COLLEGE OF ENGINEERING
BRADLEY DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING
VIRGINIA TECH.

Ph.D. Dissertation Defense:

Reconfigurable Intelligent Metasurfaces for Wireless Communication and Sensing Applications

John Hodge

11/29/21

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Motivation

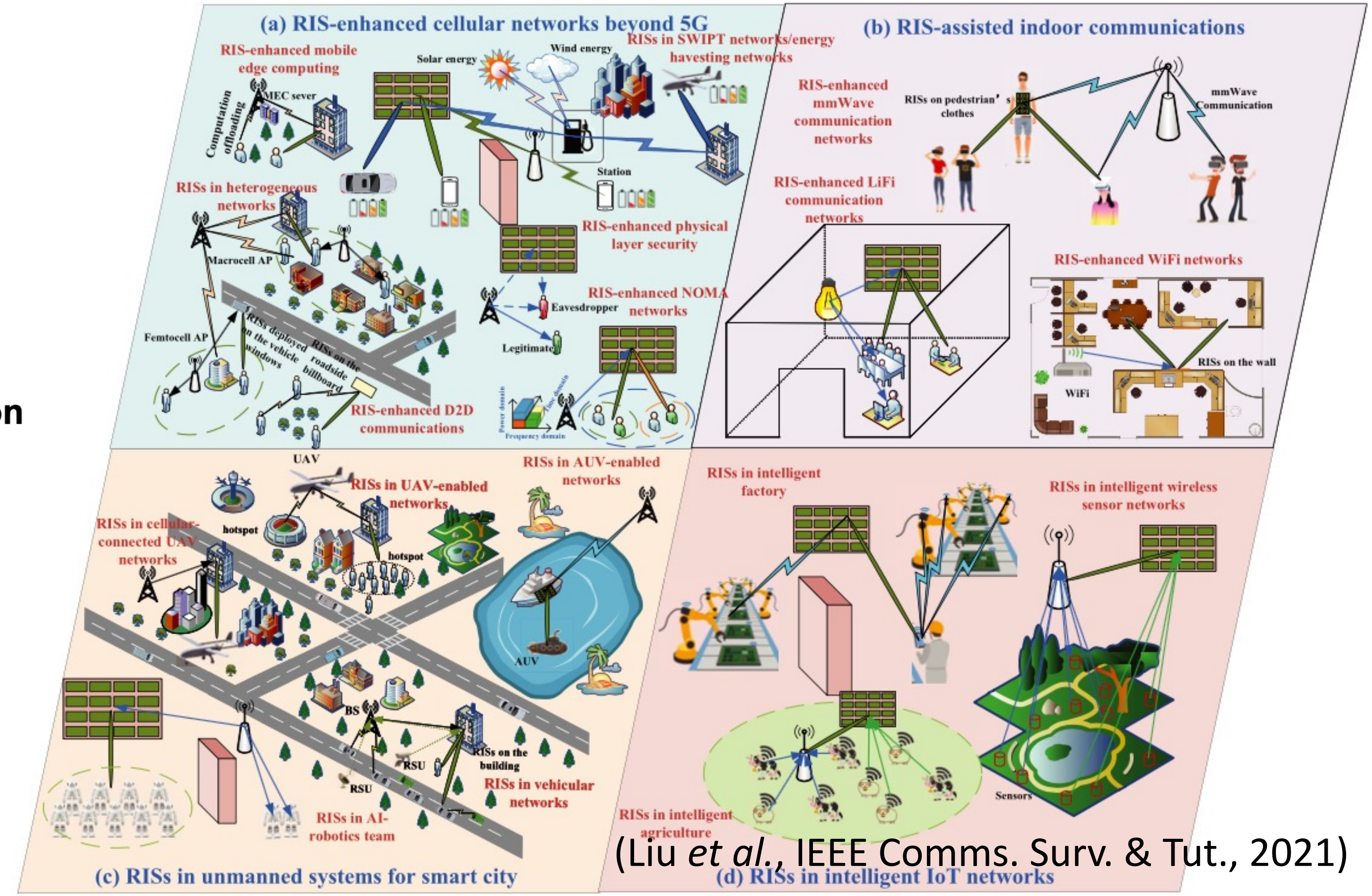
Higher data rates

Lower power consumption

Larger Coverage

Smarter devices

(Di *et al.*, IEEE ICCC, 2020)



(Liu *et al.*, IEEE Comms. Surv. & Tut., 2021)

<u>Challenge</u>: How to achieve dynamic beamforming for next-generation wireless networks using a low-cost reconfigurable aperture?

Motivation (cont.)

Prior Works:

- ➢ Reflectarray (Spence *et al.*, 2016)
- ➢ RIS for wireless comms (Basar, *et al.*, 2019)
- ➢ Coding metasurface (Zhang *et al.*, 2020)

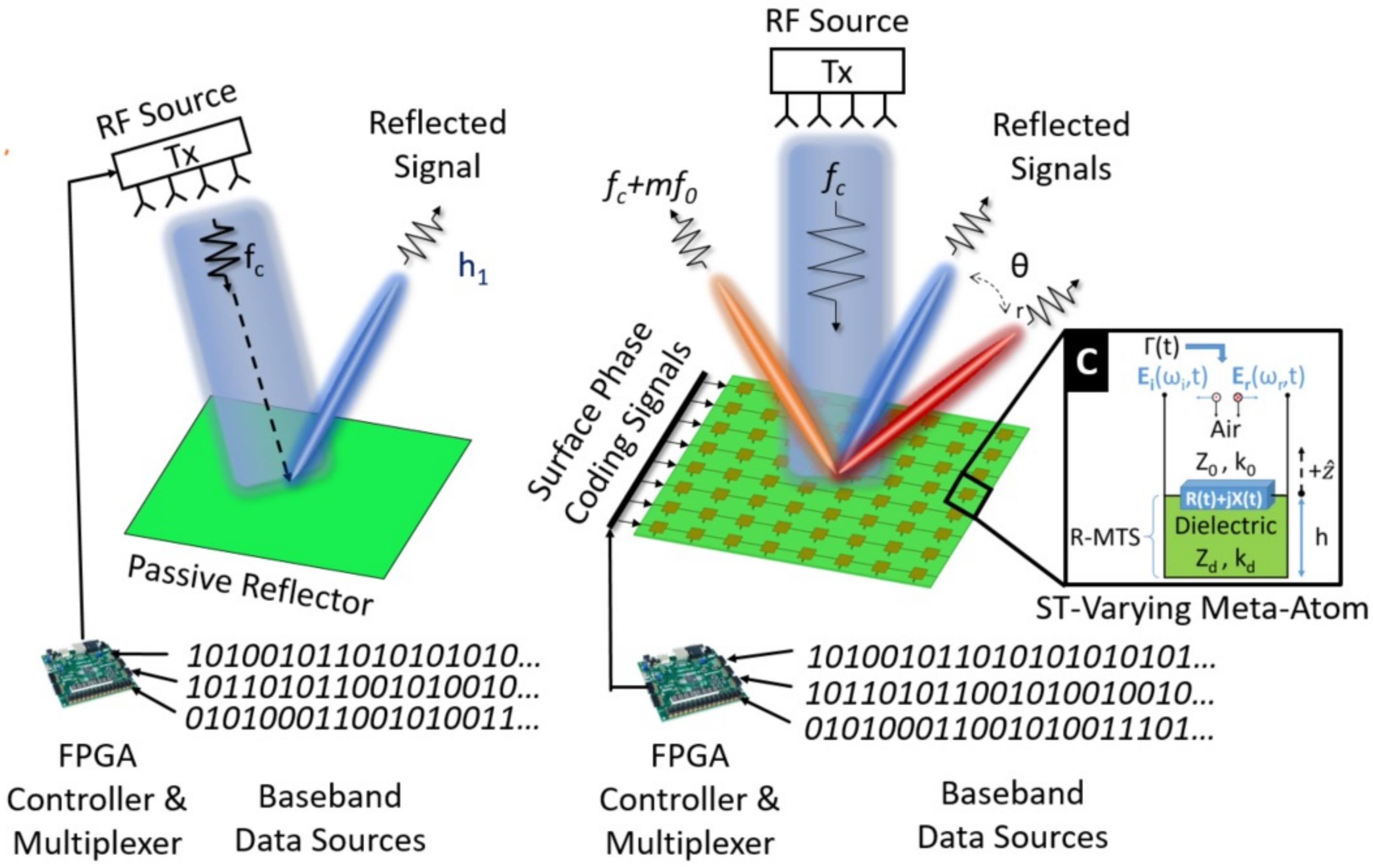
Shortcomings:

- ➢ Lack of radiation pattern control & do not consider RIS
- ➢ Lacks practical electromagnetic (EM) implementation
- ➢ Does not address index modulation (IM)
- ➢ Cost, SWaP-C, and RF complexity of traditional MIMO phased arrays designs is often prohibitive (Yoo, 2019)

Our Solution: RIS prototype using spatio-temporal coding of elements to realize:

- ➢ Programmable RIS aperture for direct modulation and IM in 6G transceivers
- ➢ EM-compliant reconfigurable design
- ➢ Beam steering and spatial multiplexing

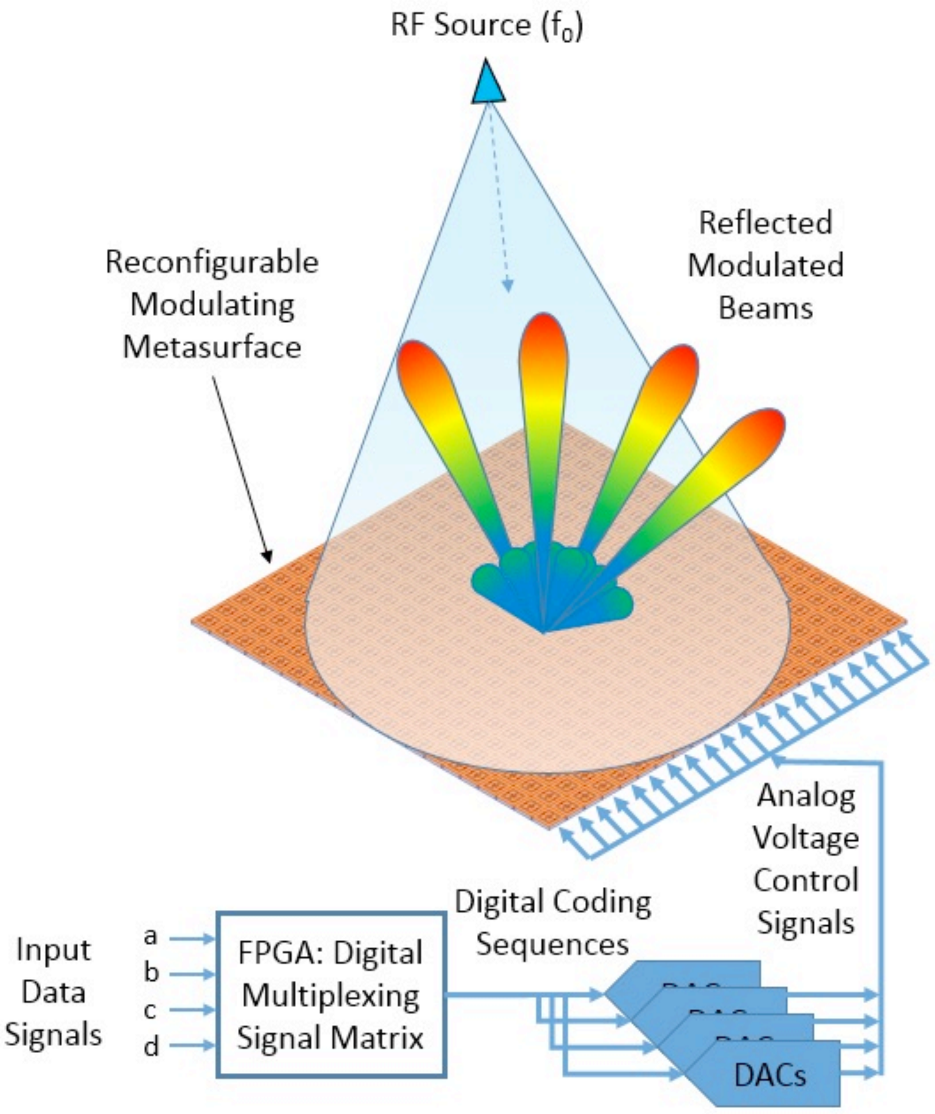
Conventional Wireless Transmitter: → Simplified RIS-Based Wireless Transmitter :



Reconfigurable Intelligent Surface (RIS)

Outline

- Introduction & Literature Survey
- Prototype Design, Fabrication, & Measurements
- Metasurfaces for Wireless Communication
- Machine Learning Assisted Metasurface Synthesis
- Summary & Conclusions

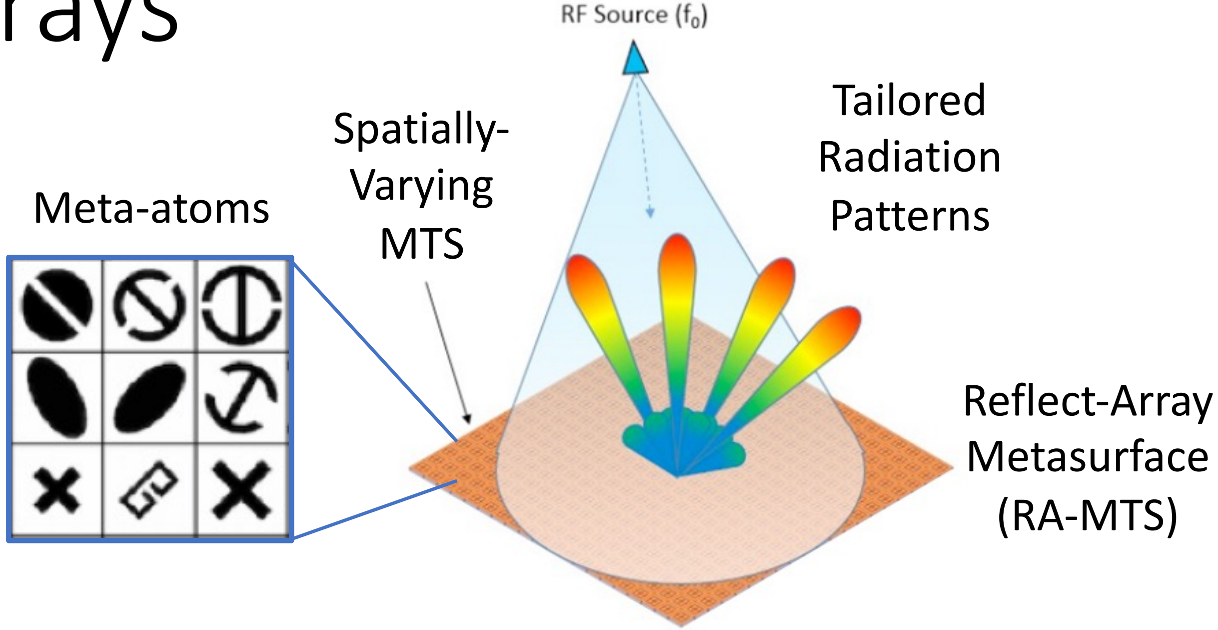


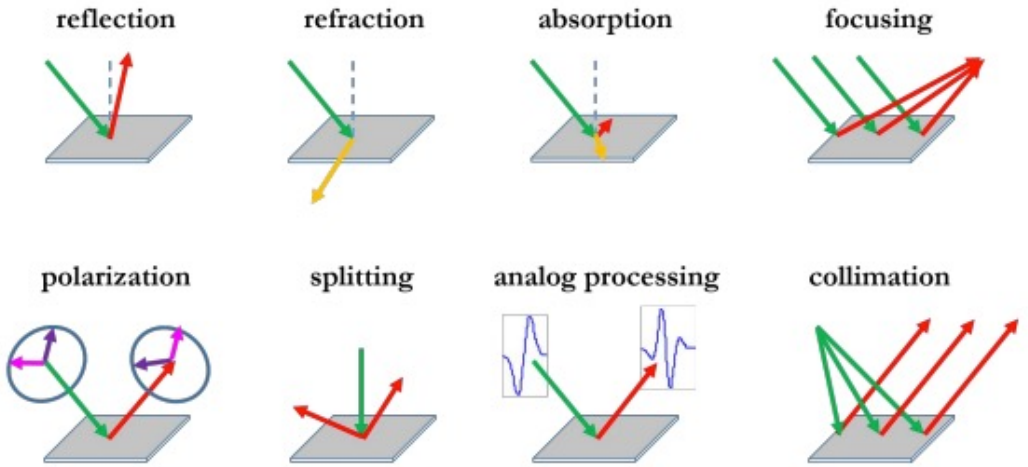
(Hodge, Mishra, Zaghloul, 2019)

RIS: Metasurface (MTS) Arrays

- 2-D array of sub-wavelength scattering inclusions (meta-atoms)
- Modified surface boundary conditions
- Transformation of EM Waves:
  - Amplitude
  - Phase
  - Frequency
  - Polarization
- Form factors:
  - Reflect-array (RA)
  - Transmit-array (TA)
  - Surface-Integrated Waveguide (SIW)
  - Leaky Wave / Surface Wave (SW)

RA-MTS Antenna





Selected EM Functionalities (Di Renzo, 2020)

Surface Electromagnetics (EM) Theory

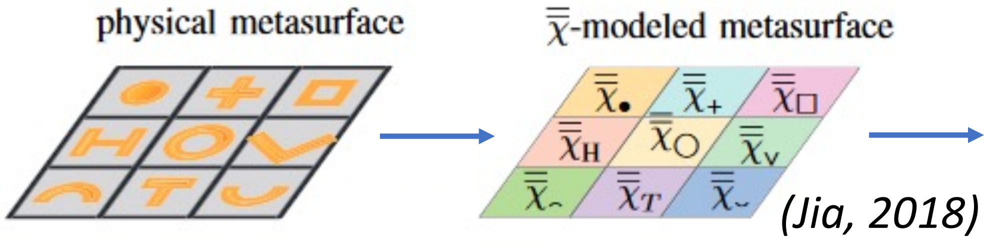
Physical Shape → EM Surface Properties → Tx/Rx Response

Effective Surface Currents

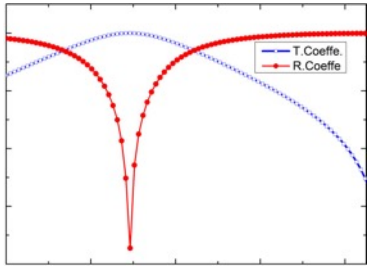
$$J_e = n \times (H_{t+} - H_{t-})$$
$$J_m = -n \times (E_{t+} - E_{t-})$$

Average Tangential Fields

$$E_{av} = \frac{1}{2}(E_t|_{z\to0+} + E_t|_{z\to0-})$$
$$H_{av} = \frac{1}{2}(H_t|_{z\to0+} + H_t|_{z\to0-})$$



(Jia, 2018)



<u>Scalar Polarizability Response</u>

$$P = \epsilon_0 \chi_e E_{av}$$
$$M = \chi_m H_{av}$$

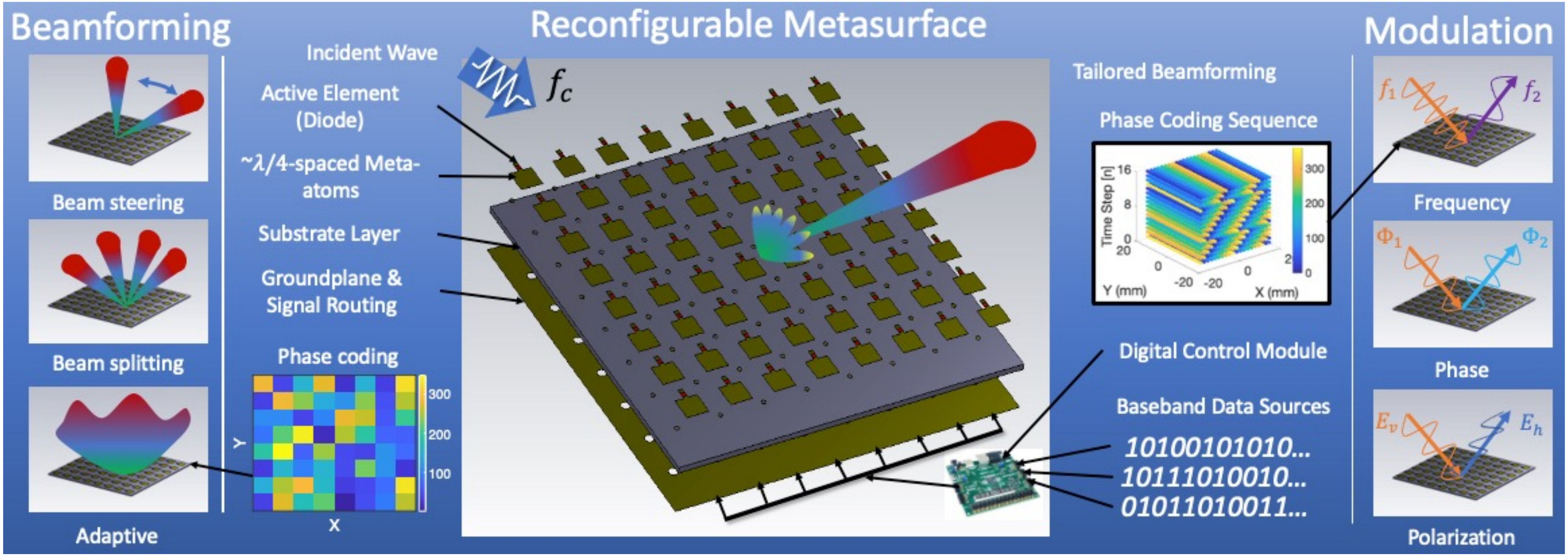
<u>Tensorial (bianisotropic) Polarizability Response</u>

$$P = \epsilon_0 \overline{\overline{\chi}}_{ee} E_{av} + \sqrt{\mu_0 \epsilon_0}\, \overline{\overline{\chi}}_{em} H_{av},$$
$$M = \sqrt{\mu_0/\epsilon_0}\, \overline{\overline{\chi}}_{me} E_{av} + \overline{\overline{\chi}}_{mm} H_{av}$$

More complex (bi-anisotropic) responses can be realized using tensorial MTSs

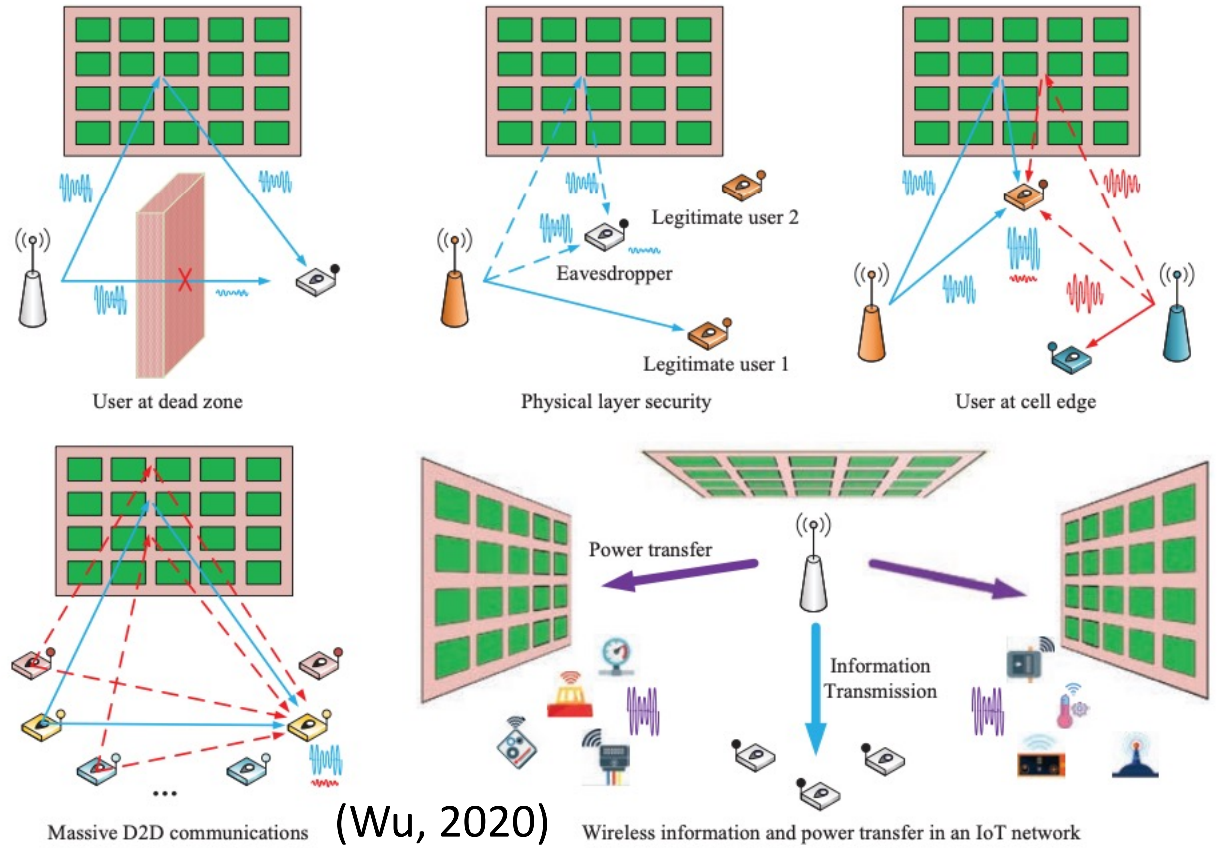
Programmable RIS Arrays

(Hodge et al., arXiv:2101.09131, 2021)

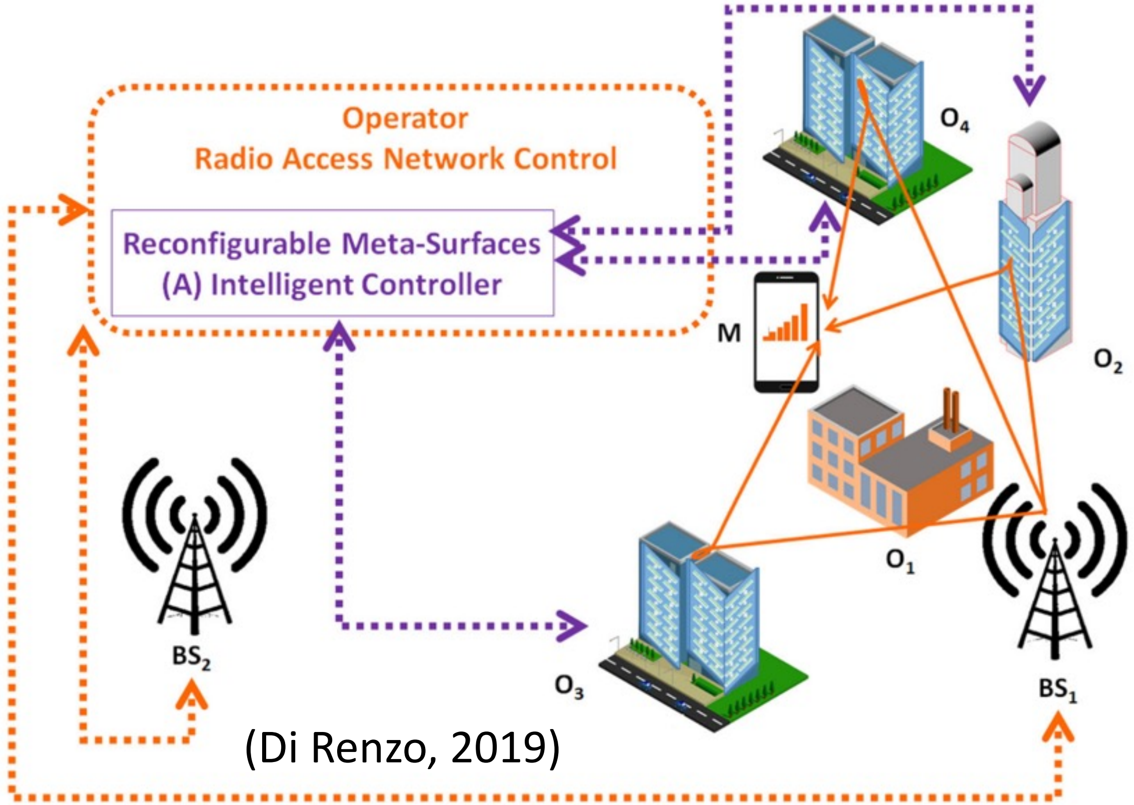


Beamforming and modulation by manipulating phase coding of constituent meta-atoms

Reconfigurable Intelligent Surfaces (RIS)



(Wu, 2020)

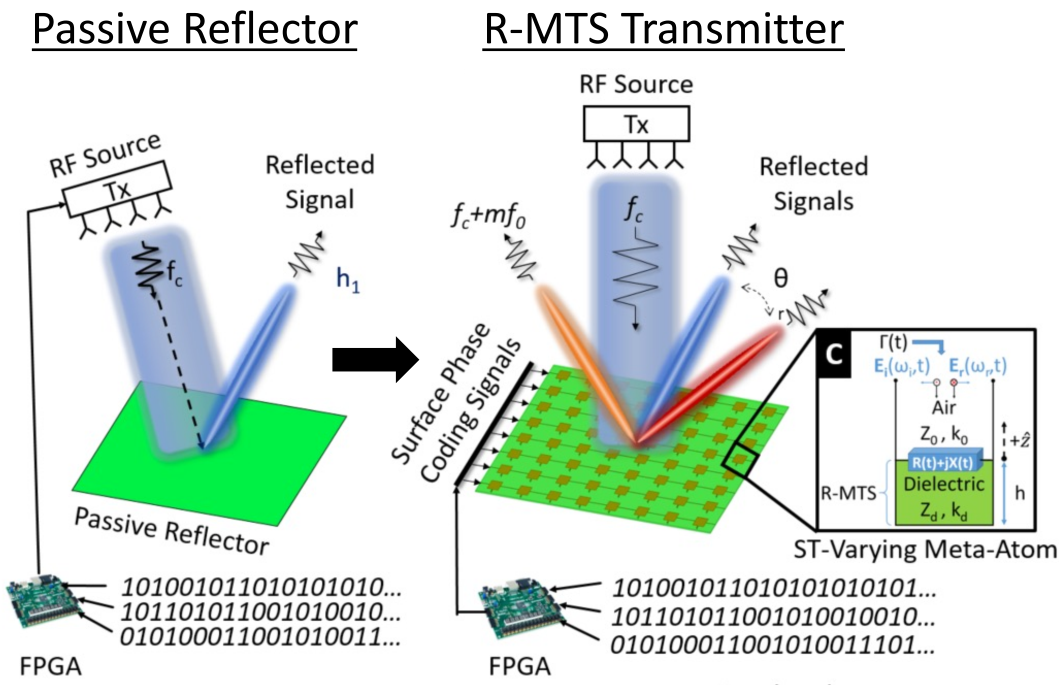


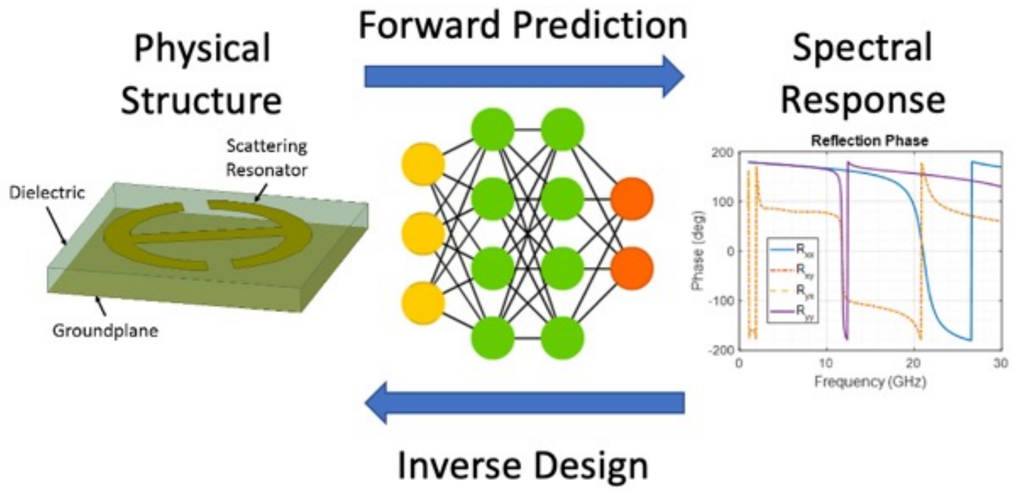
(Di Renzo, 2019)

RISs and smart radio environments empowered by AI reconfigurable MTSs have recently gathered very significant interest in the communications research community

Gaps in Previous Work

Challenges & Opportunities	This Dissertation
Traditional MTS limited by fixed functionality	Develop digitally programmable MTS antenna for comms & sensing
ST modulation creates new opportunities for EM wave manipulation	Expand capabilities of ST-modulated R-MTS antennas & provide rigorous EM-compliant models
Dynamic high-gain apertures needed for next-gen RF sensors	Provide low-cost alternative to traditional phased arrays in reduced form-factor
MTS design is a non-convex optimization problem	Apply machine learning (ML) algorithms to aid the design of MTSs and enhance dynamic operation





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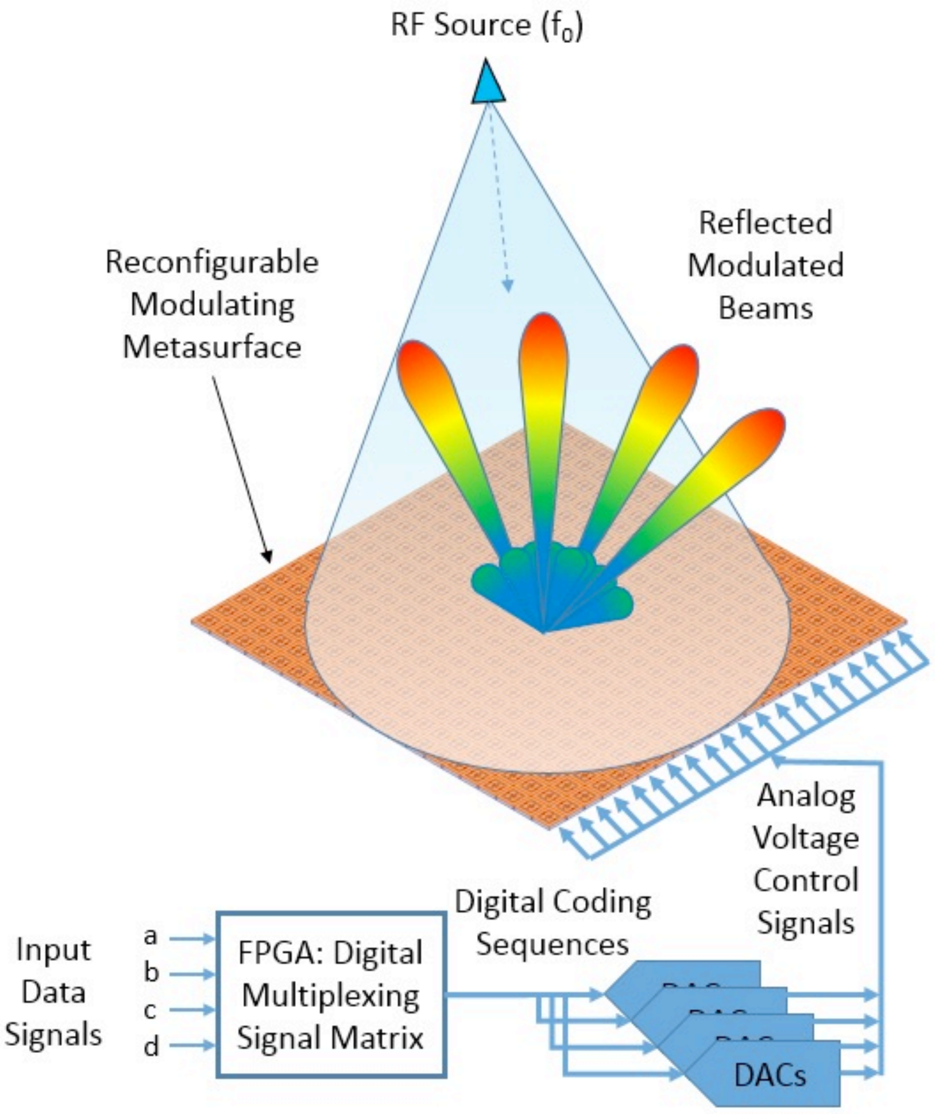
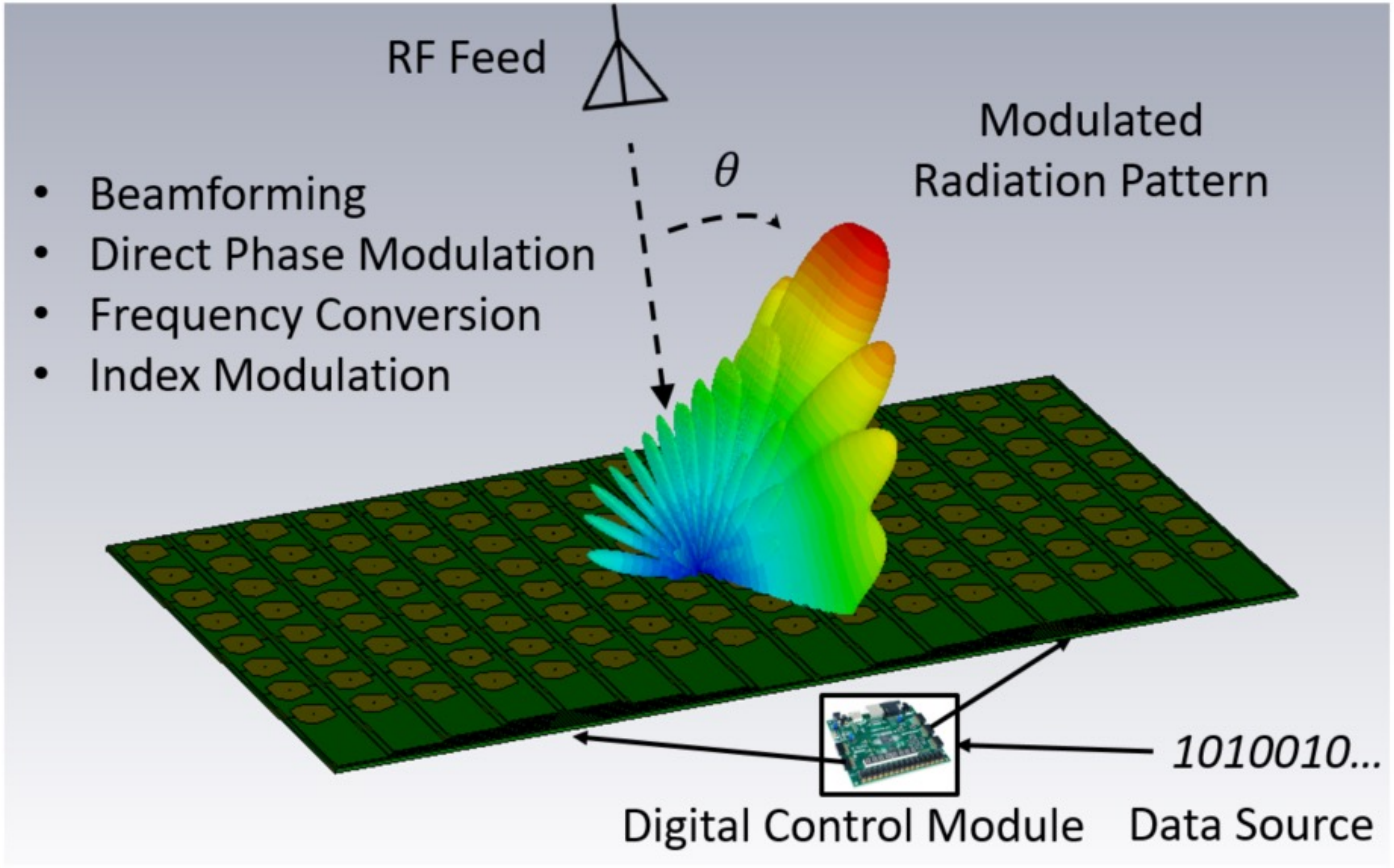


(Hodge, Mishra, Zaghloul, 2019)

Reconfigurable intelligent metasurface array prototype for dynamic beam steering and phase modulation.



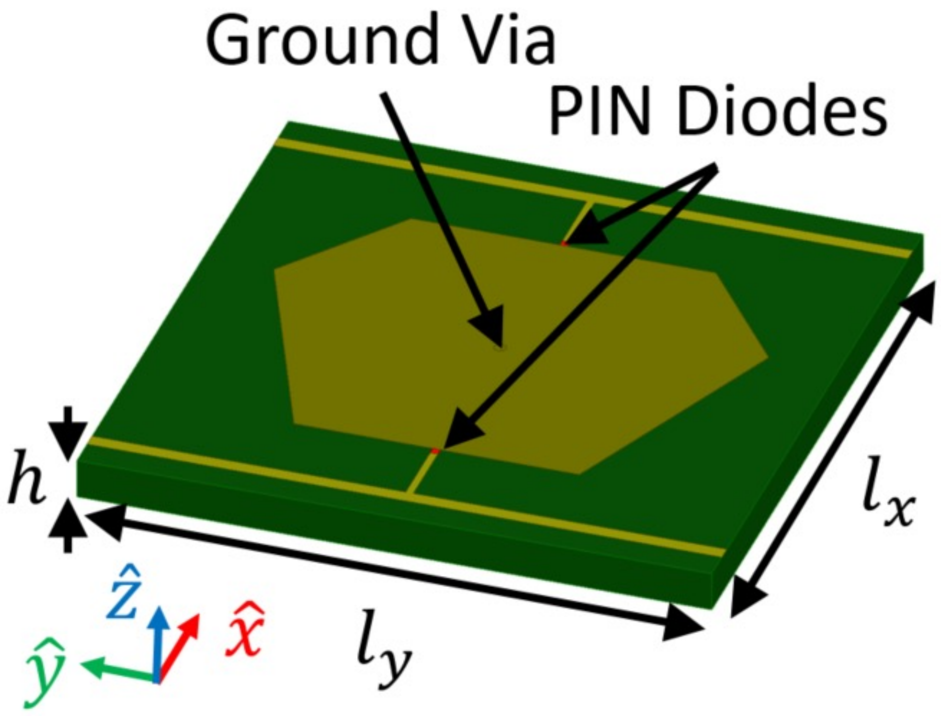
Driving requirements for metasurface prototype board.

Requirement Parameter	Requirement Value	Model Performance	Design Value
Frequency of Operation	6 GHz (λ_0 = 50 mm)		6 GHz
Aperture Size	406.4 mm by 254 mm (16” by 10”)		400 mm by 200 mm (15.75” by 7.87”)
Number of Elements	128 (16 by 8)		128 (16 by 8)
Grid Spacing	$\leq 0.5\lambda_0$ by $\leq 0.5\lambda_0$		25 mm by 25 mm ($0.5\lambda_0$ by $0.5\lambda_0$)
Element Phase Shift	2-bit Binary (+/- 5 deg)		Column-level phase control; Phase Shifts: 0, 90, 180, 270 deg @ 6 GHz
Reflection Amplitude ($\|R\|$)	$\|R\| > 0.8$ ($\|R\| < -2$ dB)		$\|R\| > 0.8$
Substrate Material	$\delta < 0.005$		Taconic TLX-8 ($\varepsilon_r = 2.55$, $\delta = 0.0019$)
Substrate Thickness (h)	1.524 mm (60 mils) < h < 5.0 mm		1.6 mm (λ_0/15.6)
Spatial Coverage	Azimuth: +/- 45 deg, El: 0 deg		Steering in Azimuth: +/- 45 deg
Directivity	N/A		Boresight: 26 dBi, Az (45 deg scan): 23.6 dBi
HPBW	N/A		Az: 6.2 deg, El: 14.0 deg

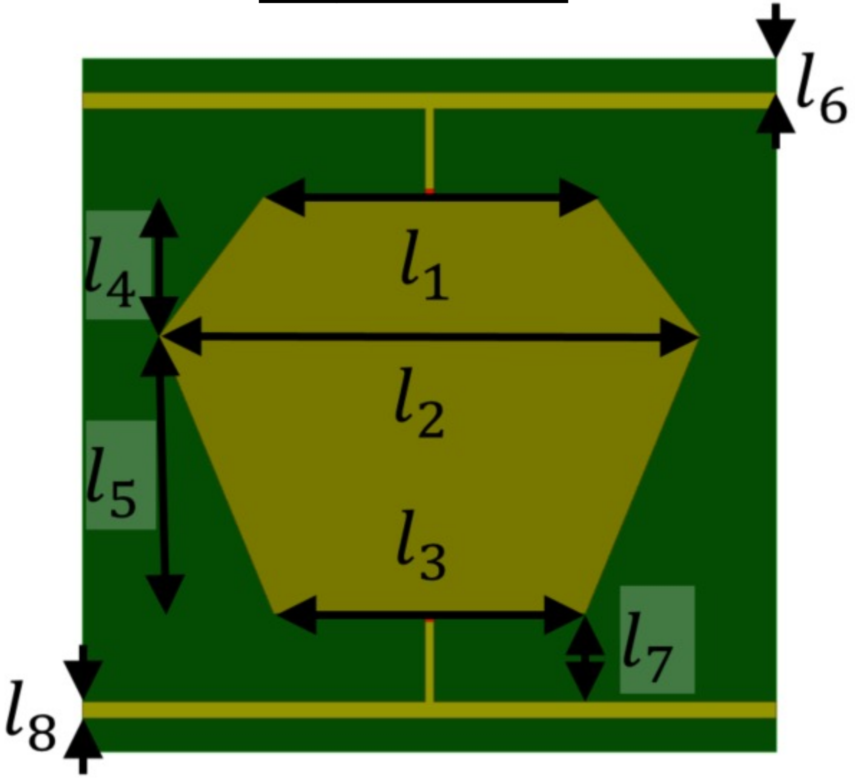
Meta-atom design for two-bit phase shift.

(Hodge *et al.*, IEEE AP-S Conf, 2021)

<u>Isometric</u>



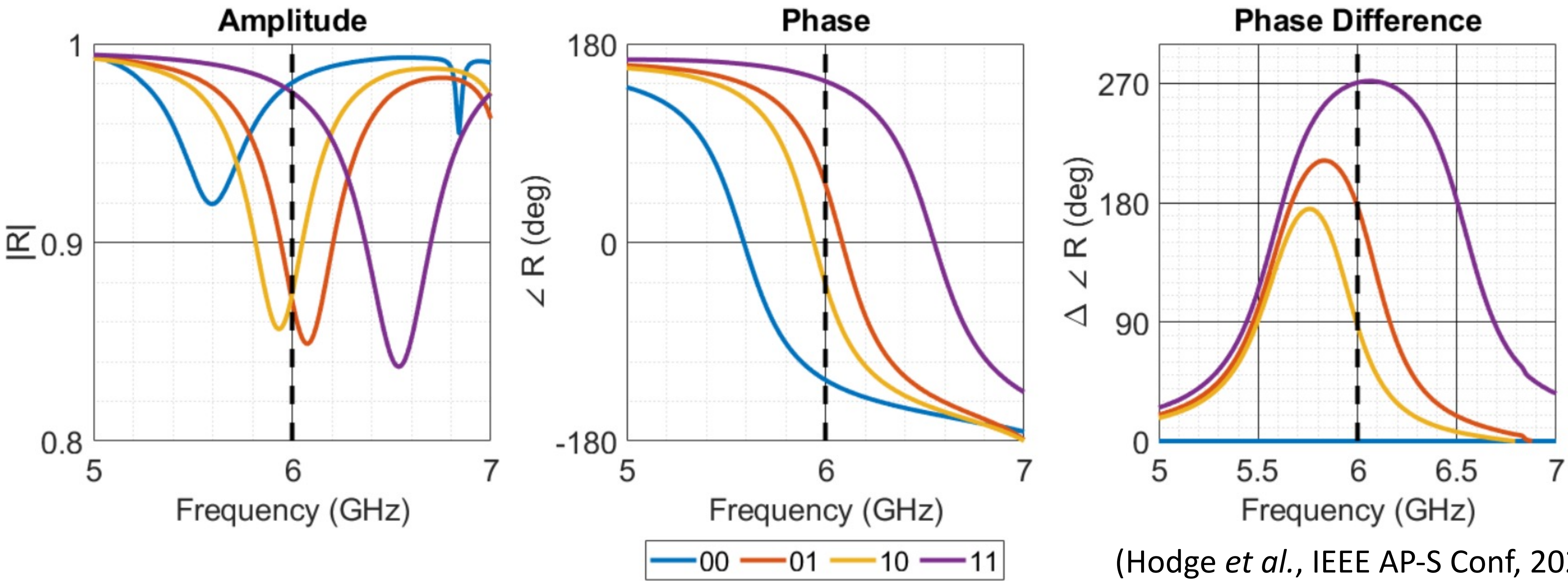
<u>Top-Down</u>



Parameter	Value
l_x	25.0 mm
l_y	25.0 mm
l_1	1.6 mm
l_2	19.5 mm
l_3	11.25 mm
l_4	5.0 mm
l_5	10 mm
l_6	0.6 mm
l_7	3.2 mm
l_8	1.2 mm

Performs co-simulation between HFSS and ADS to carefully tune meta-atom dimensions using S-parameters from MACOM MADP-000907-14020 PIN diode

Simulated meta-atom performance (HFSS & ADS) shows phase shifting capability at 6 GHz.



(Hodge *et al.*, IEEE AP-S Conf, 2021)

2-bit quantized phase shifts with an average reflection amplitude loss of 0.34 dB over all coding states

Radiation Pattern Synthesis

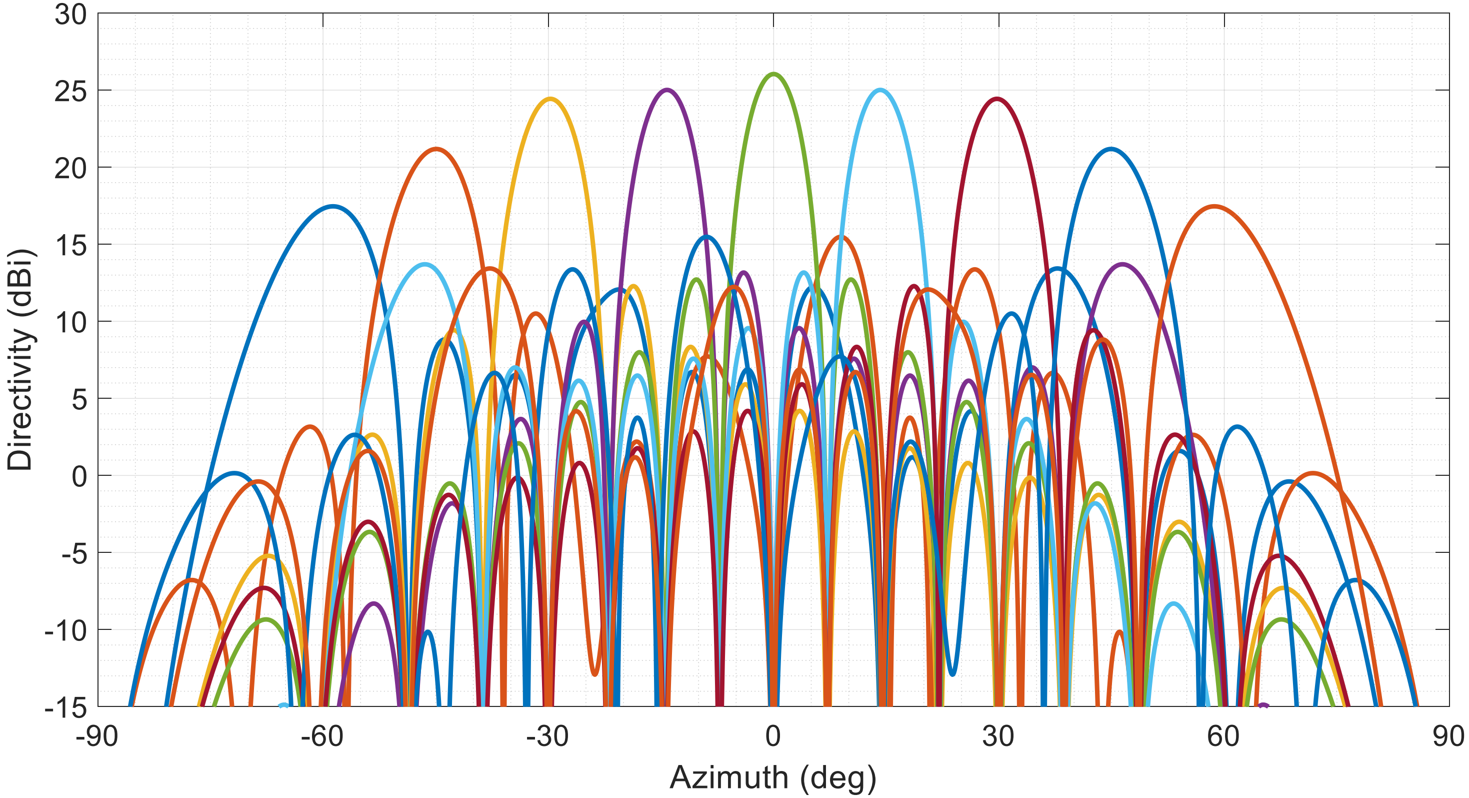
Approximate Radiation Pattern:

$$f(\theta,\phi,t) = \sum_{n=1}^{N}\sum_{m=1}^{M}\Gamma_{mn}(t)$$
$$\exp\left\{jk_0\left[(m-1)l_x \sin\theta\cos\phi + (n-1)l_y\sin\theta\sin\phi\right]\right\}$$

Scan Dependent Meta-Atom Phase:

$$\Gamma_{mn}(t) = \alpha_{mn}(t)\exp\left\{j(\beta_{mn}(t) + ml_x k_0 sin(\theta_{scan}))\right\}$$

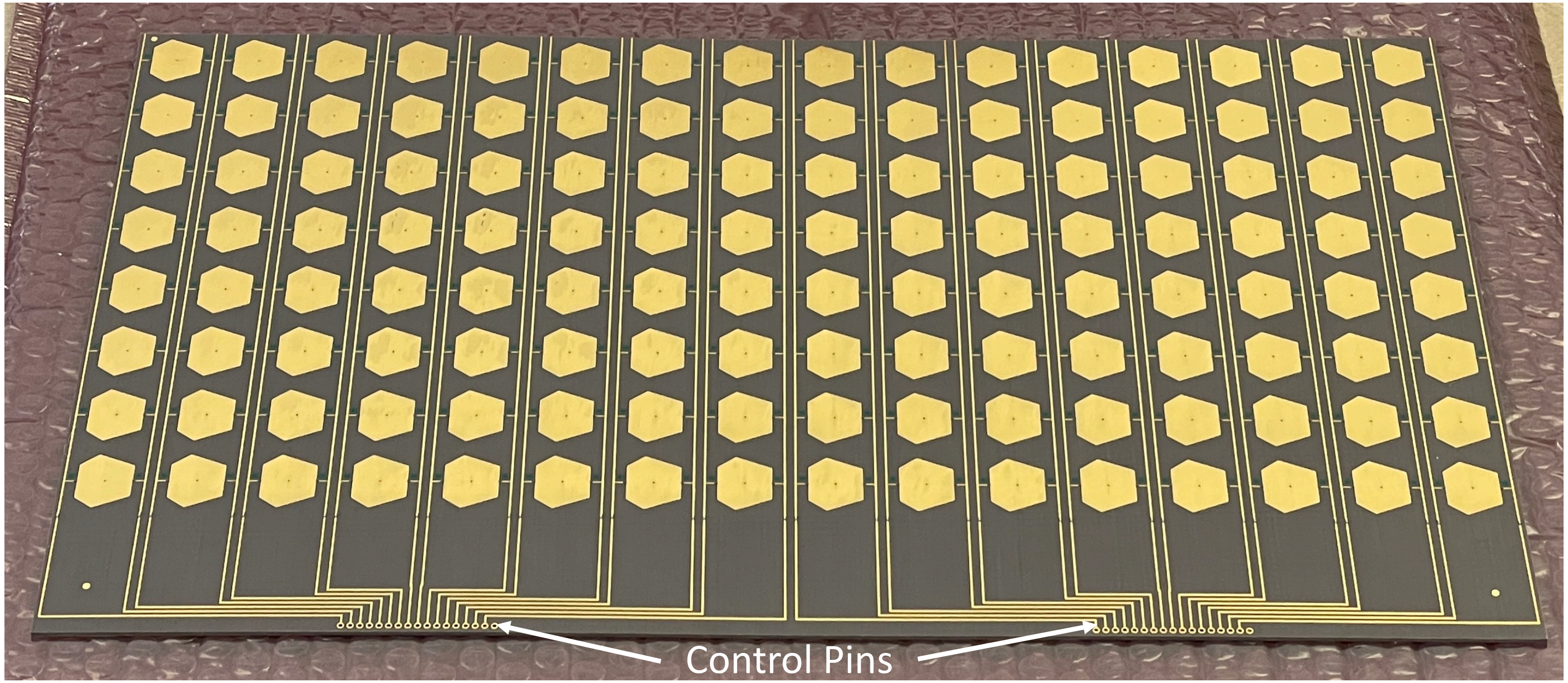
Directivity (Simulated DFT Approx.)



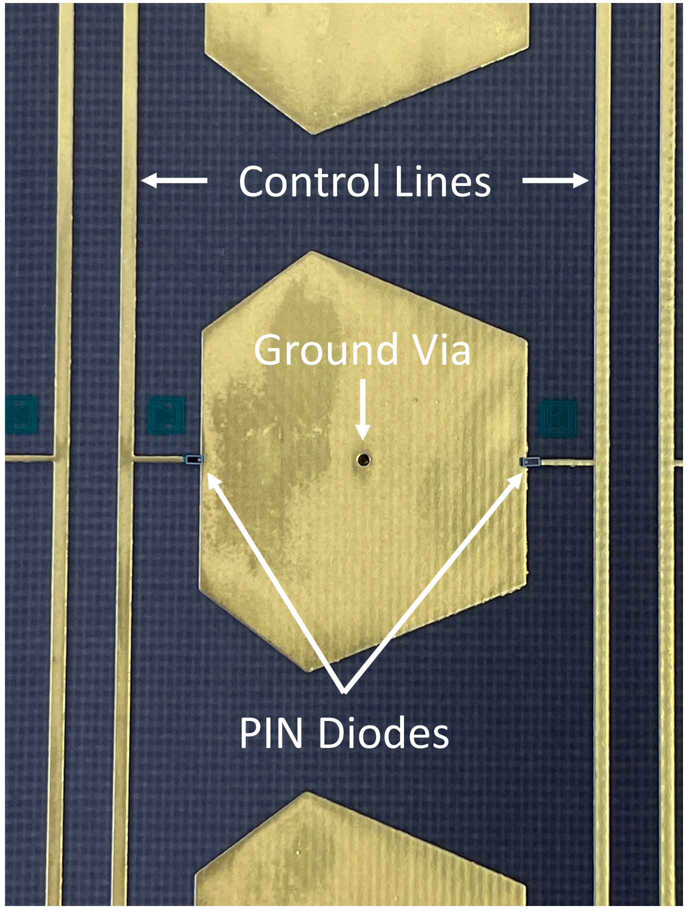
2-bit programmable meta-atom enables dynamic beamforming

Fabricated Metasurface Prototype Board

Reconfigurable Metasurface Array



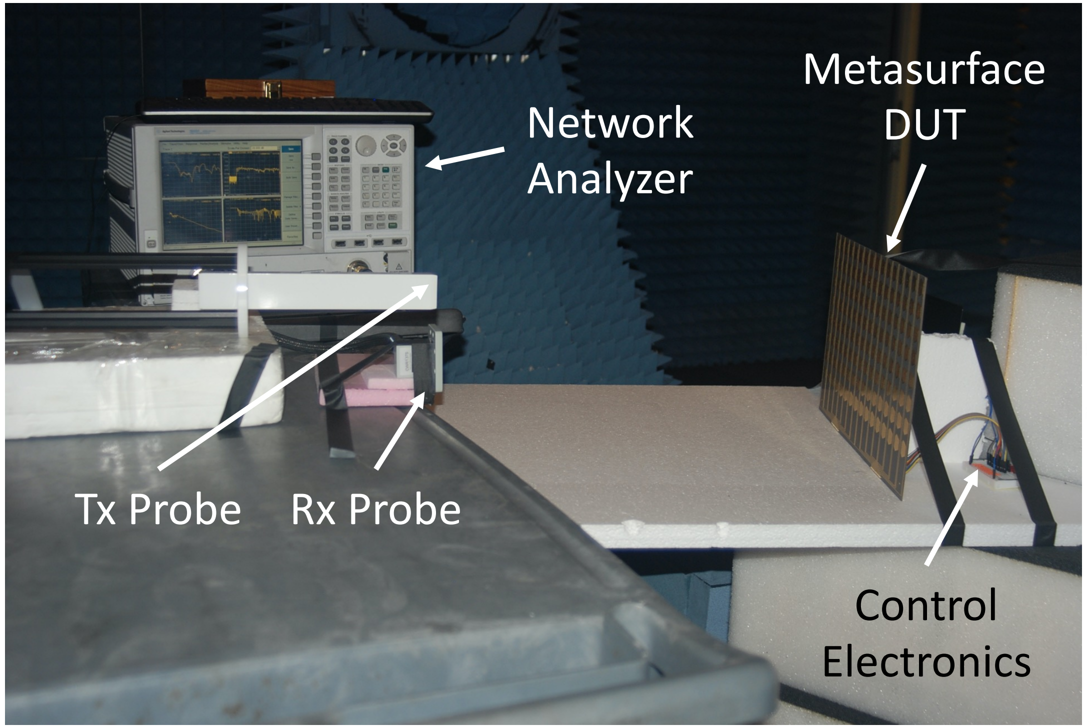
Meta-Atom

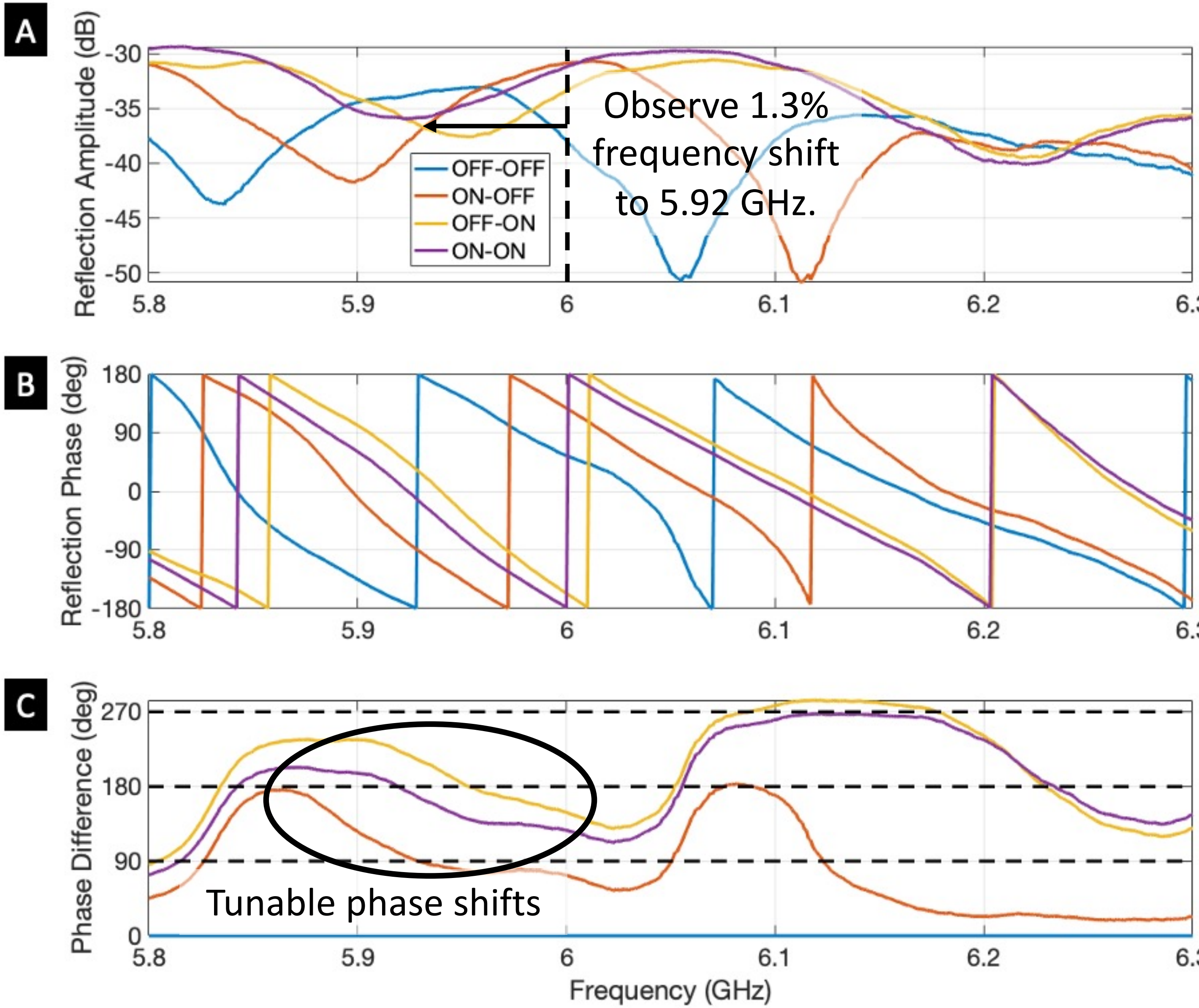


Each meta-atom column controlled by two digital signals

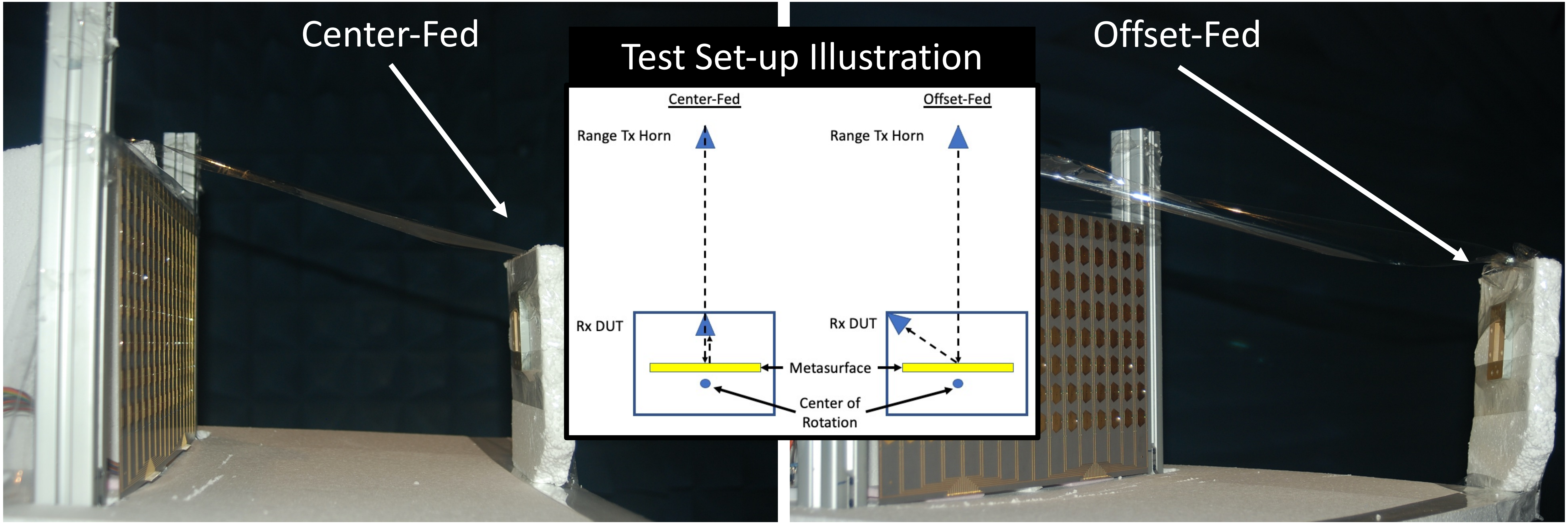
Measured reflection amplitude and phase data shows reconfigurability.

Reflection Measurement Set-up



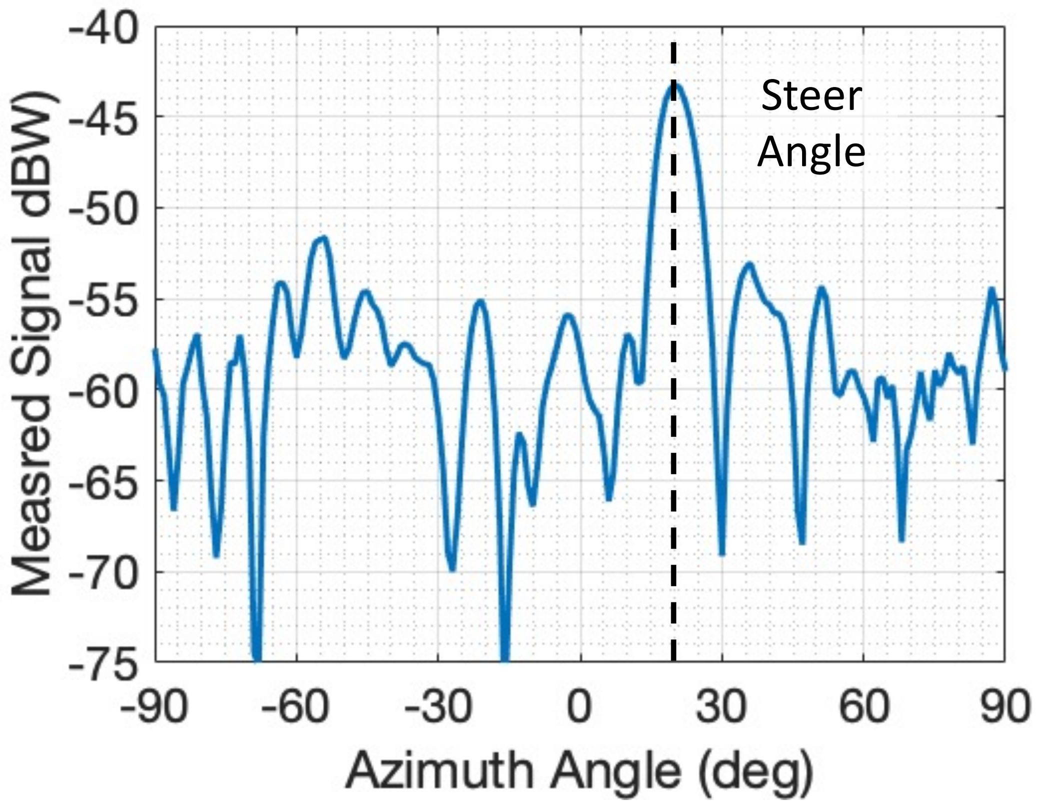


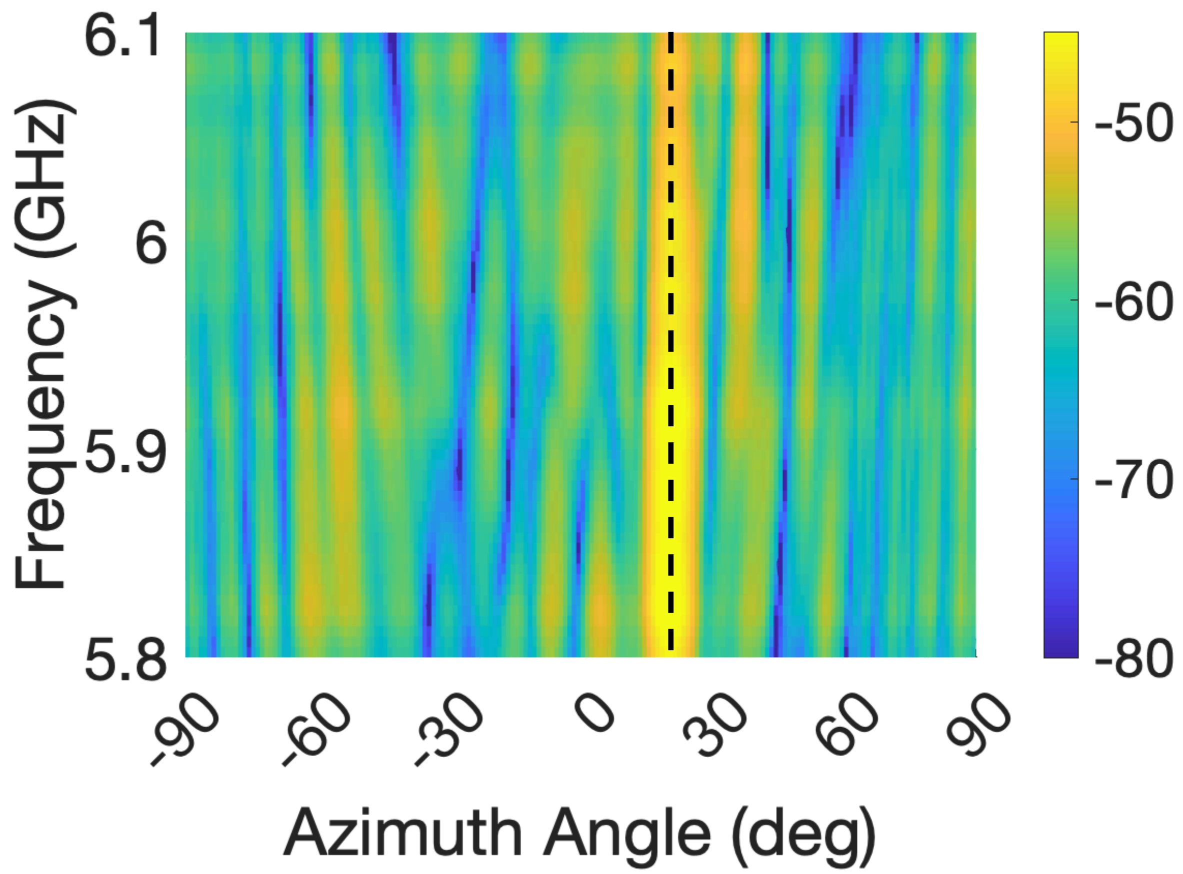
Radiation pattern measurements in the center- and offset-fed configurations in ARL tapered range.



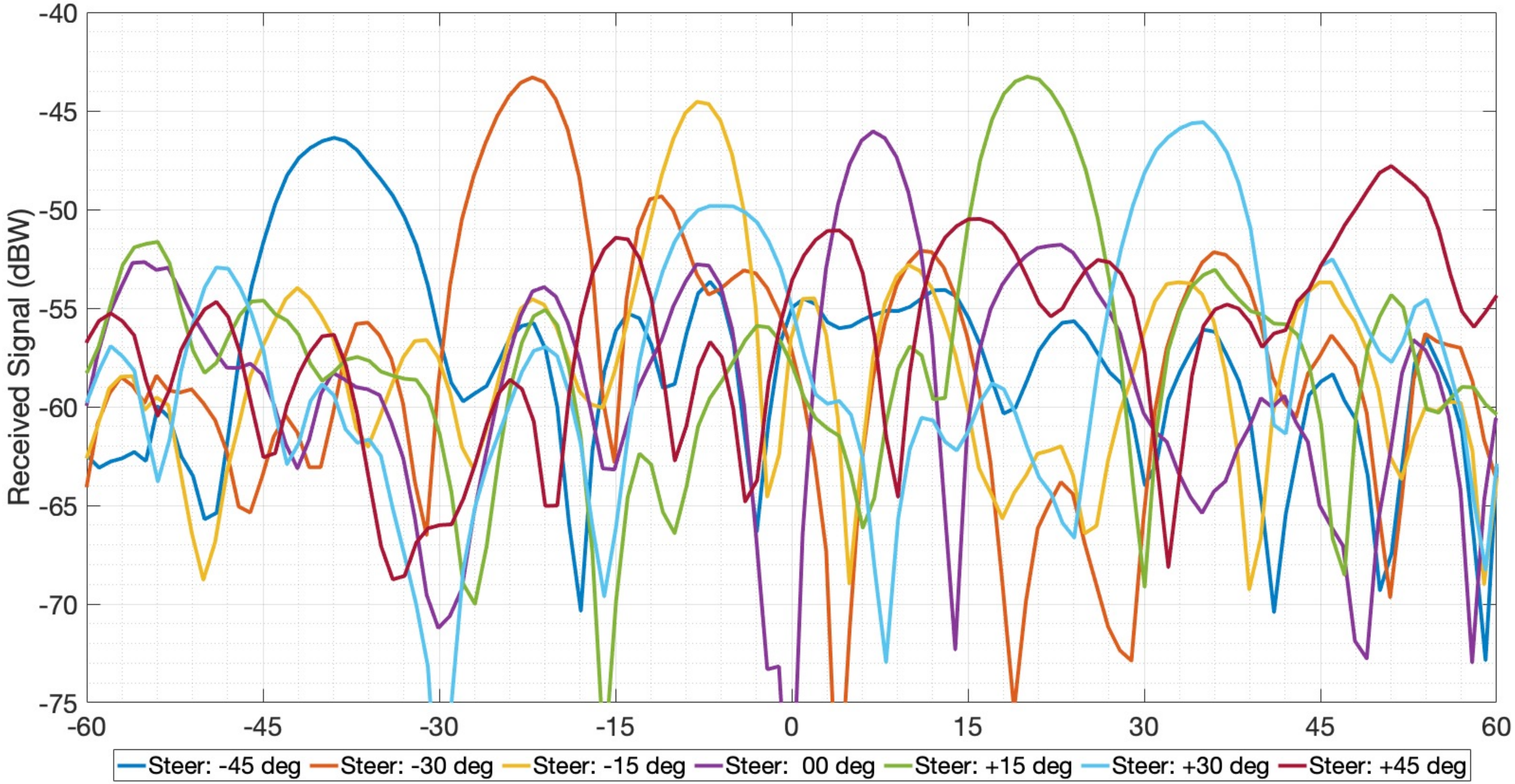
Compensates for spatial phase delay due to feed placement in programmable beamforming controller.

Radiation pattern measurement demonstrates beam steered to θ_{az} = +20 degrees in the center-fed configuration.

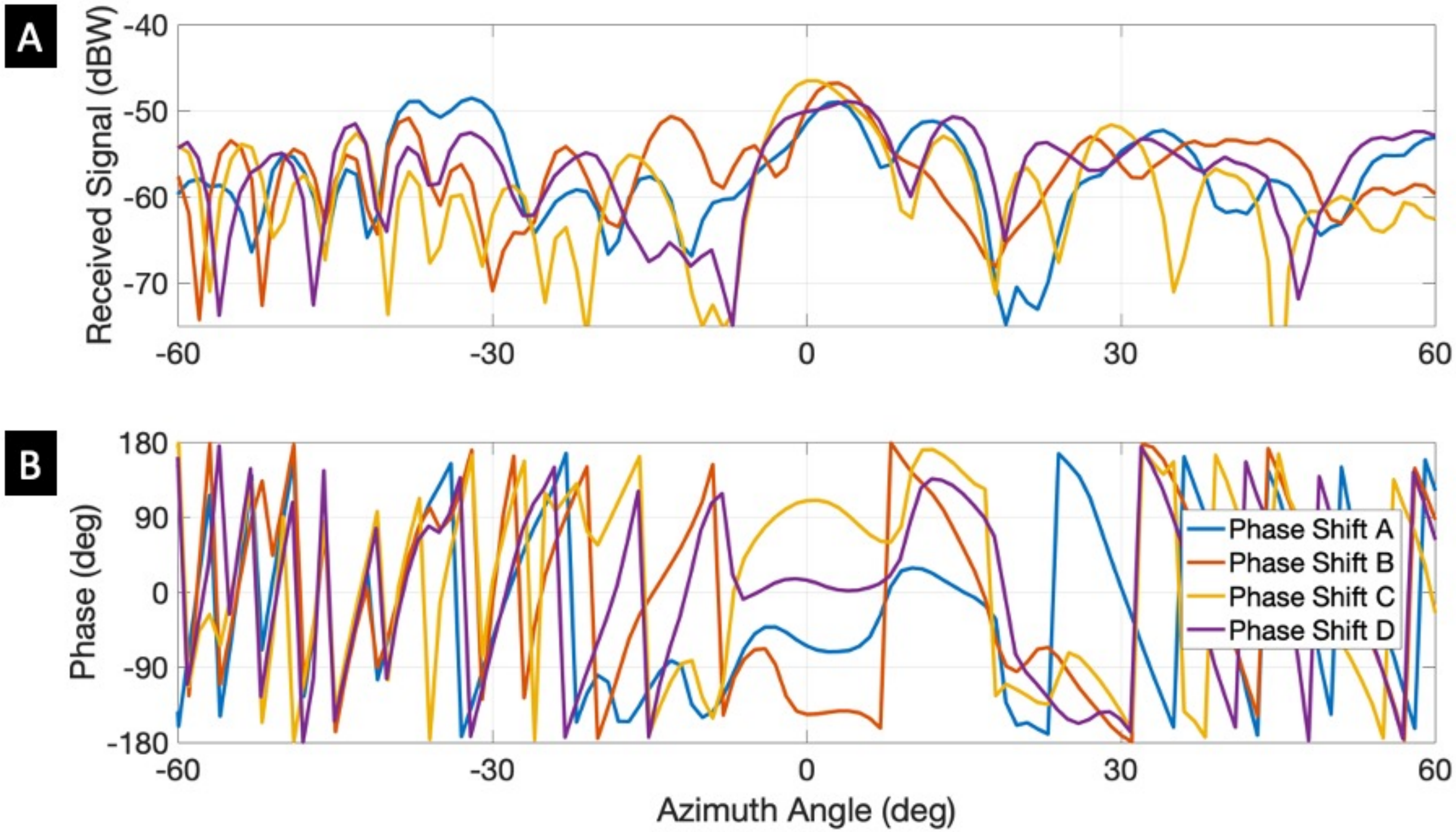




Successfully demonstrates dynamic beam steering capability over the scan volume at 5.92 GHz.



Measured radiation patterns in the offset-fed configuration at 5.92 GHz demonstrate dynamic phase modulation.



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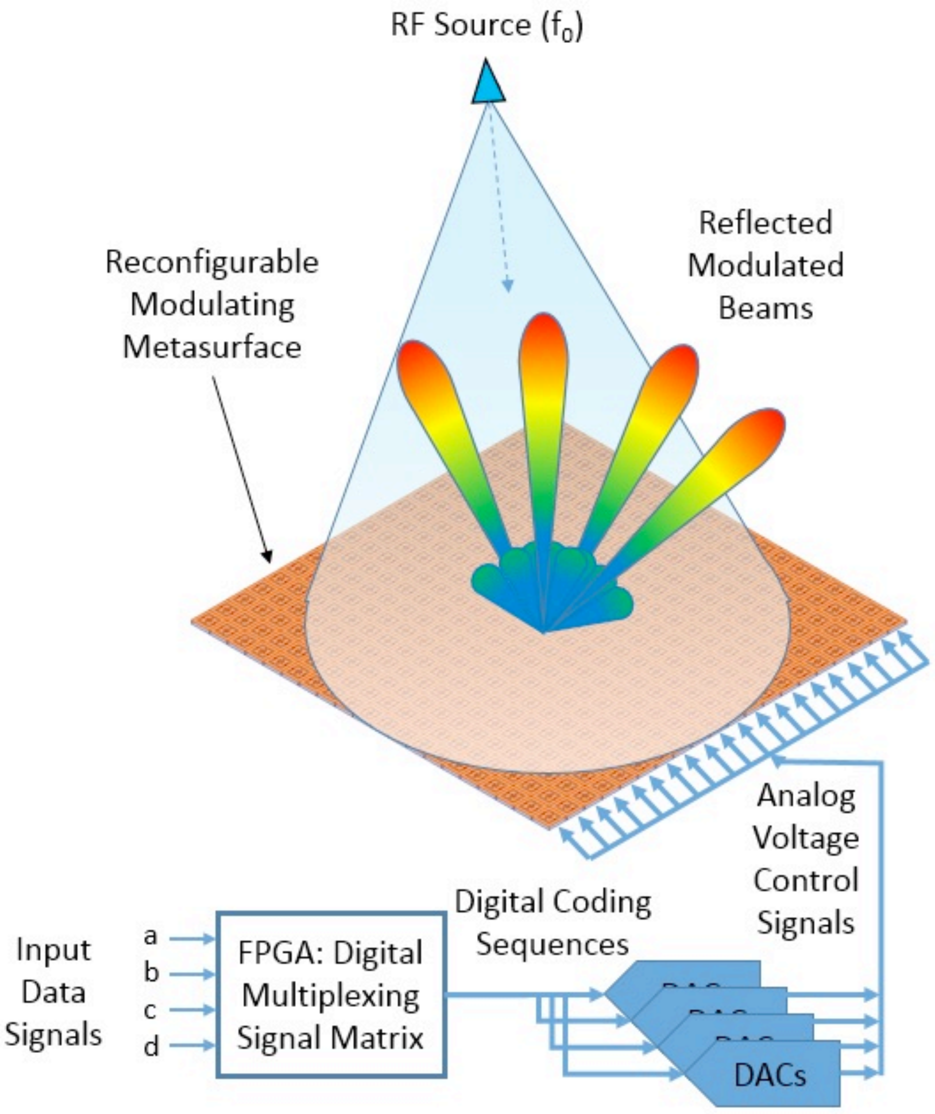


(Hodge, Mishra, Zaghloul, 2019)

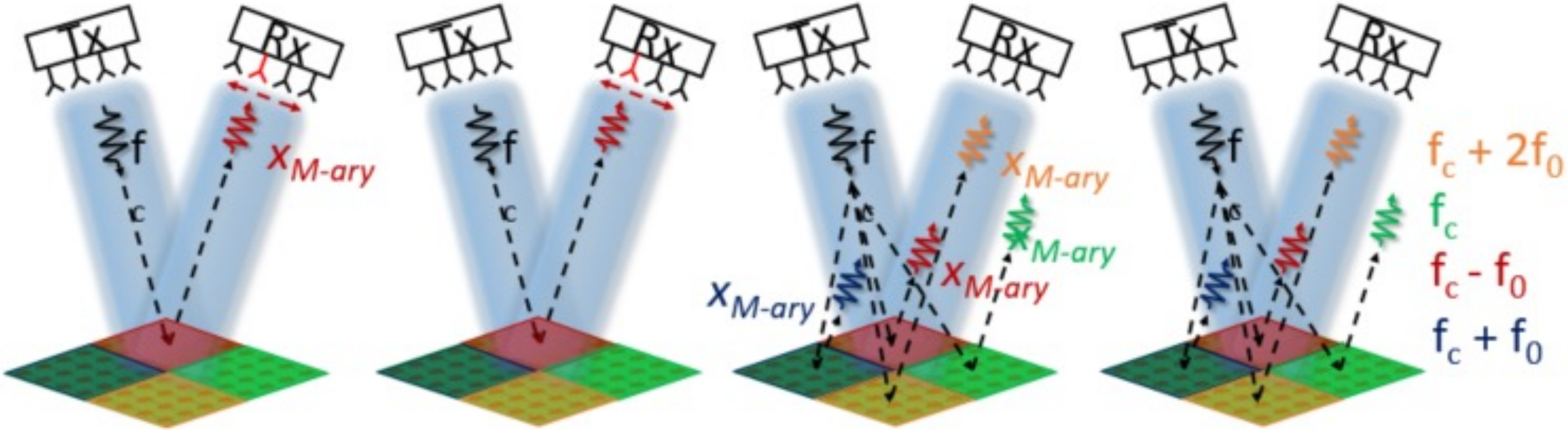
Index Modulation (IM): Spatial and Frequency

Spatial Modulation (SM): (Meslah, 2008)

Spatial Shift Keying (SSK) (Jeganathan, 2009)

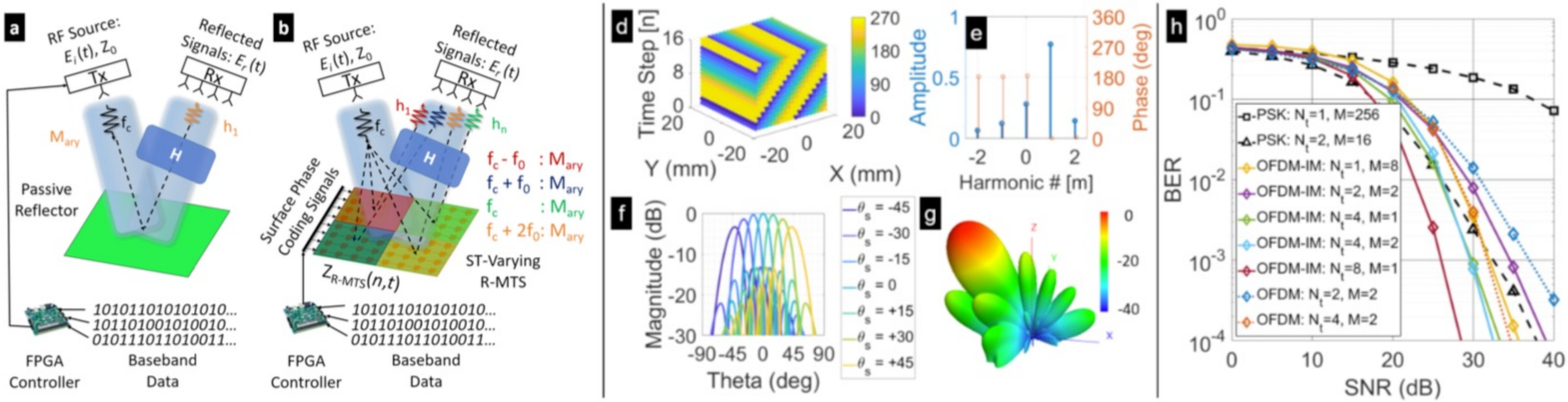
Generalized SM (GSM): (Younis, 2010)

MIMO-OFDM-IM: (Basar, 2016)



IM transmits information through permutations of indices of spatial, frequency, or temporal media

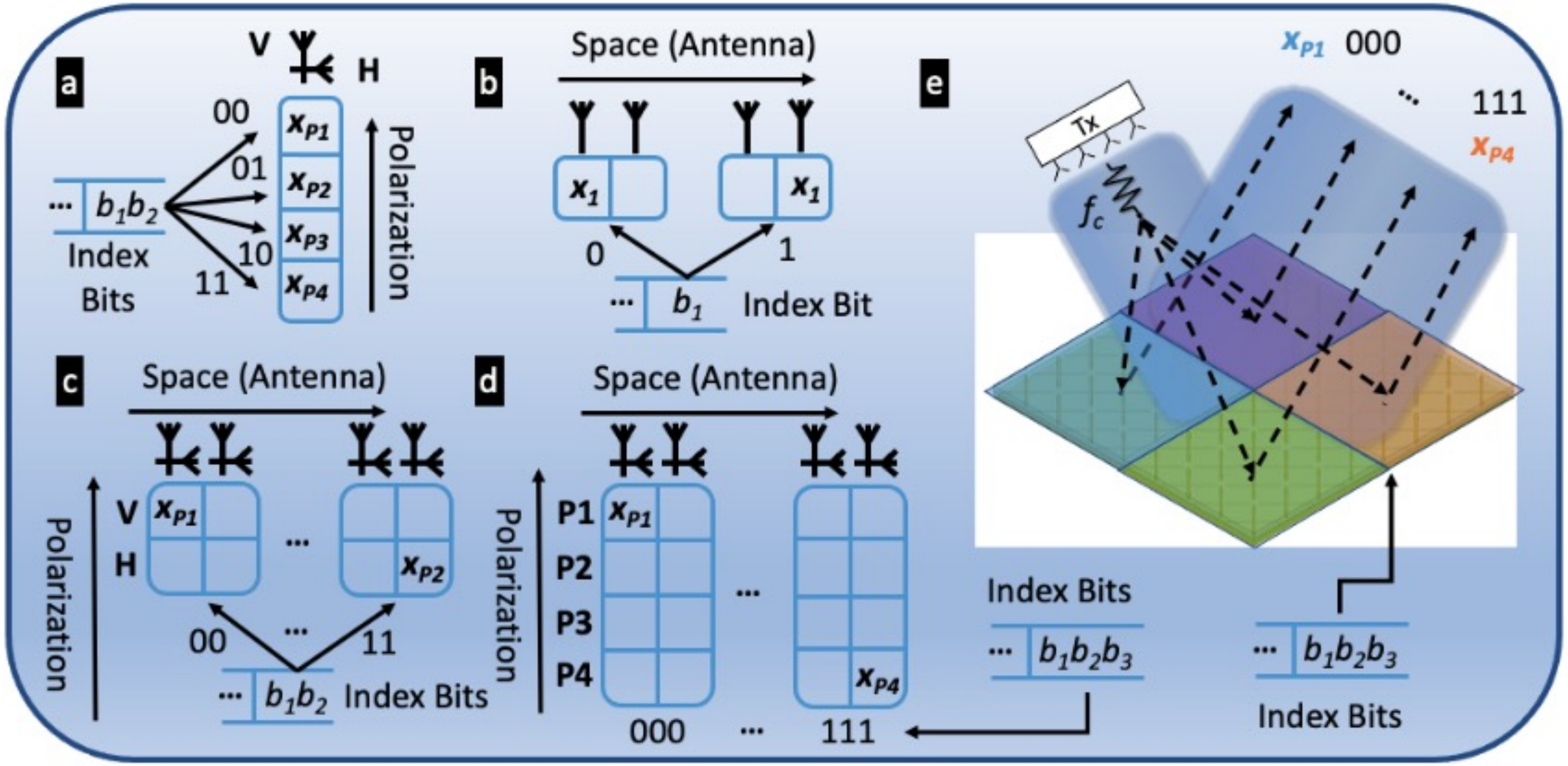
Intelligent Time-Varying Metasurface Transceiver for Index Modulation in 6G Wireless Networks

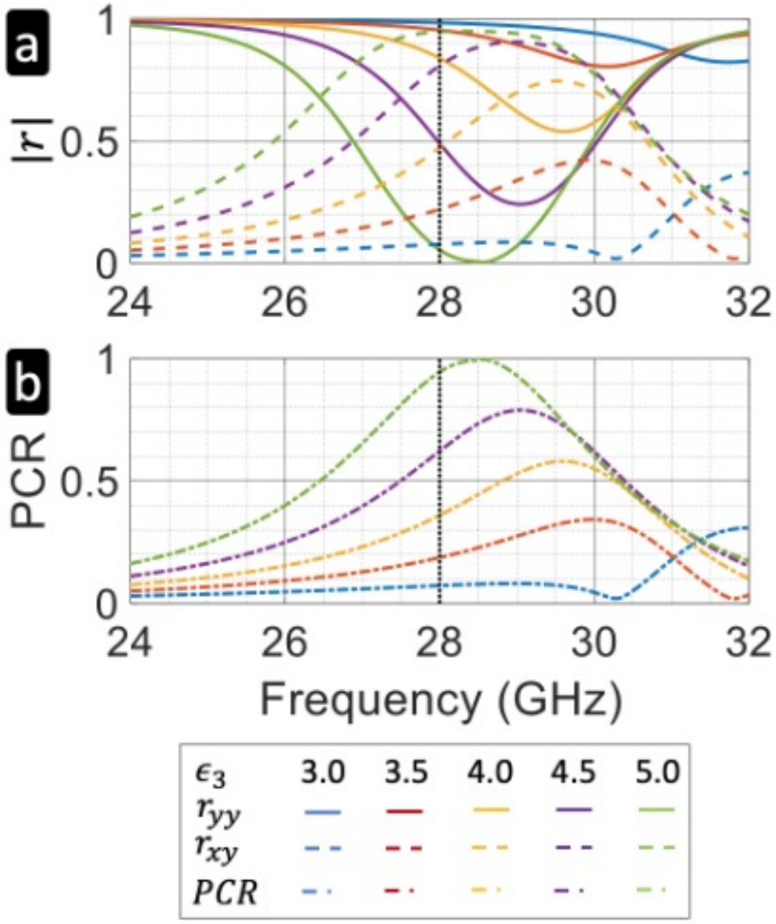


Proposes RIS-based design for frequency-domain IM (FD-IM) including MIMO-OFDM-IM using programmable frequency harmonics *(Hodge et al., AWPL, Nov 2020)*

Reconfigurable-Metasurface-Aided Multi-State Generalized Polarization-Space Modulation for Next-Gen Wireless Comms

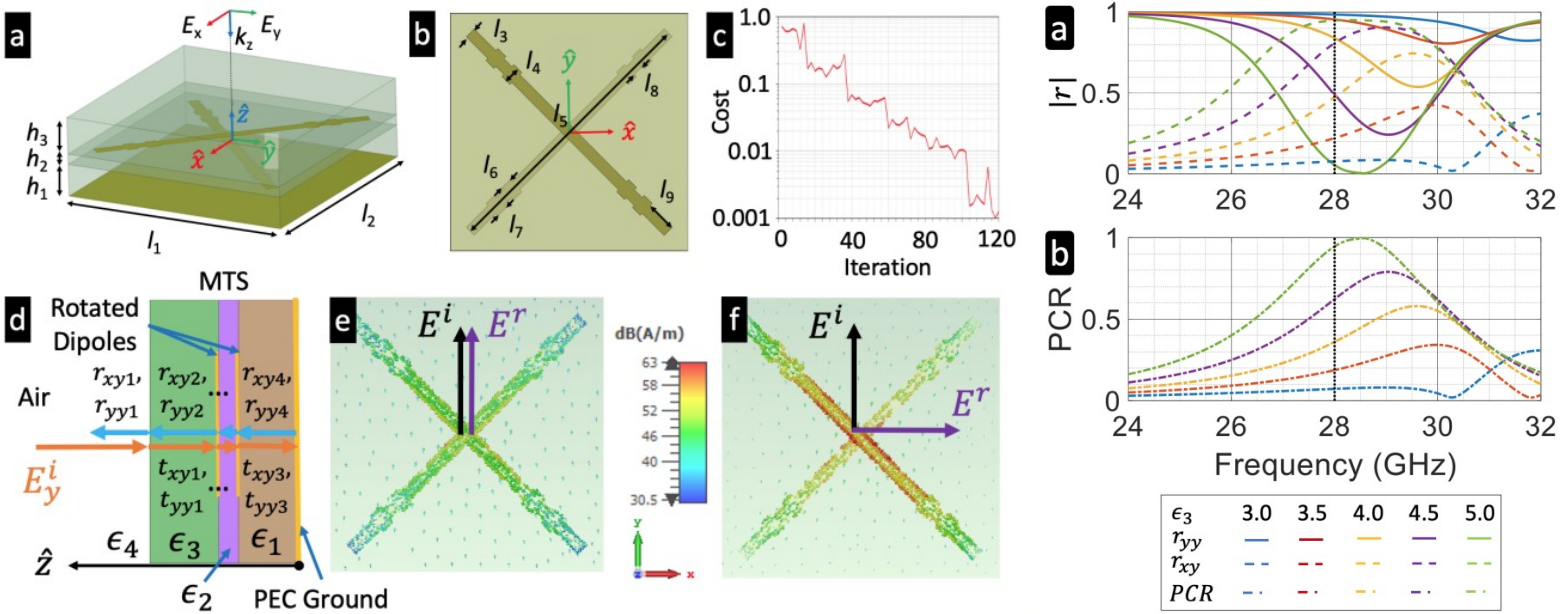
(Hodge et al., arXiv:2103.12573, 2021)





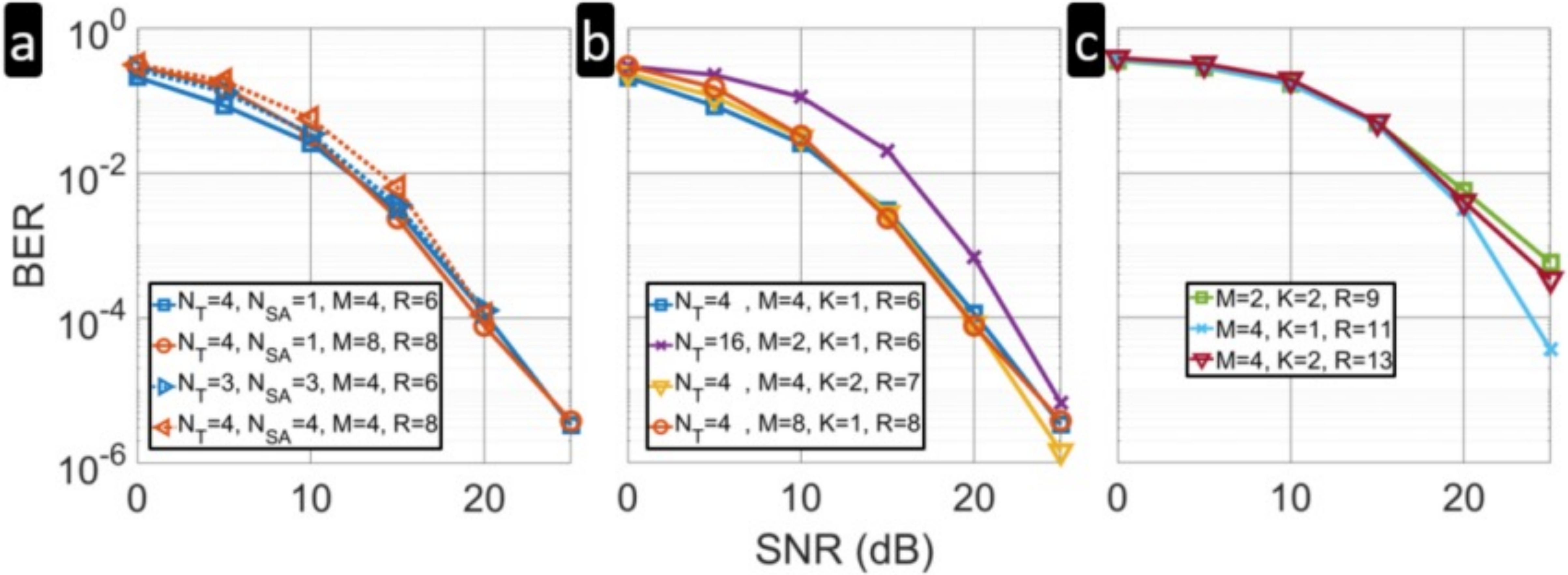
Introduces RIS-based generalized polarization-space IM

Synthesized cross dipole metasurface design to maximize polarization conversion at 28 GHz for Pol-IM.



(Hodge et al., arXiv:2103.12573, 2021)

BER versus SNR for RMTS-assisted GPSM (solid) with $N_R = 4$ Rx antennas shows benefit over MIMO-QAM (dashed).



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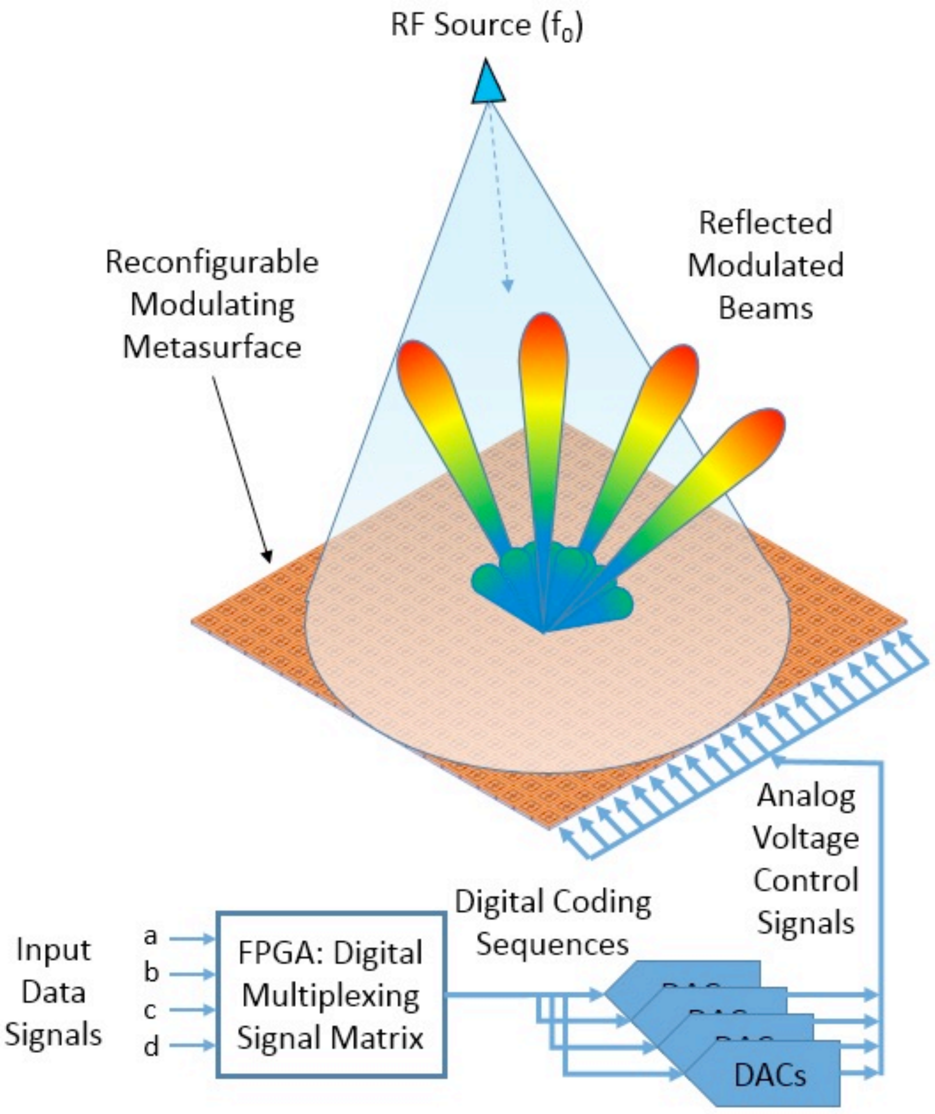
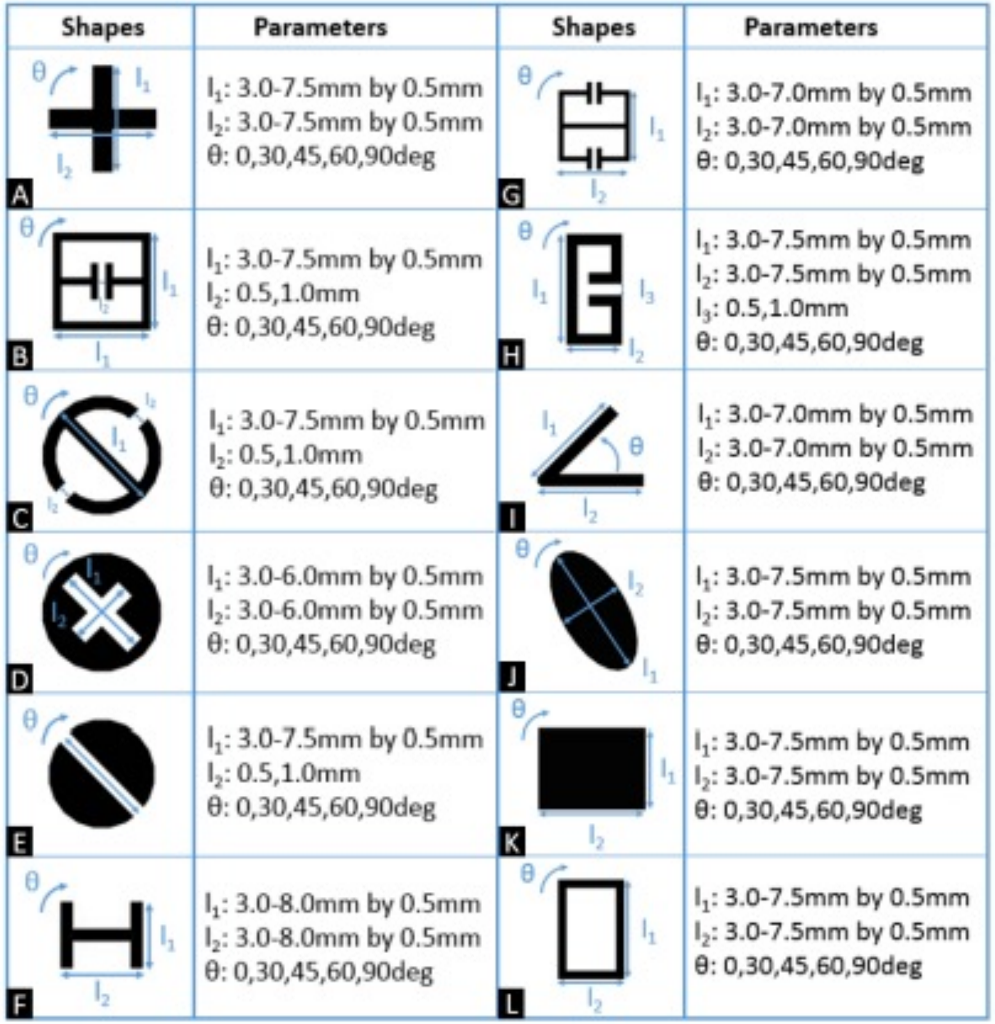


(Hodge, Mishra, Zaghloul, 2019)

Meta-Atom Design Challenges

- ➢ MTSs present many promising behaviors & functionalities
- ➢ Desired properties often difficult to realize
  - ➢ Complex EM response needed
  - ➢ Many meta-atom variations per MTS
  - ➢ Single- and multi-layer structures
- ➢ Limits practical adoption of MTSs



Shapes	Parameters	Shapes	Parameters
A	l_1: 3.0-7.5mm by 0.5mm l_2: 3.0-7.5mm by 0.5mm θ: 0,30,45,60,90deg	G	l_1: 3.0-7.0mm by 0.5mm l_2: 3.0-7.0mm by 0.5mm θ: 0,30,45,60,90deg
B	l_1: 3.0-7.5mm by 0.5mm l_2: 0.5,1.0mm θ: 0,30,45,60,90deg	H	l_1: 3.0-7.5mm by 0.5mm l_2: 3.0-7.5mm by 0.5mm l_3: 0.5,1.0mm θ: 0,30,45,60,90deg
C	l_1: 3.0-7.5mm by 0.5mm l_2: 0.5,1.0mm θ: 0,30,45,60,90deg	I	l_1: 3.0-7.0mm by 0.5mm l_2: 3.0-7.0mm by 0.5mm θ: 0,30,45,60,90deg
D	l_1: 3.0-6.0mm by 0.5mm l_2: 3.0-6.0mm by 0.5mm θ: 0,30,45,60,90deg	J	l_1: 3.0-7.5mm by 0.5mm l_2: 3.0-7.5mm by 0.5mm θ: 0,30,45,60,90deg
E	l_1: 3.0-7.5mm by 0.5mm l_2: 0.5,1.0mm θ: 0,30,45,60,90deg	K	l_1: 3.0-7.5mm by 0.5mm l_2: 3.0-7.5mm by 0.5mm θ: 0,30,45,60,90deg
F	l_1: 3.0-8.0mm by 0.5mm l_2: 3.0-8.0mm by 0.5mm θ: 0,30,45,60,90deg	L	l_1: 3.0-7.5mm by 0.5mm l_2: 3.0-7.5mm by 0.5mm θ: 0,30,45,60,90deg

(Hodge, Mishra, & Zaghloul, 2019)

<u>Design Challenges</u>:

- ➢ Metasurface design for a given response is a non-trivial & time-consuming
- ➢ Trend towards more complex structures
- ➢ Many iterations of tuning and full-wave simulations

How to implement semi-automated MTS design technique to realize complex responses?

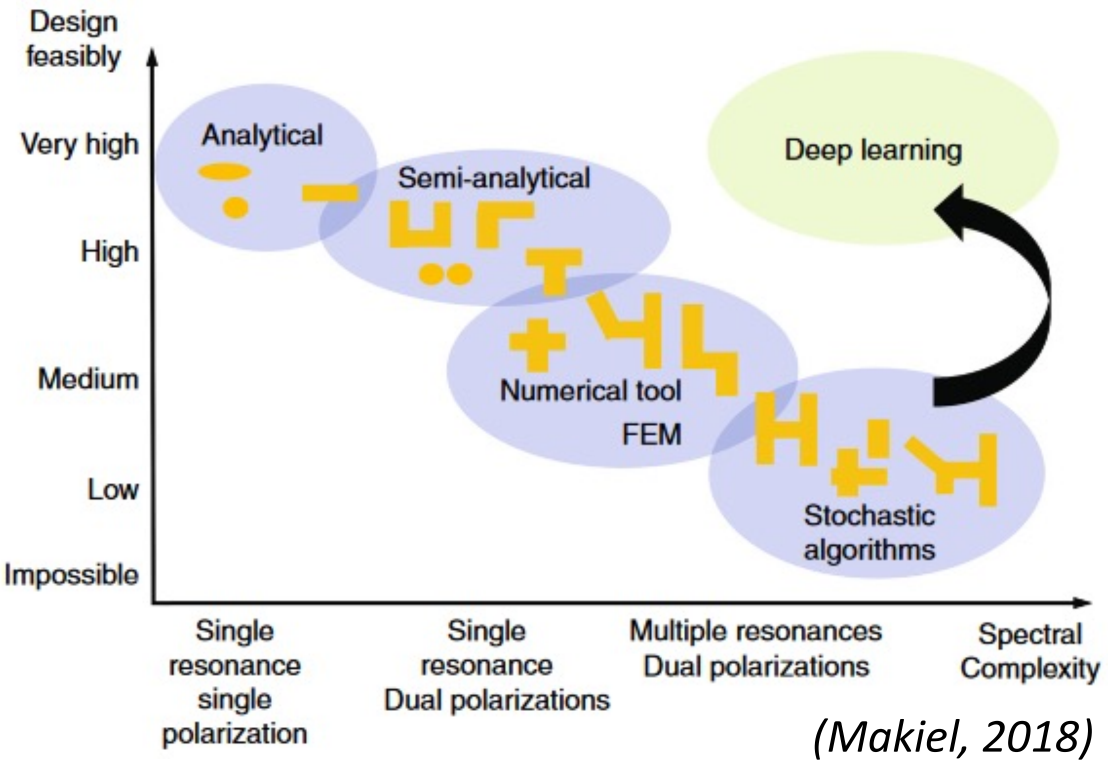
Design Challenges (cont.)

Prior Work:

- Stochastic optimization for meta-devices (Campbell, 2019)
- DL for modeling & inverse design of MTSs (Zhang, 2018)
- GAN-based design for nanophotonic structures (Liu, 2018)

Shortcomings (Lack of Generalizability):

- Fixed design parameters for input geometry (Peurifoy, 2018)
- GAN & CNN-based solutions limited to single-layer (Liu, 2018)
- Requires 50k+ simulated training examples (Zhang, 2018)

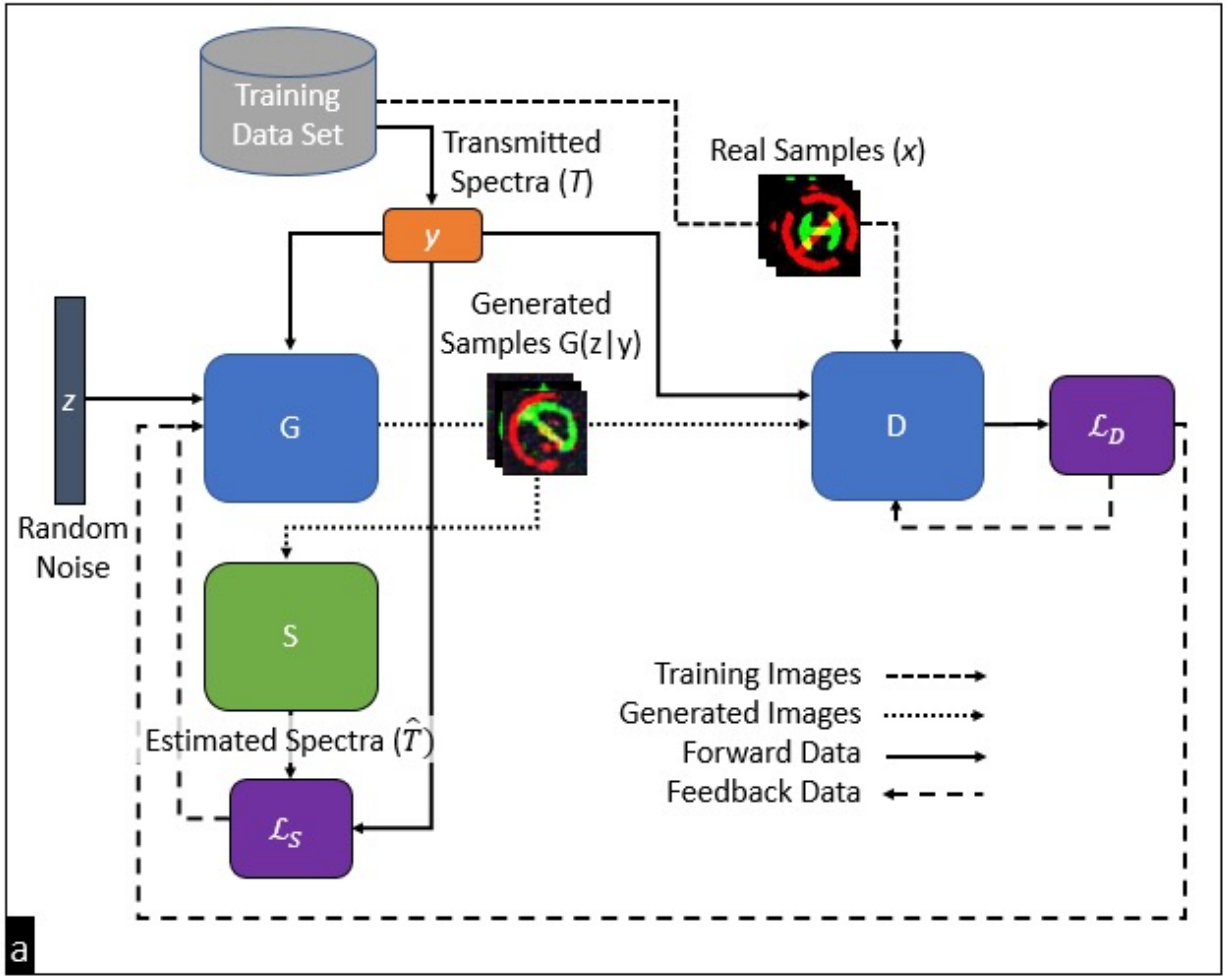


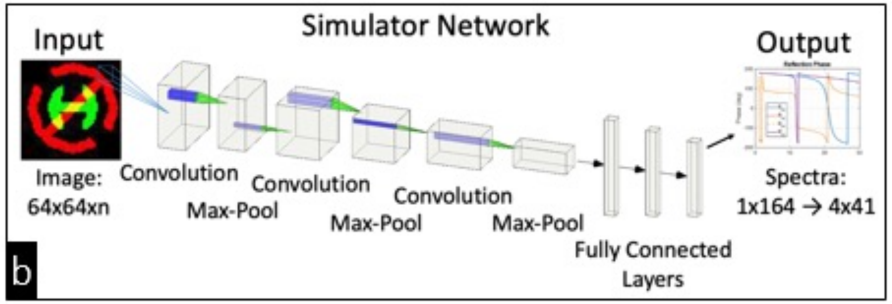
(Makiel, 2018)

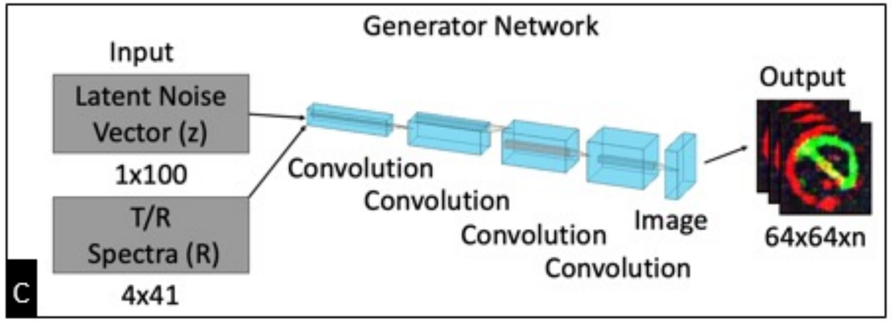
<u>Our Solution</u>: Employ DC-GANs to generate anisotropic inclusion designs for MTS arrays

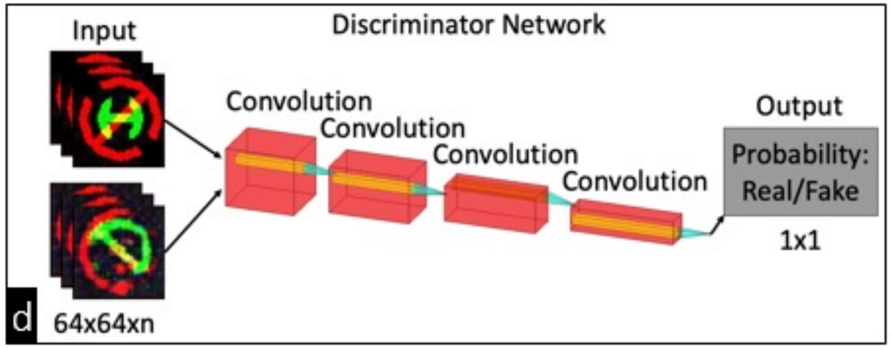
- ➢ Surrogate model that maps generalized scattering particles to spectral responses
- ➢ Generates both existing & <u>new</u> metamaterial structures from learned data
- ➢ Multi-layer & federated multi-layer GAN-based metasurface design

Multi-Layer cDC-GAN w/ Simulator



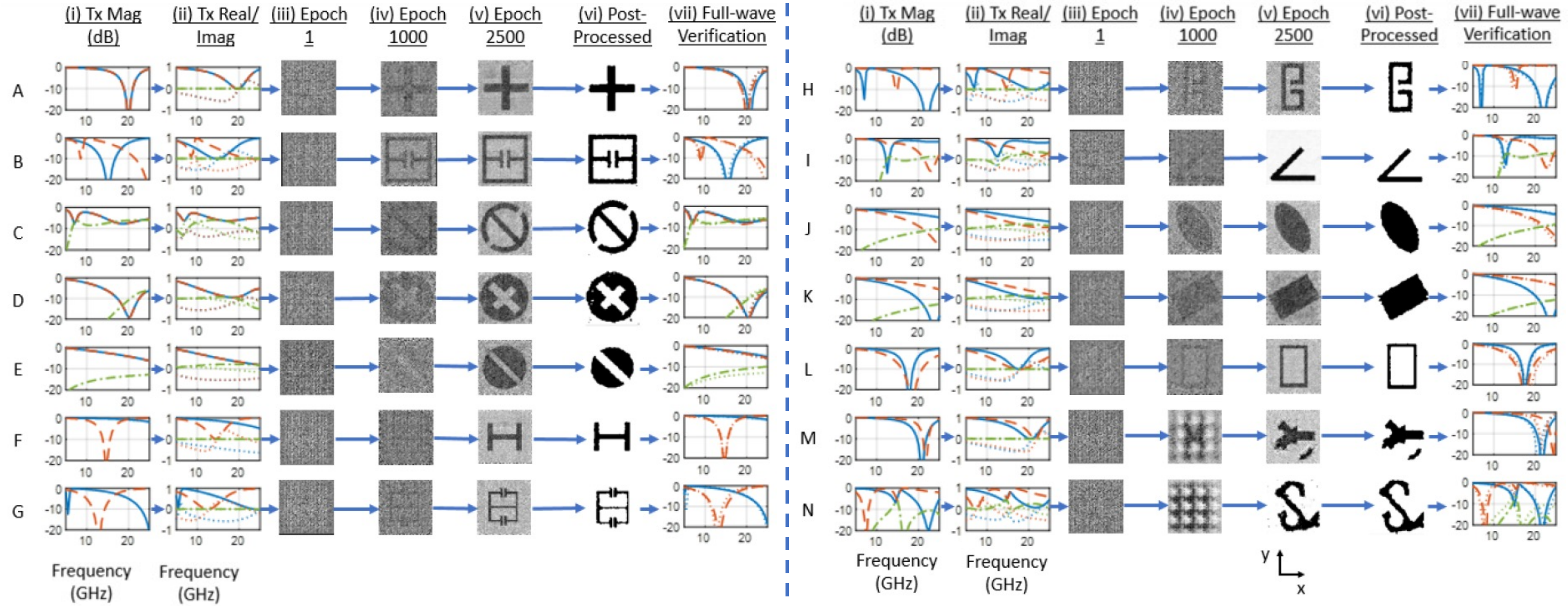






Won 3rd place student paper award, (Hodge, Mishra, & Zaghloul, MLSP, 2019)

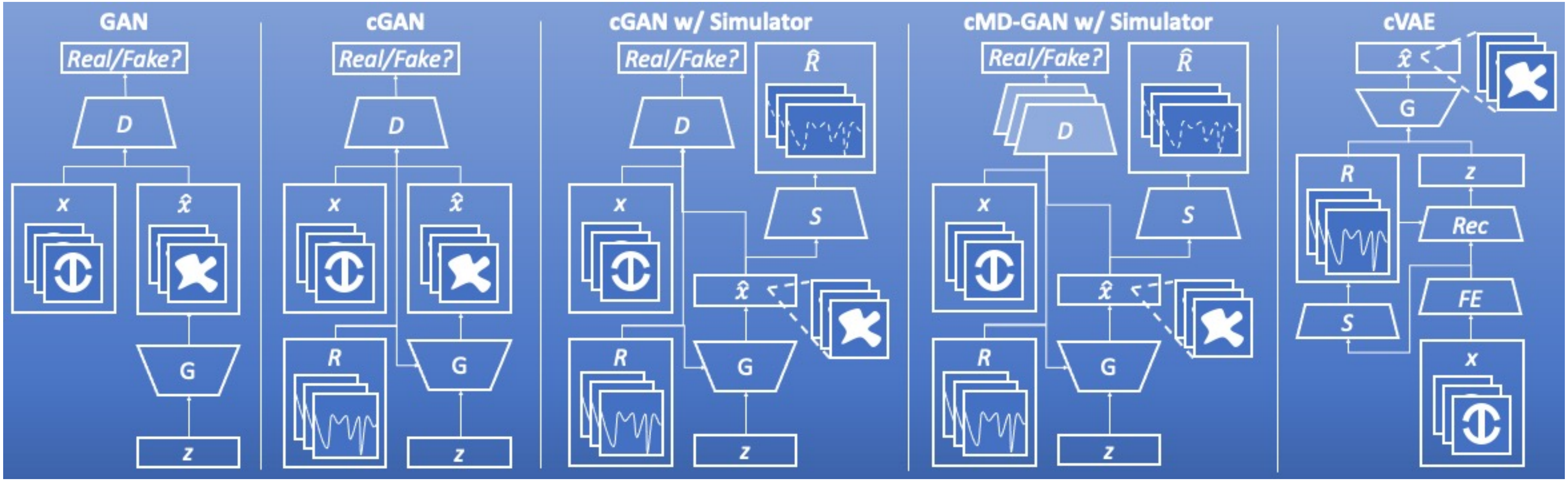
Generated Single-Layer Designs (Tx Case)



Won 3rd place student paper award, (Hodge, Mishra, & Zaghloul, MLSP, 2019)

Deep Inverse Design of Reconfigurable Metasurfaces for Future Communications

(Hodge et al., arXiv:2101.09131, 2021)

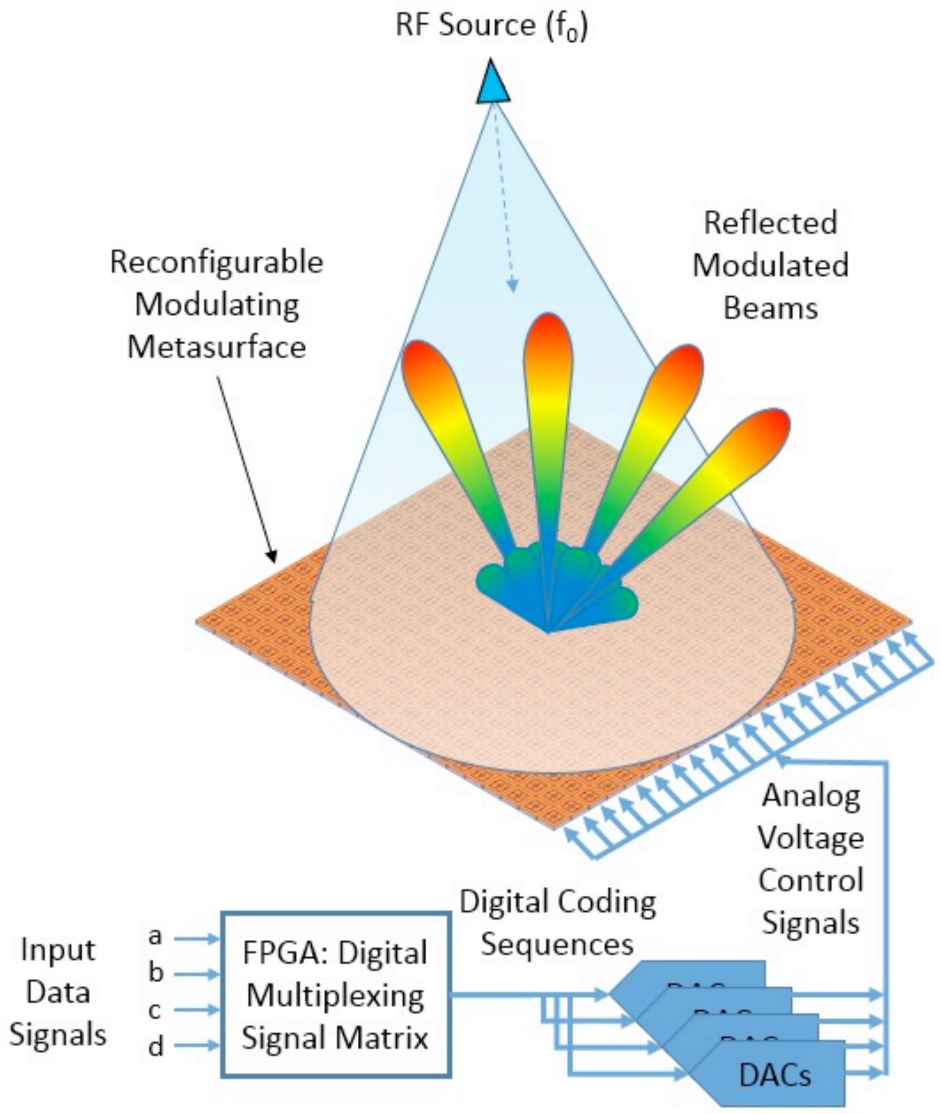


Deep generative models learn complex EM relationships for RIS inverse design

Electromagnetic (EM)

Outline

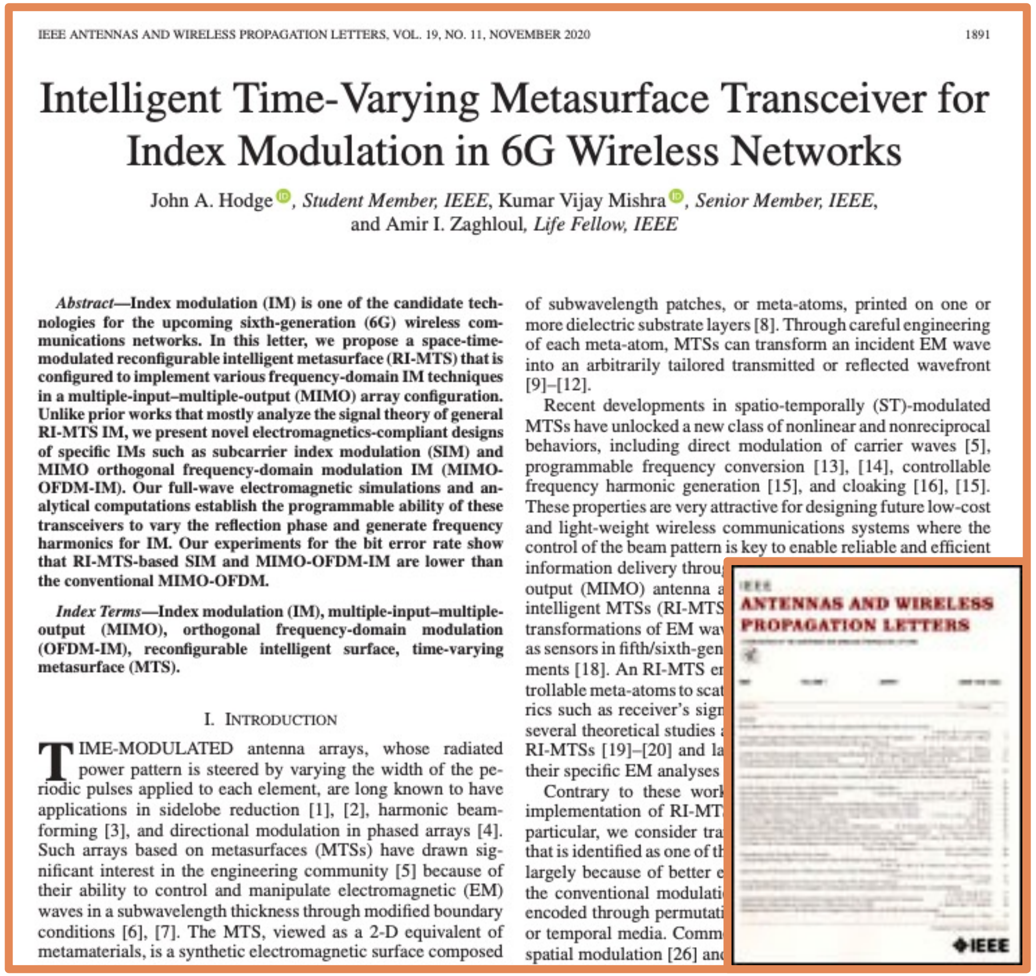
- Introduction & Literature Survey
- Prototype Design, Fabrication, & Measurements
- Metasurfaces for Wireless Communication
- Machine Learning Assisted Metasurface Synthesis
- Summary & Conclusions



(Hodge, Mishra, Zaghloul, 2019)

Contributions

- <u>Journal Publications</u>:
  - *Intelligent time-varying metasurface transceiver for index modulation in 6G wireless networks* (IEEE AWPL, 2020)
  - *Reconfigurable-metasurface-aided multi-state generalized polarization-Space modulation for next-generation wireless communications* (in-revision)
  - *Deep inverse design of reconfigurable metasurfaces for future communications* (in-revision)
  - Deep learning for electromagnetics (invited IEEE Press chapter)
- <u>Student Awards</u>:
  - Student Paper Award Finalist (AP-S Conf., 2014)
  - 2nd Place Student Paper Award (ACES Conf., 2019)
  - 3rd Place Student Paper Award (MLSP Conf., 2019)
  - Student Paper Award Honorable Mention (AP-S Conf., 2021)
- <u>Patent</u>: *Wideband reflectarray using electrically re-focusable phased array feed* (US Patent 10,897,075, 2021)
- <u>Conference Papers</u>: 20+ conference publications including IEEE AP-S, URSI, ICASSP, Asolimar, MLSP, ACES, SPIE, PAST, and GlobalSIP



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Intelligent Time-Varying Metasurface Transceiver for Index Modulation in 6G Wireless Networks

John A. Hodge, *Student Member, IEEE*, Kumar Vijay Mishra, *Senior Member, IEEE*, and Amir I. Zaghloul, *Life Fellow, IEEE*

***Abstract*—Index modulation (IM) is one of the candidate technologies for the upcoming sixth-generation (6G) wireless communications networks. In this letter, we propose a space-time-modulated reconfigurable intelligent metasurface (RI-MTS) that is configured to implement various frequency-domain IM techniques in a multiple-input–multiple-output (MIMO) array configuration. Unlike prior works that mostly analyze the signal theory of general RI-MTS IM, we present novel electromagnetics-compliant designs of specific IMs such as subcarrier index modulation (SIM) and MIMO orthogonal frequency-domain modulation IM (MIMO-OFDM-IM). Our full-wave electromagnetic simulations and analytical computations establish the programmable ability of these transceivers to vary the reflection phase and generate frequency harmonics for IM. Our experiments for the bit error rate show that RI-MTS-based SIM and MIMO-OFDM-IM are lower than the conventional MIMO-OFDM.**

***Index Terms*—Index modulation (IM), multiple-input–multiple-output (MIMO), orthogonal frequency-domain modulation (OFDM-IM), reconfigurable intelligent surface, time-varying metasurface (MTS).**

I. Introduction

TIME-MODULATED antenna arrays, whose radiated power pattern is steered by varying the width of the periodic pulses applied to each element, are long known to have applications in sidelobe reduction [1], [2], harmonic beamforming [3], and directional modulation in phased arrays [4]. Such arrays based on metasurfaces (MTSs) have drawn significant interest in the engineering community [5] because of their ability to control and manipulate electromagnetic (EM) waves in a subwavelength thickness through modified boundary conditions [6], [7]. The MTS, viewed as a 2-D equivalent of metamaterials, is a synthetic electromagnetic surface composed of subwavelength patches, or meta-atoms, printed on one or more dielectric substrate layers [8]. Through careful engineering of each meta-atom, MTSs can transform an incident EM wave into an arbitrarily tailored transmitted or reflected wavefront [9]–[12].

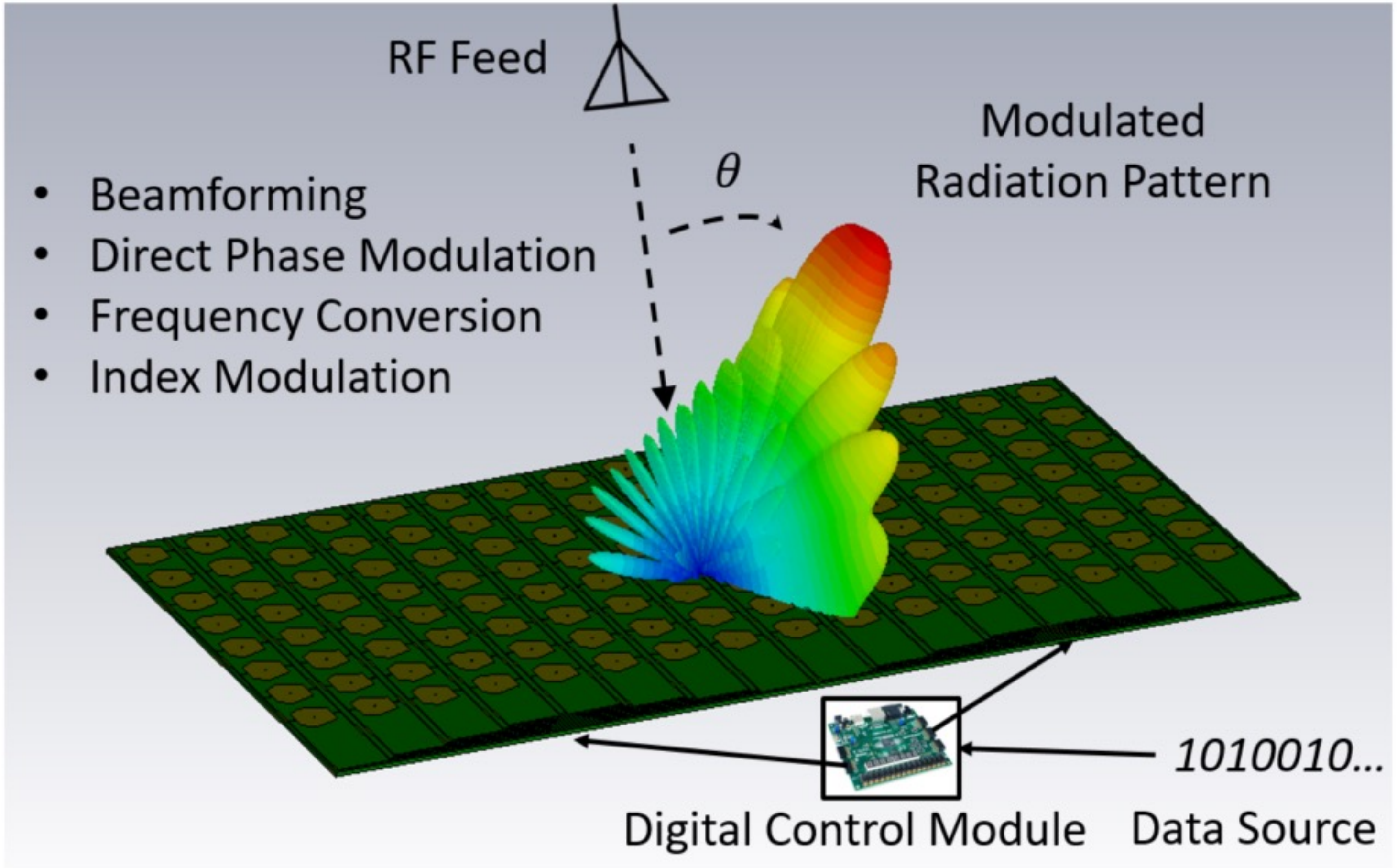
Recent developments in spatio-temporally (ST)-modulated MTSs have unlocked a new class of nonlinear and nonreciprocal behaviors, including direct modulation of carrier waves [5], programmable frequency conversion [13], [14], controllable frequency harmonic generation [15], and cloaking [16], [15]. These properties are very attractive for designing future low-cost and light-weight wireless communications systems where the control of the beam pattern is key to enable reliable and efficient information delivery throu
output (MIMO) antenna a
intelligent MTSs (RI-MTS
transformations of EM wa
as sensors in fifth/sixth-gen
ments [18]. An RI-MTS e
trollable meta-atoms to scat
rics such as receiver's sign
several theoretical studies
RI-MTSs [19]–[20] and la
their specific EM analyses

Contrary to these work
implementation of RI-MT
particular, we consider tra
that is identified as one of th
largely because of better e
the conventional modulati
encoded through permutati
or temporal media. Comm
spatial modulation [26] an

Summary

- Low-cost steerable high-gain aperture
  - Operating at 6 GHz (C-band)
  - Reflect-array configuration
  - 128 element array (16-by-8)
  - Programmable phase coding using PIN diodes
- Reduced size, weight, & power
- Wireless communication, sensing, and localization applications
  - Index modulation (phase, frequency, polarization)
- Innovative ML-assisted metasurface synthesis using cDC-GANs

Reconfigurable intelligent metasurface array



Reconfigurable intelligent metasurfaces are a promising technology for low-cost dynamic antennas in wireless communication and sensing systems

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Thank you!