Intro to Reconfigurable Intelligent Surfaces

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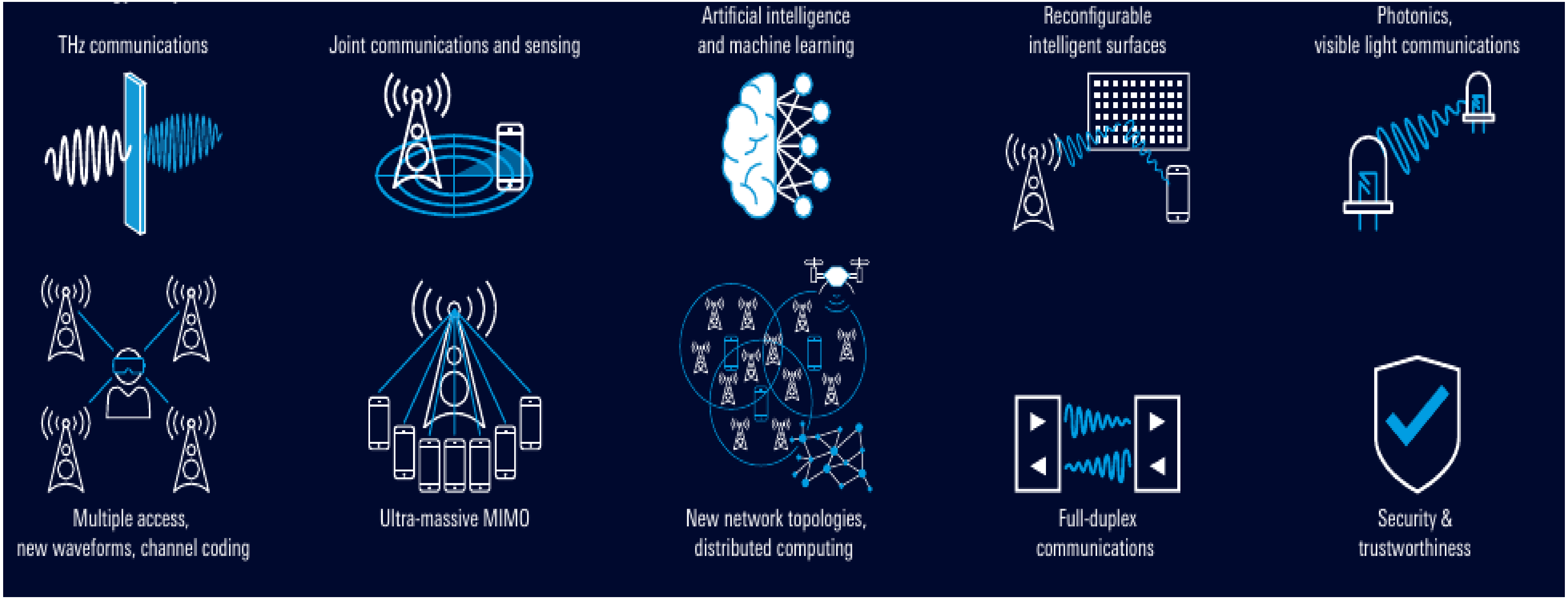
IEEE Pikes Peak Section | October 12, 2023

Acknowledgments
+ Virginia Tech National Security Institute (VTNSI)
+ Army Research Lab (ARL)

Brief Introduction and Research Interests

- From 2G to 6G and beyond
- SATCOM and localization for the defense industry
- Digital signal processing for wireless communications
- Radio frequency machine learning
- Complex-valued and Hyper-complex Neural Networks
- Electromagnetic signal information theory
- Ultra-reliable low-latency communications

Current State of Wireless Technologies



[1] Rhode & Schwartz, “Ten key enablers for 6G wireless communications”, 2023

Outline

- State of the Art, Motivation and Background
- Paradigm Shifts
- Software-Defined Environment for Wireless Networks
- Metasurfaces and Reconfigurable Intelligent Surfaces
- Operation Modes and Use Cases
- Conclusions and Outlook
- References

State of the Art

- MIMO and Massive MIMO is used in 5G
- Enables mobile real-time video
- Utilizes the spatial domain for additional degrees of freedom-over frequency only systems
- Leveraging a rich multi-path environment
- Capacity improvement over MIMO
  - Mutual coupling limited
  - Logarithmic *Marzetta Bound*
- Supports the Multi-User case
  - Interleaving data streams
- Many antenna elements enables beam-forming
  - Improve coverage and reduce transmit power

Massive MIMO

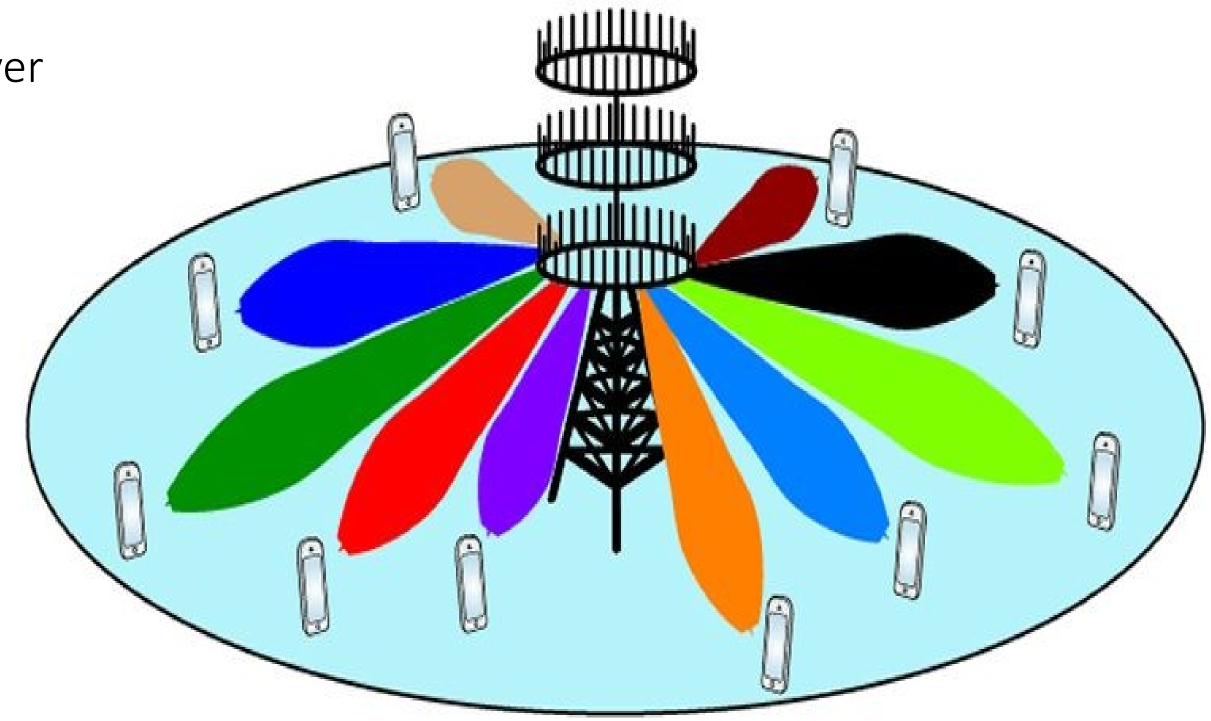


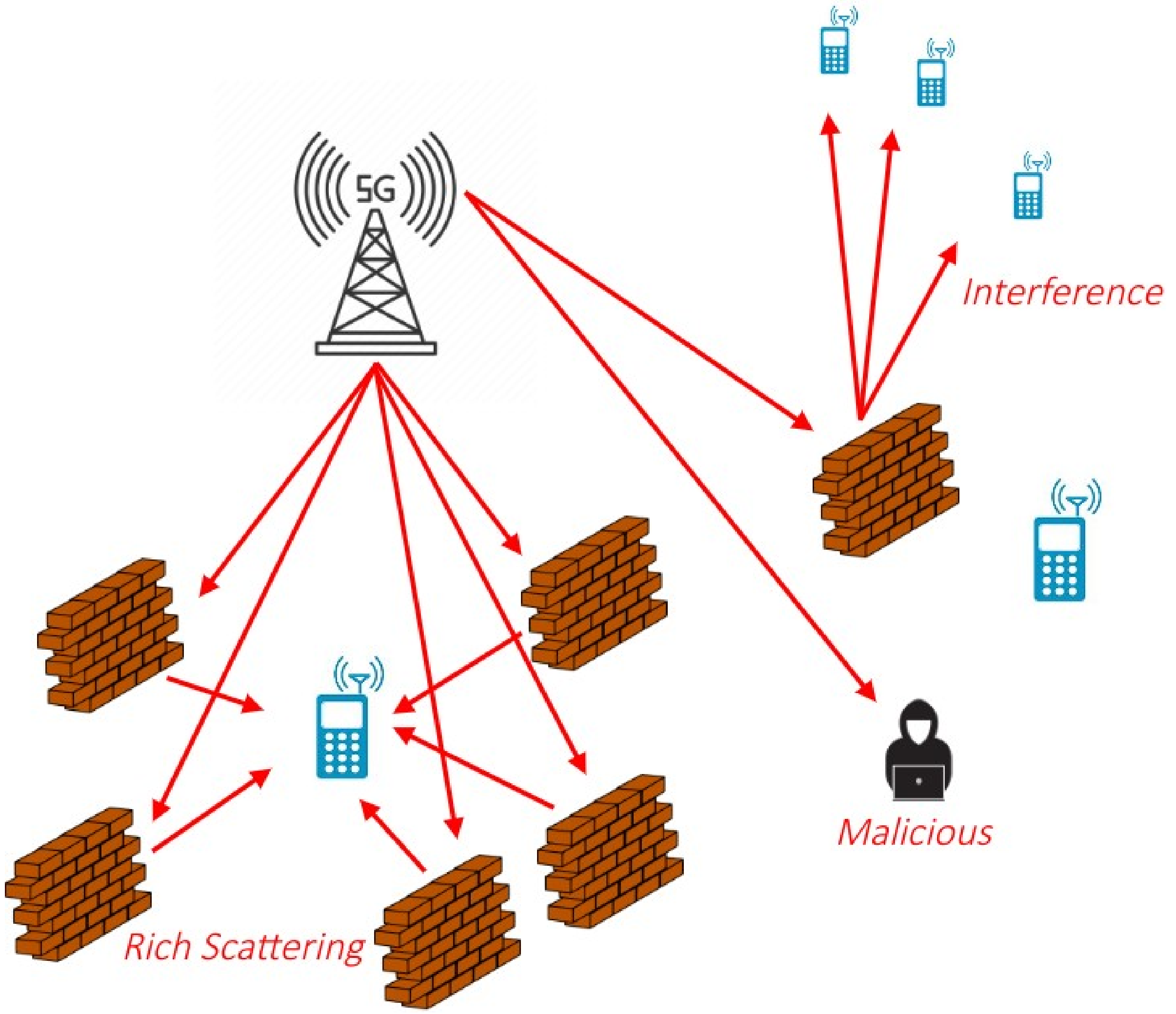
Figure: https://5g.co.uk/guides/what-is-massive-mimo-technology/

[2] T. L. Marzetta, "Fundamental limitations on the capacity of wireless links that use polarimetric antenna arrays," Proceedings IEEE International Symposium on Information Theory,, Lausanne, Switzerland, 2002, p. 51.

State of the Art and Issues

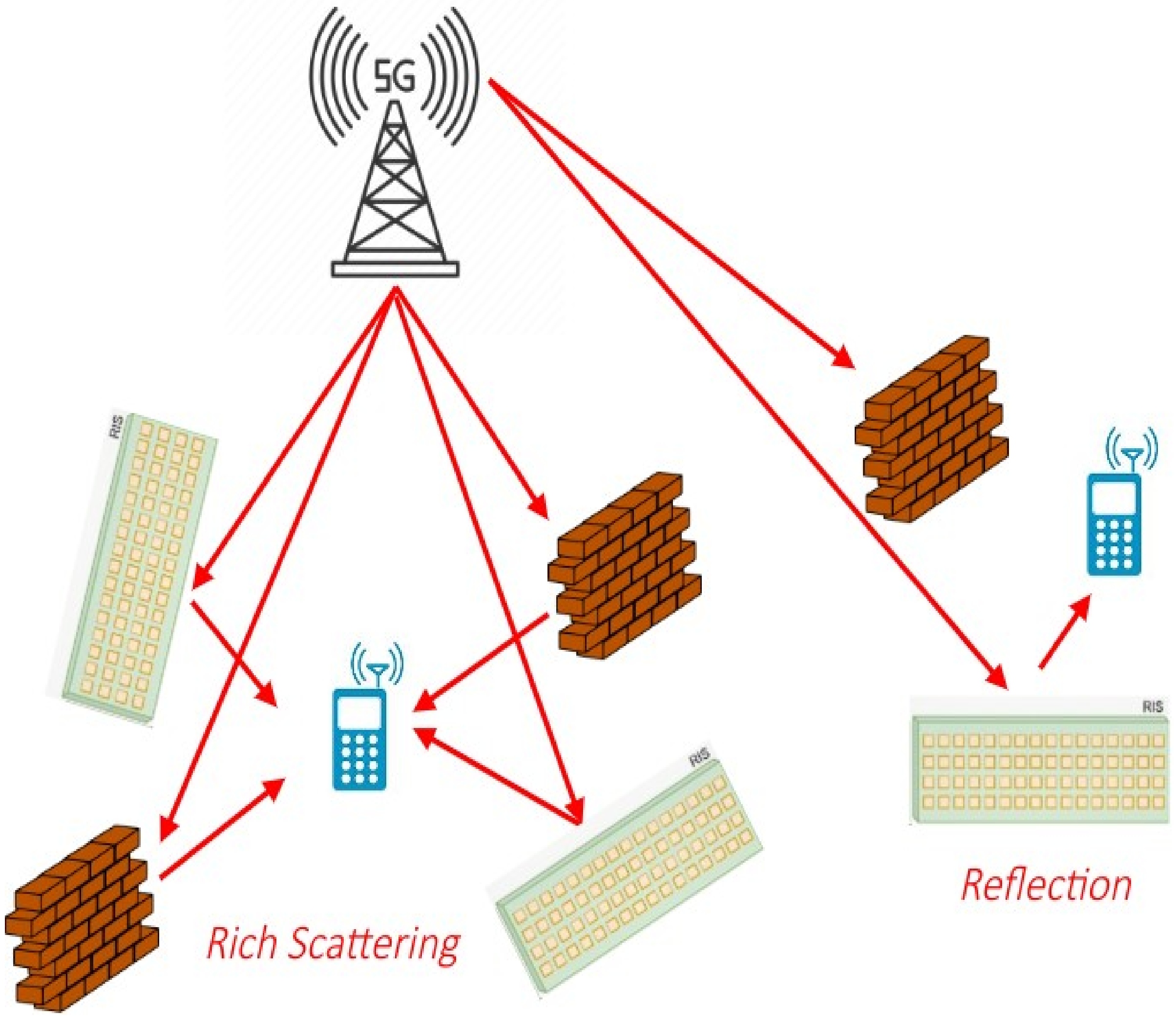
- **High Performance:**
  - MIMO exploits rich scattering multipath
  - Massive MIMO beam-forming to user
    - 64 or more antenna elements

- **Problems:**
  - mmWave/sub-THz poor propagation
  - Ground reflections loss ~ d^4
  - Potential of blockage
  - Interference
  - Eavesdropper



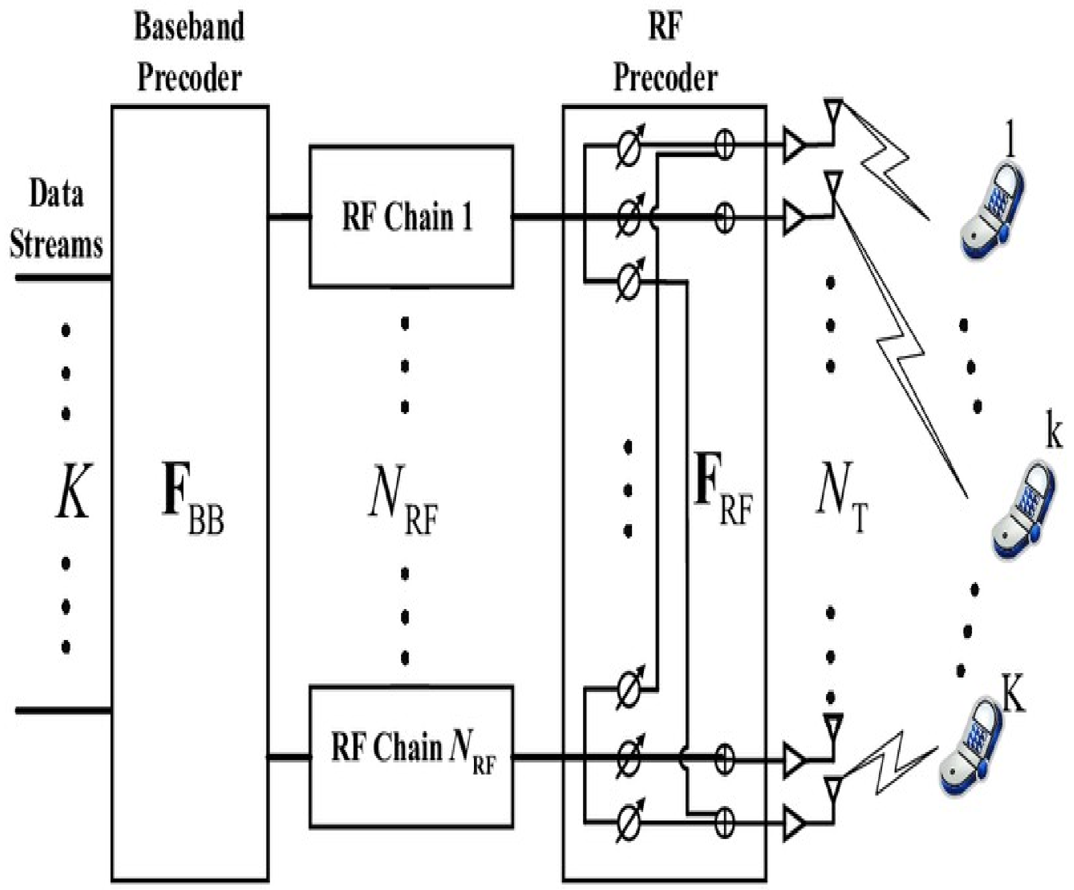
Solutions using RIS

- The *classic* RIS solution
  - Place RIS to reflect wave towards user
- Artificial multipath
  - Place RIS to enhance multipath
- Interference cancellation
  - Utilize RIS to cancel interference
- Obfuscate the eavesdropper
  - Direct wave away from eavesdropper
  - Jam the eavesdropper with reflections
- Multitude of other scenarios



Cost Motivation and Solution

- **Problem:**
  Contemporary communications systems *MIMO* and *massive MIMO* use very large antenna arrays
  - Exploits the spatial domain for bit-rate/user
  - Requires N_{RF} radio-frequency chains
  - Prohibitive cost, power and complexity
- **Solution:**
  - Reconfigurable Intelligent Surfaces
  - Neural networks for at decoding and de-noising

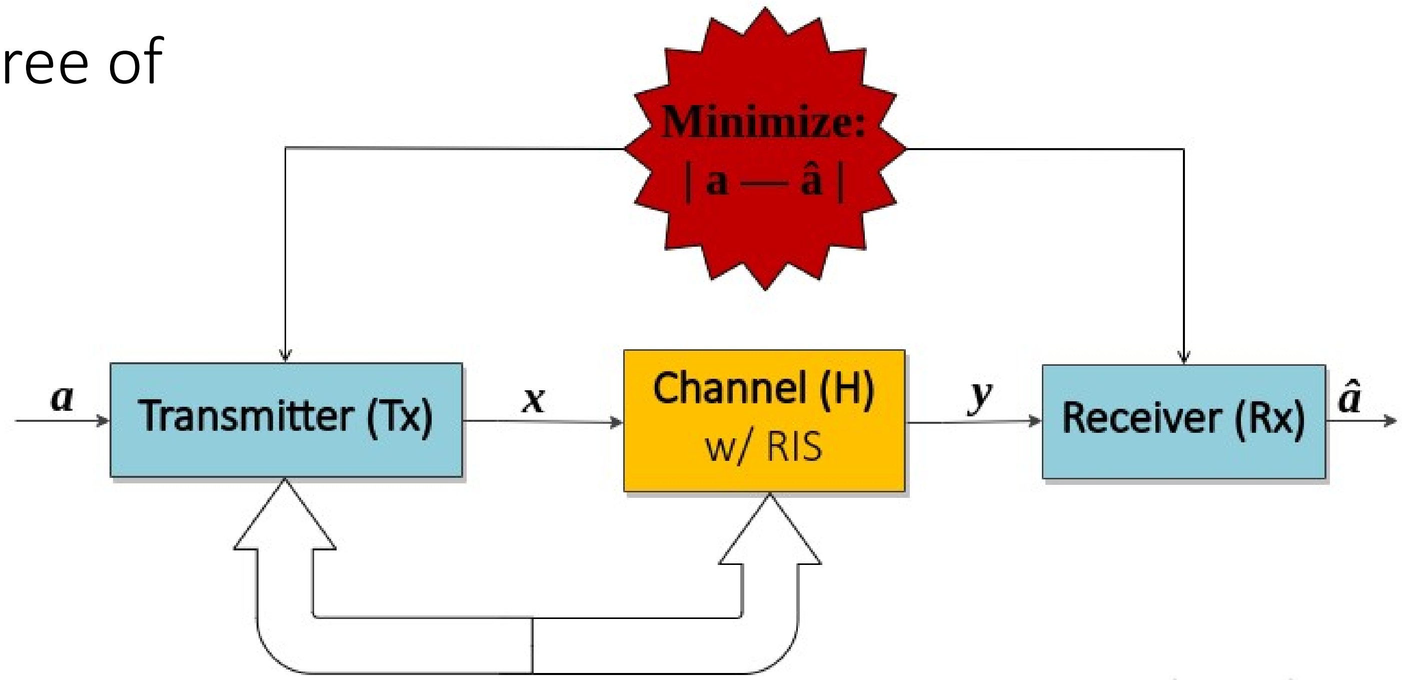


[3] P. Sabeti, A. Farhang, I. Macaluso, N. Marchetti and L. Doyle, "Blind Channel Estimation for Massive MIMO: A Deep Learning Assisted Approach," IEEE International Conference on Communications, 2020, pp. 1-6.

A True Paradigm Shift: Software-Defined Environment

- Smart radio environment
- A new concept and a true a paradigm shift
- The channel environment itself can be controlled and optimized
- The communication system has a degree of control of the channel environment

Controlled Radio Wave Propagation

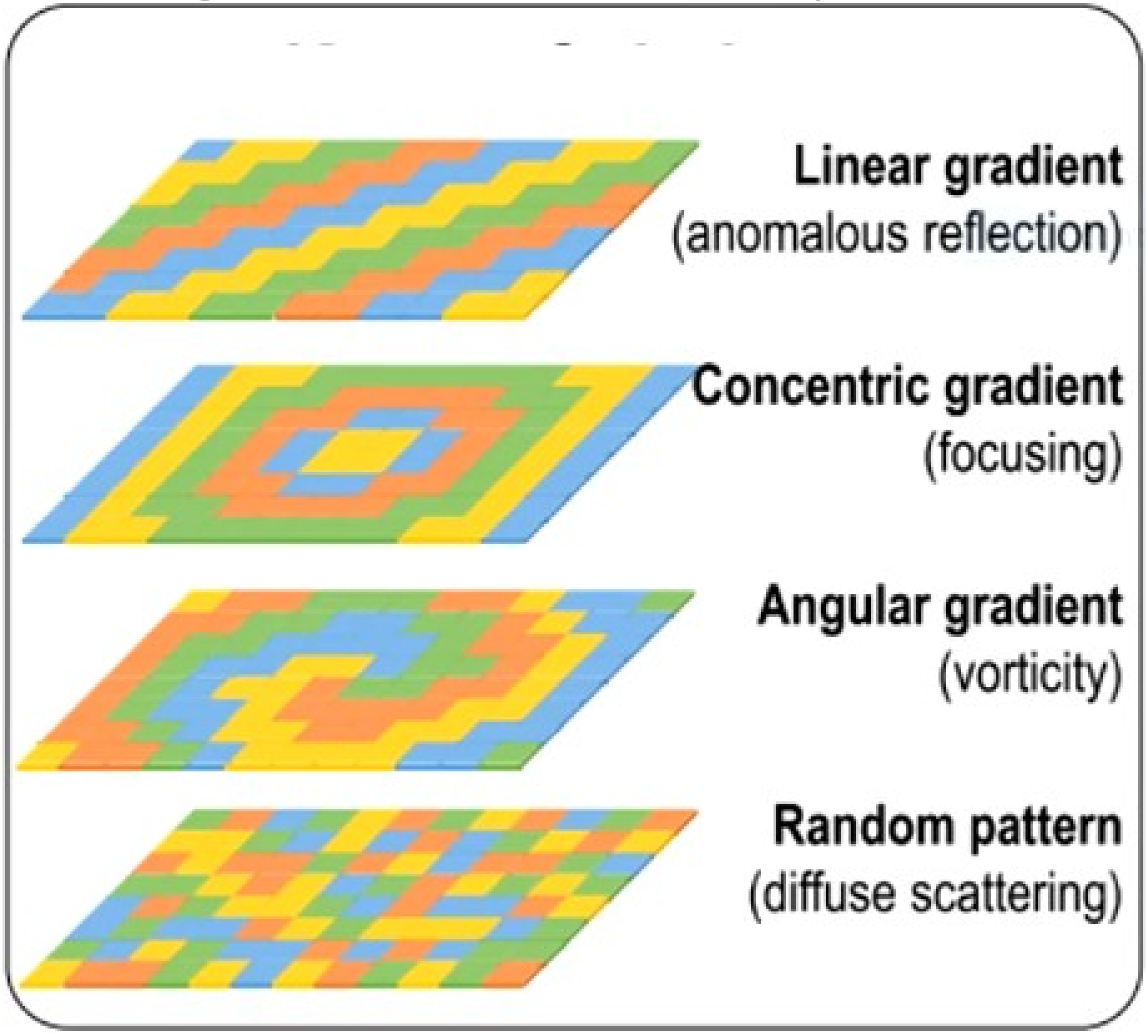


[4] M. Di Renzo et al., "Smart Radio Environments Empowered by Reconfigurable Intelligent Surfaces: How It Works, State of Research, and The Road Ahead," in IEEE Journal on Selected Areas in Communications, vol. 38, no. 11, pp. 2450-2525, 2020.

Characteristics of RIS

- Individually tuned elements
  - Element spacing: λ/5 to λ/10
- Tunable phase response
- High spatial resolution
- Nearly-passive
  - Low hardware cost
  - Low power consumption
- Two Operation Modes
  - Programming the phases using FPGA or Microcontroller
  - Normal operation
- Full duplex

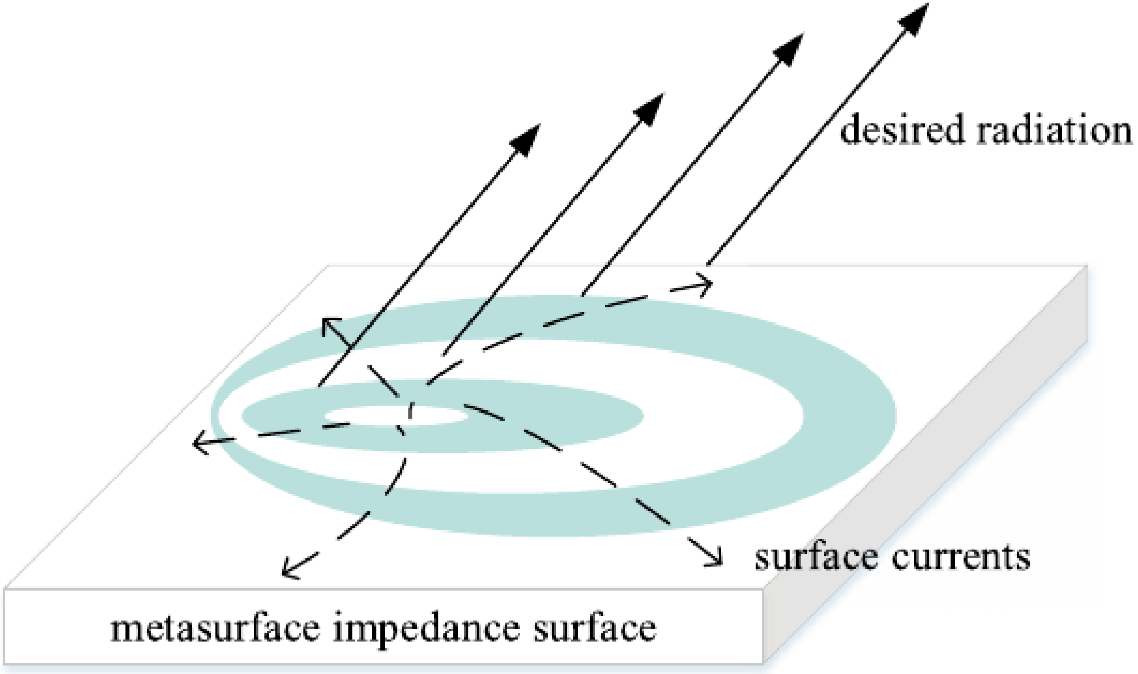
Programmable Properties



[5] S. Abadal et al., "Programmable Metamaterials for Software-Defined Electromagnetic Control: Circuits, Systems, and Architectures," in IEEE Journal on Emerging and Selected Topics in Circuits and Systems, vol. 10, no. 1, pp. 6-19, 2020.

Tuning the Electromagnetic Properties

- Metasurface, artificial material
  - Breakthrough in 2000s
- Electromagnetic properties
  - Permeability, μ_r, (Magnetization)
  - Permittivity, ϵ_r, (El. Polarizability)
  - Surface currents
  - Induced electromagnetic fields
  - Reflection coefficient



$$\Gamma = \left| \frac{Z_n(V) - Z_0}{Z_n(V) + Z_0} \right| \qquad Z_0 = \frac{|E|}{|H|}$$

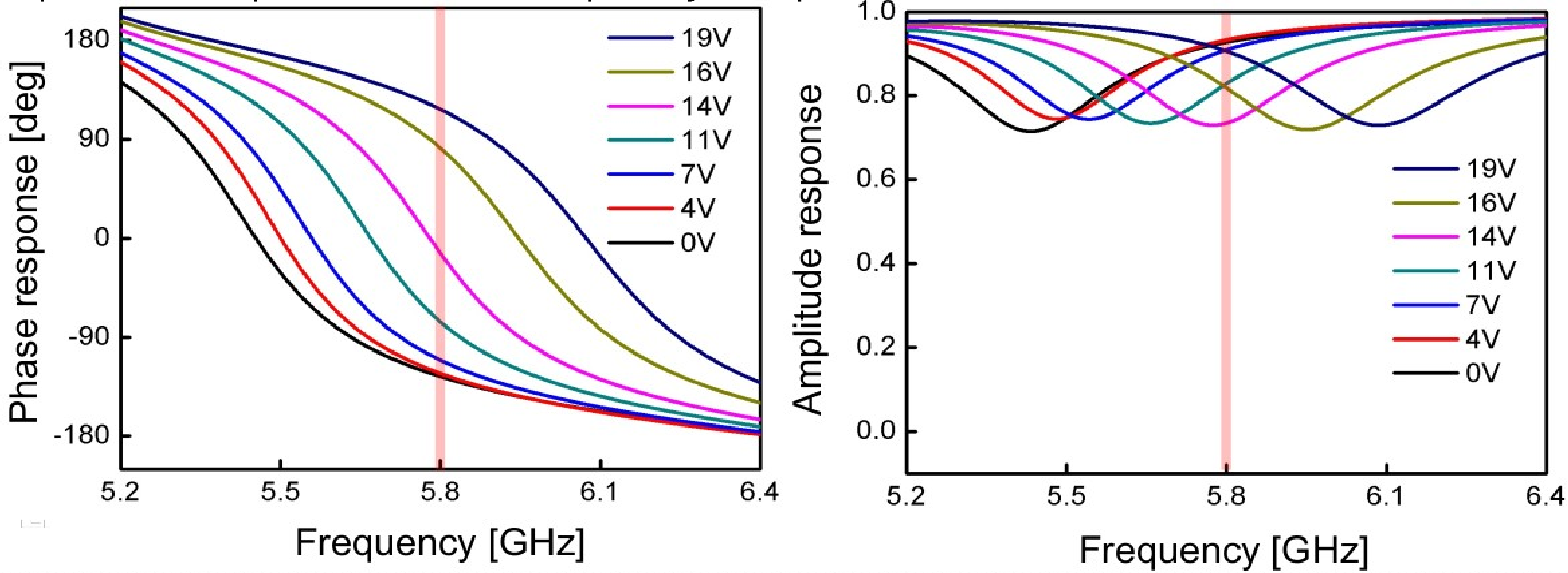
[6] Y. Liu et al., "Reconfigurable Intelligent Surfaces: Principles and Opportunities," in IEEE Communications Surveys & Tutorials, vol. 23, no. 3, pp. 1546-1577, 2021.

Reconfigurable Intelligent Surfaces – RIS Element Filter

- Tuning impedance, Z_n, of the lumped circuit controlling each unit cell depends on the bias voltage
- The coefficient depends on self and mutual impedance
- Amplitude and phase are not completely independent from each other

$$\Gamma = \left| \frac{Z_n(V) - Z_0}{Z_n(V) + Z_0} \right|$$

$$Z_0 = 376.73\,\Omega$$

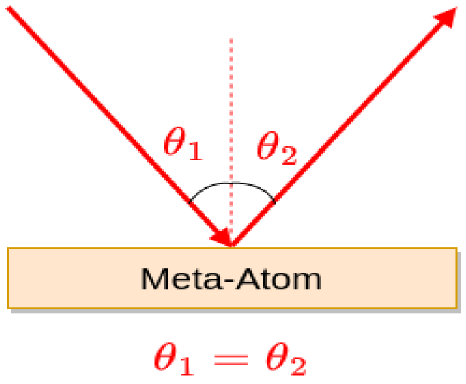


[7] X. Pei et al., "RIS-Aided Wireless Communications: Prototyping, Adaptive Beamforming, and Indoor/Outdoor Field Trials," in IEEE Transactions on Communications, vol. 69, no. 12, pp. 8627-8640, 2021.

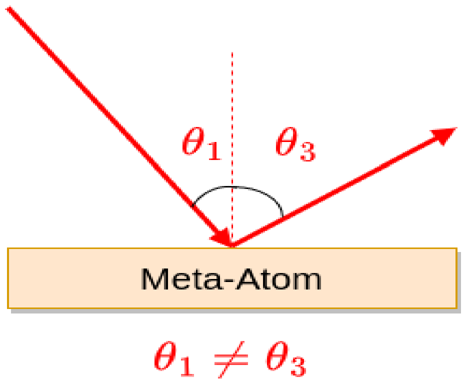
Anomalous Reflection and Refraction

- Traditional reflection of waves are specular
- The Meta-Atom can produce anomalous reflections
  - Incident and reflected angles are different
- Refraction
  - Anomalous Snell's Law
- The reflection and refraction are *programmable*
- That is, *intelligent*

Specular Reflection

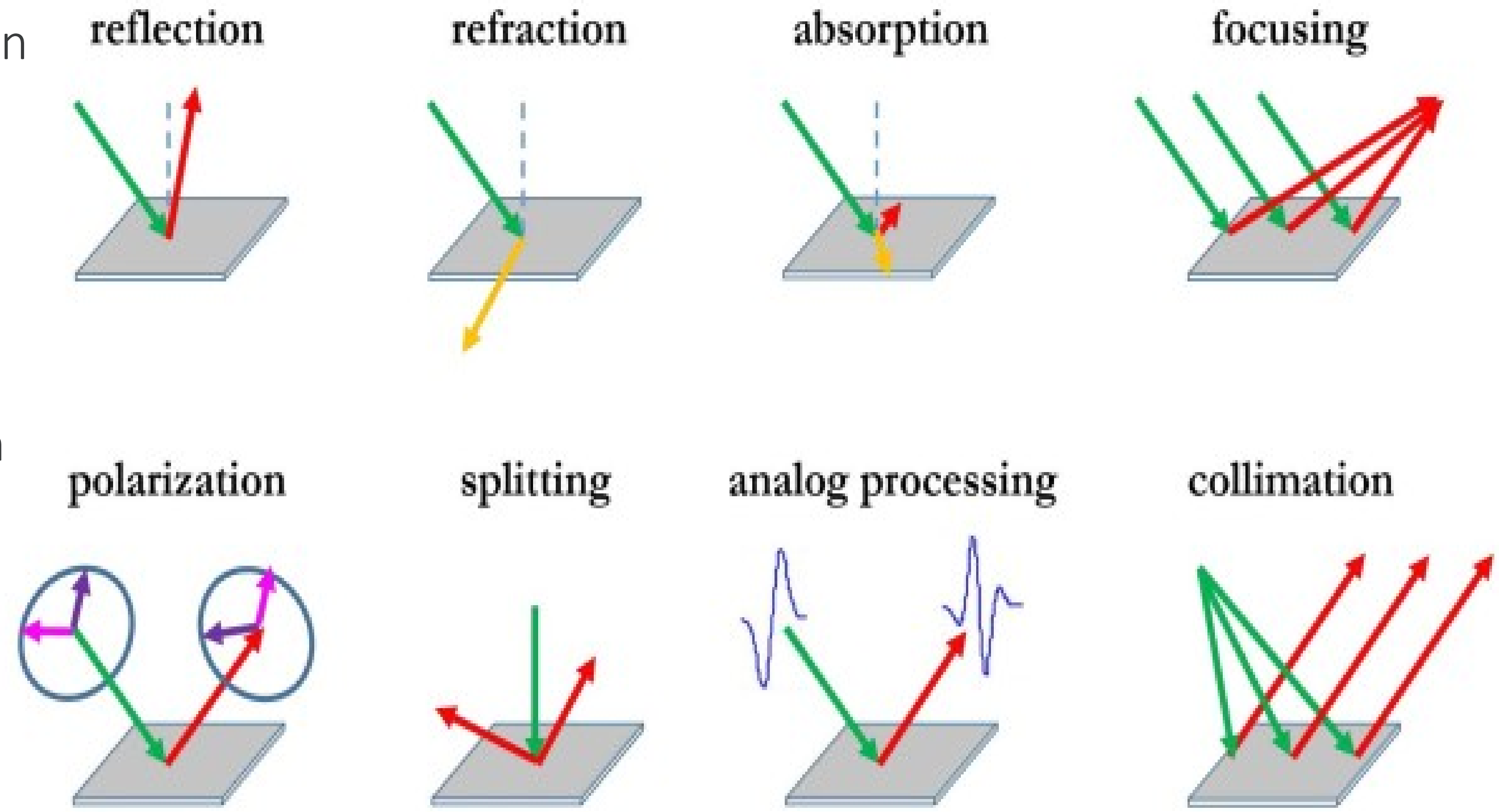


Anomalous Reflection



Electromagnetic Manipulation/Operations

- Wavefront shaping
- Beam-forming and Focusing
- Anomalous Reflection, Refraction
- Polarization
- Absorption
- Splitting
- Frequency Shifting / Modulation
- Diffuse scattering
- Vorticity
- Collimation
- Memory



[6] Y. Liu et al., "Reconfigurable Intelligent Surfaces: Principles and Opportunities," in IEEE Communications Surveys & Tutorials, vol. 23, no. 3, pp. 1546-1577, 2021.

Nomenclature

- Metasurface, Shaped meta-atoms
- R-MTS, Programmable MTS
- LIS, RIS, Software Defined Surface
  - N x M Elements, Unit cells
  - Element spacing: λ/5 to λ/10
  - Varactors, PIN-diodes, RF-MEMS
- IRS, only reflective surface

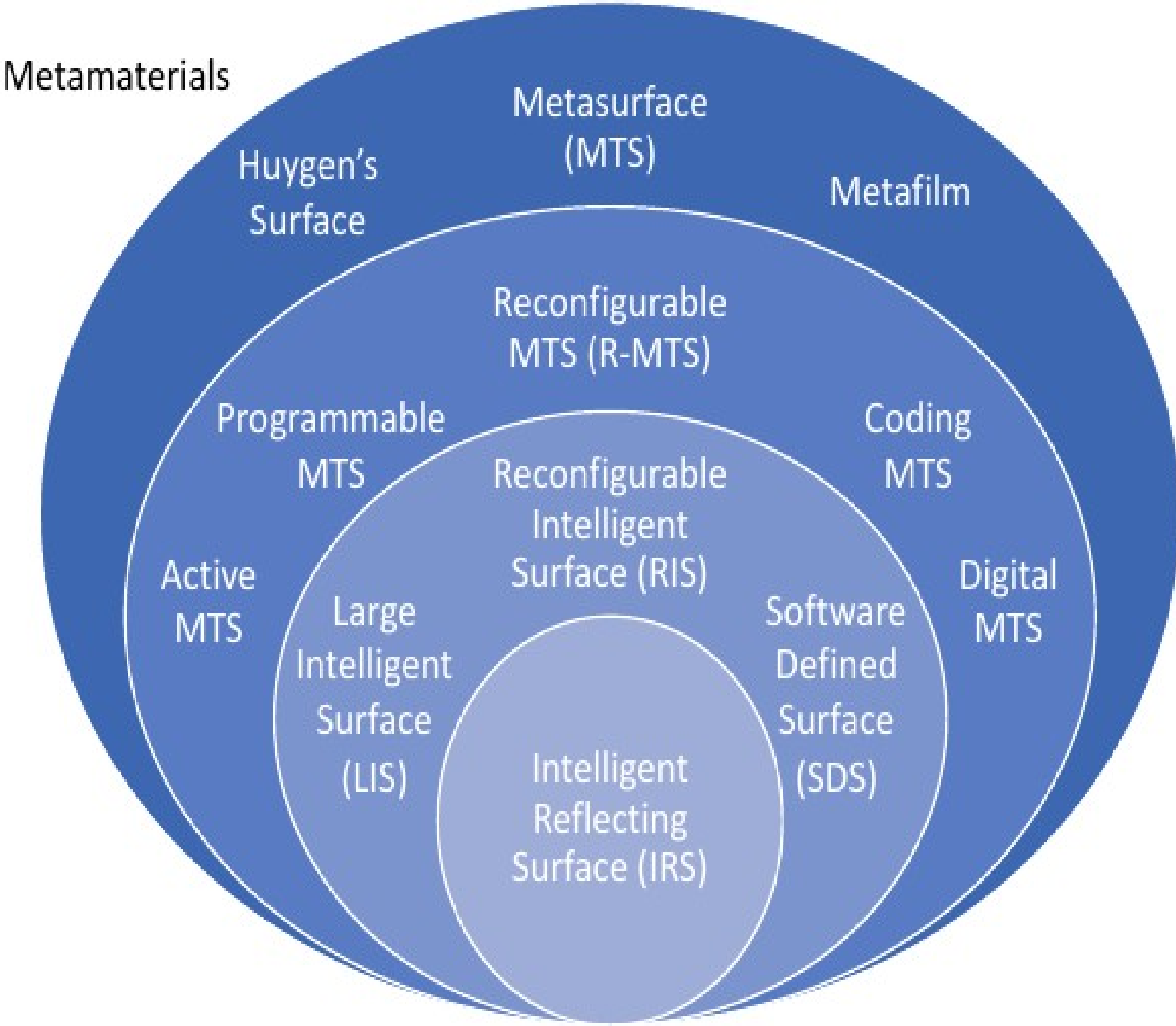
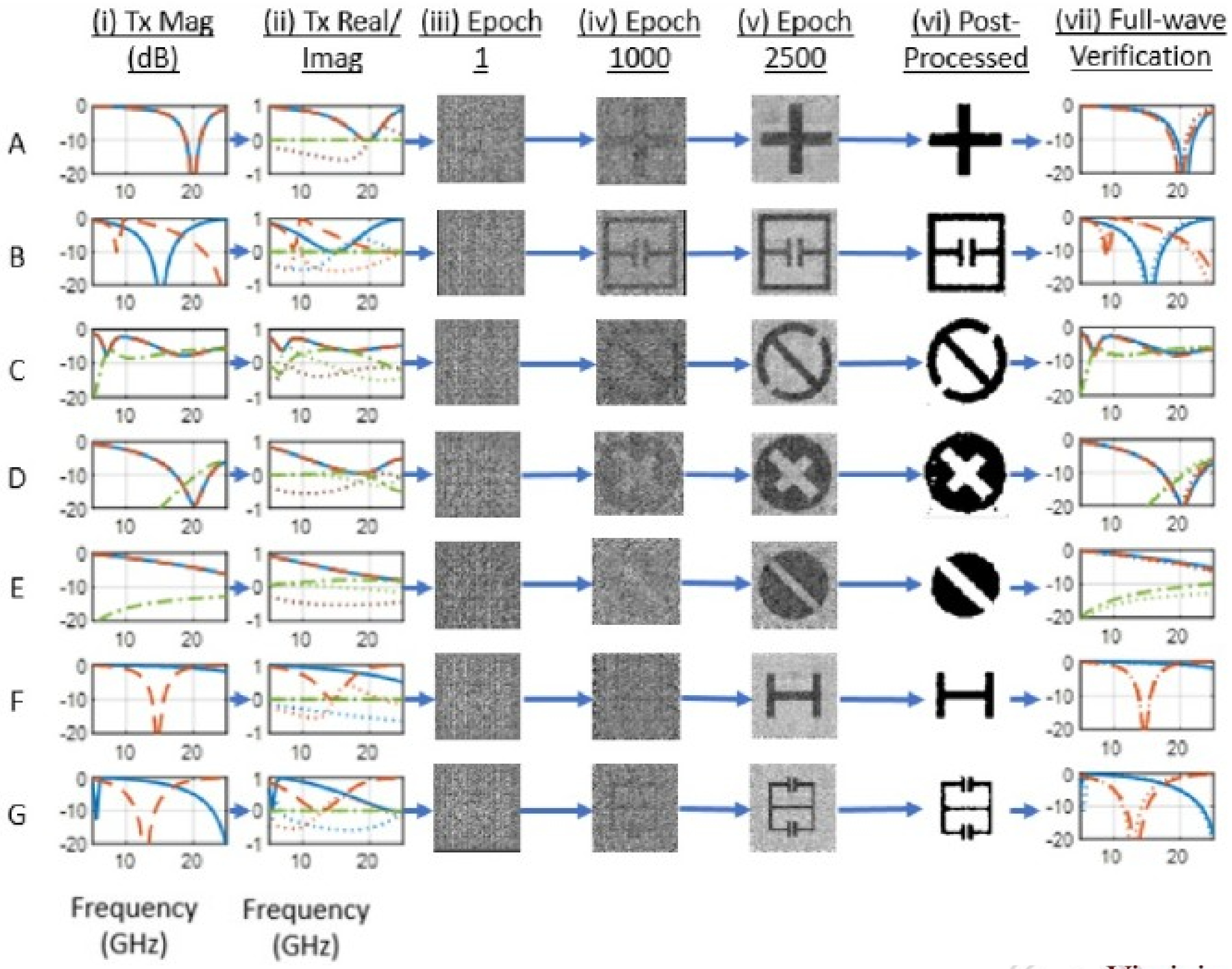


Figure: John Hodge, Dissertation, Virginia Tech, November 2021.

Machine Learning for Metasurface Design

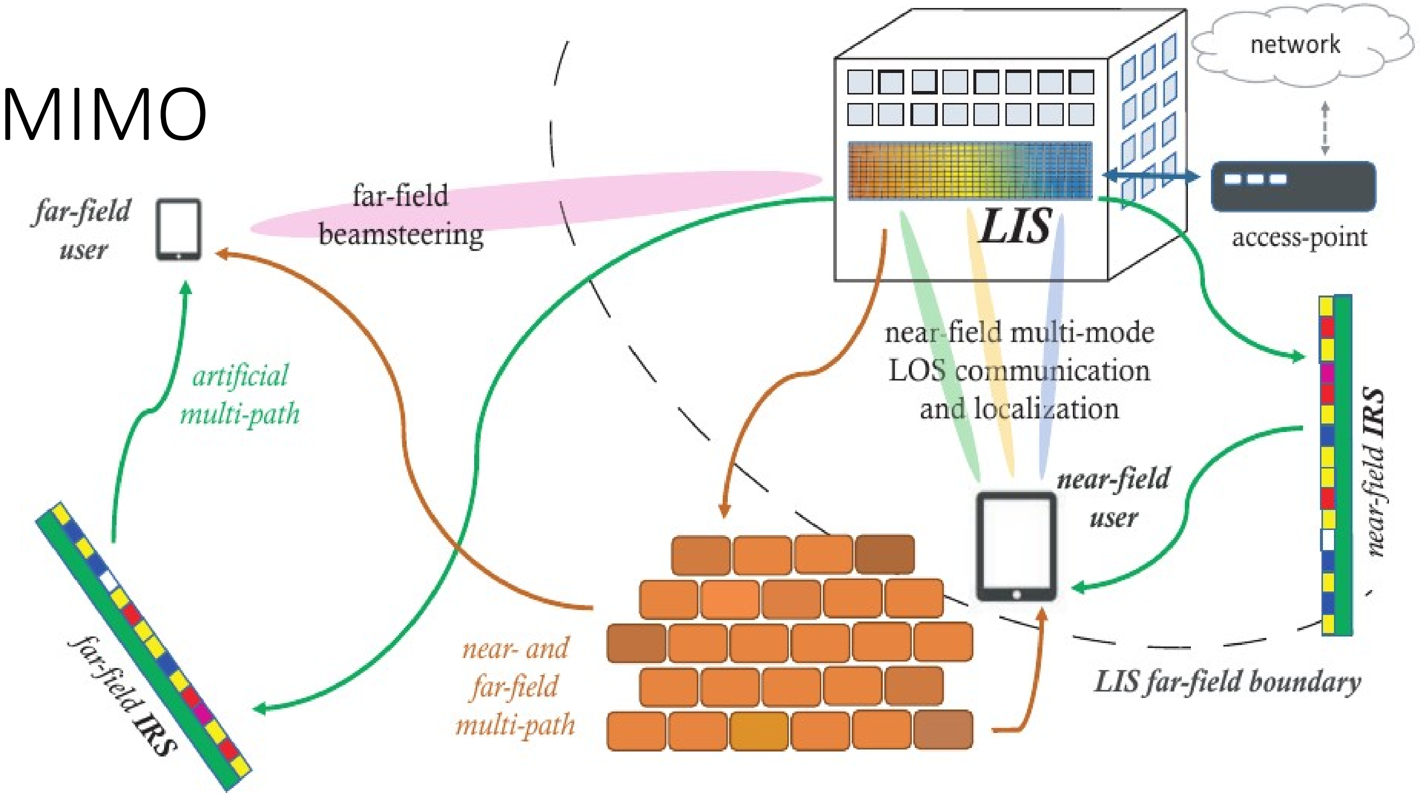
- Machine learning
- Convolutional Neural Networks
- Learn the shape of meta atom
- Barium Strontium Titanate (BST)



[8] John Hodge, Dissertation, Virginia Tech, November 2021.

Large Intelligent Surfaces

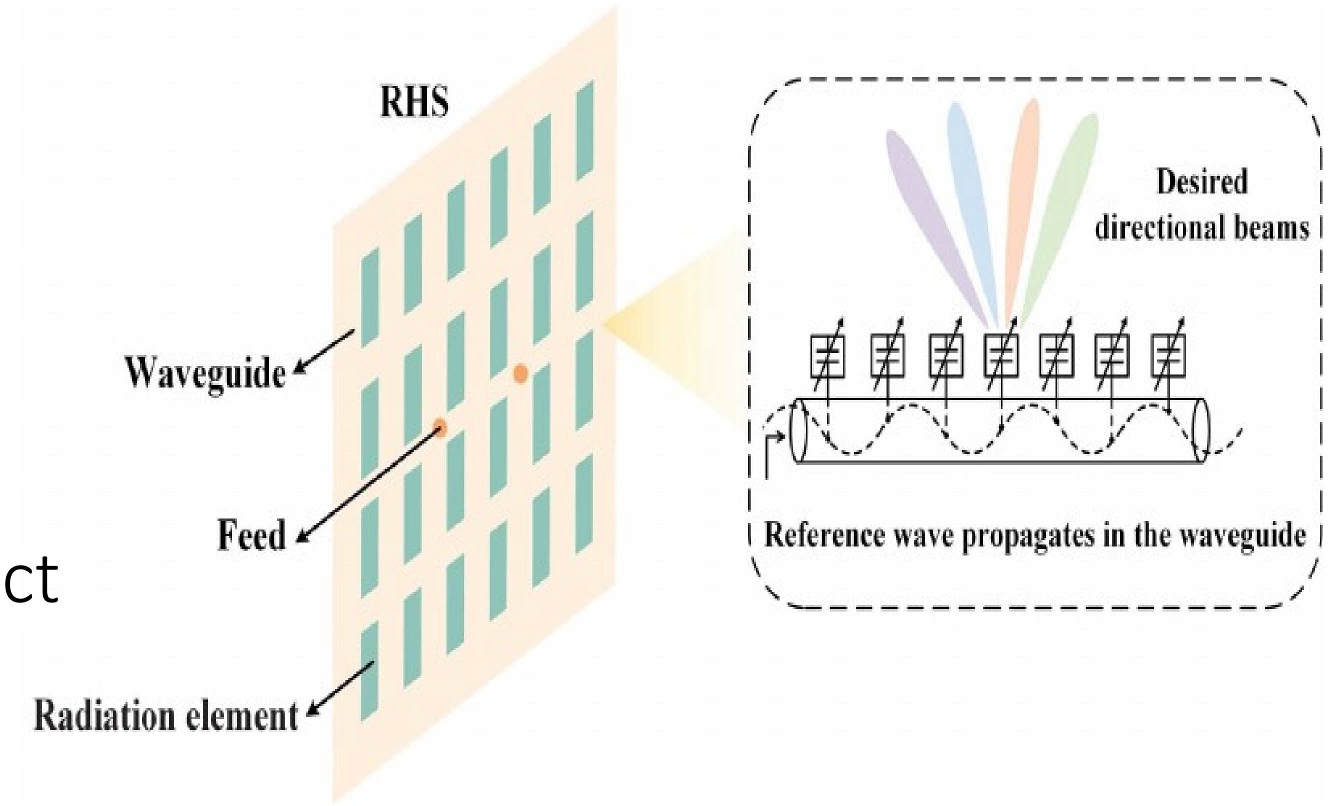
- Large Intelligent Surfaces (LIS)
  - Close relative to RIS
- LIS is next generation Massive MIMO
- Antenna array design
- Active elements
  - RF chains and Power Amplifiers
- Signal processing capabilities
- Non-zero power consumption



[9] D. Dardari and N. Decarli, "Holographic Communication Using Intelligent Surfaces," in IEEE Communications Magazine, vol. 59, no. 6, pp. 35-41, June 2021

Reconfigurable Holographic Surfaces

- Mapping signals to a holographic pattern
- Reference wave in waveguide
- Radiation elements construct a holographic pattern
- Records interference between reference wave and the desired object wave
- Desired directional beams
- *Holographic MIMO*



[10] R. Deng, B. Di, H. Zhang and L. Song, "HDMA: Holographic-Pattern Division Multiple Access," in IEEE Journal on Selected Areas in Communications, vol. 40, no. 4, pp. 1317-1332,

RIS Realization Technologies and Performance

	RF-MEMS	PIN diodes	Varactor diodes	MOSFET	Photo-conductive	Ferro-electric	Liquid crystal
Working frequency (GHz)	<40	<110	<20	<200	/	/	>20
Working voltage	High	Medium	High	High	Low	Very high	High
Power consumption	Low	Medium	High	Low	Medium	Low	Low
Time to change codebook	µs	ns	ns	ns	µs	ms	ms
Insertion loss	Low	Medium	High	Medium	Medium	/	High
Digital/analog control	D	D	A	D	D	A	A
Cost	Medium	Low	High	Medium	/	High	/

[11] ETSI ISG RIS GR002 / Rhode & Schwartz, “RIS – shaping the radio channel for best connectivity”, March 2023.

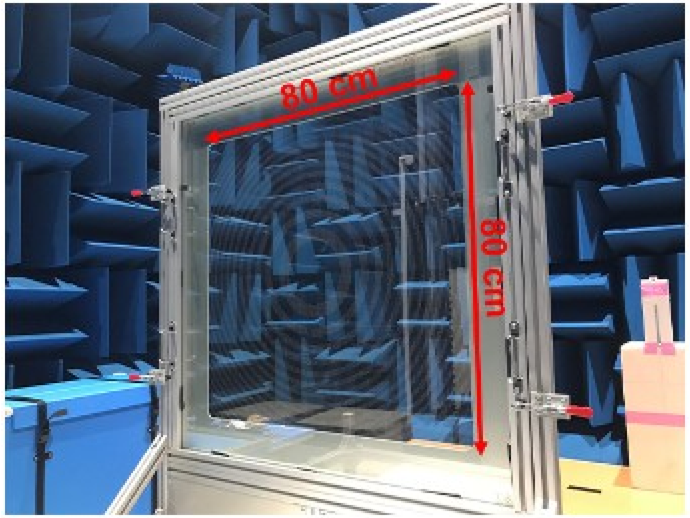
RIS Example From MIT

- MIT's RFocus prototype
- Six square meters
- 3,720 antenna elements
- 10 times signal strength
- Double the channel capacity

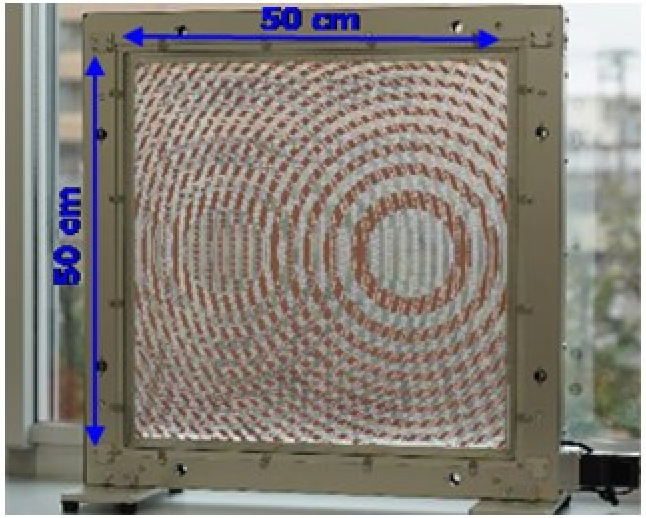
Photo: Jason Dorfman, CSAIL

Metasurface Example From DOCOMO and AGC Inc.

- Metasurface lens
- Enhance radio signal reception
- Efficiently guides mmWaves
  - Targets indoor locations
- Guides 28-GHz 5G radio signals



Static

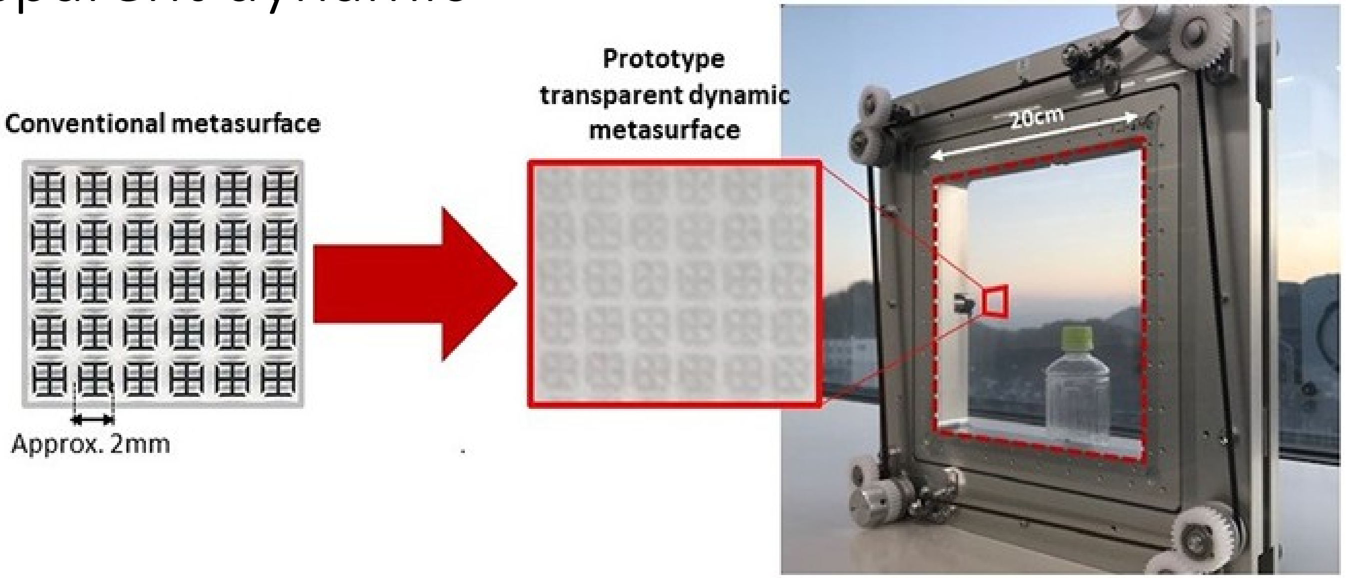


Dynamic

[12] NTT DOCOMO Inc. and AGC Inc., January 2021.

Commercial RIS

- DOCOMO World's first successful transparent dynamic metasurface
  - Transparent meta-surface on glass
  - Three modes:
    + Full penetration
    + Partial reflection
    + Full reflection



- e2ip, 5G Smart Surfaces EES Indoor Demo, July 2023
- Pivotal Commware, Holographic Beam Forming Technology

[13] NTT DOCOMO, January 2020.

RIS Towards Standardization

- IEEE ComSoc special interest groups and committees on RIS
  - RISE, RIS for smart radio environments
  - RISETI, Emerging Technology Initiative
  - Signal Processing and Computing for Communications Technical Committee
- ETSI Reports
  - ETSI GR RIS-001, April 2023
  - ETSI GR RIS-003, June 2023:
    - Defining RIS as a key wireless technology candidate for the future
- RISTA, RIS Tech Alliance, *RIS Technology White Paper*, March 2023
- 3GPP, Considered RIS for 5G-Advanced, a bridge between 5G and 6G

RIS Assisted Cell Edge Users

- Cell-edge users suffer from
  - High signal attenuation from the serving cell
  - Severe co-channel interference from neighbor cells
- Deploy a RIS at the cell edge to
  - Improve the desired signal power
  - Suppress the interference

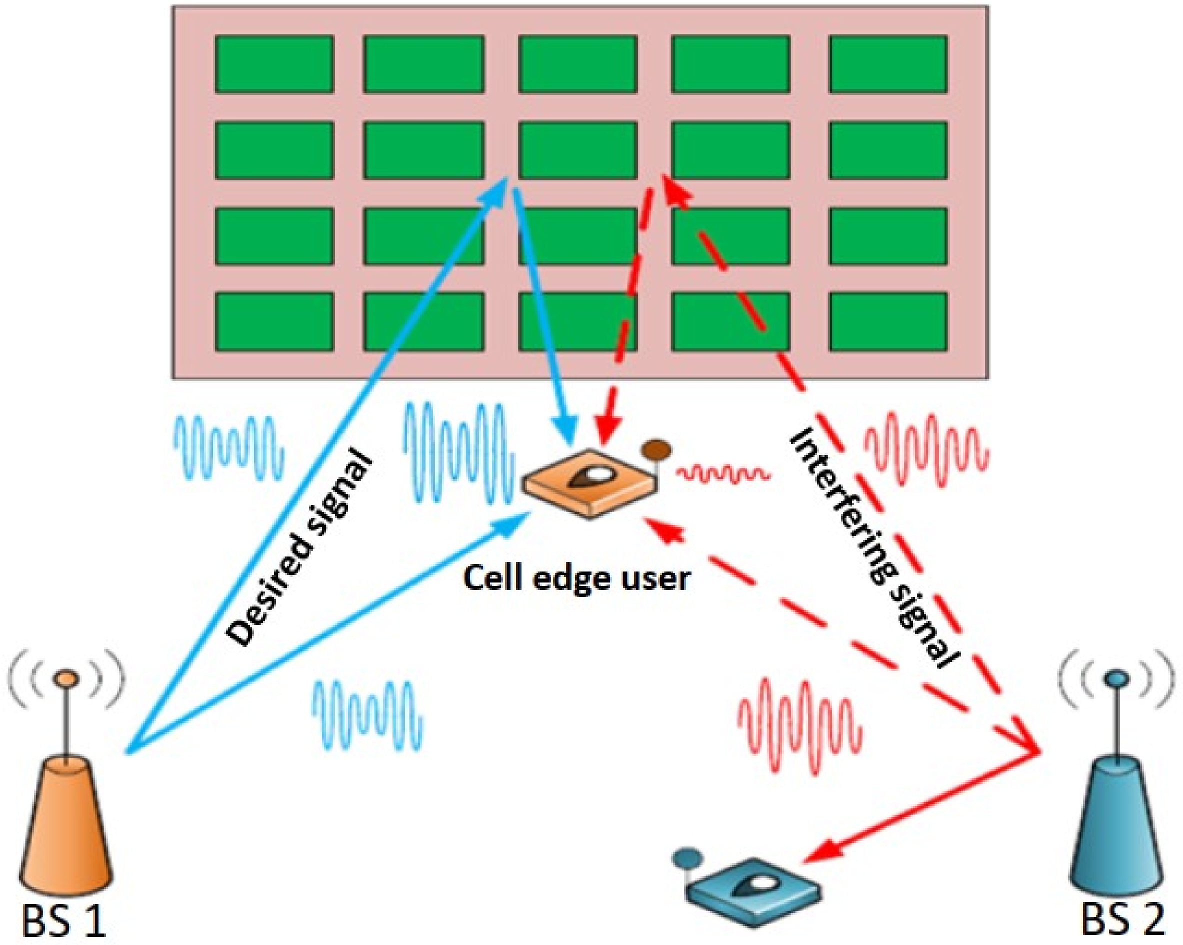
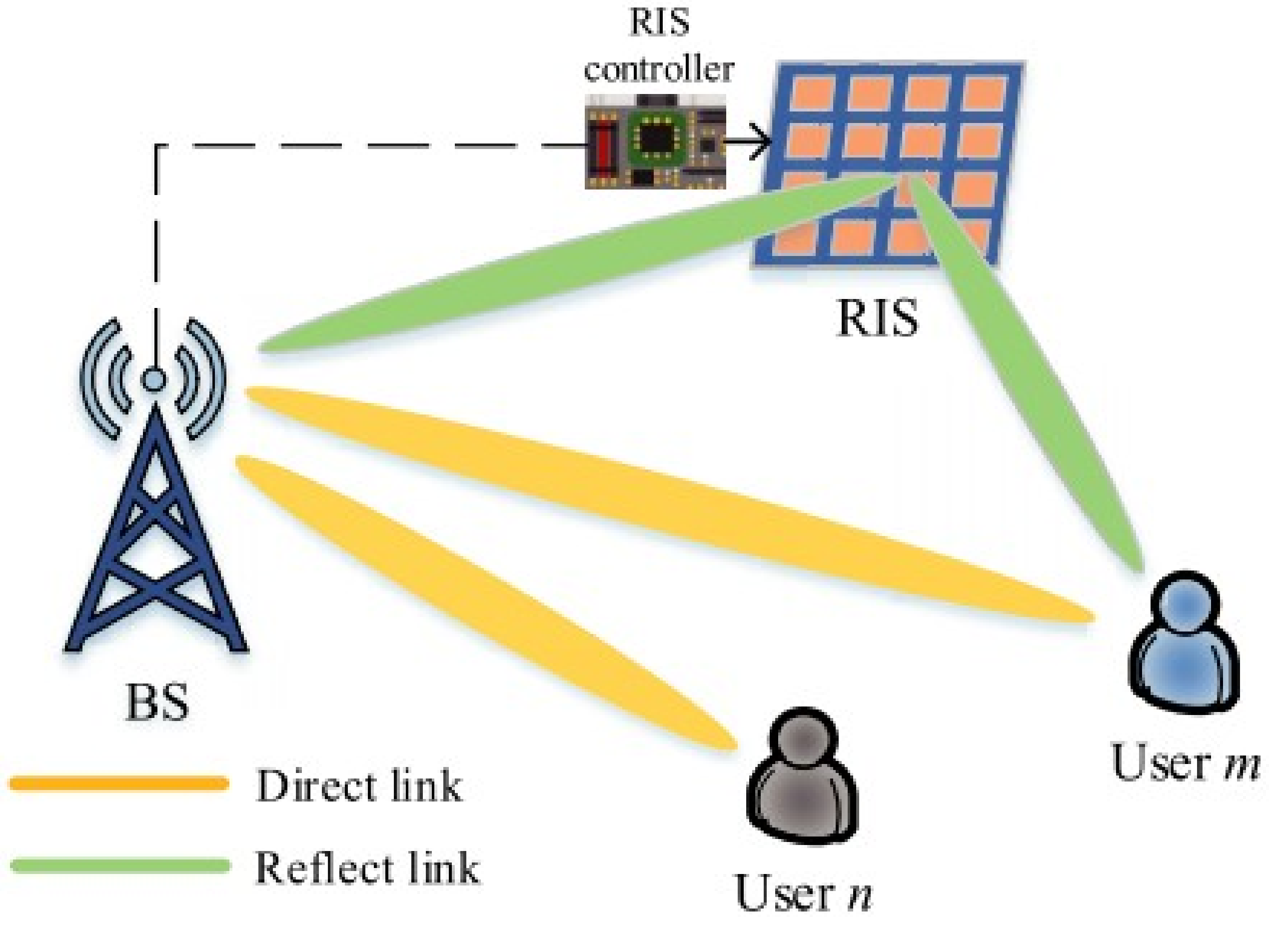


Figure: unknown source

Joint Transmit and Passive Beamforming Design

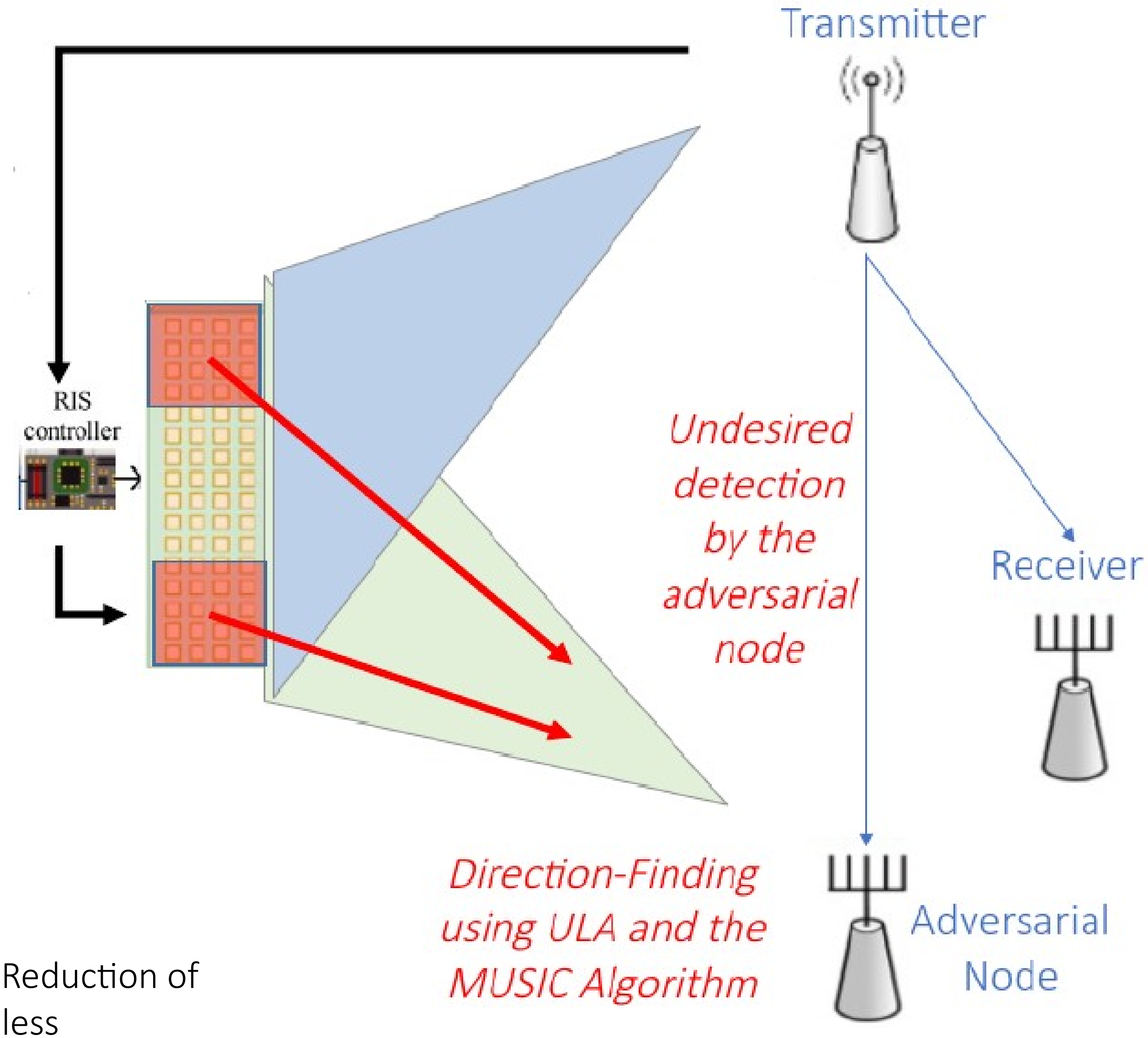
- RIS assisted links
- LOS + RIS waveform
- Increased received power
- Power ~ N^2
  - Number of elements, N



[6] Liu, Yuanwei, et al. "Reconfigurable Intelligent Surfaces: Principles and Opportunities." IEEE Communications Surveys & Tutorials, vol. 23, no. 3, 2021.

Malicious Detection

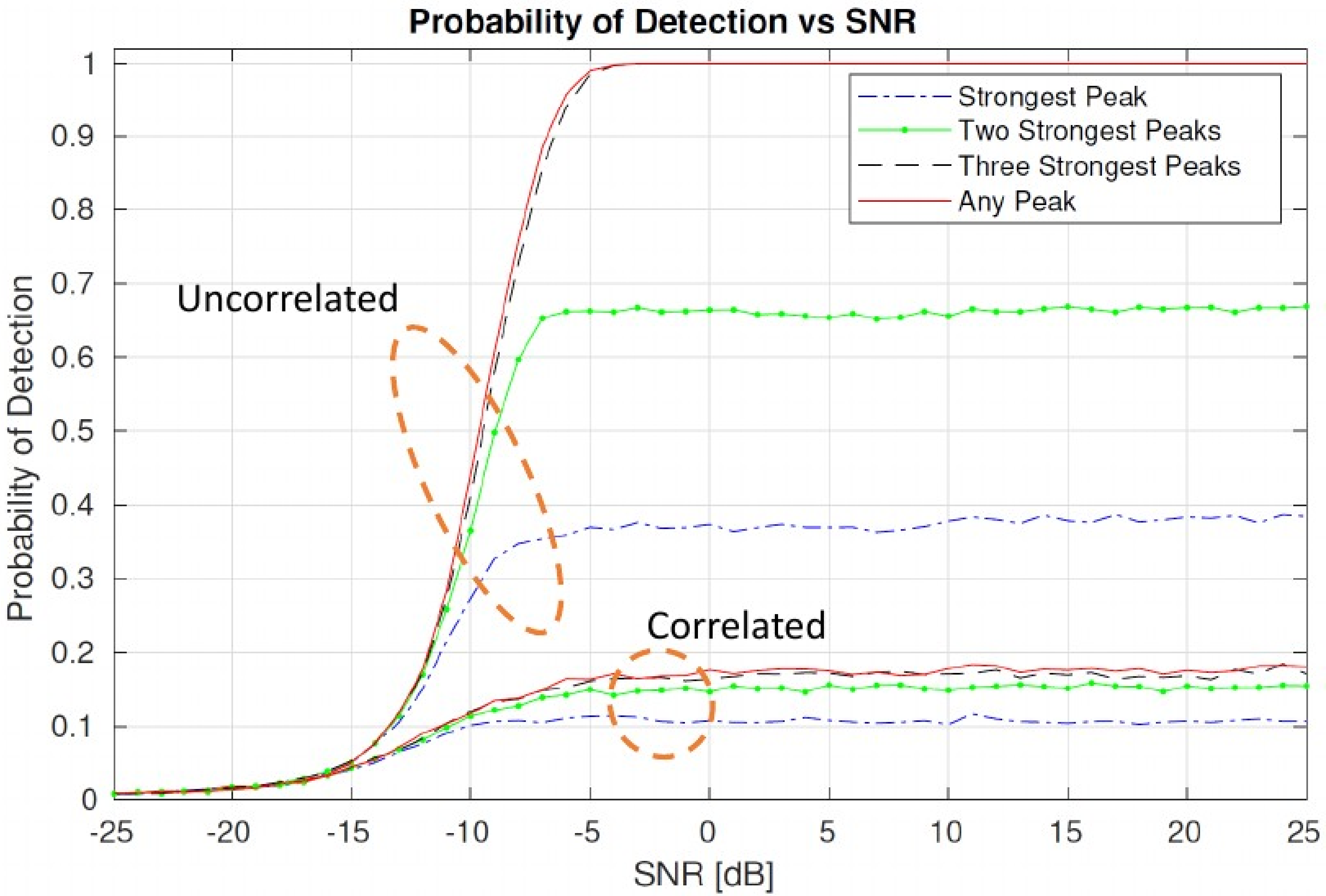
- Adversary attempts eaves dropping
- Signal detection his first step
- Project coherent multipath
- Signal detection problematic
- Adversary’s attempt obfuscated



[14] A. M. Buvarp, D. J. Jakubisin, W. C. Headley and J. H. Reed, "Probability-Reduction of Geolocation using Reconfigurable Intelligent Surface Reflections," IEEE Wireless Communications and Networking Conference, 2023, pp. 1-6.
Figure Enhancement: Dr. Daniel Jakubisin

Probability of Detection

- RIS-induced multipath
- Uncorrelated signal
  - Modest obfuscation
- Correlated signals
  - Severe obfuscation

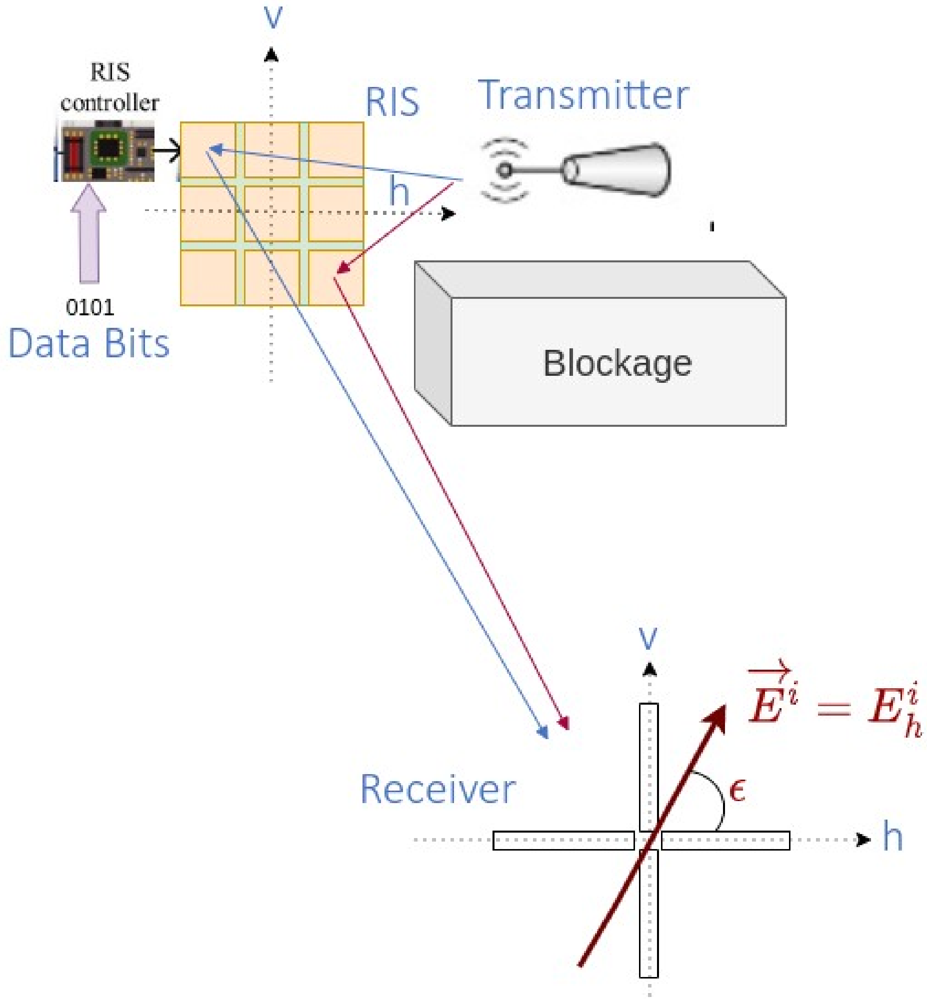


[14] A. M. Buvarp, D. J. Jakubisin, W. C. Headley and J. H. Reed, "Probability-Reduction of Geolocation using Reconfigurable Intelligent Surface Reflections," IEEE Wireless Communications and Networking Conference, 2023, pp. 1-6

Figure Enhancement: Dr. Daniel Jakubisin

RIS-Based Polarization-Space Modulation

- Carrier wave reflected by a reconfigurable intelligent surface (RIS) towards a receiver
- The RIS changes the polarization according to data bits to be transmitted
- Decoding using **Quaternion Neural Networks**
- Assumptions
  - Line-of-sight propagation (RIS to Rx)
  - Polarization unaffected by propagation path
  - Ignore parasitic effects and non-linear hardware
  - Line-of-sight from Tx to Rx is blocked
  - Perfect time/frequency synchronization

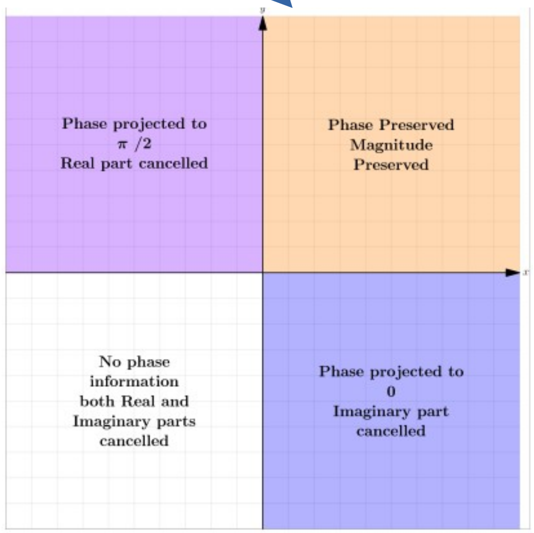


$$\vec{E^i} = E^i_h + jE^i_v$$

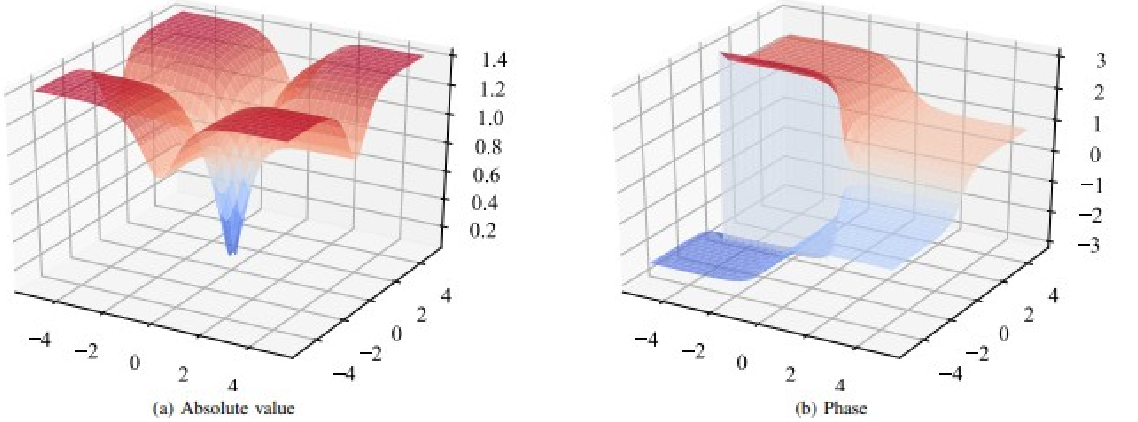
$$\begin{cases} \phi_{h,m,n} & = 2\pi f_c(\tau_{max} - \tau_{m,n}) \bmod 2\pi \\ \phi_{v,m,n} & = 2\pi f_c(\tau_{max} + \tau_\delta - \tau_{m,n}) \bmod 2\pi \end{cases}$$

Quaternion Activation Functions

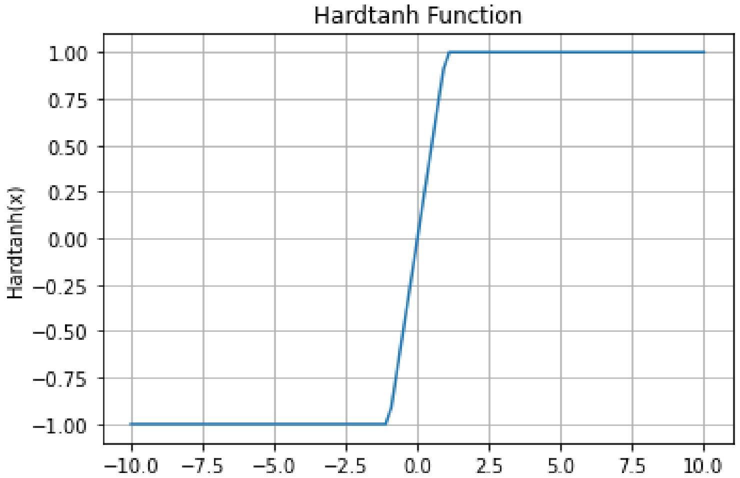
Rectified Linear Unit, ReLU



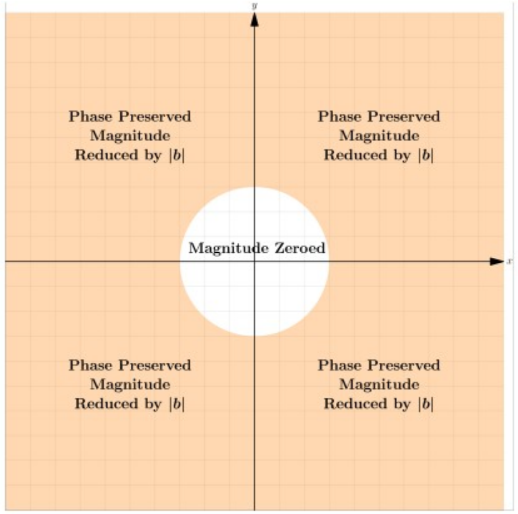
Hyperbolic Tan



Hyperbolic HardTan



Modified Rectified Linear Unit, modReLU, with bias |b|

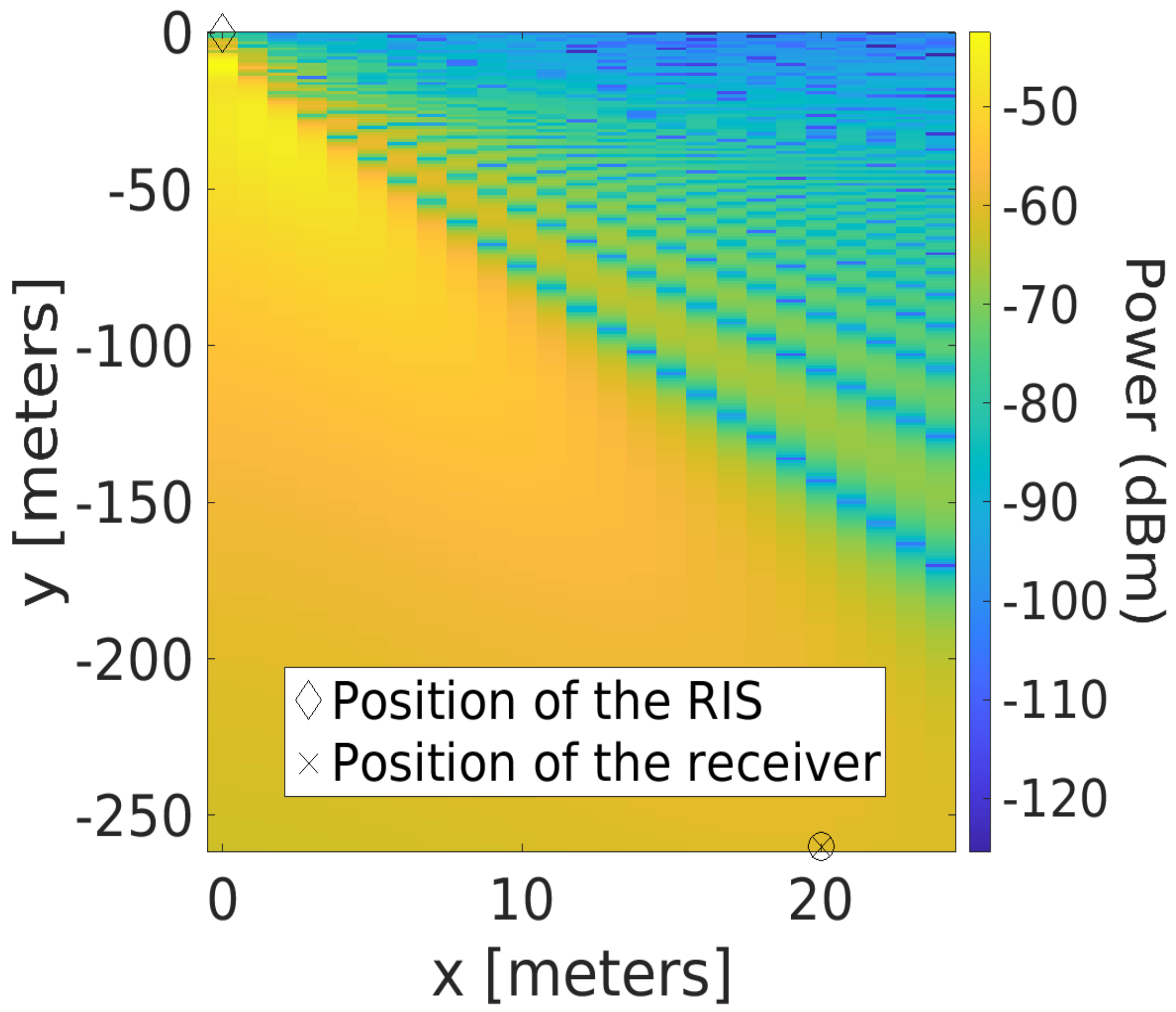


[15] Chiheb Trabelsi, "Deep Complex Networks", arXiv, 2018.

Numerical Simulations

- Reconfigurable intelligent surface
  - λ/5 element spacing (both x and z)
  - 1 m^2 650 x 650 elements
- Fraunhofer region: 260 meters
- Model is fully programmable with regards to positions/dimensions
- Receive power measured at each 1 meter in both x and y direction
- Constructive superposition at receiver

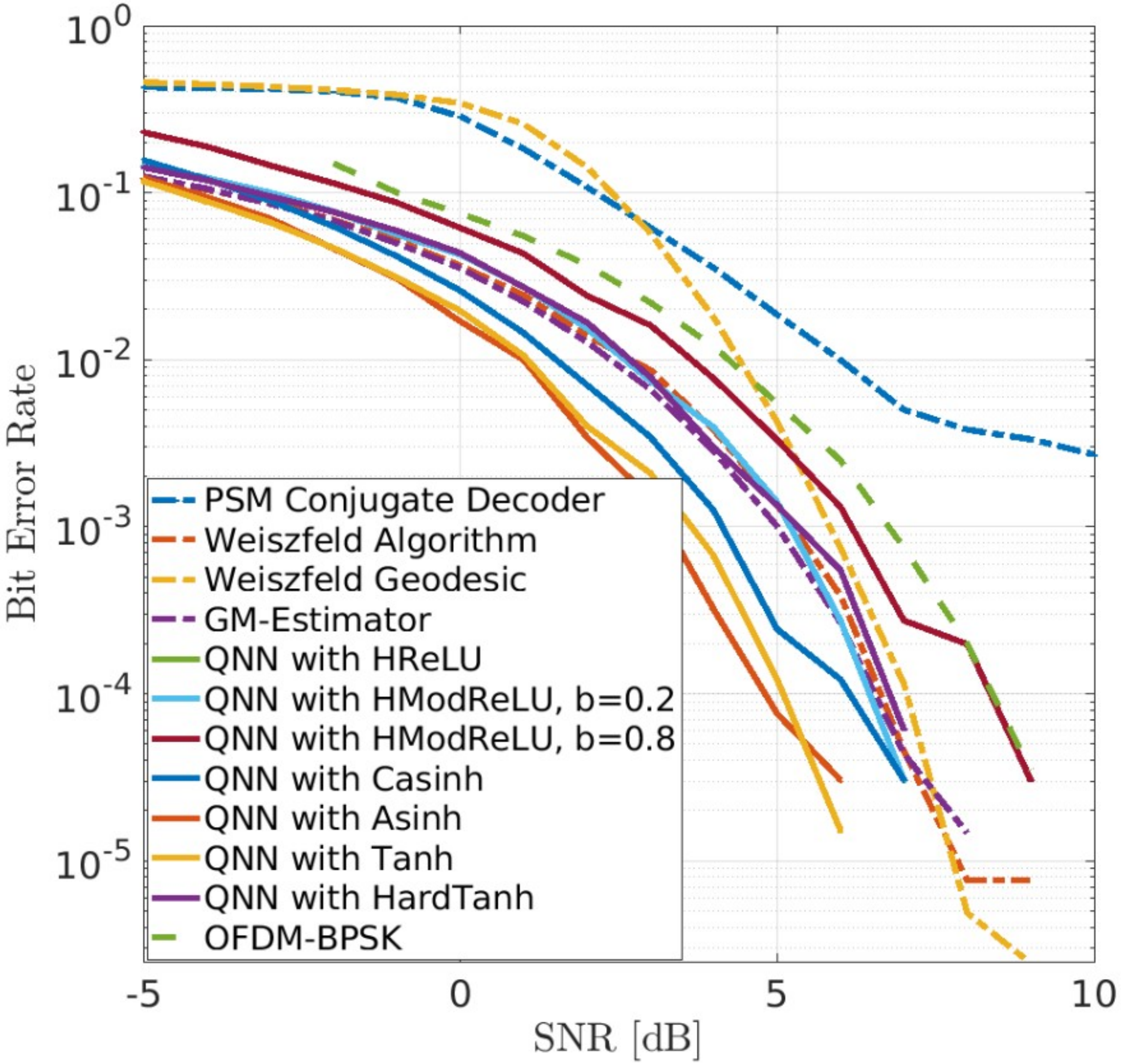
Objective: Maximize SNR at Rx [5]



[16] A. M. Buvarp, K. V. Mishra, A. I. Zaghloul and L. Mili, "Quaternion-Neural-Networks-Based Decoder for RIS-Aided Polarization-Space Modulation," IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, 2023.

Bit-Error Rate Performance

- QNN was trained with seven different activation functions
  - **b** is a bias parameter for qModReLU
- BER evaluated from -5 dB to +10 dB SNR
- The QNN follows the shape of the OFDM performance
- Asinh and Tanh yields best performance



RIS Challenges and Open Research Areas

- Channel modeling and path loss modeling
- RIS modulation and coding
- RIS channel estimation
- Analysis of stochastic geometry
- RIS resource allocation
- Beamforming optimization
- System energy minimization
- Physical layer security
- Assisted localization
- Non Orthogonal Multiple Access (NOMA)
- IoT
- Back-scattering
- UAV communication
- Wireless power transfer
- Localization

Significant Problem: RIS Channel Estimation

- Channel State Information (CSI)
  - The most important aspect of wireless communications
- Develop channel estimation methods
  - Estimation has very high complexity
  - High rank problem with M x N x P paths
    - P elements of the receive array
  - Two paths
    - RF source to RIS
    - RIS to Receiver

Conclusions

- RIS enables new paradigm of controlling the channel with software
- Power-reduction with less RF chains
- Anomalous reflections and other electromagnetic operations
- Performance enhancement with artificial multi-path

References

1. Rhode & Schwartz, “Ten key enablers for 6G wireless communications”, 2023
2. T. L. Marzetta, "Fundamental limitations on the capacity of wireless links that use polarimetric antenna arrays," Proceedings IEEE International Symposium on Information Theory,, Lausanne, Switzerland, 2002, p. 51.
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13. NTT DOCOMO, January 2020.
14. A. M. Buvarp, D. J. Jakubisin, W. C. Headley and J. H. Reed, "Probability-Reduction of Geolocation using Reconfigurable Intelligent Surface Reflections," IEEE Wireless Communications and Networking Conference, 2023, pp. 1-6.
15. Chiheb Trabelsi, “Deep Complex Networks”, arXiv, 2018.
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17. M. Imran, et al., “Intelligent Reconfigurable Surfaces (IRS) for Prospective 6G Wireless Networks”, John Wiley & Sons, Inc., Hoboken, New Jersey, 2023.

Thank You!

Q & A

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only abandoned...

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