The Vienna system-level simulator for 6G wireless networks with reconfigurable intelligent surfaces

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Motivation

RIS:

- A planar surface that consists of multiple reflecting elements
- Can modify impinging signals and steer reflected waves in any direction
- Potential of improving system throughput, coverage, and energy efficiency

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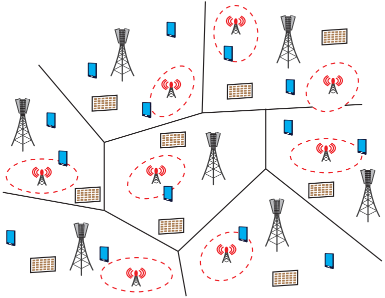
System level challenges:

- RIS modeling
- RIS deployment
- Small-scale fading (SF)
- Macroscopic Fading (MF)
- Cell association
- RIS phase shifts optimization
- Interference



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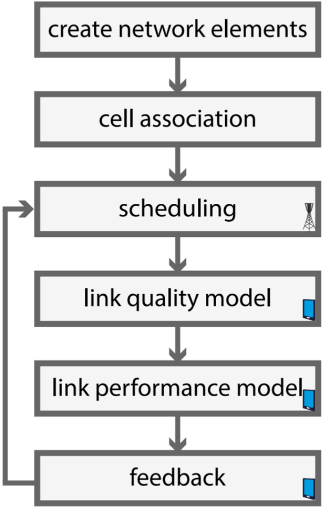
Simulation flow:

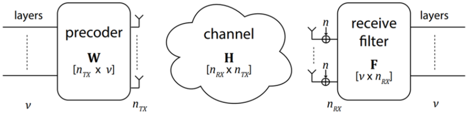


create simulation environment: BSs & antennas, UEs, RISs, city, street, building, blockage (types & properties)

assign each user to a desired BS according to the large-scale fading

user allocation, power allocation, precoder choice, Channel Quality Indicator (CQI) choice

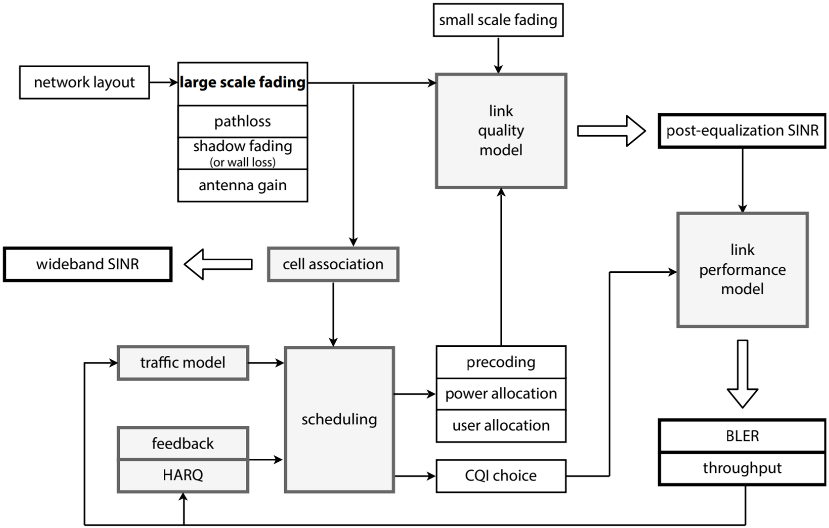
calculate post-equalization SINR



determine BLER, throughput

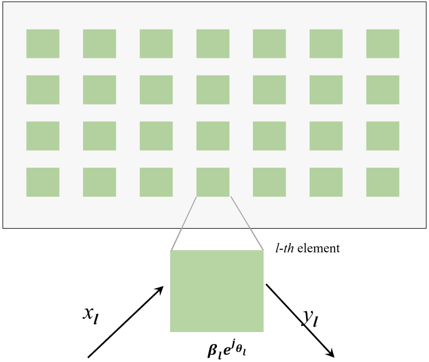
determine optimal CQI, optimal precoder, optimal number of layers

The simulator structure:



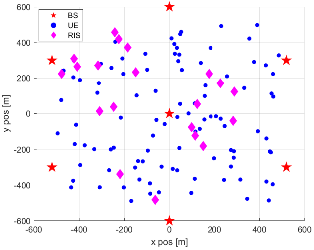
RIS modeling

- Number of rows: N
- Number of columns: M
- Number of element: $L = M \times N$
- Spacing between each element: $t, t = \frac{1}{2}\lambda$ as default
- Size of each unit cell along the x axis: dx
- Size of each unit cell along the y axis: dy
- The effective area of each RIS: $D = L \times dx \times dy$
- Fraunhofer distance: $d = \frac{2D}{\lambda}$
- Reflection coefficient of the l-th element: $V_l = \beta_l e^{j\theta_l}$
- Amplitude $\beta_l \in [0, 1]$, $\beta_l = 1$ as default
- Phase: $\theta_l \in [-\pi, \pi)$, random or optimized

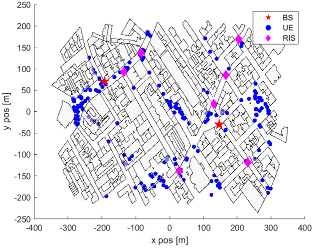


RIS deployment

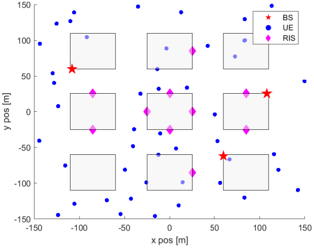
- Deployment options: Poisson distribution; user-defined locations; on building walls



Poisson distribution



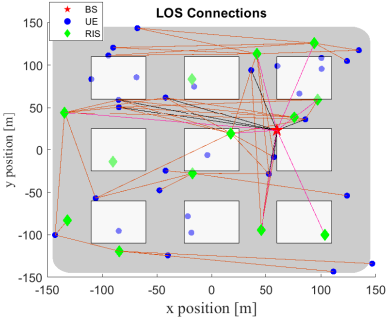
User-defined locations



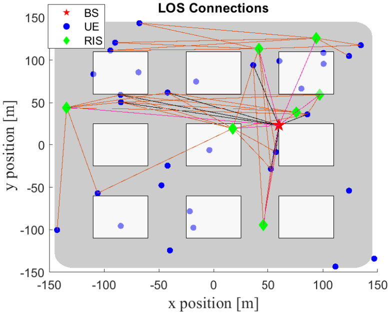
RIS on Manhattan Buildings

RIS deployment

- RIS should be placed where it has LOS connection with BS and UE → filter pure NLOS RISs



Before filtering



After filtering

Small-scale fading

- Generate channel traces for BS-UE, BS-RIS, and RIS-UE links according to the selected channel models
- Channel models: Rayleigh, AWGN, Quadriga, 3GPP models (Pedestrian A, Pedestrian B, Vehicular A, Vehicular B,...)

Small-scale fading

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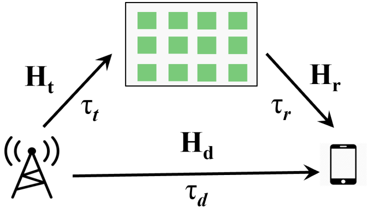
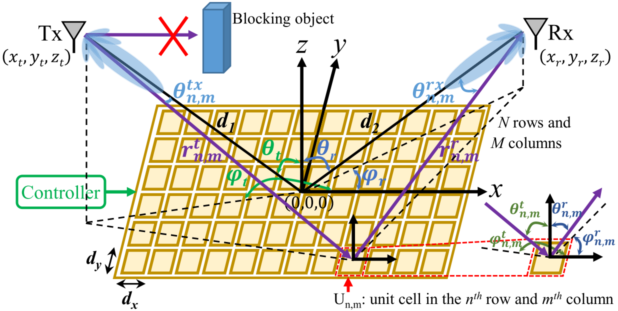
- Channel models: Rayleigh, AWGN, Quadriga, 3GPP models (Pedestrian A, Pedestrian B, Vehicular A, Vehicular B,...)
- Add relative delays to the RIS-links:
  - Delay difference: $\Delta\tau = \tau_t + \tau_r - \tau_d$.
  - $\Delta\tau_t = \Delta\tau \cdot \frac{\tau_t}{\tau_t+\tau_r}$ and $\Delta\tau_r = \Delta\tau \cdot \frac{\tau_r}{\tau_t+\tau_r}$
  - $\mathbf{H}_{t'} = \mathbf{H}_t \cdot \exp(j2\pi f \Delta\tau_t)$
  - $\mathbf{H}_{r'} = \mathbf{H}_r \cdot \exp(j2\pi f \Delta\tau_r)$
  - Channel of an RIS-aided link: $\mathbf{H}_{\text{RIS}} = \mathbf{H}_{r'} \cdot \mathbf{\Phi} \cdot \mathbf{H}_{t'}$
  - $\mathbf{\Phi} = \mathrm{diag}(e^{j\theta_1}, ..., e^{j\theta_L})$: RIS phase shifts



Pathloss model 1: RISFSPL

- Original far field free space pathloss model for RIS [1]:

$$PL = \frac{64\pi^3 {d_1}^2 {d_2}^2}{G_t G_r G M^2 N^2 d_x d_y \lambda^2 F(\theta_t, \varphi_t) F(\theta_{des}, \varphi_{des}) \beta^2}$$



[1] (Wankai Tang et al. "Wireless Communications With Reconfigurable Intelligent Surface: Path Loss Modeling and Experimental Measurement". In: *IEEE Transactions on Wireless Communications* 20.1 [2021], pp. 421–439)

Pathloss model 1: RISFSPL

- Adapt the original pathloss model to be compatible with the SLS (RISFSPL), the MF of RIS-link:

$$\mathrm{MF}_{\mathrm{ris,RISFSPL}} = \frac{P_t}{P_r} = \frac{64\pi^3 d_1^2 d_2^2}{G_t G G_r L A \lambda^2 \beta^2}.$$

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  - d_1, d_2: distance between TX-RIS and RIS-RX
  - G_t, G_r, G: TX, RX and RIS antenna gain, $G_r = G = 1$ as default
  - $L = M \times N$: number of RIS element
  - $A = dx \times dy$: effective area of each RIS element
  - $F(\theta_t, \varphi_t), F(\theta_{des}, \varphi_{des})$: normalized power radiation pattern of RIS
  - β: amplitude of each RIS element, $\beta = 1$ as default

Difference between the adapted RISFSPL and the original pathloss model:

- The original pathloss model:
  - The RIS phases are already optimized for the user when calculating the pathloss: $PL \propto \frac{1}{L^2}$
  - The RIS phase shift optimization happens purely in MF, SF is not involved
  - The direct link is not considered in [1]

[2] (Le Hao, Stefan Schwarz, and Markus Rupp. "The Extended Vienna System-Level Simulator for Reconfigurable Intelligent Surfaces". In: *2023 EuCNC & 6G Summit*. 2023)

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  - The direct link is not considered in [1]
- The RISFSPL model in the SLS:
  - The RIS phase shifts are random when calculating pathloss, since users are not assigned to BSs yet, cell association is based on the pathloss results: $PL \propto \frac{1}{L}$ [2]
  - After cell association, RIS phase shifts are optimized in SF according to the channel information of each link
  - All the direct and RIS-assisted links, the MF and SF are considered

[2] (Le Hao, Stefan Schwarz, and Markus Rupp. "The Extended Vienna System-Level Simulator for Reconfigurable Intelligent Surfaces". In: *2023 EuCNC & 6G Summit*. 2023)

Pathloss model 2: RayTracing

- Use MATLAB ray tracer to calculate pathloss
- The received power of BS-UE, RIS-UE, and BS-RIS links:

$$P_{ub} = \left| \sum_{k=1}^{K} \left(\sqrt{P_t/\mathrm{PL}_{ub}^{(k)}} \exp(-j\vartheta_{ub}^{(k)}) \right) \right|^2,$$

$$P_{ur} = \left| \sum_{b=1}^{B} \left(\sqrt{P_{\mathrm{ris}}/\mathrm{PL}_{ur}^{(b)}} \exp(-j\vartheta_{ur}^{(b)}) \right) \right|^2,$$

$$P_{rb} = \left| \sum_{c=1}^{C} \left(\sqrt{P_t/\mathrm{PL}_{rb}^{(c)}} \exp(-j\vartheta_{rb}^{(c)}) \right) \right|^2.$$

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$$P_{rb} = \left| \sum_{c=1}^{C} \left(\sqrt{P_t / \mathrm{PL}_{rb}^{(c)}} \exp(-j\vartheta_{rb}^{(c)}) \right) \right|^2 .$$

- The overall pathloss for these links:

$$\mathrm{PL}_{ub} = P_t / P_{ub},$$

$$\mathrm{PL}_{ur} = P_{\mathrm{ris}} / P_{ur},$$

$$\mathrm{PL}_{rb} = P_t / P_{rb}.$$

- $\mathrm{PL}_{ub}^{(k)}$, $\mathrm{PL}_{ur}^{(b)}$, and $\mathrm{PL}_{rb}^{(c)}$: pathloss of the specific propagation path
- $\vartheta_{ub}^{(k)}$, $\vartheta_{ur}^{(b)}$, and $\vartheta_{rb}^{(c)}$: propagation phases of these links
- P_{ris}: transmit power from the RIS = received signal power at that RIS

Pathloss model 2: RayTracing

- The MF of RIS-assisted link:

$$\mathrm{MF}_{\mathrm{ris,RT}} = \frac{\eta}{G_t}\mathrm{PL}_{ur}\mathrm{PL}_{rb},$$

  - where $\eta = \lambda^2/4\pi LA$ is a RIS size factor

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  - For RayTracing model, when $B = C = 1$, the pathloss for each link is

$$\tilde{\mathrm{PL}}_{rb} = (4\pi d_1/\lambda)^2, \qquad \tilde{\mathrm{PL}}_{ur} = (4\pi d_2/\lambda)^2, \qquad \tilde{\mathrm{MF}}_{\mathrm{ris,RT}} = \frac{1}{G_t}\tilde{\mathrm{PL}}_{rb}\tilde{\mathrm{PL}}_{ur} = \frac{256\pi^4 d_1^2 d_2^2}{G_t\lambda^4}.$$

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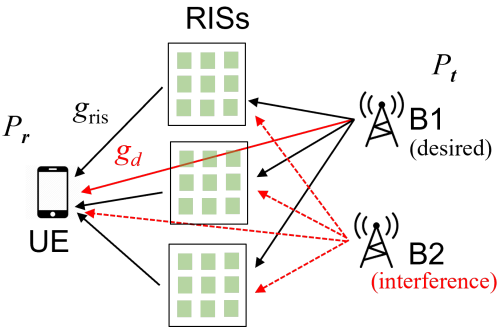
  - The difference between $\mathrm{MF}_{\mathrm{ris,RISFSPL}}$ and $\tilde{\mathrm{MF}}_{\mathrm{ris,RT}}$ is $\eta = \lambda^2/4\pi LA$

Cell association

- Strategies:
  - Maximum receive power: $P_r = P_t(g_d + g_{\text{ris}})$
    - ▶ P_t: transmit power
    - ▶ g_d: path gain of direct link
    - ▶ g_{ris}: path gain of RIS-assisted link
  - Maximum SINR: $\text{SINR} = P_r/(P_{\text{int}} + \sigma^2)$
    - ▶ P_{int}: interference power from interfering BSs
    - ▶ σ^2: noise power



RIS phase shifts optimization

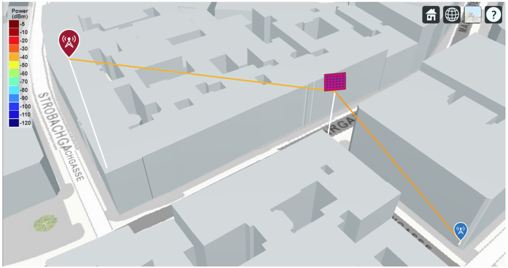
- To achieve constructive coherent combination of the direct link and RIS-assisted link
- The user receives maximum signals
- For SISO scenarios:
  - Phase of direct link: $\theta_d = \arg(H_d)$
  - Phase of RIS-assisted links: $\theta_{r,l} = \arg(\mathbf{H}_{t',l} \cdot \mathbf{H}_{r',l})$
  - Optimized phase shift for the l-th element: $\theta_l = \theta_d - \theta_{r,l}$

Contents

Simulation settings in a SISO scenario:

- One BS antenna, one RIS with L elements, one UE with one antenna
- Pathloss model: RT & RISFSPL
- Channel model: Rician and Rayleigh

- Direct link has a pathloss of 200 dB
- Transmit power: 40 W
- Center frequency: 3.5 GHz
- Bandwidth: 20 MHz



A SISO simulation scenario.

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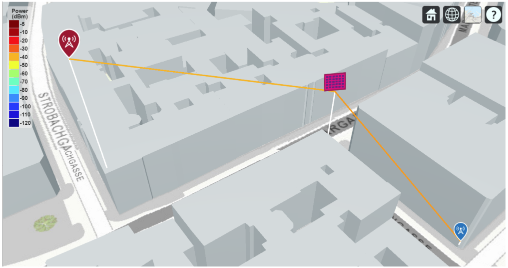

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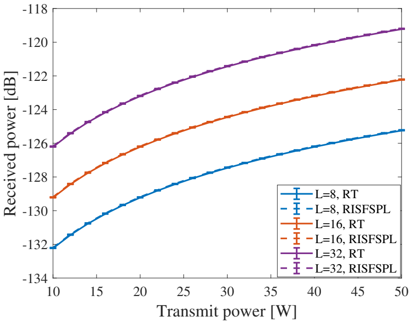

Simulation results in a SISO scenario

- Power scaling law [3]:
  - Every doubling of L achieves about 6 dB power gain for optimized RIS phase shifts and 3 dB for random phase shifts

[3] (Q. Wu and R. Zhang. "Intelligent Reflecting Surface Enhanced Wireless Network via Joint Active and Passive Beamforming". In: *IEEE Transactions on Wireless Communications* 18.11 [2019], pp. 5394–5409)

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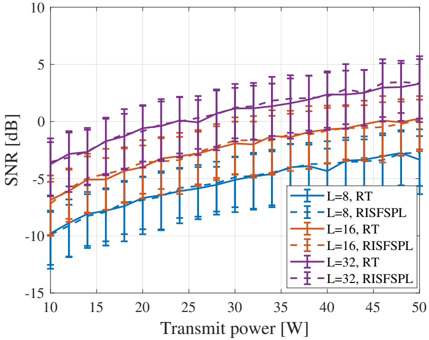

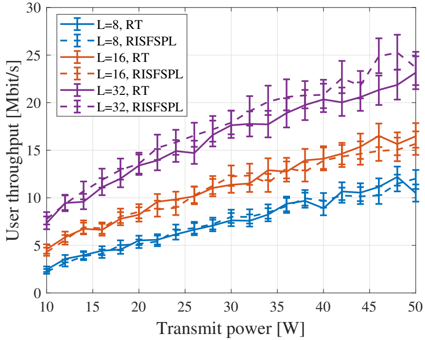

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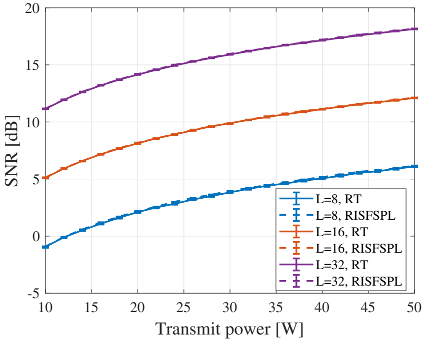
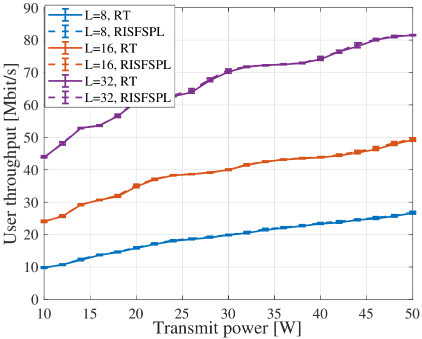
- Results with optimized RIS phase shifts:





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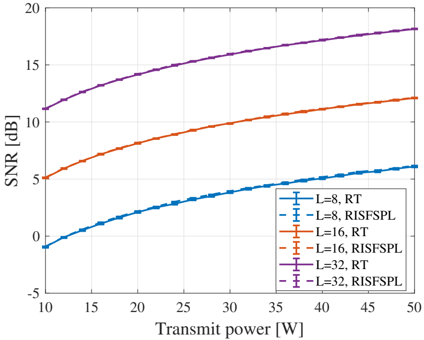
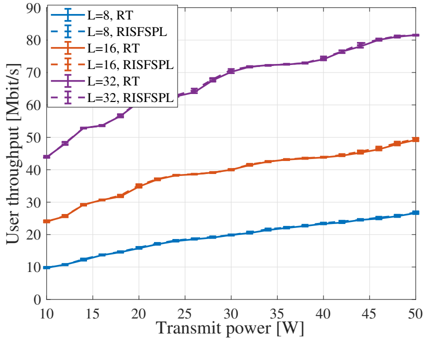
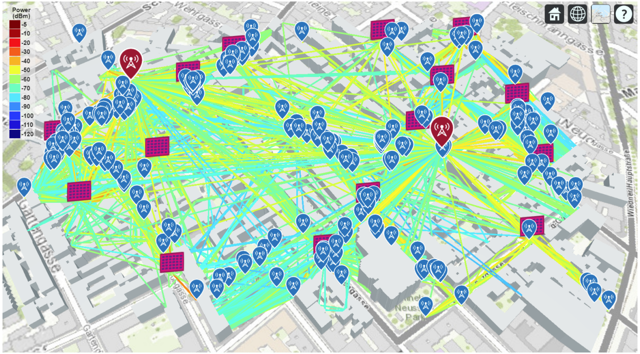




- Take away points:
  - The RT and RISFSPL show very similar results, which verifies the modified RT model
  - The results fulfill the power scaling law, which validates the RIS implementation

Simulation settings in a complex scenario

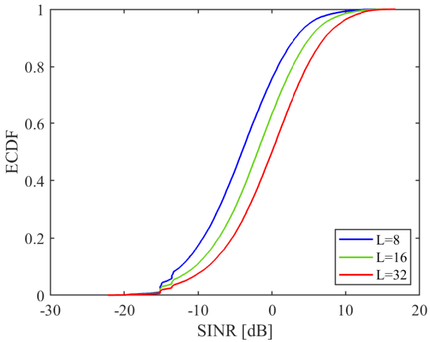
- Same setup as the previous scenario, except that there are 2 BSs, 15 RISs, and many users

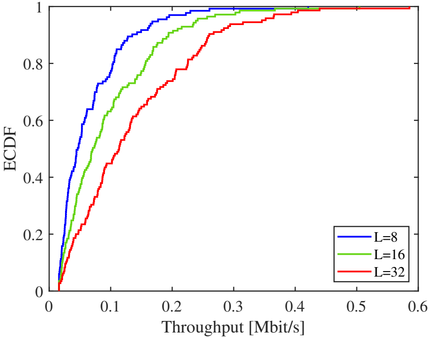


A complex simulation scenario.

Simulation results in a complex scenario

- Results with random RIS phase shifts:





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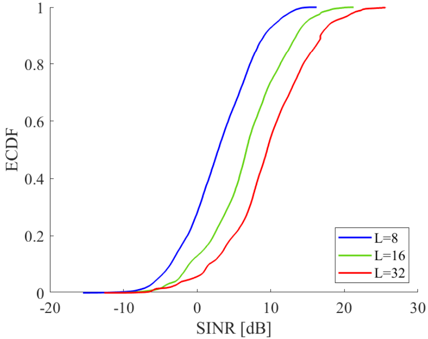

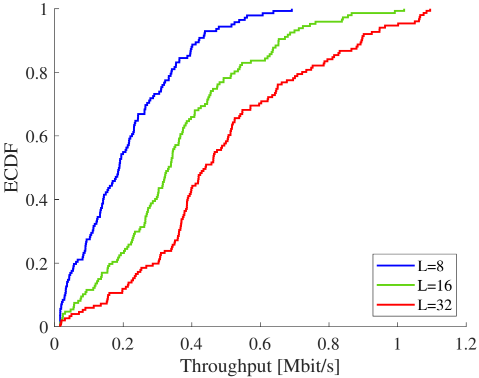

Contents

Outlook

- More realistic RIS model
- RIS in indoor scenarios
- RIS in near-field transmission
- RIS with radiation pattern properties
- RIS phase optimization for MU-MIMO scenarios
- RIS deployment optimization

Thanks for your attention!

Any questions?

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