Collaborative Research: SWIFT: LARGE: DYNAmmWIC: Dynamic mmWave Spectrum Sharing Techniques for Public Safety Communications (ECCS 2030272/2030141)

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Motivation

- **Integration of PSC solutions into the mmWave spectrum is a challenge**
- **Conventional spectrum management (i.e., allocating dedicated PSC bands) is not sustainable**
- **Goal: Fundamentally transform mmWave spectrum usage and accelerate the readiness of the wireless industry for 6G solutions while saving significant costs**

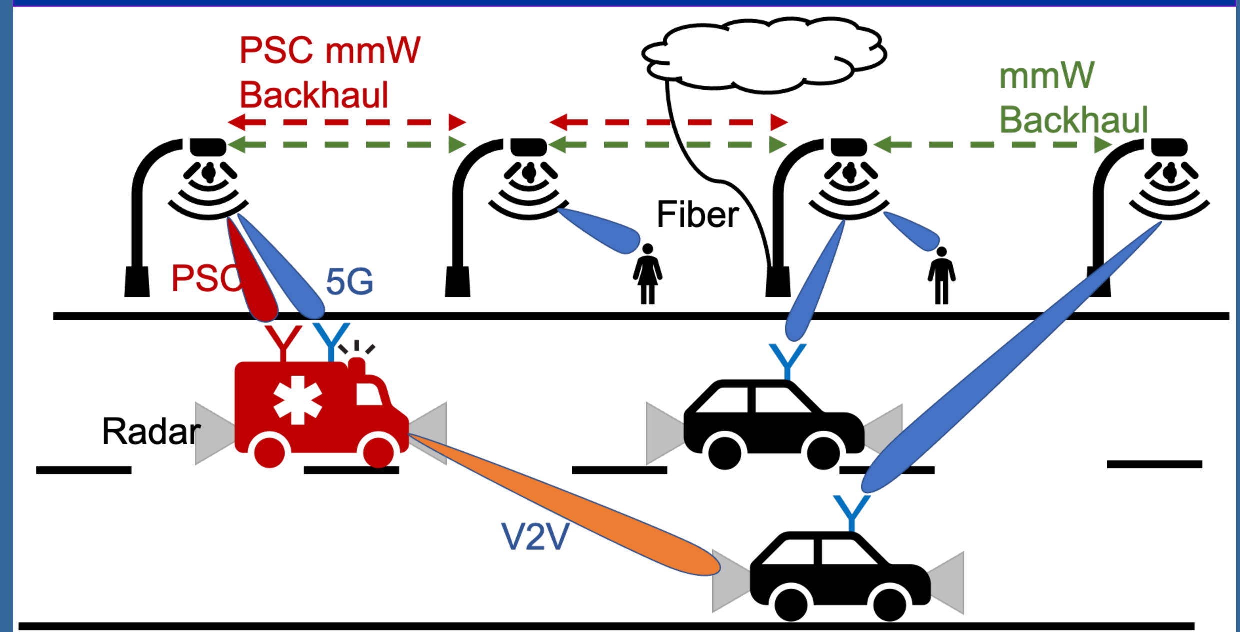
Research Goals

- **Develop dynamic mmWave spectrum sharing solutions (DYNAmmWIC) to allow for novel use cases and design the mmWave spectrum**
- **Joint-radar communication (JRC) system: Uses the same waveform for both radar sensing and data transmission in vehicles**
- **mmWave spectrum sharing: Dynamically manages the coexistence of operations for PSC, radar sensing, 5G, and V2V communications, pedestrian access, and backhaul in the mmWave spectrum**
- **mmWave next-generation radio access network (NG-RAN) architecture: Allows for higher RAN co-operation and integration through proven orchestration tools**
- **A comprehensive evaluation plan via a city-wide, remotely accessible wireless testbed**

Potential Payoffs

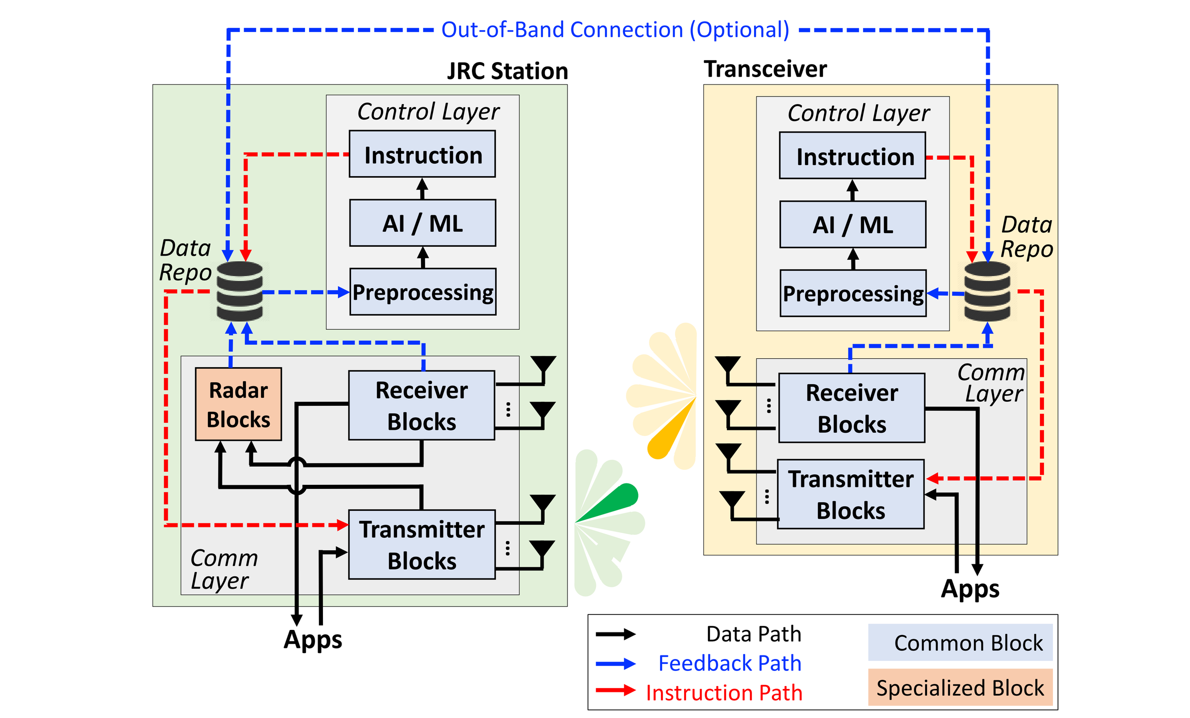
- **DSS: Fundamentally transform mmWave spectrum usage as the industry goes through the first-license-then-share approach**
- **Significantly accelerate the readiness for 6G solutions, when licensed mmWave spectrum bands will cease to provide the required resources soon**
- **Roll out educational modules that can be conducted on the remotely-accessible NEXTT testbed, lowering the barrier to wireless education**
- **Inform the local community through the well-established Ignite Lincoln channels to reach local industry and decision-makers, including the City of Lincoln and Lincoln Police Department**

DYNAmmWIC Architecture



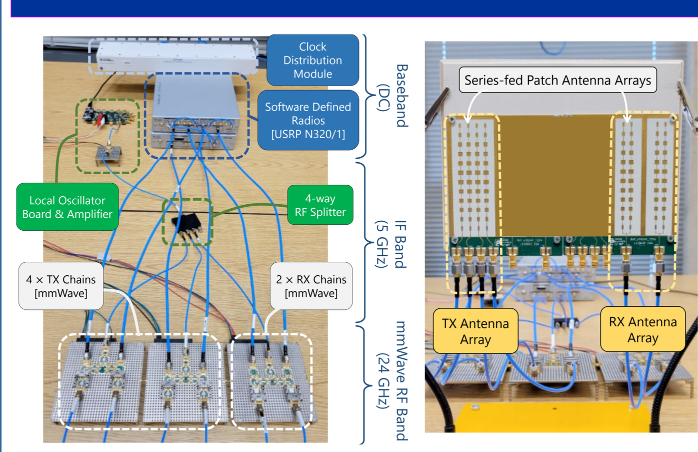
O-JRC: An Open-Source Software Platform for mmWave JRC Development and Experimentation [1]

- **Make advanced control algorithms more efficiently developed!**



- **Layered and Modular Architecture: Separates control logic from signal processing.**
- **Simplifies Integration: Facilitates the integration of advanced control algorithms developed using more efficient languages.**
- **Flexible Testing: Allows testing across various hardware setups without the need for re-coding.**

A mmWave MIMO JRC Hardware Testbed

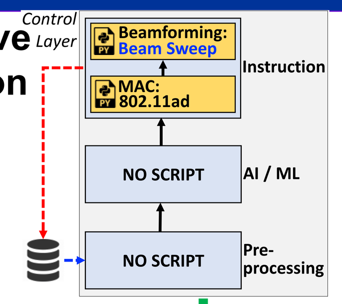


Hardware Architecture of 4 × 2 MIMO JRC Testbed

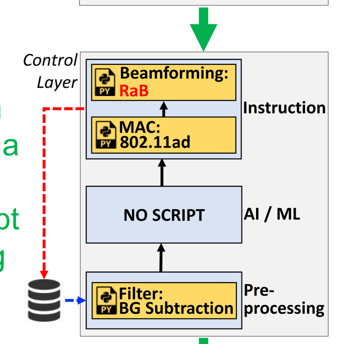
- Carrier Frequency: 24GHz
- Bandwidth: 125MHz
- Num of Subcarriers: 64
- Num of TX Chains: 4
- Num of RX Chains: 2
- Max TX Power: 21 dBm
- Range Resolution: 1.2 m
- Max Unambiguous Range: 76.8 m
- Angular Resolution: 12.5°

Learning-Enhanced JRC

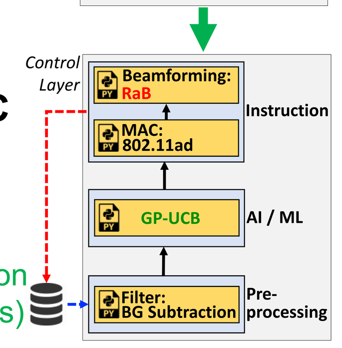
- **Native mmWave Communication**
  Incorporate Only Beam Sweep and 802.11ad MAC Scripts in the Instruction Block

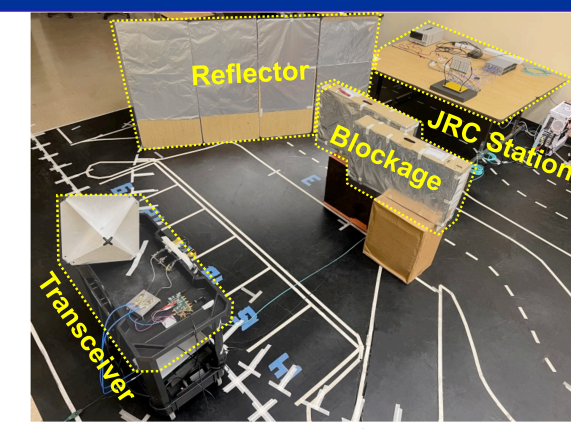


- **mmWave JRC**
  Replace the Beam Sweep Script with a Radar-Aided Beamforming Script and Add a Filtering Script

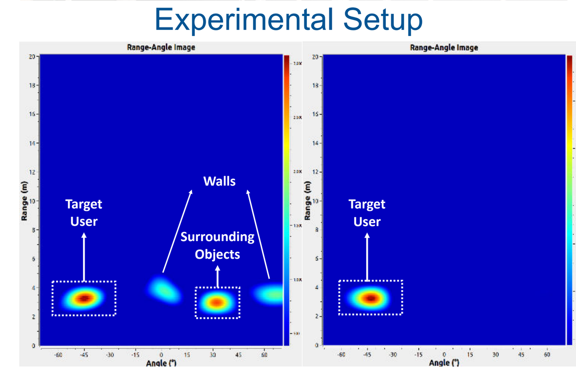


- **Learning-Enhanced JRC**
  Add a Learning Algorithm Script (GP-UCB, developed in Python within just two days)

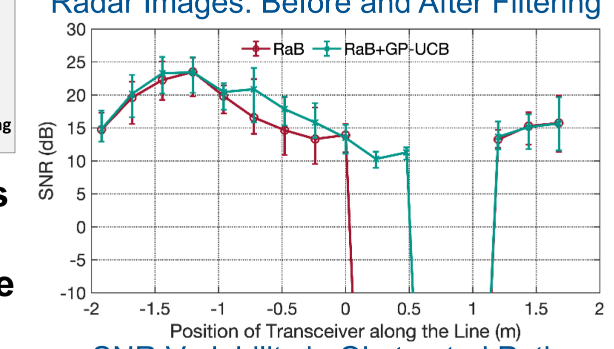




Experimental Setup



Radar Images: Before and After Filtering

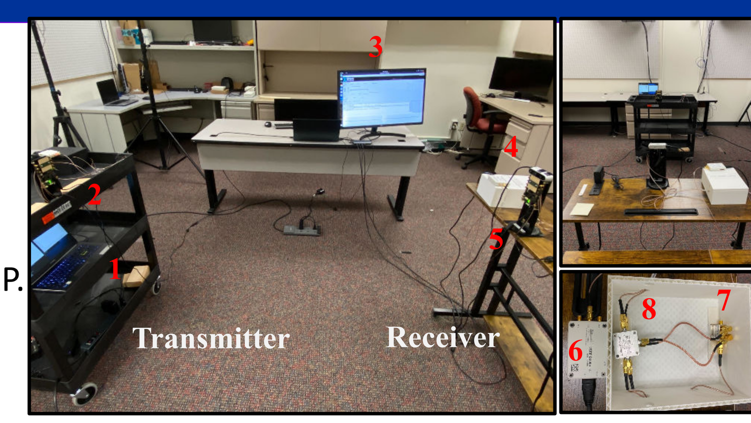


SNR Variability in Obstructed Paths

L-E JRC: Identify reflective paths from reflectors, covering areas behind blockages—an advantage over relying solely on radar.

Open-Source mmWave Testbed

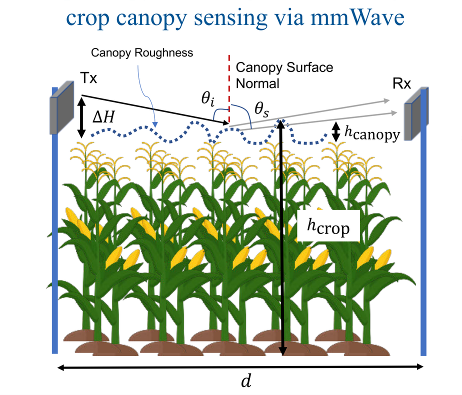
1. GNU Radio Tx Waveform.
2. Sivers EVK06002 Tx.
3. Sivers Control for Tx & Rx.
4. RealSense D435i Camera.
5. Sivers EVK06002 Rx.
6. USRP B200 mini as Rx USRP.
7. 90-degree splitter.
8. 180-degree splitter.



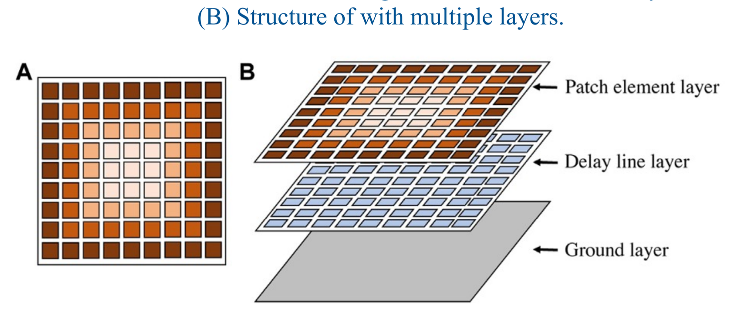
Supporting Open-Source mmWave Research

- **Publicly available mmWave experimental dataset [3] supported research in other areas [4,5]**

Crop canopy scattering loss modeling and crop canopy sensing via mmWave

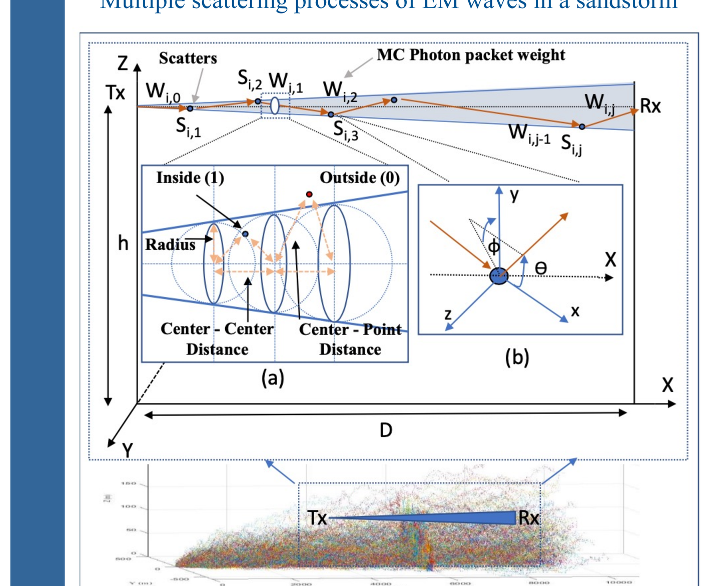


Wind-adaptive reflective intelligent surface (RIS) design, with subarrays of concentric square shape. (A) Top layer of RIS with different colors indicating the boundaries of subarrays. (B) Structure of with multiple layers.



THz Links on Mars [6]

Multiple scattering processes of EM waves in a sandstorm



- **THz scattering models Mie, Rayleigh approx., and Monte-Carlo photon packets**
- **Gravity: Mars gravity 38% Earth. 100m ant. height on Mars increases range 5.5x vs. 2m on Earth**
- **Molecular absorption: Mars offers 550GB/s higher channel capacity than Earth**
- **Dust storms: Blackout at 60m on Mars**

Dynamic Admission and Resource Leasing in 5G Private Cells [7]

Problem: The operator of a private cell

- **Makes admission decisions for the slice instances of the private cell**
- **Makes leasing decisions of unused resources to a broker**
- **May cancel the lease of a resource unit if there is an urgent need for serving a slice instance**

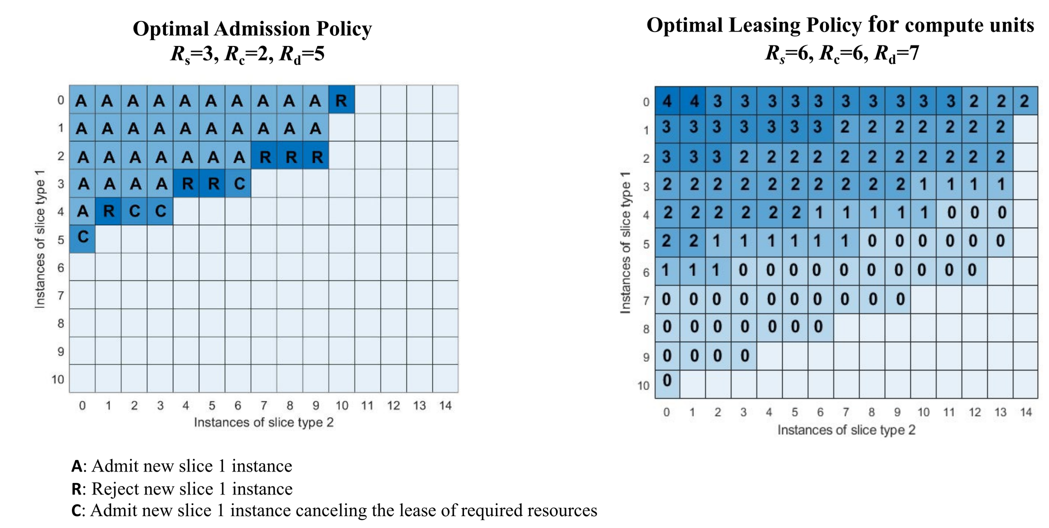
Motivation: Leasing brings additional revenue to the private cell

Objectives: 1)Find the optimal dynamic admission to serve the needs of the private cell and 2) Find the optimal leasing/cancellation policy to generate additional revenue in real-time.

Problem Formulation:

- **Markov-Decision Process (MDP)**
- **Multiple slice types (e.g., eMBB, mMTC, URLLC)**
- **Multiple resource types (spectrum (s), compute (c), storage (d))**

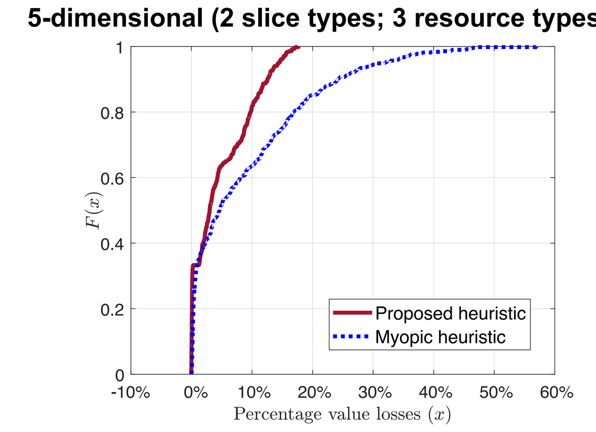
Experiments: 5-dimensional (2 slice types; 3 resource types)



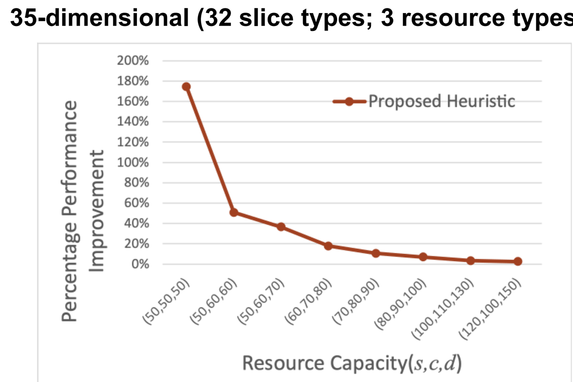
A: Admit new slice 1 instance
R: Reject new slice 1 instance
C: Admit new slice 1 instance canceling the lease of required resources

Heuristic Solution: Computationally, it is infeasible to obtain the optimal policy for large-scale problems.

5-dimensional (2 slice types; 3 resource types)



35-dimensional (32 slice types; 3 resource types)



- **Proposed heuristic is designed based on the properties of the MDP model; it is an online algorithm.**
- **Myopic heuristic is designed to maximize the immediate return.**
- **Both heuristics are tested on 486 experiment configurations.**
- **Percentage value loss (top fig.) represents deviation from optimal policy in long-run average value.**
- **Proposed heuristic diverges from optimal policy under high penalties for not serving a slice instance or cancellation—when leasing becomes too risky.**
- **Percentage performance improvement (bottom fig.) compares the proposed heuristic to the myopic heuristic. With limited resource capacity, proposed heuristic leads to >160% improvement over myopic.**

References

[1] X. Liu, H. Zhu, and E. Ekici, "O-JRC: An Open Source Software Platform for mmWave Joint-Radar Communication Development and Experimentation," *Submitted for publication*, April 2024

[2] C. D. Ozkaptan, H. Zhu, E. Ekici, and O. Altintas "A Fully Digital MIMO Joint Radar-Communication Testbed with Radar-assisted Precoding" *IEEE Transactions on Wireless Communications*, December 2023

[3] IEEE DataPort, https://ieee-dataport.org/documents/mmwave-farm-channel-modeling-wireless-agricultural-networks-broadband-millimeter-wave.

[4] S. Nie, Y. Ge, and M. C. Vuran, "On Crop Canopy Scattering for Integrated mmWave Sensing and Communication in Agricultural Fields," in Proc. *IEEE MASS 2023*, Sep. 2023.

[5] S. Nie and M. C. Vuran, "AgRIS: wind-adaptive wideband reconfigurable intelligent surfaces for resilient wireless agricultural networks at millimeter-wave spectrum," *Frontiers in Communications and Networks*, vol. 4, 2023.

[6] L. T. Wedage, B. Butler, S. Balasubramaniam, Y. Koucheryavy, and M. C. Vuran, "Comparative Analysis of Terahertz Propagation Under Dust Storm Conditions on Mars and Earth," *IEEE Journal of Selected Topics in Signal Processing*, vol. 4, no. 17, 2023.

[7] D. Batur, J. K. Ryan, M. C. Vuran, "Dynamic Resource Sharing in Private 5G Networks with Slicing," *submitted to Management Science*, April 2024.