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Electromagnetic Information Theory:

ındanentals, Modeling, Applications, and Open Probler

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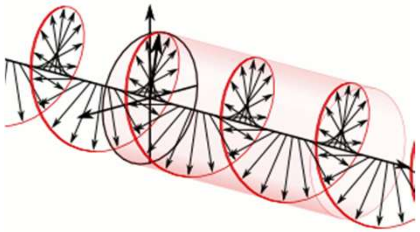
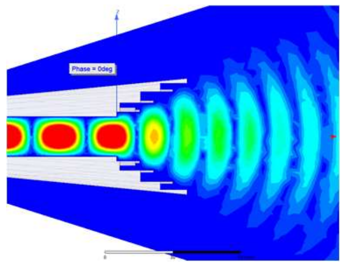
tarting from the Iceberg Effect

Different aspects of wireless communications

- **Classical communication theory**: Research on the **math-symbolized** signal processing theory
- **Electromagnetic (EM) theory**: EM waves carrying information as a **physical process**

Iceberg





Communicatio

EM Theory

How can EM theory inspire future communication research?

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- **Chapter 1: Introduction to EIT**
  - 1.1 Motivation of EIT
  - 1.2 Shannon information theory
  - 1.3 Maxwell electromagnetic theory
  - 1.4 Overview of EIT
- **Chapter 2: Fundamentals of EIT**
  - 2.1 Electromagnetic channel models for EIT
  - 2.2 DoF analysis for EIT
  - 2.3 Mutual information for EIT
- **Chapter 3: EIT-Enabled Technologies**
  - 3.1 Holographic MIMO
  - 3.2 EIT-enabled near-field communications
  - 3.3 Mutual coupling and superdirective antennas
  - 3.4 Orbital angular momentum
  - 3.5 3D antenna arrays
- **Chapter 4: EIT-Inspired Technologies**
  - 4.1 EIT-inspired channel estimation
  - 4.2 EIT-inspired channel prediction
  - 4.3 EIT-inspired self-controlled RIS
- **Chapter 5: Conclusions**

Contents

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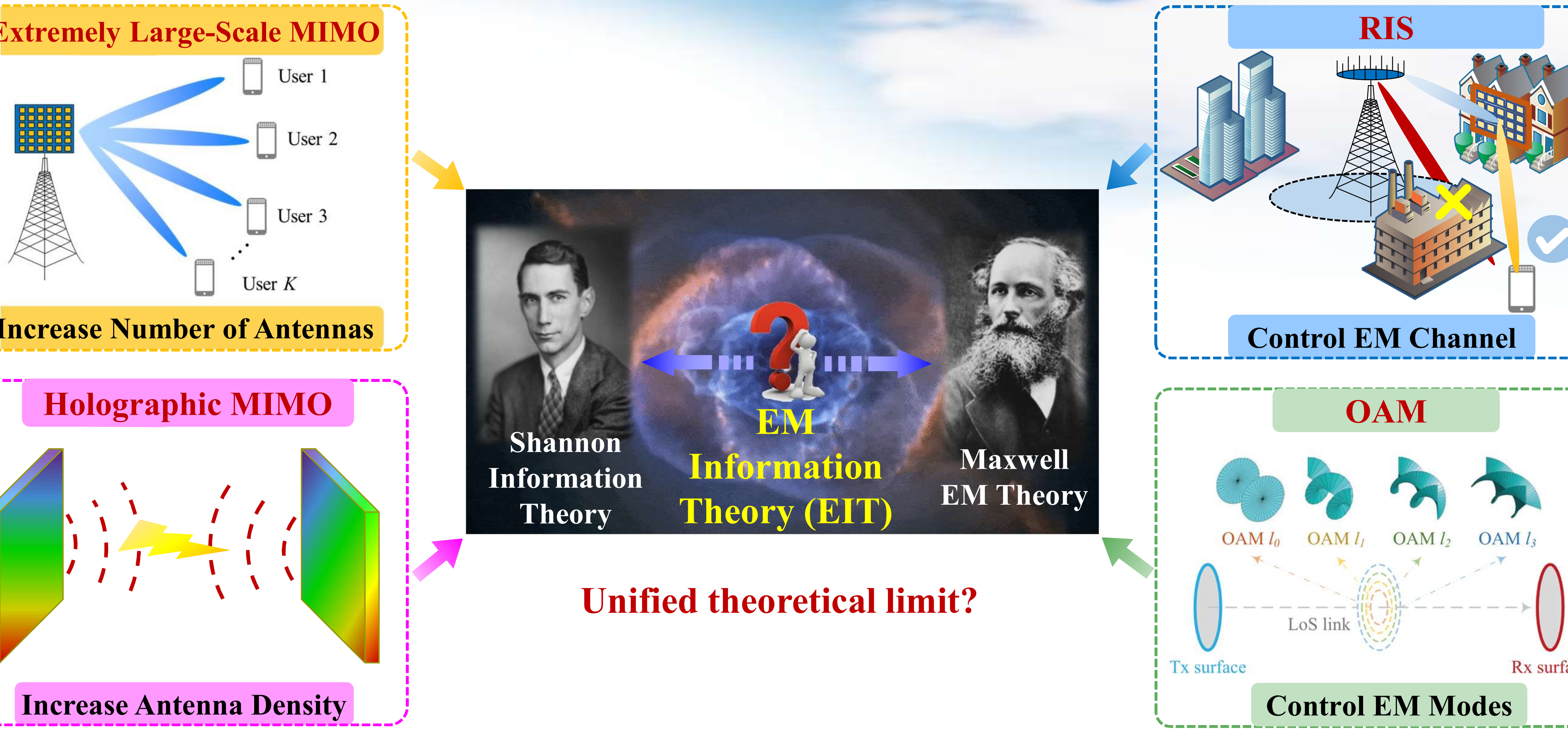
.1 EIT for 6G Novel Technologies

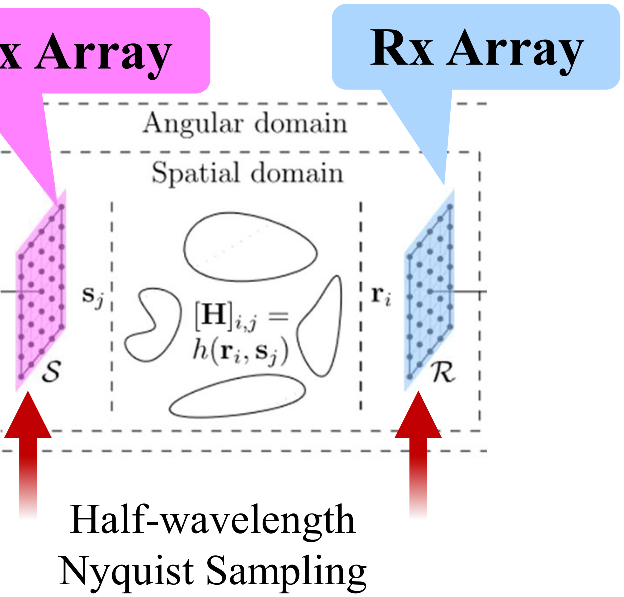


D. Li, J. Ma, Z. Feng, L. Zhang, W. E. I. Sha, H. Chen, and E.-P. Li, "An electromagnetic information theory-based model for efficient characterization of MIMO systems in c
" *IEEE Trans. Antennas Propagat.*, vol. 71, no. 4, pp. 3497-3508, Apr. 2023.

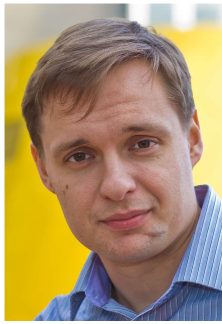
.1 Theoretical Motivation of EIT

Transmit information with EM fields in a compact space-time region

- **MIMO IT**: Apply **discretization** to EM channels for information-theoretic limits in the $T \to \infty$ re
- **EIT**: Treat EM channels as **continuous operators** for information-theoretic limits in the **finite-spacetime** regime



Engineering Constraints	Theoretical Questions		Improved Theories
Finite-time communications →	Typicality decoding is suboptimal	Y →	Finite-blocklength theory [1]
		N →	MIMO IT
Finite-aperture communications →	Nyquist sampling is suboptimal [2]	N → MIMO IT; Y →	EIT ?

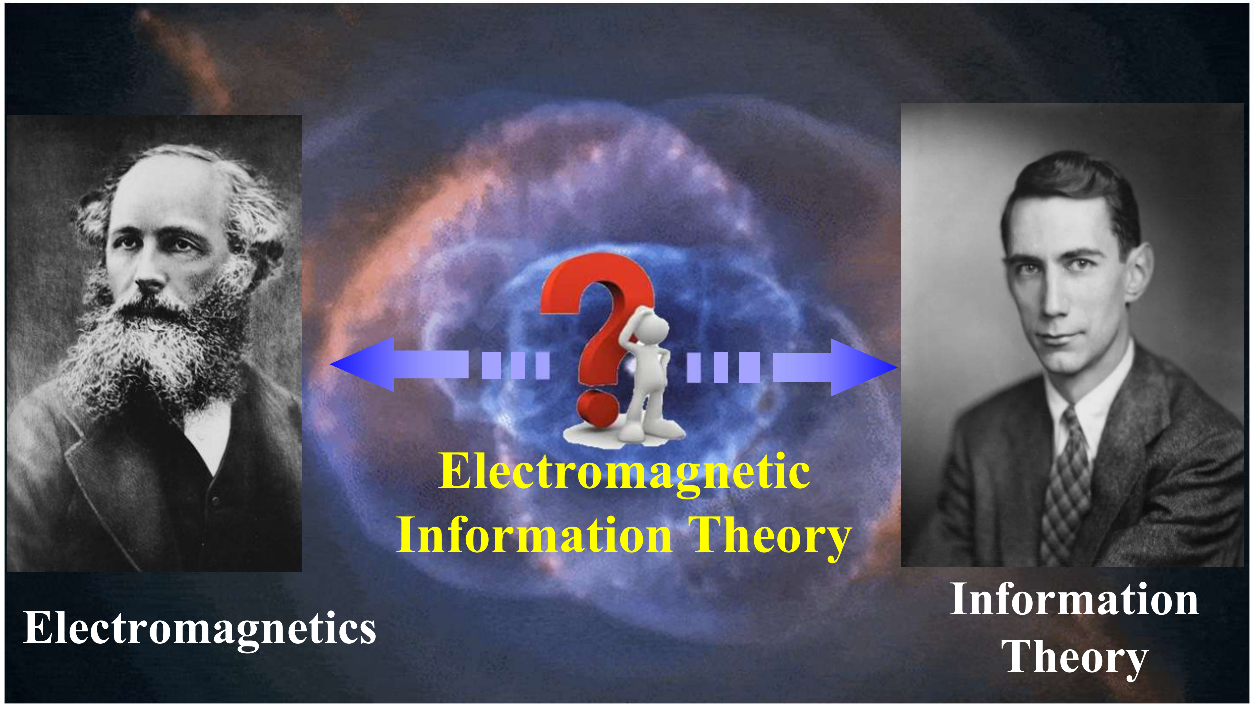


Yuri Polyans
(IEEE Fello
MIT

Polyanskiy, H. V. Poor, and S. Verdu, "Channel coding rate in the finite blocklength regime," *IEEE Trans. Inf. Theory*, vol. 56, no. 5, pp. 2307-2359, May 2010.
Pizzo, A. Torres, L. Sanguinetti, and T. L. Marzetta, "Nyquist sampling and degrees of freedom of electromagnetic fields," *IEEE Trans. Signal Process.*, vol. 70, pp. 1–12, Jun.

.1 From Classical IT to Electromagnetic IT (EIT)

EM Information Theory (EIT): An interdisciplinary subject integrating determini physical theory and probabilistic mathematical theory to provide theoreti foundations for performance evaluation and optimization of wireless systems.

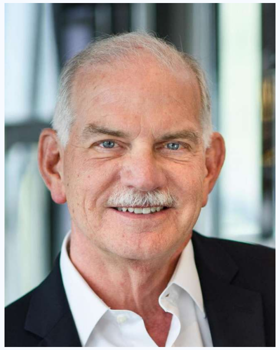


. Wan, **L. Dai**, M. Debbah, and H. V. Poor, "Electromagnetic information theory: Fundamentals, modeling, applications, and open problems," *IEEE Wireless Commun.*, vol. 31 162, Jun. 2023.

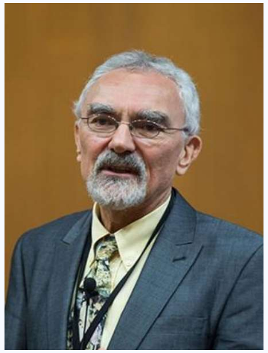
.1 Academic and Industrial Interest

Studies of EIT has attracted widespread attention from academia and industry

Academia



H. V. Poor
Member of National Academy of Sciences (US)



Lajos Hanzo
Fellow of the Royal Academy of Engineering (UK)

IEEE Globecom
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IEEE VTC-Spring
2023 Workshop

IEEE Globecom
2023 Workshop

IEEE ICC
2024 Workshop

Industry

Download:
https://www.chaspark.com/#/hotspots/857399644291072

Yang, C.-X. Wang, J. Huang, J. Thompson, and H. V. Poor, "A 3D continuous-space electromagnetic channel model for 6G tri-polarized multi-user communications," *IEEE ans. Wireless Commun.*, vol. 23, no. 11, pp. 17354-17367, Sep. 2024.
X. Wang, Y. Yang, J. Huang, X. Gao, T. J. Cui, and L. Hanzo, "Electromagnetic information theory: Fundamentals and applications for 6G wireless communication systems," *EE Wireless Commun.*, vol. 31, no. 5, pp. 279-286, Oct. 2024.

Contents

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  - 3.2 EIT-enabled near-field communications
  - 3.3 Mutual coupling and superdirective antennas
  - 3.4 Orbital angular momentum
  - 3.5 3D antenna arrays
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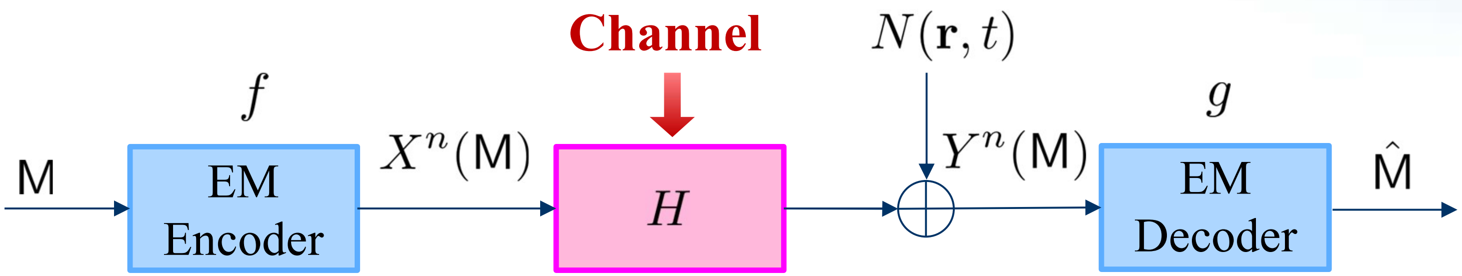
.2 Shannon Information Theory

Shannon's Noisy Channel Coding Theorem

- **Theorem: Maximum error-free transmission rate = Channel capacity**
- **Point-to-point information transmission without considering EM fields**



Channel codes

(n, P, M, ε)-code

Maximal codes

$M^*(n, P, \varepsilon) := \max\{M : \exists (n, P, M, \varepsilon)\text{-code}\}$

Shannon's theorem (modern form)

$$\lim_{\varepsilon \to 0} \liminf_{n \to \infty} \frac{1}{n} \log M^*(n, P, \varepsilon) \overset{1948}{=} C(P, H)$$

Error probability

$\varepsilon := \Pr[\mathsf{M} \neq \hat{\mathsf{M}}]$

Time constraint

$X^n \in \mathcal{X}^n, \quad Y^n \in$

Bandwidth constrai

$H \in \mathcal{B}_W$

Energy constraint

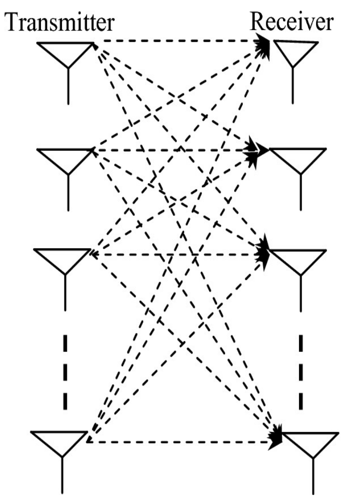
$\mathbb{E}_{\mathsf{M}}[\|X^n(\mathsf{M})\|^2] \leq n$

hannon, "A mathematical theory of communication," *Bell Syst. Technical J.*, vol. 27, no. 3, pp. 379-423, Jul. 1948.

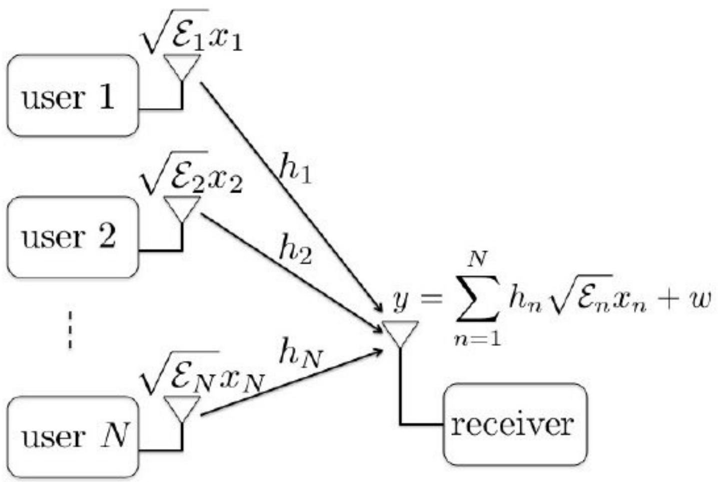
.2 Shannon Information Theory

Information theory evolution

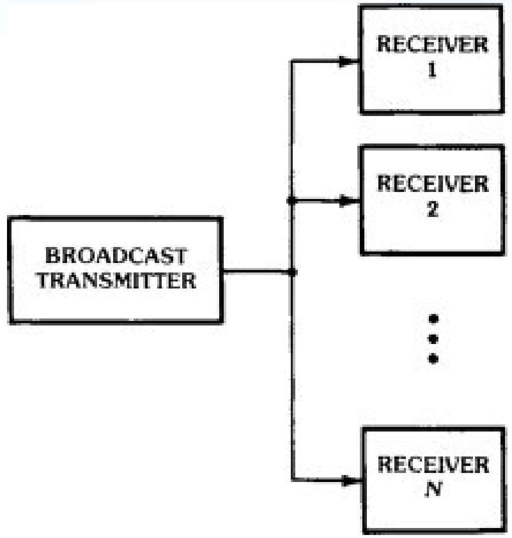
- **MIMO information theory: From point-to-point channel to MIMO channels**
- **Network information theory: Network coding for uplink multiple access channel (MAC) and downlink broadcast channel (BC)**



MIMO Channel
Point-to-point channel



Multiple Access Channel
Network channel



Broadcast Channel
Network channel

er and J. A. Thomas, *Elements of information theory*. Wiley-Interscience, 2006.

Contents

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  - 2.1 Electromagnetic channel models for EIT
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  - 3.4 Orbital angular momentum
  - 3.5 3D antenna arrays
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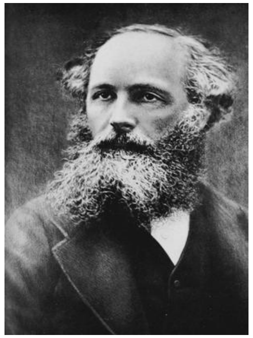
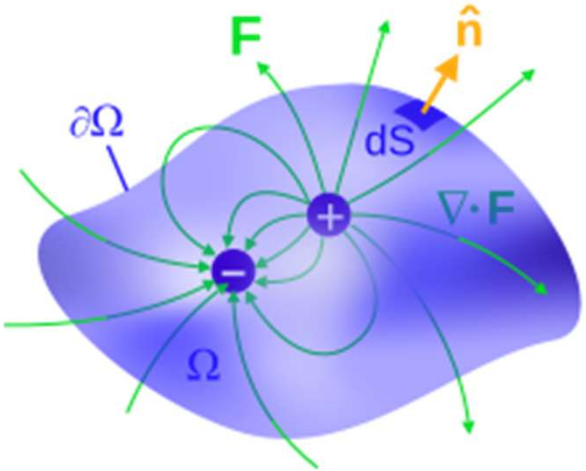
.3 Maxwell Electromagnetic Theory

Maxwell's equations: A set of coupled partial differential equations that form the foundation of classical electromagnetism

A unified mathematical model for electric, optical, and radio technologies



nes Clerk Maxwell
(1831-1879)



Gauss's law	$\nabla \cdot \mathbf{D} = \rho$
Gauss's law for magnetism	$\nabla \cdot \mathbf{B} = 0$
Ampère–Maxwell law	$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$
Maxwell–Faraday equation	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$

Maxwell, "A dynamical theory of the electromagnetic field," *Philosophical transactions of the Royal Society of London*, 1865.

.3 Maxwell Electromagnetic Theory

Lead to vector wave equation which depicts the relationship between source and generated fields

Vector wave equation $\nabla \times \nabla \times \mathbf{E}(\mathbf{r}) - \omega^2 \epsilon \mu \mathbf{E}(\mathbf{r}) = \mathrm{j}\omega\mu \mathbf{J}(\mathbf{r})$

Green's function

Green's function

$$\mathbf{E}(\mathbf{r}) = \mathrm{j}\omega \int_{V_s} \mathbf{G}(\mathbf{r}, \mathbf{r}') \mu_0 \mathbf{J}(\mathbf{r}') \mathrm{d}\mathbf{r}'$$

$$(\mathbf{r}, \mathbf{r}') = \frac{1}{4\pi} \frac{e^{\mathrm{j}\kappa_0 \|\mathbf{r}-\mathbf{r}'\|}}{\|\mathbf{r}-\mathbf{r}'\|} \left[(\mathbf{I} - \hat{\mathbf{p}}\hat{\mathbf{p}}^{\mathrm{H}}) + \frac{\mathrm{j}}{2\pi \|\mathbf{r}-\mathbf{r}'\| / \lambda} (\mathbf{I} - 3\hat{\mathbf{p}}\hat{\mathbf{p}}^{\mathrm{H}}) - \frac{1}{(2\pi \|\mathbf{r}-\mathbf{r}'\| / \lambda)^2} (\mathbf{I} - 3\hat{\mathbf{p}}\hat{\mathbf{p}}^{\mathrm{H}}) \right] [\mathrm{r}$$

Plane wave — Far-field

Spherical wave — Radiative Near-field

Evanescent wave — Reactive Near-field

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.4 Overview of EIT

Electromagnetic Information Theory (EIT): An interdisciplinary subject integra deterministic physics theory and statistical mathematical theory to provide theore foundations for performance evaluation and optimization of wireless systems

ntropy of RVs:

$$(X) = \sum_{x \in \mathcal{X}} p(x) \log_2 \left(\frac{1}{p(x)} \right)$$

lutual information of RVs:

$$X;Y) = H(X) - H(X|Y)$$

hannel capacity of additive aussian noise:

$$= \int_0^W \log \left(1 + \frac{P(f)}{N(f)} \right) \mathrm{d}f$$

Gauss's law:

$$\nabla \cdot \mathbf{D} = \rho$$

Gauss's law for magn

$$\nabla \cdot \mathbf{B} = 0$$

Ampere-Maxwell law

$$\nabla \times \mathbf{H} = \mathbf{j} + \frac{\partial \mathbf{D}}{\partial t}$$

Faraday's law:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

. Wan, **L. Dai**, M. Debbah, and H. V. Poor, "Electromagnetic information theory: Fundamentals, modeling, applications, and open problems," *IEEE Wireless Commun.*, vol. 31
162, Jun. 2023.

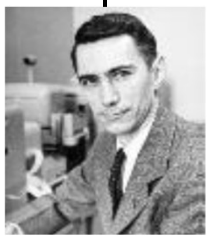
.4 Discrete MIMO IT vs. Continuous EIT

	MIMO Information Theory	Electromagnetic Information Theory
hannel model	Mathematical channel	Physical channel
hannel haracteristics	Discrete channel	Continuous channel
hannel form	Matrix	Operator (Green's function)
hannel ecomposition	SVD Matrix decomposition, Eigenvector	Spectrum decomposition of the operator, Eigenfunction
ignal model	Gaussian random vector	Gaussian random field
oise model	i.i.d. Gaussian white noise	Electromagnetic colored noise
apacity	Matrix determinant	Operator determinant (Fredholm determinant)

ansplant classical time-domain stochastic processes into spatial-domain random fie

.4 Historical Evolution of EIT

1865 — **James C. Maxwell**
proposed Maxwell's equations, connecting the electric and magnetic fields



1949 — **Claude E. Shannon**
proposed information theory, the mathematical theory of communication

1950 — **Dennis Gabor**
proposed that communication is the transmission of physical effects, connecting communication theory with physical effects

1987 — **Giorgio Franceschetti**
proposed Bucci-Franceschetti diversity limits based on the analysis of scattering field

2008 — **Massimo Franceschetti**
and his book "Wave Theory of Information" analyzed the capacity problems of MIMO

2014 — **Josef Nossek**
proposed multiport communication theory by applying circuit theory to information theory

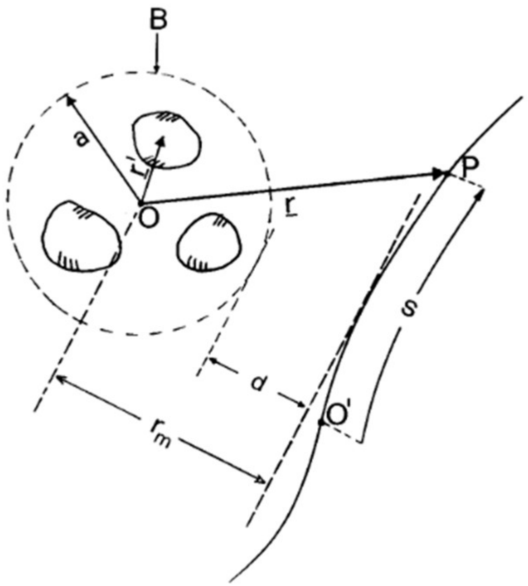
2019 — **Tapan K. Sarkar**
applied the EM theory to channel capacity issues

4 Functional Approximation of EM Fields

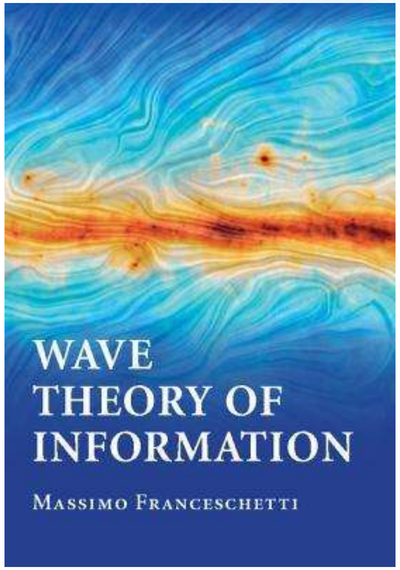
Approximating EM fields with **bandlimited functions** to get the **EM degrees of free**

- A **bandlimited EM field** with $w \geq \beta a$ suffices to reconstruct arbitrary radiated EM fields [1]
- **Functional approximation** techniques for EM fields are introduced in detail in [2]

gio Franceschetti
EE Life Fellow)



Spherical source (Tx) with linear observation (Rx)



Functional approximation and DoF analysis for EM waves

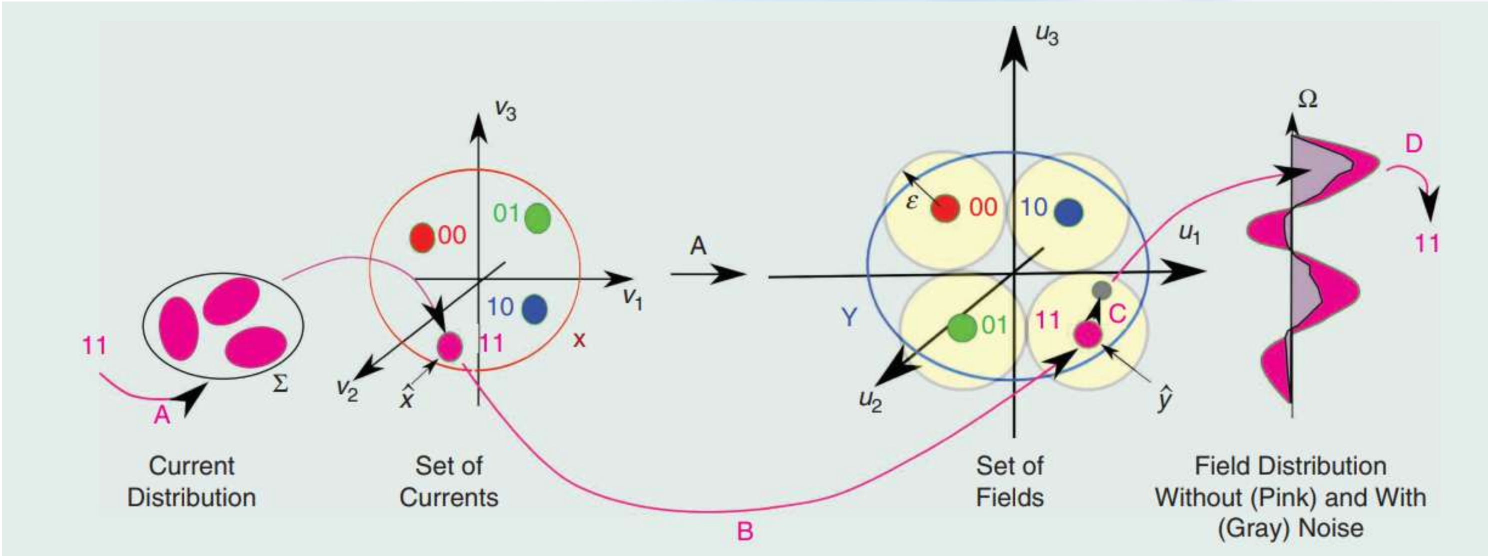
Massimo Frances
(IEEE Fellow

. M. Bucci and G. Franceschetti, "On the spatial bandwidth of scattered fields," *IEEE Trans. Antennas Propagat.*, vol. 35, no. 12, pp. 1445-1455, Dec. 1987.
. Franceschetti, *Wave Theory of Information*. Cambridge University Press, 2017.

4 Information Contained in Electromagnetic Field

Use Kolmogorov information theory which analyzes the number of distinguishable waveforms above an uncertainty level

Marco Donald Migliore
(IEEE Fellow)



Distinguishable waveforms above an uncertainty level

D. Migliore, "Horse (Electromagnetics) is more important than horseman (information) for wireless transmission," *IEEE Trans. Antennas Propagat.*, vol. 67, no. 4, pp. 2046–20
.
D. Migliore, "Shannon and Kolmogorov in space communication channels," in *Proc. 14th EuCAP. Copenhagen, Denmark*, Mar. 2020, pp. 1–4.
D. Migliore, "On electromagnetics and information theory," *IEEE Trans. Antennas Propagat.*, vol. 56, no. 10, pp. 3188–3200, Oct. 2008.

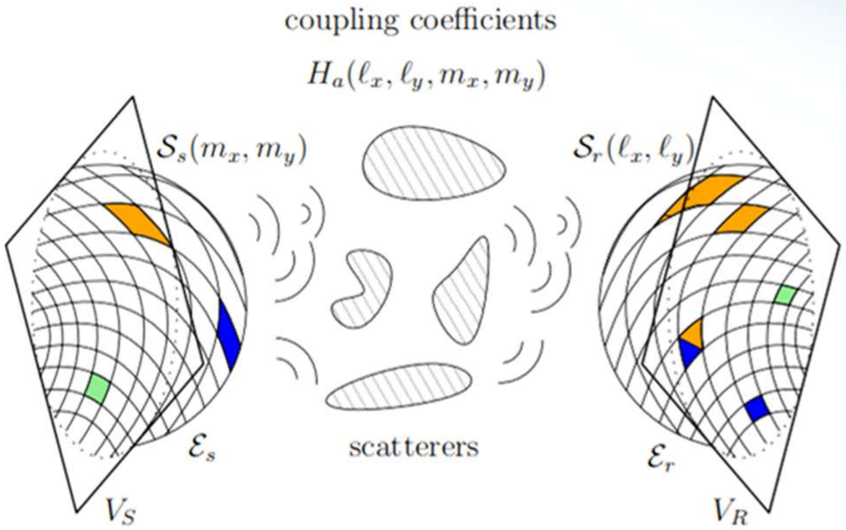
4 Channel Models for EIT

Various **channel modeling schemes** **based on** **electromagnetic theory**

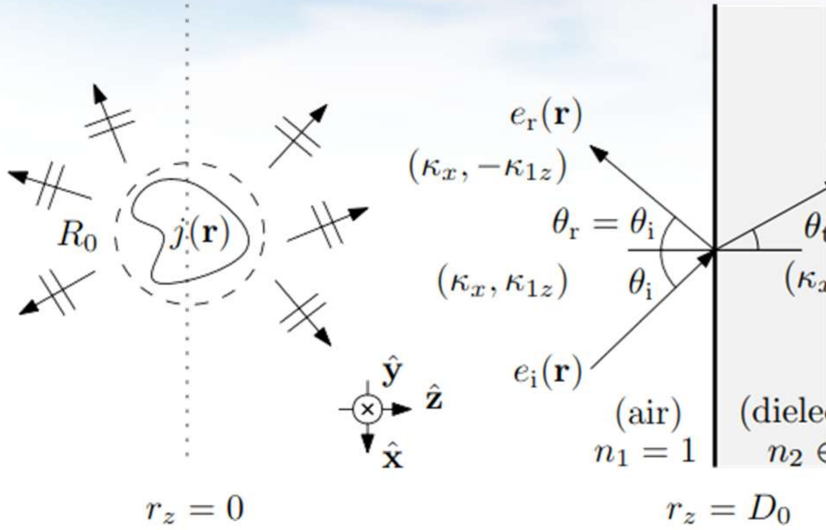
- ➤ **Spatially-stationary scattering [1], smooth surface [2], resonant cavity [3], etc.**

Thomas Marzetta

ber of the National Academy of Engineering (US)



Spatially-stationary scattering



Smooth surface

izzo, L. Sanguinetti, and T. L. Marzetta, "Fourier plane-wave series expansion for holographic MIMO communications," *IEEE Trans. Wireless Commun.*, vol. 21, no. 9, pp. 68 2022.

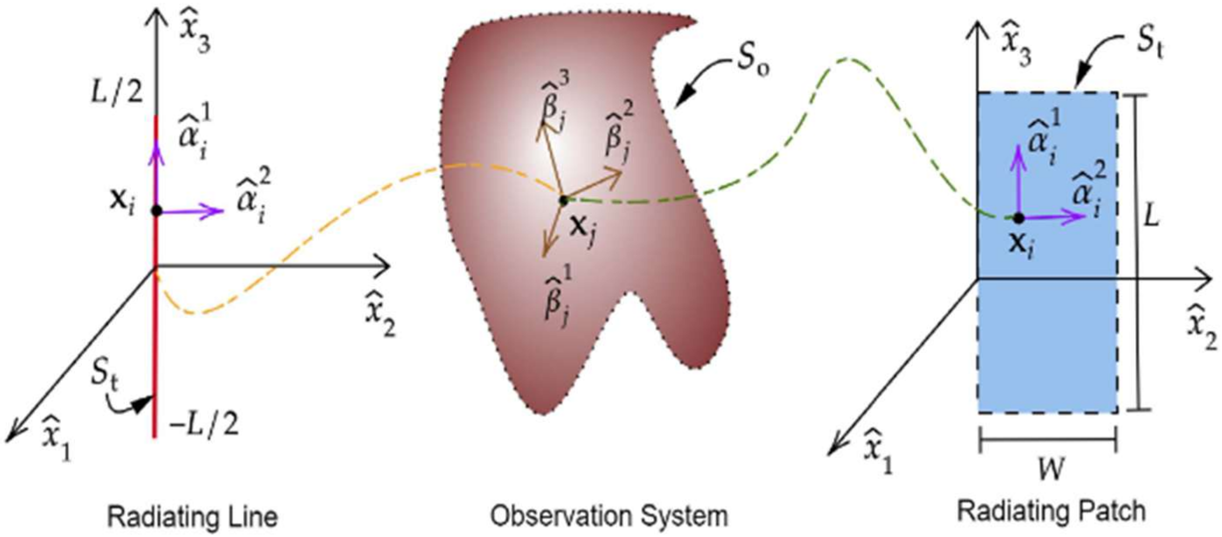
izzo, A. Lozano, S. Rangan, and T. L. Marzetta, "Wide aperture MIMO via reflection off a smooth surface," *IEEE Trans. Wireless Commun.*, vol. 22, no. 8, pp. 5229–5239, Aug

Marzetta and T. B. Hansen, "Rayleigh-jeans-clarke model for wireless noise in a resonant cavity: Scalar case," *in Proc. IEEE Global Communications Conference*, Dec. 2022, 1.

4 Information Capacity of Radiating Surfaces

Unified information-theoretic framework for arbitrary radiating systems

- **Surface or line sources are approximated by multiple discrete points**
- **Shannon information capacity is computed with this discretized model**



Channel capacity from a Tx line/patch to the Rx observation system

Said Mikki

ki, "The Shannon information capacity of an arbitrary radiating surface: An electromagnetic approach," *IEEE Trans. Antennas Propagat.*, vol. 71, no. 3, pp. 2556–2570, Mar. 2
IEEE AP-S Sergei A. Schelkonuff Transactions Prize Paper Award)

Contents

- Chapter 1: Introduction to EIT
  - 1.1 Motivation of EIT
  - 1.2 Shannon information theory
  - 1.3 Maxwell electromagnetic theory
  - 1.4 Overview of EIT
- **Chapter 2: Fundamentals of EIT**
  - 2.1 Electromagnetic channel models for EIT
  - 2.2 DoF analysis for EIT
  - 2.3 Mutual information for EIT
- Chapter 3: EIT-Enabled Technologies
  - 3.1 Holographic MIMO
  - 3.2 EIT-enabled near-field communications
  - 3.3 Mutual coupling and superdirective antennas
  - 3.4 Orbital angular momentum
  - 3.5 3D antenna arrays
- Chapter 4: EIT-Inspired Technologies
  - 4.1 EIT-inspired channel estimation
  - 4.2 EIT-inspired channel prediction
  - 4.3 EIT-inspired self-controlled RIS
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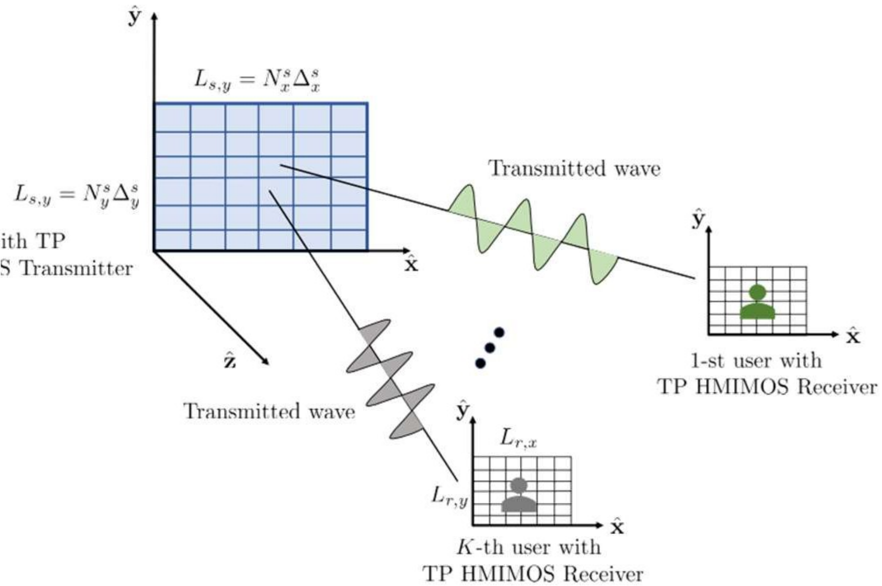
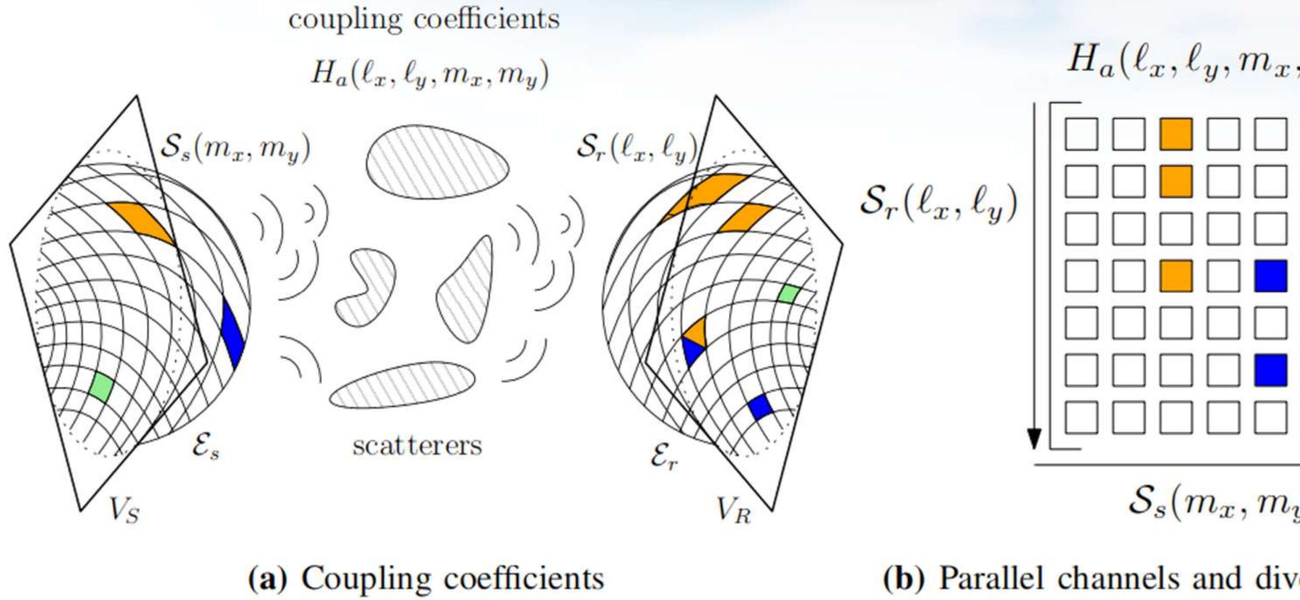
.1 EM Channel Model for EIT

Existing EM channel models

- Tri-polarized LoS channel model [1]
- Spatially-stationary scattering MIMO models with Fourier plane-wave expansion [2]



LoS channel model for EIT



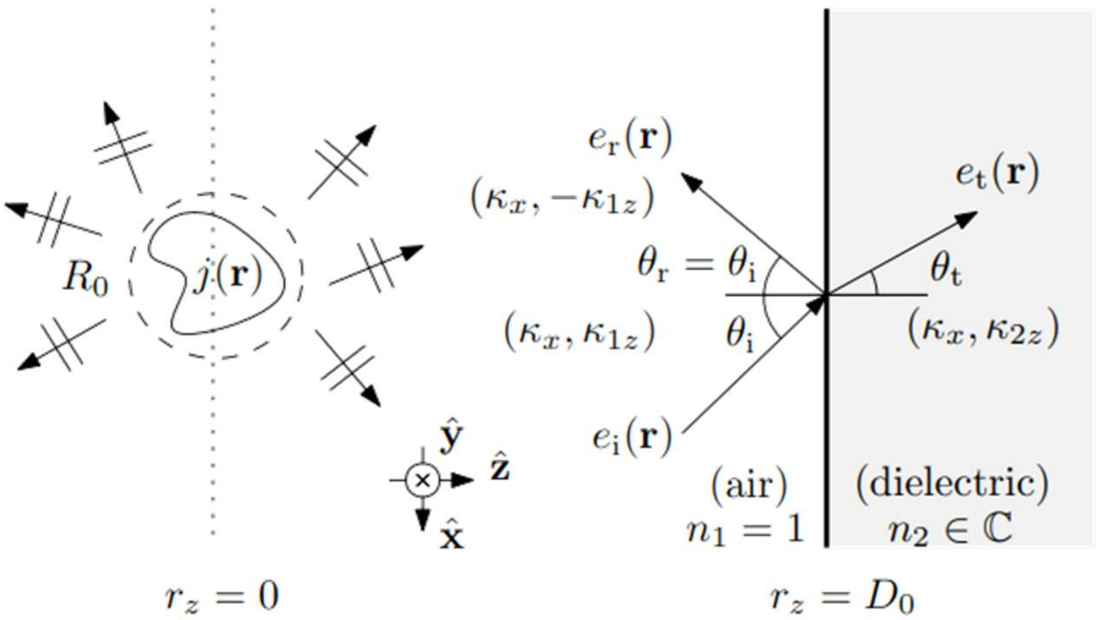
Spatially-stationary scattering

ei, C. Huang, G. C. Alexandropoulos, Z. Yang, J. Yang, E. Wei, Z. Zhang, M. Debbah, and C. Yuen, "Tri-polarized holographic MIMO surfaces for near-field communications: ling and precoding design," *IEEE Trans. Wireless Commun.*, vol. 22, no. 12, pp. 8828–8842, Dec. 2023.
zzo, L. Sanguinetti, and T. L. Marzetta, "Fourier plane-wave series expansion for holographic MIMO communications," *IEEE Trans. Wireless Commun.*, vol. 21, no. 9, pp. 689 2022.

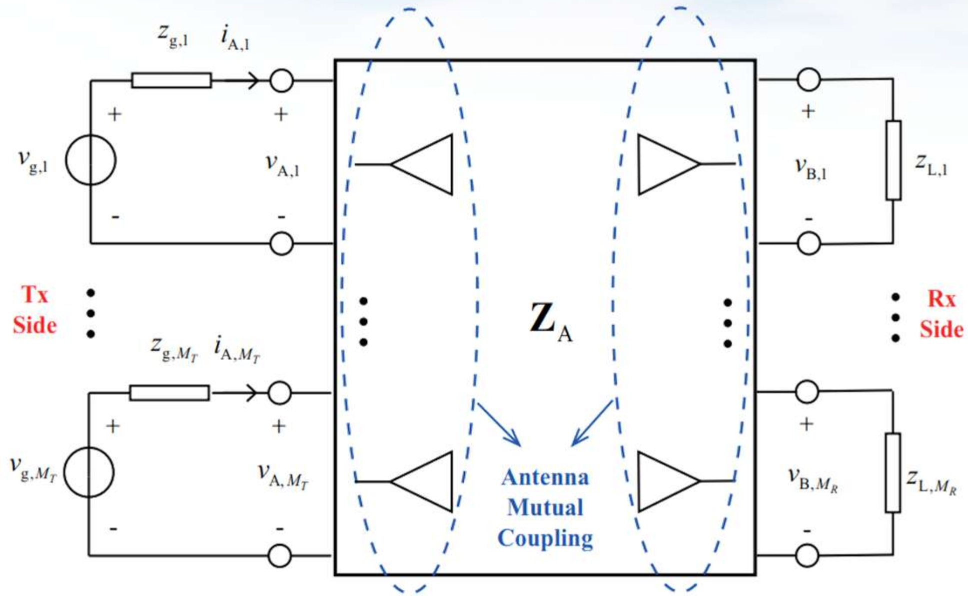
.1 EM Channel Model for EIT

Existing EM channel models

- **Wide aperture** model with **surface reflection** [3]
- **Circuit-based model** considering mutual coupling [4]



Reflection from a surface



Circuit modeling

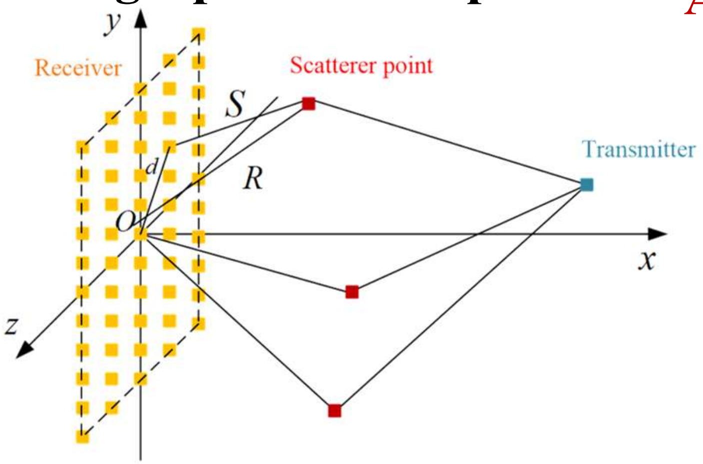
zzo, A. Lozano, S. Rangan, and T. L. Marzetta, "Wide aperture MIMO via reflection off a smooth surface," *IEEE Trans. Wireless Commun.*, vol. 22, no. 8, pp. 5229–5239, Aug
o, C.-X. Wang, J. Huang, and Y. Yang, "A novel circuit-based MIMO channel model considering antenna size and mutual coupling," in *Proc. WCSP'21*, Changsha, China, Oct

.1 EIT-Enabled Near-Field Models

Existing near-field channel modeling scheme

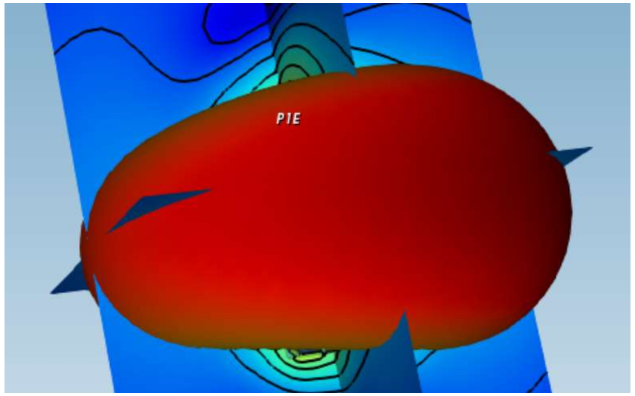
- Widely adopted schemes in wireless communication view scatterer as point: Simple but inaccura
- Schemes like full wave simulation based on electromagnetism: Accurate but complex, without analytical expression

Single point assumption



An analytical channel model that has enough accuracy

Full wave simulation



Problem: Construct an analytical channel model based on electromagnetism for wireless communication

.1 Channel Model Based on Electromagnetism

From electromagnetism, we view the scatterers as spatial inhomogeneity in the space

Maxwell's equation in inhomogeneous space

$$\nabla \times \mathbf{E}(\mathbf{r}) = \mathrm{j}\omega\mu(\mathbf{r})\mathbf{H}(\mathbf{r}), \tag{1a}$$

$$\nabla \times \mathbf{H}(\mathbf{r}) = -\mathrm{j}\omega\epsilon(\mathbf{r})\mathbf{E}(\mathbf{r}) + \mathbf{J}(\mathbf{r}), \tag{1b}$$

$$\nabla \cdot (\epsilon(\mathbf{r})\mathbf{E}(\mathbf{r})) = \rho(\mathbf{r}), \tag{1c}$$

$$\nabla \cdot (\mu(\mathbf{r})\mathbf{H}(\mathbf{r})) = 0 \tag{1d}$$

$$\nabla \times \mu(\mathbf{r})^{-1} \times (1a) + \mathrm{j}\omega \times (1b)$$

Vector wave equation

$$\nabla \times \mu(\mathbf{r})^{-1}\nabla \times \mathbf{E}(\mathbf{r}) - \omega^2\epsilon(\mathbf{r})\mathbf{E}(\mathbf{r}) = \mathrm{j}\omega\mathbf{J}(\mathbf{r})$$

Green's function

$$\mathbf{G}(\mathbf{r},\mathbf{r}') = \frac{1}{4\pi}\left(\mathbf{I} + \frac{\nabla_{\mathbf{r}}\nabla_{\mathbf{r}}^{\mathrm{H}}}{\kappa_0^2}\right)\frac{e^{\mathrm{j}\kappa_0\|\mathbf{r}-\mathbf{r}'\|}}{\|\mathbf{r}-\mathbf{r}'\|}$$

urce-destination relationship

$$\mathbf{E}(\mathbf{r}) = \mathrm{j}\omega\int_{V_s}\mathbf{G}(\mathbf{r},\mathbf{r}')\mu_0\mathbf{J}(\mathbf{r}')\mathrm{d}\mathbf{r}' + \int_V \mathbf{G}(\mathbf{r},\mathbf{r}')(k^2(\mathbf{r}') - k_0^2)\mathbf{E}(\mathbf{r}')\mathrm{d}\mathbf{r}'$$

terson, S. L. Ray, and R. Mittra, *Computational methods for electromagnetics*. Wiley-IEEE Press New York, 1998.

.1 Channel Model Based on Electromagnetism

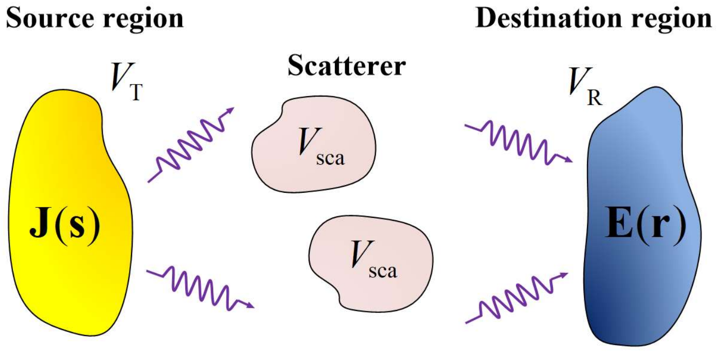
Based on electromagnetism, we can view the source current as the input signal and electric field at the destination as the output signal

The received electric field is split into two parts: Incident and scattered fields

Incident field

Scattered field

$$\mathbf{E} = \mathbf{E}_{\text{inc}} + \mathbf{E}_{\text{sca}}$$



$$\mathbf{E}_{\text{inc}}(\mathbf{r}) = j\omega \int_{V_s} \mathbf{G}(\mathbf{r}, \mathbf{r}')\mu_0 \mathbf{J}(\mathbf{r}')d\mathbf{r}'$$

Source current

$$\mathbf{E}_{\text{sca}} = \int_V \mathbf{G}(\mathbf{r}, \mathbf{r}')(k^2(\mathbf{r}') - k_0^2)\mathbf{E}(\mathbf{r}')d\mathbf{r}'$$

Electric field on the scatterer

e relationship between current and electric fields represent the channel characteris

terson, S. L. Ray, and R. Mittra, *Computational methods for electromagnetics*. Wiley-IEEE Press New York, 1998.

.1 Scalar Form Equation

For simplicity, we adopt scalar form of the wave and discard the evanescent waves

$$(\mathbf{r},\mathbf{r}') = \frac{1}{4\pi}\frac{e^{\mathrm{j}\kappa_0\|\mathbf{r}-\mathbf{r}'\|}}{\|\mathbf{r}-\mathbf{r}'\|}\left[\left(\mathbf{I}-\hat{\mathbf{p}}\hat{\mathbf{p}}^{\mathrm{H}}\right)+\frac{\mathrm{j}}{2\pi\|\mathbf{r}-\mathbf{r}'\|/\lambda}\left(\mathbf{I}-3\hat{\mathbf{p}}\hat{\mathbf{p}}^{\mathrm{H}}\right)-\frac{1}{(2\pi\|\mathbf{r}-\mathbf{r}'\|/\lambda)^2}\left(\mathbf{I}-3\hat{\mathbf{p}}\hat{\mathbf{p}}^{\mathrm{H}}\right)\right] [$$

Three polarization directions

Evanescent waves that can be ignored when the distance is far larger than wavelength

Discard evanescent waves

$$\mathbf{G}(\mathbf{r},\mathbf{r}') \approx \frac{1}{4\pi}\frac{e^{\mathrm{j}\kappa_0\|\mathbf{r}-\mathbf{r}'\|}}{\|\mathbf{r}-\mathbf{r}'\|}\left(\mathbf{I}-\hat{\mathbf{p}}\hat{\mathbf{p}}^{\mathrm{H}}\right)$$

Take average on three directions

$$\mathrm{tr}(\mathbf{I}-\hat{\mathbf{p}}\hat{\mathbf{p}}^{\mathrm{H}})(\mathbf{I}-\hat{\mathbf{p}}\hat{\mathbf{p}}^{\mathrm{H}})^{\mathrm{H}} = 2$$

Incident field

Scatterer fiel

$$E(\mathbf{r}) = \mathrm{j}\omega\mu_0\int_{V_s} g(\mathbf{r},\mathbf{r}')J(\mathbf{r}')\mathrm{d}\mathbf{r}' + \int_{V} g(\mathbf{r},\mathbf{r}')(k^2(\mathbf{r}')-k_0^2)E(\mathbf{r}')\mathrm{d}\mathbf{r}'$$

$$g(\mathbf{r},\mathbf{r}') = \frac{1}{2\pi}\frac{e^{\mathrm{j}k_0\|\mathbf{r}-\mathbf{r}'\|}}{\|\mathbf{r}-\mathbf{r}'\|}$$

.1 Incident Channel and Scattered Channel

Incident channel is fixed and simple

$$E_{\mathrm{inc}}(\mathbf{r}) = \mathrm{j}\omega\mu_0 \int_{V_s} g(\mathbf{r},\mathbf{r}')J(\mathbf{r}')\mathrm{d}\mathbf{r}' \qquad g(\mathbf{r},\mathbf{r}') = \frac{1}{2\pi}\frac{e^{\mathrm{j}k_0\|\mathbf{r}-\mathbf{r}'\|}}{\|\mathbf{r}-\mathbf{r}'\|}$$

Scattered channel relies on complex scattering environment

$$E_{\mathrm{sca}} = \int_{V} g(\mathbf{r},\mathbf{r}')\left(k^2(\mathbf{r}') - k_0^2\right)E(\mathbf{r}')\mathrm{d}\mathbf{r}'$$

Need proper assumption

Complex scattering environment:

- **Scattering region V** → **Solid circle**: $\mathrm{d}\mathbf{r} = \rho\mathrm{d}\rho\mathrm{d}\theta \begin{cases} 0 \leqslant \rho \leqslant r_0 \\ 0 \leqslant \theta \leqslant 2\pi \end{cases}$
- **$k^2(\mathbf{r}') - k_0^2$** → **Parameterized function**: $f(\mathbf{r}) = \frac{a+1}{\pi r^{2a+2}}\rho(r^2-\rho^2)^a$
- **Electric field $\mathbf{E}(\mathbf{r}')$** → **Statistical model**: $R_E(\mathbf{r},\mathbf{r}')$

.1 Decouple Integral Variables

Depict the scattering field's characteristics using the statistical model

$$_E(\mathbf{d}_1, \mathbf{d}_2) = \sum_k \beta_k \int_{\mathbf{r}} \frac{S_k^2(\mathbf{r},0)}{S_k(\mathbf{r},\mathbf{d}_1)S_k(\mathbf{r},\mathbf{d}_2)} e^{-\mathrm{j}\frac{2\pi}{\lambda}(S_k(\mathbf{r},\mathbf{d}_1)-S_k(\mathbf{r},\mathbf{d}_2))} f(\mathbf{r})\mathrm{d}\mathbf{r}$$

$$= \sqrt{(\mathbf{R}_k \cdot \hat{\boldsymbol{\mu}}_k - \mathbf{d}_1 \cdot \hat{\boldsymbol{\mu}}_k)^2 + (\mathbf{R}_k \cdot \hat{\boldsymbol{\mu}}_{k1} + \rho\cos\theta - \mathbf{d}_1 \cdot \hat{\boldsymbol{\mu}}_{k1})^2 + (\mathbf{R}_k \cdot \hat{\boldsymbol{\mu}}_{k2} + \rho\sin\theta - \mathbf{d}_1 \cdot \hat{\boldsymbol{\mu}}_{k2})^2}$$

Distance from one point on the scatterer to the destination

emma 1: Assume a circle-shaped scattering region centered at R, its radius is r, its direction $\boldsymbol{\mu}$, its concentration parameter is a. Assume that the radius is far smaller than the distance etween the scattering region and the receiver, then the received electric field at position d_1 nd d_2 has the following correlation function:

$$\tilde{R}(\mathbf{d}_1, \mathbf{d}_2) = \beta_0 \frac{A(\mathbf{d}_0)}{\sqrt{A(\mathbf{d}_1)A(\mathbf{d}_2)}} e^{-\mathrm{j}\frac{2\pi}{\lambda}R\left(\sqrt{A(\mathbf{d}_1)}-\sqrt{A(\mathbf{d}_2)}\right)} 2(a+1)2^a\Gamma(a+1)(\sqrt{C}r)^{-(a+1)} J_{a+1}(\sqrt{C}r)$$

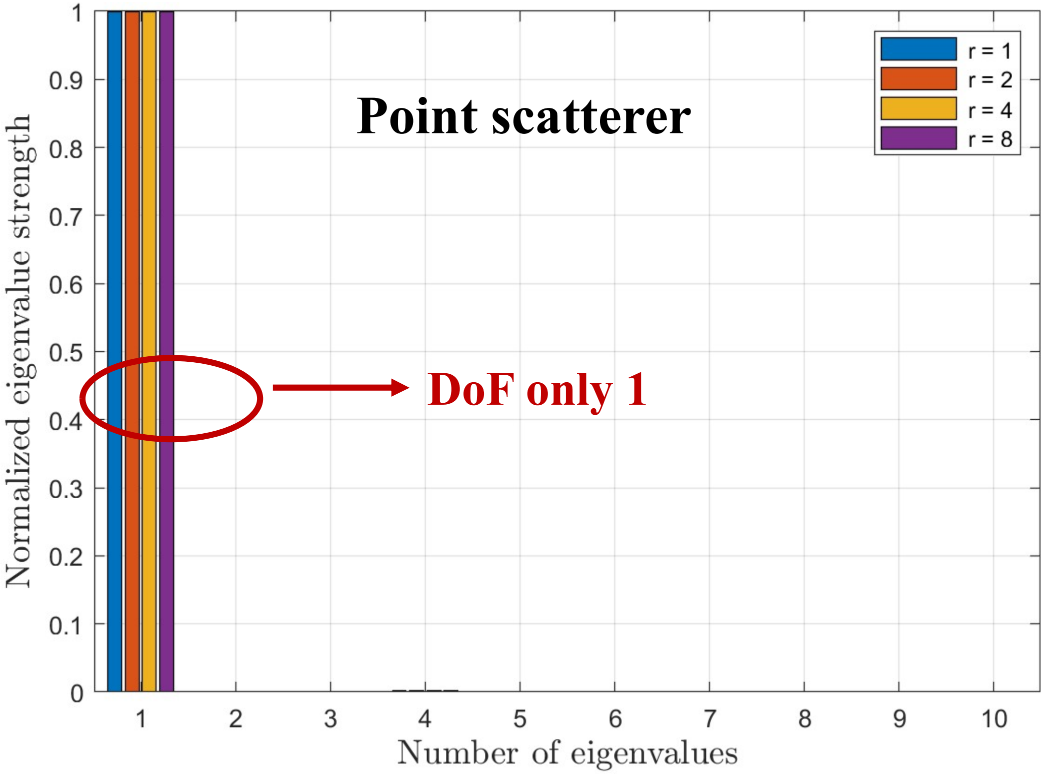
Channel can be generated by $\mathbf{h} = \mathbf{L}\mathbf{w}$ **where** $\mathbf{R} = \mathbf{L}\mathbf{L}^{\mathrm{H}}$ $\mathbf{w} \sim \mathcal{CN}(0, \mathbf{I})$

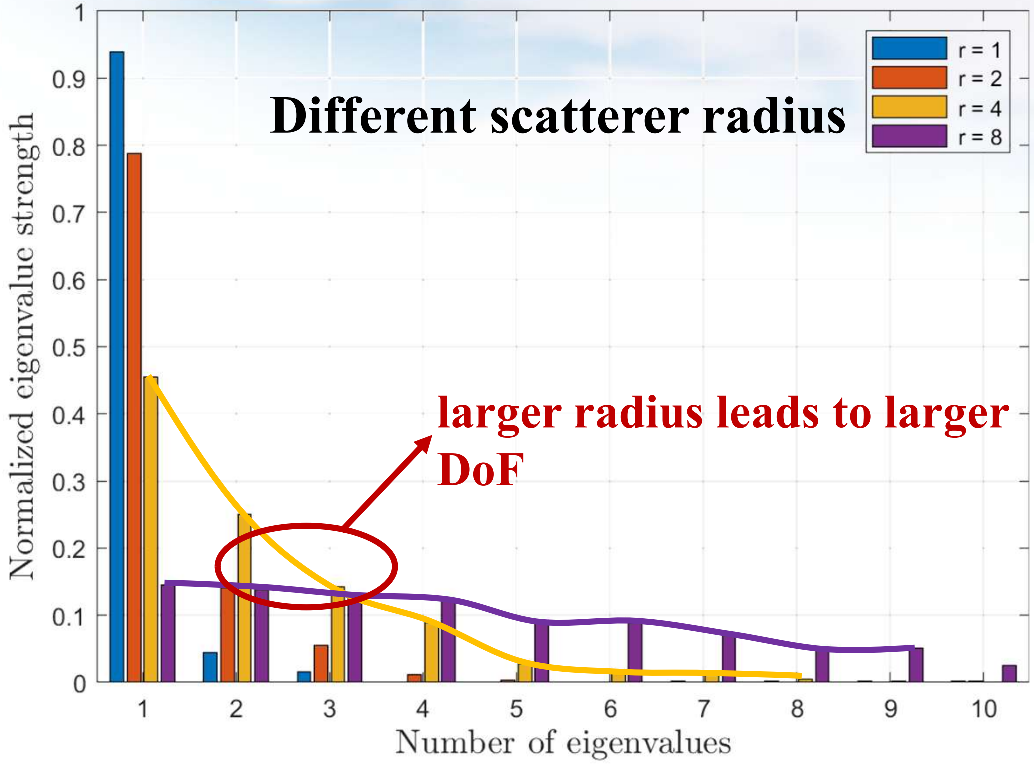
J. Zhu, and **L. Dai**, "Near-field channel modeling for electromagnetic information theory," *IEEE Trans. Wireless Commun.*, Sep. 2024.

.1 Scatterer parameters and channel DoF

Eigenvalue analysis based on the proposed correlation function of the channel

The slower the eigenvalue decay, the larger the channel DoF





The near-field channel model for EIT provides more accurate description of DoF

J. Zhu, and **L. Dai**, "Near-field channel modeling for electromagnetic information theory," *IEEE Trans. Wireless Commun.*, Sep. 2024

Contents

- Chapter 1: Introduction to EIT
  - 1.1 Motivation of EIT
  - 1.2 Shannon information theory
  - 1.3 Maxwell electromagnetic theory
  - 1.4 Overview of EIT
- **Chapter 2: Fundamentals of EIT**
  - 2.1 Electromagnetic channel models for EIT
  - 2.2 DoF analysis for EIT
  - 2.3 Mutual information for EIT
- Chapter 3: EIT-Enabled Technologies
  - 3.1 Holographic MIMO
  - 3.2 EIT-enabled near-field communications
  - 3.3 Mutual coupling and superdirective antennas
  - 3.4 Orbital angular momentum
  - 3.5 3D antenna arrays
- Chapter 4: EIT-Inspired Technologies
  - 4.1 EIT-inspired channel estimation
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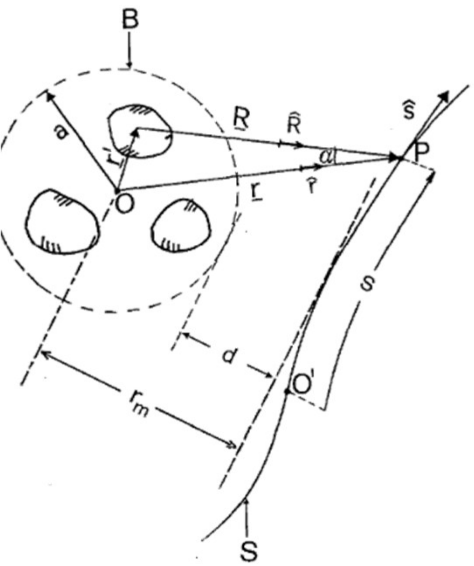
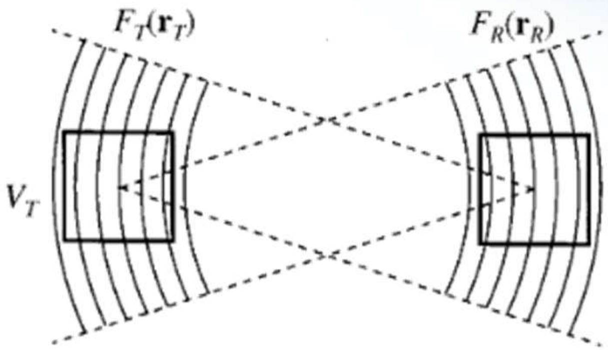
  - 4.3 EIT-inspired self-controlled RIS
- Chapter 5: Conclusions

.2 Introduction to EM DoF Analysis

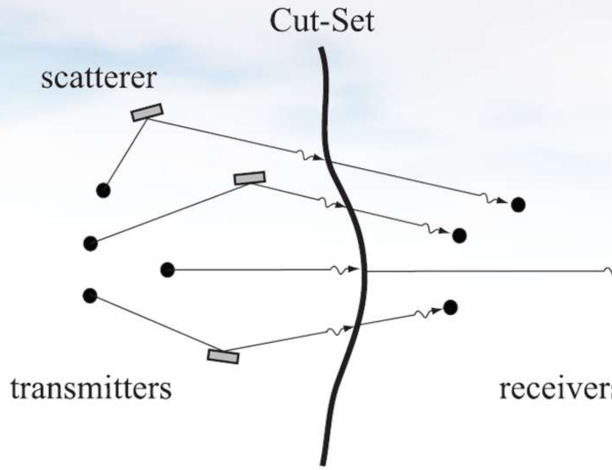
Evaluation of **EM degrees-of-freedom (DoF)**



DoF analysis via spatial bandwidth [1]



DoF analysis of a LoS volume communication system [2]



DoF analysis via information cut-set theory [3]

DoF analysis is based on continuous EM fields

. M. Bucci and G. Franceschetti, "On the spatial bandwidth of scattered fields," *IEEE Trans. Antennas Propagat.*, vol. 35, no. 12, pp. 1445-1455, Dec. 1987.

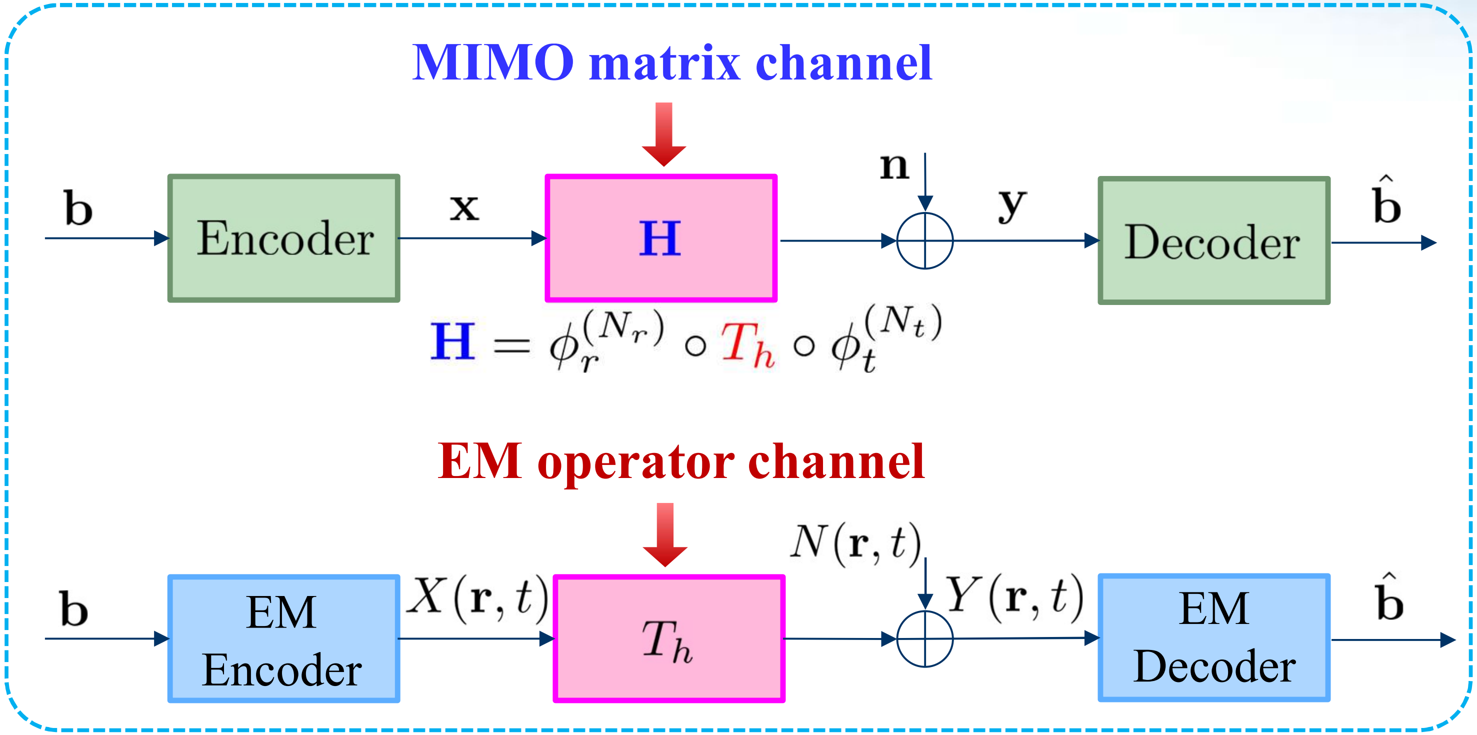
. A. B. Miller, "Communicating with waves between volmes: Evaluating orthogonal spatial channels and limits on coupling strengths," *Applied Optics*, vol. 39, no. 11, pp. 168
ov. 2000.

. Franceschetti, "On Landau's eigenvalue theorem and information cut-sets," *IEEE Trans. Inf. Theory*, vol. 61, no. 9, pp. 5042–5051, Sep. 2015.

.2 Continuous EM Transmission Model

Transmission model: From discrete matrices to continuous operators

- **Discrete MIMO model: Based on matrix theory, while neglecting continuous EM distribution**
- **EM operator model: Based on operator theory for nearly-continuous transceiver regions**



MIMO matrix model

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$$

EM operator model

$$Y = T_h X + N$$

. Dardari, "Communicating with large intelligent surfaces: Fundamental limits and models," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 11, pp. 2526–2537, Nov. 2020.

Wan, J. Zhu, Z. Zhang, **L. Dai**, and C.-B. Chae, "Mutual information for electromagnetic information theory based on random fields," *IEEE Trans. Commun.*, vol. 71, no. 4, p
982-1996, Apr. 2023.

.2 EIT Degrees of Freedom (DoFs)

The discrete-continuous comparison lemma for evaluating EM Degrees of Freedom

- **Definition: Discrete system = Continuous system cascaded with antenna system**
- **Remark: Enabling continuous analysis to be applied to discrete systems, obtaining EIT upper bo for arbitrary MIMO systems**

Rx Antenna

Tx Antenna

$$\mathbf{H} = \phi_r^{(N_r)} \circ T_h \circ \phi_t^{(N_t)}$$

Data processing inequality (dpi)

$$\mathbb{E}[C_{\mathrm{MIMO}}] \leq \mathbb{E}[C_{\mathrm{EIT}}]$$

Theorem 2.2.1 Let the Tx/Rx region be $V_{\mathrm{T}},\ V_{\mathrm{R}} \subset \mathbb{R}^3$, $T_h:\ \mathcal{L}^2(V_{\mathrm{T}}) \to \mathcal{L}^2(V_{\mathrm{R}})$ **is the channel operator,** $\phi_t^{(N_t)}:\ \mathbb{C}^{N_t} \to \mathcal{L}^2(V_{\mathrm{T}})$, $\phi_r^{(N_r)}:\ \mathcal{L}^2(V_{\mathrm{R}}) \to \mathbb{C}^{N_r}$ **are energy-conservative Tx/Rx antenna operators, then for any** $\varepsilon > 0$ **, the following inequality holds:**

$$\mathrm{DoF}(\mathbf{H}, \varepsilon) \leq \mathrm{DoF}(T_h, \varepsilon),$$

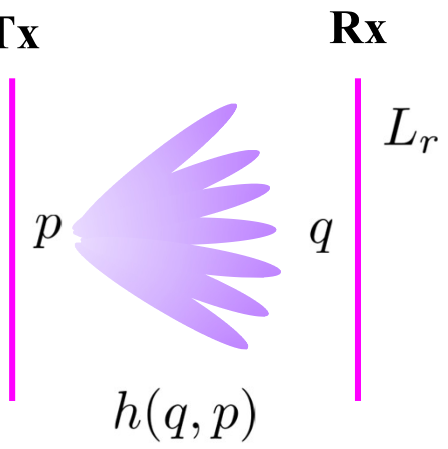
where $\mathbf{H} = \phi_r^{(N_r)} \circ T_h \circ \phi_t^{(N_t)}$ **is the discrete channel matrix,** $\mathrm{DoF}(T, \varepsilon)$ **is the operator** T**'s** ε**-DoF.**

Y. F. Tan, and **L. Dai**, "MIMO capacity analysis and channel estimation for electromagnetic information theory," submitted to *IEEE Trans. Inf. Theory*, Jun. 2024.

.2 Dual-bandlimited Property of the EM Channel

Basic properties of the EM channel: Dual-bandlimited property

- **Spatially bandlimited [1]: The spatial FT of the channel $h(q,p)$ is bandlimited on $\mathcal{A}_r \times \mathcal{A}_t \subset [-$**
- **Angularly bandlimited [2]: The angular channel $\tilde{h}(\beta,\alpha)$ is Γ-bandlimited with colored scatterin**



EM Channel

From Helmholtz equation, we have the spatially bandlimited channel

$$\tilde{h}(\beta,\alpha) = \int_{-L_r/2}^{L_r/2} \mathrm{d}q \int_{-L_t/2}^{L_t/2} \mathrm{d}p\, h(q,p) e^{-\mathrm{i}2\pi q\beta} e^{-\mathrm{i}2\pi p\alpha}.$$

For colored scattering, [2] assumes an angularly bandlimited channel

$$\mathbb{E}\left[\tilde{h}(\beta,\alpha)\tilde{h}^*(\beta',\alpha')\right] = \frac{\sigma_{\tilde{h}}^2}{\Gamma_t\Gamma_r}\mathrm{sinc}\left(\frac{\alpha-\alpha'}{\Gamma_t}\right)\cdot \mathrm{sinc}\left(\frac{\beta-\beta'}{\Gamma_r}\right).$$

David Tse
Shannon Award Recipient
Member of the National Ac
Engineering (US)

S. Poon, D. N. Tse, and R. W. Brodersen, "Impact of scattering on the capacity, diversity, and propagation range of multiple-antenna channels," *IEEE Trans. Inf. Theory*, vol. 5 1087–1100, Mar. 2006.

Nam, D. Bai, J. Lee, and I. Kang, "On the capacity limit of wireless channels under colored scattering," *IEEE Trans. Inf. Theory*, vol. 60, no. 6, pp. 3529–3543, Apr. 2014.

.2 Ergodic Capacity Analysis: Upper Bound

Dual bandlimited property leads to a special eigen problem

- **PSWF eigen problem: Find a $\mathcal{B}$ -bandlimited function that is most concentrated in $\mathcal{A}$**
- **Solution to the above eigenproblem is called $(\mathcal{A}, \mathcal{B})$-prolate spheroidal wave function (PSWF)**

Truncation $\Pi_{\mathcal{A}}: f \to f 1_{\mathcal{A}}$

Bandpass filtering $\Pi_{\mathcal{B}}: f \to \mathcal{F}^{-1}[\mathcal{F}(f) 1_{\mathcal{B}}]$

PSWF eigenproblem $\gamma_\ell \psi_\ell = \Pi_{\mathcal{B}} \Pi_{\mathcal{A}} \psi_\ell$

Upper bound of the ergodic capacity is given by the PSWF eigenvalues $\{\gamma_\ell\}_{\ell=0}^{\infty}$ [1]

hm 2.2.2[1] Assume the channel operator $T_h: \mathcal{L}^2(V_{\mathrm{T}}) \to \mathcal{L}^2(V_{\mathrm{R}})$ is spatially bandlimited in $\mathcal{A}_t = \mathcal{A}_r = \mathcal{A}$ with olored scattering bandwidth Γ. Then, the ergodic capacity $\mathbb{E}[C_{\mathrm{EIT}}(T_h, P_{\mathrm{T}}/\sigma_z^2)]$ is upper-bounded by the igenvalues of $(\mathcal{A}, \mathcal{B}_\Omega)$ -PSWF through

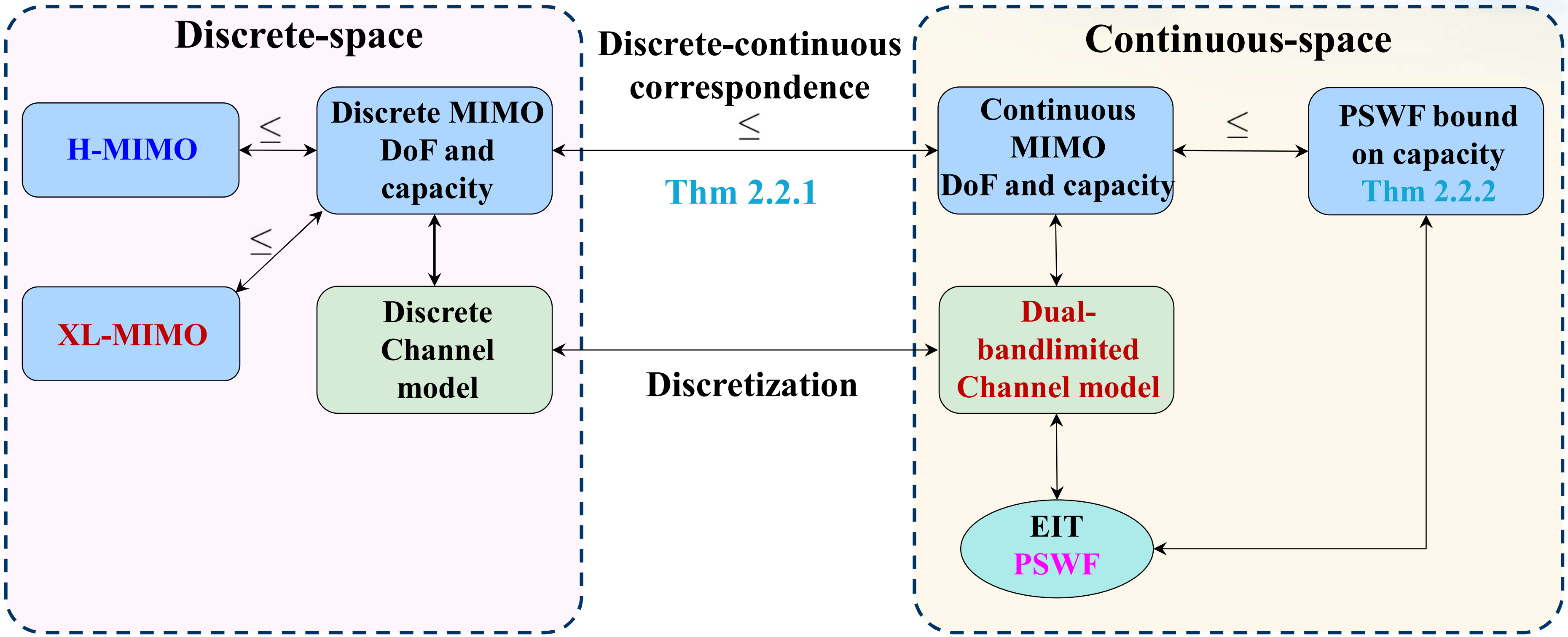
$$\mathbb{E}\left[C_{\mathrm{EIT}}\left(T_h, \frac{P_{\mathrm{T}}}{\sigma_z^2}\right)\right] \leq \sum_{\ell=0}^{\infty} \log\left(1 + \frac{P_{\mathrm{T}}}{\sigma_z^2}\gamma_\ell\right),$$ **where** $\Omega = \min\left\{\frac{L}{\lambda}, \frac{1}{\Gamma}\right\}$, L [m] **is the receiver aperture**

Nam, D. Bai, J. Lee, and I. Kang, "On the capacity limit of wireless channels under colored scattering," *IEEE Trans. Inf. Theory*, vol. 60, no. 6, pp. 3529–3543, Apr. 2014.

.2 Apply Continuous Upper Bound to Discrete Systems

Discrete-continuous comparison (Thm 2.2.1) applied to novel MIMO architectures

- **Holographic MIMO (H-MIMO): Aperture limited, but antenna spacing unlimited**
- **Extremely large-scale MIMO (XL-MIMO): Aperture unlimited, but antenna spacing limited**



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.2 Ergodic Capacity Upper Bound Algorithm

Legendre spectral method for PSWF eigenvalues $\{\gamma_\ell\}_{\ell=0}^{\infty}$

SWF
gen-problem $\gamma_\ell \psi_\ell = \Pi_{\mathcal{B}} \Pi_{\mathcal{A}} \psi_\ell$

Spatial representation

tegral operator
gen-problem

$$\lambda_n \psi_n(x) = [\mathcal{M}_c \psi_n](x) := \int_{-1}^{1} \frac{\sin(c(x-y))}{\pi(x-y)} \psi_n(y) \mathrm{d}y$$

Operator commutes
$\mathcal{M}_c \mathcal{L}_c = \mathcal{L}_c \mathcal{M}_c$

ifferential operator
gen-problem

$$c)\psi_n(x) = [\mathcal{L}_c \psi_n](x) := \left(\frac{\mathrm{d}}{\mathrm{d}x}(1-x^2)\frac{\mathrm{d}}{\mathrm{d}x} - c^2 x^2 \right) \psi_n(x)$$

Legendre series expansion

$$\psi_n(x) = \sum_{k=0}^{\infty} \beta_{nk}(c) \bar{P}_k(x)$$

latrix
gen-problem $(\mathbf{A} - \chi_n(c)\mathbf{I})\boldsymbol{\beta}_n(c) = \mathbf{0}$

Algorithm 1 Modified Bouwkamp Algorithm

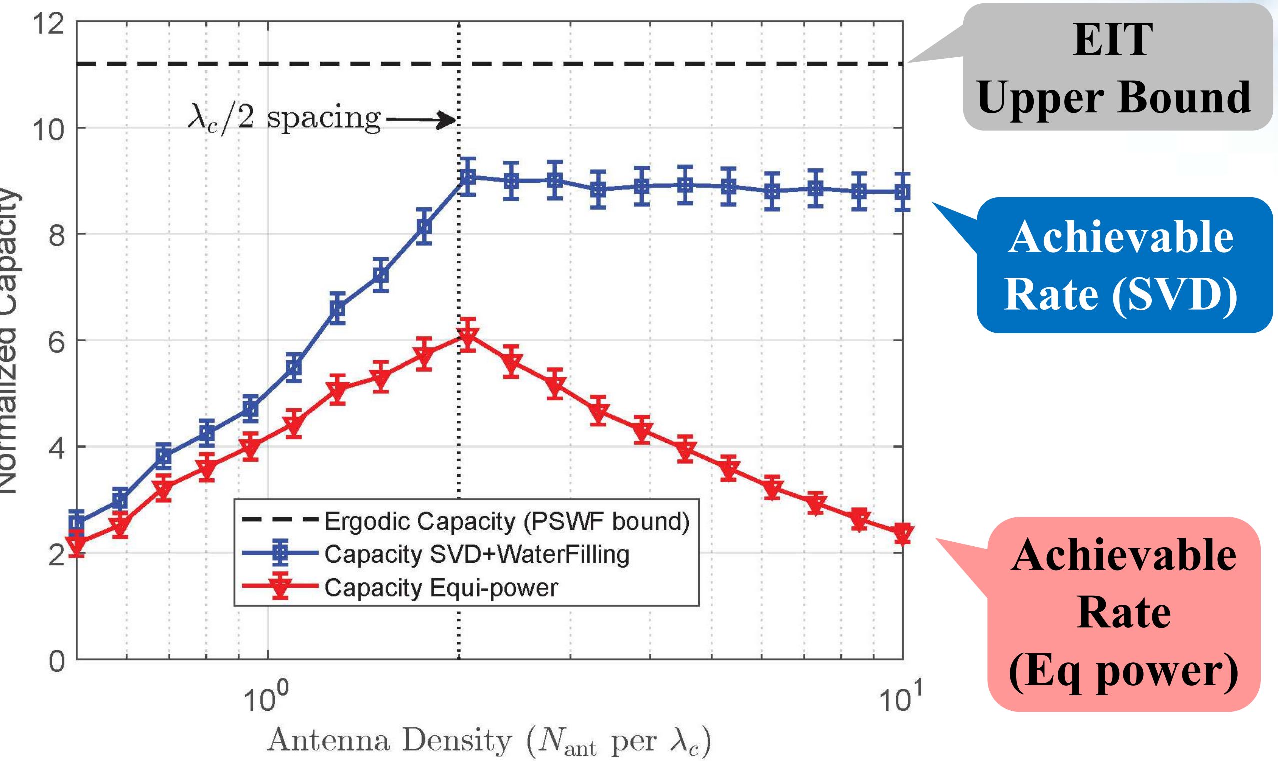
Input: Bandwidth parameter Ω; interval $\mathcal{A} = [a, b]$;
mum spectral order $n_{\max}$.
Output: Approximated PSWFs $\{\phi_\ell(x)\}_{\ell=0}^{n_{\max}}$; approx
prolate spheroidal eigenvalues $\{\gamma_\ell\}_{\ell=0}^{n_{\max}}$.

1: $c \leftarrow \pi\Omega(b-a)/2$.
2: Construct the normalized Legendre polynomials
order $n_{\max}$ by (34), and gather the polynomial coef
in the matrix $\mathbf{P} \in \mathbb{R}^{(n_{\max}+1)\times(n_{\max}+1)}$.
3: Compute $[\mathbf{V}, \mathbf{D}] = \mathrm{eig}(\mathbf{A})$ of (36) with eigenvalues
in descending order.
4: Let $\beta_{nk}(c) \leftarrow [\mathbf{V}]_{k,n}$ to determine ψ_n via (35).
5: Compute the coefficient matrix $\mathbf{P}'$ of $\bar{P}_n'(x)$ from
6: $\mu_0 \leftarrow \mathrm{Numerical}(\langle \psi_0, F_c \psi_0 \rangle)$.
7: $y_{\mathrm{prev}} \leftarrow \mathrm{Numerical}(\psi_0)$, $y'_{\mathrm{prev}} \leftarrow \mathrm{Numerical}(\psi'_0)$.
8: **for** $\ell = 1, 2, \ldots, n_{\max}$ **do**
9: $y_{\mathrm{cur}} \leftarrow \mathrm{Numerical}(\psi_\ell)$ by $\beta_{\ell k}(c)$ and $\mathbf{P}$.
10: $y'_{\mathrm{cur}} \leftarrow \mathrm{Numerical}(\psi'_\ell)$ by $\beta_{\ell k}(c)$ and $\mathbf{P}'$.
11: $a \leftarrow \mathrm{Numerical}(\langle y_{\mathrm{cur}}, y'_{\mathrm{prev}} \rangle)$.
12: $b \leftarrow \mathrm{Numerical}(\langle y'_{\mathrm{cur}}, y_{\mathrm{prev}} \rangle)$.
13: $\mu_\ell \leftarrow \mathrm{i}\mu_{\ell-1} \cdot \sqrt{|a/b|}$.
14: $y_{\mathrm{prev}} \leftarrow y_{\mathrm{cur}}$, $y'_{\mathrm{prev}} \leftarrow y'_{\mathrm{cur}}$.
15: **end for**
16: $\gamma_\ell \leftarrow c|\lambda_\ell|^2/(2\pi)$, $\forall \ell \in [n_{\max}+1]$.
17: Get ϕ_ℓ: rescale ψ_ℓ from $[-1, 1]$ to $[a, b]$ by (2
applying a re-normalization factor $\sqrt{2/(b-a)}$.
18: **return** $\{\gamma_\ell\}_{\ell=0}^{n_{\max}}$, $\{\phi_\ell\}_{\ell=0}^{n_{\max}}$.

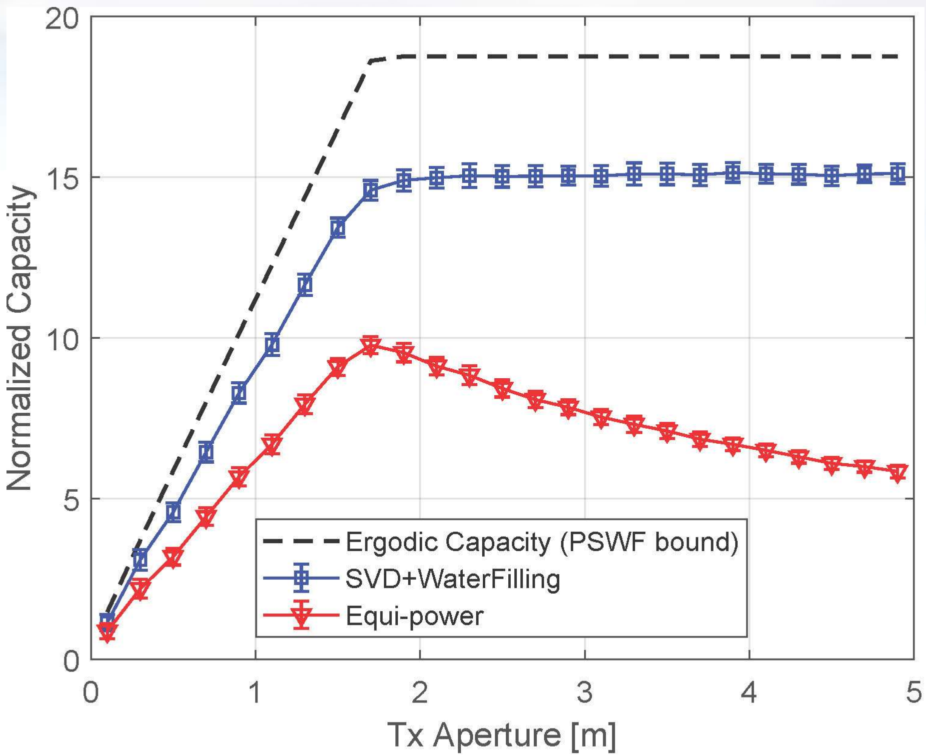
and T. Moumni, "New efficient methods of computing the prolate spheroidal wave functions and their corresponding eigenvalues," *Applied and Comput. Harmon.*, Jul. 2008.

.2 Numerical Results

EIT upper bound applied to H-MIMO and XL-MIMO architecture



H-MIMO (unlimited antenna spacing)



XL-MIMO (unlimited aperture size)

acity growth of H-MIMO and XL-MIMO is limited by EM dual-bandlimited prop

Y. F. Tan, and **L. Dai**, "MIMO capacity analysis and channel estimation for electromagnetic information theory," submitted to *IEEE Trans. Inf. Theory*, Jun. 2024.

Contents

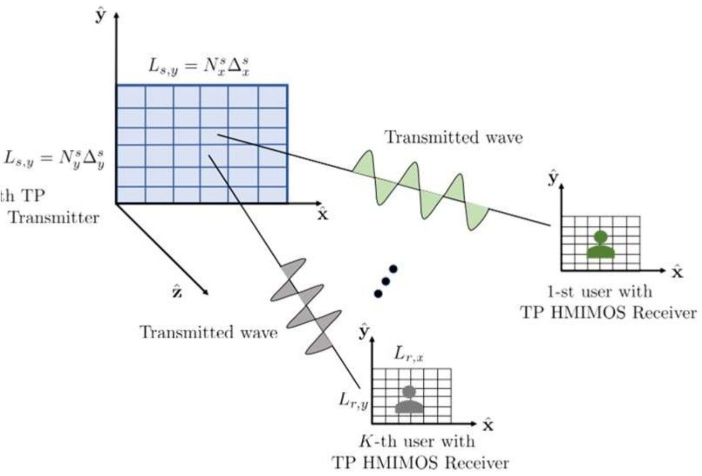
- Chapter 1: Introduction to EIT
  - 1.1 Motivation of EIT
  - 1.2 Shannon information theory
  - 1.3 Maxwell electromagnetic theory
  - 1.4 Overview of EIT
- Chapter 2: Fundamentals of EIT
  - 2.1 Electromagnetic channel models for EIT
  - 2.2 DoF analysis for EIT
  - 2.3 Mutual information for EIT
- Chapter 3: EIT-Enabled Technologies
  - 3.1 Holographic MIMO
  - 3.2 EIT-enabled near-field communications
  - 3.3 Mutual coupling and superdirective antennas
  - 3.4 Orbital angular momentum
  - 3.5 3D antenna arrays
- Chapter 4: EIT-Inspired Technologies
  - 4.1 EIT-inspired channel estimation
  - 4.2 EIT-inspired channel prediction
  - 4.3 EIT-inspired self-controlled RIS
- Chapter 5: Conclusions

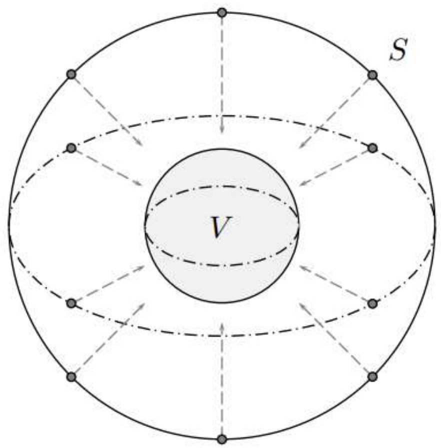
.3 Mutual Information & Capacity Analysis

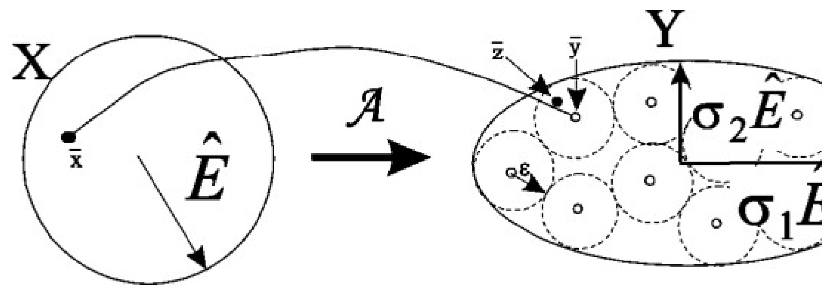
Use classical MIMO information theory based on spatial discretization of EM mod

Use spherical harmonic functions to decompose continuous fields [2]

Kolmogorov's ε-capacity considering distinguishable waveforms above an uncertai level [3]







Discretized EM model Concentric spherical transceivers Sphere packing of radiation oper

Vei, C. Huang, G. C. Alexandropoulos, Z. Yang, J. Yang, E. Wei, Z. Zhang, M. Debbah, and C. Yuen, "Tri-polarized holographic MIMO surfaces for near-field communications: nel modeling and precoding design," *IEEE Trans. Wireless Commun.*, vol. 22, no. 12, pp. 8828–8842, Dec. 2023.
eon and S.-Y. Chung, "Capacity of continuous-space electromagnetic channels with lossy transceivers," *IEEE Trans. Inf. Theory*, vol. 64, no. 3, pp. 1977–1991, Mar. 2018.
). Migliore, "On electromagnetics and information theory," *IEEE Trans. Antennas Propag.*, vol. 56, no. 10, pp. 3188–3200, Oct. 2008.

.3 Mutual Information Analysis of EIT

Input-output relationship of continuous EM model

Electric field

Green's function

From current density at transmitter
To electric field at receiver

$$\mathbf{E}(\mathbf{r}) = \int_{V_s} \mathbf{G}(\mathbf{r},\mathbf{s})\mathbf{J}(\mathbf{s})\mathrm{d}\mathbf{s}, \quad \mathbf{r} \in V_r$$

Current density

Received electric field with noise

$$\mathbf{Y}(\mathbf{r}) = \mathbf{E}(\mathbf{r}) + \mathbf{N}(\mathbf{r}) \quad \mathbf{r} \in V_r$$

Green's function (Spatial impulse response)

reen's function

$$\mathbf{G}(\mathbf{r},\mathbf{s}) = \frac{\mathrm{j}\kappa Z_0}{4\pi}\frac{e^{\mathrm{j}\kappa\|\mathbf{r}-\mathbf{s}\|}}{\|\mathbf{r}-\mathbf{s}\|}\left(\mathbf{I} + \frac{\nabla_{\mathbf{r}}\nabla_{\mathbf{r}}^{\mathrm{H}}}{\kappa^2}\right) \approx \frac{\mathrm{j}\kappa Z_0}{4\pi}\frac{e^{\mathrm{j}\kappa\|\mathbf{r}-\mathbf{s}\|}}{\|\mathbf{r}-\mathbf{s}\|}\left(\mathbf{I} - \hat{\mathbf{p}}\hat{\mathbf{p}}^{\mathrm{H}}\right)$$

$$\hat{\mathbf{p}} = \frac{\mathbf{p}}{\|\mathbf{p}\|} \qquad \mathbf{p} = \mathbf{r} - \mathbf{s}$$

Conditions: infinite boundary, homogeneous dielectric, time-harmonic field

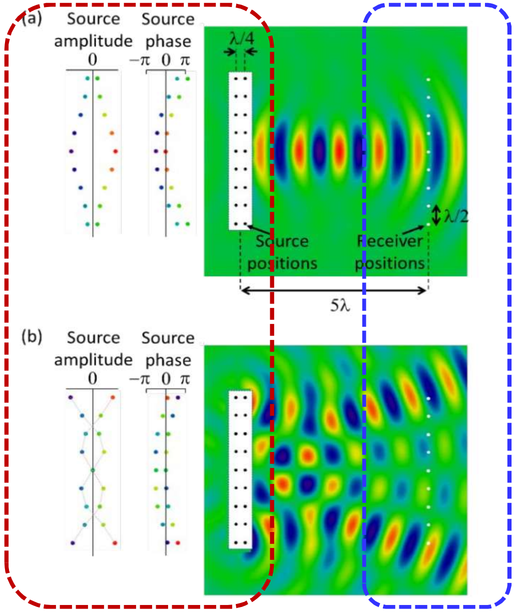
From spatially discrete model to spatially continuous model

.3 Mutual Information Analysis of EIT

Convey information by **continuous electromagnetic fields**

Mutual information: **Eliminate the uncertainty** of the current **J** from the observed electric field **Y**

- ➢ Model current and electric field by **Gaussian random fields**



Electromagnetic channel $\mathbf{E}(\mathbf{r}) = \int_{V_s} \mathrm{G}(\mathbf{r}, \mathrm{s})\mathbf{J}(\mathbf{s})\mathrm{ds}$

Noisy received field $\mathbf{Y}(\mathbf{r}) = \mathbf{E}(\mathbf{r}) + \mathbf{N}(\mathbf{r})$

Mutual information $I(\mathbf{J}; \mathbf{Y}) = \sup\{I(\mathbf{J}(\phi_1, \cdots, \phi_m), \mathbf{Y}(\psi_1, \cdots, \psi_n$

Challeng: How to drive the mutual information?

.3 Mutual Information Analysis of EIT

Use KL expansion to derive the mutual information

Random field and Correlation function

$$E(\mathbf{r}) = \sum_{k=1}^{+\infty} \xi_k \phi_k(\mathbf{r}), \quad R_E(\mathbf{r},\mathbf{r}') = \sum_{k=1}^{+\infty} \lambda_k \phi_k(\mathbf{r}) \phi_k^*(\mathbf{r}')$$

Integral equation

$$\lambda_k \phi_k(\mathbf{r}') = \int_0^l R_E(\mathbf{r},\mathbf{r}') \phi_k(\mathbf{r}) \mathrm{d}\mathbf{r}; k > 0, k \in \mathbb{N}$$

Eigenvalue: gain → **Eigenfunction: base**

Orthogonal basis, independent coefficients

$$\int \phi_{k_1}(\mathbf{r}) \phi_{k_2}(\mathbf{r}) \mathrm{d}\mathbf{r} = \delta_{k_1 k_2}, \quad \mathbb{E}[\xi_{k_1} \xi_{k_2}] = \mathbb{1}_{k_1 = k_2} \lambda_{k_1}$$

ectric field

$$E(\mathbf{r}) = \sum_{k=1}^{+\infty} \xi_k \phi_k(\mathbf{r}) \quad \lambda_k \phi_k(\mathbf{r}') = \int_0^l R_E(\mathbf{r},\mathbf{r}') \phi_k(\mathbf{r}) \mathrm{d}\mathbf{r}; k > 0, k \in \mathbb{N}$$

Noise field

$$N(\mathbf{r}) = \sum_{k=1}^{+\infty} \xi_k' \phi_k(\mathbf{r}) \quad \frac{n_0}{2} \phi_k(\mathbf{r}') = \int_0^l \frac{n_0}{2} \delta(\mathbf{r}' - \mathbf{r}) \phi_k(\mathbf{r}) \mathrm{d}\mathbf{r}; k > 0, k \in \mathbb{N}$$

→ **MI for continuous f**

$$I = \sum_{k=1}^{\infty} \log(1 + \frac{\lambda_k}{n_0/}$$

J. Zhu, Z. Zhang, **L. Dai**, and C.-B. Chae, "Mutual information for electromagnetic information theory based on random fields," *IEEE Trans. Commun.*, vol. 71, no. 4, pp. 198
23.

.3 Mutual Information Analysis of EIT

Expression of the mutual information in operator **determinant form** (**Fredholm determinant**)

	Matrix H	Operator T
Equation	$\mathbf{H}\mathbf{x}_k = \lambda \mathbf{x}_k$	$\mathrm{T}\phi_k(r) = \lambda_k \phi_k(r)$
Base	Eigenvector $\mathbf{x}_k$	Eigenfunction $\phi_k(r)$
Trace	$\sum_{k=1}^{N} \lambda_k = \sum_{i=1}^{N} H_{i,i}$	$\sum_{k=1}^{+\infty} \lambda_k = \int_0^l K(r,r)\mathrm{d}r$
Determinant	$\prod_{k=1}^{N} \lambda_k = \det(\mathrm{H})$	$\prod_{k=1}^{+\infty} \lambda_k = \det(\mathrm{T})$

$$I = \sum_{k=1}^{+\infty} \log\left(1 + \frac{\lambda_k}{n_0/2}\right)$$
$$= \log \prod \left(1 + \frac{\lambda_k}{n_0/2}\right)$$
$$= \log\left(\det(\mathbf{1} + \frac{\mathrm{T}_E}{n_0/2})\right)$$

Operator determinant

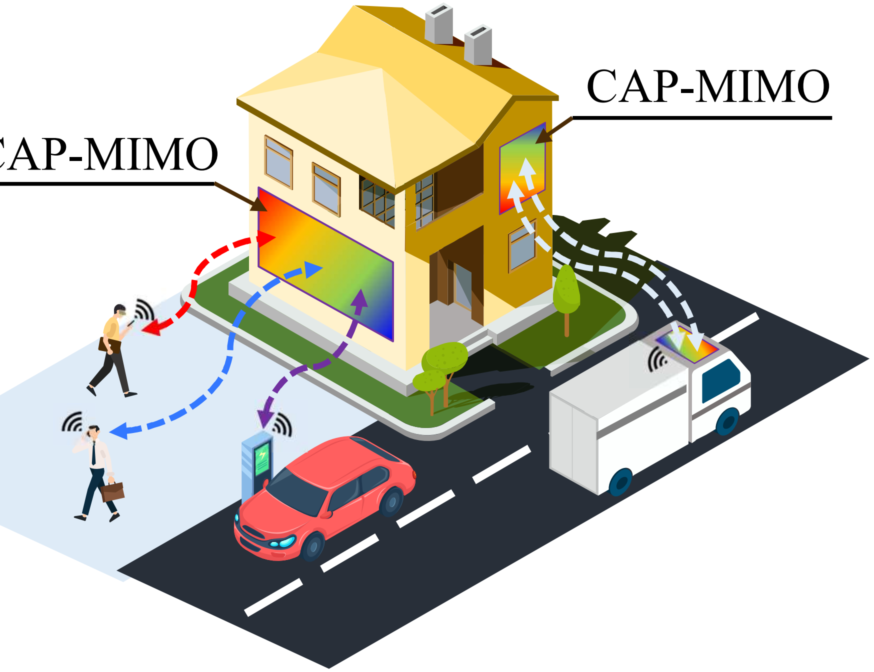
New tool to analyze the properties of mutual information between continuous fields

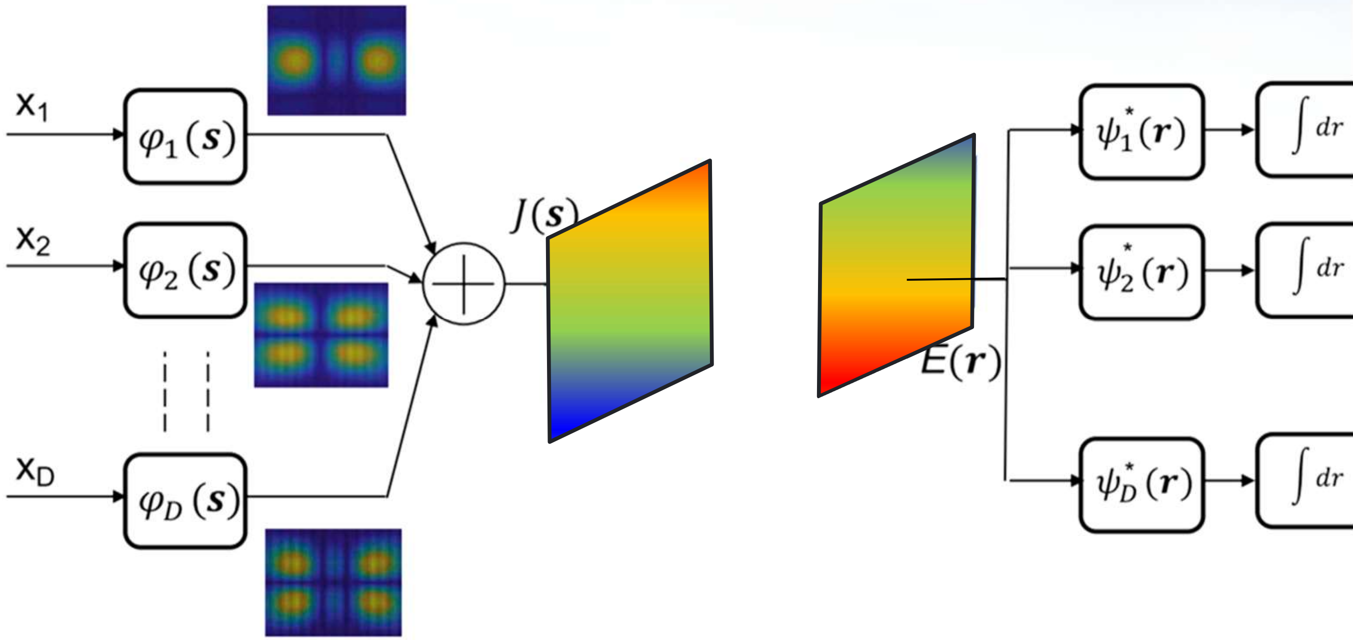
J. Zhu, Z. Zhang, **L. Dai**, and C.-B. Chae, "Mutual information for electromagnetic information theory based on random fields," *IEEE Trans. Commun.*, vol. 71, no. 4, pp. 198
23.

.3 CAP-MIMO Based Wireless Communications

Continuous-aperture MIMO (CAP-MIMO), holographic MIMO, large intelligent surface

The current density (pattern) is generated on the aperture of CAP-MIMO transmitter whi
induces the information-carrying electromagnetic waves



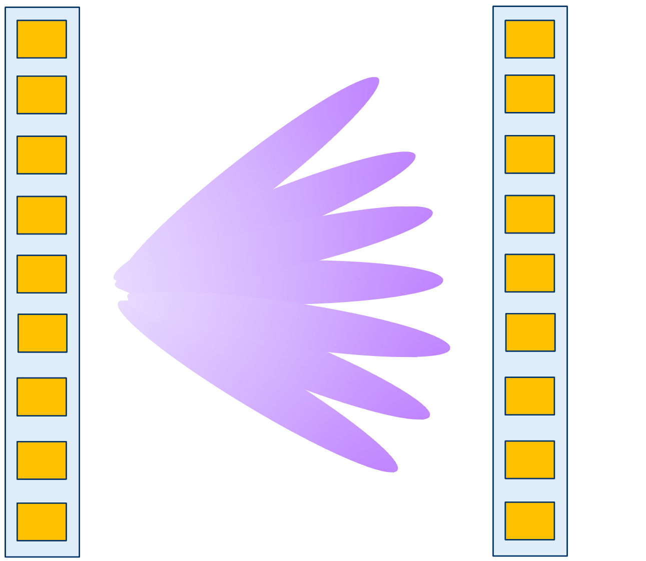


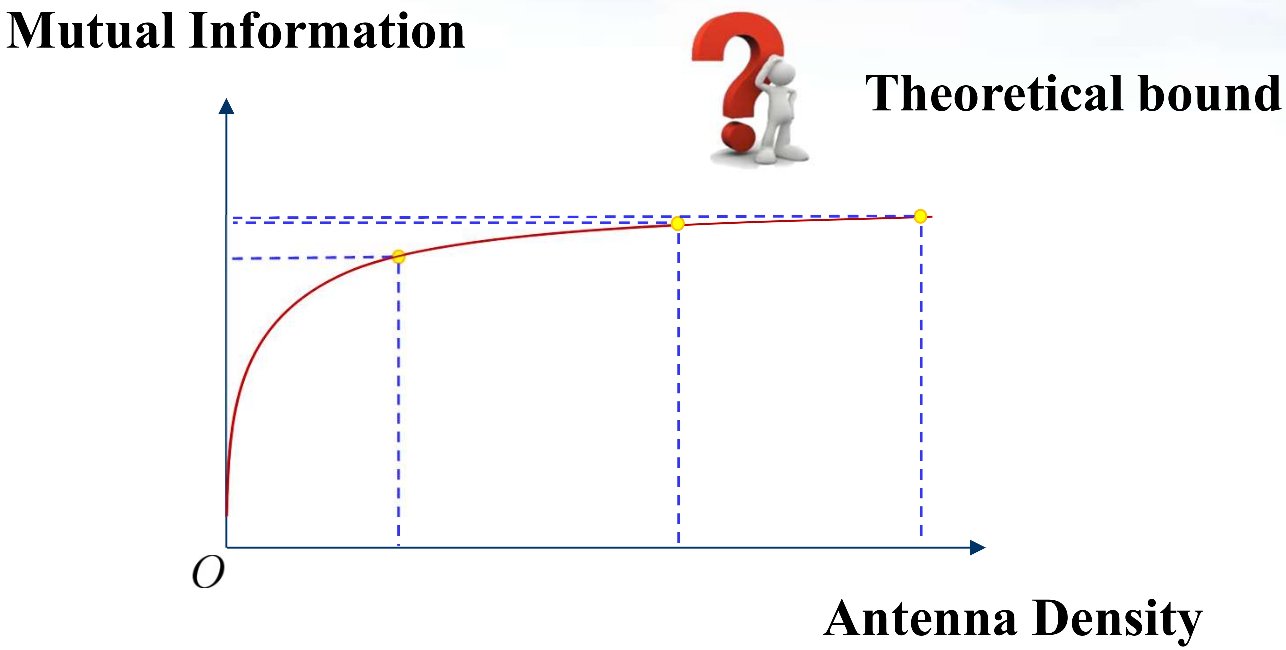
, T. L. Marzetta and L. Sanguinetti, "Spatially-stationary model for holographic MIMO small-scale fading," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 9, pp. 1964-1979, Sep. 2

.3 CAP-MIMO and Discrete MIMO

Can CAP-MIMO achieve infinite performance gain by deploying infinitely dense antennas

If not, what is the relationship between the performance of CAP-MIMO and discrete MIM





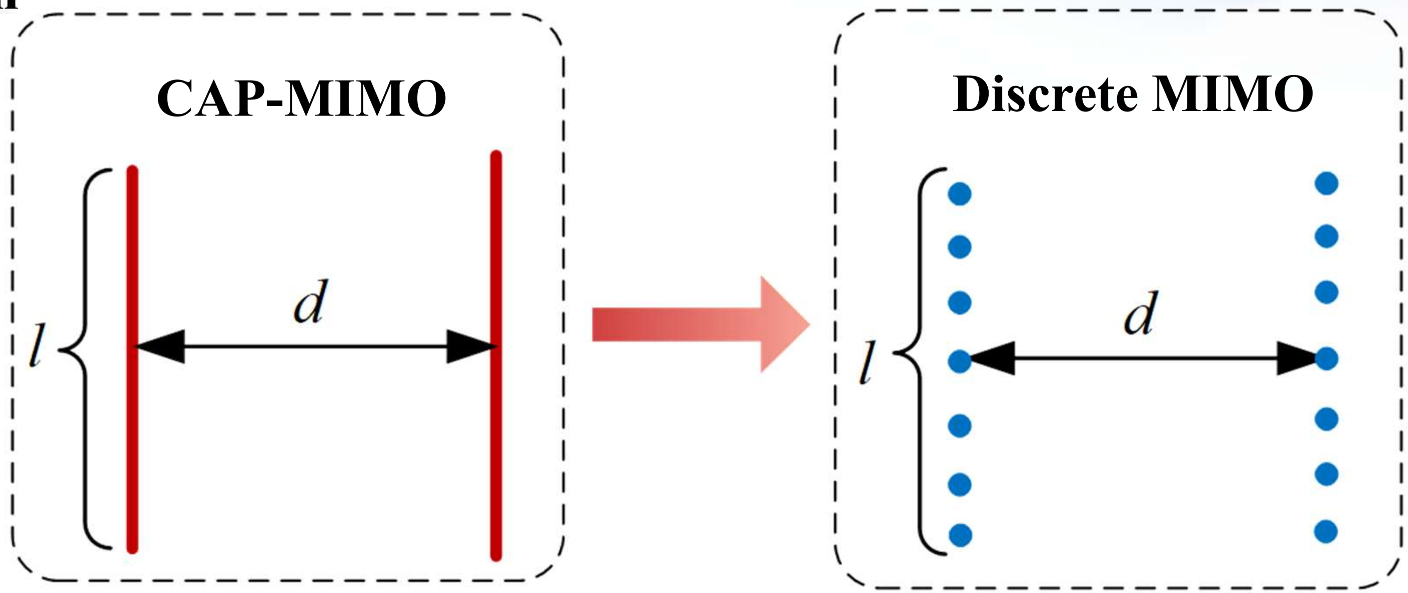
J. Zhu, and **L. Dai**, "Can continuous aperture MIMO achieve much better performance than discrete MIMO?," *IEEE Commun. Lett.*, vol. 27, no. 12, pp. 3185-3189, Dec. 202

.3 Modeling

The **distances** between transceivers are **equal** for CAP-MIMO and discrete MIMO

CAP-MIMO: Length-l transmitter and length-l receiver

Discrete MIMO: m_1 antennas in length-l transmitting region and m_2 antennas in length-l receiving region



CAP-MIMO Signal	CAP-MIMO Noise	Discrete MIMO Signal	Discrete MIMO Noise
$R_J(s,s') = P_1\delta(s-s')$	$R_N(r,r') = \frac{n_1}{2}\delta(r-r')$	$R_{\mathbf{J}} = P_2\mathbf{I}_{m_1}$	$R_{\mathbf{N}} = \frac{n_2}{2}\mathbf{I}_{m_2}$

J. Zhu, and **L. Dai**, "Can continuous aperture MIMO achieve much better performance than discrete MIMO?," *IEEE Commun. Lett.*, vol. 27, no. 12, pp. 3185-3189, Dec. 2023

.3 Performance Comparison

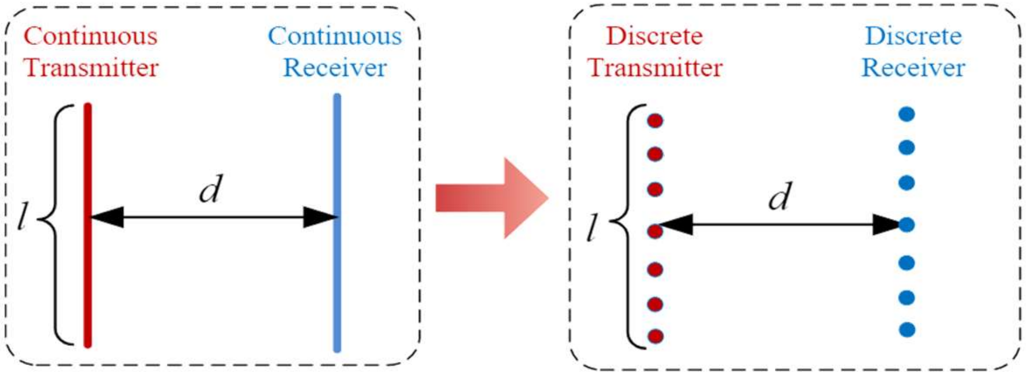
Mutual information (MI) difference between CAP-MIMO and discrete MIMO

Theorem 1: The MI difference can be bounded by

$$|I_1 - I_2| \leqslant \frac{C_1}{(\min(m_1, m_2))^2}$$

Antenna number/density

Constant C_1 is determined by various parameters including channel characteristics and transmitter sizes and distances



$$C_1 \propto x^2 e^{cx^2}$$

$$\max \left\| \frac{\partial_x^i \partial_y^j \partial_z^k g(x,y,z)}{\partial x^i \partial y^j \partial z^k} \right\|_{L^\infty((0,l)^3)}$$

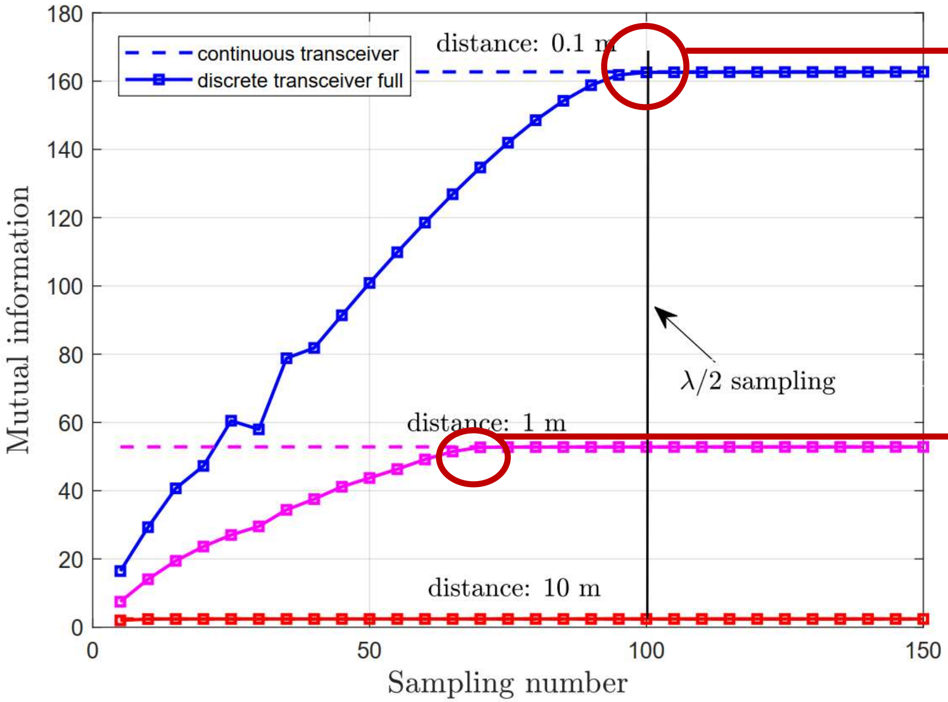
The MI difference is at most inverse proportional to square of number of antennas

J. Zhu, and **L. Dai**, "Can continuous aperture MIMO achieve much better performance than discrete MIMO?," *IEEE Commun. Lett.*, vol. 27, no. 12, pp. 3185-3189, Dec. 2023

.3 Numerical Verification: Symmetric Sampling

Comparison of mutual information

Deduction 1: When the discrete array is viewed as a compact discretization of the continuous aperture, the mutual information of discrete MIMO converges to that of CAP-MIMO



0.5λ achieves nearly all mutual information

0.7λ achieves nearly all mutual information

J. Zhu, and **L. Dai**, "Can continuous aperture MIMO achieve much better performance than discrete MIMO?," *IEEE Commun. Lett.*, vol. 27, no. 12, pp. 3185-3189, Dec. 2023

.3 Numerical Verification: Asymmetric Sampling

Comparison of mutual information

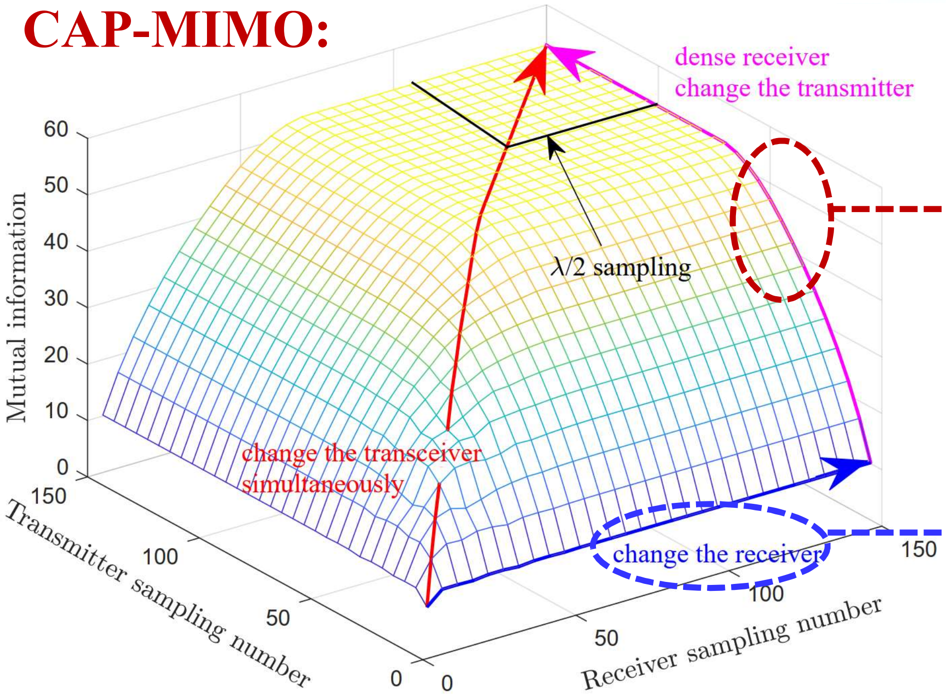
Deduction 2: The number of antennas m_1 and m_2 has duality. Moreover, their effect on the mutual information has a short-board effect.

crete MIMO:

$$\min(m_1, m_2)\log(1 + SNR)$$

has duality and short-
effect

CAP-MIMO:



Lare receiver array, when increasing transmitter samp number, mutual informatio increases rapidly

Fixed small transmitter arra when increasing receiver sa number, mutual informatio nearly keeps the same

J. Zhu, and **L. Dai**, "Can continuous aperture MIMO achieve much better performance than discrete MIMO?," *IEEE Commun. Lett.*, vol. 27, no. 12, pp. 3185-3189, Dec. 202

Contents

- Chapter 1: Introduction to EIT
  - 1.1 Motivation of EIT
  - 1.2 Shannon information theory
  - 1.3 Maxwell electromagnetic theory
  - 1.4 Overview of EIT
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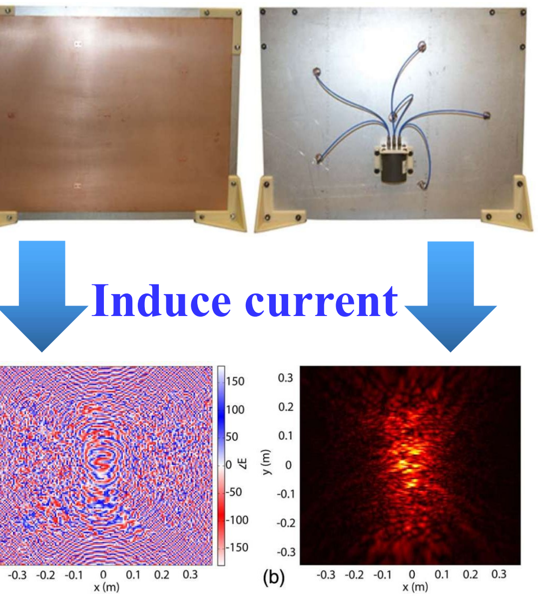
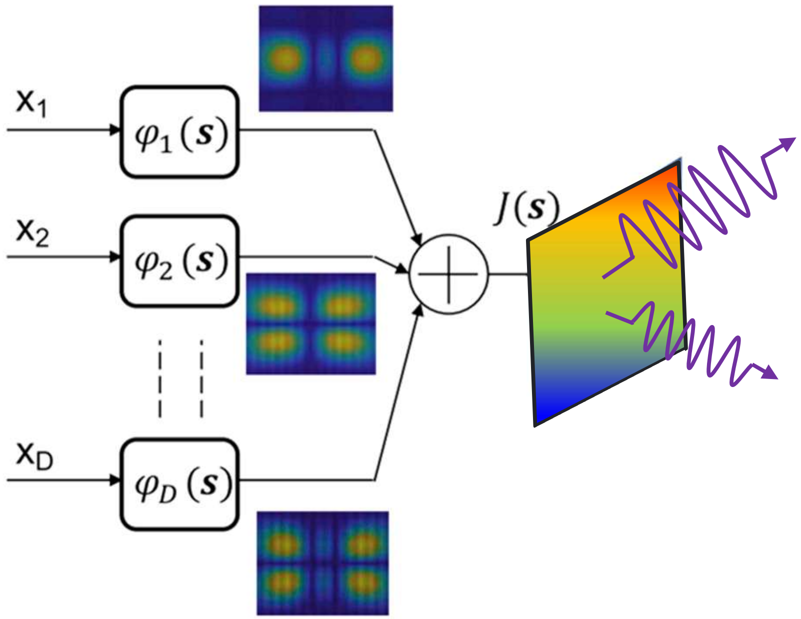
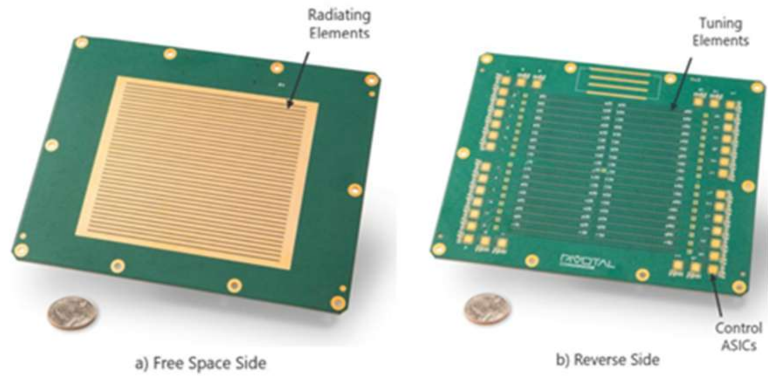
  - 2.1 Electromagnetic channel models for EIT
  - 2.2 DoF analysis for EIT
  - 2.3 Mutual information for EIT
- **Chapter 3: EIT-Enabled Technologies**
  - 3.1 Holographic MIMO
  - 3.2 EIT-enabled near-field communications
  - 3.3 Mutual coupling and superdirective antennas
  - 3.4 Orbital angular momentum
  - 3.5 3D antenna arrays
- Chapter 4: EIT-Inspired Technologies
  - 4.1 EIT-inspired channel estimation
  - 4.2 EIT-inspired channel prediction
  - 4.3 EIT-inspired self-controlled RIS
- Chapter 5: Conclusions

1 Concept of Holographic MIMO (H-MIMO)

- olographic MIMO (H-MIMO), continuous-aperture MIMO (CAP-MIMO): Densely deplo assive antennas in a compact space to form a fully adjustable EM surface
- he current density (pattern) is generated on the aperture of H-MIMO transmitter and the nformation-carrying electromagnetic wave is induced at the receiver





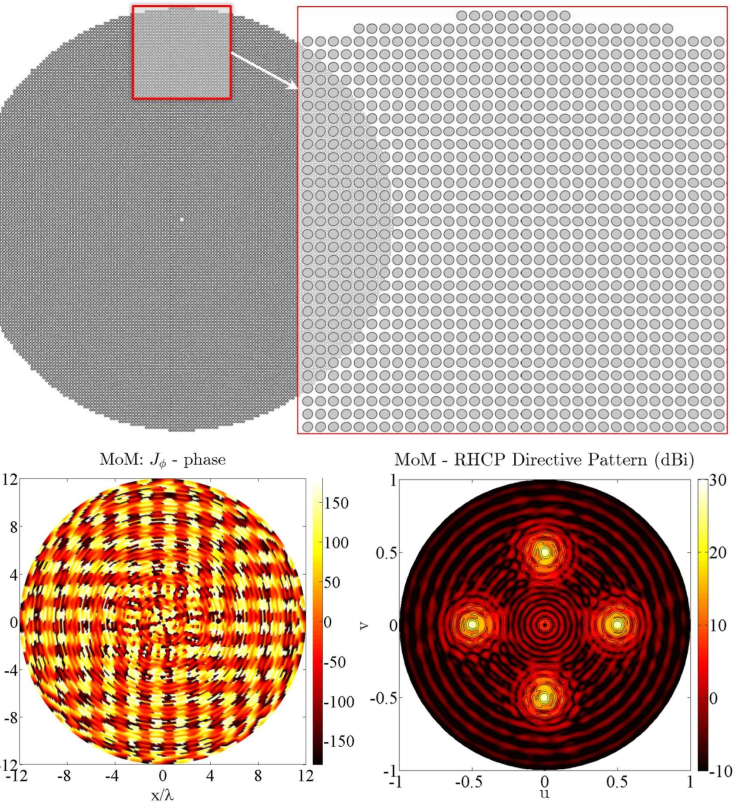


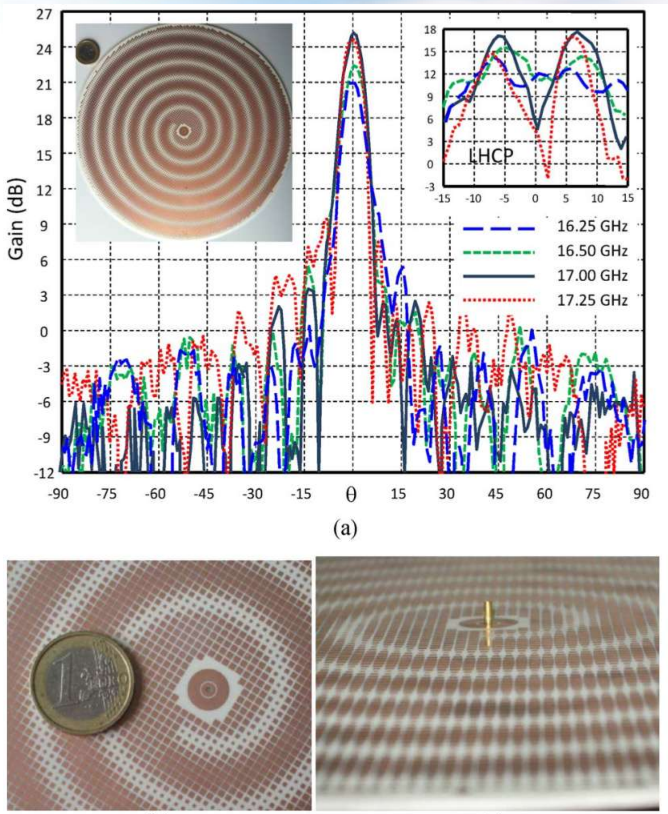
Architecture	Block Diagram	Cost	Size	Challenges
Holographic Beam Former		Super-sampled COTS design enables low price	Thin, Conformable	Single beam per polarization pe sub-aperture.

Holographic MIMO by Pivotal

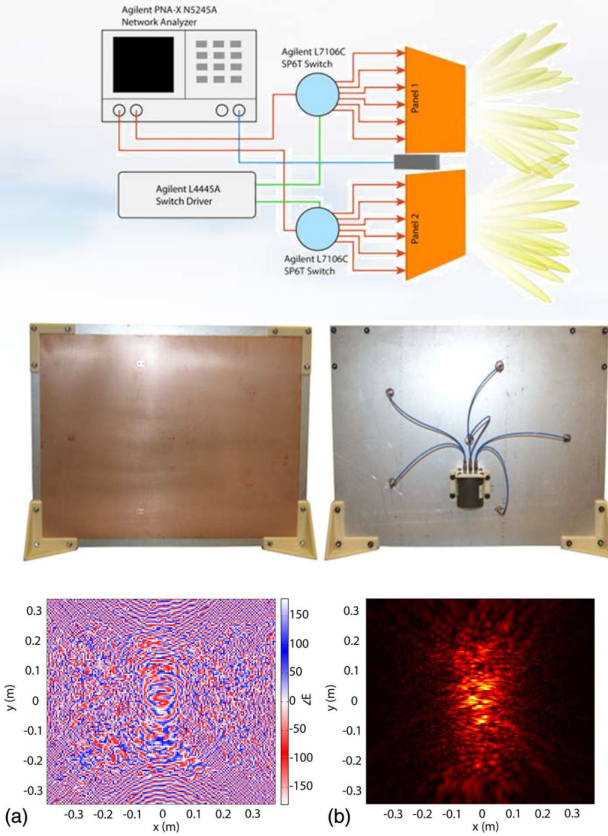
, T. L. Marzetta and L. Sanguinetti, "Spatially-stationary model for holographic MIMO small-scale fading," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 9, pp. 1964-1979, Sep. 2

1 Hardware Implementations of H-MIMO





(a)
(b)
(c)



(a)
(b)

Gonzalez-Ovejero, G. Minatti, G. Chattopadhyay, and S. Maci, "Multibeam by metasurface antennas," *IEEE Trans. Antennas Propag.*, vol. 65, no. 6, p
3-2930, Jun. 2017.
Maci, G. Minatti, M. Casaletti, and M. Bosiljevac, "Metasurfing: Addressing waves on impenetrable metasurfaces," *IEEE Antennas Wireless Propag. L*
10, pp. 1499-1502, 2011.
Hunt, J. Gollub, T. Driscoll, et al., "Metamaterial microwave holographic imaging system," *J. Opt. Soc. Am. A.*, vol. 31, no. 10, pp. 2109-2119, 2014.

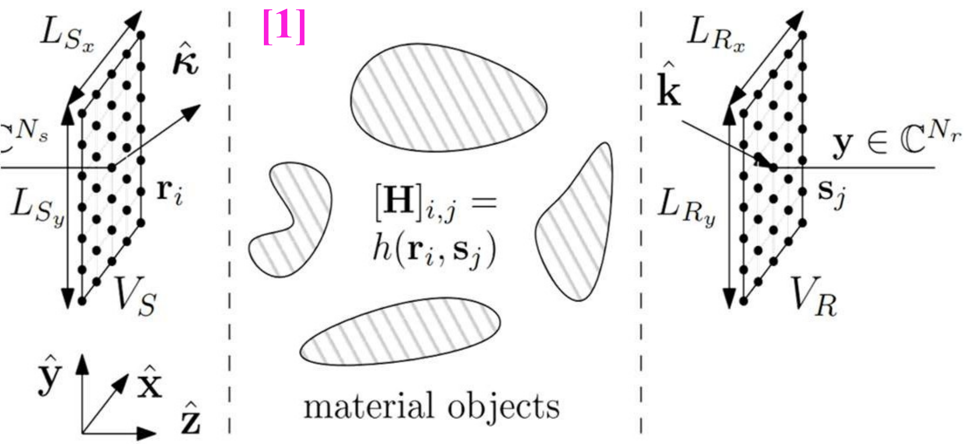
1 Existing Typical Works of H-MIMO

hannel modeling: Modeling small-scale fading of electromagnetic channel with Gaussian andom field in wavenumber domain [1]

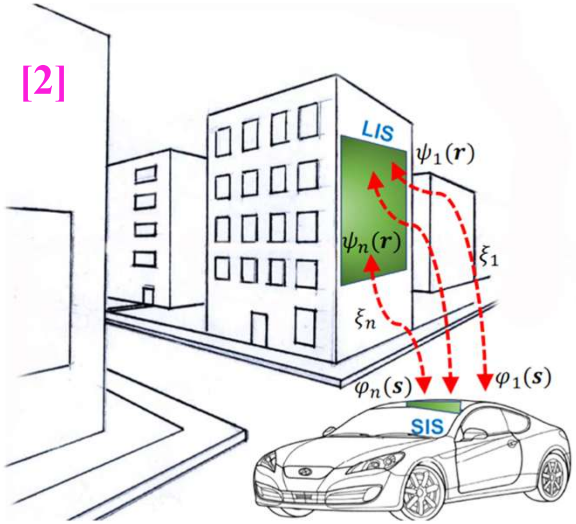
oF analysis: Degrees of freedom of communication between two H-MIMO is analyzed [2]

ransmission design: Wavenumber-division multiplexing (WDM) is proposed to modulate ymbols on different wavenumbers for sum-rate maximization [3]

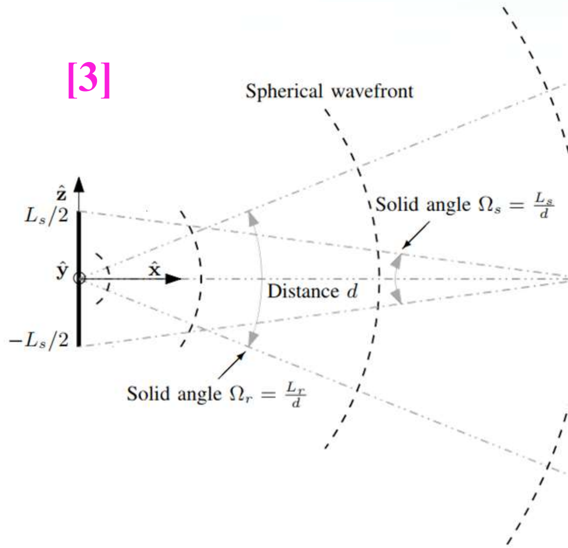
[1]



[2]



[3]



izzo, T. L. Marzetta, and L. Sanguinetti, "Spatially-stationary model for holographic MIMO small-scale fading," *IEEE J. Sel. Areas Commun.,* vol. 38, no. 9, pp. 1964-1979, Se
ardari, "Communicating with large intelligent surfaces: Fundamental limits and models," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 11, pp. 2526-2537, Nov. 2020.
anguinetti, A. A. D'Amico, and M. Debbah, "Wavenumber-division multiplexing in line-of-sight holographic MIMO communications," *IEEE Trans. Wireless Commun.*, vol. 22
-2201, Apr. 2023.

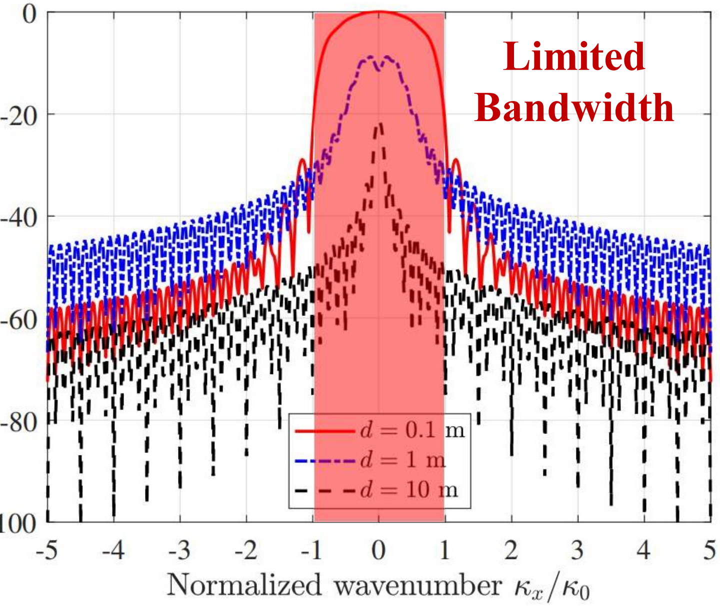
1 Proposed Pattern Design for H-MIMO

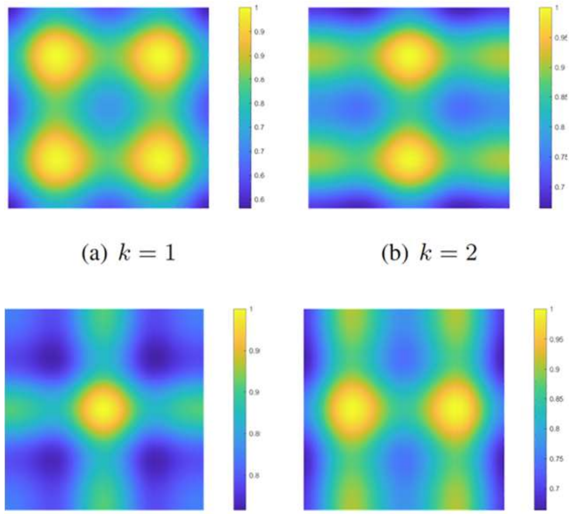
xisting methods: Use the conjugate of channel functions as the pattern

roposed method: Transform the optimization of pattern functions into their projection leng ector-form) in the wavenumber domain for sum-rate maximization

Continuous-discrete transform:

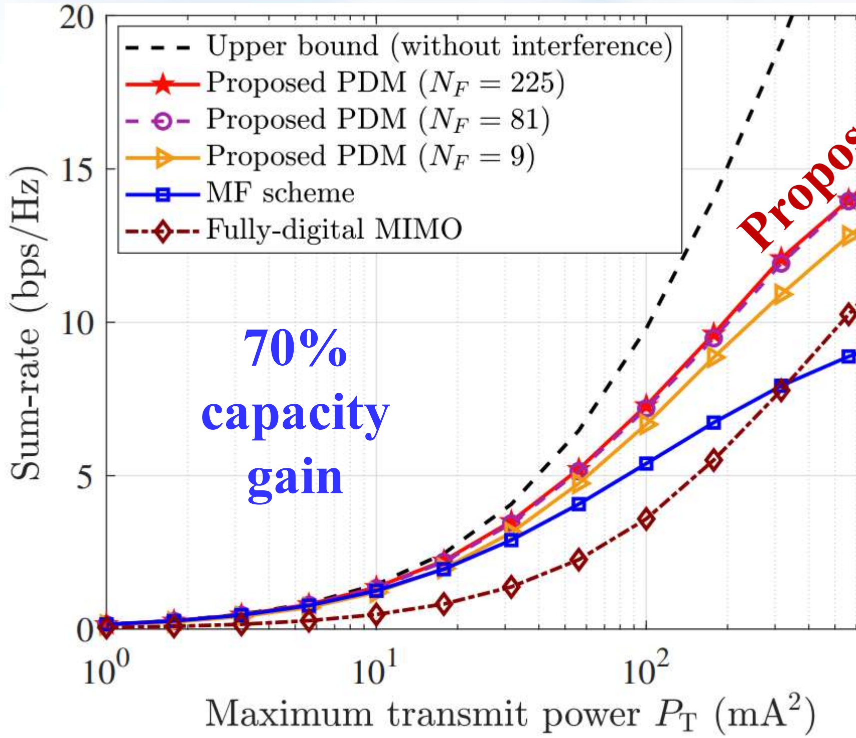
$$\int_{\mathcal{S}_{\mathrm{T}}} \mathbf{G}_k(\mathbf{s})\boldsymbol{\theta}_j(\mathbf{s})\mathrm{d}\mathbf{s} = \sum_{\mathbf{n}}^{\infty} \boldsymbol{\Omega}_{k,\mathbf{n}}\mathbf{w}_{j,\mathbf{n}}$$





(a) $k = 1$ (b) $k = 2$

(c) $k = 3$ (d) $k = 4$



and **L. Dai**, "Pattern-division multiplexing for multi-user continuous-aperture MIMO," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 8, pp. 2350-2366, Aug. 2023.

Contents

- Chapter 1: Introduction to EIT
  - 1.1 Motivation of EIT
  - 1.2 Shannon information theory
  - 1.3 Maxwell electromagnetic theory
  - 1.4 Overview of EIT
- Chapter 2: Fundamentals of EIT
  - 2.1 Electromagnetic channel models for EIT
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  - 2.3 Mutual information for EIT
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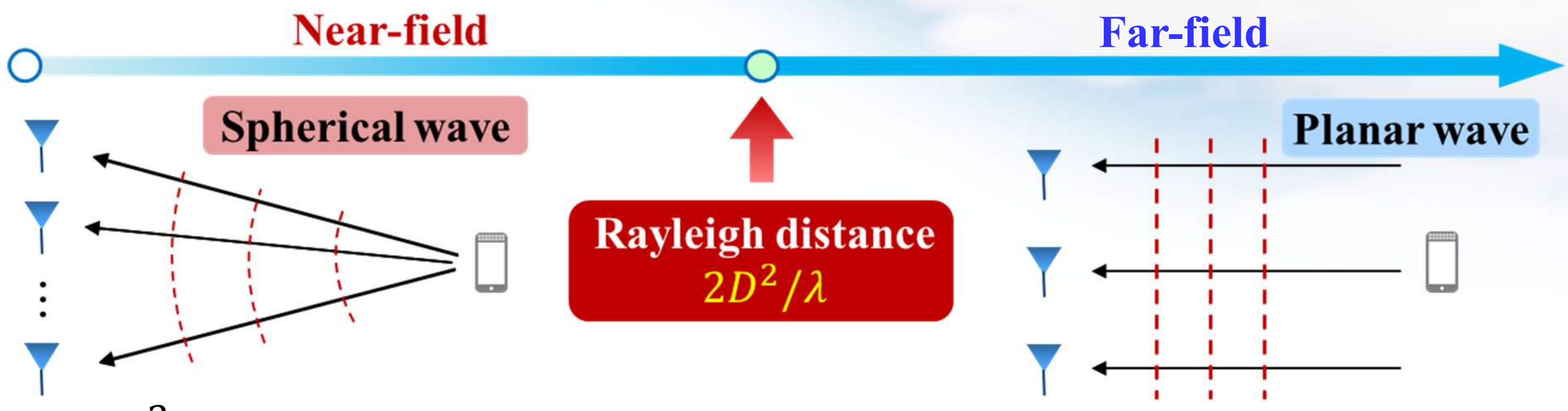
  - 3.1 Holographic MIMO
  - 3.2 EIT-enabled near-field communications
  - 3.3 Mutual coupling and superdirective antennas
  - 3.4 Orbital angular momentum
  - 3.5 3D antenna arrays
- Chapter 4: EIT-Inspired Technologies
  - 4.1 EIT-inspired channel estimation
  - 4.2 EIT-inspired channel prediction
  - 4.3 EIT-inspired self-controlled RIS
- Chapter 5: Conclusions

2 Near-Field Communications for 6G

EM propagation can be divided into far-field and near-field regions



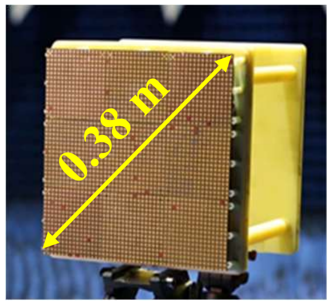
$$\phi_n^{\mathrm{near}} = \frac{2\pi}{\lambda}\left(\sqrt{r^2 - 2ndr\theta + n^2d^2} - r\right)$$

$$\phi_n^{\mathrm{far}} = -\frac{2\pi}{\lambda}nd\theta$$

. Marzetta

Table I. Rayleigh distance [m] (data from [1])

f \ D	0.1 m	0.5 m	1 m	3 m
3 GHz	0.21	5	20	180
28 GHz	1.9	47	187	/
142 GHz	9.0	237	/	/



2304 array

Evolution from massive MIMO to ELAA results in the near-field propagation

L. Sanguinetti, and T. L. Marzetta, "Fourier plane-wave series expansion for holographic MIMO communications," *IEEE Trans. Wireless Commun.*, Mar. 2022.

2 Far-Field Beamsteering v.s. Near-Field Beamfocusing

Channel model

Far-field: $\mathbf{h}^{\text{far}} = g^{\text{far}}\left[1, e^{-j\frac{2\pi}{\lambda}d\theta}, \cdots, e^{-j\frac{2\pi}{\lambda}(2N+\ )d\theta}\right]^T$

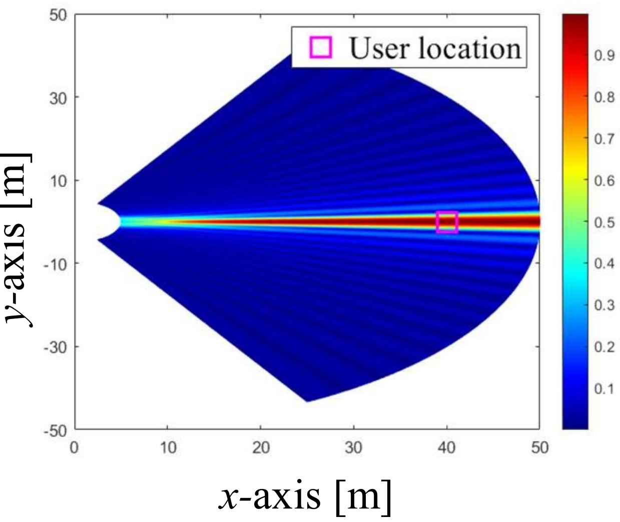
Linear phase item

Near-field: $\mathbf{h}^{\text{near}} = g\left[e^{-j\frac{2\pi}{\lambda}\phi_{-N}^{\text{near}}}, \cdots, e^{-j\frac{2\pi}{\lambda}\phi_{N}^{\text{near}}}\right]^T$

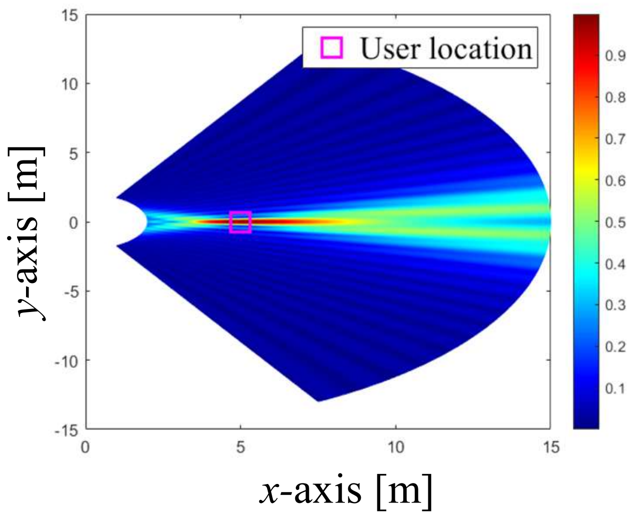
Non-linear phase item

Channel Gain

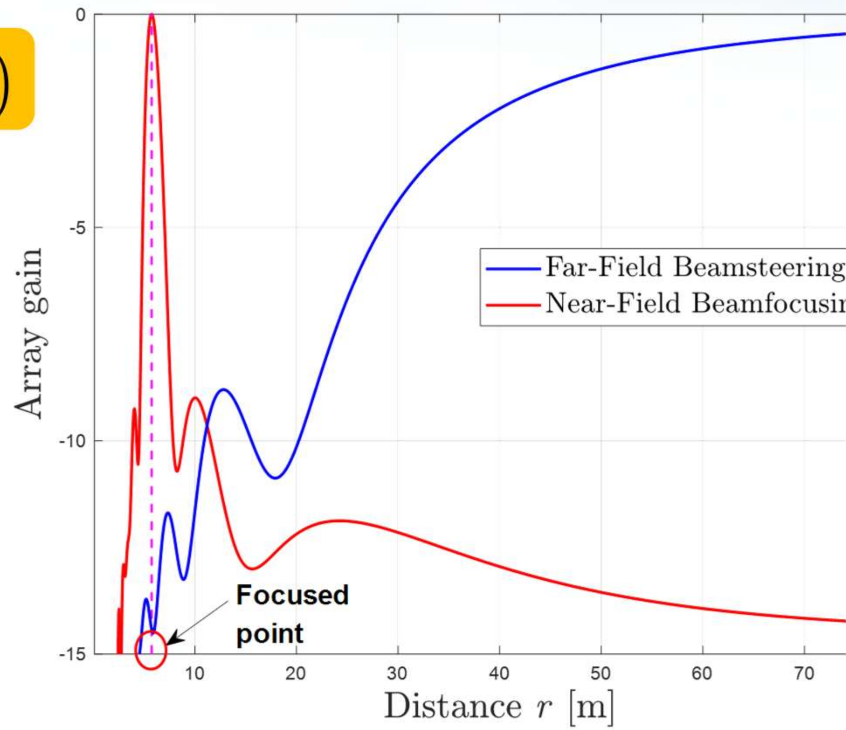
$$\phi_n^{\text{near}} = \frac{2\pi}{\lambda}\left(\sqrt{r^2 - 2ndr\theta + n^2d^2} - r\right)$$



Far-field beamsteering

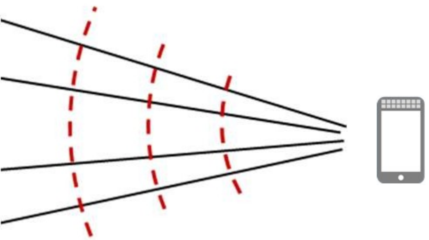


Near-field beamfocusing



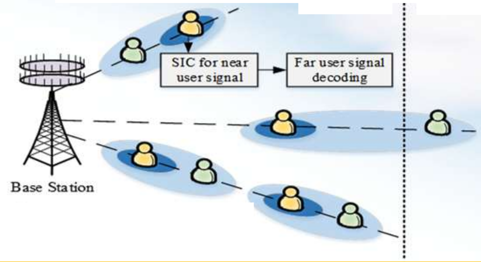
ui and **L. Dai**, "Channel estimation for extremely large-scale MIMO: Far-field or near-field?," *IEEE Trans. Commun.*, vol. 70, no. 4, pp. 2663-2677, Apr. 2022.

2 Applications of Near-Field Communications



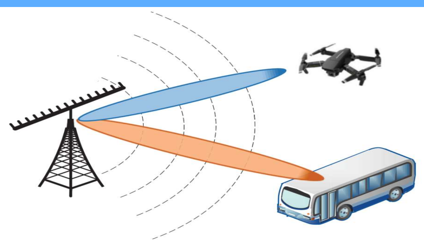
Near-Field Beamfocusing

Communications



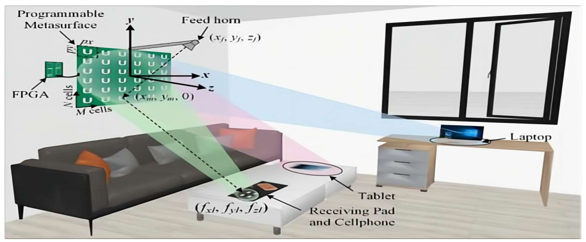
Increased capacit
through signal focus

Sensing and Localization



Higher accuracy
through distance sen

Wireless Power Transfer



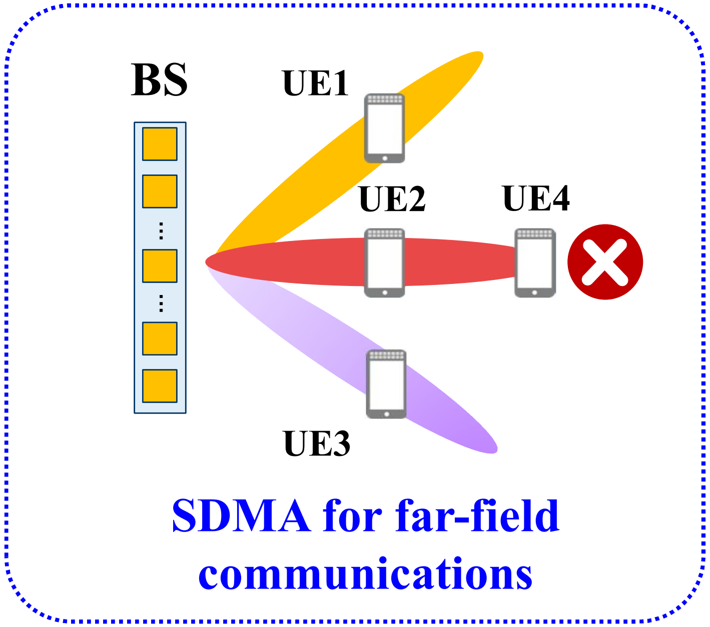
Improved efficienc
through energy focus

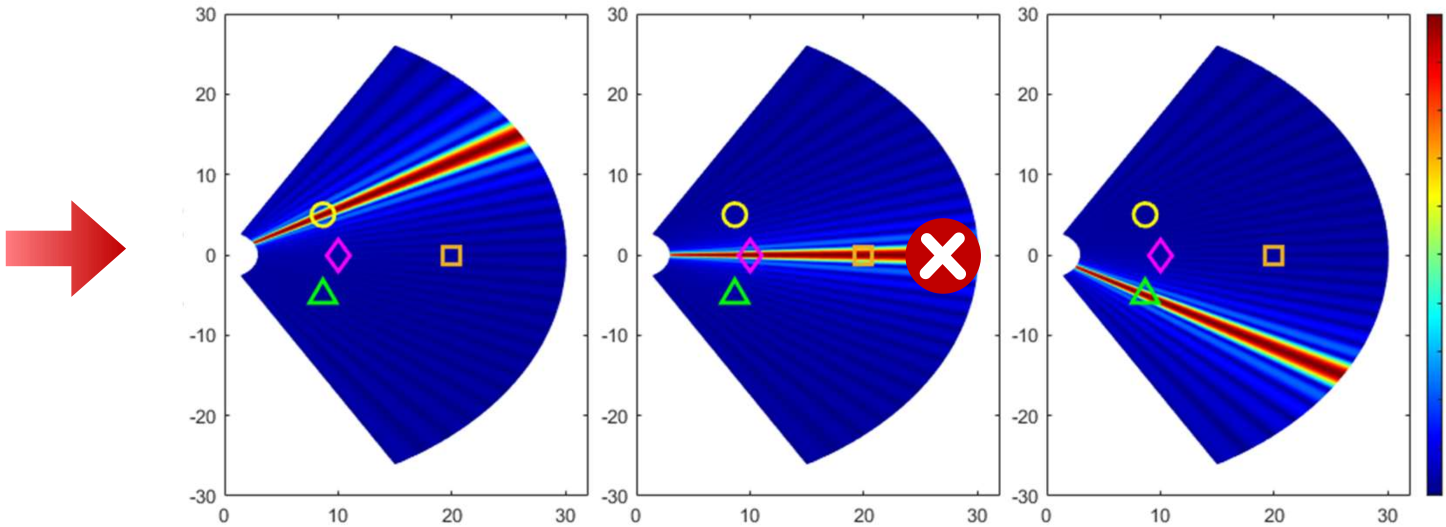
. Wu, Y. Lu, X. Wei, and **L. Dai**, "Near-field MIMO communications for 6G: Fundamentals, challenges, potentials, and future directions," *IEEE Commun. Mag.*, vol. 61, no. 1
n. 2023.

2 Challenge of SDMA for Far-Field Communication

Spatial division multiple access (SDMA) is employed by massive MIMO to multipl
data streams to different users for improving spectral efficiency

In massive MIMO systems, far-field beamsteering vectors only focus on speci
angles, which enables the multiple access for users at different angles

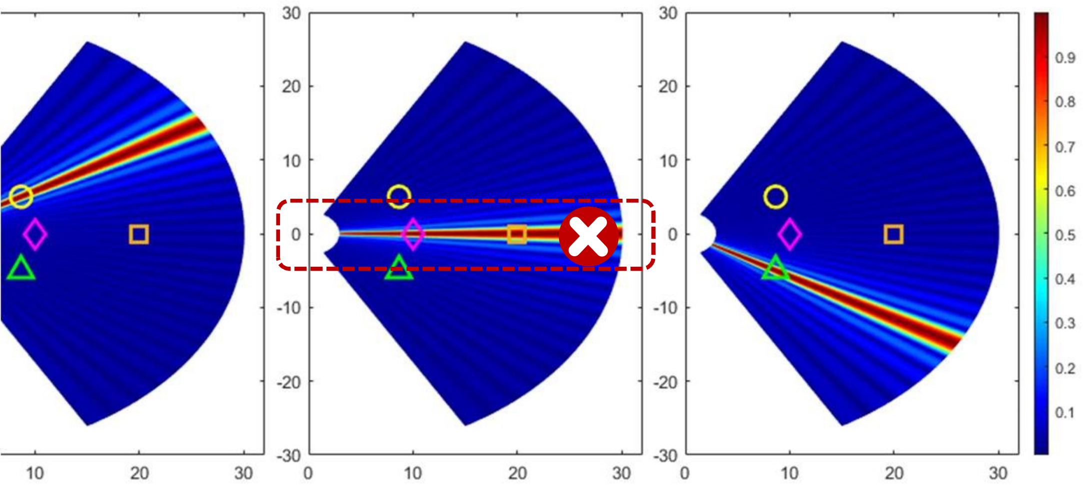




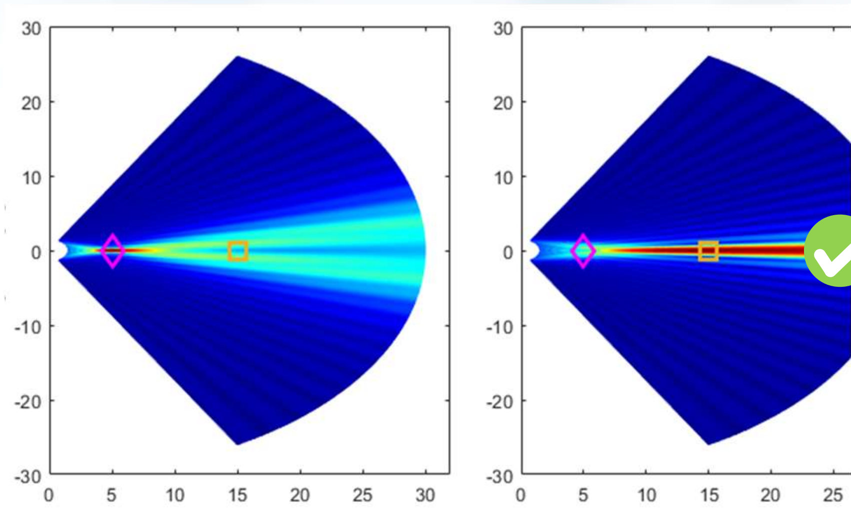
ers at the same angle cannot be simultaneously served by massive MIMO with SDM

2 Mitigated Interference with Near-Field Beamfocusing

- **Far-field beamsteering** vectors focus on specific spatial **angle**
- **Near-field beamfocusing** is capable to focus on specific **location**, which could leveraged to mitigate **inter-user interferences**



Far-field beamsteering



Near-field beamfocusing

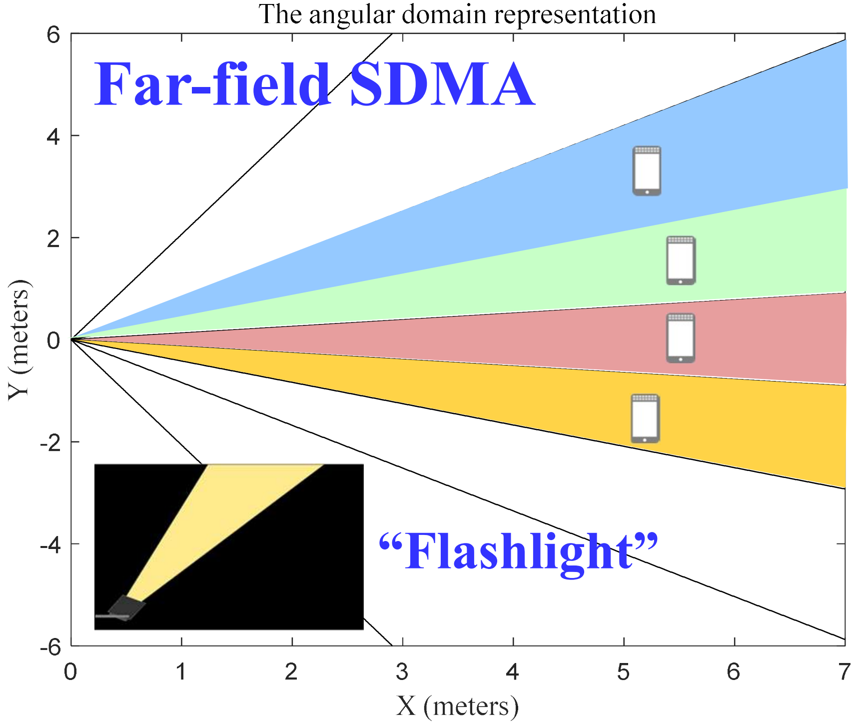
Near-field beamfocusing has the potential to serve users at the same spatial angle

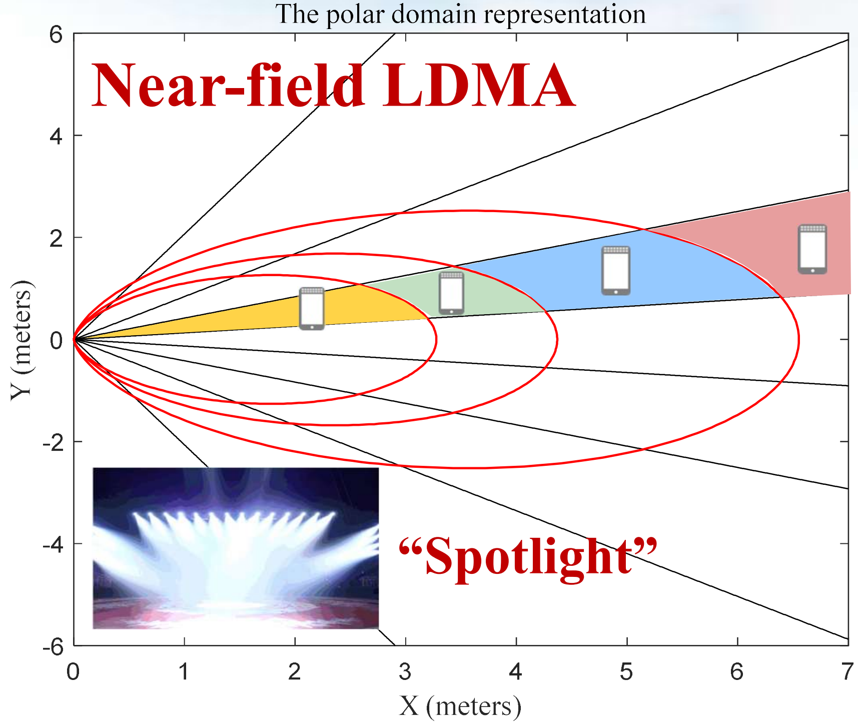
…ng, N. Shlezinger, F. Guidi, D. Dardari, and Y. C. Eldar, "6G wireless communications: From far-field beam steering to near-field beam focusing," *IEEE Commun. Mag.*, vol. … 4, pp. 72-77, Apr. 2023.

Multiple Access for Near-Field Communications: SDMA or LDMA?

- **Far-field SDMA**: Users at different **angles** can be served by orthogonal far-field bea

- **Near-field location division multiple access (LDMA)**: Users at different **locations** be simultaneously served due to property of near-field beam focusing





pared with far-field SDMA, near-field LDMA provides a new possibility for capacity improve

and **L. Dai**, "Multiple access for near-field communications: SDMA or LDMA? " *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1918-1935, Jun. 2023.

2 Distance Domain Asymptotic Orthogonality

Far-field orthogonality in angular domain

Phase: $\phi_n^{\text{far}}(\theta) = -\frac{2\pi}{\lambda} n d \theta$

Correlation: $f^{\text{far}} = |\mathbf{a}^H(\theta_1)\mathbf{a}(\theta_2)| = \frac{1}{N}\left|\frac{\sin(\frac{1}{2}Nkd(\sin\theta_1 - \sin\ _2))}{\sin(\frac{1}{2}kd(\sin\theta_1 - \sin\theta_2))}\right|$

As $N \to \infty$, interference from different angles $I^{\text{far}} \to 0$ $(\theta_1 \neq \theta_2)$

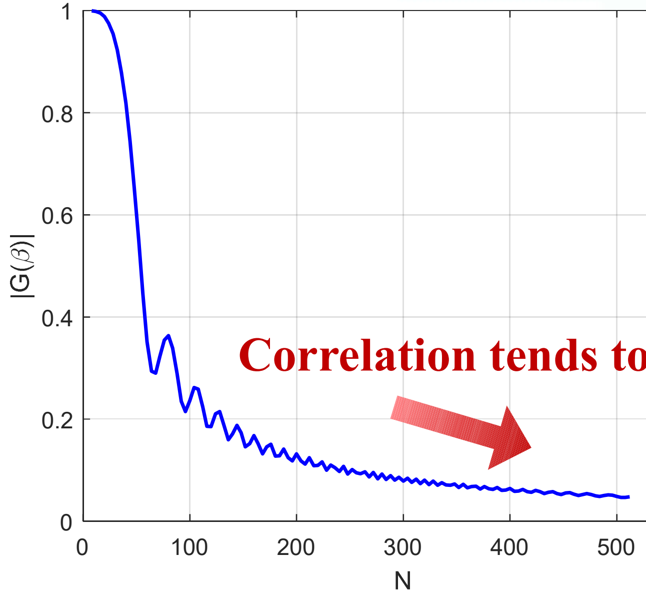
Lemma 2: Near-field orthogonality in distance domain

Phase: $\phi_n^{\text{near}}(\theta) = -\frac{2\pi}{\lambda} n d \theta + \frac{1-\theta^2}{\lambda r}\pi n^2 d^2$

Correlation: $f^{\text{near}} = |\mathbf{a}^H(\theta, r_1)\mathbf{a}(\theta, r_2)| \approx |G(\beta)| = \left|\frac{C(\beta)+jS(\beta)}{\beta}\right|$

where $\beta = \sqrt{\frac{N^2 d^2(1-\theta^2)}{2\lambda}\left|\frac{1}{r} - \frac{1}{\bar{r}}\right|}$

As $N \to \infty$, interference from different distances $I^{\text{near}} \to 0$
$(\forall\theta, r_1 \neq r_2)$



Correlation with increasing ante

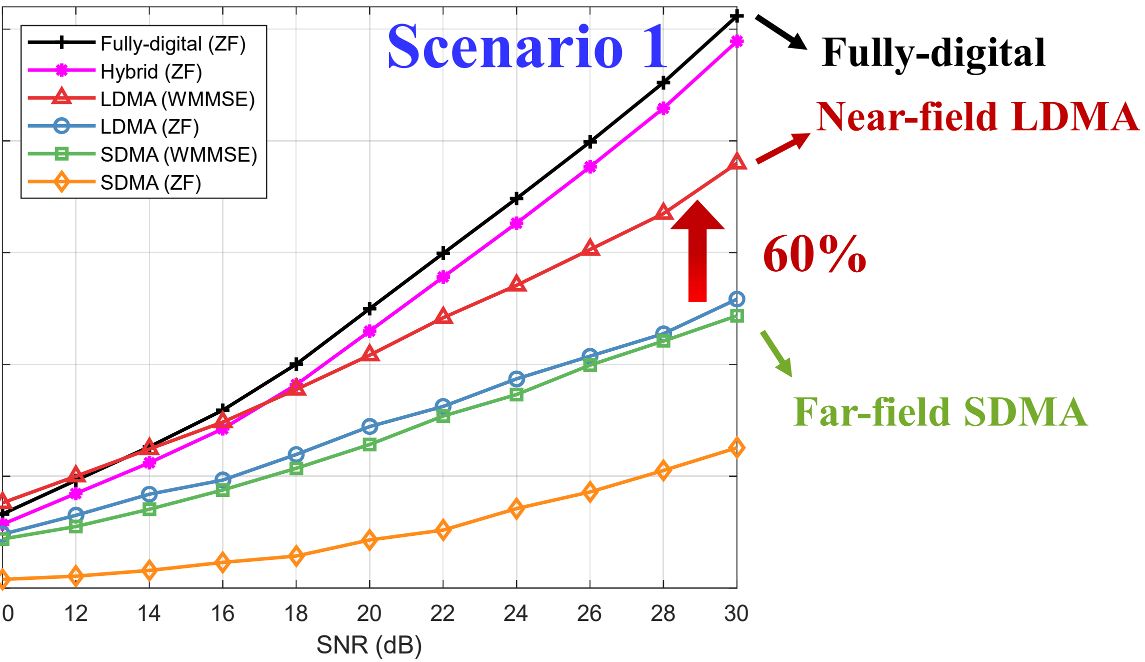
and **L. Dai**, "Multiple access for near-field communications: SDMA or LDMA? " *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1918-1935, Jun. 2023.

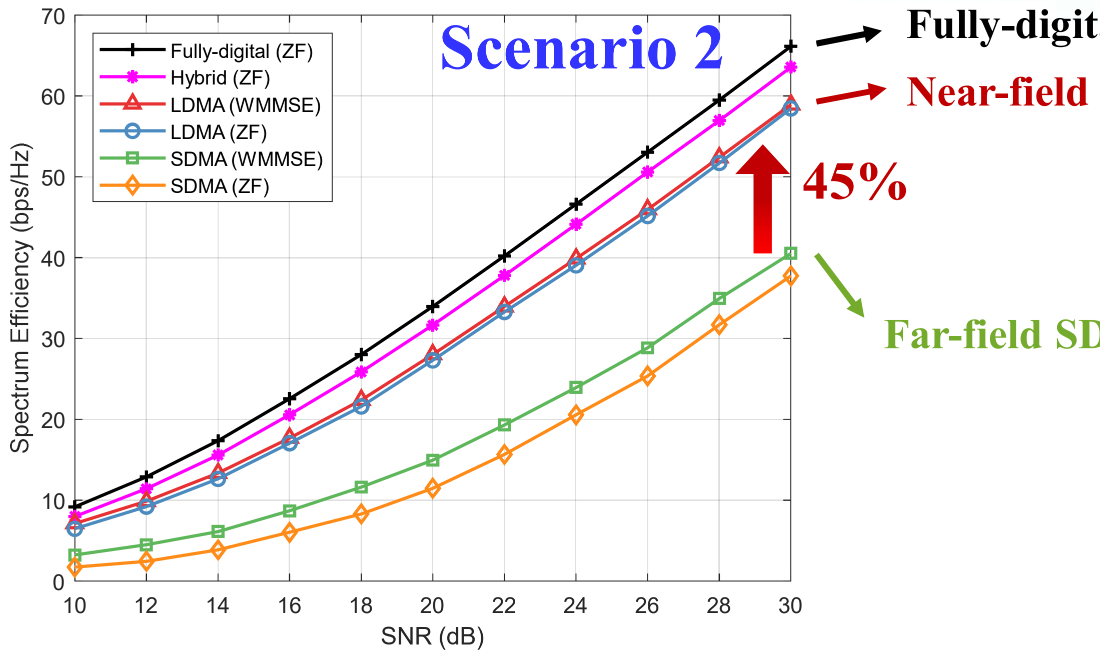
2 Simulation Results for LDMA

Scenario 1: Users are linearly distributed along the same direction

Scenario 2: Users are uniformly distributed within a cell

BS Antennas	UE Antennas	Frequency	UE Numbers	Elevation/ Azimuth Angle Range	Distance Range
256	1	30 GHz	20	$[-\pi/2, \pi/2]$	[4m, 100m]





and **L. Dai**, "Multiple access for near-field communications: SDMA or LDMA? " *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1918-1935, Jun. 2023.

Contents

- Chapter 1: Introduction to EIT
  - 1.1 Motivation of EIT
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  - 1.3 Maxwell electromagnetic theory
  - 1.4 Overview of EIT
- Chapter 2: Fundamentals of EIT
  - 2.1 Electromagnetic channel models for EIT
  - 2.2 DoF analysis for EIT
  - 2.3 Mutual information for EIT
- **Chapter 3: EIT-Enabled Technologies**
  - 3.1 Holographic MIMO
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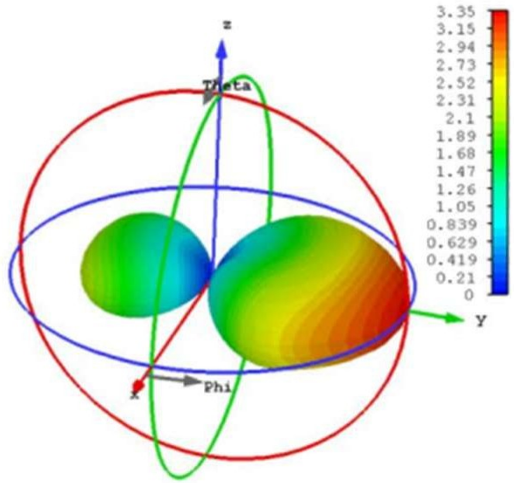
  - 3.3 Mutual coupling and superdirective antennas
  - 3.4 Orbital angular momentum
  - 3.5 3D antenna arrays
- Chapter 4: EIT-Inspired Technologies
  - 4.1 EIT-inspired channel estimation
  - 4.2 EIT-inspired channel prediction
  - 4.3 EIT-inspired self-controlled RIS
- Chapter 5: Conclusions

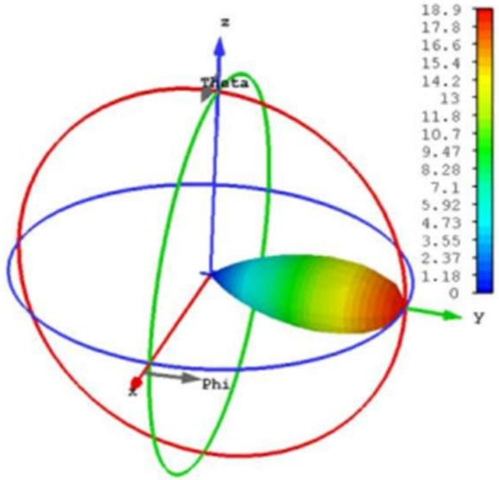
.3 Mutual Coupling and Superdirective Antennas

From avoiding mutual coupling to utilizing mutual coupling

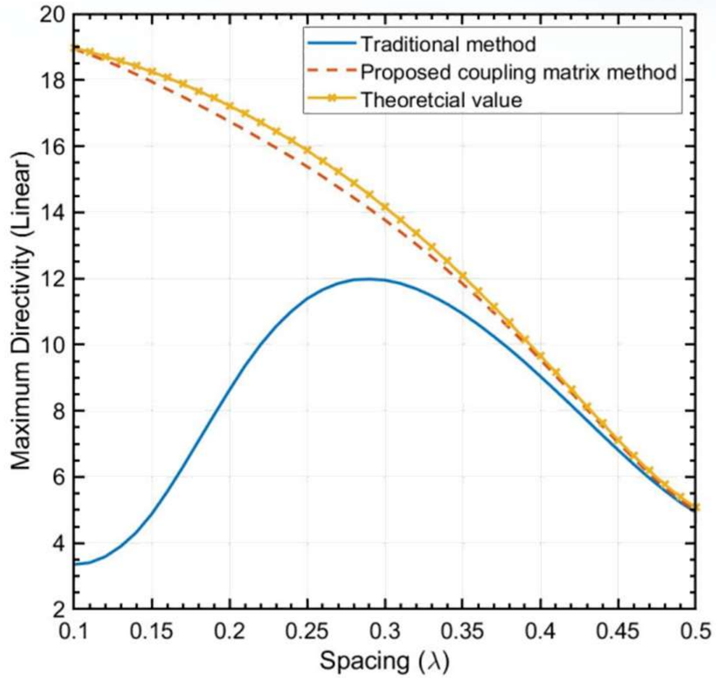
- **Mutual coupling between closely-placed antennas (especially for antenna spacing less than $\lambda/2$)**
- **Directivity of linear array can be greatly improved when antenna spacing tends to 0**
- **Challenge: The radiation efficiency will be decreased**



Directivity based on traditional model



(b) Directivity based on coupling matrix model

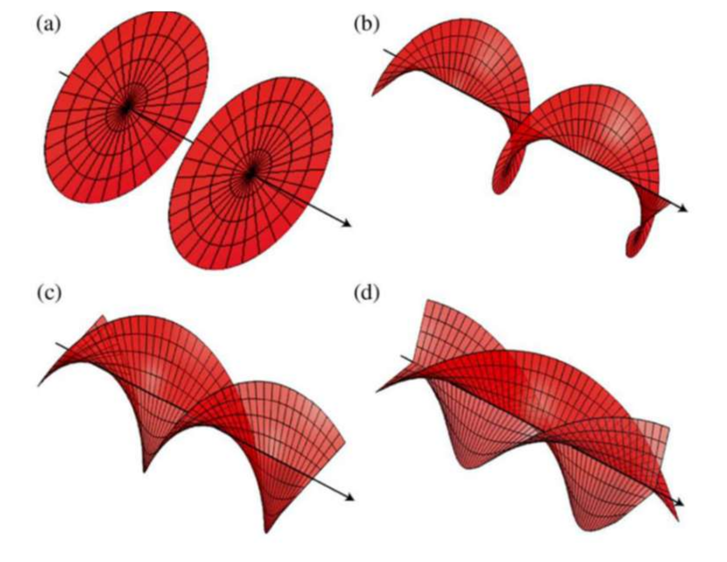


Marzetta, "Super-directive antenna arrays: Fundamentals and new perspectives," in *Proc. 53rd Asilomar Conference on Signals, Systems, and Computers*, 2019, pp. 1–4
n, H. Yin, and T. L. Marzetta, "Coupling matrix-based beamforming for superdirective antenna arrays," in *Proc. IEEE Int. Conf. Commun. (ICC),* May 2022, pp. 5159–5164.

.4 Orbital Angular Momentum

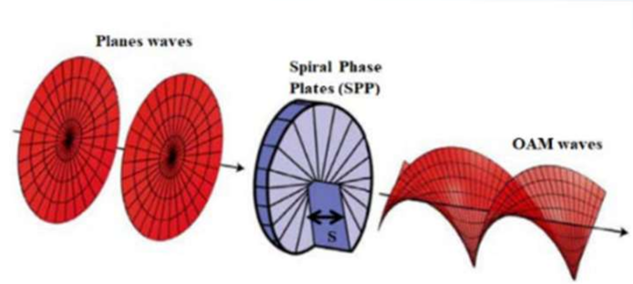
From massive MIMO to massive modes

- ➢ **Orbital angular momentum (OAM) has infinite number of modes (states) theoretically**
- ➢ **Holographic MIMO surfaces are powerful in transferring the OAM property**

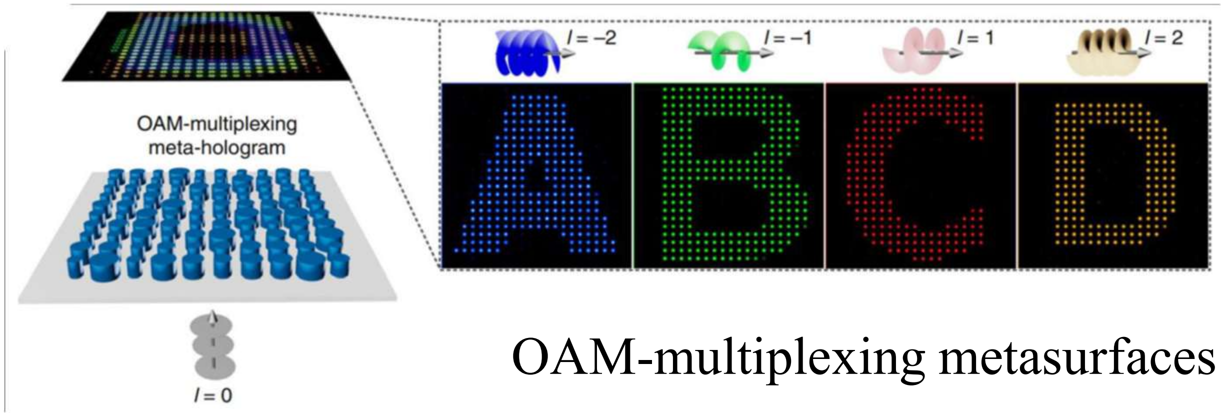


Helical phase fronts for (a) $\ell = 0$, (b) $\ell = 1$, (c) $\ell = 2$, and (d) $\ell = 3$.

OAM modes



OAM wave generation with Spiral phase plate (SPP)



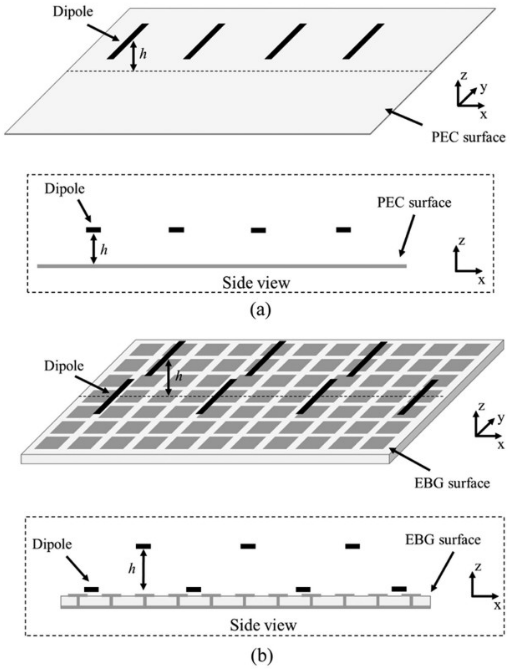
OAM-multiplexing metasurfaces

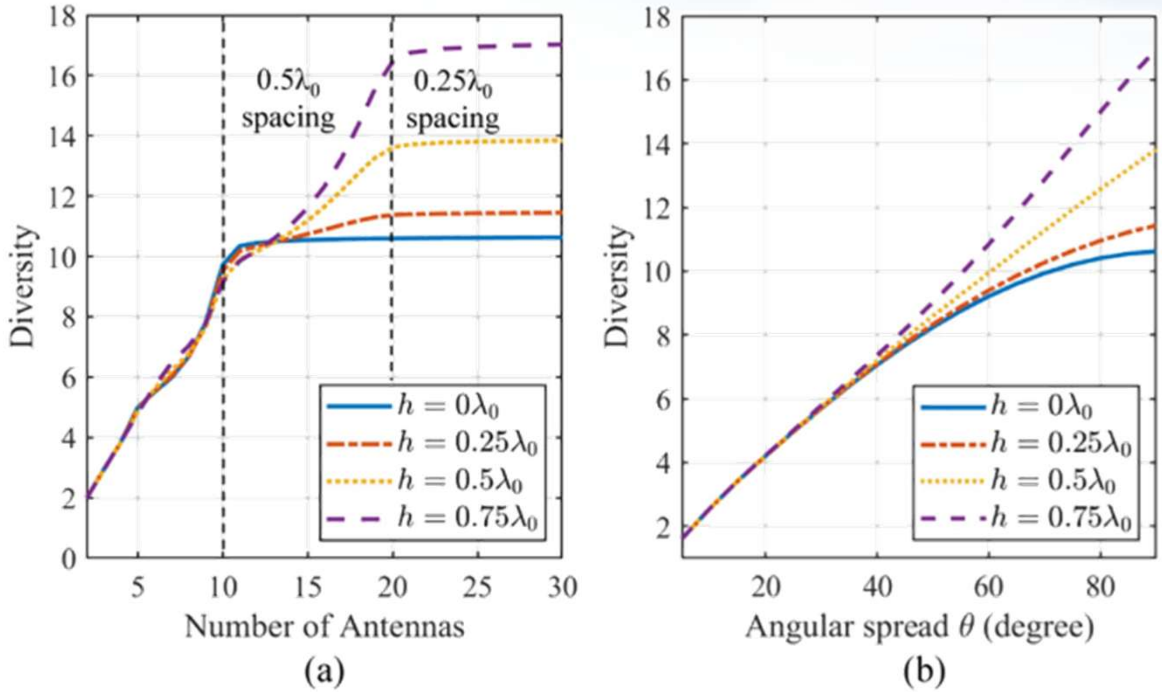
an, G. Xie, M. Lavery, H. Huang, et. al, "High-capacity millimetre-wave communications with orbital angular momentum multiplexing," *Nature Communications*, vol. 5, Sep.
. Willner, H. Huang, Y. Yan, Y. Ren, N. Ahmed, et. al., "Optical communications using orbital angular momentum beams," *Adv. Optics and Photonics*, vol. 7, no. 1, pp. 66-106, 2015.

.5 3D Antenna Array

Deploy multiple antenna array layers to explore the third spatial dimension

- **The DoF and capacity constraints of traditional holographic MIMO systems can be surpassed by adopting such a 3D antenna array**





A. Yuan, J. Wu, H. Xu, T. Wang, D. Li, X. Chen, C. Huang, S. Sun, S. Zheng, X. Zhang, E. Li, and W. E. I. Sha, "Breaking the degrees-of-freedom limit of holographic MIMO nunications: A 3-D antenna array topology," *IEEE Trans. Veh. Technol.*, vol. 73, no. 8, pp. 11276-11288, Aug. 2024.
C. Huang, X. Chen, W. Sha, Z. Zhang, J. Yang, K. Yang, C. Yuen, and M. Debbah. "Exploring Hannan limitation for 3D antenna array," *arXiv preprint arXiv:2409.01566*, Sep

Contents

- Chapter 1: Introduction to EIT
  - 1.1 Motivation of EIT
  - 1.2 Shannon information theory
  - 1.3 Maxwell electromagnetic theory
  - 1.4 Overview of EIT
- Chapter 2: Fundamentals of EIT
  - 2.1 Electromagnetic channel models for EIT
  - 2.2 DoF analysis for EIT
  - 2.3 Mutual information for EIT
- Chapter 3: EIT-Enabled Technologies
  - 3.1 Holographic MIMO
  - 3.2 EIT-enabled near-field communications
  - 3.3 Mutual coupling and superdirective antennas
  - 3.4 Orbital angular momentum
  - 3.5 3D antenna arrays
- **Chapter 4: EIT-Inspired Technologies**
  - 4.1 EIT-inspired channel estimation
  - 4.2 EIT-inspired channel prediction
  - 4.3 EIT-inspired self-controlled RIS
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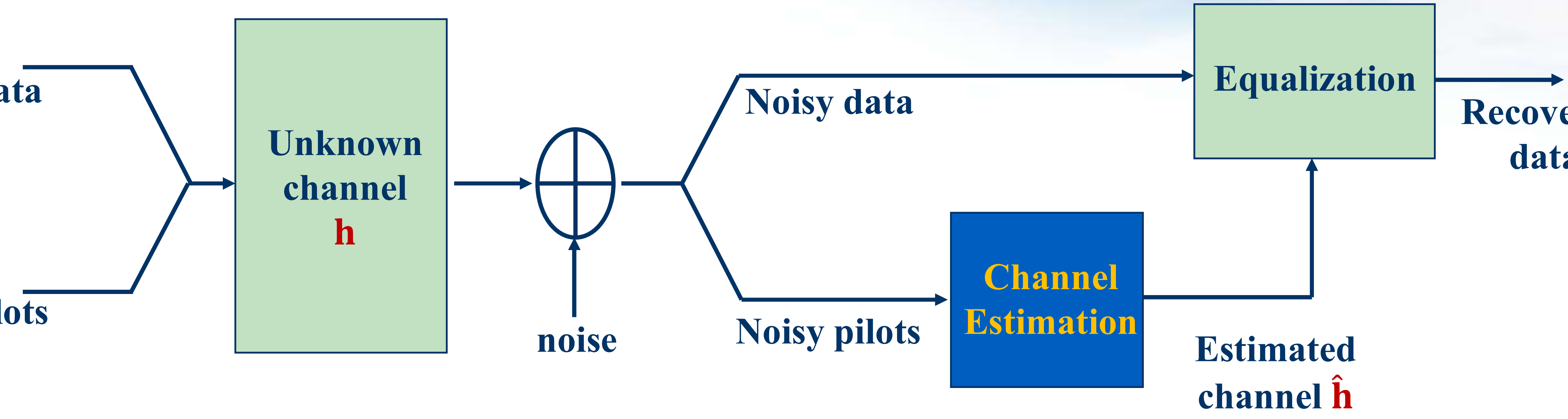
.1 Channel Estimation

Signal recovery: Get transmitted X from received y by knowing channel h

Channel estimation: Get channel h from received pilots y by knowing X



System Model

$$\mathbf{y} = \mathbf{X}\mathbf{h} + \mathbf{n}$$

.1 Existing Channel Estimators

	Least Square (LS)	Minimum Mean Square Error (MMSE)	Compressed Sensing
Loss unctions	$J(\hat{\mathbf{h}}_{\mathrm{LS}}) = \|\mathbf{y} - \mathbf{X}\hat{\mathbf{h}}_{\mathrm{LS}}\|^2$	$J(\hat{\mathbf{h}}_{\mathrm{MMSE}}) = E\{\|\mathbf{h} - \hat{\mathbf{h}}_{\mathrm{MMSE}}\|^2\}$	$J(\hat{\mathbf{h}}_{\mathrm{CS}}) = \|\mathbf{y} - \mathbf{X}\hat{\mathbf{h}}_{\mathrm{CS}}\|^2 + \beta\|\hat{\mathbf{h}}$
osed-form	$\hat{\mathbf{h}}_{\mathrm{LS}} = (\mathbf{X}^H\mathbf{X})^{-1}\mathbf{X}^H\mathbf{y}$	$\hat{\mathbf{h}}_{\mathrm{MMSE}} = \mathbf{R}_{\mathbf{h}}\left(\mathbf{R}_{\mathbf{h}} + \frac{1}{\gamma}\mathbf{I}\right)^{-1}\mathbf{X}^{-1}\mathbf{y}$	No closed-form solution
eed noise tatistics	No	Yes	No
ed channel tatistics	No	Yes	No
lvantages	**Low-complexity** and applicable to any channels	**High estimation accuracy** with strong denoising capability	**Low pilot overhead** with so denoising capability
advantages	**Sensitive to noise**	**Need extra statistical information of channel and noise**, high complexity	Only applicable to **sparse** **channels**

MMSE estimators are widely applied in real-world systems, but it requires channel statistic

.1 When EIT Meets Channel Estimation

Traditional MMSE needs channel statistics

- In classical MMSE, $\mathbf{R_h}$ represents mathematical second-order statistics
- In EIT-MMSE, $\mathbf{R_h}$ represents EM statistics calculated from EIT analysis

Classical statistics

$$\hat{\mathbf{R}}_{\mathbf{h}} = \frac{1}{T}\sum_{t} \mathbf{h}_t \mathbf{h}_t^{\mathsf{H}}$$

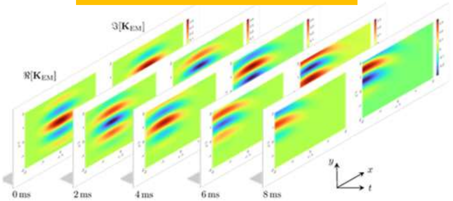
$\mathbf{R_h}$

$\mathbf{y} = \mathbf{X}\mathbf{h} + \mathbf{n}$ Pilot observation $\mathbf{y}_{\text{obs}}$ → **MMSE Estimator** → Channel estimates

$$\hat{\mathbf{h}}^{\text{MMSE}} = \mathbf{R_h}\left(\mathbf{R_h} + \frac{1}{\gamma}\mathbf{I}\right)^{-1}\mathbf{X}^{-1}\mathbf{y}$$

$\mathbf{R_h}$

EM statistics



, Z. Wan, **L. Dai**, and T. J. Cui, "Electromagnetic information theory-based statistical channel model for improved channel estimation," submitted to *IEEE Trans. Inf. Theory*, r
on, Feb. 2024.

.1 Construct EM Correlation Function (EMCF)

Apply stochastic integral to Green's function and get EM correlation function (EM

Parameter $\mu \in \mathbb{R}^3$ represents concentration, reflecting the direction of EM incidence

reen's function

$$\mathbf{G}(\mathbf{x}, \mathbf{x}') = \frac{e^{ik_0\|\mathbf{x}-\mathbf{x}'\|}}{4\pi\|\mathbf{x}-\mathbf{x}'\|}\left(\mathbf{I} - \hat{\boldsymbol{\kappa}}\hat{\boldsymbol{\kappa}}^{\mathsf{T}}\right)$$

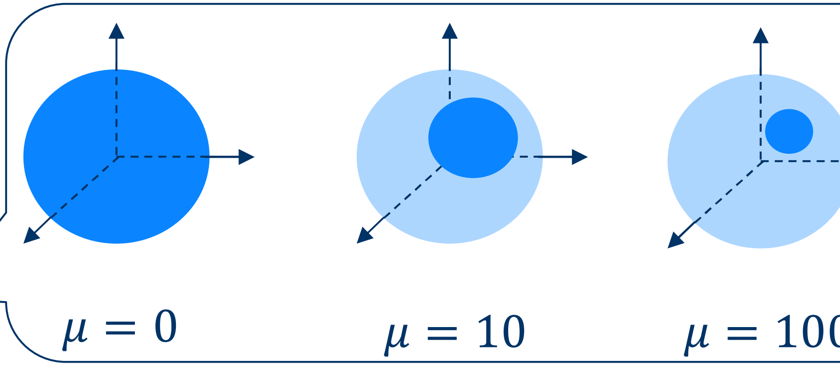
Stochastic integral

$$\mathbf{E}(\mathbf{x}) = \int_{S^2} \nu^{1/2}(\hat{\boldsymbol{\kappa}}) e^{ik_0\hat{\boldsymbol{\kappa}}\cdot\mathbf{x}}\left(\mathbf{I} - \hat{\boldsymbol{\kappa}}\hat{\boldsymbol{\kappa}}^{\mathsf{T}}\right)\cdot \mathrm{d}\mathbf{W}($$

EMCF **EM Polarization** **EM Phase**

$$\mathbf{K}_{\mathrm{EM}}(\mathbf{x}, \mathbf{x}' | \boldsymbol{\mu}) \propto \int_{S^2} \left(\mathbf{I} - \hat{\boldsymbol{\kappa}}\hat{\boldsymbol{\kappa}}^{\mathrm{T}}\right) e^{ik_0\hat{\boldsymbol{\kappa}}\cdot(\mathbf{x}-\mathbf{x}')} \nu(\hat{\boldsymbol{\kappa}}) \mathrm{d}S,$$

Angular weight



$\nu(\hat{\boldsymbol{\kappa}}) = e^{\boldsymbol{\mu}\cdot\hat{\boldsymbol{\kappa}}}$ **: Spherical von Mises-Fisher distribut**

EM propagation law is encapsulated in EMCF

.1 Closed-form EMCF and Its Properties

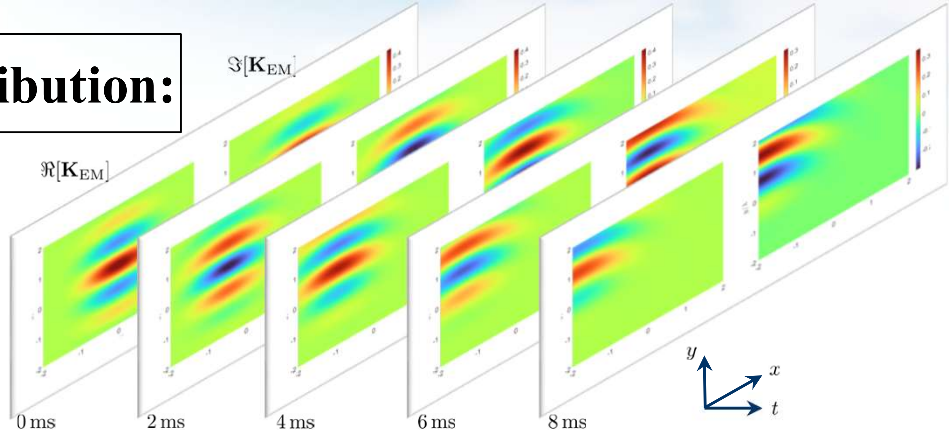
EMCF encapsulates EM propagation law and enjoys nice analytical properties

- **EMCF includes propagation properties like concentration $\boldsymbol{\mu}$, polarization, phase, Doppler effec**
- **EMCF is complex analytic w.r.t. $\boldsymbol{\mu}$, which facilitates further theoretical analysis**

MCF Definition

$$\mathrm{M} \propto \frac{1}{\int_{S^2} \nu(\hat{\boldsymbol{\kappa}}) \mathrm{d}S} \int_{\hat{\boldsymbol{\kappa}} \in S^2} (\mathbf{I} - \hat{\boldsymbol{\kappa}}\hat{\boldsymbol{\kappa}}^{\mathsf{T}}) e^{\mathrm{i} k_0 \hat{\boldsymbol{\kappa}} \cdot (\mathbf{x} - \mathbf{x}')} \nu(\hat{\boldsymbol{\kappa}}) \mathrm{d}S$$

EMCF Space-time Distribution:



Thm 4.1.1 **Assume that the incident EM wave is distributed in the angular domain according to the von Mises-Fisher distribution** $f(\hat{\boldsymbol{\kappa}}|\boldsymbol{\mu}) = e^{\hat{\boldsymbol{\kappa}} \cdot \boldsymbol{\mu}} / C(\|\boldsymbol{\mu}\|)$ **. Then the receiver correlation function is expressed as**

$$\mathbf{K}_{\mathrm{EM}}(\mathbf{x}, \mathbf{x}' | \boldsymbol{\mu}, \sigma^2) := \mathbb{E}\left\{\mathbf{E}(\mathbf{x})\mathbf{E}(\mathbf{x}')^{\mathsf{H}}\right\} = \frac{\sigma^2}{C(\|\boldsymbol{\mu}\|)} \boldsymbol{\Sigma}(k_0 \mathbf{z}) \in \mathbb{C}^{3 \times 3},$$

where $\boldsymbol{\Sigma}(\mathbf{w}) := \frac{1}{8}(f_0 + f_2)\mathbf{I}_3 + \frac{1}{8}(f_0 - 3f_2)\hat{\mathbf{w}}\hat{\mathbf{w}}^{\mathsf{T}}$ **,** $\mathbf{w} := k_0 \mathbf{z} = k_0(\mathbf{x} - \mathbf{x}') - \mathrm{i}\boldsymbol{\mu} \in \mathbb{C}^3, \; f_n(\beta) = \int_{-1}^{1} x^n e^{\mathrm{i}\beta x} \mathrm{d}x.$

.1 Parameter Learning

How to determine the EMCF parameter μ? Learn from the observed data

- **EMCF parameter learning: Tune the concentration parameter μ to fit the actual communicatio environment**

Propagation environment fitting

$$\begin{aligned} &\text{find best} && \boldsymbol{\mu} \\ &\text{s.t.} && \mathbf{K}_{\mathrm{EM}}(\mathbf{x};\mathbf{x}'|\boldsymbol{\mu}) \ \text{fits}\ \mathbf{y}_{\mathrm{obs}} \end{aligned}$$

Maximum Likelihood

Optimization problem

$$\begin{aligned} \hat{\boldsymbol{\mu}} &= \underset{\boldsymbol{\mu}\in\mathsf{F}}{\operatorname{argmax}}\ \ell(\boldsymbol{\mu}|\mathbf{y}_{\mathrm{obs}}) \\ &= \underset{\boldsymbol{\mu}\in\mathsf{F}}{\operatorname{argmax}}\ \big(\underbrace{-\mathbf{y}_{\mathrm{obs}}^{\mathsf{H}}\mathbf{K}_{\mathbf{y}}^{-1}(\boldsymbol{\mu})\mathbf{y}_{\mathrm{obs}}}_{\text{Data fitness}} \underbrace{-\log\det \mathbf{K}_{\mathbf{y}}(\boldsymbol{\mu})}_{\text{Model Complexity}}\big) \end{aligned}$$

Thm 4.1.2 The derivatives of EMCF $\mathbf{K}_{\mathrm{EM}}(\mathbf{x},\mathbf{x}'|\boldsymbol{\mu},\sigma^2)$ w.r.t. $\boldsymbol{\mu}$ and σ^2 are

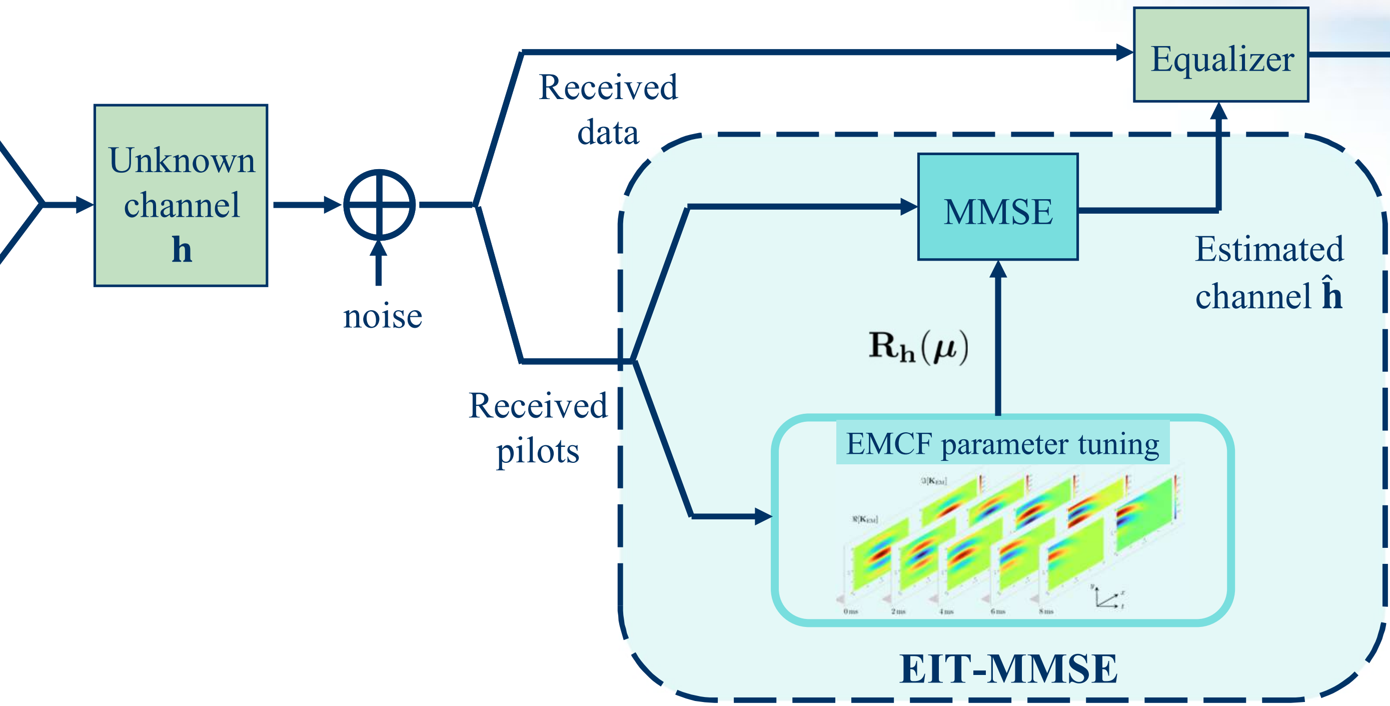
$$\frac{\partial \mathbf{K}_{\mathrm{EM}}}{\partial \boldsymbol{\mu}(k)} = -\frac{\sigma^2}{C(\mu)}\left[\mathrm{i}\frac{\partial \boldsymbol{\Sigma}(\mathbf{w})}{\partial \mathbf{w}(k)} + \frac{C'(\mu)\boldsymbol{\mu}(k)}{C(\mu)\mu}\boldsymbol{\Sigma}(\mathbf{w})\right] \ \text{and}\ \frac{\partial \mathbf{K}_{\mathrm{EM}}}{\partial(\sigma^2)} = \frac{1}{C(\mu)}\boldsymbol{\Sigma}(\mathbf{w}),$$

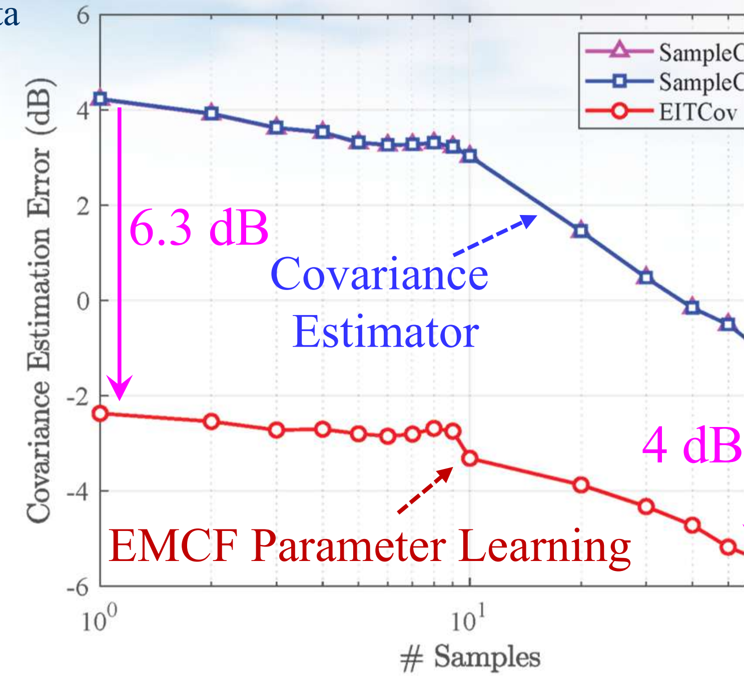
$$\text{where}\quad \frac{\partial \boldsymbol{\Sigma}(\mathbf{w})}{\partial \mathbf{w}(k)} = \frac{1}{8}\left[\mathrm{i}(f_1+f_3)\hat{\mathbf{w}}(k)\mathbf{I}_3 + \mathrm{i}(f_1-3f_3)\hat{\mathbf{w}}(k)\hat{\mathbf{w}}\hat{\mathbf{w}}^{\mathsf{T}} + (f_0-3f_2)(\partial_k\hat{\mathbf{w}}\cdot\hat{\mathbf{w}}^{\mathsf{T}} + \hat{\mathbf{w}}\cdot\partial_k\hat{\mathbf{w}}^{\mathsf{T}})\right].$$

Apply gradient ascent to the EMCF likelihood function for parameter learning

.1 EIT-Inspired Channel Estimator

Extract EM statistical information from EMCF, improving the performance of classical LMMSE channel estimator





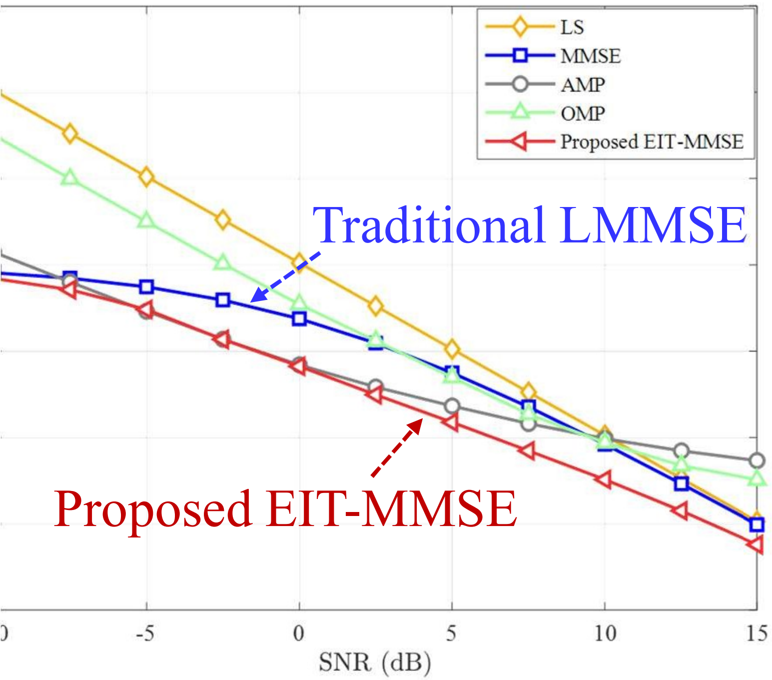
EIT-MMSE utilizes EM prior to compute more accurate channel correlation

, Z. Wan, **L. Dai**, and T. J. Cui, "Electromagnetic information theory-based statistical channel model for improved channel estimation," submitted to *IEEE Trans. Inf. Theory*, r
on, Feb. 2024.

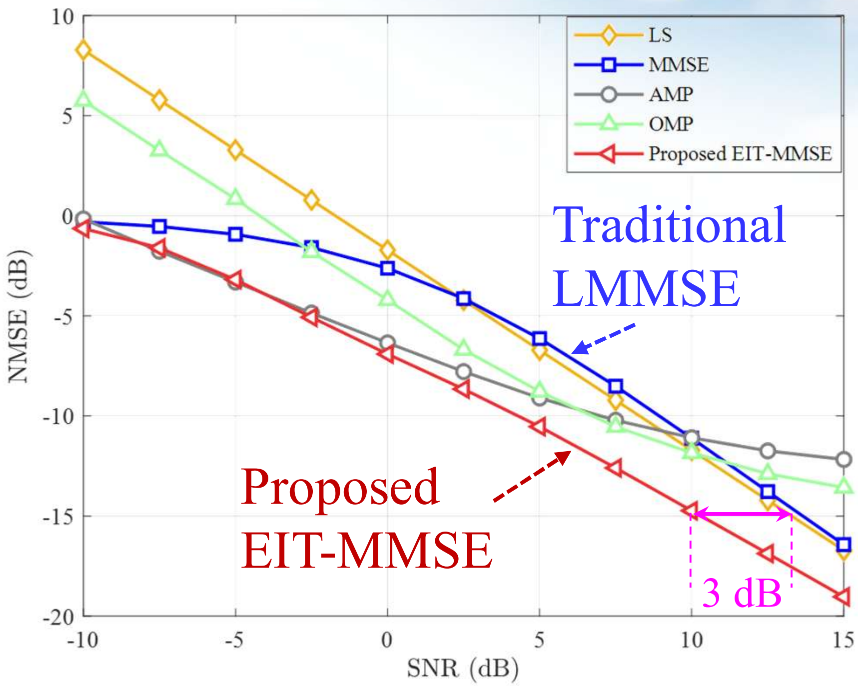
.1 Simulation Results

Derive **EMCF** from EIT to obtain the **EIT-MMSE channel estimator**

EIT-MMSE channel estimator achieves better **NMSE performance**



SCM channel model (7 paths)



3GPP CDL-A channel model (21 paths)

Simulation Parameter	Value
BS Antenna	32
Array	Half-wavelength
Polarization	Y direction
Carrier	3.5 GHz
Rician factor	10 dB

EIT is able to improve the channel estimation accuracy

, Z. Wan, **L. Dai**, and T. J. Cui, "Electromagnetic information theory-based statistical channel model for improved channel estimation," submitted to *IEEE Trans. Inf. Theory*, n
on, Feb. 2024.

Contents

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  - 1.4 Overview of EIT
- Chapter 2: Fundamentals of EIT
  - 2.1 Electromagnetic channel models for EIT
  - 2.2 DoF analysis for EIT
  - 2.3 Mutual information for EIT
- Chapter 3: EIT-Enabled Technologies
  - 3.1 Holographic MIMO
  - 3.2 EIT-enabled near-field communications
  - 3.3 Mutual coupling and superdirective antennas
  - 3.4 Orbital angular momentum
  - 3.5 3D antenna arrays
- **Chapter 4: EIT-Inspired Technologies**
  - 4.1 EIT-inspired channel estimation
  - 4.2 EIT-inspired channel prediction
  - 4.3 EIT-inspired self-controlled RIS
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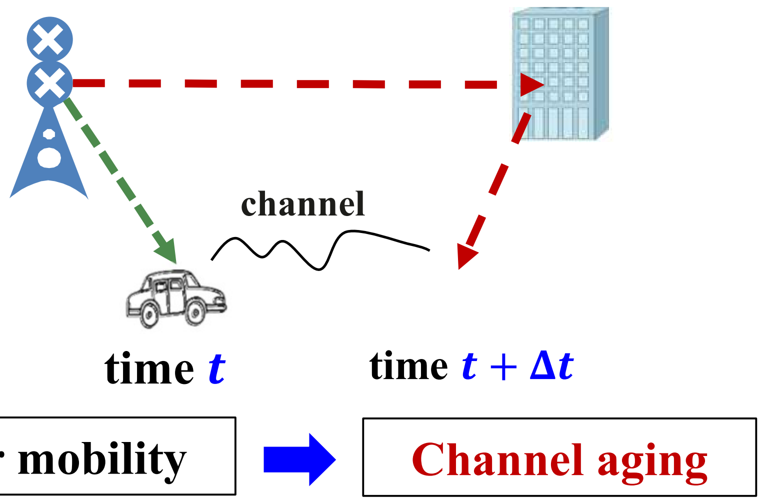
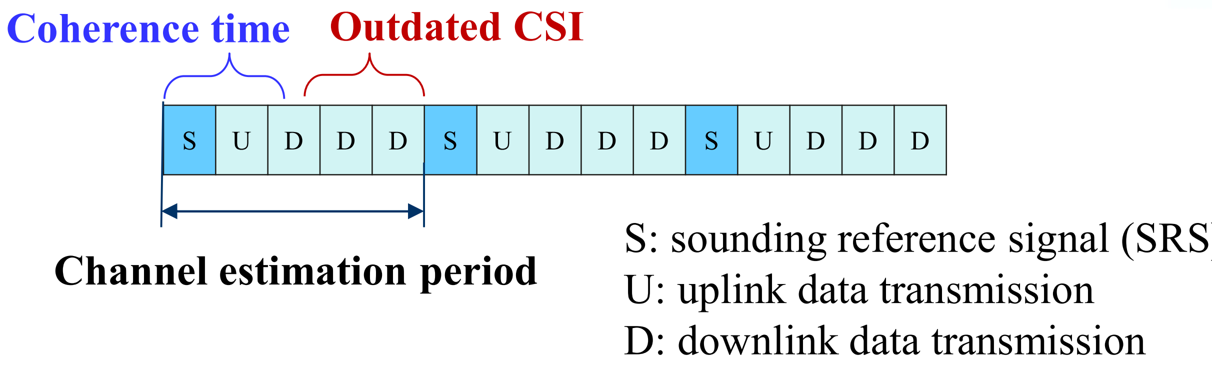
.2 Channel Aging Problem

User mobility leads to **channel aging**

- ➢ **Channel estimation is performed periodically**
- ➢ **Significant channel changes may occur within a single period, leading to outdated CSI in high mobility scenarios**





Frame structure of communication system

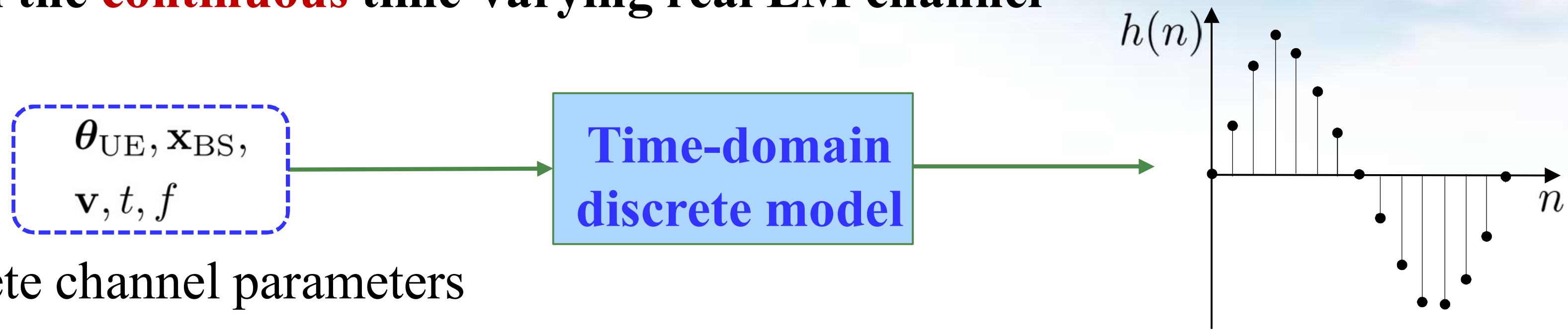
Channel prediction technology is needed in mobile scenarios to alleviate channel aging

, X. Yi, Y. Zhu, W. Wang, L. You, and X. Gao, "Channel prediction in high-mobility massive MIMO: From spatio-temporal autoregression to deep learning," *IEEE J. Sel. Area. un.*, vol. 39, no. 7, pp. 1915–1930, Jul. 2021.

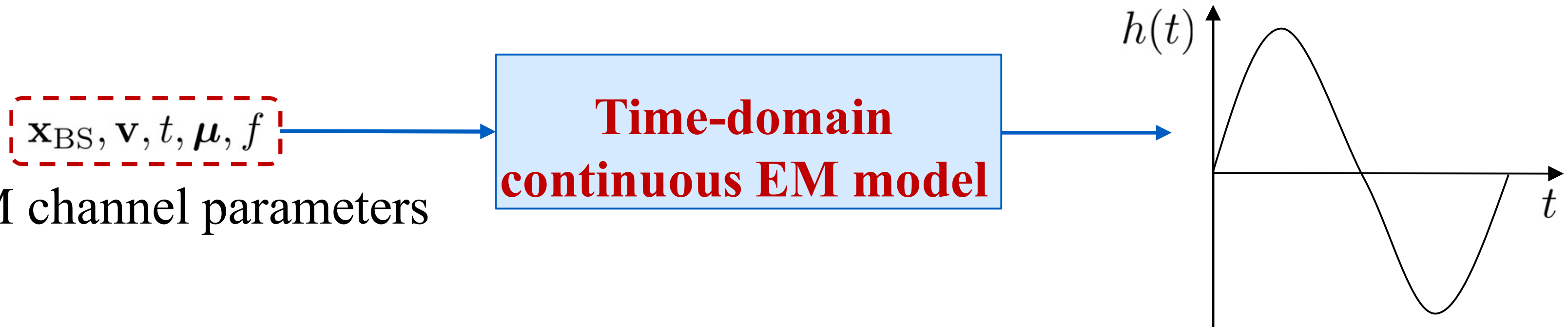
.2 Discrete v.s. Continuous Channel Model

Existing channel predictors

- **Represent channel process as time-domain discrete model**
- **Mismatch the continuous time-varying real EM channel**



Problem: How to design a channel predictor that can accurately capture the continuous time-varying characteristics of EM channels in high-mobility scenarios



.2 STEM-CF Based Channel Predictor

Spatial-temporal EM correlation function (STEM-CF)

- **Channel correlation** is contained in the STEM-CF
- Parameter μ represents **concentration**, reflecting the direction of EM incidence
- Parameter $\mathbf{v}$ represents **user velocity**, reflecting the time-varying characteristics of the channel

$$\mathbf{K}_{\mathrm{STEM}}(\mathbf{x},\mathbf{x}',t,t'|\boldsymbol{\mu},\mathbf{v}) \propto \frac{1}{\int_{S^2}\nu(\hat{\boldsymbol{\kappa}})\mathrm{d}S}\int_{\hat{\boldsymbol{\kappa}}\in S^2}(\mathbf{I}-\hat{\boldsymbol{\kappa}}\hat{\boldsymbol{\kappa}}^{\mathsf{T}})e^{\mathrm{i}k_0\hat{\boldsymbol{\kappa}}\cdot((\mathbf{x}-\mathbf{x}')+\mathbf{v}(t-t'))}\nu(\hat{\boldsymbol{\kappa}})\mathrm{d}S, \quad \nu(\hat{\boldsymbol{\kappa}}) = e^{\boldsymbol{\mu}\cdot\hat{\boldsymbol{\kappa}}}$$

Continuous channel predictor based on STEM-CF

- According to the **MMSE** criterion, channel prediction can be achieved by utilizing the **spatial-temporal correlation** between **past and future** channels

$$\mathbf{h}_{\mathcal{F}} = \mathbf{K}_{\mathcal{P}\mathcal{F}}^{\mathsf{H}}(\mathbf{K}_{\mathcal{P}} + \sigma^2\mathbf{I})^{-1}\mathbf{y}$$

STEM correlation between past and future channels

STEM correlation between past channels

STEM-CF utilizes EM spatial-temporal correlation to achieve channel prediction

J. Zhu and **L. Dai**, "Accurate channel prediction based on spatial-temporal electromagnetic kernel learning," submitted to *IEEE Int. Conf. Commun. (IEEE ICC'25)*, Nov. 2024

.2 STEM-CF Parameter Learning

Using **ML** criterion, **concentration μ** and **velocity v** that are most suitable for the current communication environment can be solved through **alternating iterations**

Propagation environment fitting → **STEM parameter learning**

find best $\boldsymbol{\mu}, \mathbf{v}$

s.t. $\mathbf{K}_{\text{STEM}}(\mathbf{x}, \mathbf{x}', t, t' | \boldsymbol{\mu}, \mathbf{v})$ fits $\mathbf{y}_{\text{obs}}$

$$(\hat{\boldsymbol{\mu}}, \hat{\mathbf{v}}) = \arg\max_{(\boldsymbol{\mu},\mathbf{v})\in\Omega} l(\boldsymbol{\mu}, \mathbf{v} | \mathbf{y}_{\text{obs}})$$

$$= \arg\max_{(\boldsymbol{\mu},\mathbf{v})\in\Omega} (\underbrace{-\ln\det \mathbf{K}_{\mathbf{y}}(\boldsymbol{\mu}, \mathbf{v})}_{\text{Model Complexity}} \underbrace{- \mathbf{y}_{\text{obs}}^{\mathsf{H}} \mathbf{K}_{\mathbf{y}}^{-1}(\boldsymbol{\mu}, \mathbf{v}) \mathbf{y}_{\text{o}}}_{\text{Data fitness}}$$

Thm 4.2.1 **The derivatives of EMCF $\mathbf{K}_{\text{STEM}}(\mathbf{x}, \mathbf{x}', t, t' | \boldsymbol{\mu}, \mathbf{v})$ w.r.t. $\boldsymbol{\mu}$ and $\mathbf{v}$ are**

$$\frac{\partial \mathbf{K}_{\text{STEM}}}{\partial \boldsymbol{\mu}(k)} = -\frac{\sigma^2}{C(\mu)} \left[\frac{C'(\mu)\boldsymbol{\mu}(k)}{C(\mu)\mu} \boldsymbol{\Sigma}(\mathbf{w}) + \mathrm{i} \frac{\partial \boldsymbol{\Sigma}(\mathbf{w})}{\partial \mathbf{w}(k)} \right] \quad \textbf{and} \quad \frac{\partial \mathbf{K}_{\text{STEM}}}{\partial \mathbf{v}(k)} = \frac{\sigma^2 k_0 (t - t')}{C(\mu)} \frac{\partial \boldsymbol{\Sigma}(\mathbf{w})}{\partial \mathbf{w}(k)}, \quad k = 1, 2, 3,$$

where $$\frac{\partial \boldsymbol{\Sigma}(\mathbf{w})}{\partial \mathbf{w}(k)} = \frac{1}{8} \left[\mathrm{i}(f_1 + f_3)\hat{\mathbf{w}}(k)\mathbf{I}_3 + \mathrm{i}(f_1 - 3f_3)\hat{\mathbf{w}}(k)\hat{\mathbf{w}}\hat{\mathbf{w}}^{\mathsf{T}} + (f_0 - 3f_2)(\partial_k \hat{\mathbf{w}} \cdot \hat{\mathbf{w}}^{\mathsf{T}} + \hat{\mathbf{w}} \cdot \partial_k \hat{\mathbf{w}}^{\mathsf{T}}) \right].$$

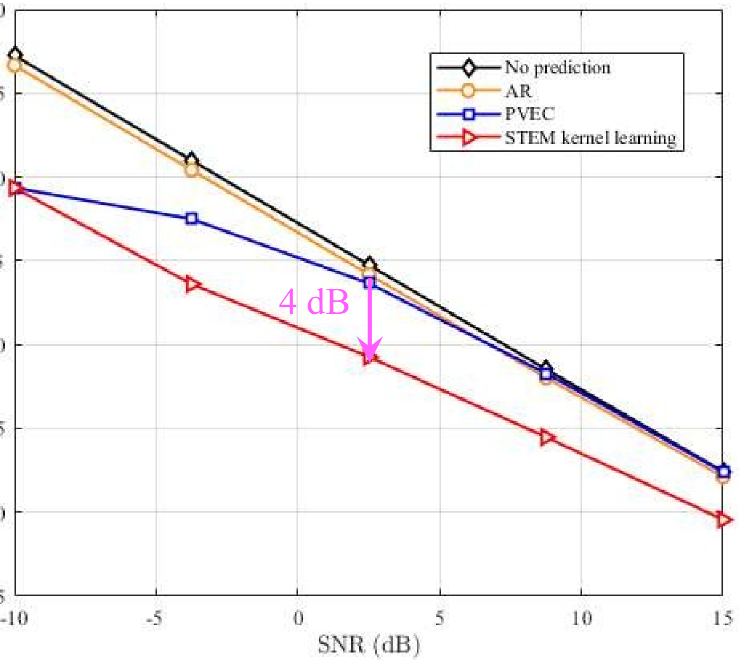
Apply gradient ascent to optimize STEM parameters to fit time-varying channels

J. Zhu and **L. Dai**, "Accurate channel prediction based on spatial-temporal electromagnetic kernel learning," submitted to *IEEE Int. Conf. Commun. (IEEE ICC'25)*, Nov. 2024

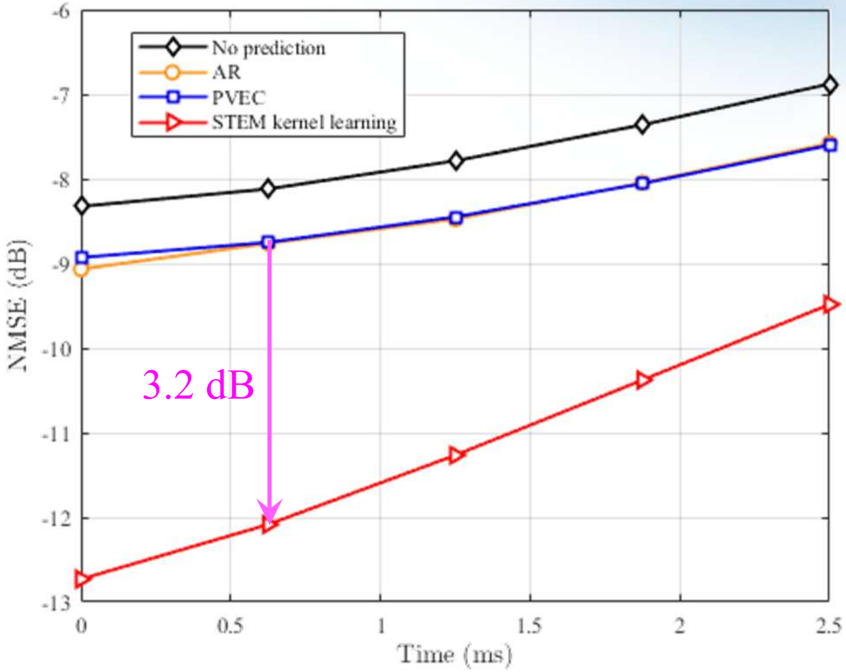
.2 Simulation Results

Based on **STEM kernel learning**, the EIT channel predictor is obtained

The proposed channel predictors outperforms other schemes



NMSE versus SNR



NMSE versus time

Simulation parameters	Value
Number of BS antennas	256
Array form	Half wav length UL
Antenna polarization	Y-axis direc
User speed	72 km/h

EIT can improve channel prediction accuracy

J. Zhu and **L. Dai**, "Accurate channel prediction based on spatial-temporal electromagnetic kernel learning," submitted to *IEEE Int. Conf. Commun. (IEEE ICC'25)*, Nov. 2024

Contents

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  - 2.3 Mutual information for EIT
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  - 3.1 Holographic MIMO
  - 3.2 EIT-enabled near-field communications
  - 3.3 Mutual coupling and superdirective antennas
  - 3.4 Orbital angular momentum
  - 3.5 3D antenna arrays
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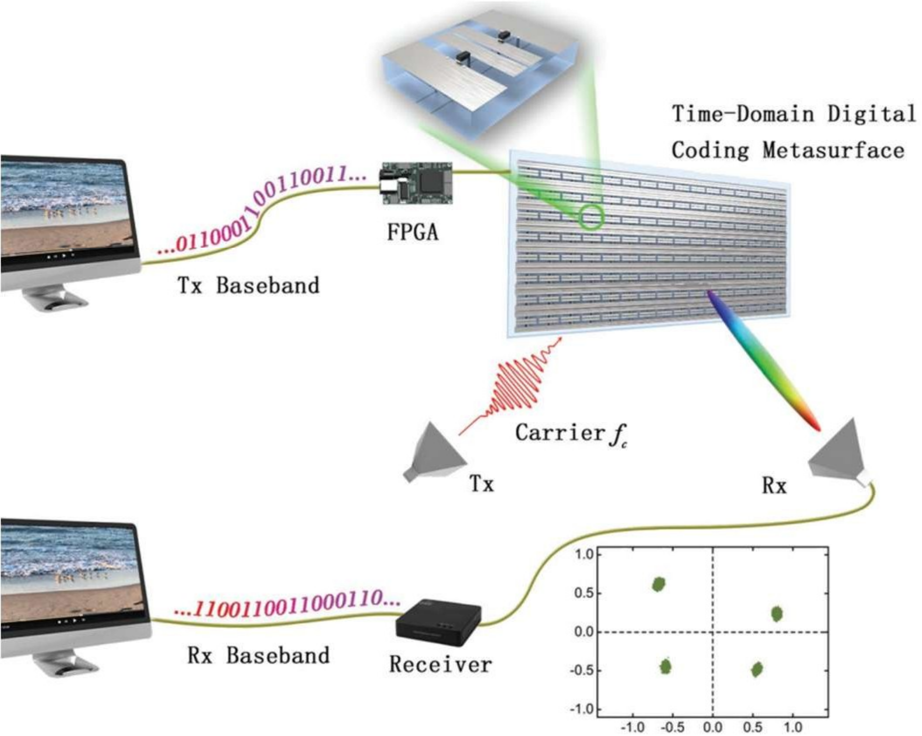
  - 4.2 EIT-inspired channel prediction
  - 4.3 EIT-inspired self-controlled RIS
- Chapter 5: Conclusions

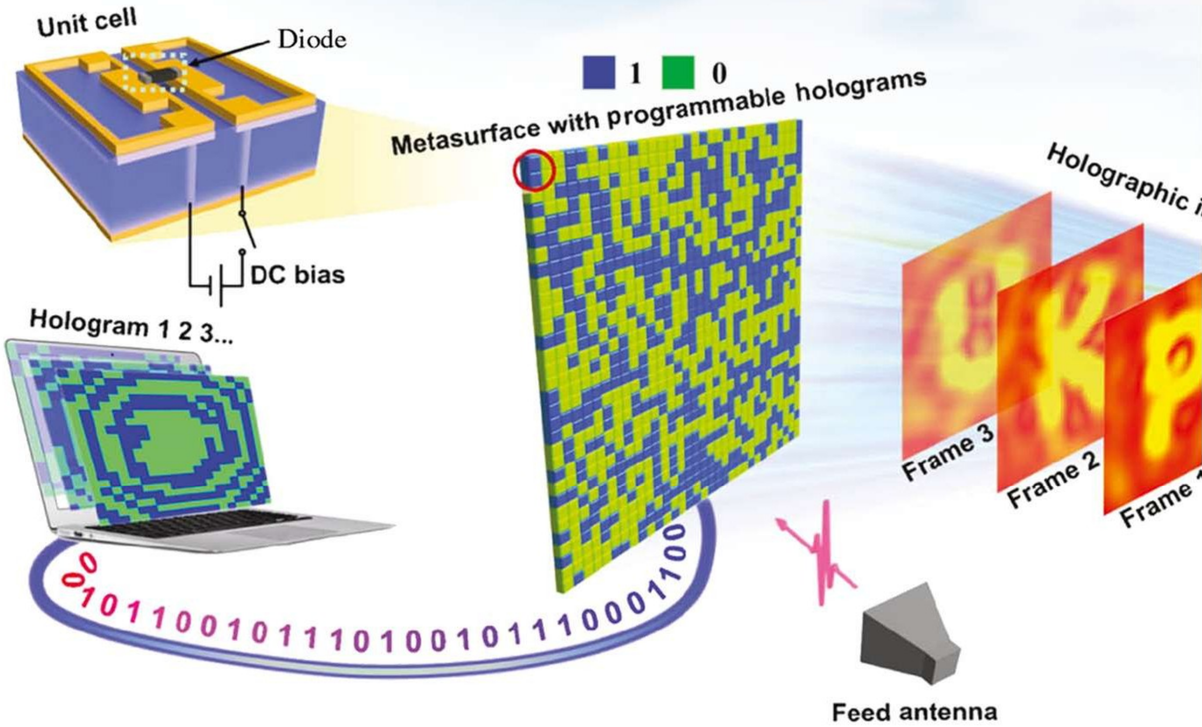
3 Information Metamaterials

econfigurable intelligent surface (RIS)

lethod 1: Use RIS to replace the RF components of transceivers

lethod 2: Use RIS to reconfigure the EM environments





Cui, and S. Liu, "An information science view of metamaterials," *Optics and Photonics News*, vol. 27, no. 12, pp. 59-59, 2016.
and T. -J. Cui, "Information metamaterials–from effective media to real-time information processing systems," *Nanophotonics*, vol. 8, no. 5, pp. 703-7

3 Hardware Implementations of RISs

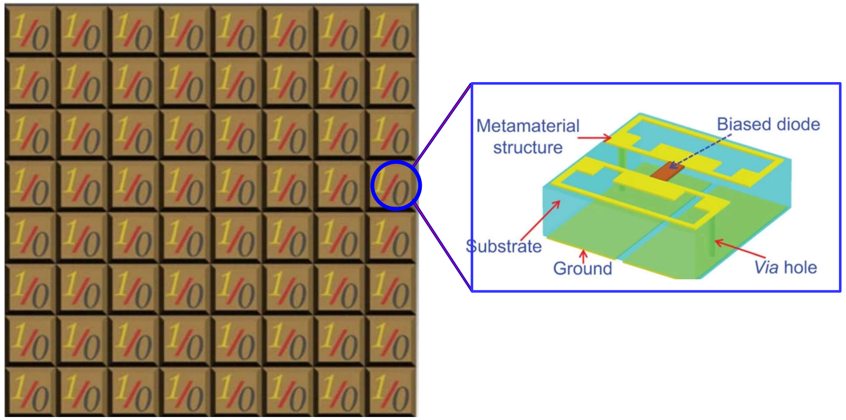
letamaterial: Artificial material with a structure that exhibits unnatural propertie

letasurface: Two-dimensional (2D) structure composed of individual elements to nanipulate signals

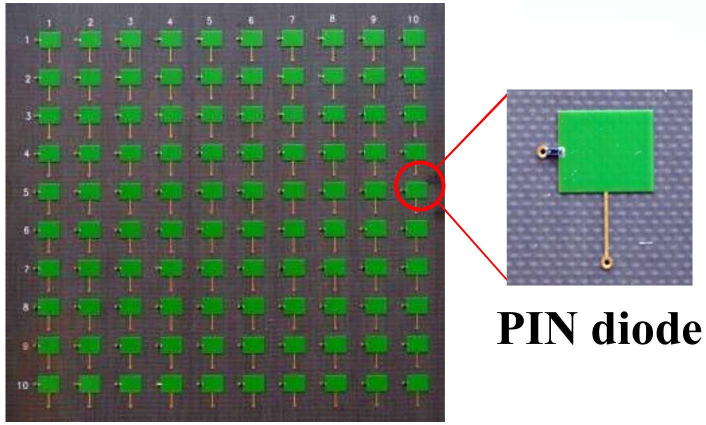
'our typical realizations: Electric/magnetic/thermal/light-sensitive

Capasso, 2011

Cui, 2014



Yang, 2016

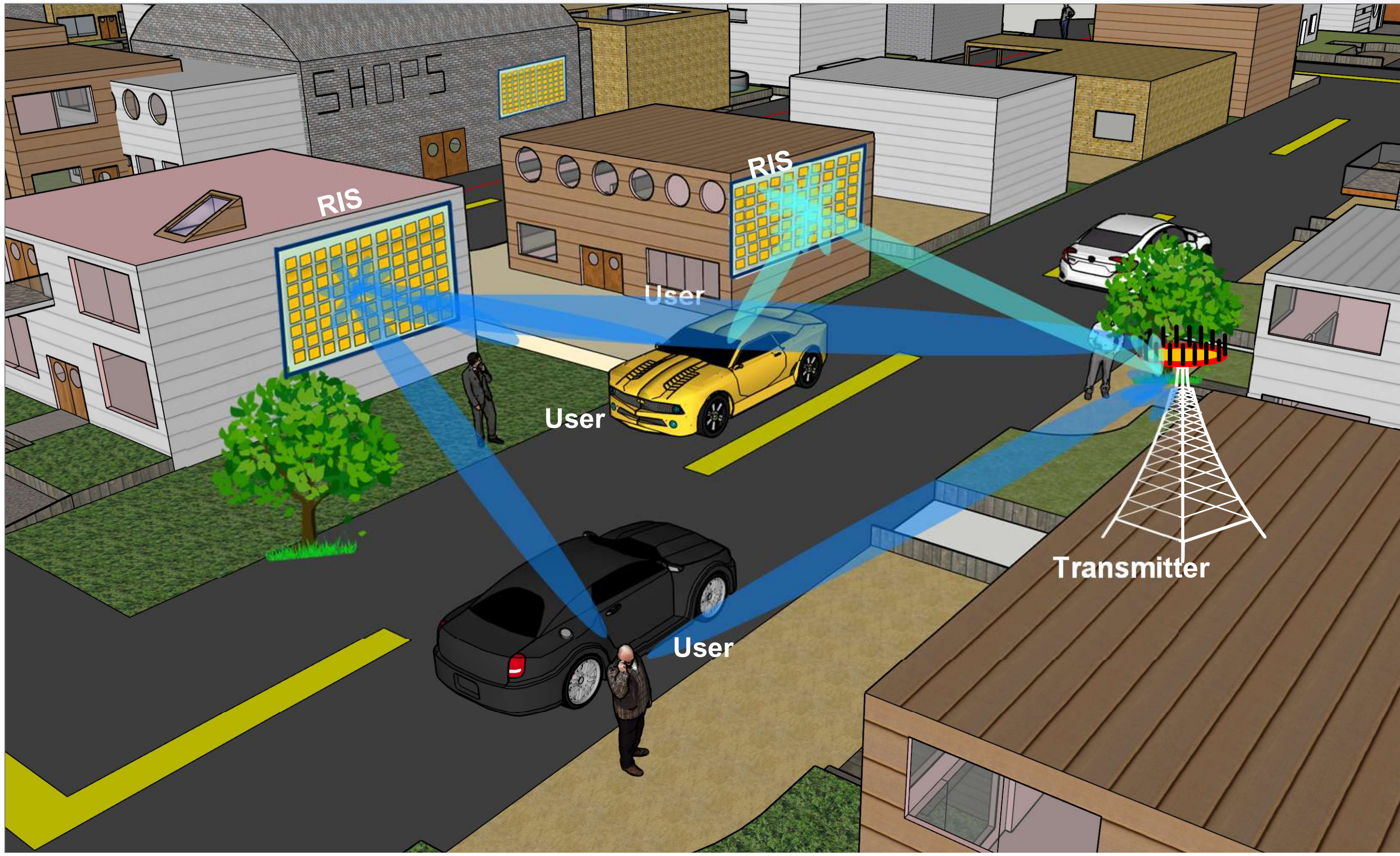


PIN diode

F. Yu, P. Genevet, M. A. Kats, F. Aieta, J.-P. Tetienne, F. Capasso, and Z. Gaburro, "Light propagation with phase discontinuities: Generalized laws of ection and refraction," *Science*, vol. 334, pp. 333–337, Oct. 2011.
Cui, M. Qi, X. Wan, J. Zhao, and Q. Cheng, "Coding metamaterials, digital metamaterials and programmable metamaterials," *Light: Science & Applica* . 3, p. 218, Oct. 2014.
Yang, X. Cao, F. Yang, J. Gao, S. Xu, M. Li, X. Chen, Y. Zhao, Y. Zheng, and S. Li, "A programmable metasurface with dynamic polarization, scatterin using control," *Scientific Reports*, vol. 6, p. 35692 EP, Oct. 2016.

3 RIS-Aided Wireless Communications

-)vercome the **blockage**
- 'rovide communication links
- :nhance the **signal quality**
- ncrease spectrum efficiency
- ave the **power consumption**
- ncrease the energy efficiency
- ……

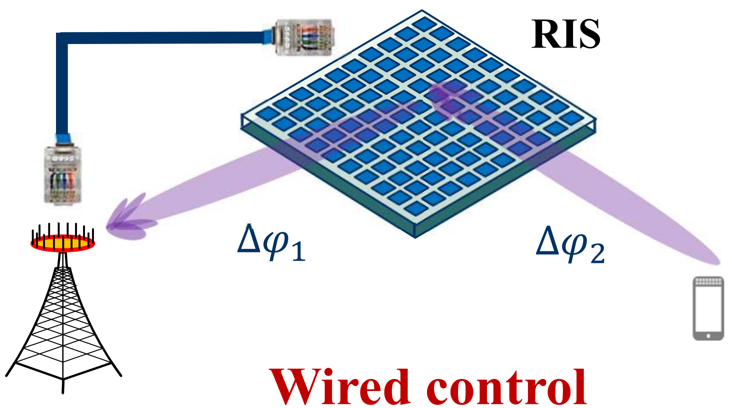


nang and **L. Dai**, "Reconfigurable intelligent surfaces for 6G: Nine fundamental issues and one critical problem," *Tsinghua Sci. Technol.*, vol. 28, no. 5
939, Oct. 2023.

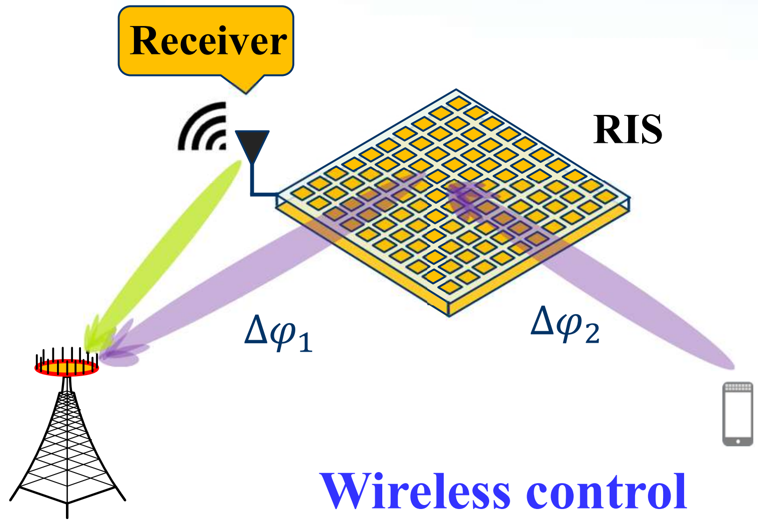
3 Challenge: Complex Control Process

RIS is usually controlled by the **base station**

- Complex control process: Channel estimation → Precoding → Control signal for RIS
- **Wired control**: High cost on laying out cables
- **Wireless control**: Extra receiver on RIS



Wired control



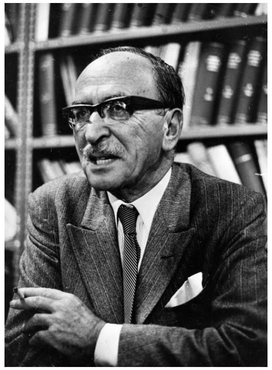
Wireless control

RIS controlled by the BS is difficult to be massively deployed

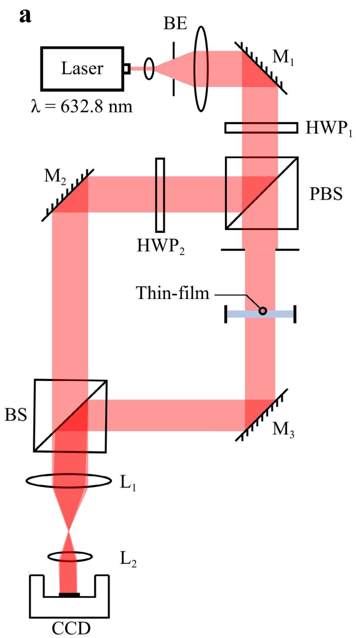
3 The Idea of Holography

Holographic imaging

- The physical principle of holographic imaging is optical interference
- Restoring 3D information of objects through algorithms



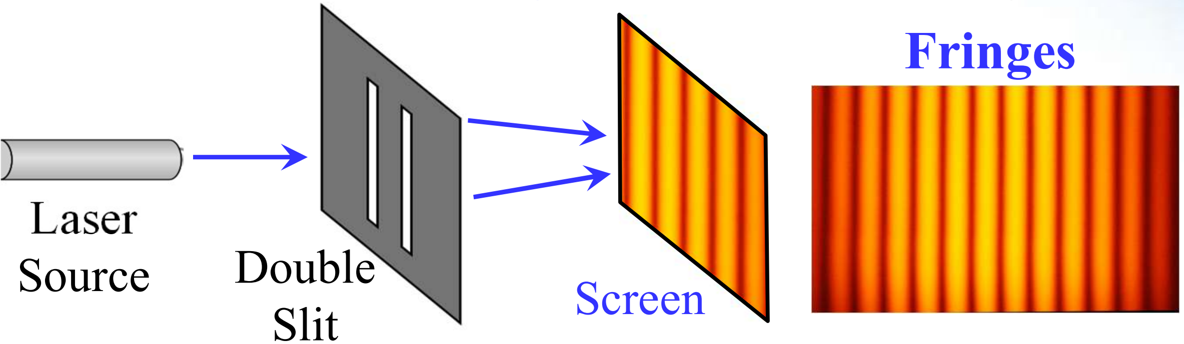
Dennis Gabor
Nobel Prize in Physics (1971)



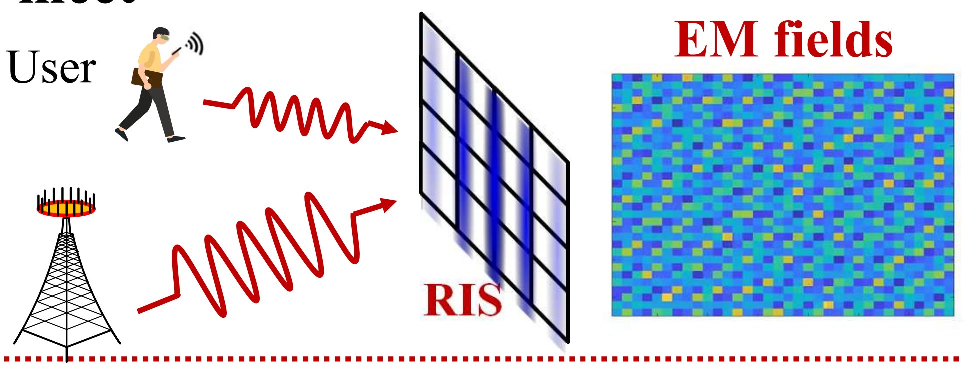
Basic principle of holography

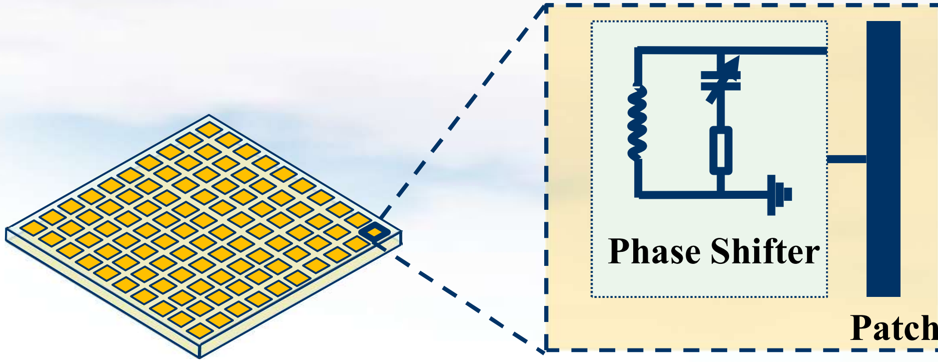
3 EIT-Inspired Self-Controlled RIS

ptical Inference: Fringes created when lights meet

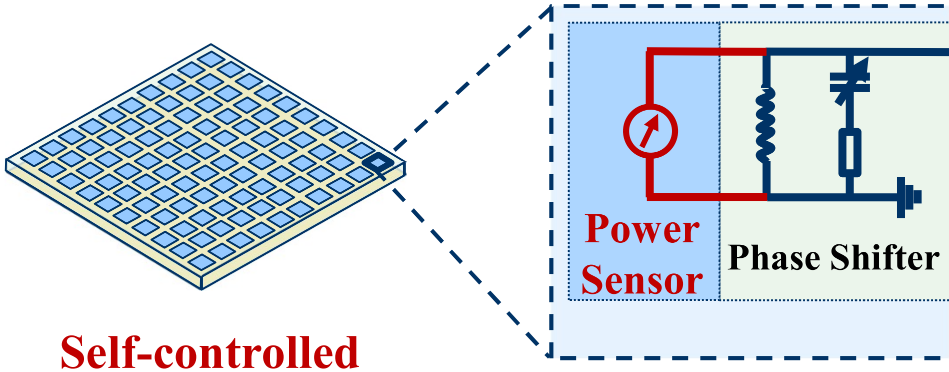


M Interference: Intensity pattern created when M waves meet





Traditional RIS

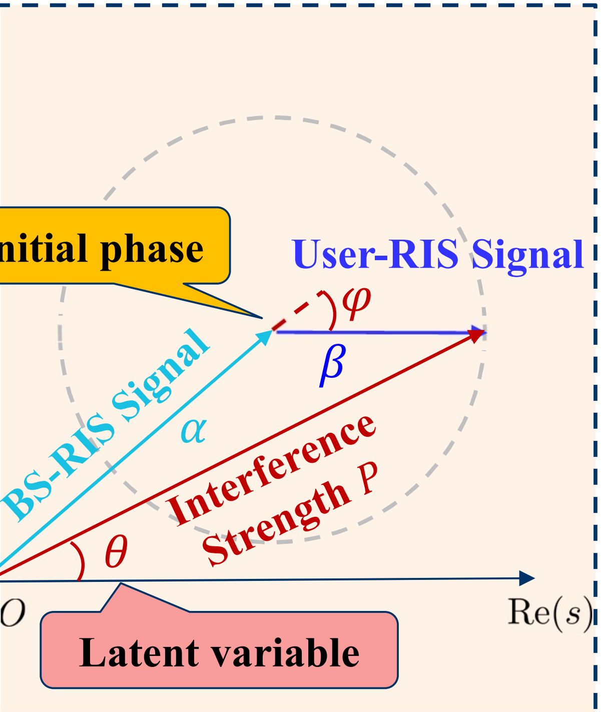


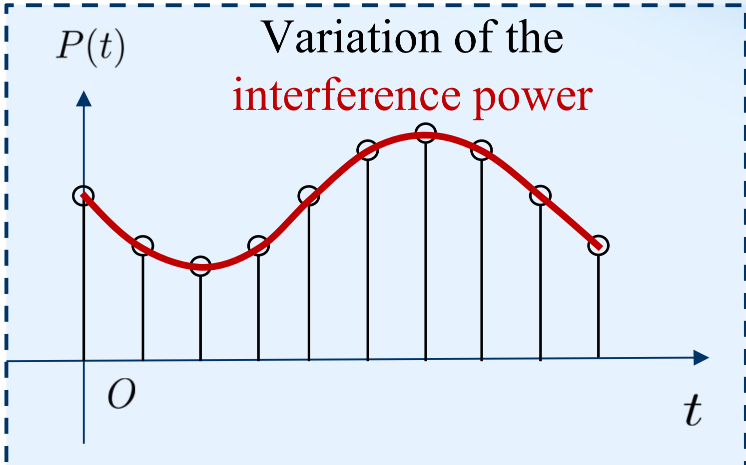
Self-controlled RIS

Liu, Z. Wan, **L. Dai**, T. J. Cui, and H. V. Poor, "Sensing RISs: Enabling dimension-independent CSI acquisition for beamforming," *IEEE Trans. Inf. Theory*, vol. 69, no. 6, pp. 3795-3813, Jun.

3 Self-Controlled RIS: Phase Estimation Algorith

- **Signal:** **Cosine signal $P(t)$ with initial phase φ**
- **Algorithm:** **FFT + iterative expectation-maximization (EM)**





$$P = \alpha^2 + \beta^2 + 2\alpha\beta\cos(\varphi)$$

$$P(t) = \alpha^2 + \beta^2 + 2\alpha\beta\cos(\varphi + \omega t)$$

Algorithm 2 von Mises-EM phase estimation (VM-EM algorithm)

Input: Incident wave intensity α, β; sensor data $P[l]$; amplification fact σ_v^2; predefined phase shifts $\psi_l = \omega t_l$.

Output: $\hat{\varphi}$

$s_l \leftarrow \sqrt{P[l]/A}, \quad \forall l \in \{L\}$

$\hat{\varphi} \leftarrow \arg\{\mathrm{FFT}(P)[1]\}$ — **Obtain initia phase φ via**

$\kappa \leftarrow 1$

while $\hat{\varphi}$ not convergence **do** — **Iterative up by EM algo**

$\mu_l \leftarrow \alpha + \beta e^{j(\hat{\varphi}+\psi_l)}, \quad \forall l \in \{L\}$

$w_l \leftarrow s_l e^{j\arg(\mu_l)} - \alpha, \quad \forall l \in \{L\}$

$z_\varphi \leftarrow \kappa e^{j\hat{\varphi}} + \beta\left(\sum_{l=0}^{L-1} w_l e^{-j\psi_l}\right)/(\sigma_v^2/2)$

$\hat{\varphi} \leftarrow \arg(z_\varphi)$

$\kappa \leftarrow |z_\varphi|$

end while

return $\hat{\varphi}$

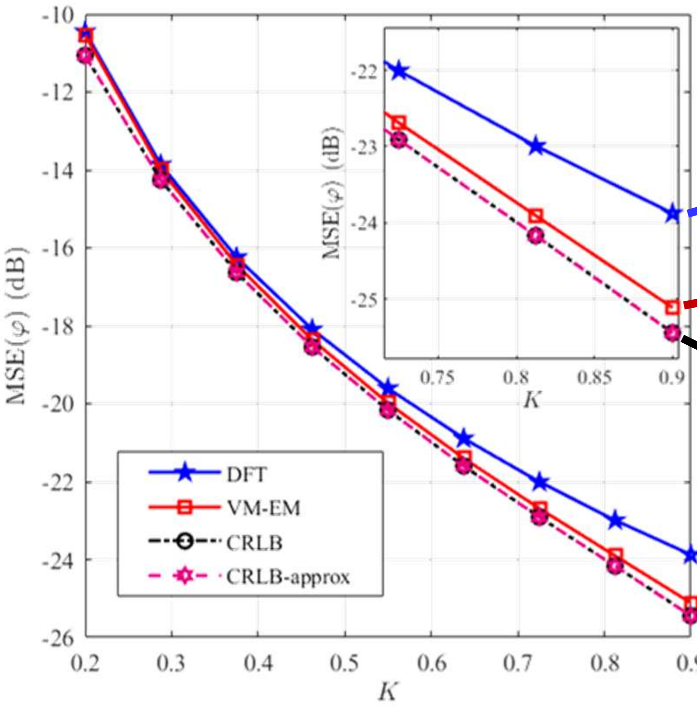
Phase estimation algorithm: Extract channel phase information from dynamic interference signals

Liu, Z. Wan, **L. Dai**, T. J. Cui, and H. V. Poor, "Sensing RISs: Enabling dimension-independent CSI acquisition for beamforming," *IEEE Trans. Inf. Theory*, vol. 69, no. 6, pp. 3795-3813, Jun.

3 Simulation Results

MSE of phase estimation approach CRLB

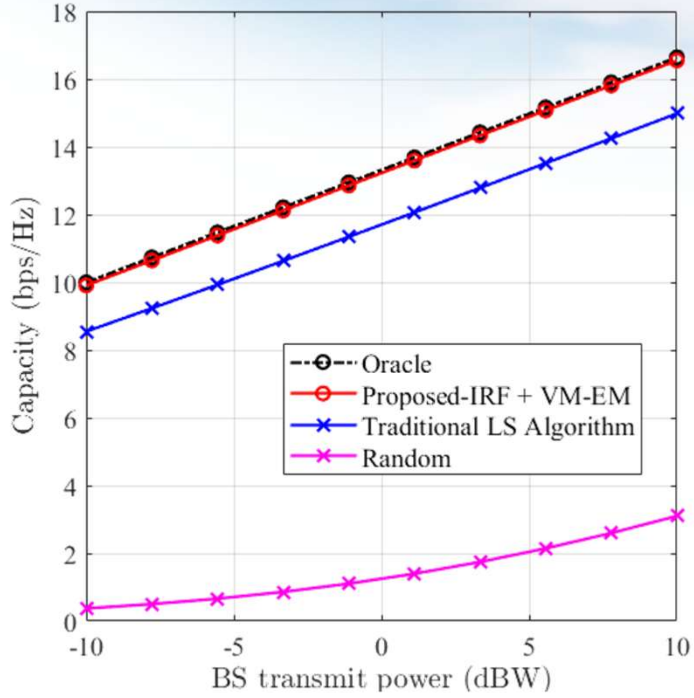
The average capacity approaches traditional RIS system with known CSI



LS estimation

Proposed method

CRLB



Perfect CSI

Proposed meth

Traditional algorithm

RIS random phase

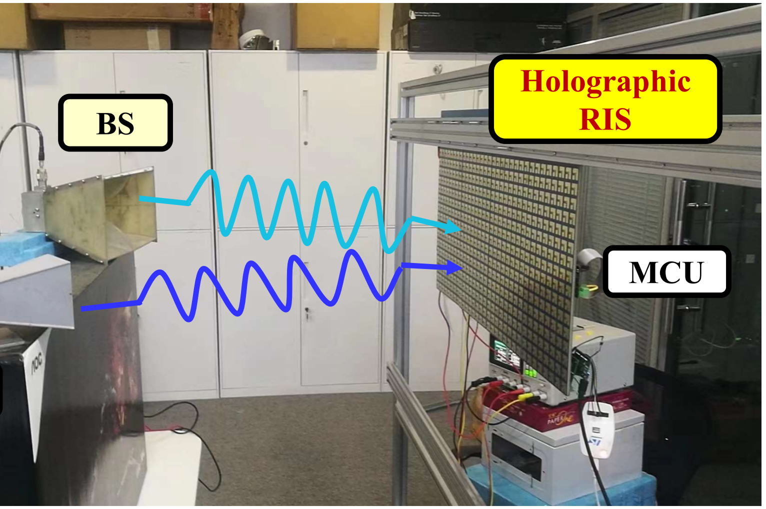
Self-controlled RIS can automatically sense the channel and perform beamforming

Liu, Z. Wan, **L. Dai**, T. J. Cui, and H. V. Poor, "Sensing RISs: Enabling dimension-independent CSI acquisition for beamforming," *IEEE Trans. Inf. Theory*, vol. 69, no. 6, pp. 3795-3813, Jun.

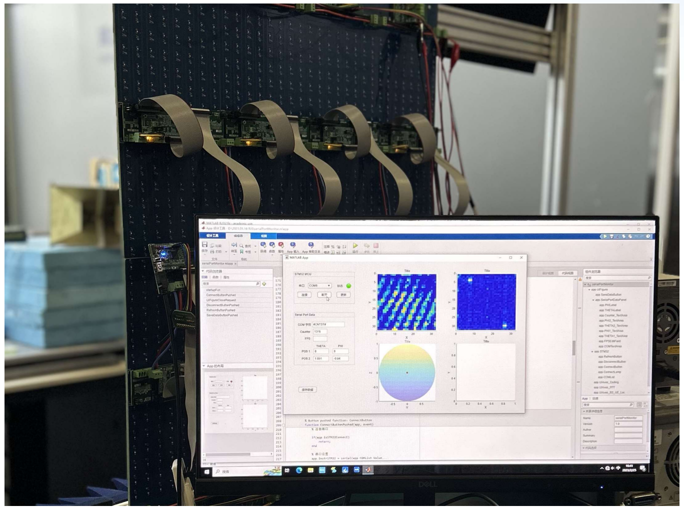
3 Hardware Design and Test

Design **32×32 self-controlled RIS** and observe the effect of electromagnetic interfe

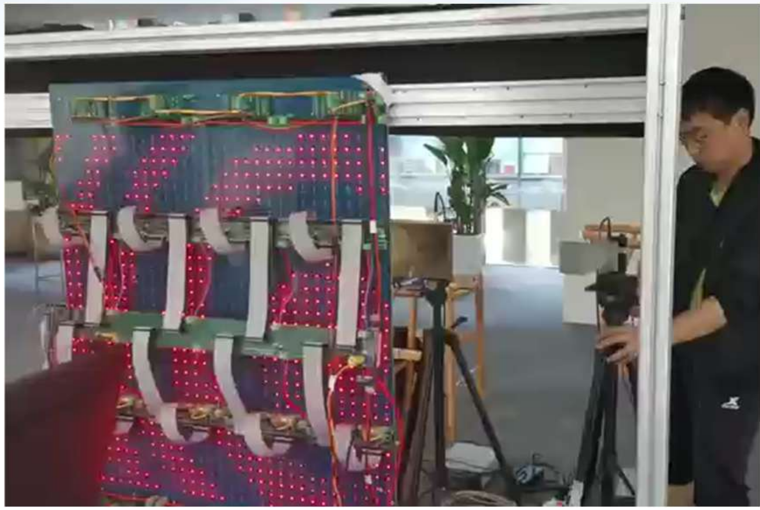
Estimate the location of user with proposed algorithm



lf-controlled RIS hardware system



Visual electromagnetic interference



Autonomous closed-loop trackin of mobile users

Verified the software and hardware joint design for self-controlled RIS

Contents

- Chapter 1: Introduction to EIT
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  - 1.2 Shannon information theory
  - 1.3 Maxwell electromagnetic theory
  - 1.4 Overview of EIT
- Chapter 2: Fundamentals of EIT
  - 2.1 Electromagnetic channel models for EIT
  - 2.2 DoF analysis for EIT
  - 2.3 Mutual information for EIT
- Chapter 3: EIT-Enabled Technologies
  - 3.1 Holographic MIMO
  - 3.2 EIT-enabled near-field communications
  - 3.3 Mutual coupling and superdirective antennas
  - 3.4 Orbital angular momentum
  - 3.5 3D antenna arrays
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  - 4.1 EIT-inspired channel estimation
  - 4.2 EIT-inspired channel prediction
  - 4.3 EIT-inspired self-controlled RIS
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Conclusions

Introduction to EIT

- EIT for 6G advanced MIMO architectures
- EIT: Combining Shannon and Maxwell theory
- EIT v.s. MIMO theory
- EIT: History and recent achievements

Fundamentals of EIT

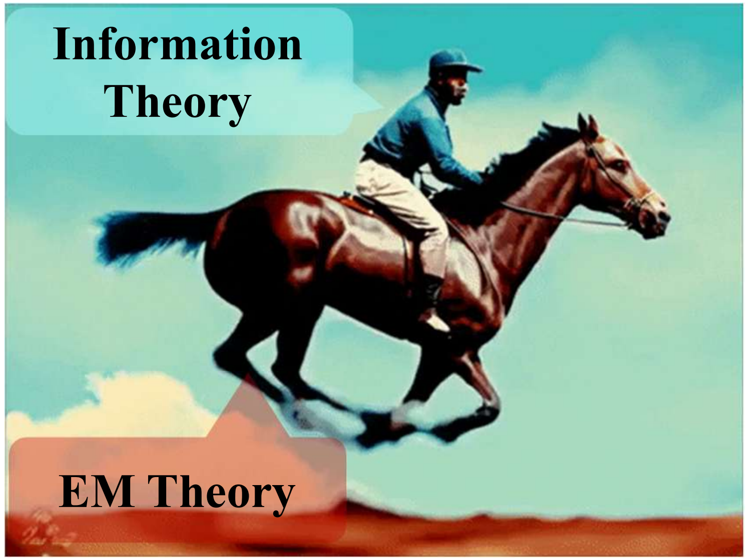
- EIT channel models with near-field correlation
- EIT DoF/capacity bounds by EM dual-bandlimited property
- EIT mutual information by F-determinants

EIT-Enabled Technologies

- Holographic MIMO fully exploits EM DoF
- Near-field LDMA for EM multiple access
- Mutual coupling leads to superdirectivity
- Orbital angular momentum brings infinite DoFs
- 3D Antenna Arrays explore the third spatial dimension

EIT-Inspired Technologies

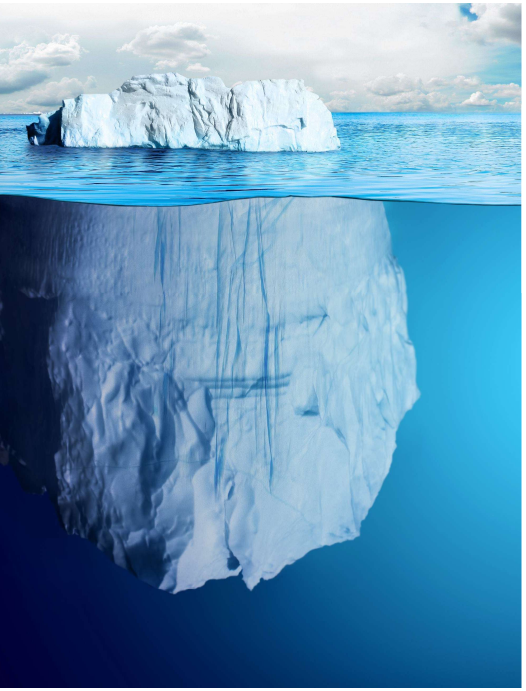
- EIT statistical information improves chan
  estimation
- EIT statistical information improves chan
  prediction
- EM interference enables self-controlled R

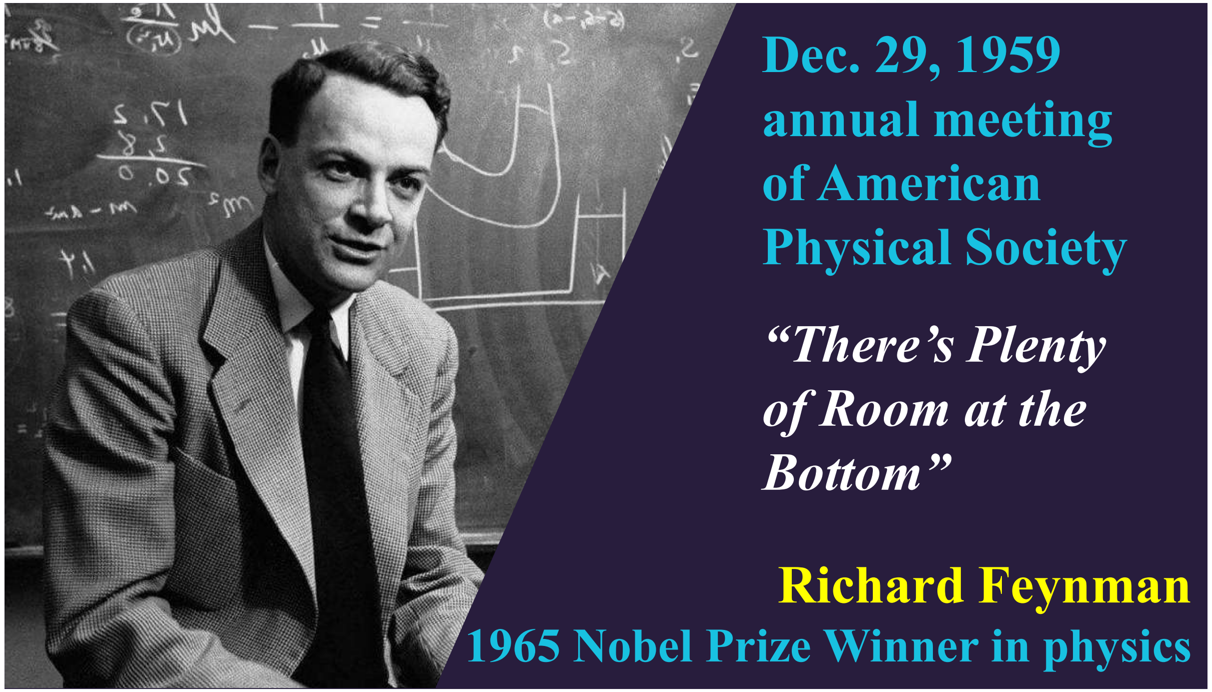


IT for Future Wireless

The Iceberg Effect

- **Above the water: Mathematical description of classical communication theory**
- **Below the water: Physical EM mechanism inspiring new paradigm shift in communication theory and technologies**





Application Layer

Representation Laye

Session Layer

Transmission Layer

Network Layer

MAC Layer

EM Physical Layer [1]

u, Z. Wan, **L. Dai**, M. Debbah, and H. V. Poor, "Electromagnetic information theory: Fundamentals, modeling, applications, and open problems," *IEEE Wireless Commun.*, vol
156-162, Jun. 2023.

EEE ComSoc ETI on ESIT

pproved by IEEE ComSoc in Nov. 2024

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e aim is to bring together both the industry and demic peers likewise the amalgamation of ctromagnetic wave principles with information theory l signal processing tools.

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are also establishing a list of **active contributors** so join us by contacting the Chairs

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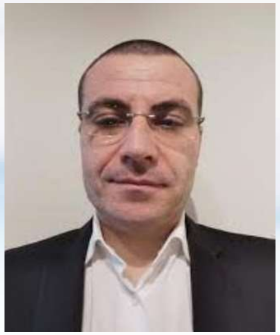

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The world's first white paper on near-field technologies was published at 2024 Glo 6G Conference (contributed by 200+ people, 40+ global entities of 12 countries)

Released at the Global 6G Conference, 2024

The first white paper

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o, L. Dai, J. Zhang, *et al*. "6G near-field technologies white paper," FuTURE Forum, Nanjing, China, Apr. 2024.

Thanks for your attention!

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