Enabling Massive Connectivity via RIS-Assisted Code-Domain MIMO-NOMA

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Internal Workshop of the Doctoral School 5G Internet of Things

September 2021

Technische Universität Wien

Institute of Telecommunications

Introduction - NOMA

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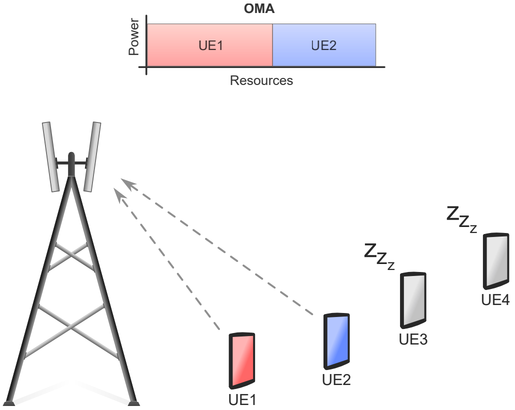
  - are allocated disjoint sets of resources
  - wait for the BS to grant them access



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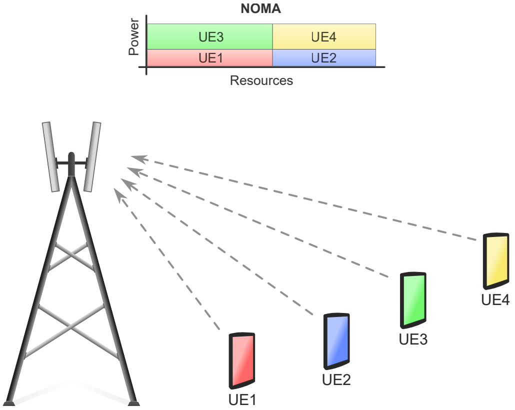

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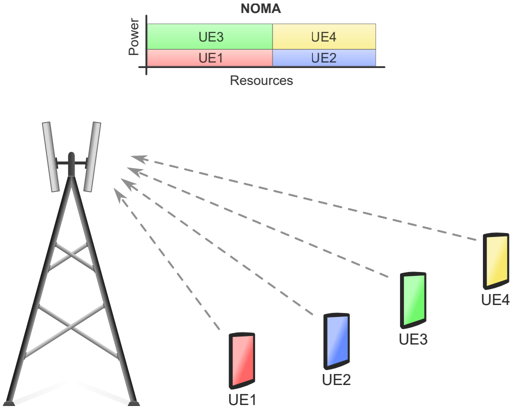

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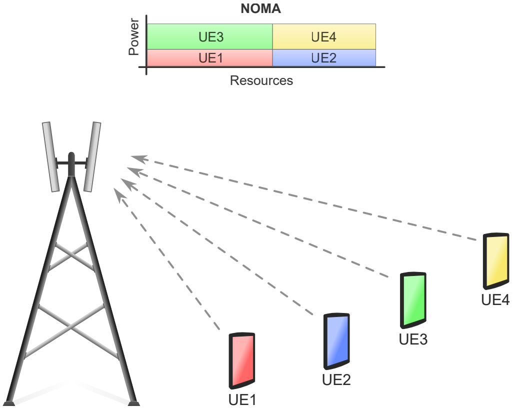

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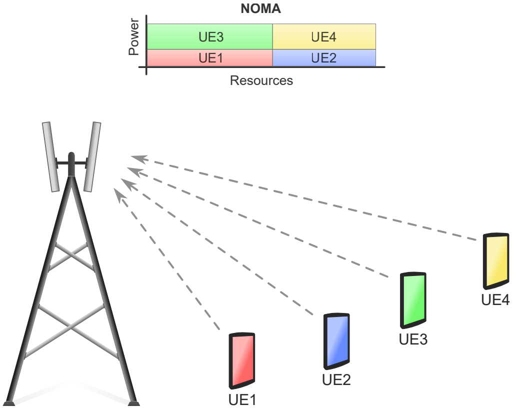

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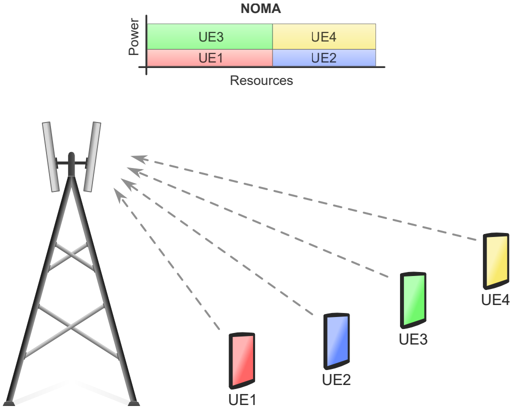
  - Multiuser interference → higher detection complexity



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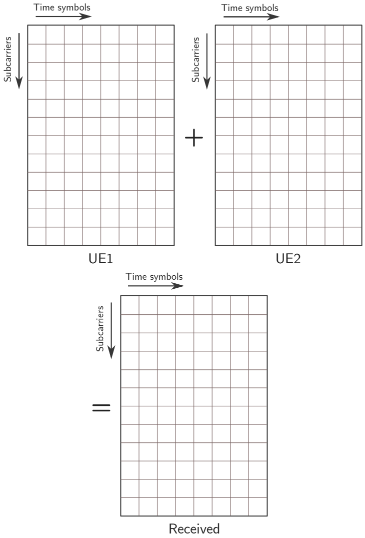

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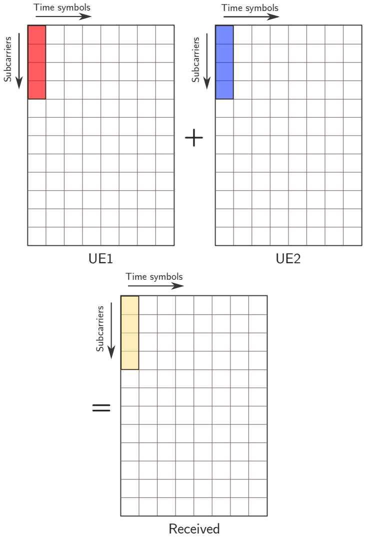

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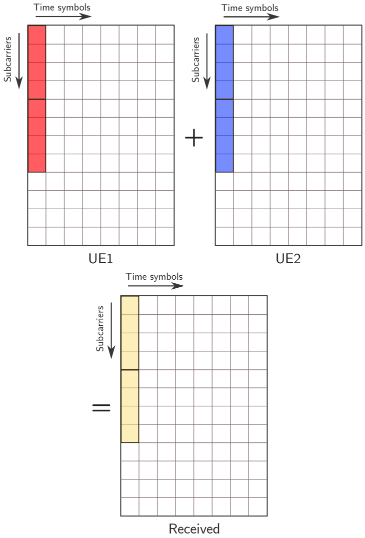

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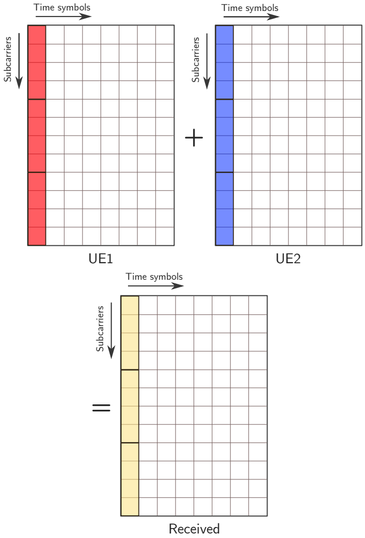

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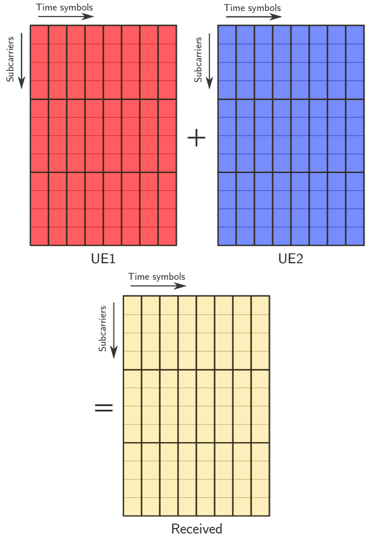

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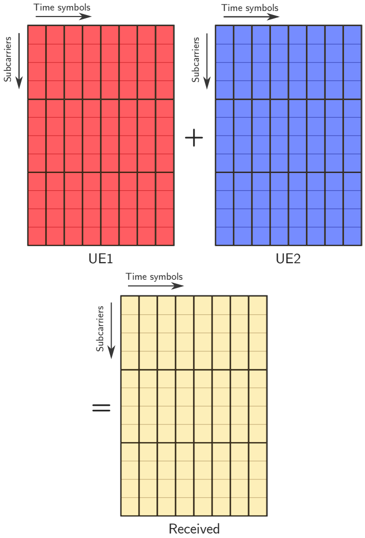
- The superposition can either be pure power-domain, or paired with code-domain signatures
- The signatures, e.g., spreading sequences, help with
  - interference suppression → high user overloading
  - user activity detection → grant-free access



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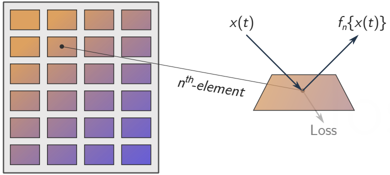
- Each element is controlled electrically to produce reflected waves with modified
  - amplitude
  - phase
  - polarization
  - frequency



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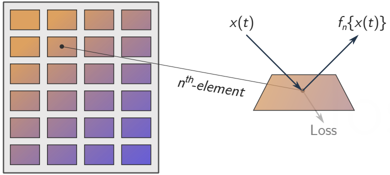

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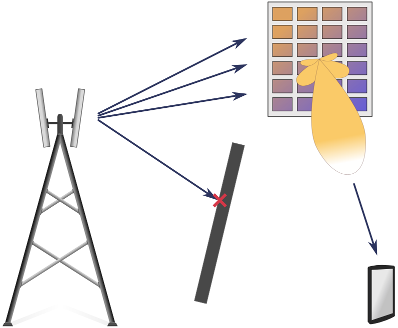
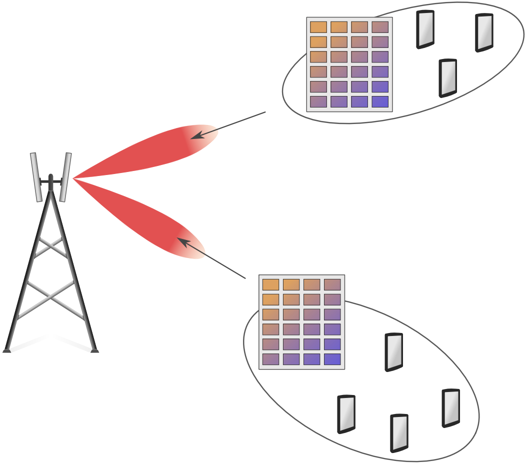
  - E.g., boosting a user in blockage



Clustered Code-Domain RIS-NOMA

- Consider an uplink cluster-based deployment, e.g., streets
  - The clusters are separated spatially
- RISs are installed in each cluster
  - The BS has LOS to the surface
  - Forms a beam towards it



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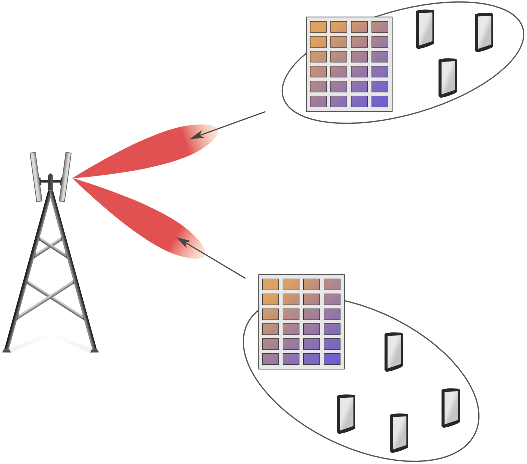

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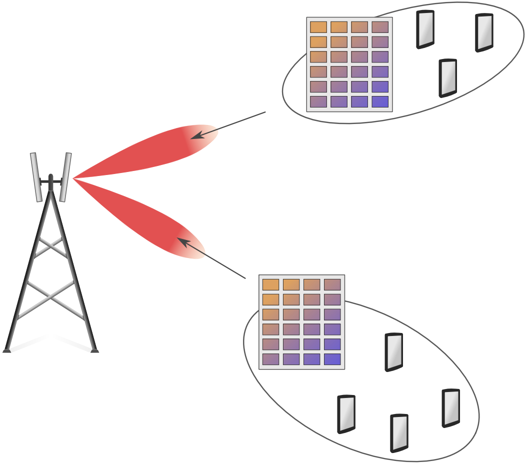
- **How to configure the phase-shifts at the RISs?**



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- The received signal is given by

$$\mathbf{y} = \sum_{k=1}^{K} \sqrt{\ell_{\mathrm{BS}} \ell_{h_k} P_k L} \left(\mathbf{H}_{\mathrm{BS}} \boldsymbol{\Phi} \mathbf{h}_k \otimes \mathbf{s}_k \right) x_k + \mathbf{z} + \mathbf{n}$$

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- LOS BS-RIS channels: $\mathbf{H}_{\mathrm{BS}} = \mathbf{a}\mathbf{b}^H$, and we have

$$\mathbf{y} = \left(\mathbf{a} \otimes \mathbf{I}_L \right) \sum_{k=1}^{K} \sqrt{\ell_{\mathrm{BS}} \ell_{h_k} P_k L} \left(\mathbf{b}^H \mathbf{\Phi} \mathbf{h}_k \otimes \mathbf{s}_k \right) x_k + \mathbf{z} + \mathbf{n}$$

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- Under MRC spatial filtering

$$(\mathbf{a}^H \otimes \mathbf{I}_L)\mathbf{y} = (\mathbf{a}^H \mathbf{a} \otimes \mathbf{I}_L) \sum_{k=1}^{K} \sqrt{\ell_{\mathrm{BS}} \ell_{h_k} P_k L}\,(\mathbf{b}^H \boldsymbol{\Phi} \mathbf{h}_k \otimes \mathbf{s}_k) x_k + (\mathbf{a}^H \otimes \mathbf{I}_L)\mathbf{z} + (\mathbf{a}^H \otimes \mathbf{I}_L)\mathbf{n},$$

$$\tilde{\mathbf{y}} = \sum_{k=1}^{K} \sqrt{N_r^2 \ell_{\mathrm{BS}} \ell_{h_k} P_k L}\,(\mathbf{b}^H \boldsymbol{\Phi} \mathbf{h}_k \otimes \mathbf{s}_k) x_k + \tilde{\mathbf{n}}$$

Clustered Code-Domain RIS-NOMA

- Let $\beta_k = \sqrt{N_r^2 \ell_{\mathrm{BS}} \ell_{h_k} P_k L}$, $\mathbf{w} = \mathrm{diag}(\mathbf{\Phi}^H)$, $\hat{\mathbf{h}}_k = \mathbf{b}^* \circ \mathbf{h}_k$, we finally have

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- Assuming a cancellation order of UE1, UE2, ..., UEK

$$\mathrm{SINR}_k = \frac{|\beta_k (\mathbf{w}^H \hat{\mathbf{h}}_k) \mathbf{v}_k^H \mathbf{s}_k|^2}{\sum_{l=k+1}^{K} |\beta_l (\mathbf{w}^H \hat{\mathbf{h}}_l) \mathbf{v}_k^H \mathbf{s}_l|^2 + \sigma_{\tilde{\mathbf{n}}}^2 \|\mathbf{v}_k\|^2}, \qquad k = 1, 2, \ldots, K$$

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- The goal now is to design $\mathbf{w}$ such that

$$\mathrm{SINR}_k \geq \epsilon_k, \qquad \forall k, \; k = 1, 2, \ldots, K$$

- Not easy to solve
  - The detection order and the MMSE filters are coupled with the RIS weights
  - Even if we know them separately, how to solve such a system of inequalities?

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- We relax it to a conventional quadratic problem, and set

$$[\mathbf{w}_{\text{sum}}]_n = \exp(j\angle[\mathbf{u}_{\max}]_n), \quad n = 1, 2, \ldots, N_s$$

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- MMSE filters:
  - The applied MMSE filter per stage is given by

$$\mathbf{v}_k = \mathbf{g}_k^H \left(\sum_{l=k}^{K} \mathbf{g}_l \mathbf{g}_l^H + \mathbf{I}_L \sigma_{\tilde{\mathbf{n}}}^2 \right)^{-1},$$

where $\mathbf{g}_k = \beta_k (\mathbf{w}_{\text{sum}}^H \hat{\mathbf{h}}_k)\, \mathbf{s}_k$

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- Having the detection order and the filters, our optimization is

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- To find a solution, we relax it into a semidefinite program (SDP)
- First, we rewrite the SINR condition as

$$\frac{\mathbf{w}^H \left(\beta_k^2 |\mathbf{v}_k^H \mathbf{s}_k|^2 \, \hat{\mathbf{h}}_k \hat{\mathbf{h}}_k^H\right) \mathbf{w}}{\mathbf{w}^H \left(\sum_{l=k+1}^{K} \beta_l^2 |\mathbf{v}_k^H \mathbf{s}_l|^2 \, \hat{\mathbf{h}}_l \hat{\mathbf{h}}_l^H + \frac{\sigma_{\tilde{\mathbf{n}}}^2 \|\mathbf{v}_k\|^2}{N_s} \mathbf{I}_{N_s}\right) \mathbf{w}} \geq \epsilon_k$$

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- Let

$$\mathbf{A}_k = \beta_k^2|\mathbf{v}_k^H\mathbf{s}_k|^2\,\hat{\mathbf{h}}_k\hat{\mathbf{h}}_k^H, \qquad \mathbf{B}_k = \sum_{l=k+1}^{K}\beta_l^2|\mathbf{v}_k^H\mathbf{s}_l|^2\,\hat{\mathbf{h}}_l\hat{\mathbf{h}}_l^H+\frac{\sigma_{\tilde{\mathbf{n}}}^2\|\mathbf{v}_k\|^2}{N_s}\mathbf{I}_{N_s}$$

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- The SINR condition is then

$$\frac{\mathbf{w}^H \mathbf{A}_k \mathbf{w}}{\mathbf{w}^H \mathbf{B}_k \mathbf{w}} \geq \epsilon_k$$

- Let $\mathbf{W} = \mathbf{w}\mathbf{w}^H$; we have

$$\begin{aligned} \mathbf{w}^H \mathbf{A}_k \mathbf{w} &= \mathrm{tr}\big(\mathbf{A}_k \mathbf{W}\big), \\ \mathbf{w}^H \mathbf{B}_k \mathbf{w} &= \mathrm{tr}\big(\mathbf{B}_k \mathbf{W}\big) \end{aligned}$$

  and the SINR condition becomes

$$\begin{aligned} \mathrm{tr}\big(\mathbf{A}_k \mathbf{W}\big) - \epsilon_k \, \mathrm{tr}\big(\mathbf{B}_k \mathbf{W}\big) &\geq 0 \\ \mathrm{tr}\Big(\big[\mathbf{A}_k - \epsilon_k \mathbf{B}_k\big] \mathbf{W}\Big) &\geq 0 \end{aligned}$$

Decoupled Optimization Problem

- The SDP-relaxed problem is finally given by

$$
\begin{aligned}
\text{find} \quad & \mathbf{W} \\
\text{s.t.} \quad & \mathrm{tr}\Big(\big[\mathbf{A}_k - \epsilon_k \mathbf{B}_k\big]\mathbf{W}\Big) \geq 0, \quad && k = 1,\, 2,\, \ldots,\, K, \\
& \mathbf{W} \succcurlyeq 0,\; [\mathbf{W}]_{n,n} = 1, && n = 1,\, 2,\, \ldots,\, N_s,
\end{aligned}
$$

- We apply a rank-1 approximation based on the strongest eigenvector of $\mathbf{W}$
  - If no solution is feasible, the sum-rate solution is used

Example Simulation Scenario

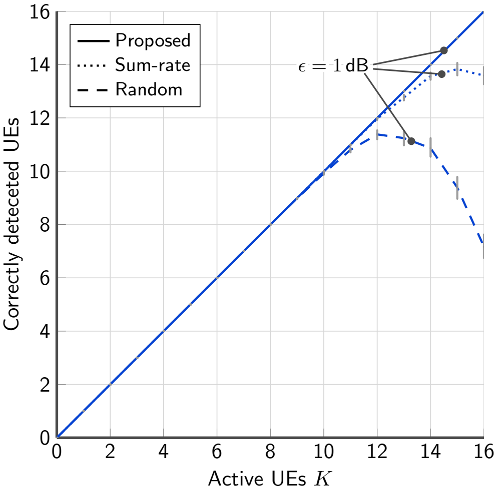
- Simulation parameters

Parameter	Value
#users per cluster	$K = 1$ to 16
Signature length	$L = 4$
#BS antennas	$N_r = 32$
#RIS elements	$N_s = 32$
NOMA codebook	4×16 Grassmannian
BS-RIS channel	LOS; 65 dB pathloss
RIS-UE channel	Rayleigh; 65 dB mean pathloss + spread of $[-s, s]$ dB
Transmit power	$P_k = 30$ dBm (all users equal)
Noise power	$\sigma_{\mathbf{n}}^2 = -110$ dBm
Receiver	MMSE-IC

- The RIS-UE channels have a pathloss spread of $[-s, s]$ dB, e.g,
  - when $s = 0$, all users have equal RIS-UE pathloss of 65 dB
  - when $s = 3$, the users pathloss is uniformly drawn from the range $[62, 68]$ dB

Example Scenario - User Detectability

- $N_s = 32$, pathloss spread is $[-3, 3]$ dB



Example Scenario - User Detectability

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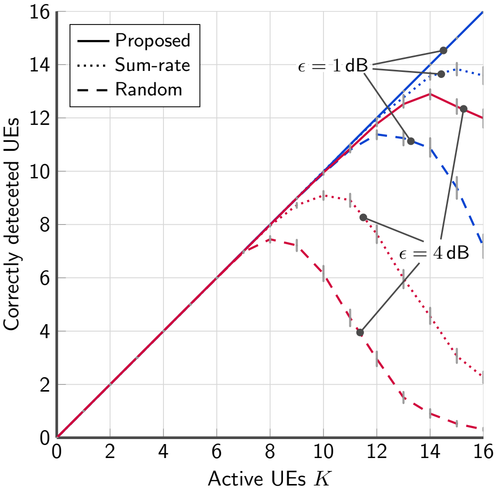
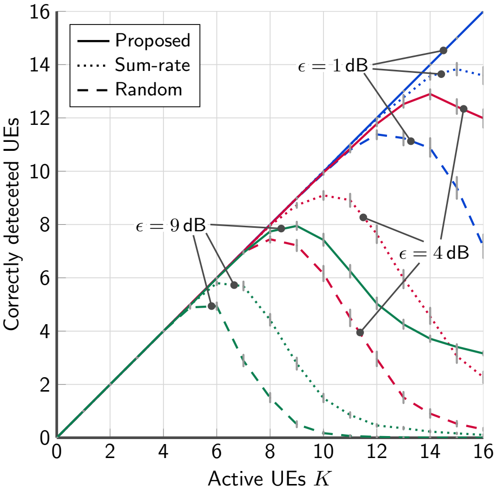


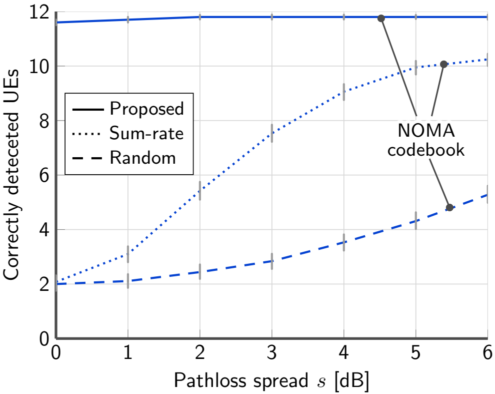
Example Scenario - User Detectability

- $N_s = 32$, pathloss spread is $[-3, 3]$ dB



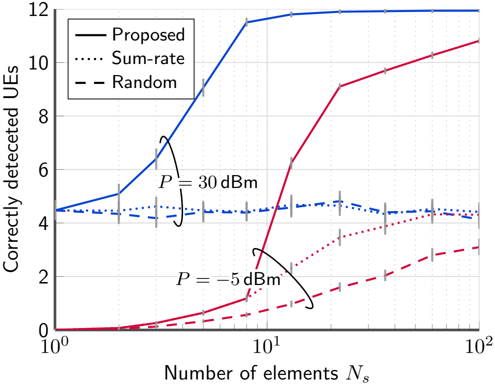
Example Scenario - Impact of Pathloss Spread

- $N_s = 32,\ K = 12,\ \epsilon = 4\,\text{dB}$



Example Scenario - Impact of P and N_s

- Pathloss spread is $[0,\ 0]$ dB, $K = 12$, $\epsilon = 3$ dB



Summary

- We consider a cluster-based RIS-assisted MIMO-NOMA setup

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- In order to handle the coupling of the different variables, sum-rate optimized phase-shifts are used an initial solution
- Once the variables are decoupled, we solve for the final phase-shifts by a convex relaxation of the problem

Summary

- We consider a cluster-based RIS-assisted MIMO-NOMA setup
- In order to handle the coupling of the different variables, sum-rate optimized phase-shifts are used an initial solution
- Once the variables are decoupled, we solve for the final phase-shifts by a convex relaxation of the problem
- Substantial gain can be observed for the number of correctly detected users

Thank you

Questions?

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