Holographic MIMO Communications

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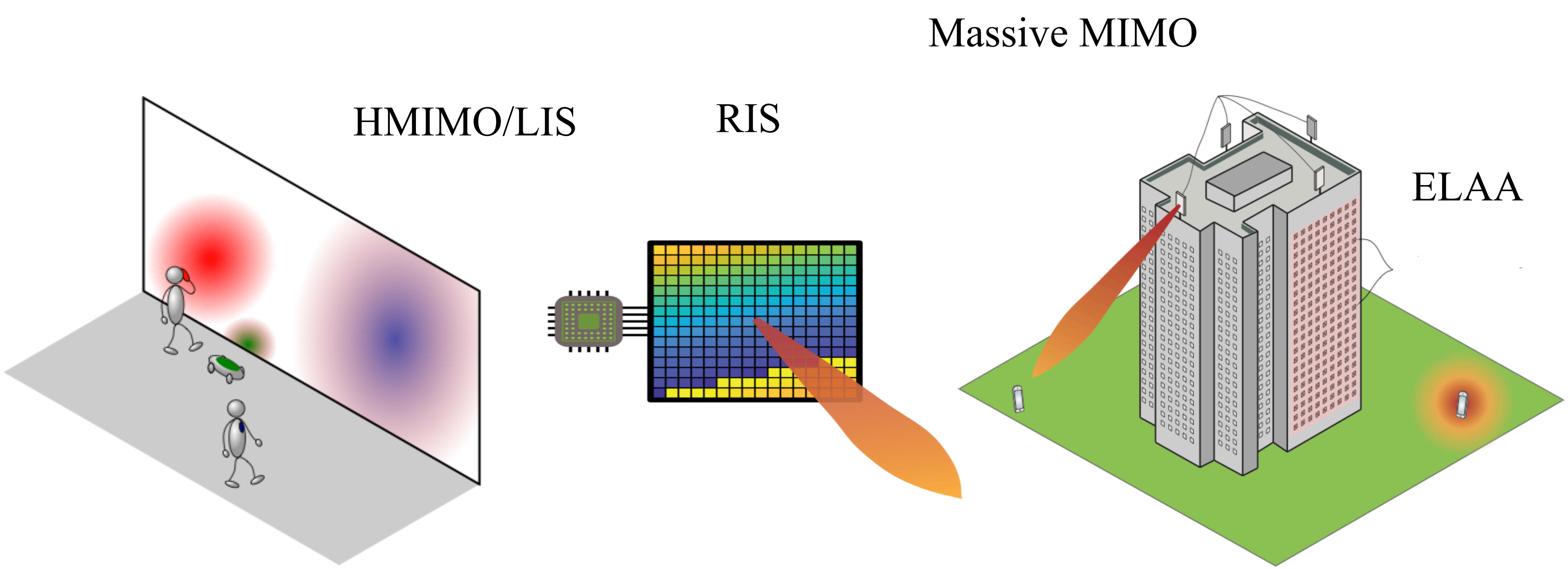
GTTI workshop

"Wireless Intelligence: From Reconfigurable Surfaces to Edge/Cloud Communications"

Promising wireless applications

- Holographic MIMO, Large intelligent surfaces (LIS), Reconfigurable intelligent surfaces (RIS), Extremely large aperture arrays (ELAA)
- All aiming at increasing the spectral efficiency (bit/s/Hz)



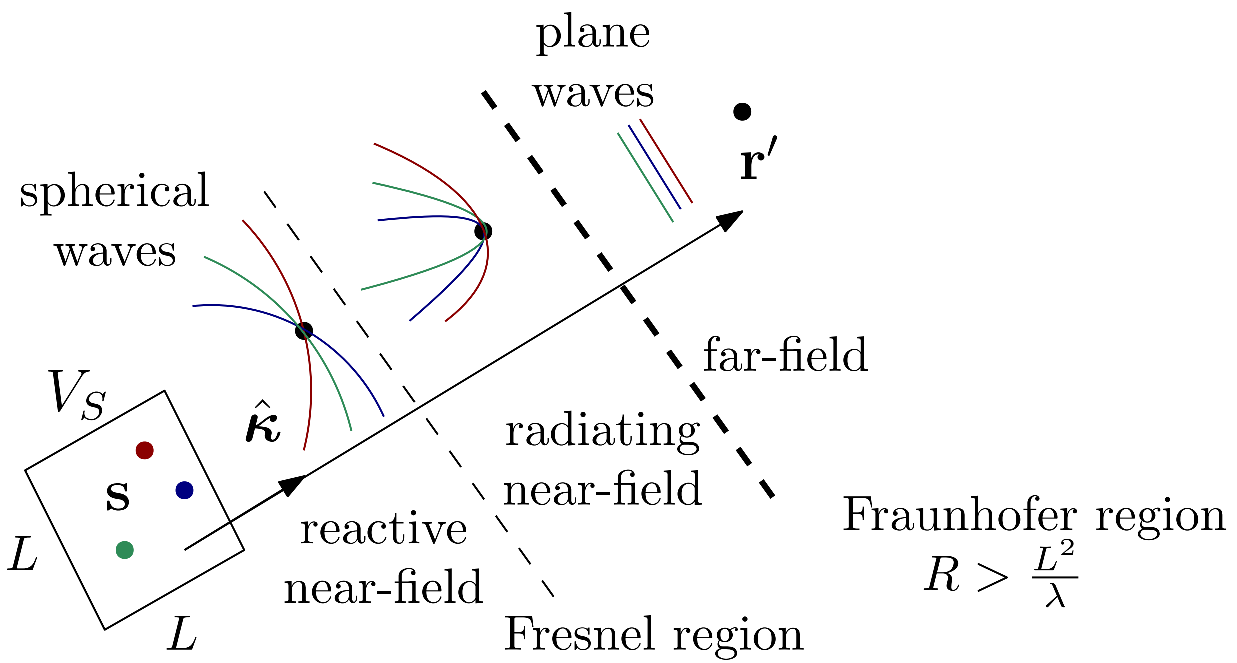
The Fraunhofer far-field assumption

- The shift towards these applications poses new challenges
- The far-field assumption $R > L^2/\lambda$ may break down in some of these applications
- Three examples at 3GHz:

Massive MIMO	HMIMO/LIS	ELAA
8x8 array, half-wavelength		
$L = 4\,\lambda$	L = 3 m	L = 100 m
$R > 16\,\lambda = 1.6$ m	R > 90 m	R > 100 km
YES	NO	NO

A closer look at wave propagation

- New applications push us towards the Fresnel near-field region
- Wavefronts are not locally planar
- Communication theorists typically rely on classical MIMO far-field channel models



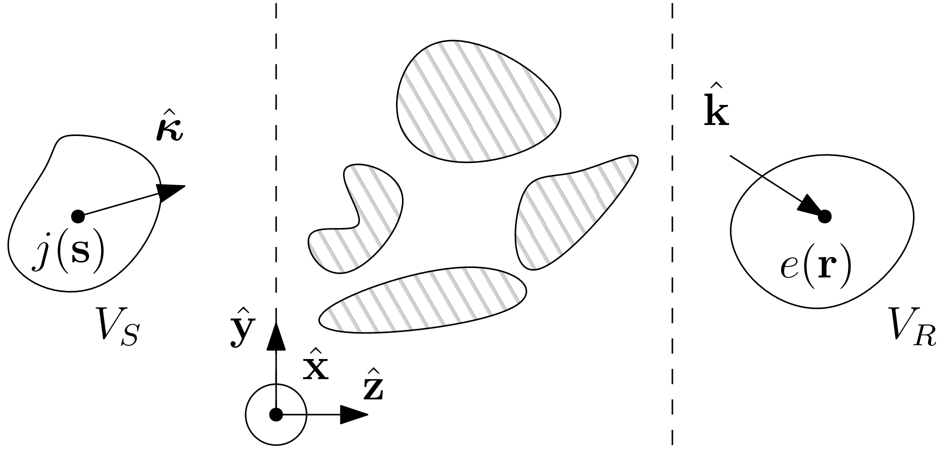
Models for Wave Propagation

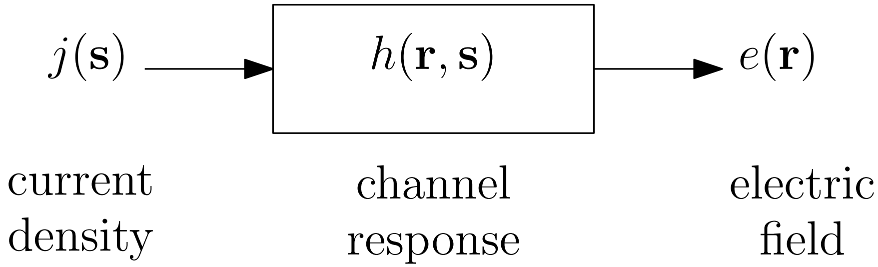
- Numerical electromagnetic solvers not useful for communication theorists
- i.i.d. Rayleigh fading overestimates the available DoF (proportional to the antennas)
- Stochastic random field models typically have a physically meaningless correlation
- No physically-tenable channel model to work with

The only class of meaningful channel model is the **Fourier plane-wave model**!

Linear-system theoretic formulation

- We model wave propagation as a linear and space-variant system
- Stationary channels are <u>low-pass bandlimited</u> in the spatial-frequency domain

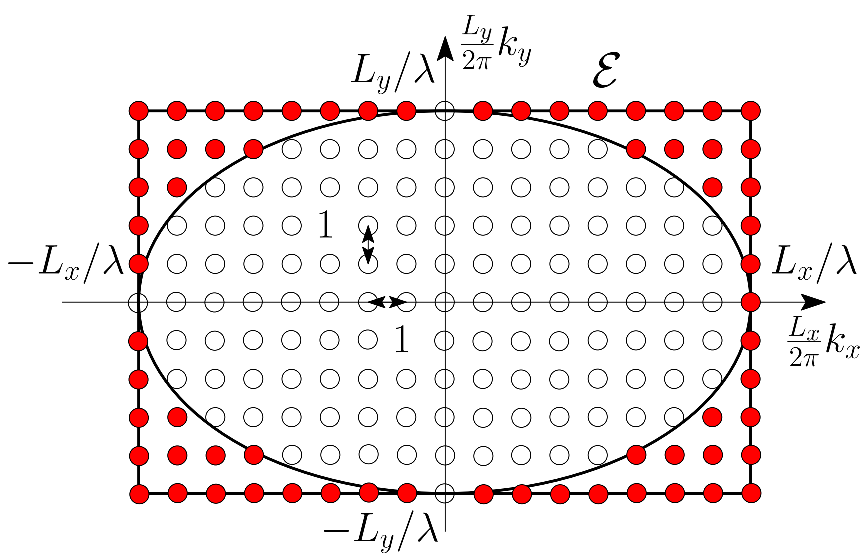




Fourier plane-wave series expansion

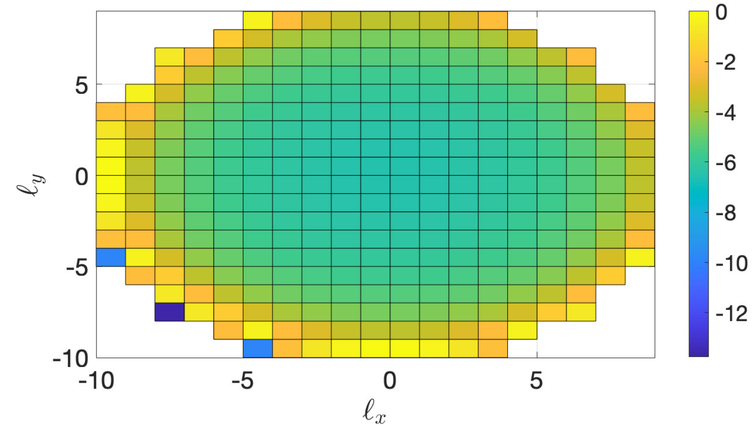
- The channel response can be decomposed in terms of plane-waves
- Valid in the Fresnel near-field region and for arbitrary scattering
- Orthonormal description of the channel with statistically-independent Gaussian coefficients

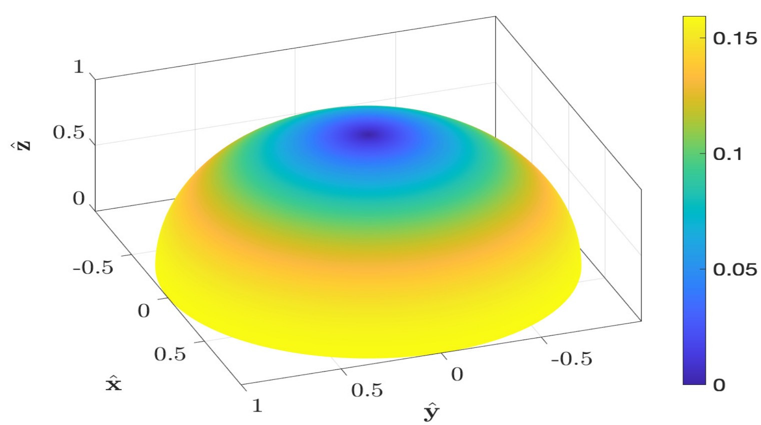
$$h(\mathbf{r},\mathbf{s}) \approx \sum_{(\ell_\mathbf{x},\ell_\mathbf{y})\in\mathcal{E}_\mathbf{r}} \sum_{(\mathbf{m_x},\mathbf{m_y})\in\mathcal{E}_\mathbf{s}} \mathbf{a_r}(\ell_\mathbf{x},\ell_\mathbf{y},\mathbf{r})\mathbf{H_a}(\ell_\mathbf{x},\ell_\mathbf{y},\mathbf{m_x},\mathbf{m_y})\mathbf{a_s}(\mathbf{m_x},\mathbf{m_y},\mathbf{s})$$



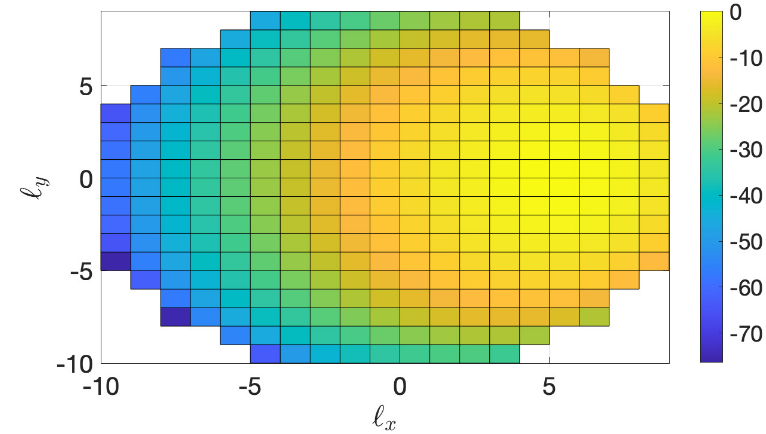
Variance of the Fourier coefficients

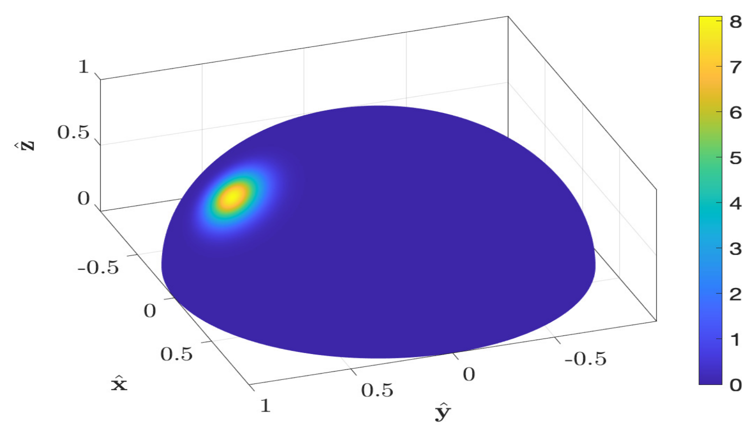
Isotropic propagation (360° angle spread)





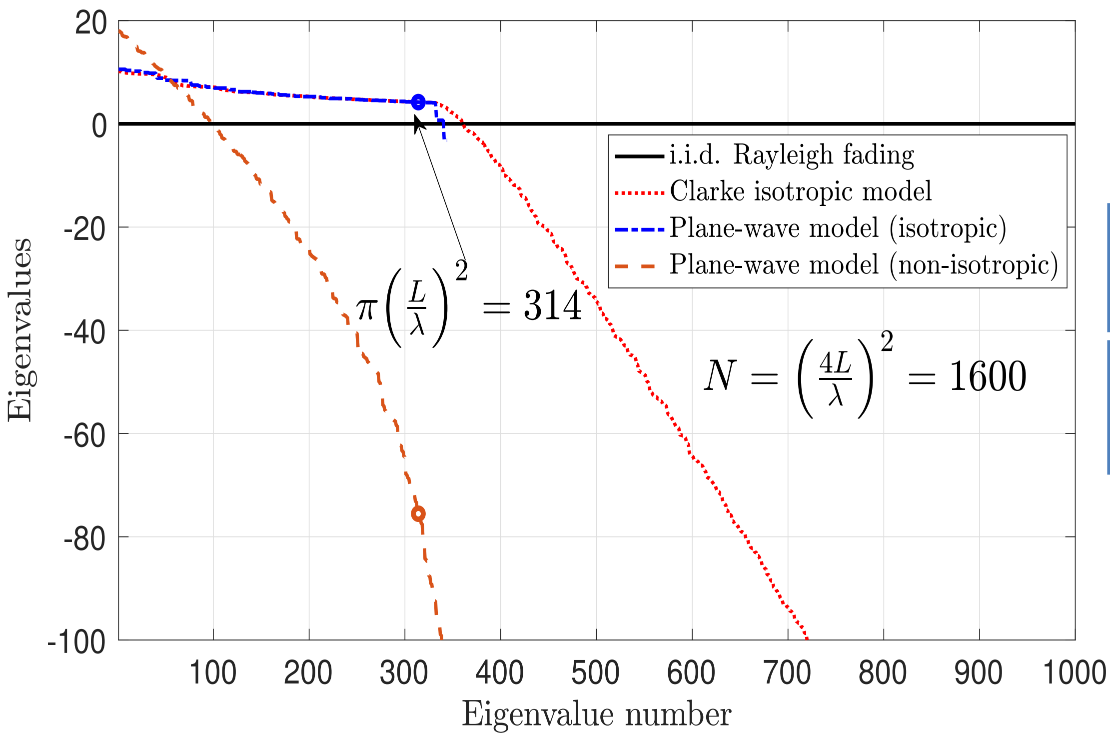
Non-isotropic propagation (5° angle spread)





Channel eigenvalues

- Planar squared array of side length L/λ=10
- $\lambda/4$-spaced antenna elements



	Fourier plane-wave	i.i.d. Rayleigh $\lambda/4$ array
DoF	$\pi\left(\frac{L}{\lambda}\right)^2$	$\left(\frac{4L}{\lambda}\right)^2$

Practical implications

- Closed-form, mathematically-tractable SVD of the channel response
- Valid in both the near-field and far-field and with arbitrary scattering
- Available DoF do not scale with the number of antennas
  - 3D (volume) arrays offer no extra DoF over two planar arrays
- Angular domain unitarily equivalent to the spatial domain but less redundant
- FFT-complexity data processing algorithms and channel estimation

Wish to know more?

1. T. L. Marzetta, “Spatially-Stationary Propagating Random Field Model for Massive MIMO Small-Scale Fading,” in 2018 IEEE ISIT, pp. 391–395.
2. A. Pizzo, T. L. Marzetta, and L. Sanguinetti, “Spatially-Stationary Model for Holographic MIMO Small-Scale Fading,” IEEE JSAC, 2020.
3. A. Pizzo, T. L. Marzetta, and L. Sanguinetti, “Degrees of Freedom of Holographic MIMO Channels,” in 2020 IEEE SPAWC.
4. A. Pizzo, T. L. Marzetta, and L. Sanguinetti, “Holographic MIMO Communications Under Spatially-Stationary Scattering,” in 2020 IEEE Asilomar (available on arXiv.org)
5. A. Pizzo, L. Sanguinetti, and T. L. Marzetta, “Spatial Characterization of Electromagnetic Random Channels,” 2021. [Online]. Available: https://arxiv.org/abs/2103.15666.