Creating New Radio Frequency Wave Technology for 6G

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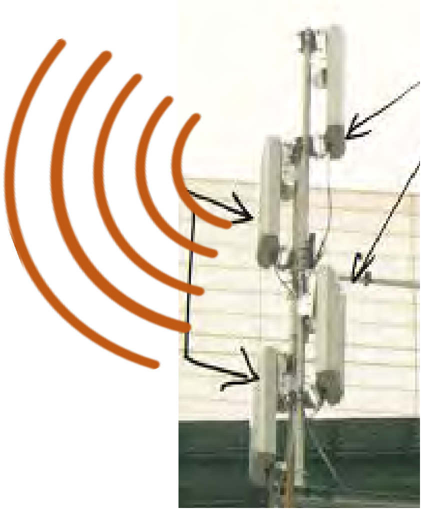
THE HONG KONG
UNIVERSITY OF SCIENCE
AND TECHNOLOGY

The Wireless World Today

Radio

Cellular Systems



TV

Many, many, radio sources everywhere

WiFi

The Wireless "Fog" of RF Waves

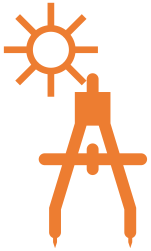
New Resource to be Harnessed

- “Illuminate” its potential with an analogy with sunlight

Camera

Solar energy

Heliostat



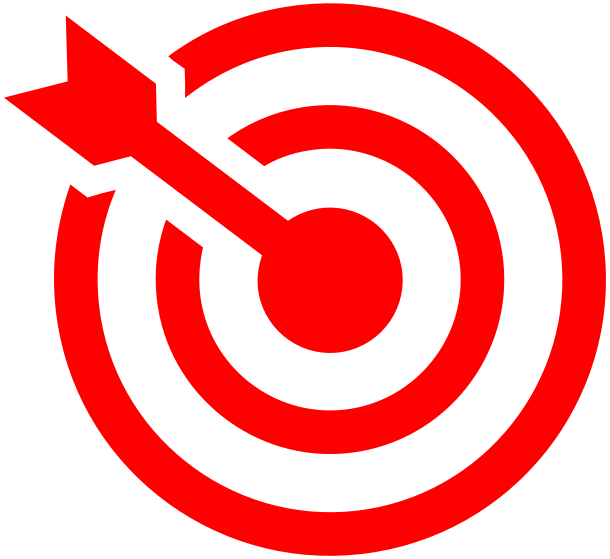
Sextant

Heliograph

- Attempt to do the same and more for RF waves
  - Imaging, communication, signal coverage, navigation, energy harvesting and new applications
  - Provide game changing technologies for multiple industries
    - Wireless communications, Internet of things and smart city for example
  - Creating New RF Wave Technologies: 6G

Talk Target

- Introduce potential electromagnetic technologies for 6G



The talk tells the story of our published research…

1. **A., Dubey S. Deshmukh, L. Pan, X. Chen and R. Murch, "A Phaseless Extended Rytov Approximation for Strongly Scattering Low-Loss Media and Its Application to Indoor Imaging," in *IEEE Transactions on Geoscience and Remote Sensing,* vol. 60, pp. 1-17, 2022, Art no. 2005017.**
2. **A. Dubey, P. Sood, J. Santos, D. Ma, C. -Y. Chiu and R. Murch, "An Enhanced Approach to Imaging the Indoor Environment Using WiFi RSSI Measurements," in *IEEE Transactions on Vehicular Technology*, vol. 70, no. 9, pp. 8415-8430, Sept. 2021.**
3. **A. Dubey, S. Deshmukh, D. Ma, Q. Chen and R. Murch, "Physics Assisted Deep Learning for Indoor Imaging using Phaseless Wi-Fi Measurements," in *IEEE Transactions on Antennas and Propagation*, doi: 10.1109/TAP.2022.3177533.**
4. **S. Deshmukh, A. Dubey and R. Murch, "End-to-end Deep Prior based solution to Non-linear Phaseless Inverse Scattering Problems." Submitted to *IEEE Transactions on Geoscience and Remote Sensing***
5. **P. Sood, A. Dubey, C. Y. Chiu and R. Murch, "Demonstrating Device-free Localization based on Radio Tomographic Imaging," *IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting*, 2020**
6. **J. Rao, Y. Zhang, Shiwen Tang, Zan Li, Shanpu Shen, Chi-Yuk Chiu, and Ross Murch, "A Novel Reconfigurable Intelligent Surface for Wide-Angle Passive Beamforming," in IEEE Transactions on Microwave Theory and Techniques, 2022, doi: 10.1109/TMTT.2022.3195224**
7. **N. K. Kundu, Z. Li, J. Rao, S. Shen, M. R. McKay and R. Murch, "Optimal Grouping Strategy for Reconfigurable Intelligent Surface Assisted Wireless Communications," in IEEE Wireless Communications Letters, vol. 11, no. 5, pp. 1082-1086, May 2022, doi: 10.1109/LWC.2022.3156978.**
8. **S. Shen, B. Clerckx and R. Murch, "Modeling and Architecture Design of Reconfigurable Intelligent Surfaces Using Scattering Parameter Network Analysis," in IEEE Transactions on Wireless Communications, vol. 21, no. 2, pp. 1229-1243, Feb. 2022, doi: 10.1109/TWC.2021.3103256.**
9. **Z. Han, Y. Zhang, S. Shen, Y. Li, C.-Y. Chiu, and R. Murch, “Characteristic mode analysis of ESPAR for single-RF MIMO systems,” IEEE Transactions on Wireless Communications, vol. 20, no. 4, pp. 2353–2367, 2021.**
10. **Y. Zhang, S. Shen, Z. Han, C.-Y. Chiu, and R. Murch, “Compact MIMO Systems Utilizing a Pixelated Surface: Capacity Maximization,” IEEE Transactions on Vehicular Technology, vol. 70, no. 9, pp. 8453-8467, 2021.**
11. **Z. Han, S. Shen, Y. Zhang, C.-Y. Chiu, and R. Murch, “A pattern correlation decomposition method for analysis of ESPAR in single-RF MIMO systems,” IEEE Transactions on Wireless Communications, 2022**
12. **Z. Han, C.-Y. Chiu, and R. Murch, “Investigation of continuous tunable load-modulated MIMO transmitters,” in 2020 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting, 2020, pp. 1469–1470.**
13. **Z. Han, S. Shen, Y. Zhang, S. Tang, C.-Y. Chiu, and R. Murch, “Using Loaded N-Port Structures to Achieve the Continuous-Space Electromagnetic Channel Capacity Bound,” IEEE Transactions on Wireless Communications (ArXiv).**
14. **S. Shen, Y. Zhang, C. -Y. Chiu and R. Murch, "Directional Multiport Ambient RF Energy-Harvesting System for the Internet of Things," in IEEE Internet of Things Journal, vol. 8, no. 7, pp. 5850-5865, 1 April1, 2021, doi: 10.1109/JIOT.2020.3032435.**
15. **W. Liu, S. Shen, D. H. K. Tsang and R. Murch, "Enhancing Ambient Backscatter Communication Utilizing Coherent and Non-Coherent Space-Time Codes," in IEEE Transactions on Wireless Communications, vol. 20, no. 10, pp. 6884-6897, Oct. 2021, doi: 10.1109/TWC.2021.3078051.**
16. **S. Shen, Y. Zhang, C. -Y. Chiu and R. Murch, "A Triple-Band High-Gain Multibeam Ambient RF Energy Harvesting System Utilizing Hybrid Combining," in IEEE Transactions on Industrial Electronics, vol. 67, no. 11, pp. 9215-9226, Nov. 2020, doi: 10.1109/TIE.2019.2952819.**
17. **S. Shen, Y. Zhang, C. -Y. Chiu and R. Murch, "An Ambient RF Energy Harvesting System Where the Number of Antenna Ports is Dependent on Frequency," in IEEE Transactions on Microwave Theory and Techniques, vol. 67, no. 9, pp. 3821-3832, Sept. 2019, doi: 10.1109/TMTT.2019.2906598.**
18. **Y. Zhang, S. Shen, C. Y. Chiu and R. Murch, "Hybrid RF-Solar Energy Harvesting Systems Utilizing Transparent Multiport Micromeshed Antennas," in IEEE Transactions on Microwave Theory and Techniques, vol. 67, no. 11, pp. 4534-4546, Nov. 2019, doi: 10.1109/TMTT.2019.2930507.**
19. **S. Shen, C. -Y. Chiu and R. D. Murch, "A Dual-Port Triple-Band L-Probe Microstrip Patch Rectenna for Ambient RF Energy Harvesting," in IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 3071-3074, 2017, doi: 10.1109/LAWP.2017.2761397.**
20. **Y. Zhang, S. Tang, Z. Han, J. Rao, S. Shen, M. Li, C. Y. Chiu and R. Murch, "A Low-Profile Microstrip Vertically Polarized Endfire Antenna With 360° Beam-Scanning and High Beam-Shaping Capability," (Special Issue) IEEE Transactions on Antennas and Propagation, 2022.**

New RF Wave Technology

- Approach
- RF Imaging
- Reconfigurable Intelligent Surface
- Massive MIMO Antennas
- Ambient RF Energy Harvesting
- Key point summary

Approach

- Develop area holistically
  - Ambient RF waves are a new resource to be harnessed
  - Pursue fundamental research to specifically study
    - Ambient RF wave shaping
    - Ambient RF wave sensing
    - Ambient RF wave characterization

Shape or control the “fog” and we can make use of it for our own purposes

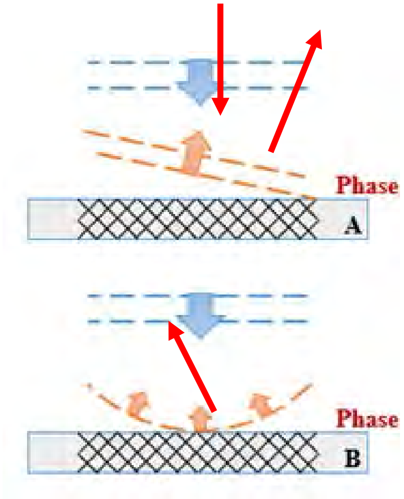
Sense the “fog” and we can estimate the environment its passing through

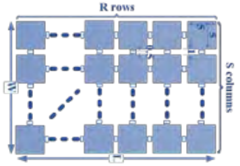
Characterize the “fog” and we can determine its properties and how best to shape and sense it

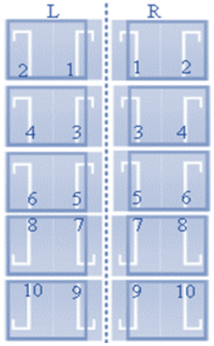
Fundamental building blocks upon which we can create applications

Wave Shaping

- Develop techniques for manipulating ambient RF waves in time, frequency and space
  - Fundamental for communication and enhancing sensing by focusing
- Develop wave shaping using surfaces
  - Metasurfaces made up of meta-atoms
  - Antenna arrays with loaded ports
  - Pixel surfaces with connections
  - Reconfiguration, mutual coupling, bandwidth, phase control, anomalous reflection
- Temporally optimize the surface
  - Determine optimum wave shaping state for applications using channel estimation
- Collaborative effort
  - Wave phenomena and systems cannot be separated



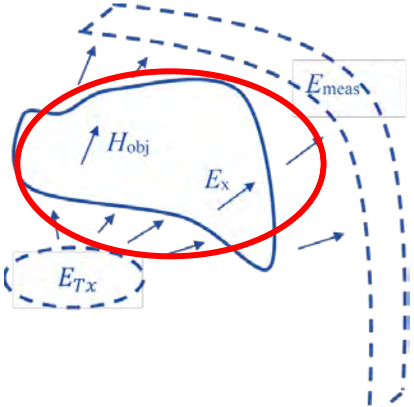




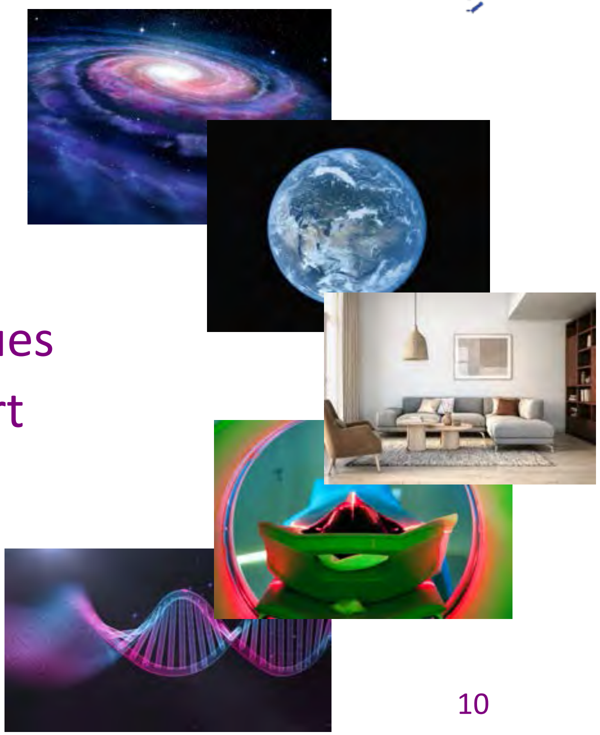
Wave Sensing

- Sense the environment with ambient RF waves
- Detect movement, people, emergencies
- Inverse problem
  - Estimating the environment from scattered measurements

$$\boldsymbol{E}_{meas}(\boldsymbol{r}) = \iiint_B \boldsymbol{H}_{obj}(\boldsymbol{r}')\boldsymbol{E}_x(\boldsymbol{r}')\boldsymbol{g}(\boldsymbol{r},\boldsymbol{r}')d\boldsymbol{V}(\boldsymbol{r}')$$

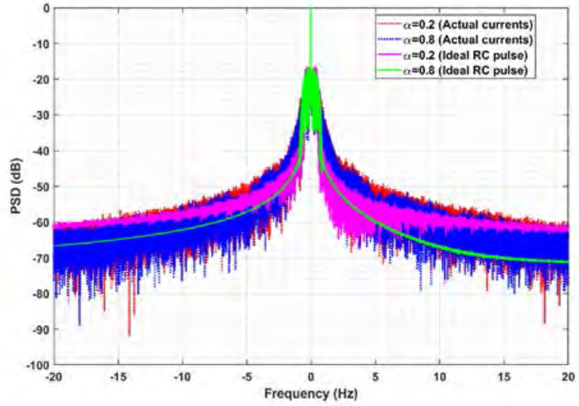


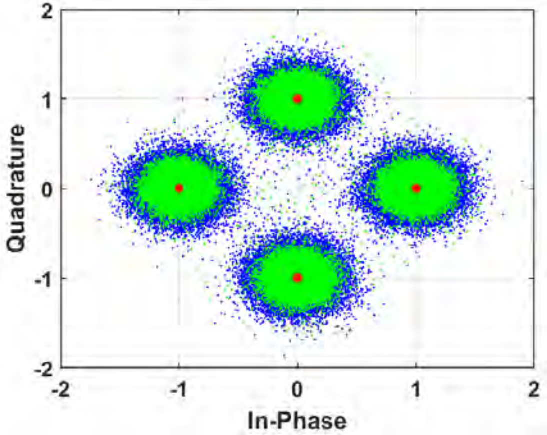
  - Difficult ill-posed problem- both object and wavefield unknown inside
- Difficult scale
  - Between the size scales of established techniques
  - Wavelength in awkward range- not long or short
  - Approximate techniques poor
  - Full electromagnetic techniques limiting



Space-Time Electromagnetic Techniques

- We think of electromagnetic structures existing in 3D space only
    - Static structures such as antennas and even RIS
- However, we can also change the structure with time
    - Dynamic structures that can be thought as being in 4D
    - Change at speeds of 0.1-1 MHz is enough to bring special properties
- Opens up a new dimension in electromagnetics
    - Sidelobe and bandwidth control, analog baseband processing
- Reconfigurable systems are electromagnetic systems that are switched and are time- dynamic
- Reconfiguration is one of the areas that we specialize in and enables space-time electromagnetic structures
- Not a new area but technology can now enable it:
    - Shanks, H.E. and Bickmore, R.W., "Four-dimensional electromagnetic radiators", Canadian Journal of Physics, 1959, Jan, vol 37, 263, doi 10.1139/p59-031





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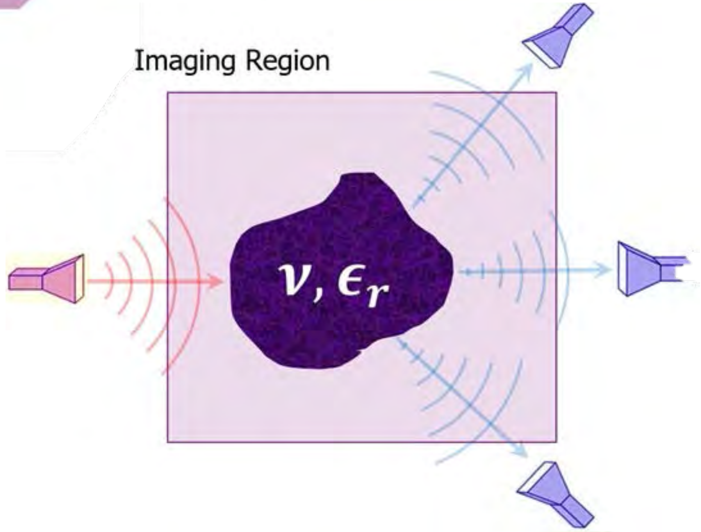
RF Imaging

- Device free
  - Localize, track changes, security,
- Conventional Approach
  - Radar
- Include in 6G as JCAS
  - But it needs a duplexer
  - Cannot directly estimate material properties- only object boundaries

- Can we do better?

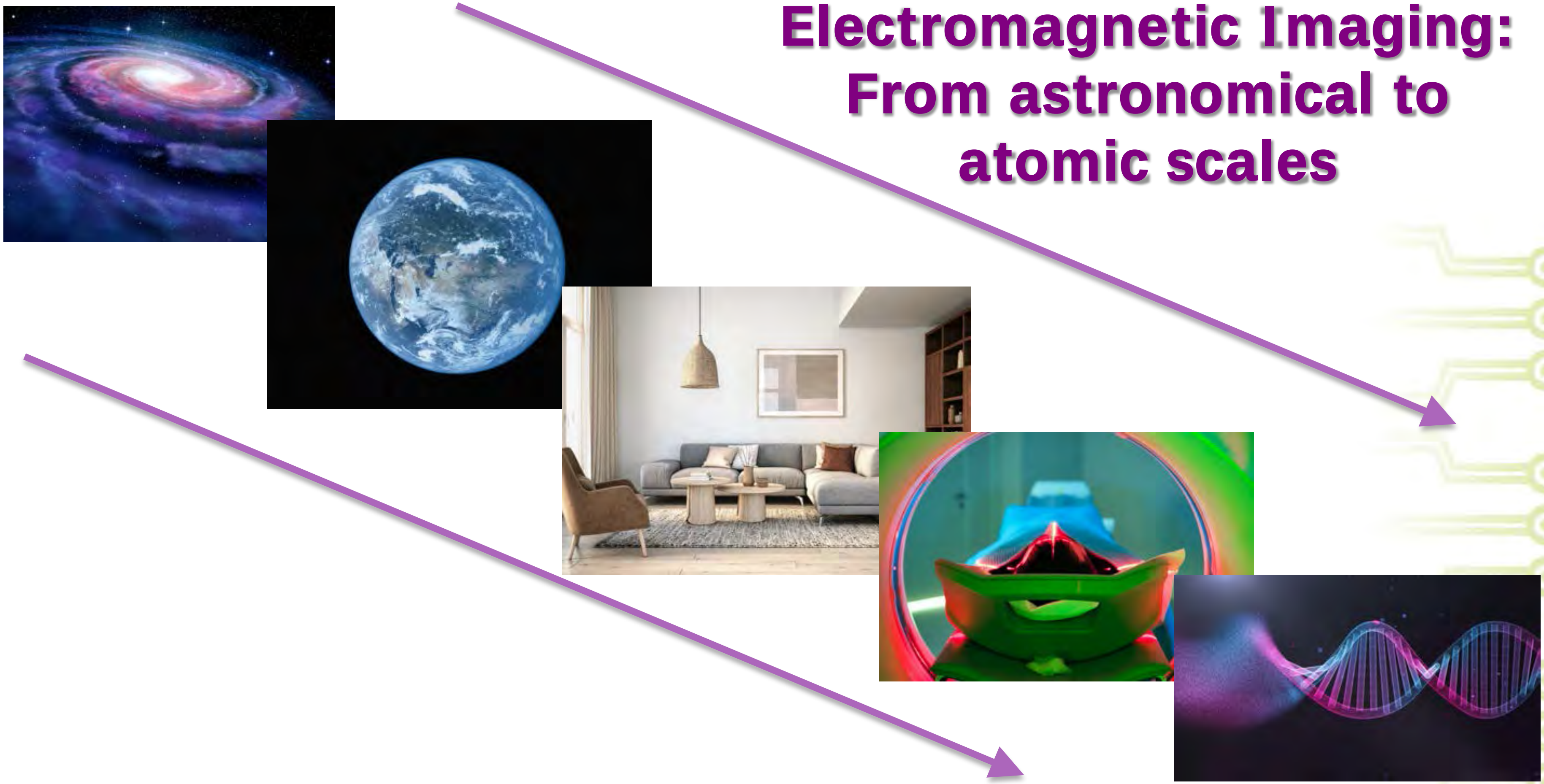
Imaging

- Imaging however is much more general
  - Tomography
  - Radio Tomographic Imaging
  - Diffraction Tomography
  - Inverse Scattering
- Signals passing through the objects contain significant information
- Estimate material type
- No need for duplexers
- Using reflections, such as in radar, are just half the story...



Comparisons with other Techniques

Electromagnetic Imaging:
From astronomical to
atomic scales



Key Objectives

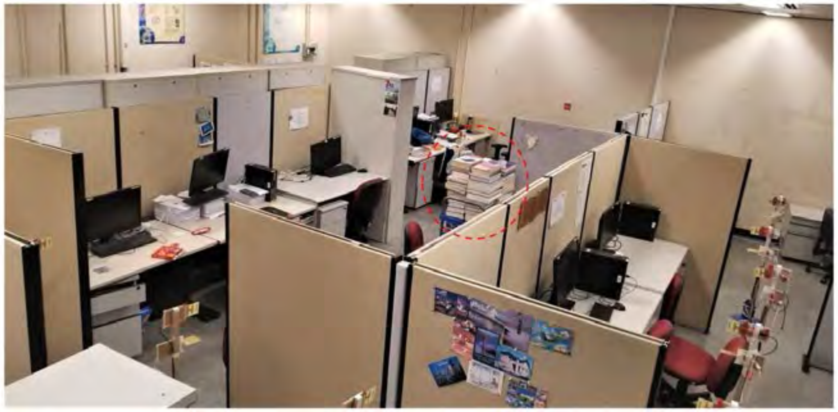
- **Develop phaseless inverse scattering techniques**
  - Low computation
  - High validity for many material types (handle extremely strong scattering and low-loss)
- **Practically Feasible**
  - Simple measurement system (only RSS data)
  - Handle experimental noise
- **Remove multipath reflections from clutter** (such as from walls, ceilings, floors)
- **Perform Indoor Imaging (using Wi-Fi RSS data)**

2D Cross-section Refractive Index Image

Experimental Results

Partially Controlled Indoor Environment

- $3 \times 3\ m^2$ DOI
- Dense clutter outside DOI



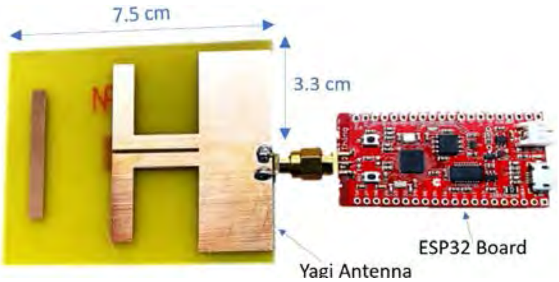
Densely Cluttered Indoor Environment

- $5 \times 5\ m^2$ DOI
- Dense clutter inside & outside DOI (Through-the-wall Imaging)

Standard off-the shelf receivers

SparkFun ESP32 2.4 GHz Wi-Fi transceivers

With Yagi antenna (6.6 dBi)



Experimental Results

Books: $\epsilon_r = 3.4 + 0.25j$

Water-Can: $\epsilon_r = 77 + 7j$

Books: $\epsilon_r = 3.4 + 0.25j$

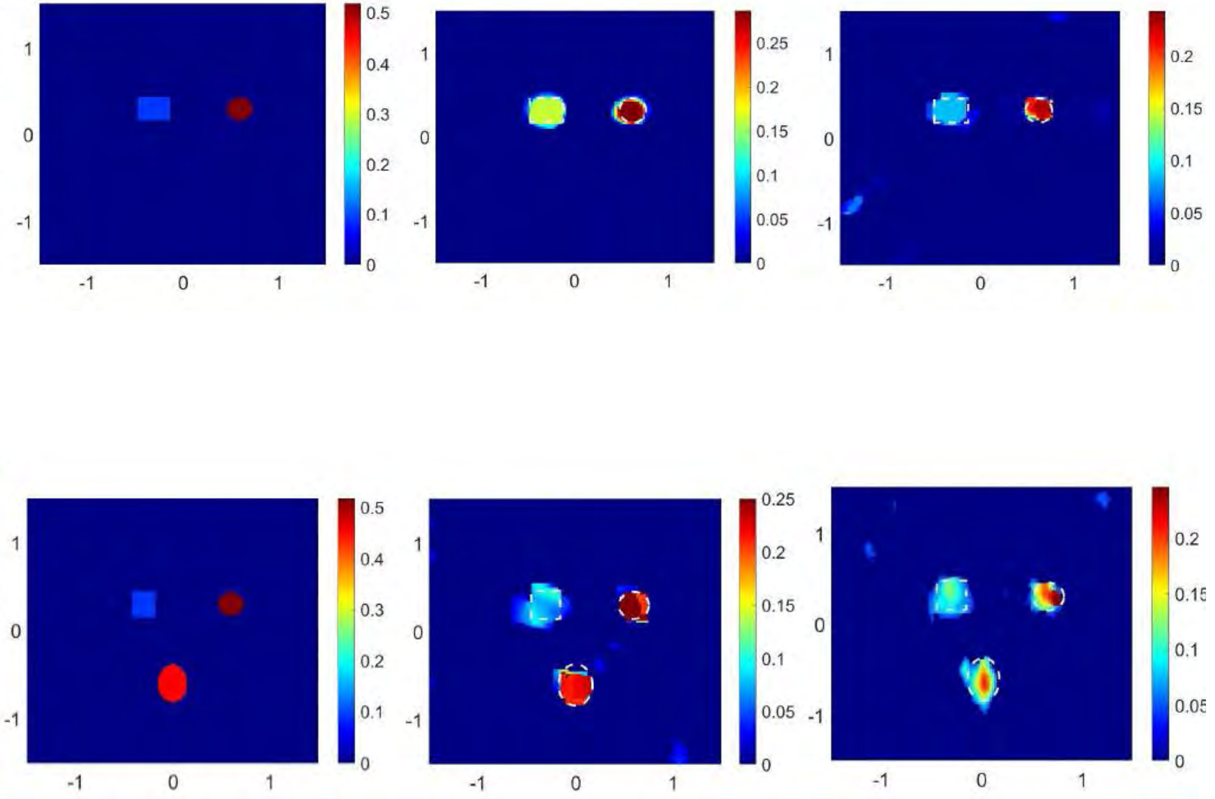
Water-Can: $\epsilon_r = 77 + 7j$

Human body**:** $(10 + 1\mathrm{j}) \leq \epsilon_r \leq (77 + 7j)$

Ground Truth: $\mathrm{Im}(\chi_{\mathrm{RI}})$

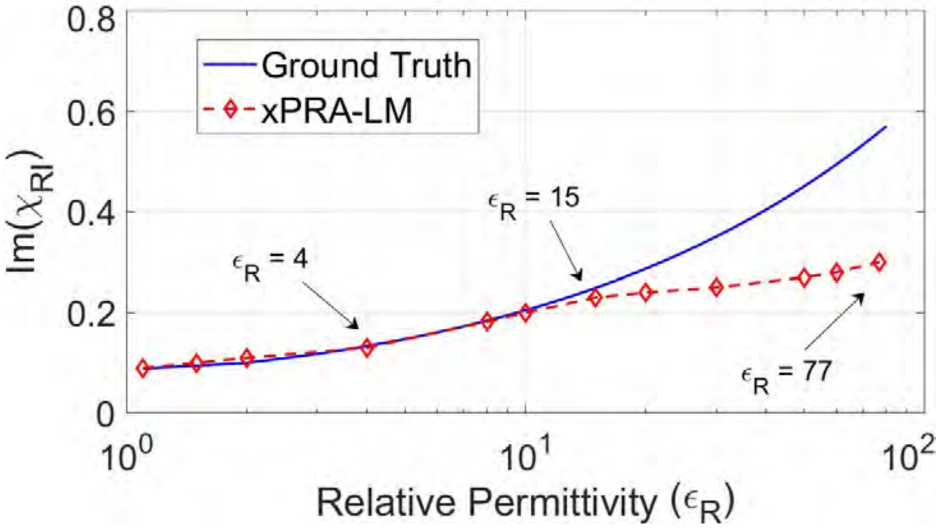
Using simulated data

Using experimental data



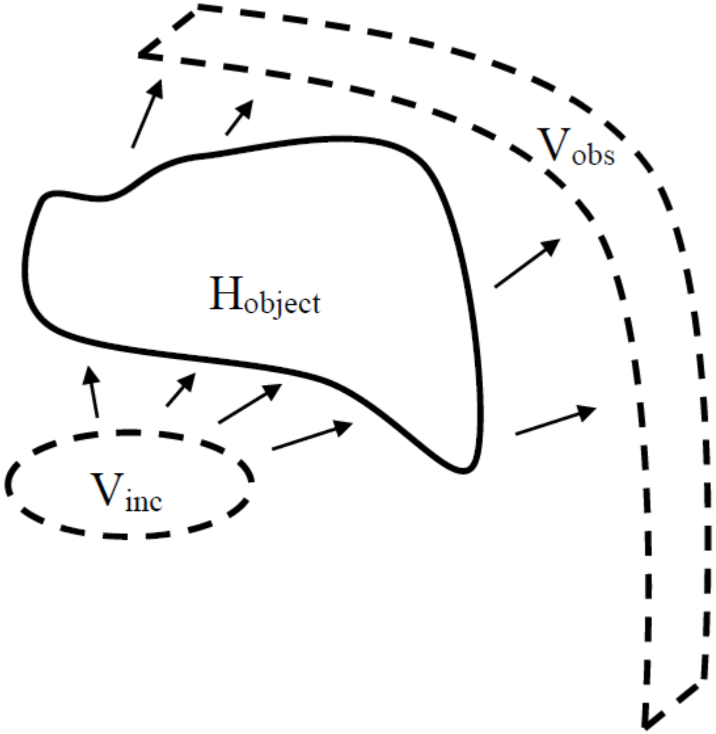
Background Subtraction required

Simulation Results



- Shape reconstruction: $\boldsymbol{\epsilon_r \leq 77}$
- Amplitude reconstruction: $\boldsymbol{\epsilon_r \leq 15}$
- Constraints: **Low-loss**, **piece-wise homogeneous**

Imaging is an Inverse Problem



Direct Problem

$$V_{inc} + Hobject \longrightarrow V_{obs}$$

Inverse Problem

$$V_{inc} + V_{obs} \longrightarrow H_{object}$$

Why it is Difficult?

$$E_{meas}(\boldsymbol{r}) = \iiint_B \boxed{H_{obj}(\boldsymbol{r}')E_x(\boldsymbol{r}')}\, g(\boldsymbol{r},\boldsymbol{r}')dV(\boldsymbol{r}')$$

$$\frac{E(\boldsymbol{r})}{E_i(\boldsymbol{r})} = \exp\left(\frac{k^2}{E_i(\boldsymbol{r})}\int_A g(\boldsymbol{r},\boldsymbol{r'})\Big[\nu(\boldsymbol{r'})^2 - 1 - \nabla\phi_s(\boldsymbol{r'})\cdot\nabla\phi_s(\boldsymbol{r'})\Big]E_i(\boldsymbol{r'})d\boldsymbol{r'}^2\right)$$

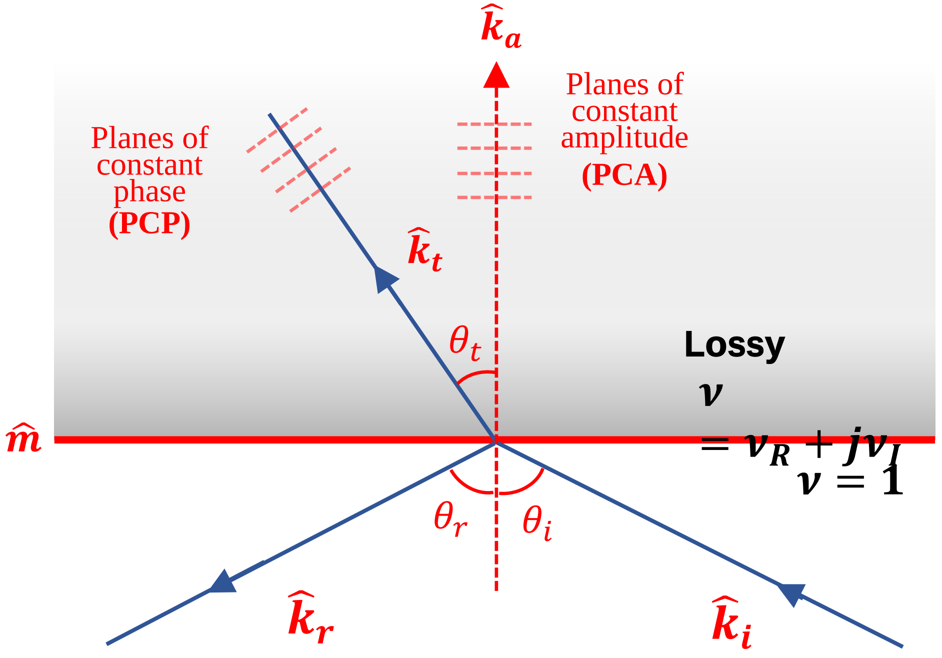
$$P(\boldsymbol{r})[\mathrm{dB}] = P_i(\boldsymbol{r})[\mathrm{dB}] + C_0\cdot\mathrm{Re}\left(\frac{k^2}{E_i(\boldsymbol{r})}\int_A g(\boldsymbol{r},\boldsymbol{r'})\chi_{\mathrm{RI}}(\boldsymbol{r'})E_i(\boldsymbol{r'})d\boldsymbol{r'}^2\right)$$

$$\nabla\phi_s(\boldsymbol{r})\cdot\nabla\phi_s(\boldsymbol{r}) = \Big[V_R^2 + 1 - 2V_R\cos\theta_s - V_I^2 + 2j(V_R V_I\cos\theta_t - V_I\cos\theta_i)\Big] - \frac{1}{k_0^2}(\nabla\tilde{A}\cdot\nabla\tilde{A}) - j\frac{2}{k_0}(\nabla\tilde{A})(V_R\,\hat{\boldsymbol{k}}_{\boldsymbol{t}} - \hat{\boldsymbol{k}}_{\boldsymbol{i}}) + \frac{2}{k_0}(\nabla\tilde{A})V_I\hat{\boldsymbol{k}}_{\boldsymbol{a}}$$

$$\chi_{\mathrm{RI}}(\boldsymbol{r}) = \Bigg(\underbrace{2(\sqrt{\epsilon_R}\cos\theta_s - 1)}_{\mathrm{R}_1} + \underbrace{\frac{1}{k_0^2}(\nabla\tilde{A}\cdot\nabla\tilde{A})}_{\mathrm{R}_2\ \text{(crosstalk)}} - \underbrace{\frac{2}{k_0}(\nabla\tilde{A})V_I\hat{\boldsymbol{k}}_{\boldsymbol{a}}}_{\mathrm{R}_3\ \text{(crosstalk)}}\Bigg) + j\Bigg(\underbrace{\frac{\epsilon_I}{\sqrt{\epsilon_R - \sin^2\theta_i}}\cos\theta_i}_{\mathrm{I}_1} + \underbrace{\frac{2}{k_0}(\nabla\tilde{A})(\nu_R(\boldsymbol{r})\,\hat{\boldsymbol{k}}_{\boldsymbol{t}} - \hat{\boldsymbol{k}}_{\boldsymbol{i}})}_{\mathrm{I}_2\ \text{(crosstalk)}}\Bigg)$$

$$\boxed{\mathrm{Im}(\chi_{\mathrm{RI}}) = \frac{2\epsilon_I}{\pi}\sin^{-1}\left(\frac{1}{\sqrt{\epsilon_R}}\right)}$$

High-frequency Theory Of Inhomogeneous Wave Propagation in Lossy Media



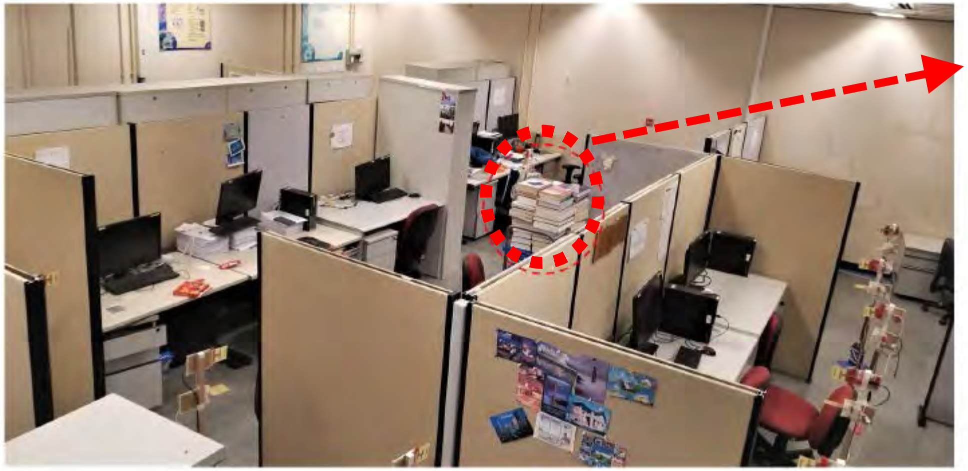
- Conventional Geometrical Optics (GO)

  $$\sin\theta_i = (\nu_R + j\,\nu_I)\sin\theta_t$$

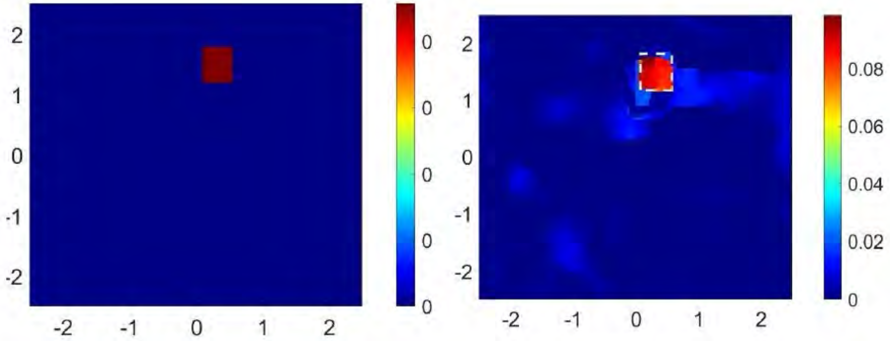
- θ_i and θ_t becomes complex-valued
- Inhomogeneous waves
  - PCP & PCA not parallel
  - Not interpretable using GO become
- Require intuitive reformulation to avoid complex angles

Transmitted Field: $\boldsymbol{k_t} = k_0\left(\underbrace{V_R\,\hat{\boldsymbol{k}}_t + jV_I\hat{\boldsymbol{k}}_a}_{\text{Effective Refractive index}}\right)$

Experimental Results

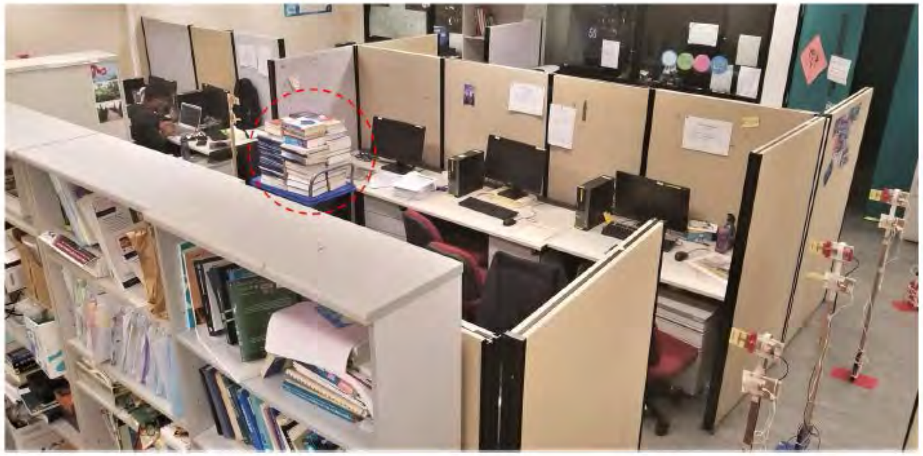


Books: $\boldsymbol{\epsilon_r = 3.4 + 0.25j}$



Ground Truth:
$\mathrm{Im}(\chi_{\mathrm{RI}}) = 0.09$

Reconstruction



Summary

- Developed linear phaseless inverse scattering technique called xPRA-LM
  - A breakthrough technique
- Based on the corrections to Rytov Approximation
- High Validity Range with Linear Formulation
  - Up to 20 times higher validity range!
  - Constraints: Low-loss, piece-wise homogeneous
- Background Subtraction framework
  - Remove multipath reflections from clutter
  - Efficient calibration
- Simulation and Experimental results for Indoor Imaging application (using Wi-Fi RSS data)
- Integrate with 6G

Publications

1. A., Dubey S. Deshmukh, L. Pan, X. Chen and R. Murch, "A Phaseless Extended Rytov Approximation for Strongly Scattering Low-Loss Media and Its Application to Indoor Imaging," in ***IEEE Transactions on Geoscience and Remote Sensing,*** vol. 60, pp. 1-17, 2022, Art no. 2005017.
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New RF Wave Technology

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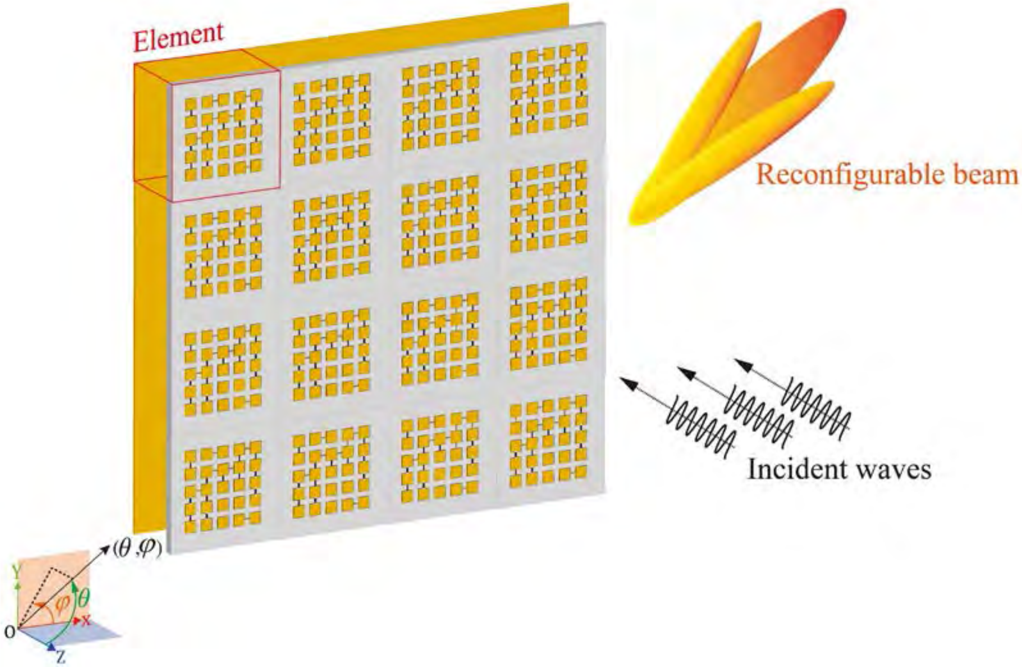
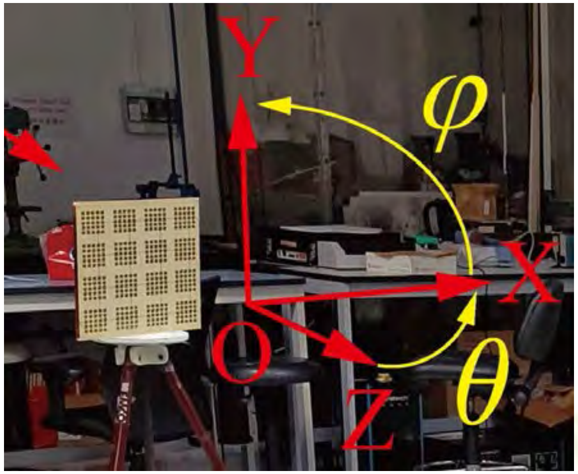
- Reconfigurable Intelligent Surface
- Electromagnetic Information Theory
- Ambient RF Energy Harvesting
- Key point summary

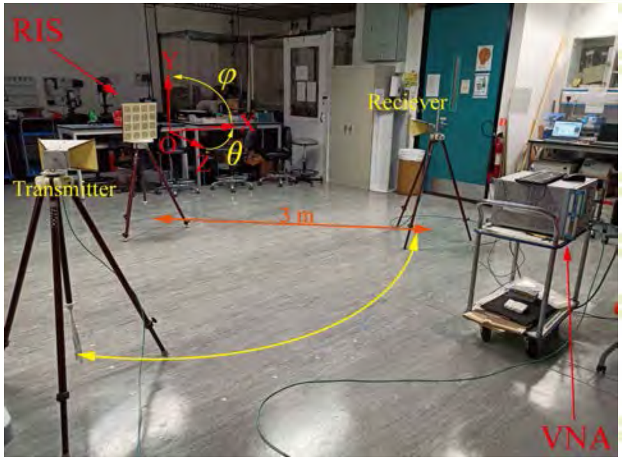
Reconfigurable Intelligent Surfaces

- Enormous number of system results
- Less knowledge of practical feasibility and the design limitations
- We explore the development of an RIS
- Because they are reconfigurable they can also be utilized as a space-time electromagnetic structure

Prototype







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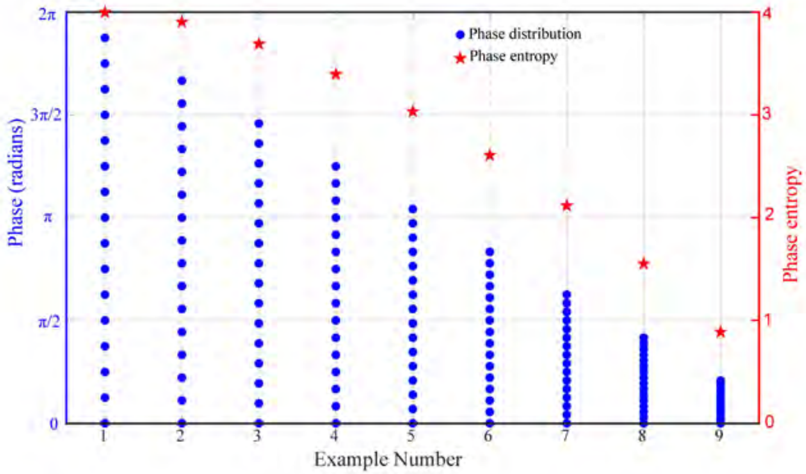
Our Design Goal- Phase

- Control phase across surface
  - Q bit control of each element

$$\begin{cases} \Delta\varphi_i = \varphi_{i+1} - \varphi_i, & 1 \leqslant i < 2^Q \\ \Delta\varphi_i = 2\pi + \varphi_1 - \varphi_i, & i = 2^Q \end{cases}$$

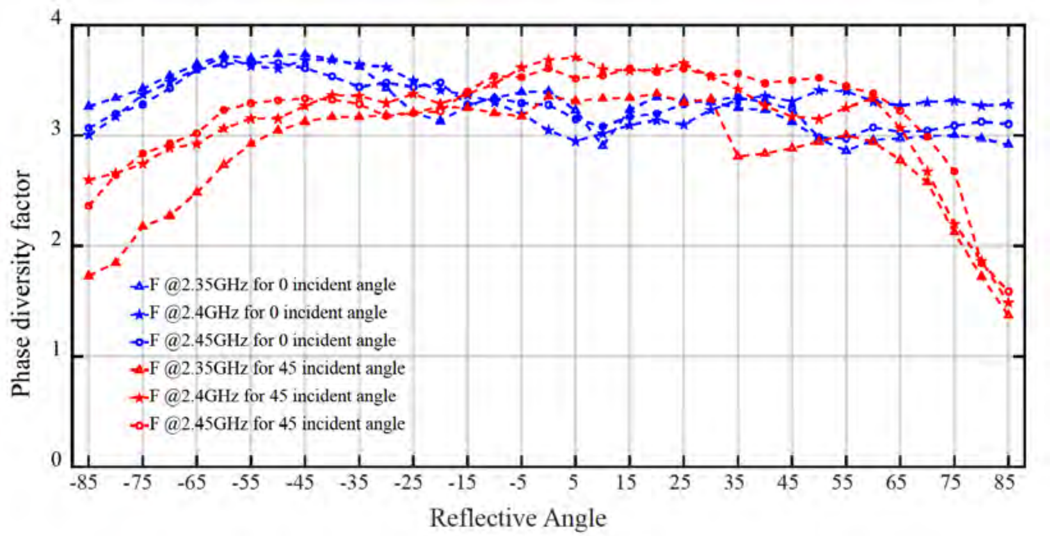
- Define phase entropy

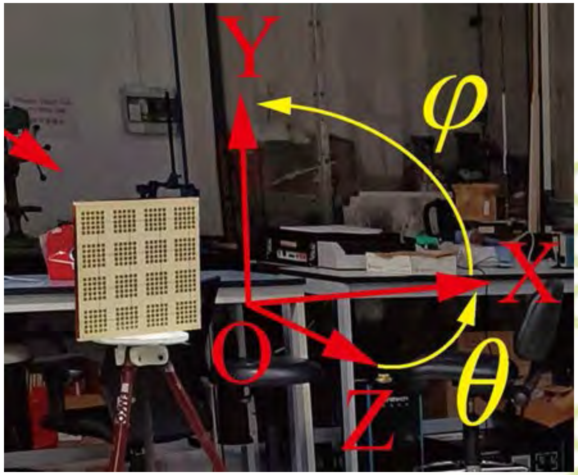
$$H(\Omega_{\text{inc}}, \Omega_s, f, \bar{\mathbf{x}}) = -\sum_{i=1}^{2^Q}\left(\frac{\Delta\varphi_i}{2\pi}\log_2\left(\frac{\Delta\varphi_i}{2\pi}\right)\right)$$



Our Design Goal- Phase

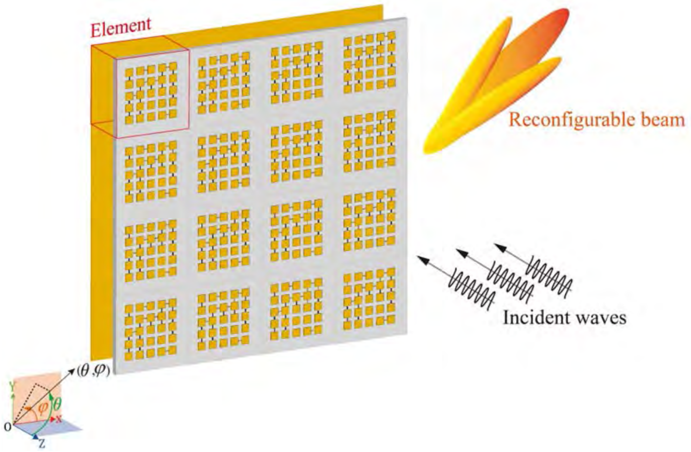
- But needs to be good for wide frequency range and wide incident and reflection angles

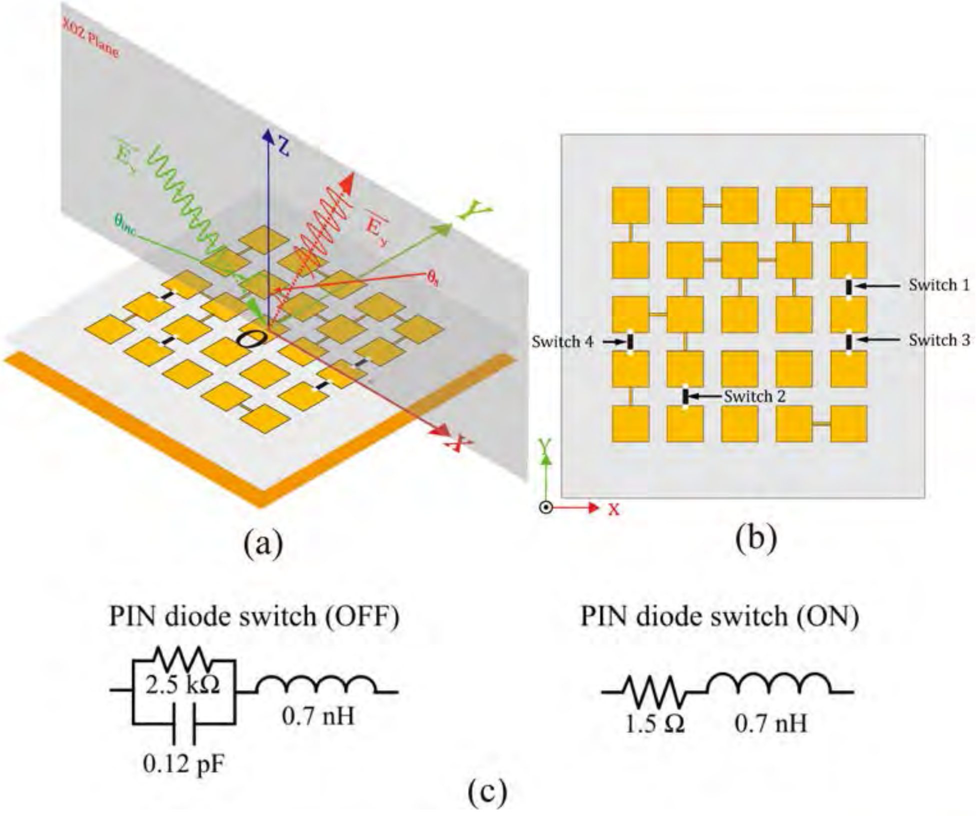




$$H(\bar{\mathbf{x}}) = \frac{1}{\mathrm{NKL}} \sum_{n=1}^{N} \sum_{k=1}^{K} \sum_{l=1}^{L} H\left(\Omega_{\mathrm{inc},n}, \Omega_k, f_l, \bar{\mathbf{x}}\right)$$

Element Structure

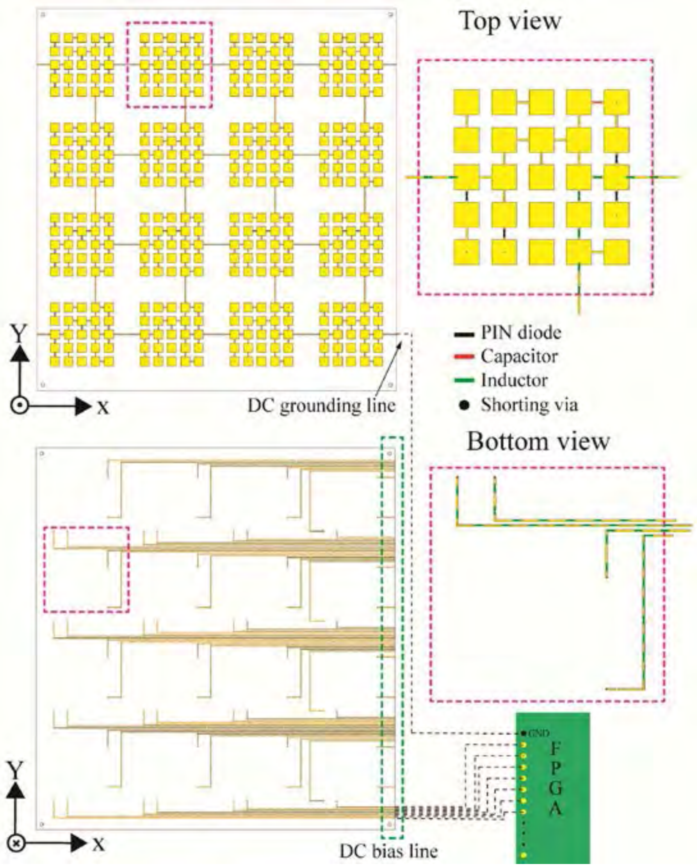


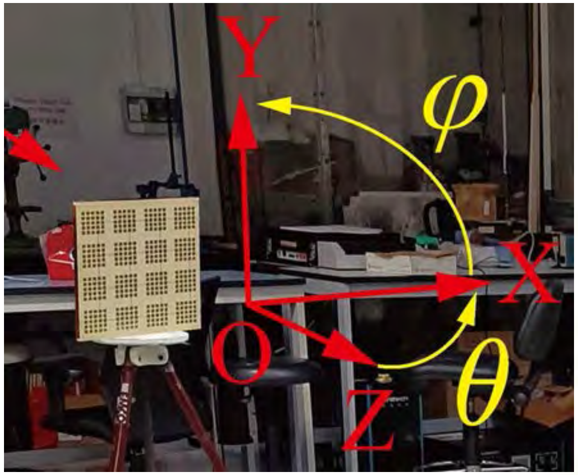


(a) (b)

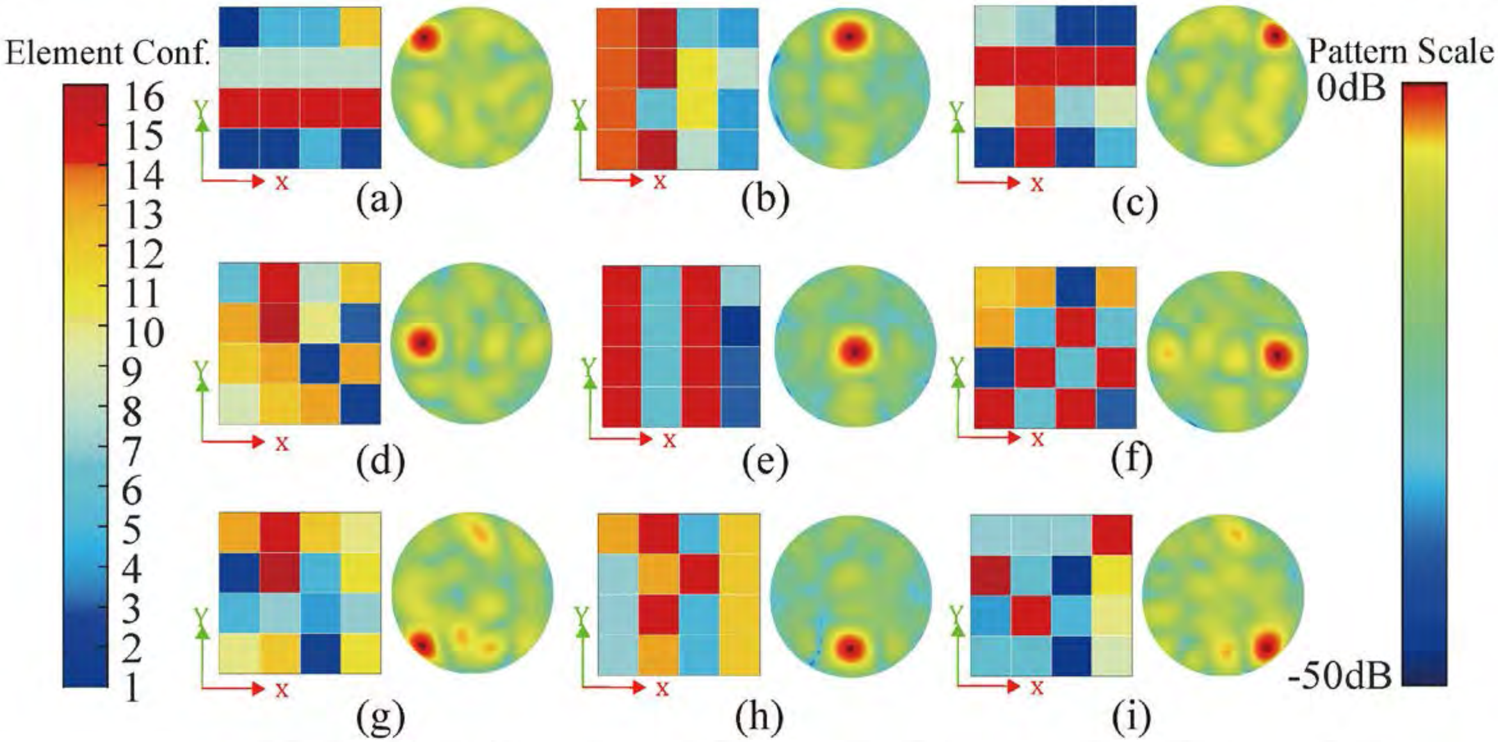
(c)

Design details



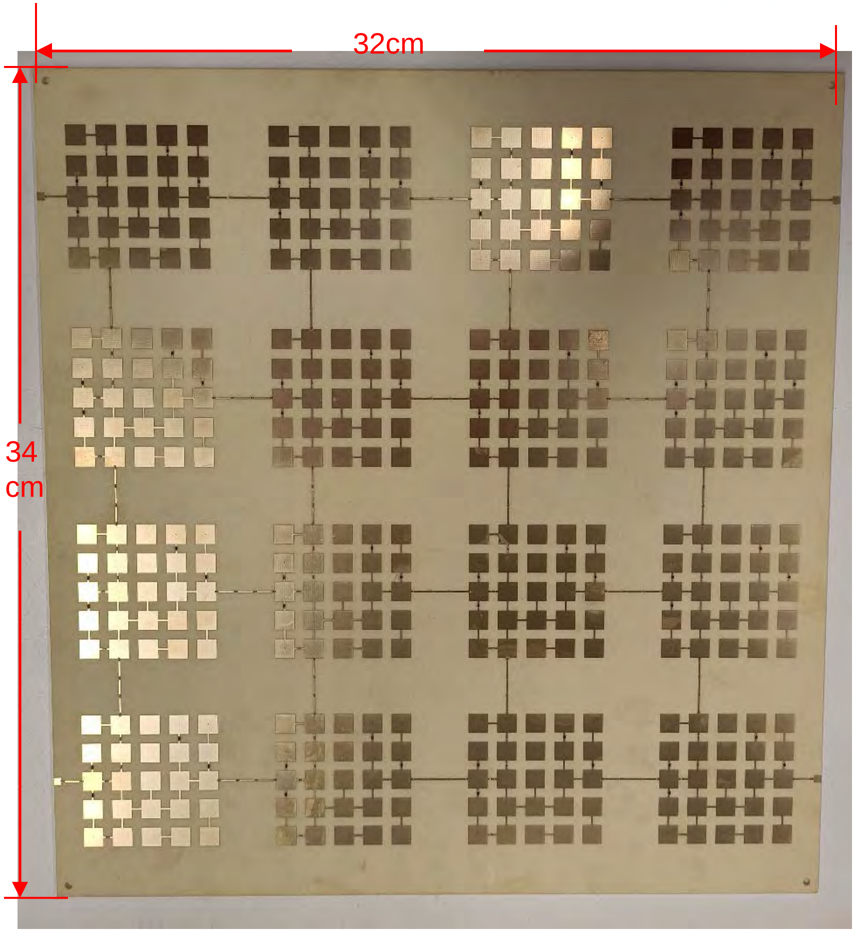


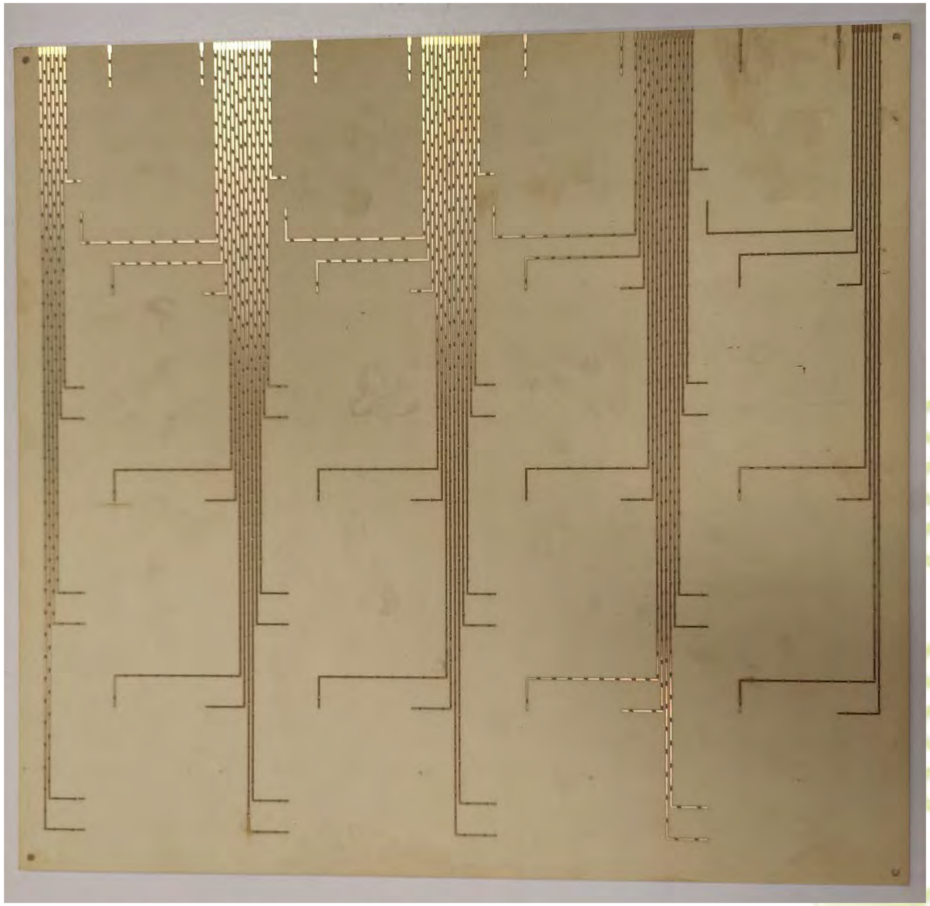
Simulations



Nine examples of the simulated normalized scattered wave pattern and RF switch configurations for 2.4 GHz when θ_{inc} is 45° when the main beam has been optimized to steer to (a) $(\theta, \phi)_{\text{beam}} = (50°, 315°)$, (b) $(\theta, \phi)_{\text{beam}} = (40°, 0°)$, (c) $(\theta, \phi)_{\text{beam}} = (50°, 45°)$, (d) $(\theta, \phi)_{\text{beam}} = (40°, 270°)$, (e) $(\theta, \phi)_{\text{beam}} = (0°, 0°)$, (f) $(\theta, \phi)_{\text{beam}} = (40°, 90°)$, (g) $(\theta, \phi)_{\text{beam}} = (50°, 225°)$, (h) $(\theta, \phi)_{\text{beam}} = (40°, 180°)$, and (i) $(\theta, \phi)_{\text{beam}} = (50°, 135°)$.

Fabrication of the RIS





Summary

- Prototyped an RIS that is proven to operate over wide angles and WiFi frequency band while maintain 16-bit phase control
- Spatial Modulation and precoding
- Meta-surface structures
- What type of wave forming required
- Transparent antennas
- How to integrate in the everyday environment

Publications

1. J. Rao, Y. Zhang, Shiwen Tang, Zan Li, Shanpu Shen, Chi-Yuk Chiu, and Ross Murch, "A Novel Reconfigurable Intelligent Surface for Wide-Angle Passive Beamforming," in IEEE Transactions on Microwave Theory and Techniques, 2022, doi: 10.1109/TMTT.2022.3195224
2. N. K. Kundu, Z. Li, J. Rao, S. Shen, M. R. McKay and R. Murch, "Optimal Grouping Strategy for Reconfigurable Intelligent Surface Assisted Wireless Communications," in IEEE Wireless Communications Letters, vol. 11, no. 5, pp. 1082-1086, May 2022, doi: 10.1109/LWC.2022.3156978.
3. S. Shen, B. Clerckx and R. Murch, "Modeling and Architecture Design of Reconfigurable Intelligent Surfaces Using Scattering Parameter Network Analysis," in IEEE Transactions on Wireless Communications, vol. 21, no. 2, pp. 1229-1243, Feb. 2022, doi: 10.1109/TWC.2021.3103256.

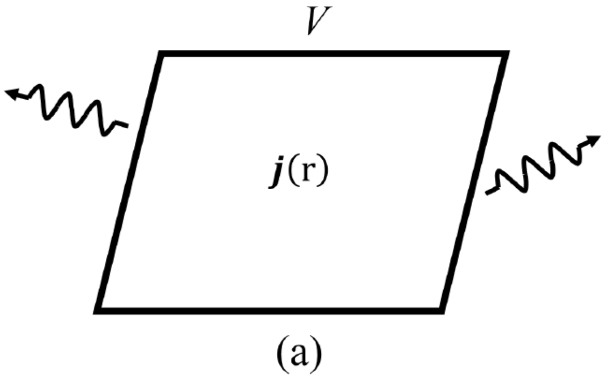
New RF Wave Technology

- Approach
- RF Imaging
- Reconfigurable Intelligent Surface
- Electromagnetic Information Theory
- Ambient RF Energy Harvesting
- Key point summary

Electromagnetic Information Theory (EIT)

- Joint study and optimization for electromagnetic wireless communication system
- Maximizing channel capacity provided by antenna systems restricted to a given volume or area

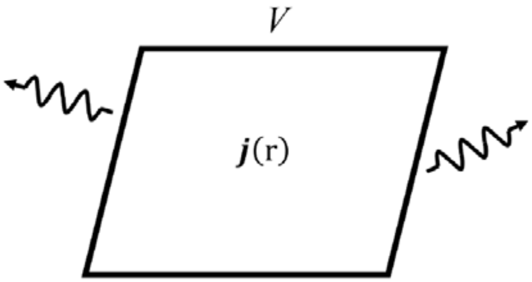
1. Continuous current sources are analyzed without providing method of antenna design



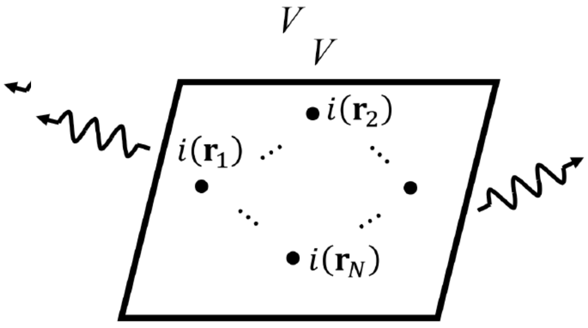
2. Antenna design with decoupling method has no link with continuous-space approach

- Link continuous-space electromagnetic channel capacity bound to MIMO antenna design

Electromagnetic Information Theory (EIT)



(a)



(b)

- Continuous-space electromagnetic (EM) channel
  - Consider continuous current distribution $\mathbf{j}(\vec{\mathbf{r}})$ confined to volume V
  - Maximizing capacity with proper $\mathbf{j}(\vec{\mathbf{r}})$ and channel to achieve continuous-space EM channel capacity bound
  - Challenge: designing MIMO antenna (discrete ports) that can best approximate $\mathbf{j}(\vec{\mathbf{r}})$

- Loaded N-port structure
  - Discretizing given volume by a certain number of ports
  - Enable to form any current distribution to achieve capacity bound by
    - Setting ports with small separation (e.g. less than 0.1 wavelength)
    - Utilizing proper reactive loads
  - Enable discrete feeds required in MIMO antenna design

Channel Capacity Formulation

1. Capacity with radiated power constraint

$$\max_{\mathbf{R}_\beta} \quad \log_2 \left| \mathbf{U}_M + \frac{\mathbf{H}_{\text{iid}}\mathbf{R}_\beta\mathbf{H}_{\text{iid}}^H}{\sigma^2} \right|$$

$$\text{s.t.} \quad \text{Tr}\left(\mathbf{R}_\beta\right) \leqslant P_{\text{rad}}.$$

- The same as capacity optimization problem of ideal MIMO.
- Current norm is unconstrained

2. Capacity with current constraint

$$\max_{\mathbf{R}_\gamma} \quad \log_2 \left| \mathbf{U}_M + \frac{\mathbf{H}_{\text{iid}}\Lambda^{\frac{1}{2}}\mathbf{R}_\gamma\Lambda^{\frac{1}{2}}\mathbf{H}_{\text{iid}}^H}{\sigma^2} \right|$$

$$\text{s.t.} \quad \text{Tr}\left(\mathbf{R}_\gamma\right) \leqslant I_{\text{in}}^2.$$

- The radiated power of each basis in is not equal and proportional to the corresponding eigenvalues
- Radiated power is unconstrained

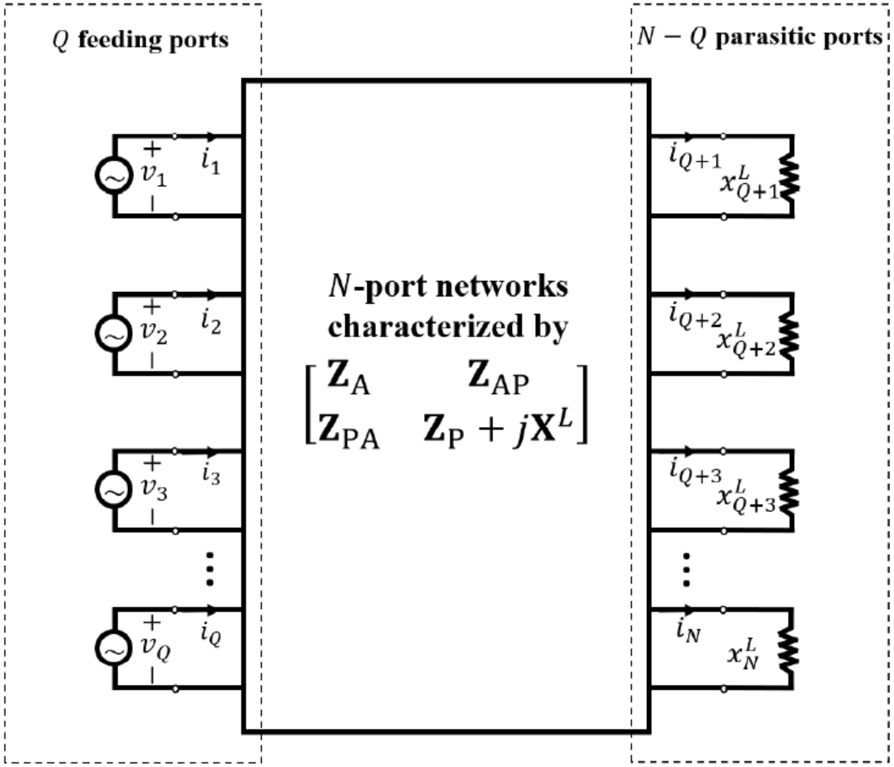
3. Capacity with dual constraint

- Solve EADoF by performing equal power (EP) allocation to first N_{eff} basis and define $\epsilon = \frac{I_{\text{in}}^2}{P_{\text{rad}}}$

$$\sum_{i=1}^{N_{\text{eff}}} \frac{\lambda_i^{-1}}{N_{\text{eff}}} \leqslant \epsilon$$

- Equal Power (EP) Allocation (for first P basis)

Loaded N-port Structure Analysis



- Formulation of N-port network

$$\begin{bmatrix} \mathbf{v}_\mathrm{A} \\ \mathbf{v}_\mathrm{P} \end{bmatrix} = \begin{bmatrix} \mathbf{Z}_\mathrm{A} & \mathbf{Z}_\mathrm{AP} \\ \mathbf{Z}_\mathrm{PA} & \mathbf{Z}_\mathrm{P} + j\mathbf{X}^L \end{bmatrix} \begin{bmatrix} \mathbf{i}_\mathrm{A} \\ \mathbf{i}_\mathrm{P} \end{bmatrix}$$

- Radiation patterns for Q feeding ports

$$\mathbf{E}_T\left(\Omega, \mathbf{X}^L\right) = \mathbf{E}_\mathrm{A}(\Omega) - \mathbf{E}_\mathrm{P}(\Omega)\left(\mathbf{Z}_\mathrm{P} + j\mathbf{X}^L\right)^{-1}\mathbf{Z}_\mathrm{PA}$$

- Defining correlation coefficient

$$\rho_{jk}\left(\mathbf{X}^L\right) = \frac{\left\langle \mathbf{e}_{T,j}\left(\Omega, \mathbf{X}^L\right), \mathbf{e}_{T,k}\left(\Omega, \mathbf{X}^L\right)\right\rangle}{\left\|\mathbf{e}_{T,j}\left(\Omega, \mathbf{X}^L\right)\right\| \left\|\mathbf{e}_{T,k}\left(\Omega, \mathbf{X}^L\right)\right\|}$$

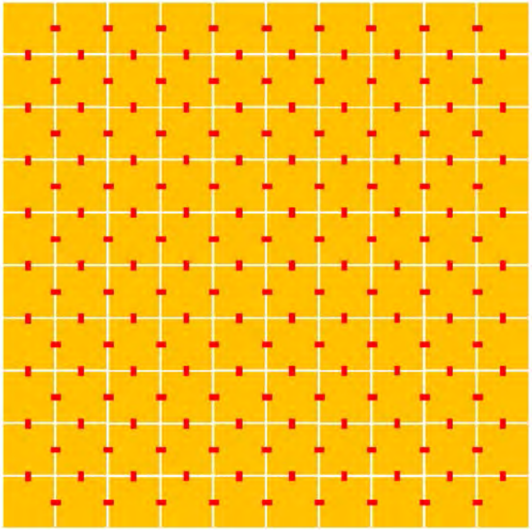
- Formulating the optimization problem as

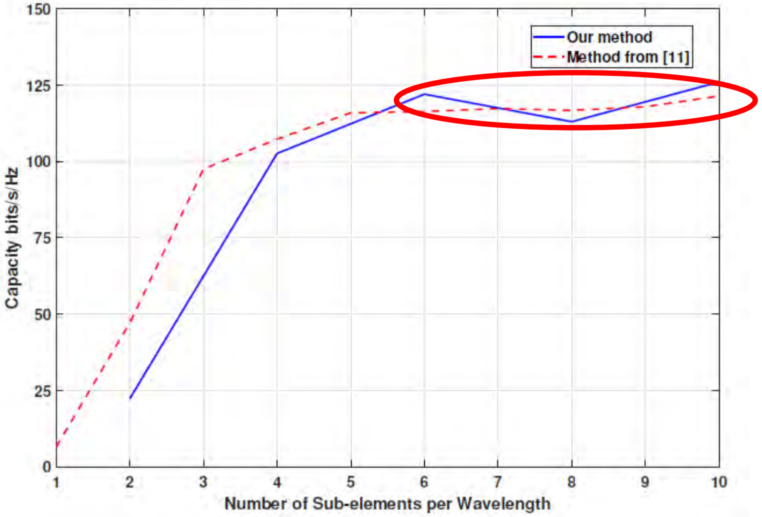
$$\min_{\mathcal{P}, \mathbf{X}^L} \sum_{k\in\mathcal{P}} \sum_{j\in\mathcal{P}}^{j\neq k} \left|\rho_{jk}\left(\mathbf{X}^L\right)\right|$$

- Solving by alternating optimization

Numerical Simulation

- Comparison with previous work
  - 2D PAS, single polarization, Rayleigh fading channel, current constraint, $1\lambda^2$ size PEC



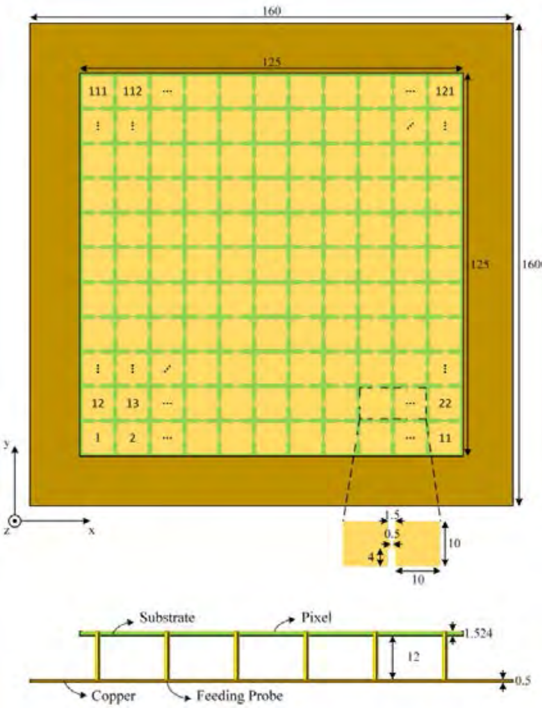


  - By using our method, the system capacity approaches that using the method in [11] when the number of sub-elements per wavelength is more than four.

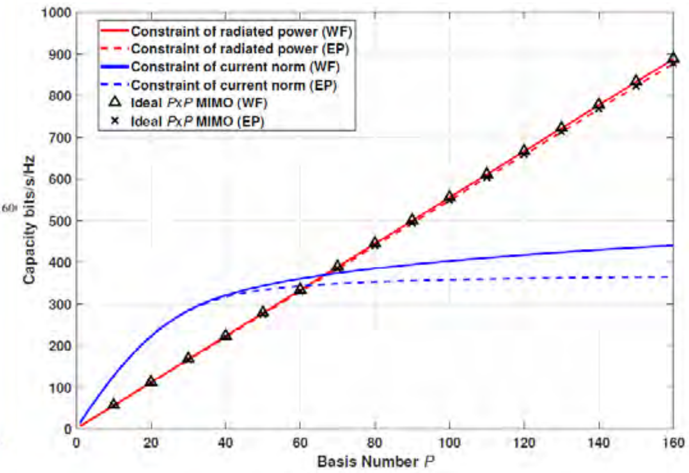
- [11] M. A. Jensen and J. W. Wallace, "Capacity of the continuous-space electromagnetic channel," IEEE Trans. Antennas Propag., vol. 56, no. 2, pp. 524–531, 2008.

Numerical Simulation

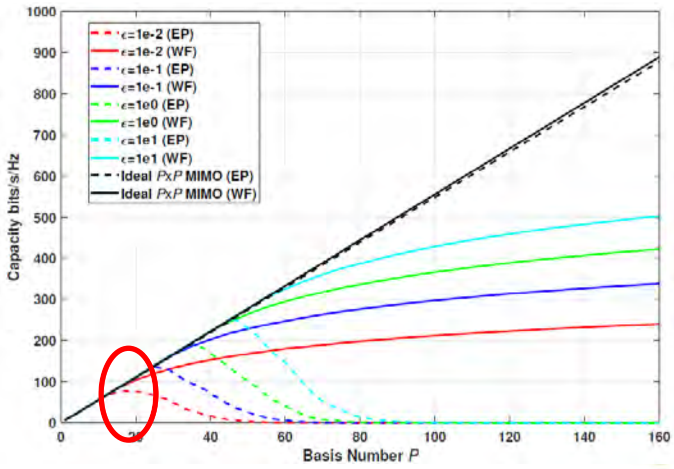
- Antenna Design and capacity bound



➢ Individual constraint



➢ Dual constraints



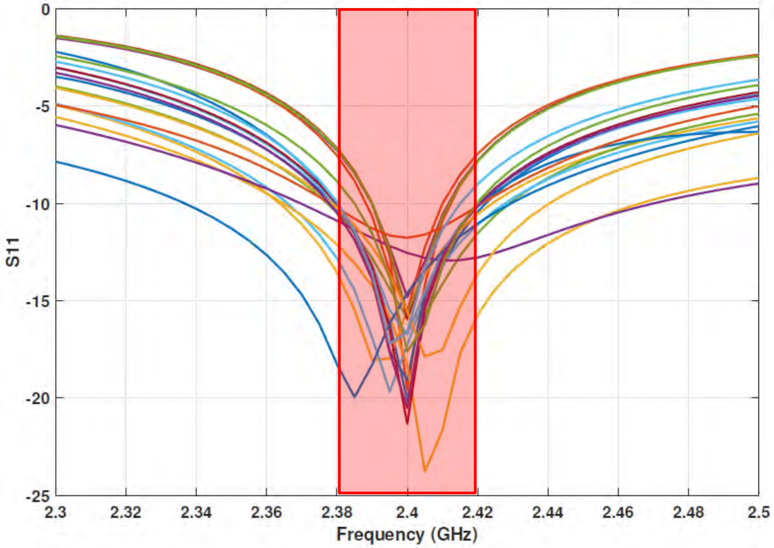
- Same capacity as ideal MIMO when with radiated power constraint
- Higher capacity for first 50 basis when with current constraint

- 18 ports can be supported when

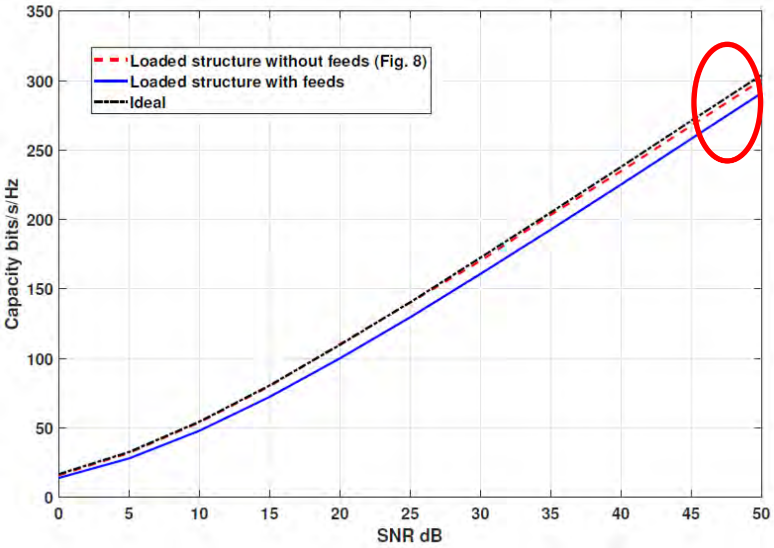
$$\epsilon = I_{\text{in}}^2 / P_{\text{rad}} = 1/Z_{\text{in}} = 0.02$$

Numerical Simulation

- MIMO antenna design results for 20x20 MIMO System
  - S-parameters



  - System Capacity



- Bandwidth is around 40 MHz with extra T or Π-type matching network for each port
- MIMO antenna using the loaded structure with 20 feeds achieves performance close to ideal MIMO

Summary

- We propose a novel method for designing antennas that approach the continuous-space electromagnetic channel capacity bounds.
- Cosed-form expressions for the channel capacity limits using a beamspace channel model with various constraints are derived.
- We also show that at least 18 ports can be supported in a one wavelength square structure to achieve the continuous-space electromagnetic channel capacity bound.

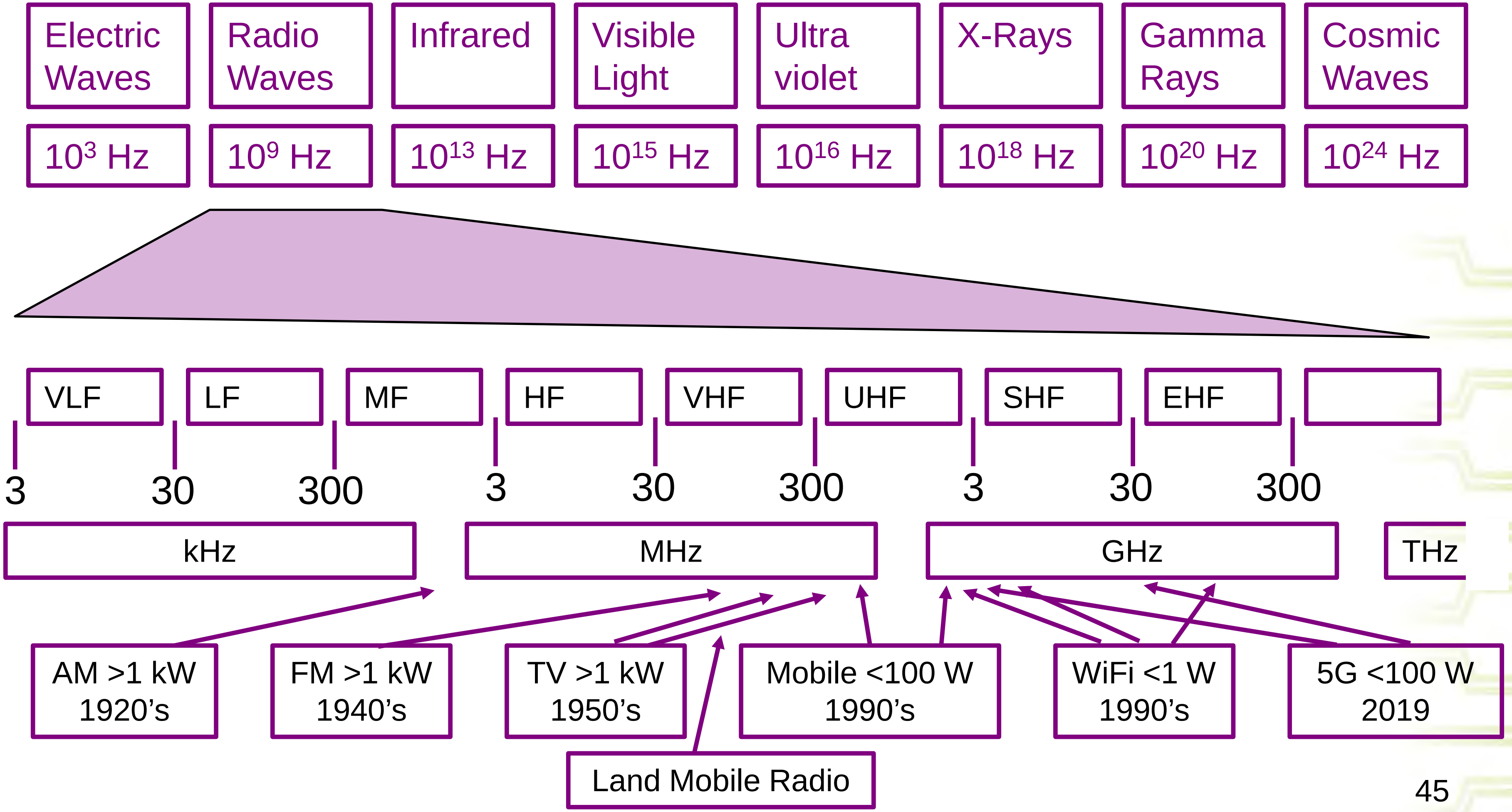
Publications

1. Z. Han, Y. Zhang, S. Shen, Y. Li, C.-Y. Chiu, and R. Murch, “Characteristic mode analysis of ESPAR for single-RF MIMO systems,” IEEE Transactions on Wireless Communications, vol. 20, no. 4, pp. 2353–2367, 2021.
2. Y. Zhang, S. Shen, Z. Han, C.-Y. Chiu, and R. Murch, “Compact MIMO Systems Utilizing a Pixelated Surface: Capacity Maximization,” IEEE Transactions on Vehicular Technology, vol. 70, no. 9, pp. 8453-8467, 2021.
3. Z. Han, S. Shen, Y. Zhang, C.-Y. Chiu, and R. Murch, “A pattern correlation decomposition method for analysis of ESPAR in single-RF MIMO systems,” IEEE Transactions on Wireless Communications, 2022
4. Z. Han, C.-Y. Chiu, and R. Murch, “Investigation of continuous tunable load-modulated MIMO transmitters,” in 2020 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting, 2020, pp. 1469–1470.
5. Z. Han, S. Shen, Y. Zhang, S. Tang, C.-Y. Chiu, and R. Murch, “Using Loaded N-Port Structures to Achieve the Continuous-Space Electromagnetic Channel Capacity Bound,” IEEE Transactions on Wireless Communications (ArXiv).

New RF Wave Technology

- Approach
- RF Imaging
- Reconfigurable Intelligent Surface
- Electromagnetic Information Theory
- Ambient RF Energy Harvesting ←
- Key point summary

The Electromagnetic Spectrum



Electric Waves	Radio Waves	Infrared	Visible Light	Ultra violet	X-Rays	Gamma Rays	Cosmic Waves
10^3 Hz	10^9 Hz	10^{13} Hz	10^{15} Hz	10^{16} Hz	10^{18} Hz	10^{20} Hz	10^{24} Hz

AM >1 kW
1920’s

FM >1 kW
1940’s

TV >1 kW
1950’s

Mobile <100 W
1990’s

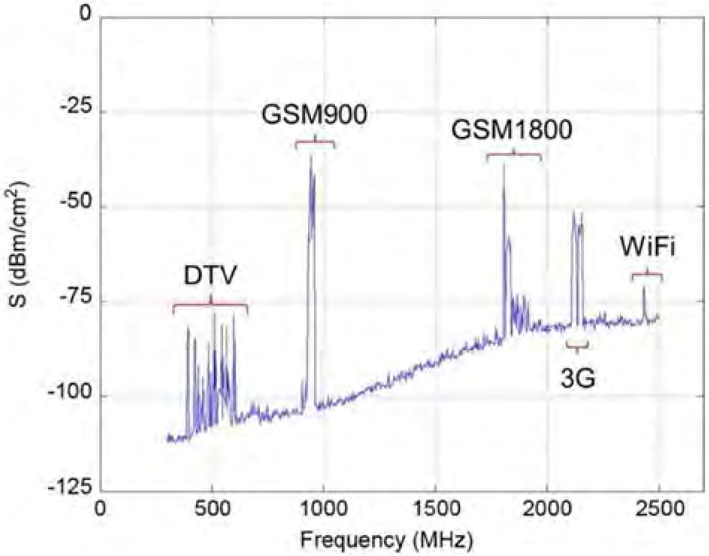
WiFi <1 W
1990’s

5G <100 W
2019

Land Mobile Radio

Ambient RF “Fog” Measurements?

- Outside London Underground stations

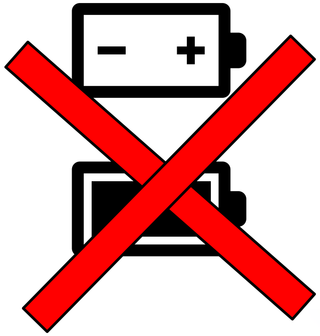


- Pinuela, M.; Mitcheson, P.D.; Lucyszyn, S., "Ambient RF Energy Harvesting in Urban and Semi-Urban Environments," in Microwave Theory and Techniques, IEEE Transactions on , vol.61, no.7, pp.2715-2726, July 2013

Applications

- “Things” have data and the “Cloud” wants data

- Predicted to be trillions of IoT devices
- Impossible to use batteries
- Use Ambient RF Energy harvesting instead

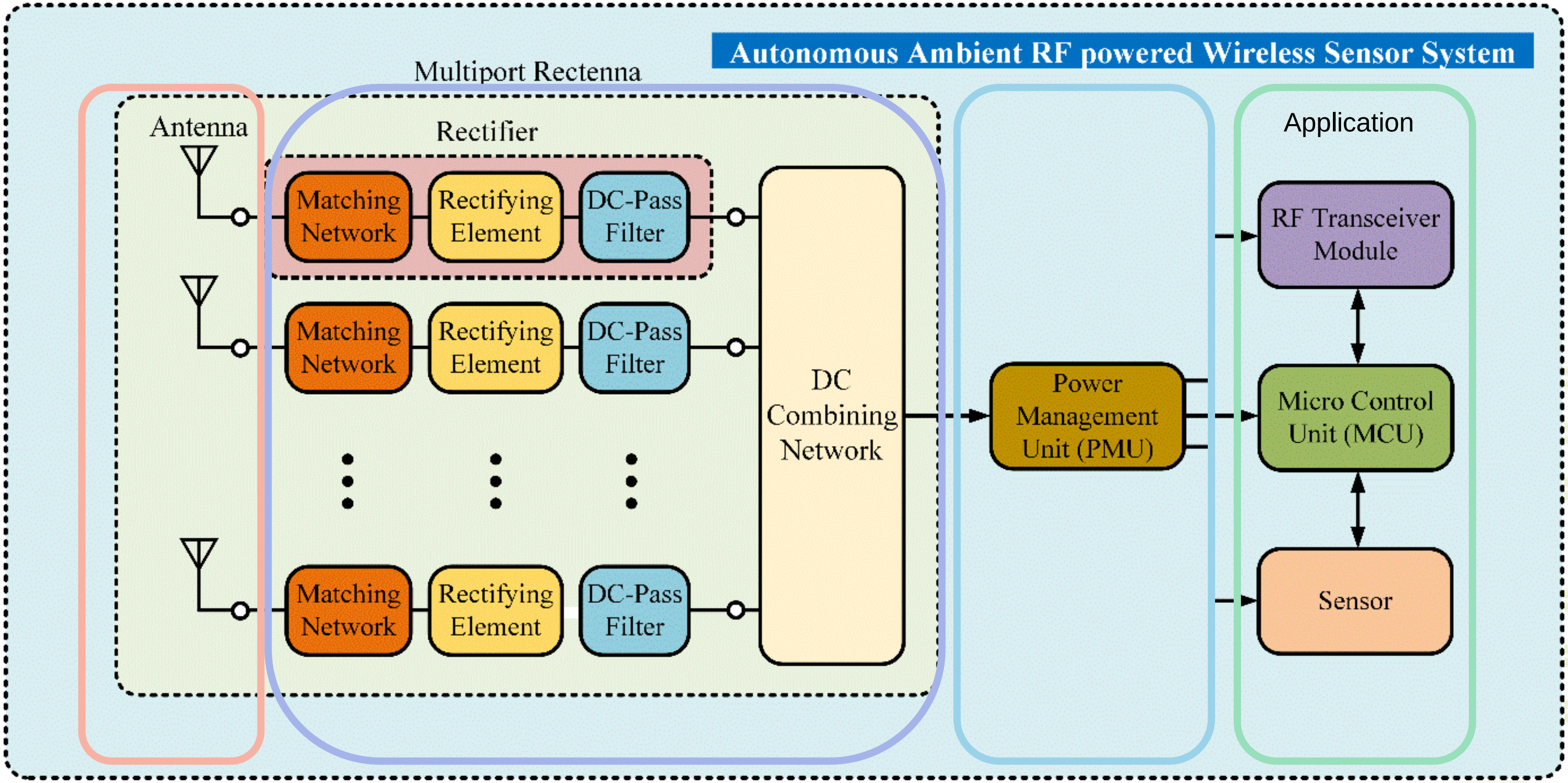


Goal

- Demonstrate that ambient RF energy is enough to power an IoT device
- Core challenge is the low ambient Rf power
- Make us of novel multiple antenna structure we have developed for MIMo communications

The prototyped system

Overview

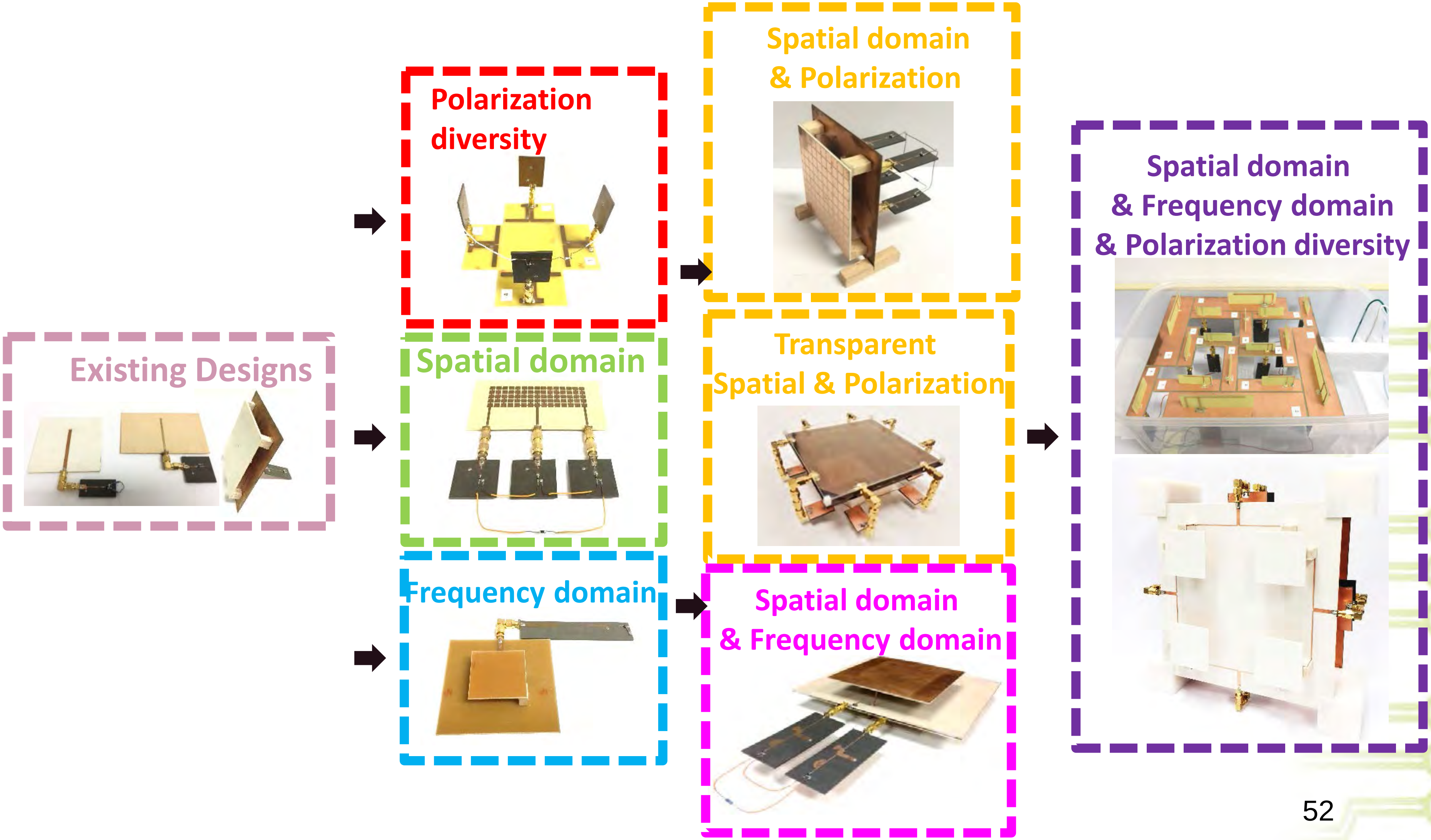

Autonomous Ambient RF powered Wireless Sensor System
Multiport Rectenna
Antenna
Rectifier
Matching Network
Rectifying Element
DC-Pass Filter
Matching Network
Rectifying Element
DC-Pass Filter
Matching Network
Rectifying Element
DC-Pass Filter
DC Combining Network
Power Management Unit (PMU)
Application
RF Transceiver Module
Micro Control Unit (MCU)
Sensor

Field Investigation

measurement result

	Corridor 7/F HKUST		Computer Barn A HKUST	
	Prototype 1	Prototype 2	Prototype 1	Prototype 2
950 (dBm)	-17		-19	
1800 (dBm)	-35		-38	
2100 (dBm)	-46		-41	
Time for data updated	3 min	8 min	7 to 10 min	15 to 20 min
Time for cold start	2.5 hours	3.5 hours	5.5 hours	6 hours

Energy Harvesting Antenna Designs



Existing Designs

Polarization diversity

Spatial domain

Frequency domain

Spatial domain & Polarization

Transparent Spatial & Polarization

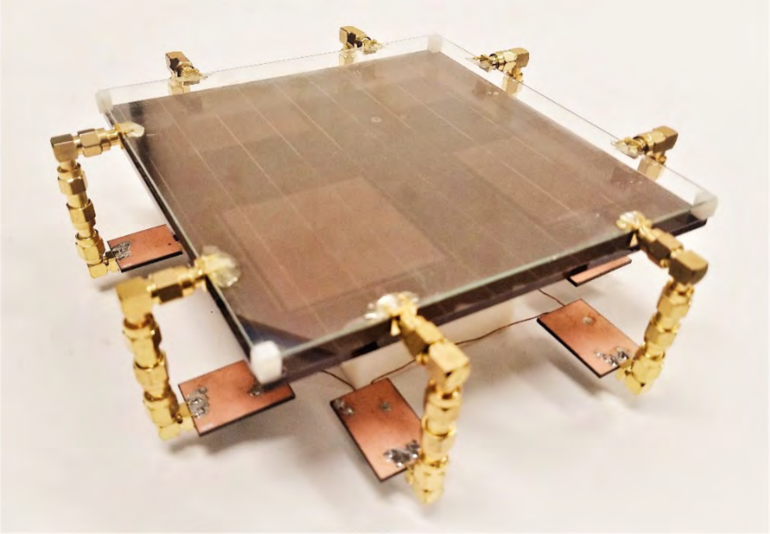
Spatial domain & Frequency domain

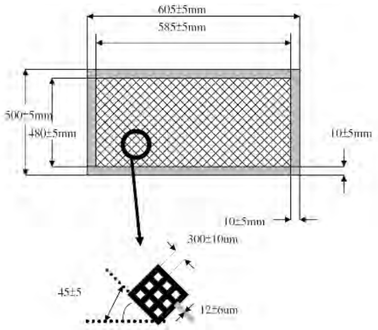
Spatial domain & Frequency domain & Polarization diversity

Energy from RF Fog

-Ambient RF Energy Harvesting Antenna Prototype

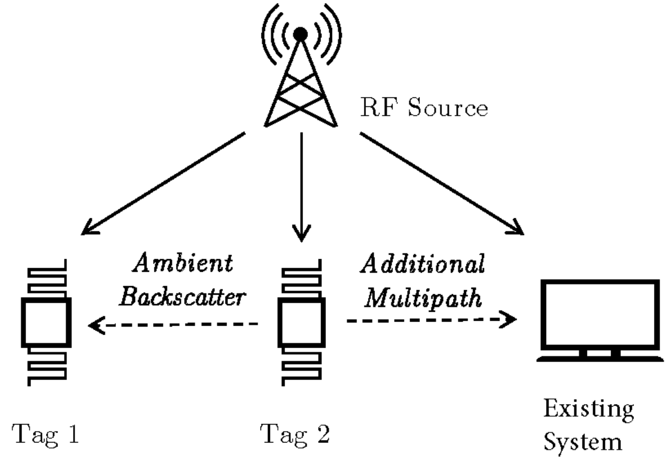
- Features:
  - Transparent
  - Hybrid with solar cell underneath
  - 8-port
  - DC combining



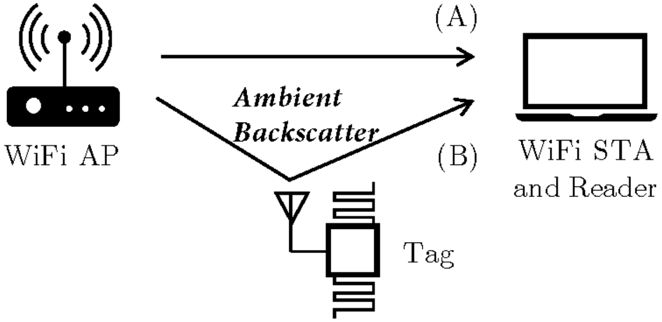


Ambient Backscatter Communication

- Can be thought of as a simplified RFID
- No spectrum required
- No infrastructure
- No battery



- Suffers from very low signals and low throughputs



Summary

- Demonstrate feasibility of ambient RF energy harvesting
- Handles cold start and 15 min duty cycle
- Operational down to -30 dBm
- Large scale electromagnetic structures
- Extend to ambient backscatter communications

Publications

1. S. Shen, Y. Zhang, C. -Y. Chiu and R. Murch, "Directional Multiport Ambient RF Energy-Harvesting System for the Internet of Things," in IEEE Internet of Things Journal, vol. 8, no. 7, pp. 5850-5865, 1 April1, 2021, doi: 10.1109/JIOT.2020.3032435.
2. W. Liu, S. Shen, D. H. K. Tsang and R. Murch, "Enhancing Ambient Backscatter Communication Utilizing Coherent and Non-Coherent Space-Time Codes," in IEEE Transactions on Wireless Communications, vol. 20, no. 10, pp. 6884-6897, Oct. 2021, doi: 10.1109/TWC.2021.3078051.
3. S. Shen, Y. Zhang, C. -Y. Chiu and R. Murch, "A Triple-Band High-Gain Multibeam Ambient RF Energy Harvesting System Utilizing Hybrid Combining," in IEEE Transactions on Industrial Electronics, vol. 67, no. 11, pp. 9215-9226, Nov. 2020, doi: 10.1109/TIE.2019.2952819.
4. S. Shen, Y. Zhang, C. -Y. Chiu and R. Murch, "An Ambient RF Energy Harvesting System Where the Number of Antenna Ports is Dependent on Frequency," in IEEE Transactions on Microwave Theory and Techniques, vol. 67, no. 9, pp. 3821-3832, Sept. 2019, doi: 10.1109/TMTT.2019.2906598.
5. Y. Zhang, S. Shen, C. Y. Chiu and R. Murch, "Hybrid RF-Solar Energy Harvesting Systems Utilizing Transparent Multiport Micromeshed Antennas," in IEEE Transactions on Microwave Theory and Techniques, vol. 67, no. 11, pp. 4534-4546, Nov. 2019, doi: 10.1109/TMTT.2019.2930507.
6. S. Shen, C. -Y. Chiu and R. D. Murch, "A Dual-Port Triple-Band L-Probe Microstrip Patch Rectenna for Ambient RF Energy Harvesting," in IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 3071-3074, 2017, doi: 10.1109/LAWP.2017.2761397.

New RF Wave Technology

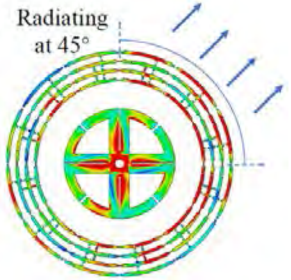
- RF Imaging
- Reconfigurable Intelligent Surface
- Electromagnetic Information Theory
- Ambient RF Energy Harvesting
- Key point summary

Key Points to Take Away

- RF Waves are everywhere and we can make use of them
- We can harness them much better than we have been to provide enhancements to future 6G wireless communication
- Enhancements
  - RF Imaging
  - Electromagnetic Information Theory
  - Energy harvesting
  - Energy harvesting, communication and Imaging
  - Space-time electromagnetic structures
- Reconfiguration is a key area to develop

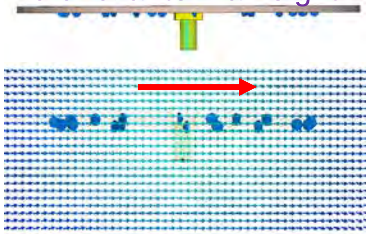
Reconfiguration is a core effort in our group

Low-profile Vertically Polarized Highly Pattern-Reconfigurable Antenna



Current is parallel
to the substrate

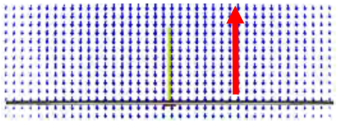
0.026l antenna height



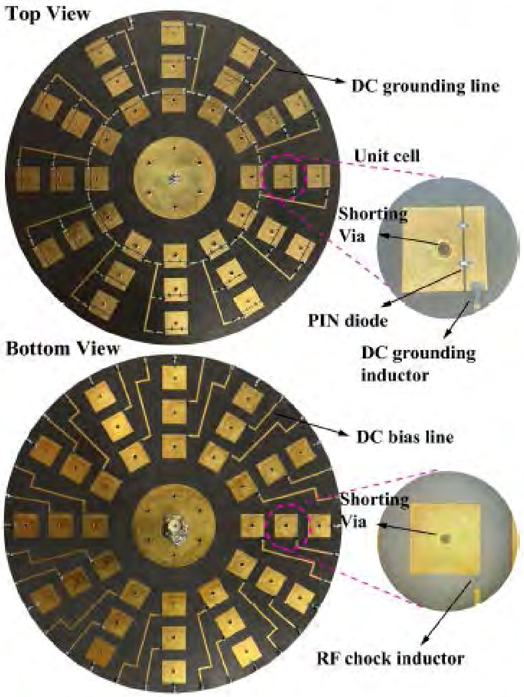
Horizontally Polarized
Electric Field

$\frac{1}{4}\lambda; 15mm$
$@\ 5\ GHz$

Monopole Antenna
is vertically polarized
but with large profile

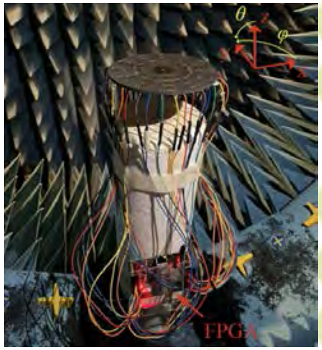


Vertically Polarized
Electric Field



Features:

Low-profile
Electric dipole
+
Distributed
Reconfigurable
Meta-resonator



Y. Zhang, S. Tang, Z. Han, J. Rao, S. Shen, M. Li, C. Y. Chiu and R. Murch, "A Low-Profile Microstrip Vertically Polarized Endfire Antenna With 360° Beam-Scanning and High Beam-Shaping Capability," (Special Issue) IEEE Transactions on Antennas and Propagation, 2022.

Thank you from the Team!

- RF Indoor imaging
  - WiFi approaches for indoor imaging Amar Dubey (PhD), Sammy Deshmukh (MPhil)
  - Conventional microwave approaches Dingfei Ma (PhD), Hongxin Zhou* (PhD), Anders Wong (MPhil),
- RF systems
  - Ambient backscatter communications Wenjing Liu (PhD), Jun Qian (Post Doc)
  - Reconfigurable intelligent surfaces Junhui Rai (PhD)
- Energy harvesting
  - Multiple antenna approach Shanpu Shen (RAP)
  - Ambient RF systems Charles Ng (MPhil)
  - Wireless power transfer Chi Zhang (PhD)
- Electromagnetic Information Theory
  - mm Wave antennas for mobile handsets Shiwen Tang (PhD)
  - Reconfigurable and Pixel antennas: Jerry Yujie Zhang (Post Doc), Tianriu Qiao* (PhD), Jun Qian (Post Doc), Frankie Chiu (RAP), Zihao Xu
- Space-time electromagnetics and reconfiguration
  - Zhaoyang Ming (PhD), Jerry Yujie Zhang (Post Doc), Shanpu Shen (RAP)

All the details are in the published papers listed below

1. A., Dubey S. Deshmukh, L. Pan, X. Chen and R. Murch, "A Phaseless Extended Rytov Approximation for Strongly Scattering Low-Loss Media and Its Application to Indoor Imaging," in *IEEE Transactions on Geoscience and Remote Sensing,* vol. 60, pp. 1-17, 2022, Art no. 2005017.
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3. A. Dubey, S. Deshmukh, D. Ma, Q. Chen and R. Murch, "Physics Assisted Deep Learning for Indoor Imaging using Phaseless Wi-Fi Measurements," in *IEEE Transactions on Antennas and Propagation*, doi: 10.1109/TAP.2022.3177533.
4. S. Deshmukh, A. Dubey and R. Murch, "End-to-end Deep Prior based solution to Non-linear Phaseless Inverse Scattering Problems." Submitted to *IEEE Transactions on Geoscience and Remote Sensing*
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6. J. Rao, Y. Zhang, Shiwen Tang, Zan Li, Shanpu Shen, Chi-Yuk Chiu, and Ross Murch, "A Novel Reconfigurable Intelligent Surface for Wide-Angle Passive Beamforming," in IEEE Transactions on Microwave Theory and Techniques, 2022, doi: 10.1109/TMTT.2022.3195224
7. N. K. Kundu, Z. Li, J. Rao, S. Shen, M. R. McKay and R. Murch, "Optimal Grouping Strategy for Reconfigurable Intelligent Surface Assisted Wireless Communications," in IEEE Wireless Communications Letters, vol. 11, no. 5, pp. 1082-1086, May 2022, doi: 10.1109/LWC.2022.3156978.
8. S. Shen, B. Clerckx and R. Murch, "Modeling and Architecture Design of Reconfigurable Intelligent Surfaces Using Scattering Parameter Network Analysis," in IEEE Transactions on Wireless Communications, vol. 21, no. 2, pp. 1229-1243, Feb. 2022, doi: 10.1109/TWC.2021.3103256.
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