distance resolution.

III. Antenna Development

A. Antenna Concept and Design

Based on the derived requirements, a specialized leaky-wave antenna design was developed for operation in the 55 GHz to 65 GHz frequency range. The design utilizes a parallel plate waveguide, where the lower plate remains smooth while the upper plate incorporates precisely arranged slots. These slots enhance the beam squint, which would be significantly smaller in a conventional slotted waveguide. Additionally, the antenna features two ports, effectively doubling the total scanning angle. Using a dual-port approach, each port provides an individual squint angle of approximately 21°, resulting in a total scan range of 42°. Furthermore, a tapered waveguide structure ensures optimal broadband impedance matching. [2]

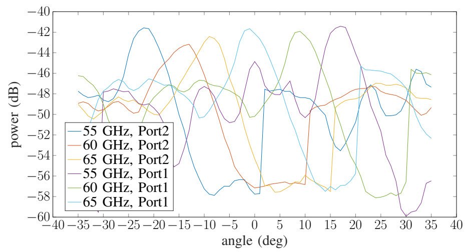

Fig. 2. Farfield measurement of the antenna at both ports in the frequency range from 55 GHz to 65 GHz.

B. Fabrication, Simulation, and Measurement

The developed antenna design was initially validated through electromagnetic simulations using CST Studio Suite. The simulations confirmed a consistent beam squint of approximately 2.1° per GHz and an antenna gain ranging between 13 dBi and 15 dBi. For practical implementation, the prototype was fabricated using stereolithography (SLA) 3D printing, followed by metallization via the Tollens reaction to achieve the necessary conductivity. Initial measurements confirmed that the fabricated antenna exhibits the expected beam squint characteristics along with low return loss.

IV. Signal Processing

A key innovation in this design is the integration of a second port, introduced to maximize the scanning angle of the entire antenna. In addition to increasing the squint angle, it is crucial to ensure that each bandwidth segment is sufficiently wide to prevent significant degradation of range resolution. During the azimuth scan, performed using a frequency ramp of the transmitted signal, the half-power beamwidth determines the duration for which the scanning beam illuminates the target. To optimize this process, the antenna is designed to utilize both ports, with a waveguide switch enabling seamless switching between them. By toggling the switch and altering the feeding direction, the antenna effectively achieves a virtual sweep bandwidth of 20 GHz, despite having a physical bandwidth of only 10 GHz. This approach results in a substantially increased bandwidth per target during beam scanning, providing a significant advantage in range resolution.

V. Conclusion

This report presented the overall concept for enhancing angle estimation using a frequency-scanning antenna. Simulations demonstrated that frequency-dependent beam squint effects can be effectively leveraged to extract precise angular information in a SISO radar system. Based on these findings, the derived antenna requirements were implemented in a specialized leaky-wave antenna design operating in the 60 GHz range. The antenna prototype was fabricated using 3D printing, simulated, and successfully measured. Additionally, a signal processing concept was introduced, incorporating range-Doppler plot analysis and power curve extraction. For the final implementation of the complete system and the completion of this dissertation, the PCB-to-antenna transition and final system measurements are currently in progress.

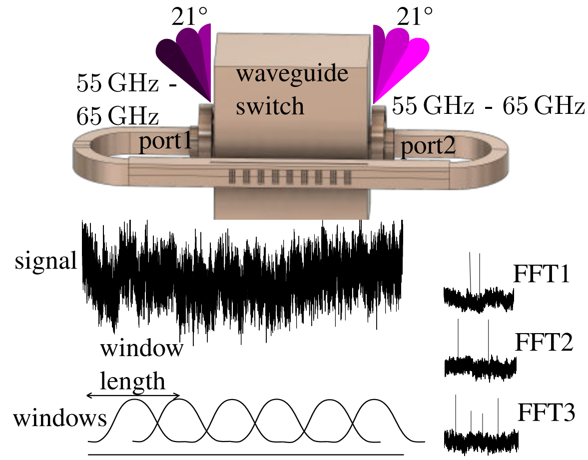

Fig. 3. Overview of the overall concept with waveguide switch.

VI. Impact of the Fellowship, IMS 2024 Experience, and Future Plans

I would like to express my sincere gratitude to IEEE MTT-S for supporting my research activities through the MTT-S Graduate Fellowship 2024. This recognition has further motivated me to advance my work in the field of high-frequency radar systems and explore new innovative approaches. The fellowship allowed me to attend IMS 2024 in Washington, which was an invaluable experience. The conference provided the opportunity to connect with leading experts and researchers from around the world, gaining deep insights into the latest research developments and technological advancements. The exchange with fellow researchers was particularly inspiring and gave me numerous new ideas for future projects. A major highlight was the success of my paper at Radio and Wireless Week 2025, which was developed as part of the fellowship and won the Student Paper Contest. As a result, I now have the opportunity to contribute an article to the *Microwave Magazine*. Additionally, I am currently preparing a journal paper on this topic, which I plan to submit by the end of the month. My next goal is to complete my Ph.D. this year and continue my scientific work in the field of radar systems. I look forward to expanding my research and developing innovative concepts in high-frequency technology. Finally, I would like to encourage all graduate students in microwave engineering to apply for the MTT-S Graduate Fellowship, as it provides an excellent opportunity to support one's research and establish international connections.

References

[1] J. Gabsteiger, T. Kurin, C. Dorn, A. Koelpin and F. Lurz, "Antenna Model and Simulation Platform for Angle Estimation with a SISO Radar System," 2024 21st European Radar Conference (EuRAD), Paris, France, 2024, pp. 192-195, doi: 10.23919/EuRAD61604.2024.10734874.

[2] J. Gabsteiger, D. Langer, C. Dorn, A. Koelpin and F. Lurz, "60 GHz Leaky-Wave Antenna Design for SISO Radar Systems with Angle Estimation," 2025 Radio Wireless Symposion (RWS), San Juan, Puerto Rico, 2025