Low-cost software-controlled phase shifting network for generating spatiotemporally variable waveforms

Kobe Prior, Aidan Malensek, Matthew Dodd, and Atef Z. Elsherbeni
Colorado School of Mines, Colorado, USA
kdprior@mines.edu, aidan_malensek@mines.edu, mdodd@mines.edu, aelsherb@mines.edu

***Abstract*—The design of a low-cost, reconfigurable phase shifting network is essential for enabling rapid prototyping and supporting educational and research applications related to antenna arrays. Such a network provides a flexible platform to generate spatiotemporally variable waveforms (STVWs), allowing researchers and students to explore advanced concepts in beamforming and array processing without the prohibitive cost of commercial hardware. By lowering barriers to experimentation, this approach accelerates innovation, hands-on learning, and facilitates the development of next-generation antenna array systems.**

Keywords—Phase Shifting Network; Orbital Angular Momentum (OAM); Spatiotemporally Variable Waveforms (STVWs)

I. Introduction

Prior work has demonstrated that uniform circular arrays (UCA) with progressive phase shifting can generate electromagnetic radiation carrying orbital angular momentum (OAM), closely resembling Laguerre-Gaussian beams [1]. Similarly, Hermite-Gaussian-like beams [2] and other spatiotemporally variable waveforms can be generated by selectively phasing antenna elements within an array. However, there are economic constraints that limit the study of real-world spatiotemporally variable waveforms (STVWs) because of the high cost and limited availability of multi-channel, high-resolution RF phase control hardware. This project aims to address this challenge by presenting a highly reconfigurable, low-cost platform for array phasing. The proposed system is intended to be rapidly reconfigurable to support different antenna systems as well as different excitation schemes through an easy-to-use software interface.

II. Background and Motivation

There are different ways to manipulate and encode information like time, frequency, phase, amplitude, and polarization. There is an additional degree of freedom unlocked by some STVWs: spatial distribution, which allows for information to be carried via electromagnetic radiation.

A. Communication Systems

This work is specifically concerned with structured waves carrying OAM beams with the general form $E(\phi) = E_0 e^{jl\phi}$, where $l \in \mathbb{Z}$ is the azimuthal mode index and $\phi \in [0, 2\pi]$ is the azimuth coordinate orthogonal to the propagation direction. For example, OAM beams with different modes are orthogonal, meaning that they do not interfere with one another, i.e., multiple OAM modes can be transmitted simultaneously over the same frequency channel [3]. The direct result is the potential for higher channel capacity wireless communication systems [4].

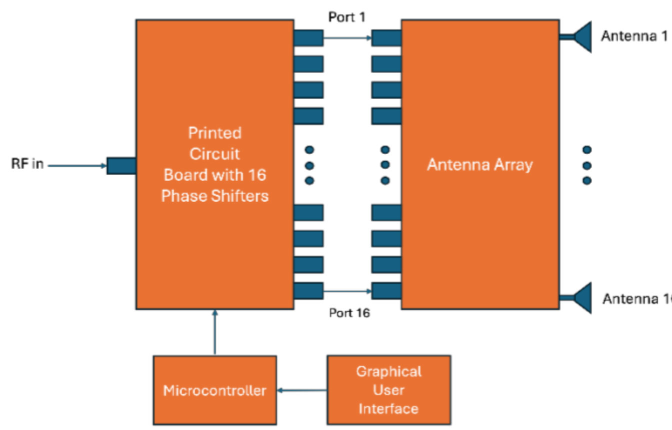

Figure 1: Block diagram of the 16-port phasing network.

B. Radar applications for STVWs

The additional spatial degree of freedom increases the information content of a radar pulse in systems using STVWs. In turn, the reflected energy contains more information about the target that can be used to construct images with higher resolution [5] or detect the angular velocity of the target [6]. These types of applications imply a relationship between the target geometry and the optimal STVW to illuminate it. For future research, as well as deployment, it is critical to have rapidly reconfigurable excitation systems with amplitude and phase variations.

C. Current Solutions for Generating OAM Beams

Alternative low-cost solutions for generating OAM beams and other STVWs include fixed feeding networks or spiral phase plates [3], meta-surfaces [7], and single-element designs [8], each with respective downsides. The major downside to fixed feeding networks, spiral phase plates, and meta-surfaces is the limited reconfigurability. Spiral phase plates and fixed feeding networks can only provide a single OAM mode based on the geometric configuration, and similarly, meta-surfaces have fixed mode outputs; although some meta-surfaces acting as transmit arrays can generate different modes depending on the incident polarization [9]. Single-element designs are simple and compact and potentially useful for some applications, but often lack high-gain characteristics and waveform reconfiguration capabilities desired in advanced radar systems, high-capacity data transmission, or long-distance communications.

III. System Design

The proposed system shown in Figure 1 would leverage 16 low-cost Peregrine Semiconductor PE44820 8-bit RF digital phase shifters, allowing for 256 different phase possibilities for each shifter on a custom printed circuit board, coupled with a microcontroller to allow the user to manually define the desired phase for each port or select from default phase excitations in a graphical user interface.

The system offers the key advantage of reconfigurability, enabling users to test an array under different phasing configurations or substitute different physical arrays or multi-fed antennas, thereby providing a means to validate simulated results. This will also reduce the prototyping cost and effort of testing multiple antenna array configurations, as the feeding network and electronics are manufactured separately from the antenna elements themselves. Another advantage of our phase shifting network is the bidirectionality, e.g., the system can work in transmit mode and receive mode.

A. Hardware Development

A total of 16 PE44820 digital phase shifters are used on a custom-fabricated printed circuit board, each requiring three serial control signals: serial in, clock, and latch enable. To minimize pin usage and to increase speed, the phase shifters are divided into two groups, each with an independent serial input S2 and S3 (S1 is occupied by USB communication with the microcontroller), a shared clock line, and a shared latch enable. This configuration allows the microcontroller to address two phase shifters nearly simultaneously.

The ADALM-PLUTO software-defined radio (SDR) can be used as an RF source to drive the phase shifting network directly or drive a transmit antenna to test the phase shifting network in receive mode. Since this SDR supports full-duplex operation with both transmit and receive ports and the phase shifting network is bidirectional, it provides a compact and all-encompassing solution. Considering a beam steering system with a 2D array, the SDR can be used in transmit mode to excite the antenna array while a separate receive antenna is physically moved to qualitatively map out the gain pattern under different phasing conditions. By reciprocity, the same approach can be applied in reverse, e.g., placing a transmit antenna at angular offsets θ and ϕ relative to the array center by iterating through phase combinations to determine the direction of maximum reception.

B. Software Development

To make the system easy to use for a variety of purposes, the control software will provide both a graphical user interface as well as a Python abstraction. This will allow for integration with automated test configurations or pre-programmed time-variant waveforms.

C. Educational Value

An educational use case for this system is the ability for an instructor to test several different arrays that students have designed and fabricated. These arrays could consist of up to 16 elements, which is more than enough to demonstrate beam steering or spatiotemporally variable waveform generation.

IV. Conclusion

To summarize, the proposed phase shifting network provides a low-cost, highly reconfigurable platform to research and prototype advanced antenna array systems, including the generation of spatial variant waveforms which have been largely financially inaccessible in the past. Additionally, the system is modular in nature, enabling the end user to swap out different antenna arrays, apply different phasing configurations, and use the antenna in both receive and transmit modes, all while offering an intuitive graphical user interface and Python Abstraction.

In the future, it would be valuable to integrate digital attenuators into the network to enable amplitude modulation in addition to phase shifting capabilities. This would be particularly useful in receive mode for reducing side lobe levels at steep steering angles, potentially by applying or replicating the deep learning methods presented in [10], but at a significantly lower cost.

References

[1] S. Tan, J. Dong, M. Wang, Z. Jiang, X. Zhuang, and L. Deng, ‘New Circular Array Configurations for Generating Orbital Angular Momentum (OAM) Beams’, in 2018 International Applied Computational Electromagnetics Society Symposium - China (ACES), 2018, pp. 1–2.

[2] H. Yao et al., ‘Patch Antenna Array for the Generation of Millimeter-Wave Hermite–Gaussian Beams’, IEEE Antennas and Wireless Propagation Letters, vol. 15, pp. 1947–1950, 2016.

[3] A. Papathanasopoulos and Y. Rahmat-Samii, ‘A Review on Orbital Angular Momentum (OAM) Beams: Fundamental Concepts, Potential Applications, and Perspectives’, in *2021 XXXIVth General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS)*, 2021, pp. 1–4.

[4] H. Jing, W. Cheng, X.-G. Xia, and H. Zhang, ‘Orbital-Angular-Momentum Versus MIMO: Orthogonality, Degree of Freedom, and Capacity’, in *2018 IEEE 29th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, 2018, pp. 1–7.

[5] J. Wang, K. Liu, H. Liu, K. Cao, Y. Cheng, and H. Wang, “3-D Object Imaging Method With Electromagnetic Vortex,” *IEEE Transactions on Geoscience and Remote Sensing*, vol. 60, pp. 1–12, 2022, doi: 10.1109/TGRS.2021.3069914.

[6] M. P. J. Lavery, F. C. Speirits, S. M. Barnett, and M. J. Padgett, “Detection of a Spinning Object Using Light’s Orbital Angular Momentum,” *Science*, vol. 341, no. 6145, pp. 537–540, Aug. 2013, doi: 10.1126/science.12399

[7] J. Xu *et al.*, ‘A Small-Divergence-Angle Orbital Angular Momentum Metasurface Antenna’, *Research*, vol. 2019, 2019.

[8] Q. Li, W. Li, J. Zhu, L. Zhang, and Y. Liu, ‘Implementing orbital angular momentum modes using single-fed rectangular patch antenna’, International Journal of RF and Microwave Computer-Aided Engineering, vol. 30, no. 5, p. e22165, 2020.

[9] L. Guan, Z. He, D. Ding, Y. Yu, W. Zhang, and R. Chen, ‘Polarization-Controlled Shared-Aperture Metasurface for Generating a Vortex Beam With Different Modes’, IEEE Transactions on Antennas and Propagation, vol. 66, no. 12, pp. 7455–7459, 2018.

[10] M. A. Abdullah, A. Zaib, S. U. Khan, S. Khattak, B. D. Braaten, I. Ullah, “Antenna Array Pattern with Sidelobe Level Control using Deep Learning”, Applied Computational Electromagnetics Society Journal, vol. 40, no. 5, pp. 428-435, May 2025.