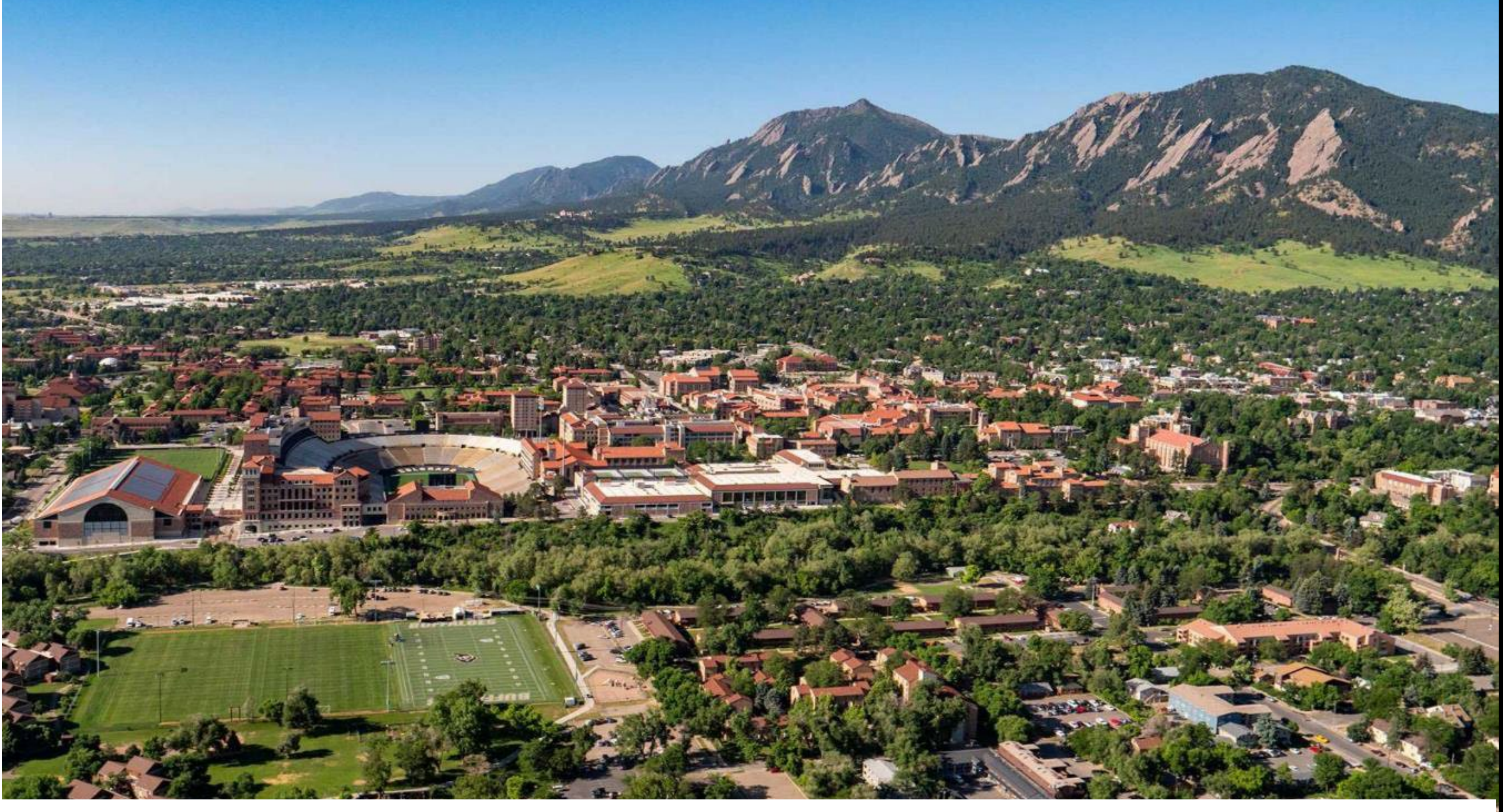
ISART 2026

Boulder, CO | August 11-13, 2026



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CENTER FOR NATIONAL SECURITY INITIATIVES

Emerging Hardware Architectures for AI-Enabled Spectrum Systems

Ryan Montoya,
Center for National Security Initiatives

08-13-2026

University of Colorado Boulder

NSI Vision and Approach

Vision

Accelerate the delivery of advanced capability needs of the Department of War and the Intelligence Community through leading-edge, high impact research and workforce development

Approach

- **Applied Research**
  Coordinate world-class capabilities of NSI and CU campus to mature concepts from basic ideas to products
- **Workforce Development**
  Train students to meet unique national security workforce requirements
- **Collaboration**
  Foster close relations with government and industry to develop effective partnerships for transition of capabilities

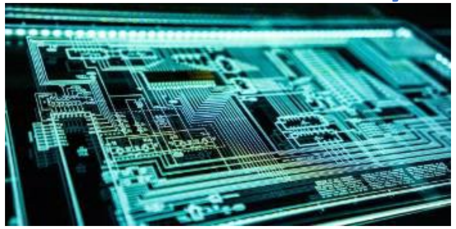
Core Capabilities

Multiple-research teams aligned with campus and regional strengths

Hypersonics

RF Engineering

Micro-Electronics & Cyber



Space Domain Awareness

Remote Sensing

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College of Engineering & Applied Science

40+ faculty across campus:
College of Engineering and Applied Sciences
College of Arts and Sciences

LASP

Key Campus Partners

Office of Contracts and Grants
Office of Research Integrity
(including Research Security and Export Control)
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Office of Information Technology
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University of Colorado Boulder

Outline

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1. Motivation – Next Generation Systems Powered by AI/ML
2. Digital-at-the-Element Front End Architectures
   - Simultaneous Transmit and Receive
   - Wideband Arrays
3. Metasurface Front End Architectures
4. AI/ML Enabled Spectrum Systems
   - Gradient-based design and optimization
   - Fully differentiable digital twins
   - Physics informed AI/ML co-design
5. Conclusions

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Hardware Drivers

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Significant changes driving hardware redesign for 6G/FutureG:

Full-Duplex Communications (FD)

Non-Terrestrial Networks (NTN)

Holographic Communications (HOLO)

Integrated Sensing and Communications (ISAC)

Interdependent Electromagnetic Problems

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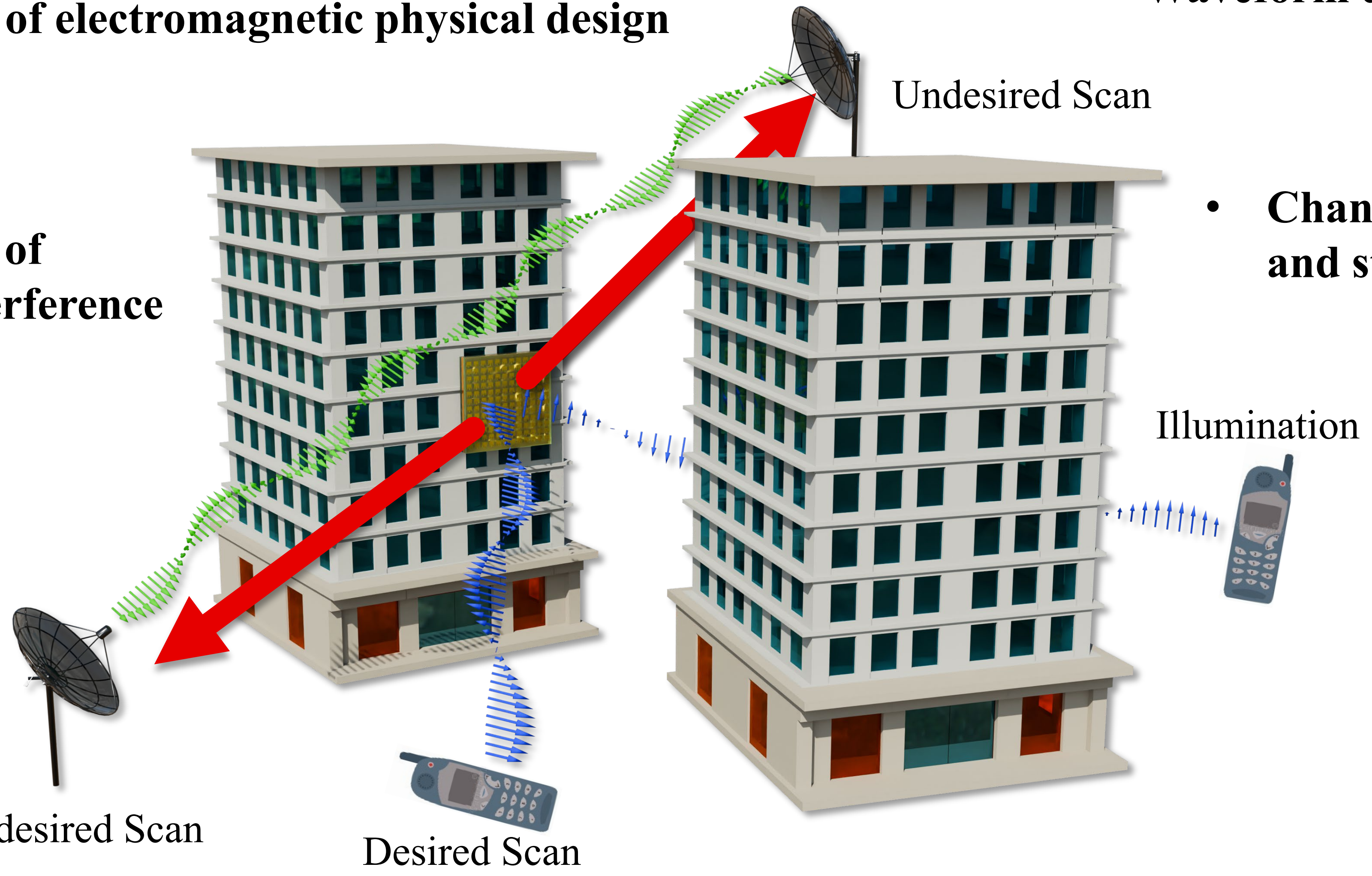
- **Optimization of adaptive array state**
- **Optimization of electromagnetic physical design**

- **Waveform design and control**

- **Coordination of resources/interference management**

- **Channel estimation and state-awareness**



If AI/ML is imagined to mitigate these complexities – how can we enable it?

AI/ML Spectrum Systems

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Three steps are crucial to the effective enablement of AI/ML spectrum systems:

1. Flexible, scalable, and capable RF front ends

- Without adequate front-end architectures, AI/ML enabled systems are limited

2. Electromagnetic-aware models and digital twins

- Models and twins must be high fidelity
- Capture full-wave effects such as mutual coupling, and large-scale effects such as fading
- Can be used to pre-train and design systems/networks

3. Data capture and calibration

- Data capture is highly challenging for NG systems
- Therefore, pre-training on simulated results is necessary
- Data capture alone does **NOT** solve co-design problem of next-generation systems

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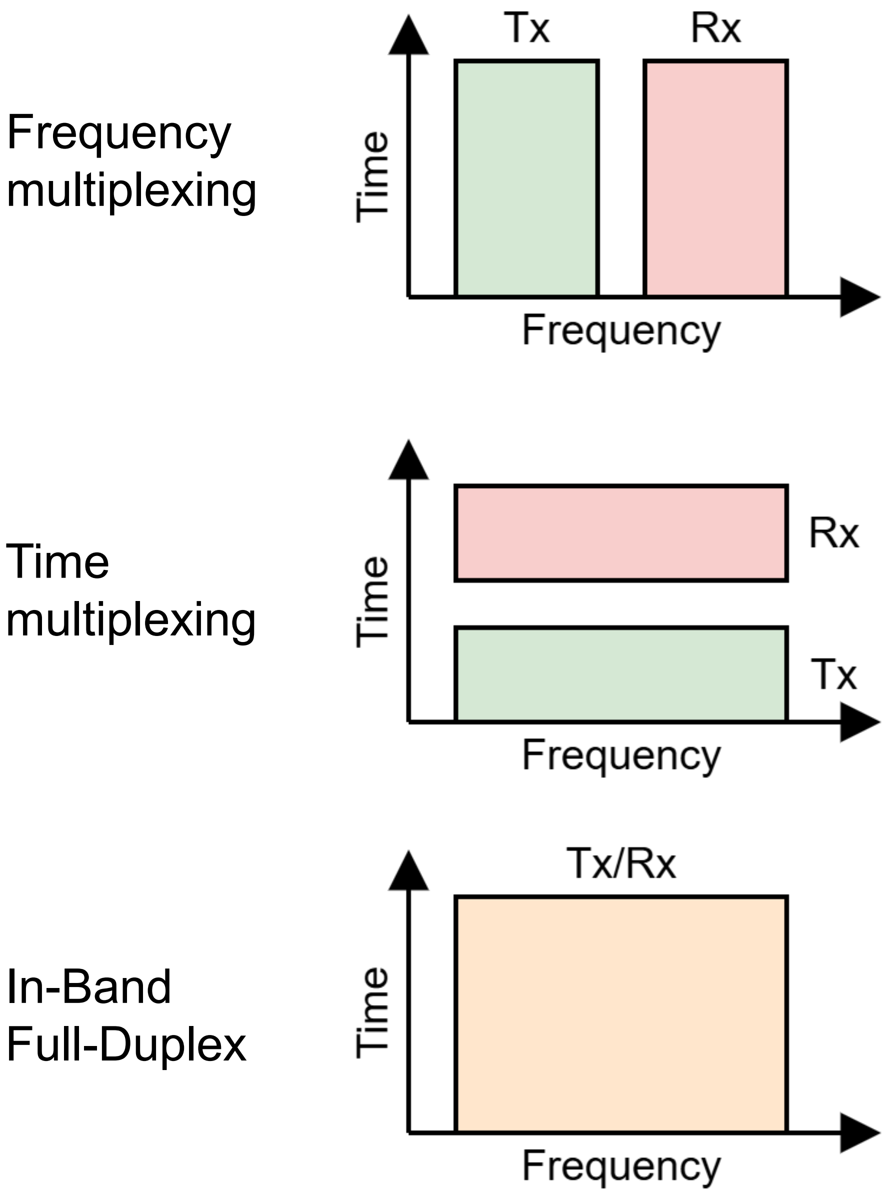
Simultaneous Transmit and Receive (STAR)

AKA – In Band Full Duplex (IBFD)
AKA – Same-Frequency STAR (SF-STAR)
Uses Self-Interference Cancellation (SIC)

Nominal required isolation:

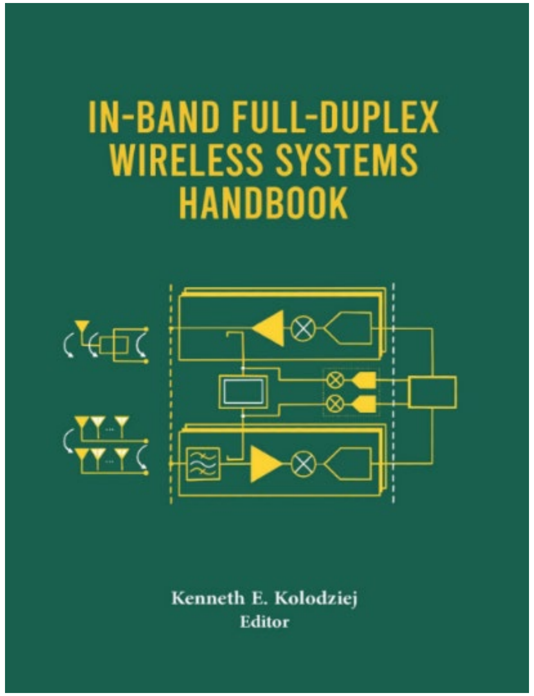
- ~100dB for 1mW TX power
- ~150dB for 100W TX power

In Band Full Duplex (IBFD) allows for the simultaneous transmission and intelligible reception of radio signals at the same frequency, time, and polarization.



Methods for IBFD

- This is achieved through self interference cancellation (SIC), which is achieved through 3 domains:
  - **Propagation**
  - **Analog**
  - Digital



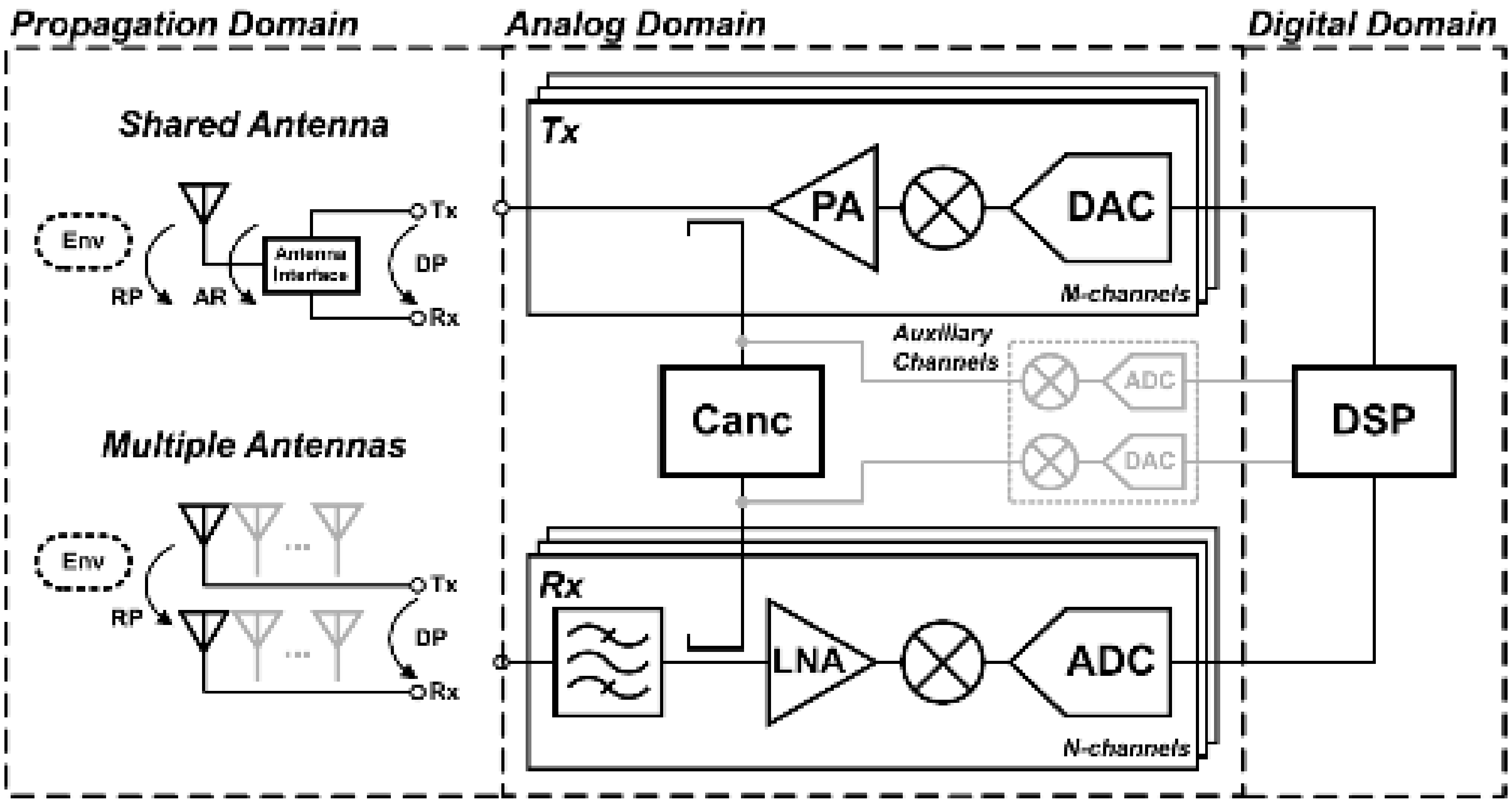


Figure 1.1 Generic IBFD transceiver, highlighting the propagation, analog, and digital domains.

Kenneth Kolodziej, *In-Band Full-Duplex Wireless Systems Handbook*, Artech, 2021.

Recent Wideband Arrays

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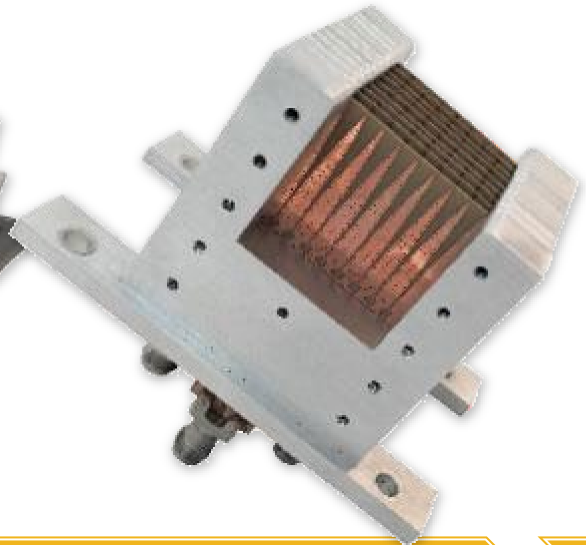
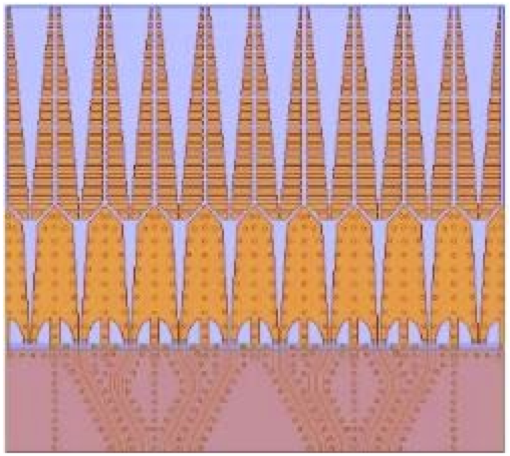
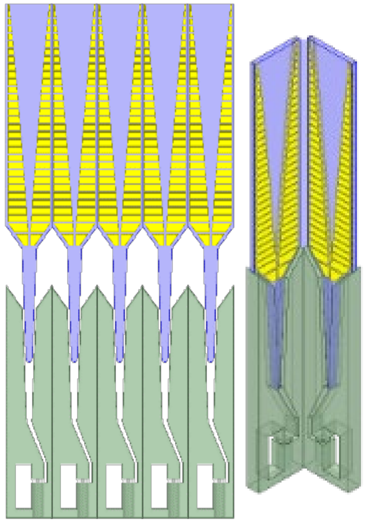
~0.5-3.5 GHz	~5-60 GHz	~3.5-60 GHz	~3.5-60 GHz







Tightly Coupled Dipole Arrays → Tapered Slot Antenna Arrays → Sliced Notch Antenna Arrays → Integration

Digital at-the-element architectures enable:

Multi-Beam Steering, T/R Isolation, MIMO, Multi-Mission, Multi-Function

SWAP-C Challenges of Phased Arrays

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- Digital-at-the-element arrays have poor SWAP-C
  - Most flexible architecture
  - Power and cost limit scalability

Hybrid architectures are most economical and/or practical!

TABLE 2. **Beamforming networks - performance vs. trade-offs.**

BFN	Pros	Cons
Analog	Cost & complexity, Moderate power	Limited flexibility, poor isolation
Digital	Calibration, reconfiguration	Device count, high power
Hybrid	Optimize between analog and digital	Device count, Complexity
Lens	Low power, low cost	Large footprint, unused ports, fix beam angles
Circuit	Simple & scalable, low power & cost	Lossy, fix beam angles

Goal: multi-mission, multi-function modular hybrid front-ends

Umar, M., Ramzan, M., Kamal, S., Sajjad Ahmad, M., & Sen, P. (2025). Possibilities and Challenges for a Phased Array Antenna System in ISAC: A Hardware Perspective. *IEEE Access*, *13*, 146032–146051. https://doi.org/10.1109/ACCESS.2025.3599680

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Reconfigurable Intelligent Surfaces (RIS)

Programmable, passive array formed by many elements

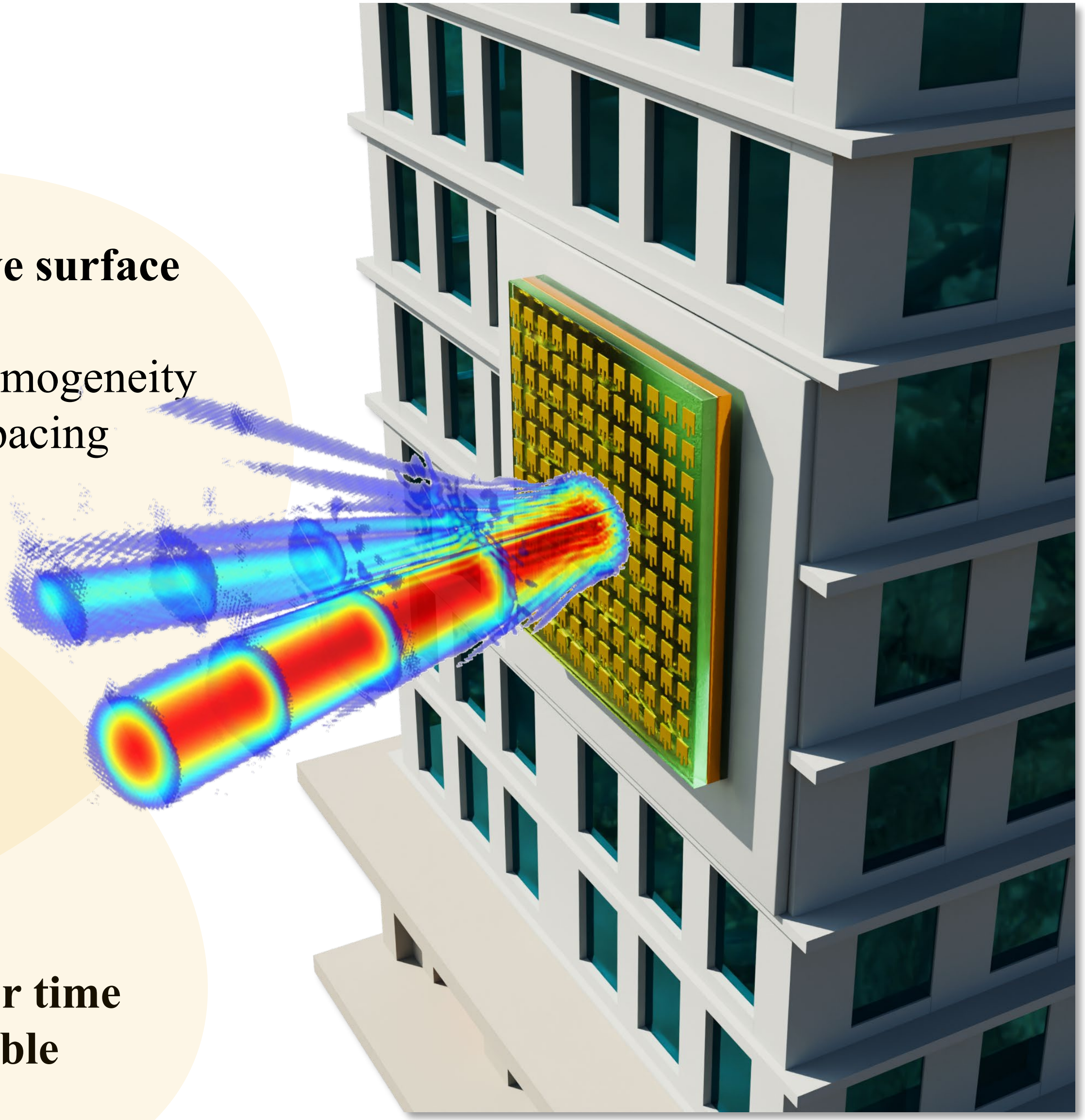
Metasurface:
- Tightly coupled
- Typically very subwavelength (e.g., $\lambda/10$)

Frequency selective surface (FSS):
- Large scale inhomogeneity
- $\sim\lambda/2$ to $\lambda/10$ spacing

Reconfigurable Intelligent Surface (RIS)

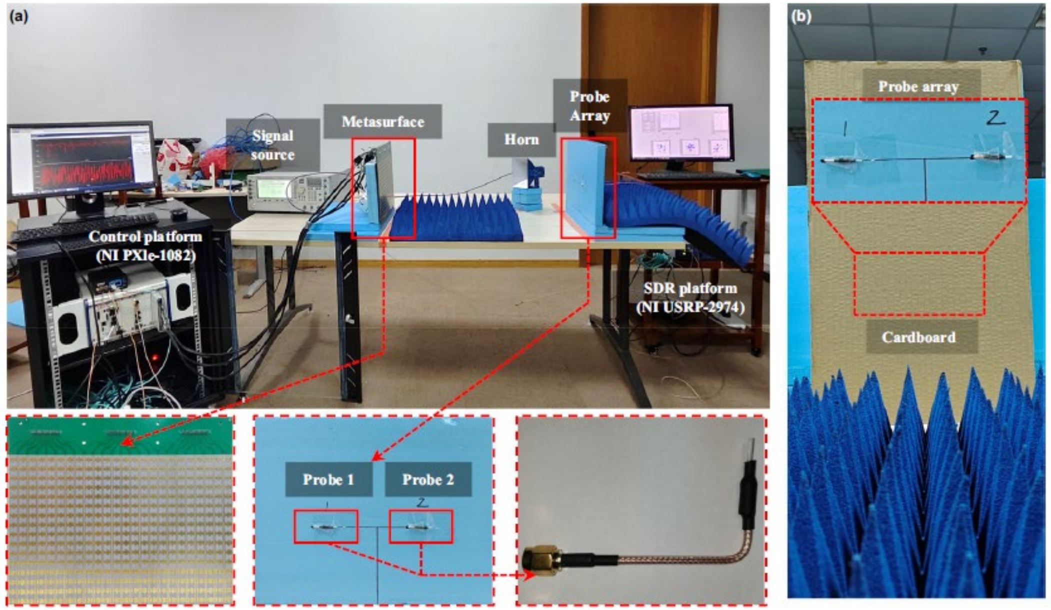
Electrical control
- Varactor diodes
- PIN diodes

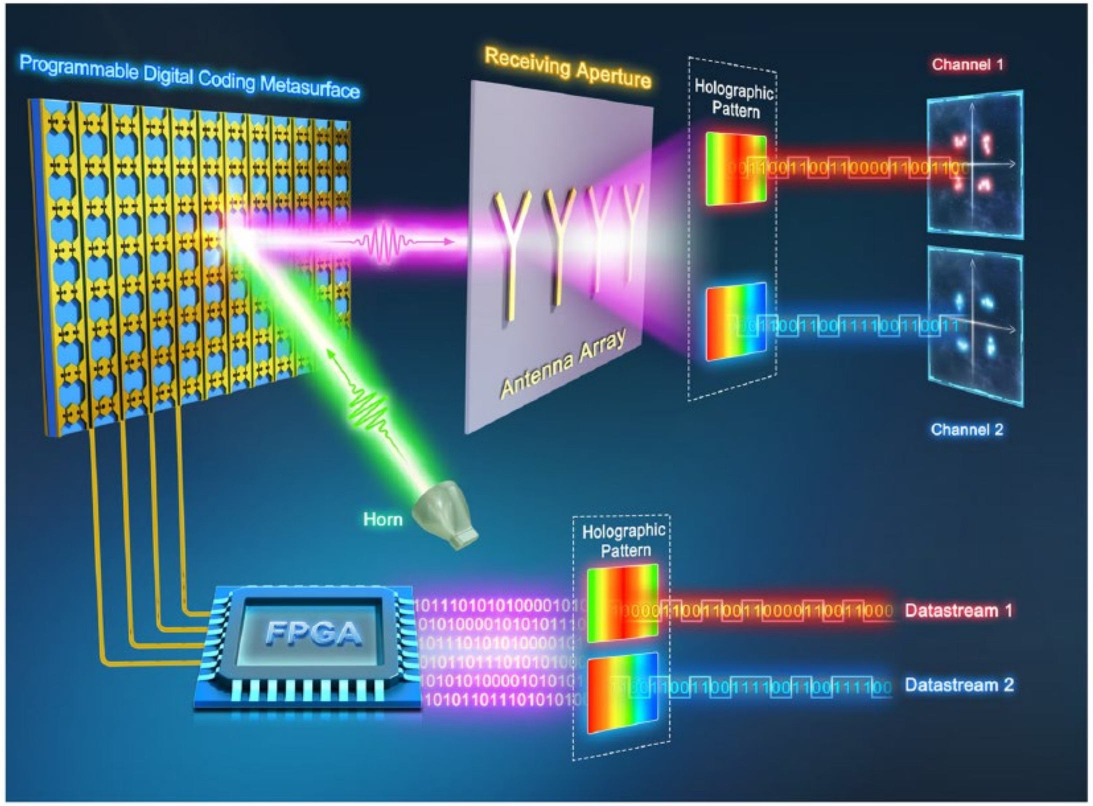
Space and/or time programmable



Holographic MIMO

- Integrated **active** and **passive** elements
- Massive apertures enabling near-field holography
  - Example: Aperture level duplexing





Hybrid metasurface-phased array designs achieve modularity and scalability!

Shao, R. W., Wu, J. W., Li, J., Meng, S., Xu, Y., Wang, Z. X., Tang, W., Cheng, Q., Jin, S., & Cui, T. J. (2025). Dual-channel near-field holographic MIMO communications based on programmable digital coding metasurface and electromagnetic theory. *Nature Communications 2025 16:1*, *16*(1), 915-. https://doi.org/10.1038/s41467-025-56209-x

Challenge: Hybrid Front-End Complexity

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There are (3) complexity challenges with metasurface-hybrid front ends

Theoretical Modelling

- Interactions between active and passive elements
- Potentially significant mutual coupling
- Edge-effects/finite array modelling

Hardware Design

- Complex, multi-leveled design
- Performance depends on deployment/wireless environment

Control/ Operation

- Large, reconfigurable front-ends have many degrees-of-freedom
- Optimal state is highly dependent on in-situ wireless conditions

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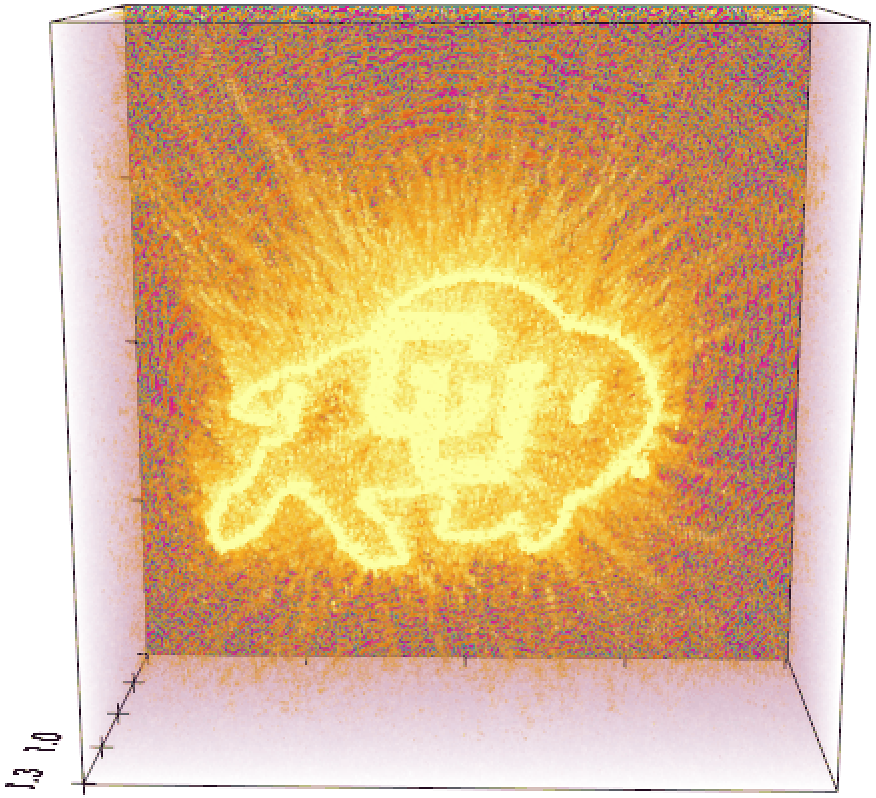
Scalable, Gradient-Based State Optimization

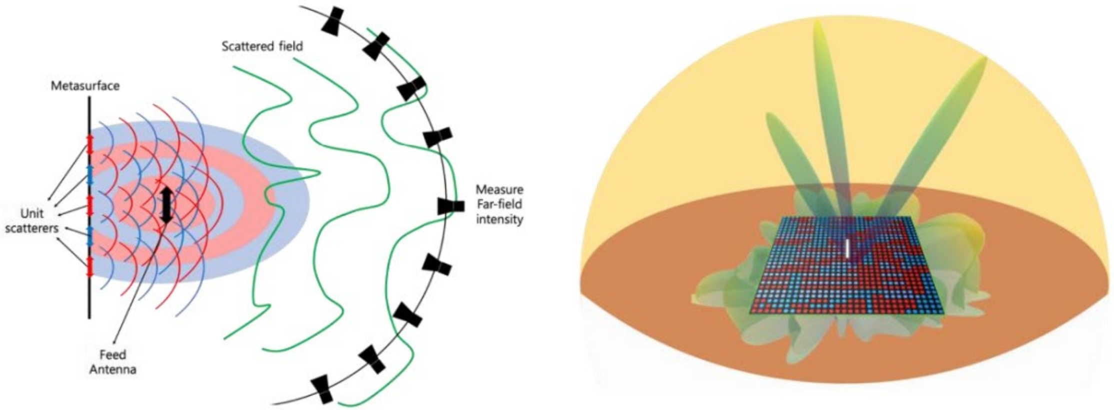
- Mutual coupling aware synthesis methods **are differentiable [1]**
- Benefits from GPU/TPU accelerated libraries (Tensorflow, Jax, Pytorch)

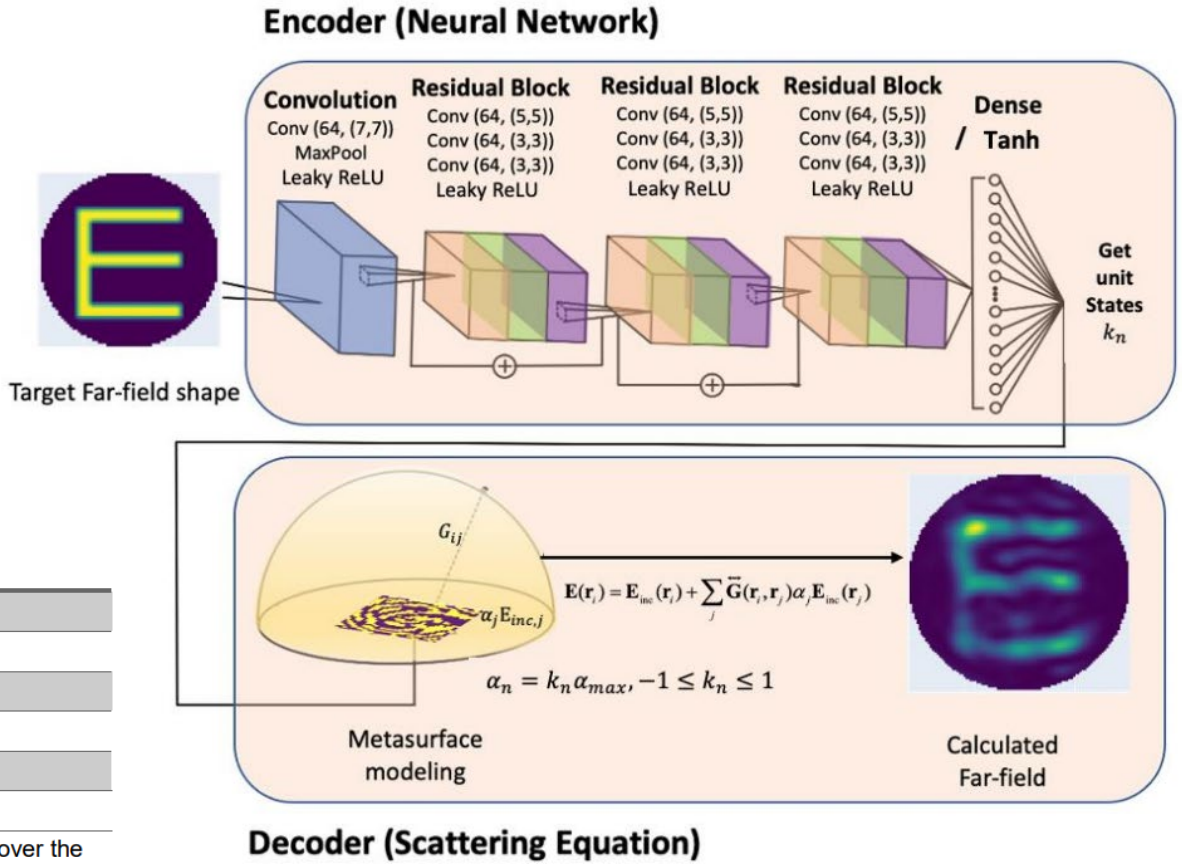
Spacetime modulated near field scattering: 12.5 GHz carrier, 100 MHz framerate, 131k tunable elements



[1] R. D. Montoya, A. S. Brannon, and C. Scarborough, "Hybrid spatial-spectral adjoint method optimization of reconfigurable intelligent surfaces," Submitted to IEEE Transactions on Antennas and Propagation, 2026.

Real-time Holographic Beam Steering





Methods	Calculation time	
	Training time	Calculation time
AutoEncoder & first-order Born	1854 sec	194 μs
AutoEncoder & second-order Born	1921 sec	192 μs
AutoEncoder & third-order Born	2077 sec	185 μs
Genetic Algorithm	232 sec	
Gerchberg-Saxton	1.25 sec	

Table 1. Calculation time according to the proposed methods, calculation time except Genetic Algorithm is averaged over the MNIST dataset. Genetic algorithm calculation time is averaged over the cases of Fig. 4.

Ma, H., et al. "Deep-learning-assisted reconfigurable metasurface antenna for real-time holographic beam steering," in *Nanophotonics*, vol. 12, no. 13, pp. 2415–2423, 2023.

Differentiable Physical Layer Simulation

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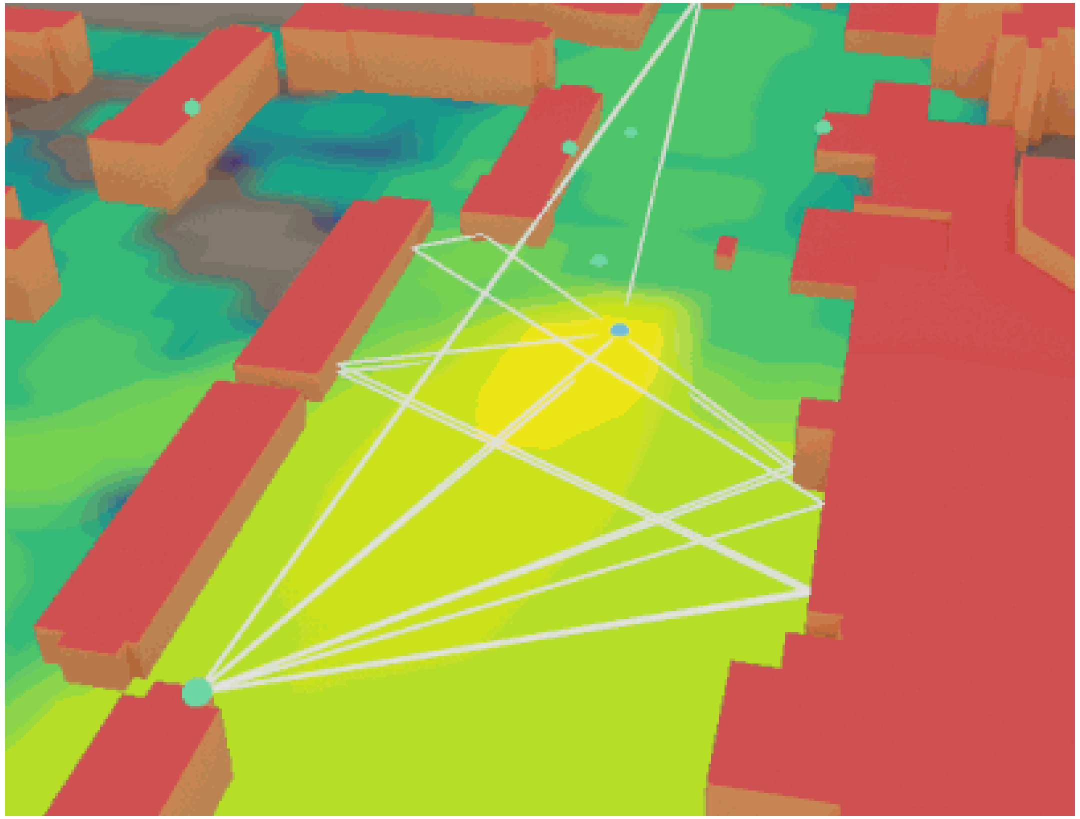
- Geometric ray tracers can simulate channel conditions based on digital twin
- Differentiable ray tracers [1] track gradients through 5G waveform (link-layer) and environment scattering (physical layer)



Evolving channel conditions, simulated and visualized using NVIDIA Sionna [1]

[1] Hoydis, J., Cammerer, S., A¨ıt, F., Aoudia, A., Vem, A., Binder, N., Marcus, G., & Keller, A. (2022). *Sionna: An Open-Source Library for Next-Generation Physical Layer Research*. https://arxiv.org/pdf/2203.11854

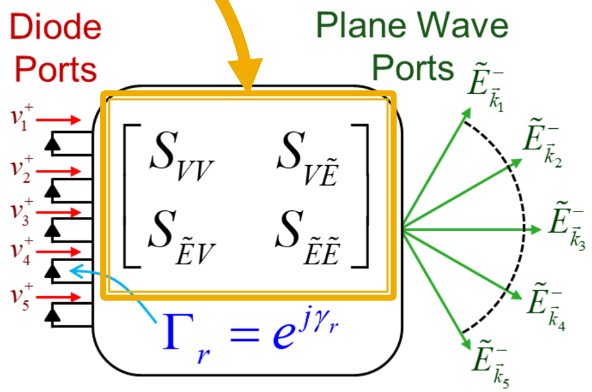
Fully Differentiable Digital Twinning

python™ + TensorFlow

Ansys

HFSS

- Full-wave simulation (FEM)
  - **Inputs:** geometry, materials, sources
  - **Outputs:** S-parameters



Forward-Scattering Models

- Network-parameter based
  - **Inputs:** incident plane waves, lumped element impedances
  - **Outputs:** outgoing plane waves

$\tilde{E}_k^-$

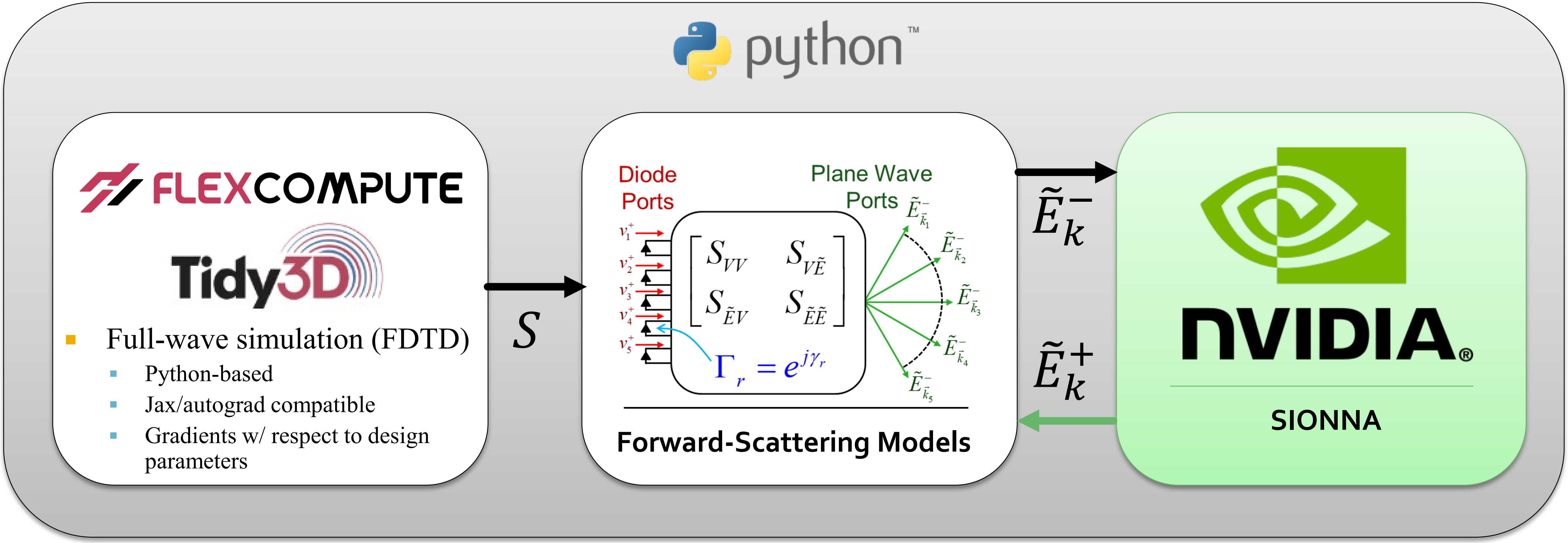
$\tilde{E}_k^+$

NVIDIA

SIONNA

- Geometric ray tracing
  - **Inputs:** 3D scene/geometry, large movement, material properties
  - **Outputs:** channels, incident/outgoing plane waves, telecom metrics (BER)

Fully Differentiable Design



Python + automatic differentiation

(1) Inverse design, (2) Physics-informed machine learning (3) Fully-scriptable

Conclusion

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- Next-generation networks are complex, and interdependent between hardware, software, and situational context
- Adaptive, capable systems require adaptive and capable RF front ends
- Design and optimization of AI/ML spectrum systems requires:
  1. Electromagnetically aware digital twins
  2. Ideally, differentiable digital twins
  3. In-situ data capture to refine systems and models (future work)

Theory: Mutual Coupling Aware Scattering

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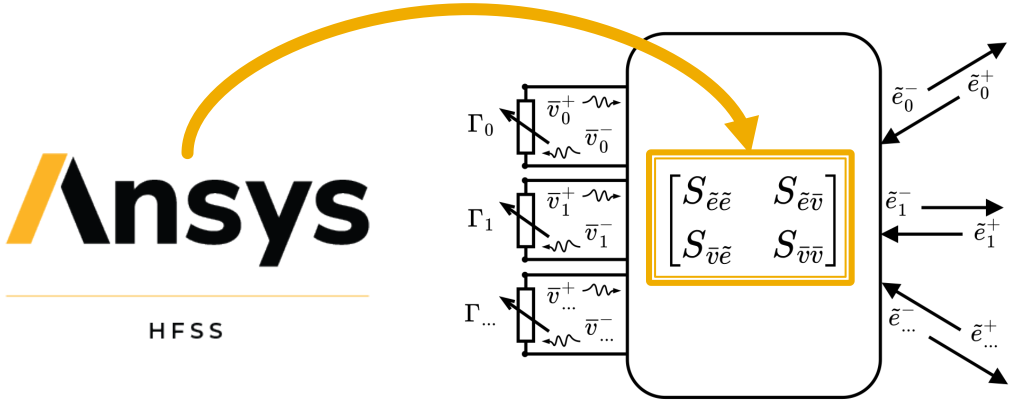
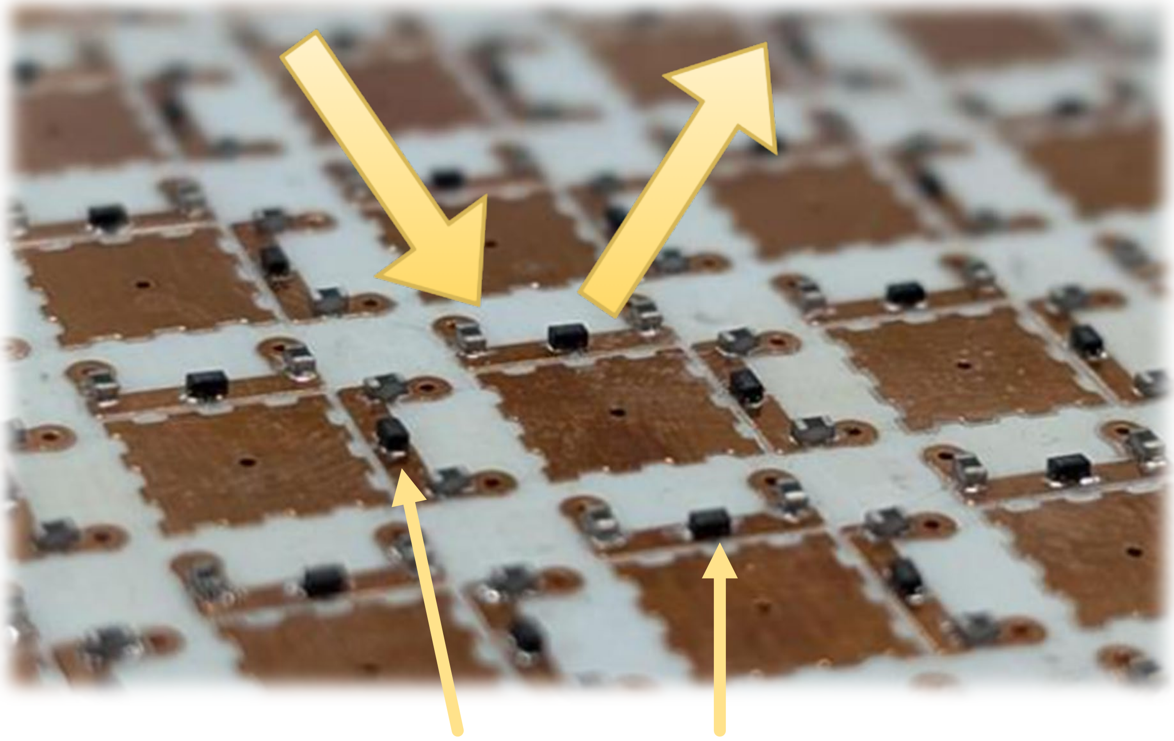
1. Relate the **spatial** port voltages of a periodic RIS to incoming/outgoing plane wave spectrum
2. Determine the **outgoing** plane wave spectrum given biased element states $Z \rightarrow \Gamma$

Full-wave simulation performed only once, then scattering can be solved efficiently during deployment!



Incoming/outgoing plane wave spectrum



Tunable reflection coefficients

R. D. Montoya, A. S. Brannon, and C. Scarborough, "Hybrid spatial-spectral adjoint method optimization of reconfigurable intelligent surfaces," Submitted to IEEE Transactions on Antennas and Propagation, 2026.

Example Architecture

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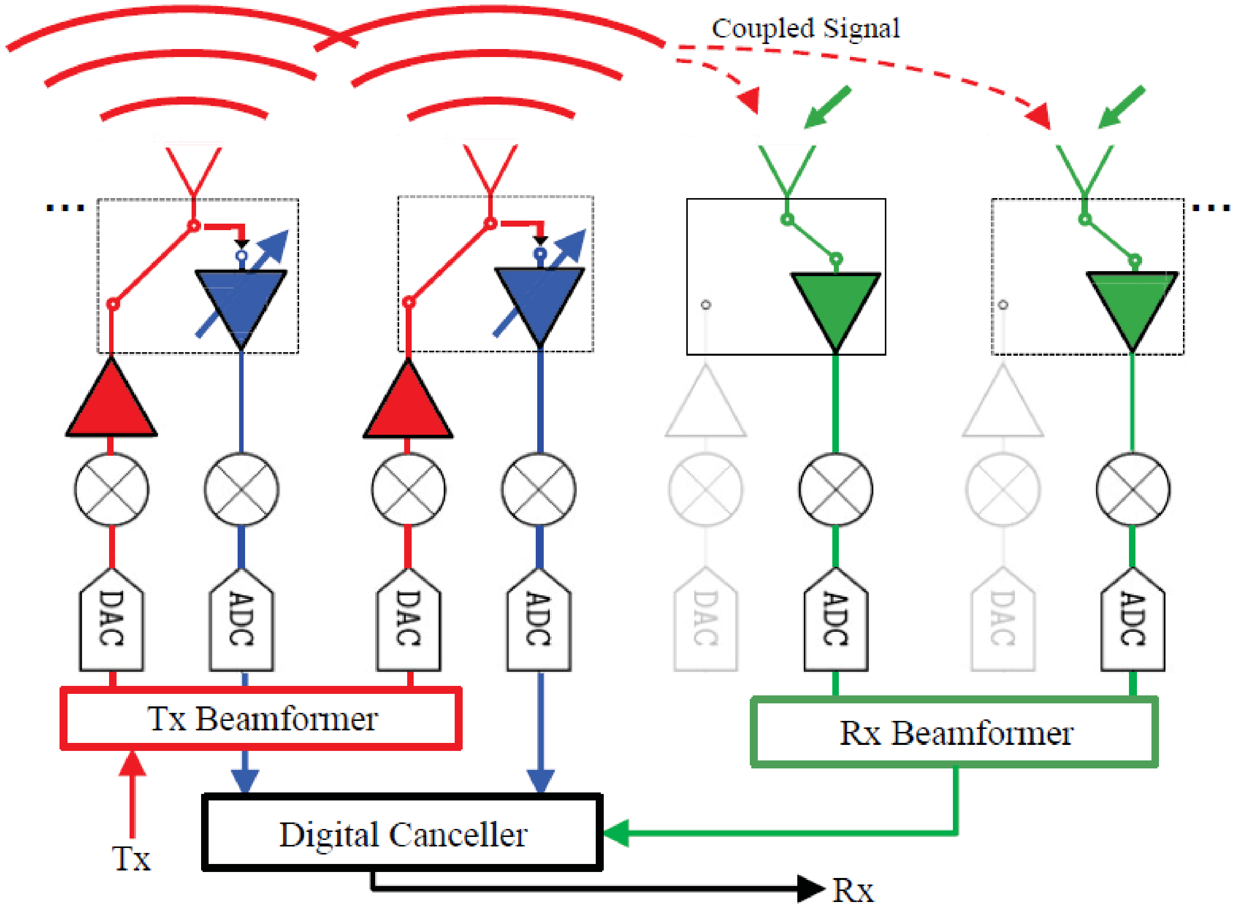
- Switch isolation for sampling of the transmit-path signal
  - Assist digital self-interference cancellation (SIC)
- A fraction of the elements transmit while the remaining elements receive
- Switched half-duplex T/R module in each element
  - Reconfigured in terms of number and location of each T and R element



Adaptive beamforming on TX & RX
Aperture-level simultaneous transmit and receive (ALSTAR)

S. Johannes, *et al.*, "Co-Designed Switch-LNA GaN MMIC for Improving Self-Interference Cancellation by Transmit-Signal Observation," *2023 16th International Conference on Advanced Technologies, Systems and Services in Telecommunications (TELSIKS)*, Nis, Serbia, 2023.

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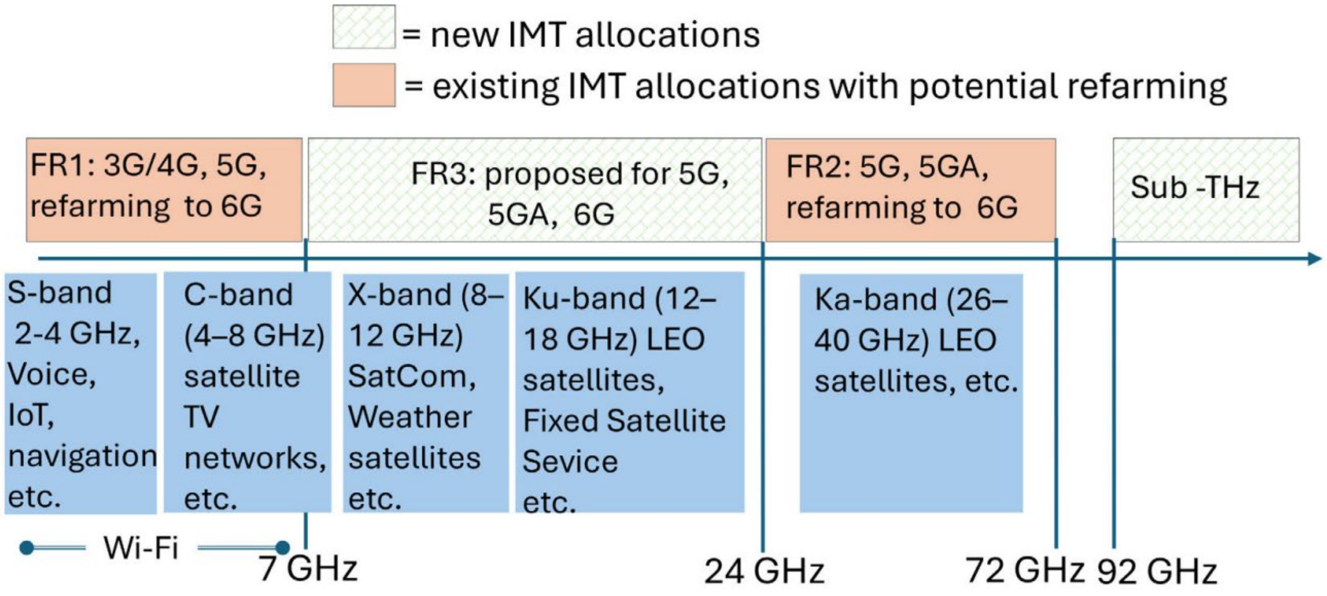
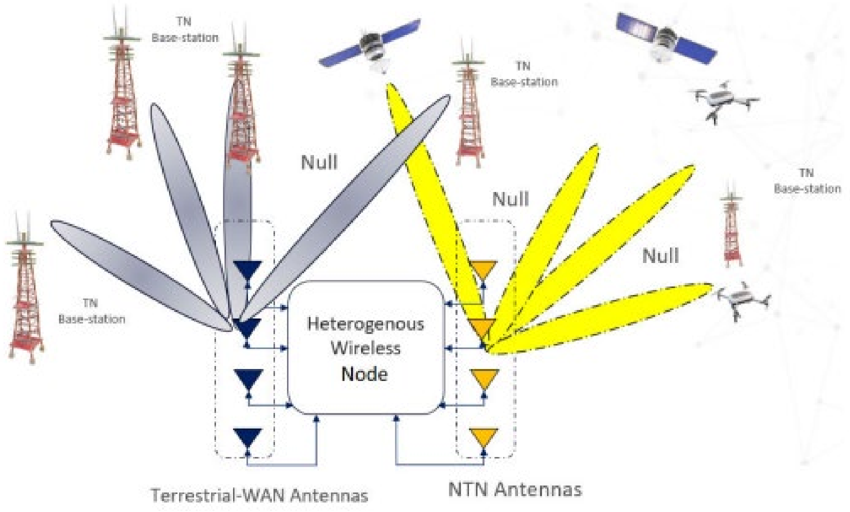
3GPP Spectrum Occupation

- Significant spectrum overlap in 5G, 6G
- High fidelity spatiotemporal control needed for interference mitigation



[1] Overlapping spectrum bands of cellular networks, satellites, and Wi-Fi



[1] Interference mitigation through antenna beam optimization

Flinck, H., Kumar, T., Ramabadran, P., Katranaras, E., Garcia, L. G. U., Hmedoush, I., Hassan, S. S., Wilhelm, M., Meyer, S., Drewes, C., & Mähönen, P. (2025). An Overview of Flexible Spectrum Management Approaches for 6G. *IEEE Access*, *13*, 207396–207411. https://doi.org/10.1109/ACCESS.2025.3638140

The Toolbox: Gradient Descent

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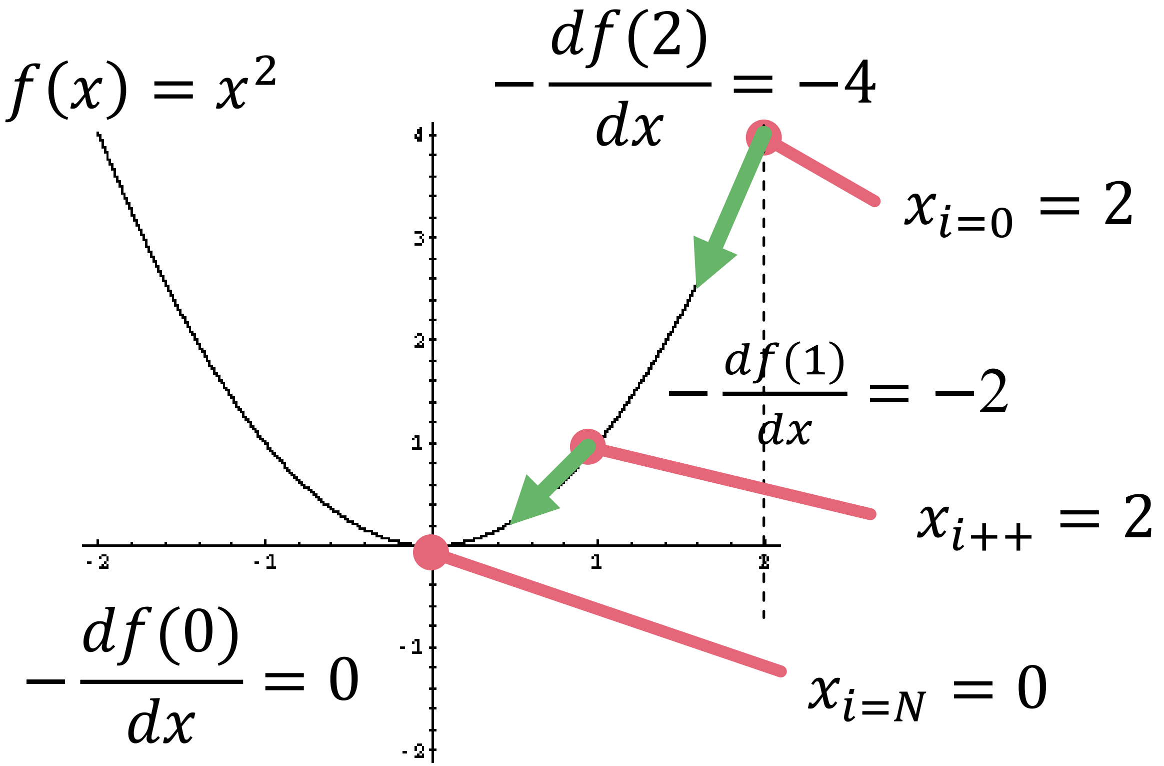
The **gradient** of a function is a vector of partial derivatives

- E.g., given some error function, it is the vector of derivatives with respect to each parameter

The gradient can be used to optimize (minimize or maximize) some objective function f



e.g., 1-D convex optimization (trivial)

Modern AI/ML relies on automatic differentiation and the adjoint variable method (backpropagation) to efficiently compute gradients for highly parameterized neural networks

RF Engineering **Research Lead:** Brannon (NSI)

Faculty: Popovic, Filipovic, Gasiewski, Barton, Piket-May, Scarborough (ECEE)

NATIONAL SECURITY INITIATIVES

Overview

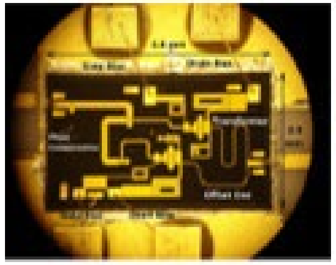
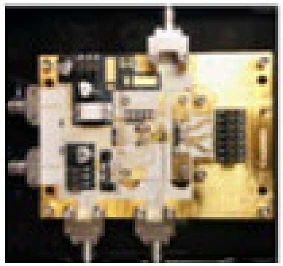
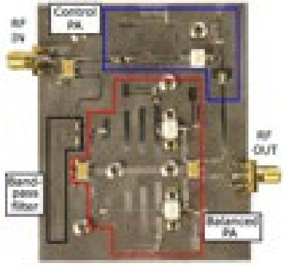
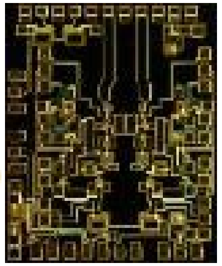
- **Missions:** RF Communications, Spectrum Operations, Electronic Warfare, Remote Sensing
- **Challenges:** Bandwidth, power, size, integration, resilience, LPI/D, reconfigurability, security
- **CU Strengths:** 5G/XG, antennas, power amps, filters, RF AI/ML, MMIC design, photonics
- **Federal Agencies:** DARPA, Air Force, Army, Navy, NSF, NASA, NIST, Space Force, OUSD…
- **Industry Partners:** Lockheed-Martin, Northrop Grumman, Boeing, Qorvo, L3-Harris, BAE, HRL, CACI, SRI, Azure Summit…

Apertures and Passive Circuits



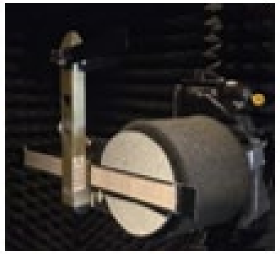
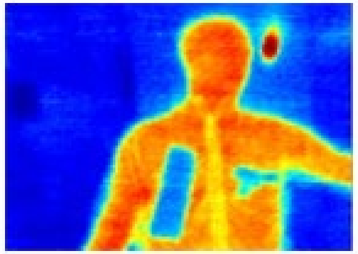
- Wideband, small, efficient, high-power antennas
- STAR antennas, arrays, and analog front-ends
- RF co-designed electrically-tunable front-ends
- High power, tunable, small RF filters

Active and Integrated Circuits

- High-efficiency power amplifiers for telemetry, radar, communications, and medical applications
- Low phase noise oscillators, time and frequency stability
- Low noise amplifiers, MMIC design
- Package design for high active device efficiency

Quantum Sensing & Metrology

- RF & RF-photonic front-ends for EW, communications, radar, telemetry, full-duplex radios, small satellites
- Quantum sensors (quantum magnetometers, Rydberg sensors)
- Wireless power transfer, MRI, non-invasive sensing, and other medical applications