Decentralized Intelligent Spectrum Sharing in UAV Networks (DISH-uNET) via Hardware-software Co-design

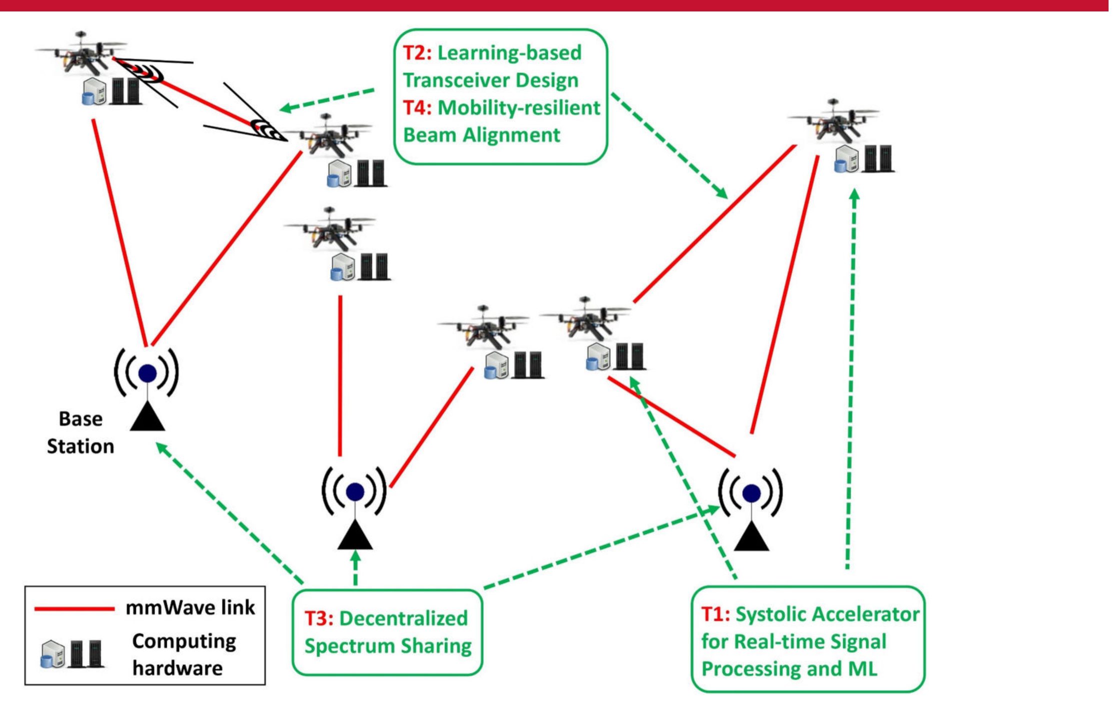
Mingyue Ji[1], Rong-Rong Chen[1], Cunxi Yu[2], Zhangyu Guan[3]

[1] Department of Electrical & Computer Engineering, University of Utah

[2] Department of Electrical & Computer Engineering, University of Maryland, College Park

[3] Department of Electrical Engineering, University at Buffalo

Research Overview



1. Develop novel approaches for decentralized intelligent spectrum sharing in mmWave UAV networks (DISH-uNET)
2. Achieve high efficiency and resilience based on hardware-software co-design
3. Design domain-specific energy-efficient systolic accelerators
4. Develop novel learning-based transceiver design for high mobility UAVs
5. Design new decentralized spectrum sharing multiple access control
6. Enable fast adaptation of mobility resilient mmWave beam learning for UAV networks

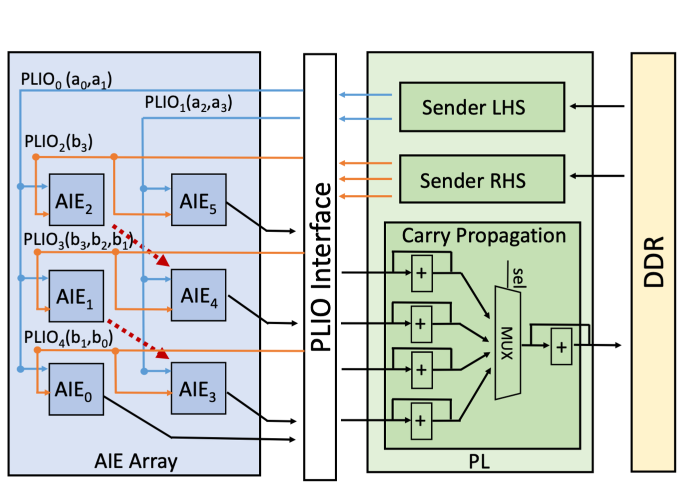
RESEARCH Topic 1: Energy-efficient Systolic Accelerator for Simultaneous Real-time Signal Processing and ML

Main Research Problems

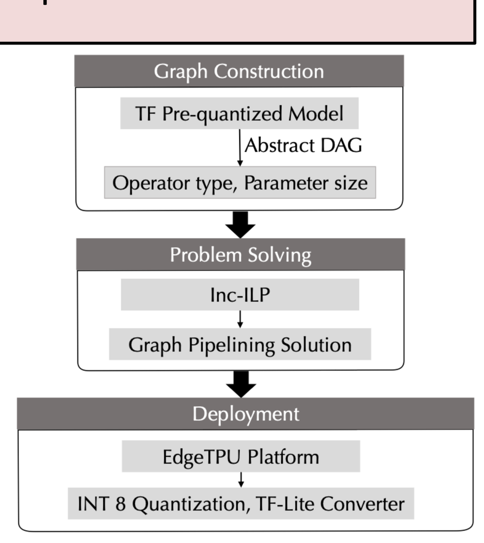
- **Optimizing datapaths** for hybrid signal processing and deep learning applications is crucial to achieving high-performance, energy-efficient systems.
- Develop **specialized hardware accelerators** tailored for specific signal processing or deep learning tasks.
- **Heterogeneous scheduling** – In a heterogeneous computing environment with hybrid workloads, specificized scheduling requirements need to be carefully considered.

Main Results

- **In the AIM framework**, we explore energy efficiency improvements in CPUs and GPUs, focusing on their vector units. Unlike these, FPGA relies on DSPs and LUTs, which are less efficient. We introduce a novel "FPGA+vector units" approach, utilizing the AMD/Xilinx Versal ACAP architecture—a heterogeneous platform combining AI engine tensor cores, FPGA logic, and a general-purpose CPU. We present the AIM framework for arbitrary-precision integer multiplication on Versal ACAP, aiming to optimize design through analytical models and automatic code generation. Tested on various applications, AIM significantly outperforms traditional accelerators, achieving substantial energy efficiency gains compared to leading CPU and GPU technologies.
- **Intelligent edge device scheduler (Inc-ILP)** -- Compilation of hybrid DNNs and signal processing tasks has a great impact on the performance of resource-constrained (e.g., computation, I/O, and memory-bound) edge computing systems. We continue our success from the previous version RESPECT (DAC'23) sponsored by this award, and further improve 1) optimality control, and 2) refine-tuning the on-chip cost models.



AIM: Reconfigurable Computing on Versal ACAP [ICCAD'23]



Hybrid ML-ILP solving for on-chip scheduling [ICCAD'23]

Future Plan

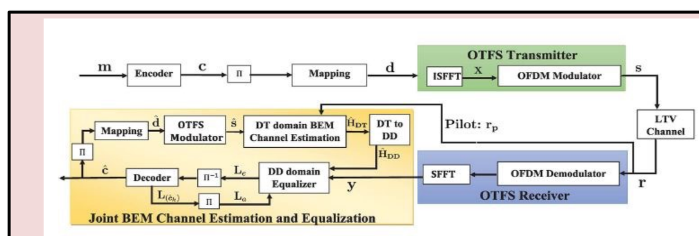
- Develop customized datapath architecture to deploy synchronous signal processing and DNNs workloads. With the success of AIM, we believe the energy efficiency of the hybrid workloads will be more enhanced on Versal other than traditional FPGA architecture.
- Further explore heterogenous scheduling in both general computing scenarios (CPU/GPU/XPU) and our customized accelerators, using GNNs and reinforcement learning.

RESEARCH Topic 2: Transceiver Design for High Mobility UAV Communication

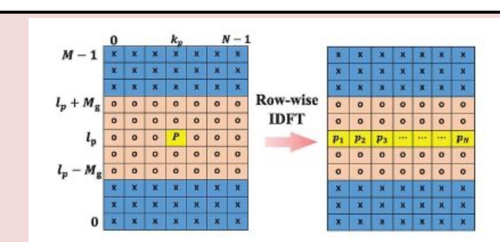
Main Research Problems

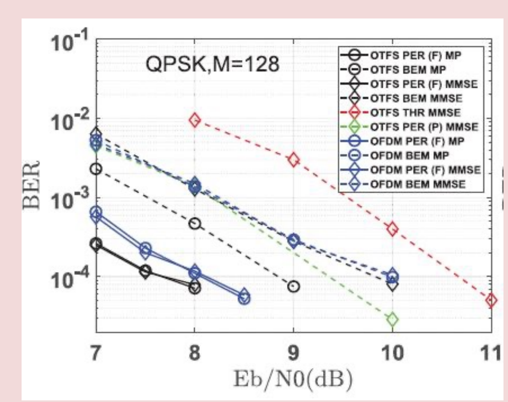
- A mobility-resilient physical-layer for mmWave UAV communication using Orthogonal time-frequency space (OTFS) modulation.
- New neural network based receivers for OTFS physical layer to better suppress interference and improve spectrum utilization.

Main Results

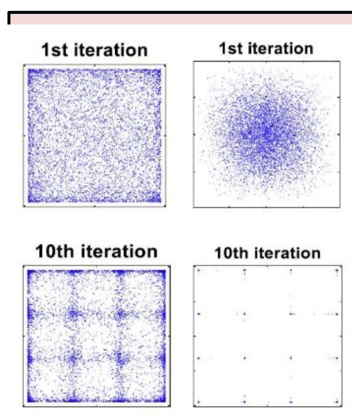


(a) Block diagram of the OFDM-based OTFS system.

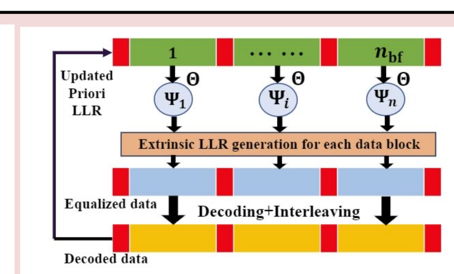


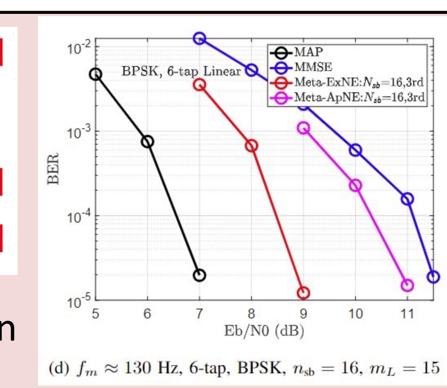


- OTFS: Spread users' data over time, space, and frequency to enhance spectrum utilization.
- Developed a basis-expansion model (BEM) based channel estimation for OTFS. Outperforms threshold based channel estimation.



(e) 16-QAM ExNE (f) 16-QAM Decoder





- Meta-ExNE Evaluation
- ExNE successfully recovers transmitted symbols after 10 iters of turbo equalization.
- Developed an Meta learning based extrinsic neural network equalizer (Meta-ExNE) that can effectively remove inter-symbol-interference over time-varying unknown channels. It outperforms the soft MMSE equalizer under turbo equalization.

Future Plan

- Develop BEM-based channel estimation for multiple antenna OTFS system over mmWave band.
- Extend Meta-ExNE to channels with faster Doppler rates.

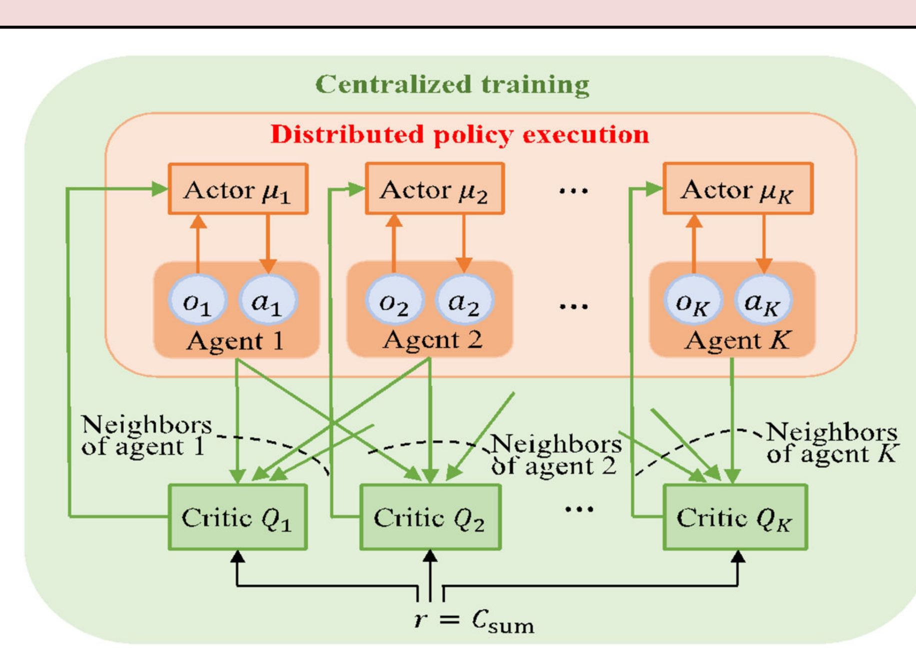
RESEARCH Topic 3: Bridging Lyapunov Optimization Framework, Game Theory, and Reinforcement Learning in Decentralized Spectrum Sharing

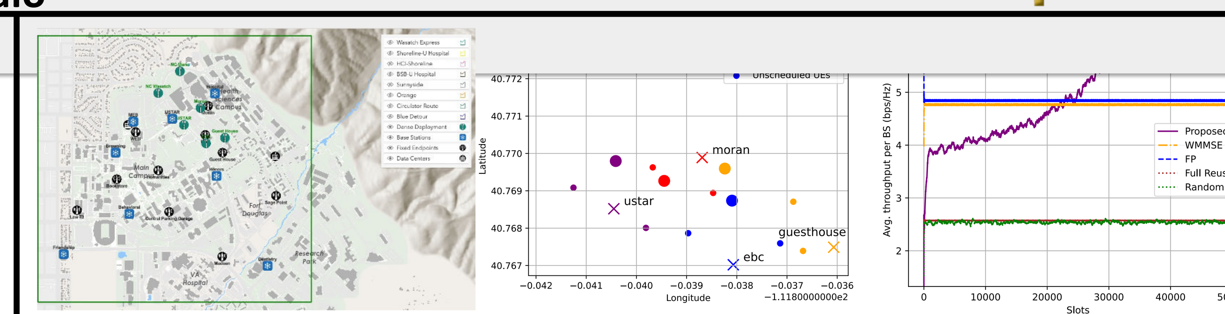
Main Research Problems

- Optimal decentralized spectrum sharing algorithm using distributed reinforcement learning.
- Optimal Semi-decentralized spectrum sharing and fundamental understanding of Lyapunov optimization framework boosted by reinforcement learning.

Main Results

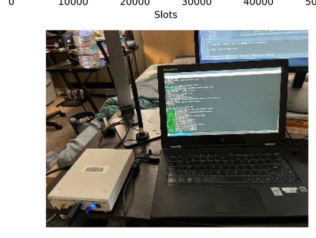
- We propose a distributed continuous power allocation scheme based on a modified version of multi-agent Deep Deterministic Policy Gradient (MADDPG) that is tailored for the distributed multiple-agent setting.
- The proposed scheme employs a centralized-training-distributed-execution framework where Q-functions are trained over subsets of BSs while each BS determines its transmit power based only on its own local observation. It admits constant per-BS communication and computation complexity and is thus scalable to large networks.
- We ran the proposed MADDPG algorithm using the channel measurements on POWDER at the University of Utah and can achieve comparable or better performance than several state-of-the-art non-learning approaches.





- Use dense base station deployment on POWDER.
- Bandwidth: 220kHz.
- CBRS frequency band.

Dense Base Station



UE

Future Plan

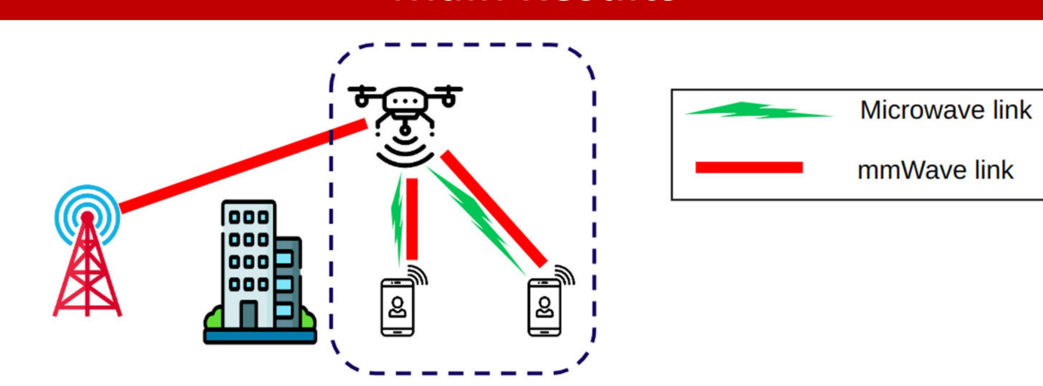
- Implement and test the proposed MADDPG algorithm in POWDER and AERPAW using both sub-6G band and mmWave band.
- Incorporate both distributed and semi-distributed reinforcement learning approach into Lyapunov optimization framework.

RESEARCH Topic 4: Mobility-Resilient mmWave Beam Learning

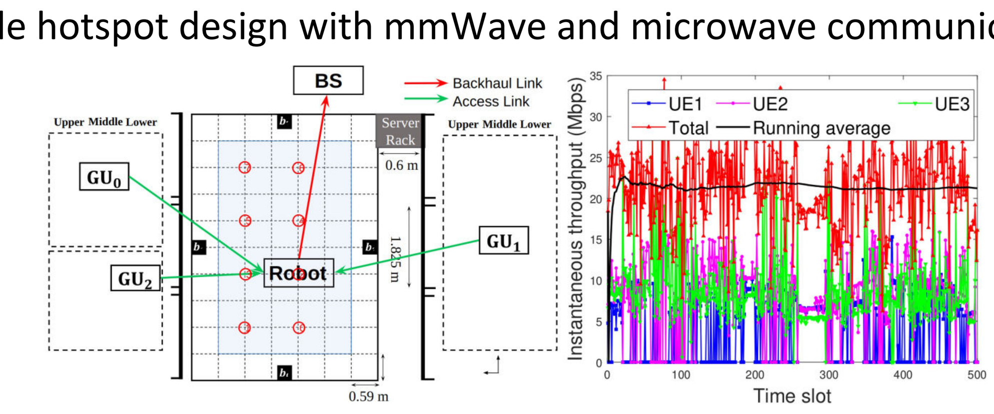
Main Research Problems

- Beam learning design with unknown mobility uncertainty
- Robust beamforming learning with mismatching mobility patterns
- Indoor and outdoor experimental evaluation

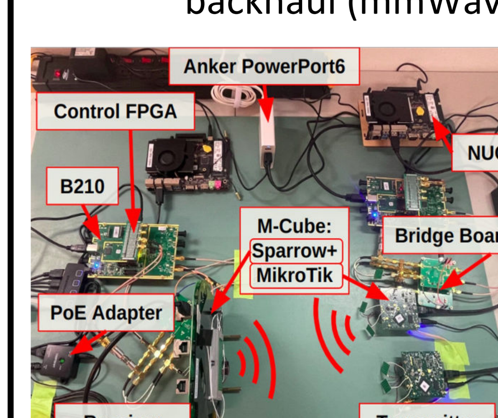
Main Results



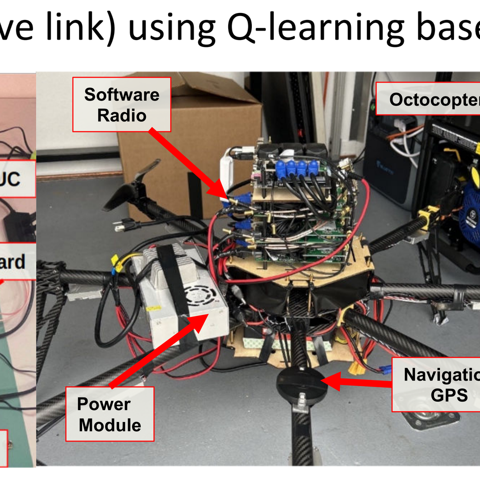
Mobile hotspot design with mmWave and microwave communications



Mobile hotspot navigation with integrated access (microwave link) and backhaul (mmWave link) using Q-learning based control



MmWave software radio setup



Medium-duty octocopter (middle) with USRP N210s and power supply system (right) for long time outdoor experiments

Future Plan: Outdoor experiments over NSF PAWR platform AERPAW

References

- Z. Yang, J. Zhuang, J. Yin, C. Yu, A. Jones and P. Zhou, "AIM: Accelerating Arbitrary-precision Integer Multiplication on Heterogeneous Reconfigurable Computing Platform Versal ACAP," ACM/IEEE International Conference on Computer-Aided Design (ICCAD'23).
- J. Yin, C. Yu, "Accelerating Exact Combinatorial Optimization via RL-based Initialization -- A Case Study in Scheduling," ACM/IEEE International Conference on Computer-Aided Design (ICCAD'23).
- M. McManus, T. Rinchen, S. M. Suhail, S. Santhinivas, A. Dey, S. Pagidimarri, Y. Cui, J. Hu, J. Z. Zhang, X. L. Wang, M. Ji, N. Mastronarde, and Z. Guan, "Demo Abstract: UnionLabs: AWS-based Remote Access and Sharing of NextG and IoT Testbeds," in Proc. of IEEE International Conference on Computer Communications (INFOCOM), Vancouver, Canada, May 2024.
- S. K. Moorthy, N. Mastronarde, E. S. Bentley, M. Medley, and Z. Guan, "OSWireless: Hiding the Specification Complexity for Zero-Touch Software-Defined Wireless Networks," Computer Networks (Elsevier), vol. 237, December 2023.
- M. McManus, Y. Cui, J. Zhang, J. Hu, S. K. Moorthy, N. Mastronarde, E. S. Bentley, M. Medley, and Z. Guan, "Digital Twin-Enabled Domain Adaptation for Zero-Touch UAV Networks: Survey and Challenges," Computer Networks (Elsevier), vol. 236, November 2023.
- X. Huang, A. Farhang, and R-R. Chen, ``Channel Estimation and Turbo Equalization for Coded OTFS and OFDM: A Comparison," IEEE Wireless Communications Letters, 2023.
- X. Zhang, A. Bhuyan, S. K. Kasera and M. Ji, "Distributed Power Allocation for 6-GHz Unlicensed Spectrum Sharing via Multi-agent Deep Reinforcement Learning," 2023 IEEE International Conference on Industrial Technology (ICIT).

Acknowledgement

- NSF SWIFT-2229562, NSF SWIFT-2229563