

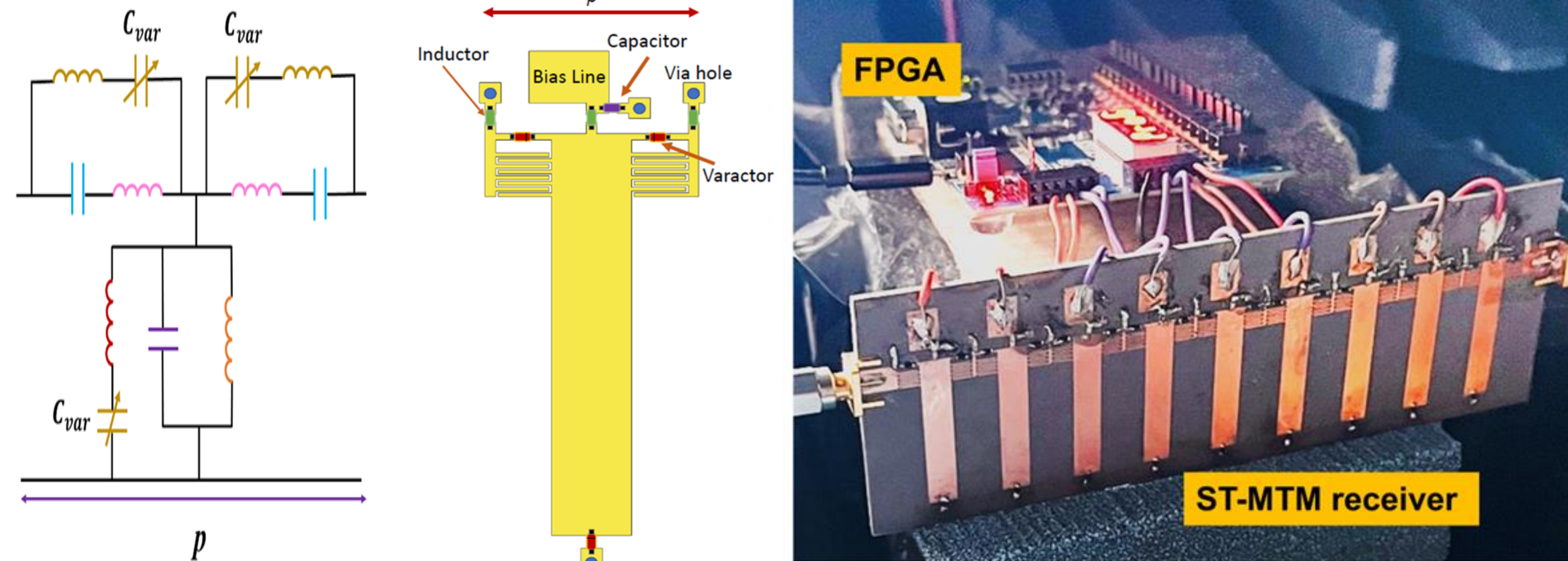
Summary

This project introduces space-time modulation for an array of metamaterial (MTM) unit cells and exploits their spatial dispersion control capability. The resulting system can provide not only dynamic control of radiation characteristics that allows for improved spectrum utilization, but also Physical Layer (PHY) Security for wireless links enabled by Directional Modulation (DM). The proposed research will also extend this functionality to PHY security in dense multipath environments, discuss mitigation of beam squint effects that bottleneck the extension of the system to wideband settings, explore secure multicast functionalities, and analyze channel estimation and classification techniques for this system. A hybrid model-based and learning-based approach (HyPhyLearn) is also proposed to conduct channel classification even under limited training samples for authentication.

Research Progress To Date

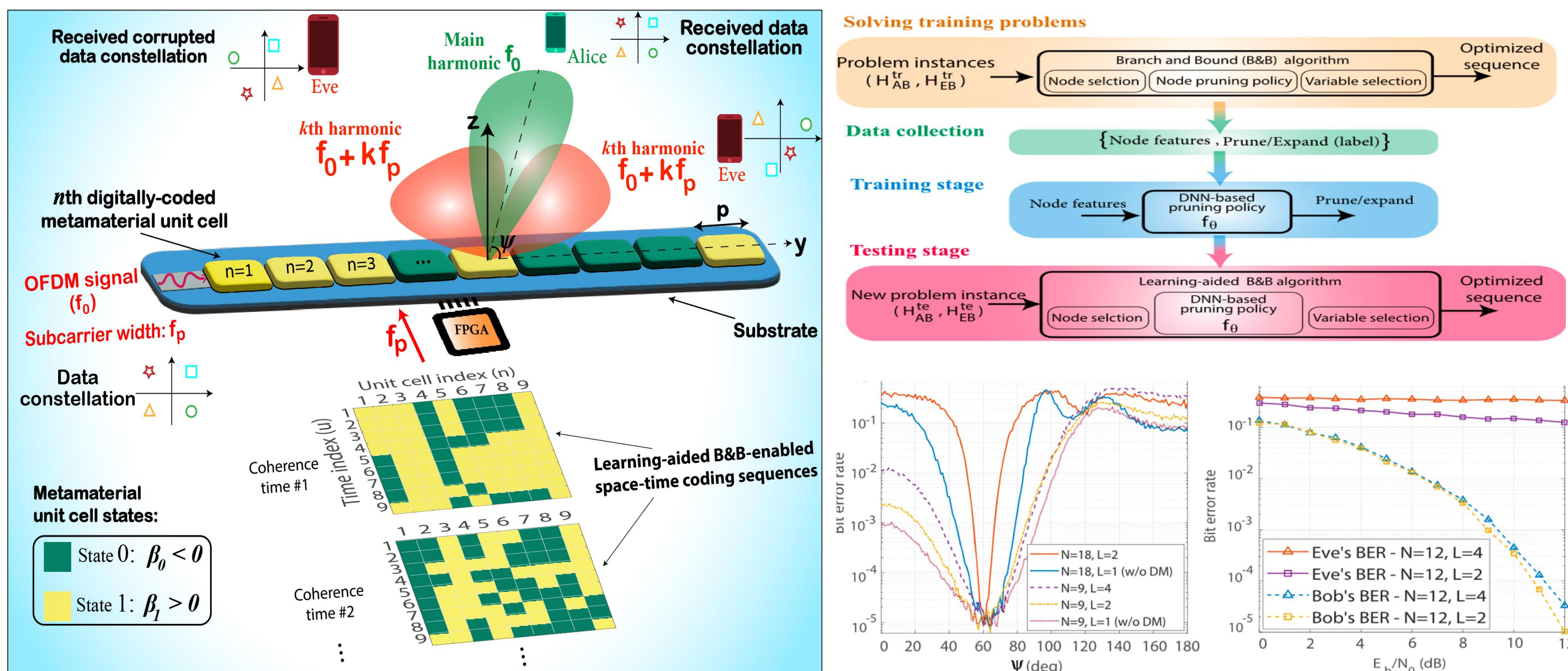
Design and Development of A Programmable Space-Time Coded MTM Array

- A programmable composite composite right/left-handed (CRLH) leaky wave antenna with tunable unit cells is designed
- The unit cells are tuned by changing the bias voltages of their varactors between a "0" state and a "1" state, each resulting in a distinct phase constant of the unit cells (referred to as β_0 and β_1 respectively)
- Harmonic Beam Scanning is achieved by feeding periodic sequences of bias voltages (henceforth referred to as code sequences, denoted by Q) to the unit cells with an FPGA
- N: number of unit cells, L: periodicity of the code sequence



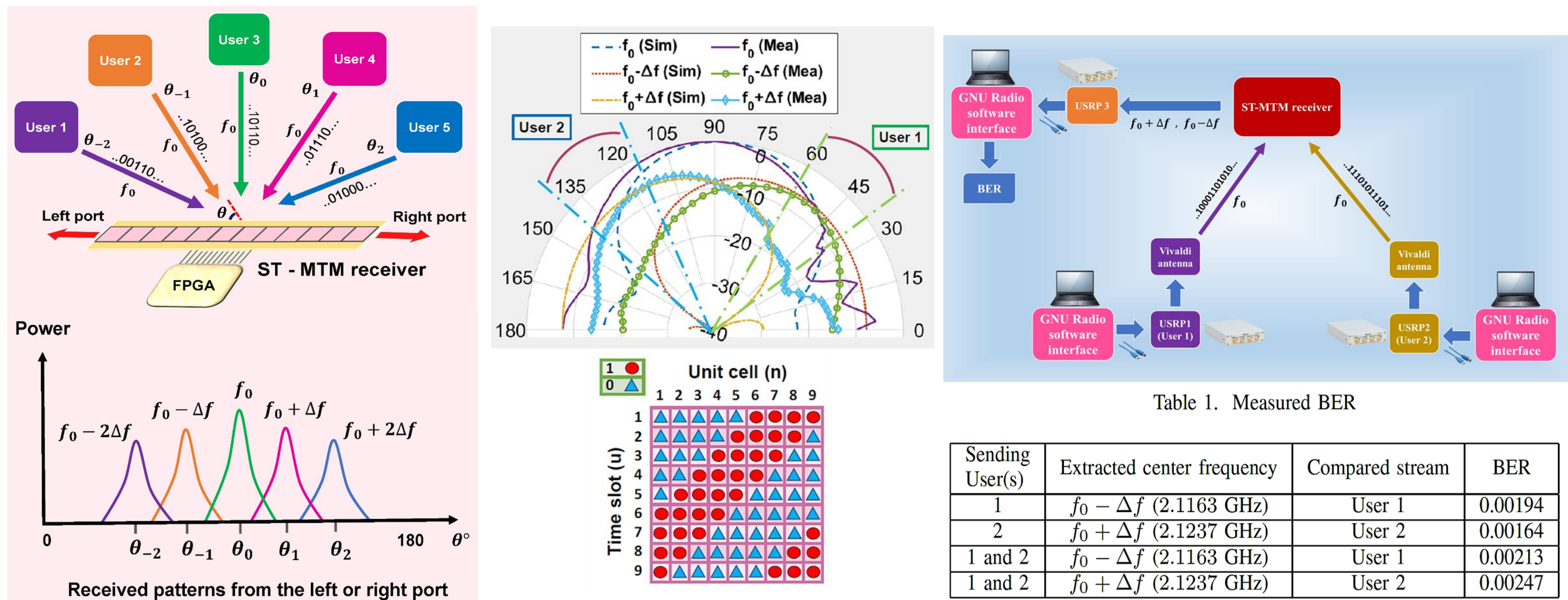
DM for Orthogonal Frequency Division Multiplexing (OFDM) using MTM Arrays

- DM is achieved when the switching frequency corresponds to the OFDM subcarrier spacing
 - Preserving the OFDM signal (suppressing generated harmonics) along the direction of the desired user (ψ_0)
 - Distorting the OFDM signal (increasing generated harmonics) along other directions
- This in turn is achieved by choosing the optimal code sequence, a problem that can be formulated as a mixed-integer non-linear program (MINLP) – exponentially complex in N and L
- Developed HyPhyLearn, a Machine Learning aided branch and bound (B&B) algorithm to reduce the time taken to solve for the optimal code sequence in wireless environments (39.8x faster)
- Experimentally validated the spectral harmonic patterns and tested the bit error rate (BER) performance of the MTM OFDM system on a fabricated prototype



Multi-User Reception using Spatial Spectral Mapping of MTM Antenna

- Generated harmonics at different frequencies have different main beam directions, which can be exploited to provide cross beam isolation between different users
- Information from each user is mapped to a distinct harmonic frequency component within the received spectrum
- Experimentally validated that the MTM array can simultaneously decode data from two spectrally overlapping (center frequency 2.12 GHz, Bandwidth 0.96 MHz) but spatially separated streams, thus proving the feasibility of the array as a beamspace MIMO receiver



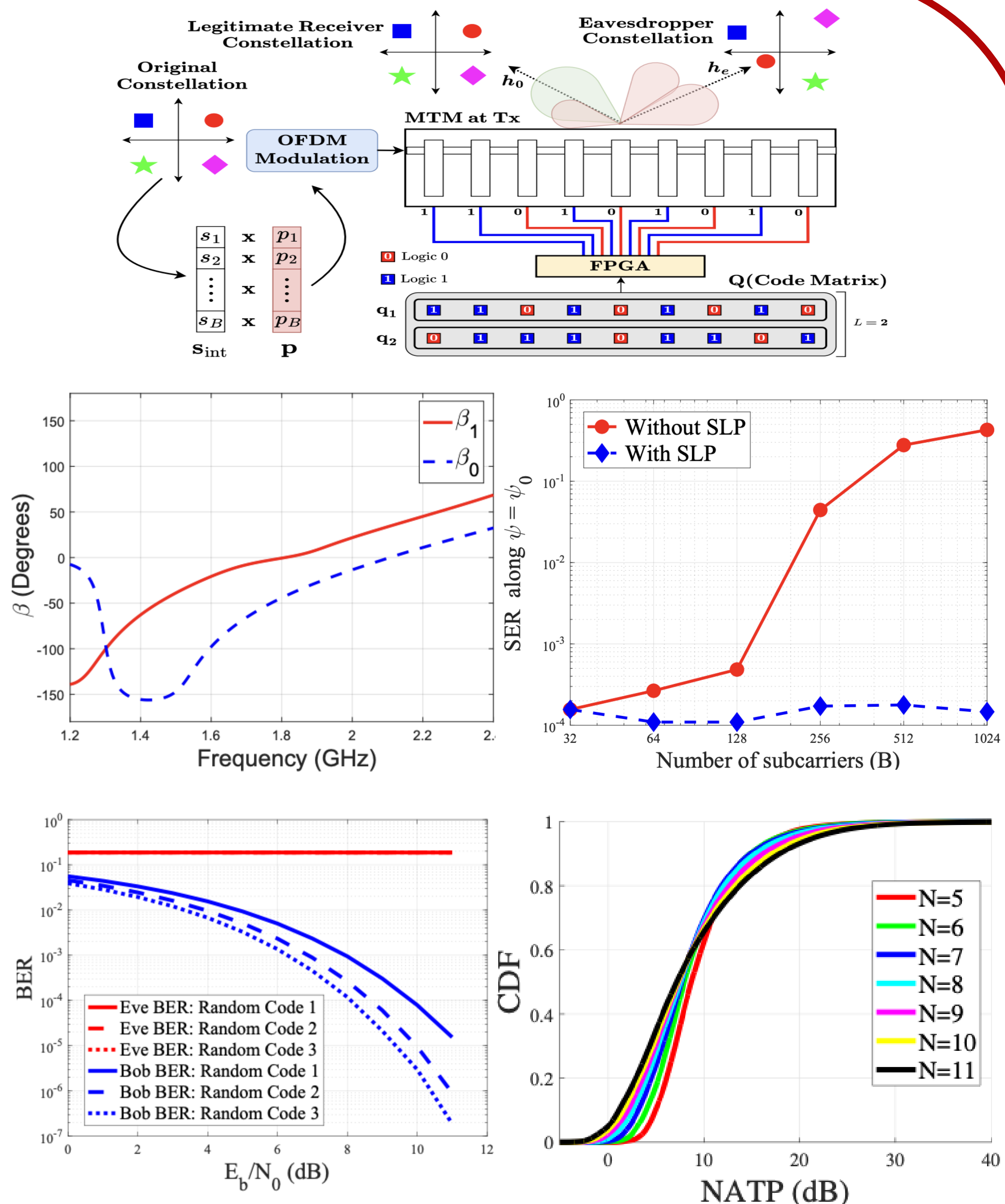
Current Research Work

Motivation for an improved system design

- The phase constants β_0 and β_1 vary over frequency causing the main beam direction to change over the bandwidth of the signal (beam squint) causing errors at the desired receiver when using wideband signals
- If an eavesdropper knows the location of the desired receiver with respect to the transmitter, they can compute the code sequence being used by solving the same optimization problem. It can then be shown that the eavesdropper can correctly decode s_{int} , the symbols intended for the desired user
- The search space of the MINLP increases exponentially with N and L, making the algorithm computationally complex
- The notion of a single direction along which the signal needs to be preserved breaks down when discussing multipath environments where multiple paths along the different directions make up the channel between the transmitter and desired receiver

Symbol Level Precoding (SLP) based MTM array system

- SLP allows for mitigation of beam squint as the variation in phase constants over frequency can be accounted for in the precoding calculations. Thus, reliable communication is established with the desired user (referred to as Bob in the plots)
- SLP allows for secure communication to a desired user irrespective of the code sequence being used, thereby removing the reliance on a single code sequence. Random code sequences can also be used to augment security
- Computation of the precoding vector p scales polynomially in N and L as opposed to the exponential scaling MINLP
- A new channel model which accounts for the various paths in the environment is proposed, using which the SLP based system provides PHY security in multipath environments as well
- The cost associated with randomized codes is the variation in Normalized Average Transmit Power (NATP). The distribution of this quantity over all possible codes is studied to investigate this cost and in turn, the viability of using randomized codes in our scheme



Future Directions

- ❑ Design of secure and spectrum efficient space-time-modulated MIMO transceivers
- ❑ Channel-based spoofing detection via hybrid model and learning-based approach
- ❑ Incorporating multi-user secure transmissions in the wireless channel
- ❑ Study of trade-off between security, capacity and complexity
- ❑ Information theoretic bounds on security and capacity of these systems
- ❑ Experimental verification of proposed systems

Publications

- Venkat, H., Vosoughitabar, S., Li, S., Wu, C.T.M., Mandayam, N. B., Bajwa, W. U., "Symbol-Level Precoding for Multipath-Tolerant Physical-Layer Secured Communication with Space-Time Modulated Metamaterial Antennas" accepted in MILCOM 2025
- S. Vosoughitabar, A. Nooraiepour, W. Bajwa, N. Mandayam and C. -T. M. Wu, "Spatial-Spectral Mapping Beamspace MIMO Receiver Enabled by a Programmable Space-Time-Modulated Metamaterial Antenna," 2024 IEEE/MTT-S International Microwave Symposium - IMS 2024, Washington, DC, USA, 2024
- Nooraiepour, A., Vosoughitabar, S., Wu, C. T. M., Bajwa, W. U., and Mandayam, N. B. "Programming Wireless Security Through Learning-Aided Spatiotemporal Digital Coding Metamaterial Antenna" Advanced Intelligent Systems 5.10 (2023)
- Vosoughitabar, S., and Wu, C. T. M. "Programming Nonreciprocity and Harmonic Beam Steering via A Digitally Space-Time-Coded Metamaterial Antenna" Scientific reports 13.1 (2023)