Near-Field Multipath MIMO Channel Model for Imperfect Surface Reflection

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Outline

1- Motivation

2- Existing Channel Models

3- Proposed MIMO NF Channel Model

4- Performance Evaluation

5- Conclusions

6- References

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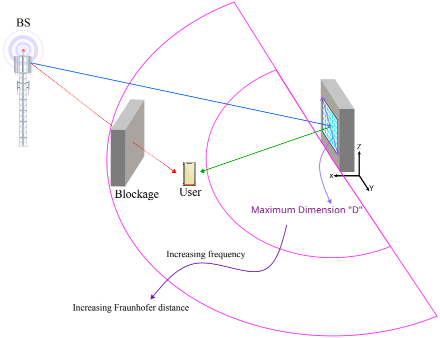
Motivation
Higher Frequencies in Future

- Demands:
  Higher data rates and capacity are required in modern communication systems (e.g., 5G, 6G).
- To provide higher data rates, expanding available bandwidth through increased frequency is essential.

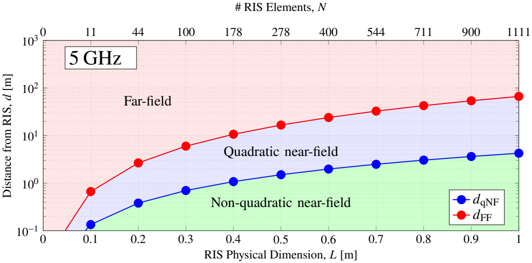


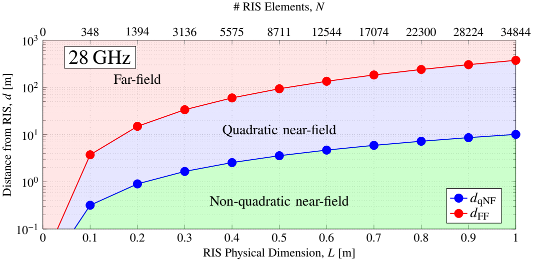
[R1] M. Delbari, G. C. Alexandropoulos, R. Schober, H. V. Poor, and V. Jamali. "Near-Field Multipath MIMO Channel Model for Imperfect Surface Reflection."*accepted for publication in IEEE Globecom Workshops*, arXiv:2409.17041, 2024.

Motivation

Results of the Higher Frequencies

- Near-field (NF) effects become critical when designing for larger surfaces and higher frequencies. $d_{FF} = \frac{2D^2}{\lambda}$



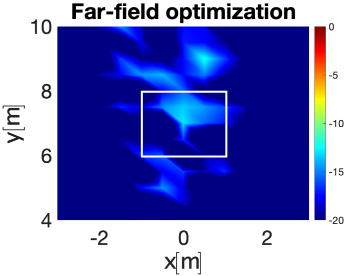


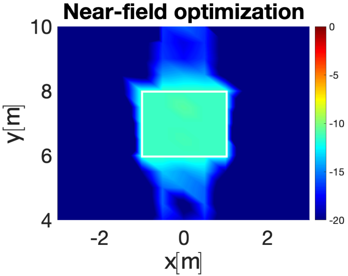
[R2] M. Delbari, G. C. Alexandropoulos, R. Schober, and V. Jamali, “Far- versus near-field RIS modeling and beam design,” in *Reconfigurable Metasurfaces for Wireless Communications: Architectures, Modeling, and Optimization. Springer*, arXiv preprint: https://arxiv.org/pdf/2401.08237, 2023

Motivation

Overlooking near-field effects can lead to suboptimal system performance

- Consider a scenario where a user is in the near-field regime of an RIS, and the RIS phase shifts are designed based on whether the far-field or near-field considerations.





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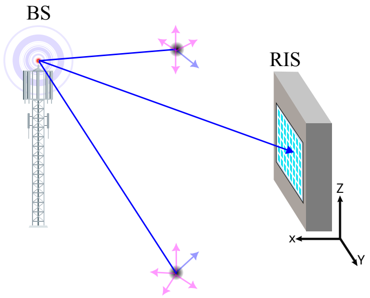
Existing Channel Models

Non-reconfigurable and non-intelligent surfaces (NSs)

$$\mathbf{H}_{\mathrm{NF}} = c_0 \mathbf{H}_{\mathrm{NF}}^{\mathrm{LOS}} + \sum_{s=1}^{S} c_s \mathbf{H}_s^{\mathrm{scat}}, \quad \text{[R3]}$$

In practice, the dominant non-LOS components are mainly generated by objects that have significant reflection surfaces, such as walls, ground, and ceiling [R4, R5]. **Point scattering** model is invalid for these reflectors.



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[R4] Y. Wu et al., "6G mobile wireless networks," in *Springer*, Berlin, Germany 2021.
[R5] C. Jansen et al., "Diffuse Scattering From Rough Surfaces in THz Communication Channels," in *IEEE Transactions on Terahertz Science and Technology*, vol. 1, no. 2, pp. 462-472, Nov. 2011.

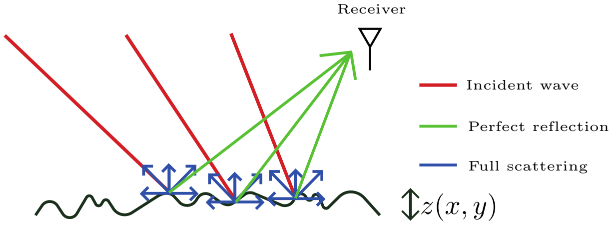
Outline

Proposed MIMO NF Channel Model

Background and the main idea

$$c_r \mathbf{H}_r^{\mathrm{rfl}} = c_{d,r} \mathbf{H}_r^{d} + c_{n,r} \mathbf{H}_r^{n},$$

- $c_{d,r}\mathbf{H}_r^{d} \triangleq \mathbb{E}\{c_r \mathbf{H}_r^{\mathrm{rfl}}\}$ is the deterministic component.
- $c_{n,r}\mathbf{H}_r^{n}$ is the stochastic component.



Proposed MIMO NF Channel Model
Deterministic component

$$c_{d,r}(g) \propto \frac{\mathrm{e}^{-\frac{g}{2}}}{\|\mathbf{u}^r_{\mathrm{vrx}} - \mathbf{u}_{\mathrm{tx}}\|} = \frac{\mathrm{e}^{-\frac{g}{2}}}{\|\mathbf{u}_{\mathrm{rx}} - \mathbf{u}^r_{\mathrm{vtx}}\|}$$

$$\left[\mathbf{H}^d_r\right]_{m,n} = \mathrm{e}^{\mathrm{j}\kappa\|\mathbf{u}^r_{\mathrm{vrx},m} - \mathbf{u}_{\mathrm{tx},n}\|} = \mathrm{e}^{\mathrm{j}\kappa\|\mathbf{u}_{\mathrm{rx},m} - \mathbf{u}^r_{\mathrm{vtx},n}\|},$$

$$\boxed{g = \left(\kappa\sigma_z\left(\cos(\theta_{\mathrm{tx}}) + \cos(\theta_{\mathrm{rx}})\right)\right)^2.}$$

Proposed MIMO NF Channel Model

Deterministic component

$$c_{d,r}(g) \propto \frac{\mathrm{e}^{-\frac{g}{2}}}{\left\|\mathbf{u}^{r}_{\mathrm{vrx}} - \mathbf{u}_{\mathrm{tx}}\right\|} = \frac{\mathrm{e}^{-\frac{g}{2}}}{\left\|\mathbf{u}_{\mathrm{rx}} - \mathbf{u}^{r}_{\mathrm{vtx}}\right\|}$$

$$\left[\mathbf{H}^{d}_{r}\right]_{m,n} = \mathrm{e}^{\mathrm{j}\kappa\left\|\mathbf{u}^{r}_{\mathrm{vrx},m} - \mathbf{u}_{\mathrm{tx},n}\right\|} = \mathrm{e}^{\mathrm{j}\kappa\left\|\mathbf{u}_{\mathrm{rx},m} - \mathbf{u}^{r}_{\mathrm{vtx},n}\right\|},$$

$$g = \Big(\kappa\sigma_z\big(\cos(\theta_{\mathrm{tx}}) + \cos(\theta_{\mathrm{rx}})\big)\Big)^2.$$

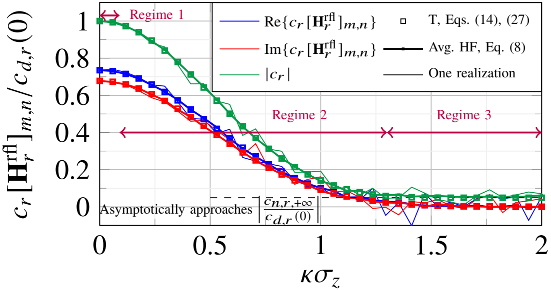
Huygens-Fresnel (HF), Numerical evaluation

$$c_r\mathbf{H}^{\mathrm{rfl}}_{r} = \frac{\zeta}{\mathrm{j}\lambda}\iint_{\mathbf{u}\in\mathbb{U}} \frac{z_{\mathrm{tx},n}}{\left\|\mathbf{u} - \mathbf{u}_{\mathrm{tx},n}\right\|^2}\frac{z_{\mathrm{rx},m}}{\left\|\mathbf{u}_{\mathrm{rx},m} - \mathbf{u}\right\|^2} \times \mathrm{e}^{\mathrm{j}\kappa\left\|\mathbf{u}-\mathbf{u}_{\mathrm{tx},n}\right\|}\mathrm{e}^{\mathrm{j}\kappa\left\|\mathbf{u}_{\mathrm{rx},m}-\mathbf{u}\right\|}\mathrm{d}A,$$

Proposed MIMO NF Channel Model

Three different regimes

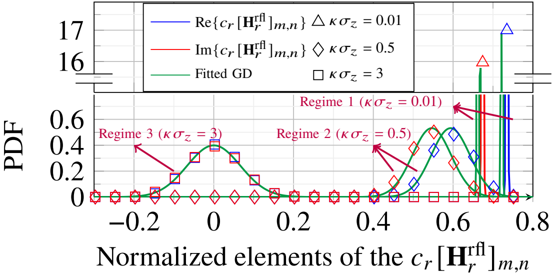
Regime 1: $\kappa\sigma_z \ll 1$: In this case, the NS is sufficiently smooth leading to perfect surface reflection.
Regime 2: This is a transient regime between Regimes 1 and 3, where both surface reflection and scattering are present.
Regime 3: $\kappa\sigma_z \gg 1$: In this case, the NS scatters the wave in all directions leading to full surface scattering.



Proposed MIMO NF Channel Model
Stochastic component

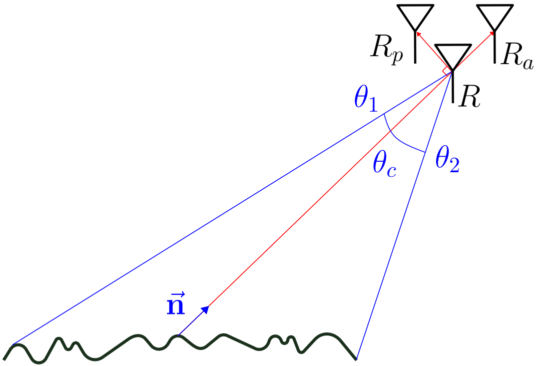
- **Probability Density Function (PDF):** Gaussian distribution for the elements of $\mathbf{H}_r^n$, i.e., $[\mathbf{H}_r^n]_{m,n} \sim \mathcal{CN}(0,1)$

- **Channel Power Gain:**
  Regime 1: Deterministic
  Regime 3: Law of conversation of energy and the symmetry of full scattering, denoted as $|c_{n,r,+\infty}|^2$
  Regime 2: Proposed $\mathbb{E}\{|c_{n,r}(g)|^2\} = (1 - e^{-\frac{g}{2}})^2 |c_{n,r,+\infty}|^2$

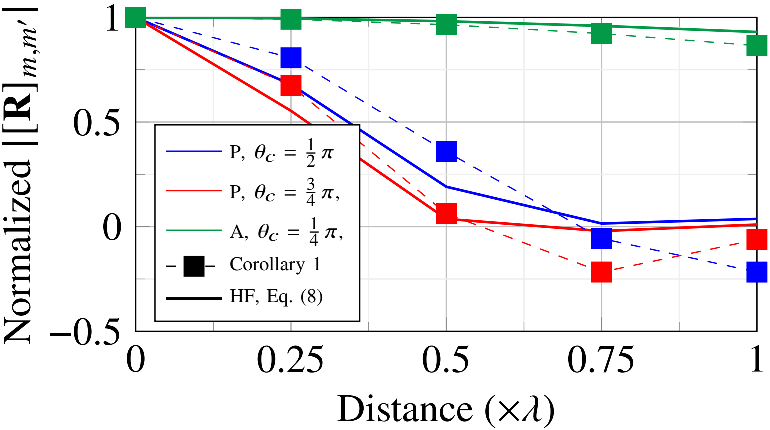


Proposed MIMO NF Channel Model
Stochastic component

- **Spatial correlation:**
- Case 1: $\mathrm{sinc}\left(\frac{2\|\mathbf{u}_R - \mathbf{u}_{R_a}\|}{\lambda}\sin^2\left(\frac{\theta_c}{2}\right)\right)$
  where $\theta_1 = -\frac{\pi}{2}$, $\theta_2 = -\frac{\pi}{2} + \theta_c$,
- Case 2: $\mathrm{sinc}\left(\frac{2\|\mathbf{u}_R - \mathbf{u}_{R_p}\|}{\lambda}\sin\left(\frac{\theta_c}{2}\right)\right)$,
  where $\theta_1 = -\frac{\theta_c}{2}$, $\theta_2 = \frac{\theta_c}{2}$
- $\theta_c \triangleq \theta_2 - \theta_1$
- $\mathrm{sinc}(x) = \frac{\sin(\pi x)}{\pi x}$



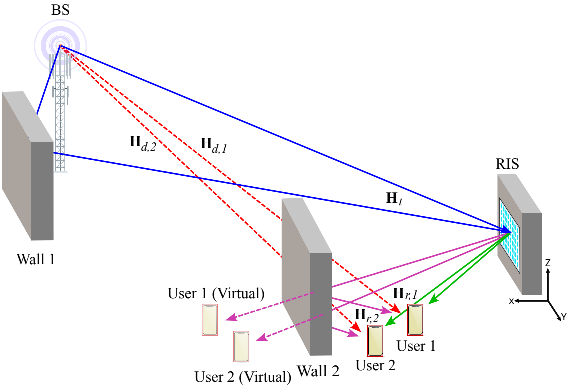
Proposed MIMO NF Channel Model
Stochastic component



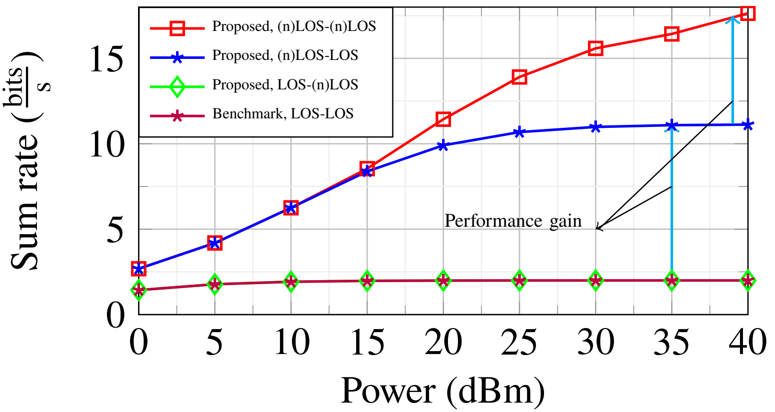
Outline

Performance Evaluation
Simulation Setup

Parameter	Value
Frequency	28 GHz
Bandwidth	20 MHz
Transmission Power	(0-40) dBm
BS Antennas (x – z axes)	4×4
RIS Elements (y – z axes)	100×100
Channel Model	Ricean
Path Loss Model	$\beta(\frac{1}{d})^{\eta}$
Noise Level	-95 dBm
Direct Blockage	- 40 dB
Walls' loss	- 3 dB



Performance Evaluation
Simulation result



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Conclusions
Summary and takeaways

Summary:

- Developed a novel NF MIMO channel model that accounts for imperfect reflections from NSs.
- The accuracy of the proposed model is verified by comparing it with the numerical evaluation of the HF integral.
- The impact of NSs is not only non-negligible but also beneficial for achieving a multiplexing gain in multi-user communication scenarios.

Conclusions

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- Developed a novel NF MIMO channel model that accounts for imperfect reflections from NSs.
- The accuracy of the proposed model is verified by comparing it with the numerical evaluation of the HF integral.
- The impact of NSs is not only non-negligible but also beneficial for achieving a multiplexing gain in multi-user communication scenarios.

Future research directions:

- Arbitrary surface geometries when $z(x, y) \gg \lambda$.

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Thank you for your attention!

Questions?

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