Intelligent Spatio-Temporal Metamaterial Massive MIMO Aperture Arrays with Hybrid Learning-based Channel Classifiers for Spectrum-Efficient Secured Wireless Communication

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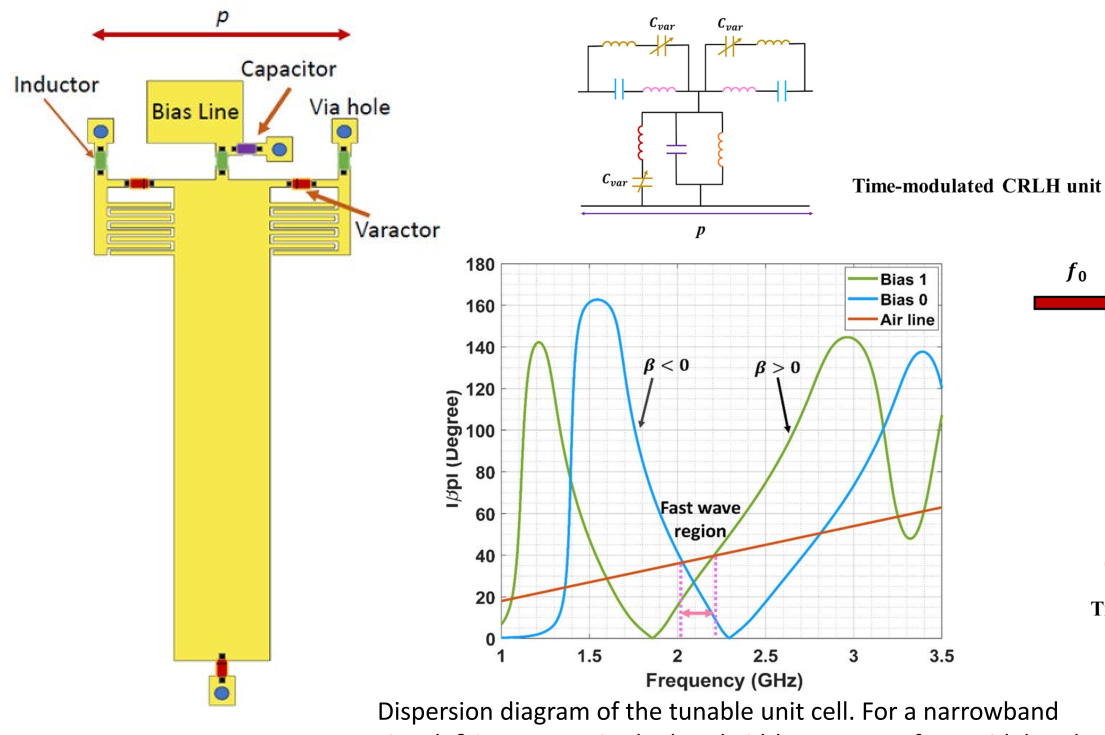
Summary

This project exploits the spatial dispersion control capability and introduces time modulation for MTM (metamaterial) unit cells. The proposed research will create an intelligent space-time modulated MTM antenna aperture which can provide not only dynamic control of radiation characteristics allowing improved spectrum utilization, but also PHY (physical layer security) secure transmission for wireless links enabled by directional modulation. Moreover, a hybrid model-based and learning-based approach (HyPhyLearn) will be incorporated to conduct channel classification even under limited training samples for authentication. The proposed IST-MTM-based secure communication scheme along with the HyPhyLearn channel classifier will have a profound impact in next-generation wireless networks by providing a highly secured and spectrum-efficient communication scheme, which can be deployed in future 6G networks for smart homes/cities, vehicle-to-vehicle communications, and MIMO transceivers to provide spectrum efficient secure communication links in a multiple access setting.

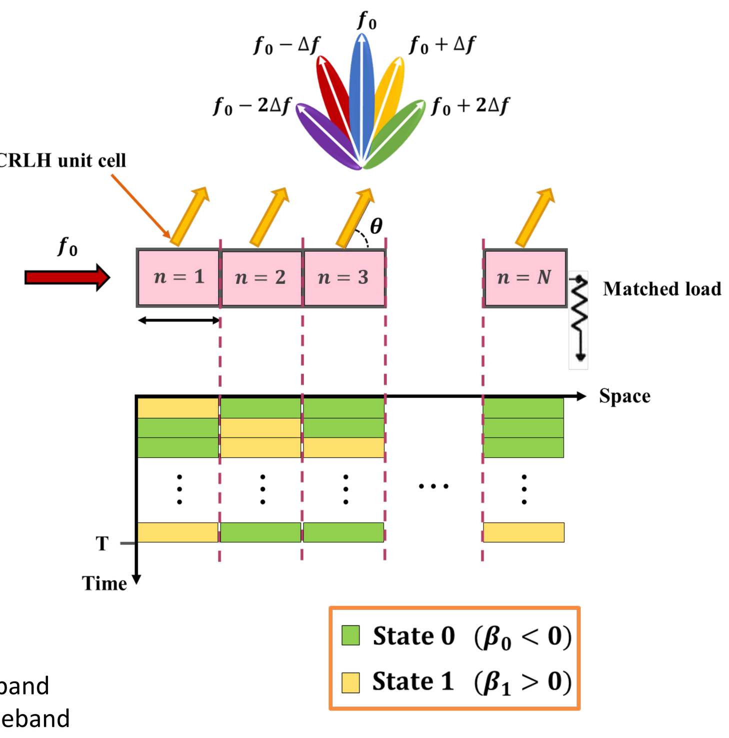
Research Progress

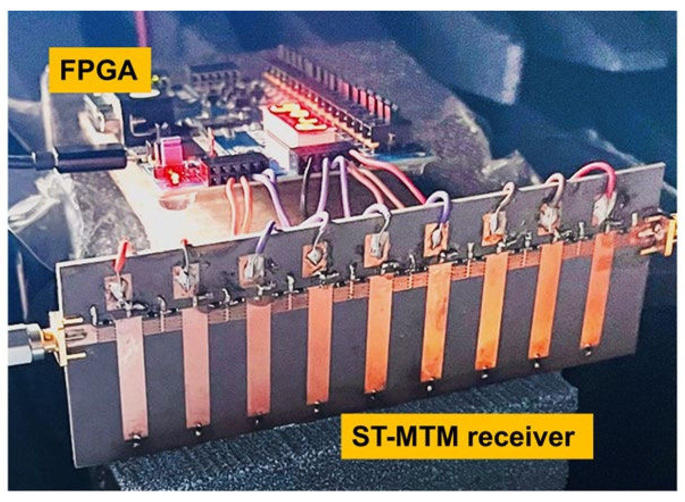
Design of A Programmable Space-Time-Coded Metamaterial Antenna

- Design of a programmable composite right/left-handed (CRLH) leaky wave antenna with tunable unit cells
- The phase constant (β) of each unit cell can be negative (state 0) or positive (state 1) depending on the incorporated varactors' bias voltages
- Generation of harmonic frequencies with different main beam directions (Harmonic beam scanning) by feeding prespecified periodic sequences to the unit cells
- Enabling many applications, such as simultaneous transmission and reception, directional modulation for physical layer security, radar sensing, and MIMO beamformer



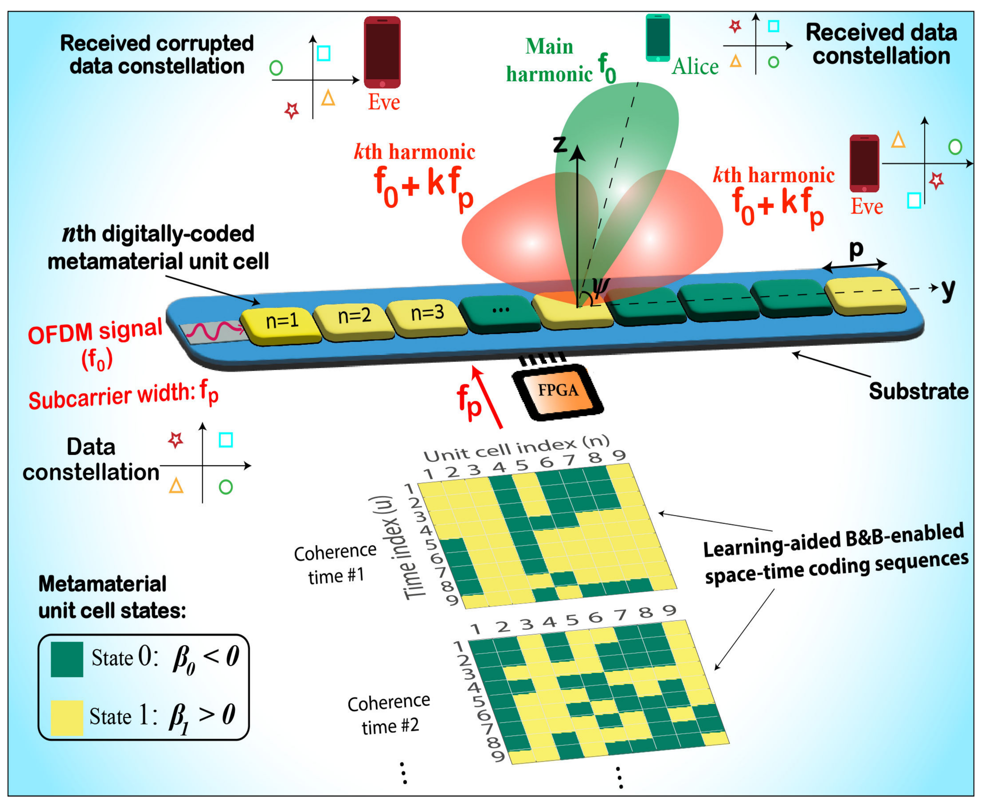
Dispersion diagram of the tunable unit cell. For a narrowband signal, β is constant in the bandwidth. However, for a wideband signal, β is not constant in the entire bandwidth.

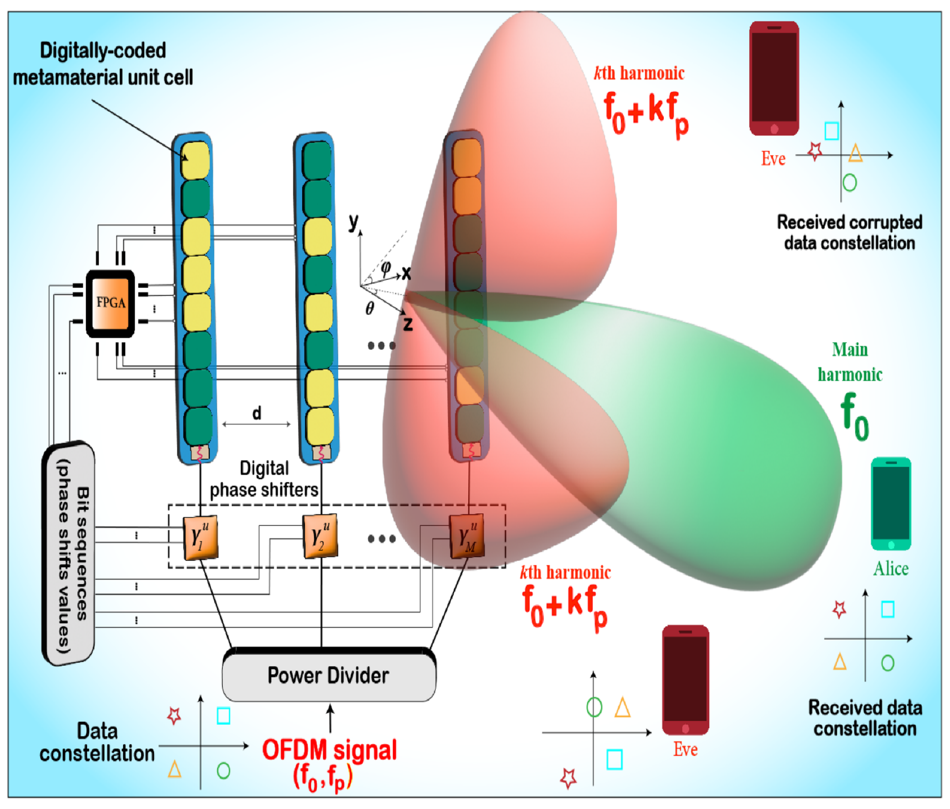


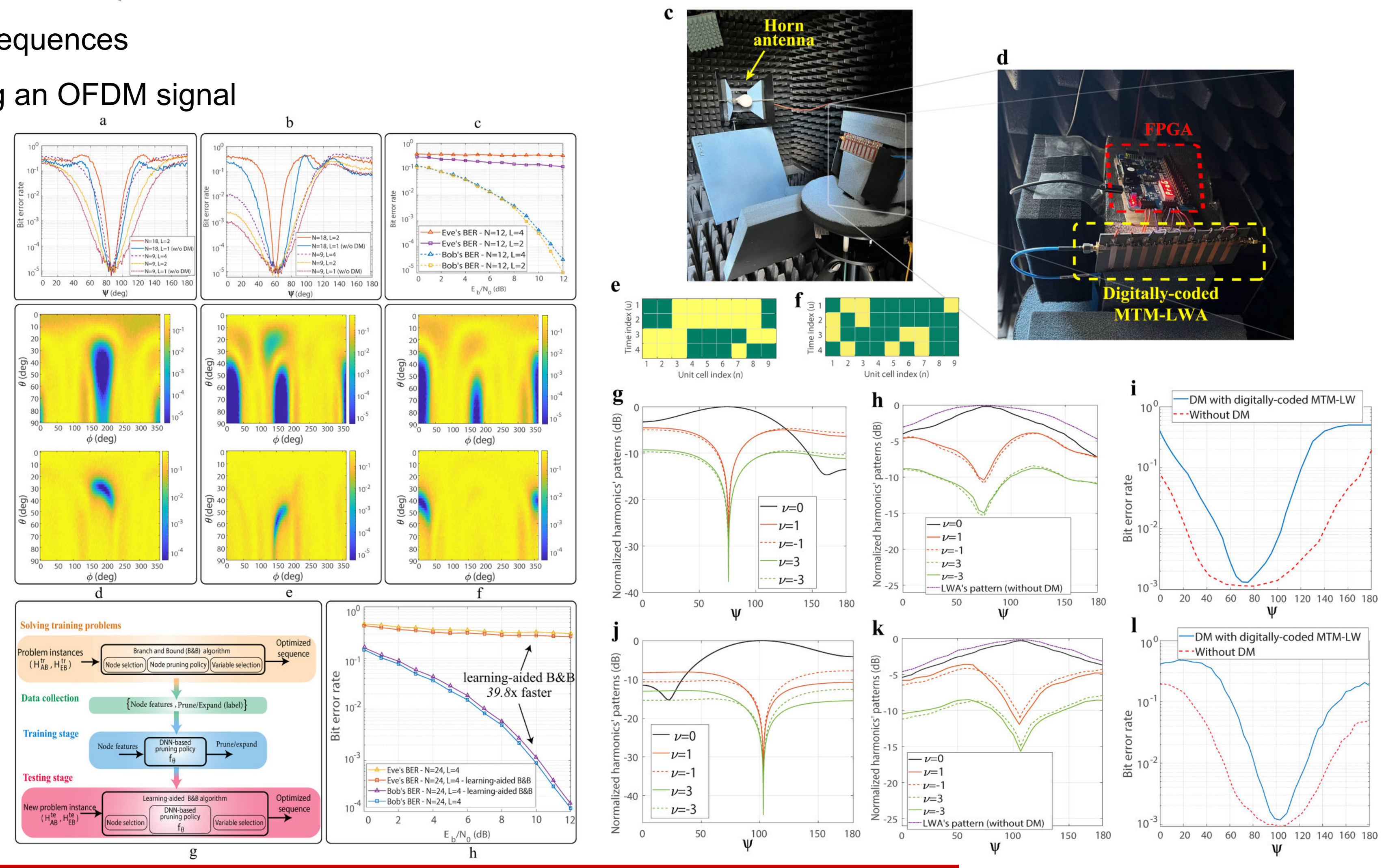


Directional Modulation (DM) for Physical Layer (PHY) Security for a narrowband OFDM signal

- Enabling PHY security by achieving the functionalities of DM through satisfying the following constraints:
  1. Preservation of the original OFDM constellations along the desire spatial direction through suppressing the generated harmonics in this direction
  2. Distortion of the transmitted signal along the other directions by increasing the levels of the generated harmonics in these directions
- Design of varactors' control waveforms through solving a mixed-integer non-linear programming (MINLP) optimization problem
- Considering Wireless channel and using machine learning aided branch and bound (B&B) optimized coding sequences
- Spectral harmonic patterns and bit-error-rate (BER) measurements on the fabricated prototype by transmitting an OFDM signal
- Providing a framework for a 2D directional modulation transmitter

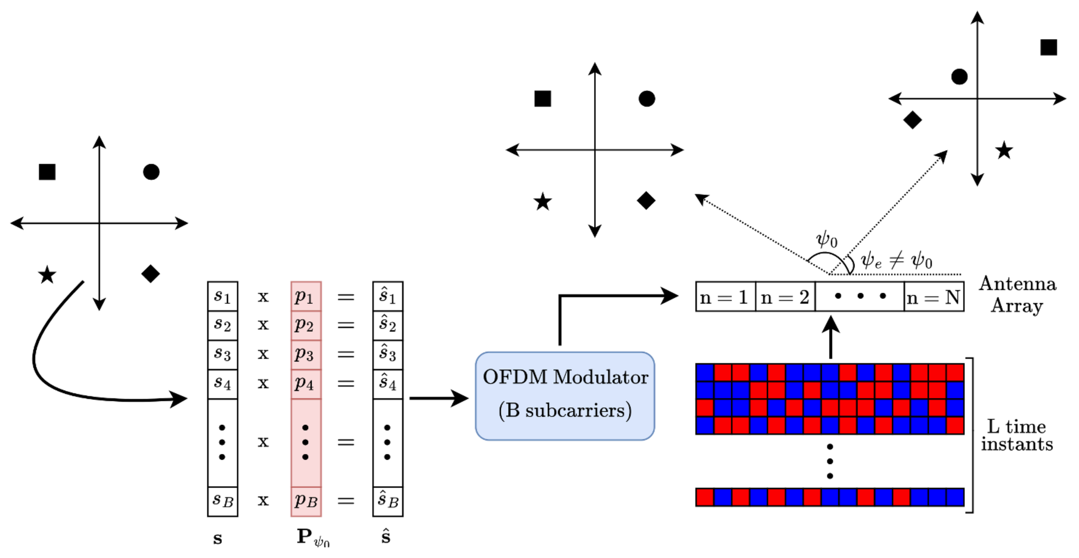


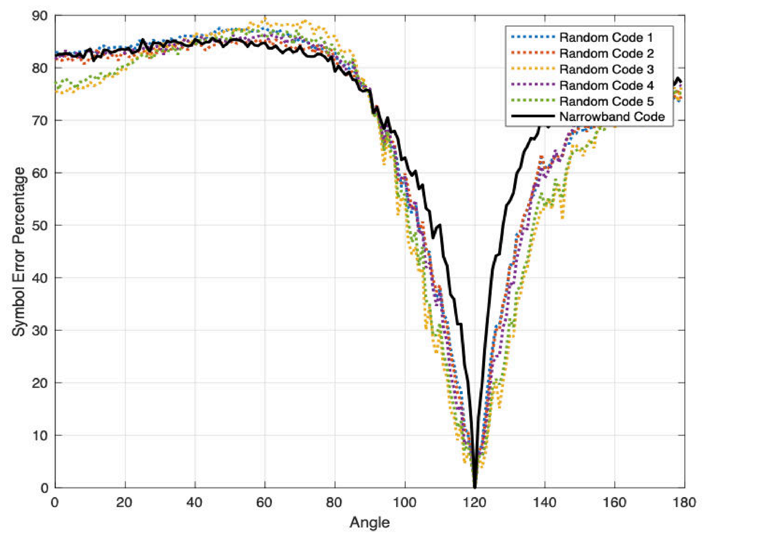




Physical Layer Security in Wireless Communication Links for a wideband OFDM signal

- Variation in β over frequency affects a wideband OFDM signal with large number of subcarriers.
- Symbol precoding allows us to tackle this frequency dependency of β
- Increasing L causes the BER plot to have a sharper minima at the desired direction (ψ_0)
  - Computational complexity increases exponentially with increasing L
  - Precoding can be used with any coding sequence to achieve reliable communication at ψ_0
- Randomized sequences can be used along with precoding to add another layer of security
  - Symbol precoding for random sequence is data and channel dependent
  - Randomized sequence perform worse in terms of power requirement

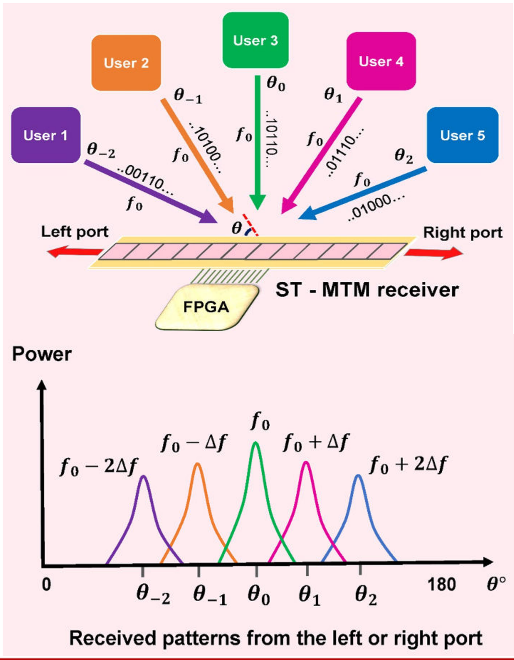


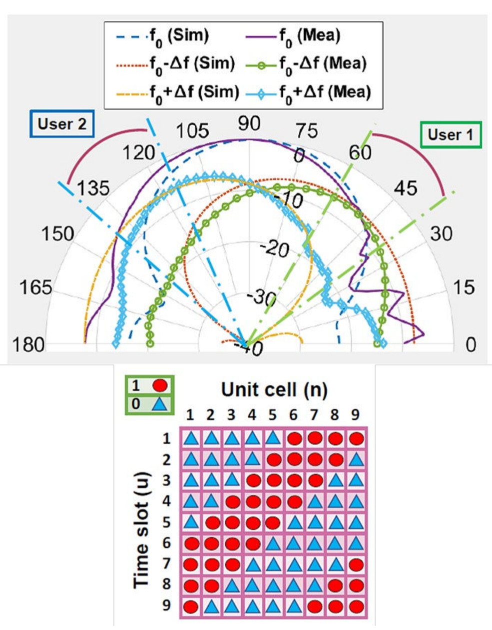


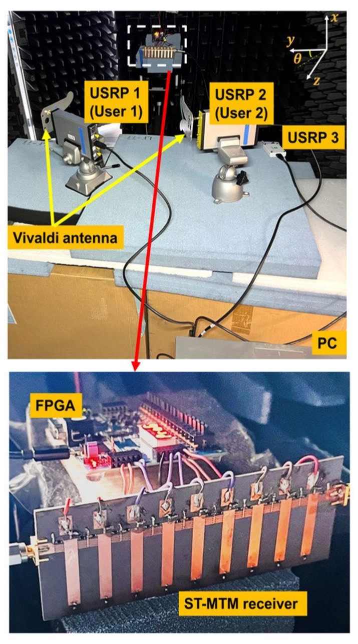
Precoding can be used on any arbitrary coding sequence to achieve a low symbol error percentage for a reliable communication at ψ_0. The OFDM signal bandwidth is 40 MHz in this plot.

Spatial-Spectral Mapping Beamspace MIMO Receiver

- Generation of harmonic frequencies with different main beam directions when a signal with a specific frequency is radiated to the antenna from the θ angle
- Spatial-Spectral Mapping Beamspace MIMO Receiver enabled through having cross beam isolation
- The information received from each user, located in a specific direction, is mapped to a distinct harmonic frequency component within the received spectrum







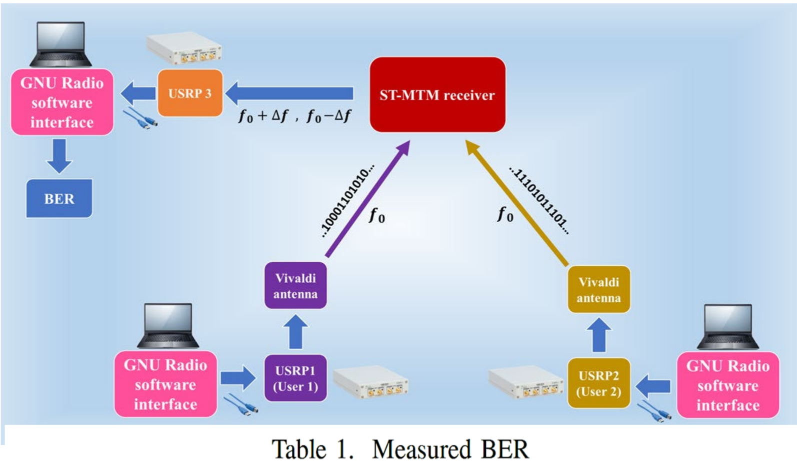


Table 1. Measured BER

Sending User(s)	Extracted center frequency	Compared stream	BER
1	$f_0 - \Delta f$ (2.1163 GHz)	User 1	0.00194
2	$f_0 + \Delta f$ (2.1237 GHz)	User 2	0.00164
1 and 2	$f_0 - \Delta f$ (2.1163 GHz)	User 1	0.00213
1 and 2	$f_0 + \Delta f$ (2.1237 GHz)	User 2	0.00247

Future Directions

- Design of secure and spectrum efficient space-time-modulated MIMO transceivers
- Channel-based spoofing detection via hybrid model and learning-based approach
- Generating secret keys enabled by directional modulation
- Capacity evaluation of communication links under the proposed secure DM scheme
- Study of trade-off between security, capacity and complexity
- Probabilistic proofs (bounds on security) to show system can work in random channels

Publications

- Vosoughitabar, S., Nooraiepour, A., Bajwa, W. U., Mandayam, N. B., and Wu, C. T. M. "Spatial-Spectral Mapping Beamspace MIMO Receiver Enabled by A Programmable Space-Time-Modulated Metamaterial Antenna" accepted for presentation in 2024 IEEE/MTT-S International Microwave Symposium - IMS 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).