Channel Estimation and Spectral Efficiency of Reflecting Intelligent Surface Aided Communications

Nhan Thanh Nguyen, Jiguang He, and Markku Juntti

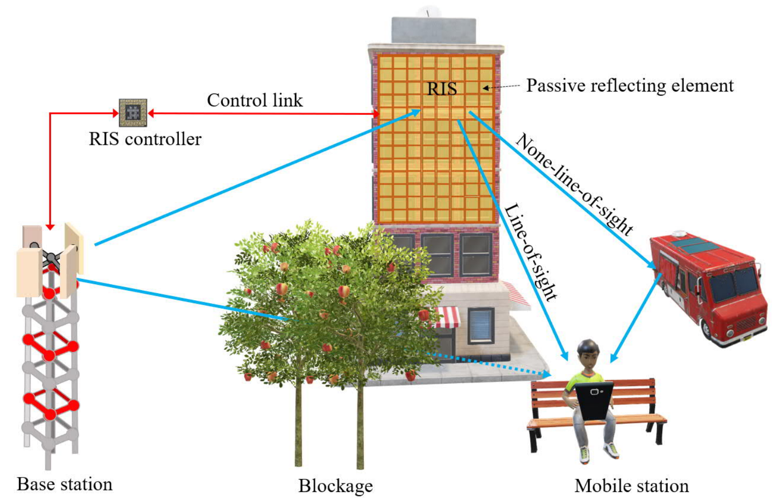
Centre for Wireless Communications (CWC), University of Oulu, Finland

WWRF Workshop: THz Waves: Fast Lane Journey to 6G

22 April 2021

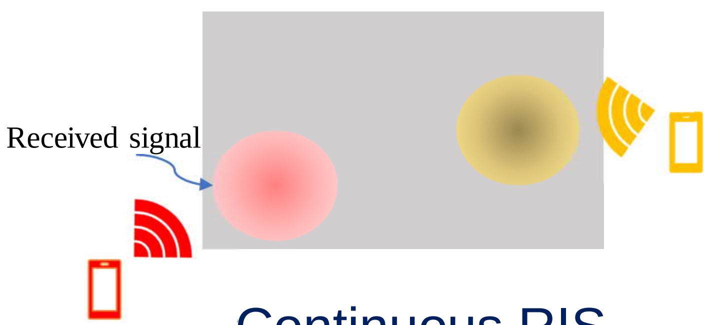
Introduction

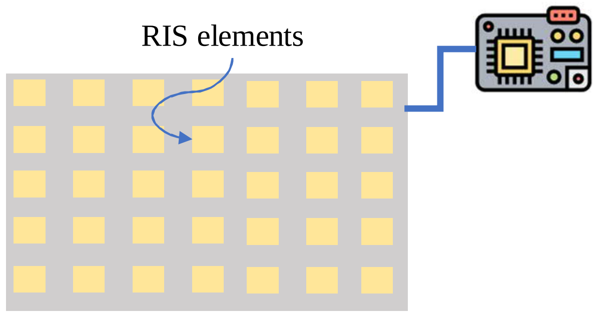
- Reconfigurable intelligent surfaces (RISs)
  - Low-cost and low-energy consumption passive reflecting elements
  - Customize physical propagation environment
  - Cost-efficient and energy-efficient



- Challenges:
  - Passive reflection in RISs limits the beamforming gains.
  - Performance loss due to limited phase shift resolution.
  - Channel estimation

What is a RIS? Continuous vs. Discrete





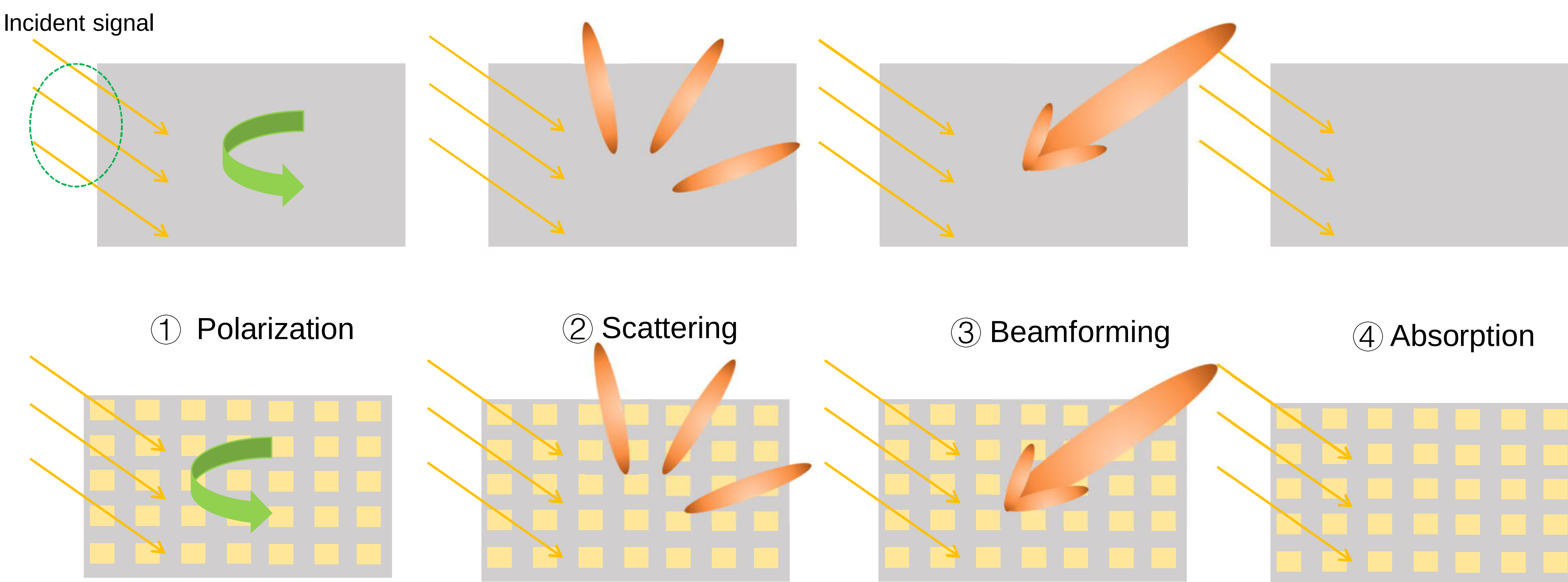
Continuous RIS

Mainly used as active transceivers

Discrete RIS

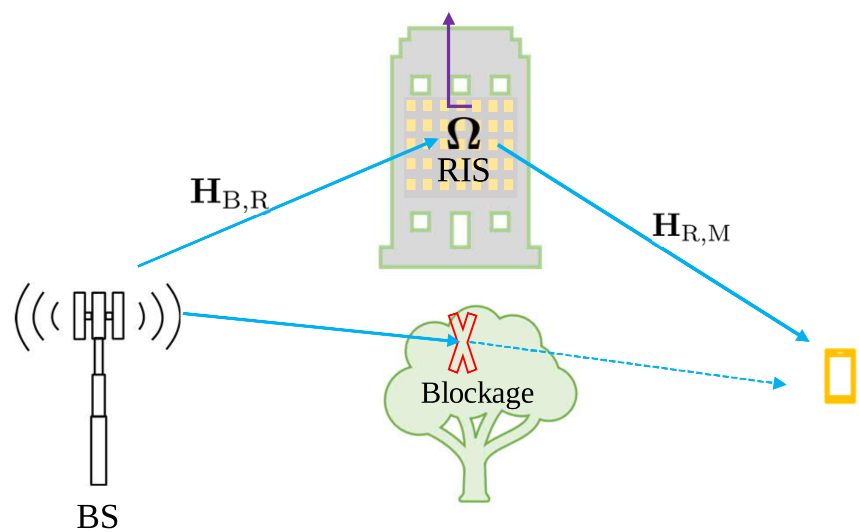
Mainly used as passive reflectors

RIS Operation Modes



Channel Estimation with RIS

– RIS is a passive element.
– Channel observed in the final receiver only.
➢ Product channel observed
➢ Estimation of the component channels is difficult.



An example system application for downlink transmission.

Channel Estimation Approaches

– Purely passive RIS based CE

- Two-stage approach with matrix factorization and completion [1]
- Matrix-calibration-based cascaded CE [2]

– Active sensors-based CE

- Deep learning [3]
- Compressive sensing [4]

[1] Z.-Q. He and X. Yuan, "Cascaded channel estimation for large intelligent metasurface assisted massive MIMO,"IEEE Wireless Commun. Lett., vol. 9, no. 2, pp. 210–214, Feb. 2019.
[2] H. Liu, X. Yuan, and Y.-J. A. Zhang, "Matrix-calibration-based cascaded channel estimation for reconfigurable intelligent surface assisted multiuser MIMO,"IEEE JSAC, 2020
[3] A. Taha, M. Alrabeiah, and A. Alkhateeb, "Enabling large intelligent surfaces with compressive sensing and deep learning," Apr. 2019.[Online]. Available: https://arxiv.org/abs/1904.10136
[4] R. Schroeder, J. He, and M. Juntti, "Passive RIS vs. Hybrid RIS: A Comparative Study on Channel Estimation", arXiv, 2020.

Parametric Channel Model

– Direct channel between BS and RIS

$$\mathbf{H}_{\mathrm{B,R}} = \sum_{l=0}^{L_{\mathrm{B,R}}} \boldsymbol{\rho}_{\mathrm{B,R},l}\boldsymbol{\alpha}(\boldsymbol{\phi}_{\mathrm{B,R},l})\boldsymbol{\alpha}^{\mathsf{H}}(\boldsymbol{\theta}_{\mathrm{B,R},l})$$

$$= \mathbf{A}(\boldsymbol{\phi}_{\mathrm{B,R}})\mathrm{diag}(\boldsymbol{\rho}_{\mathrm{B,R}})\mathbf{A}^{\mathsf{H}}(\boldsymbol{\theta}_{\mathrm{B,R}})$$

Array response vector

Propagation path gains

Angle of arrival

Angle of departure

$l = 0$: LoS path

$l \geq 1$: NLoS paths

– Composite channel

$$\boldsymbol{\Omega} = \mathrm{diag}(\exp\{j\omega_1\}, \cdots, \exp\{j\omega_{N_{\mathrm{R}}}\}) \in \mathbb{C}^{N_{\mathrm{R}} \times N_{\mathrm{R}}}$$

RIS phase control matrix ⇒ Diagonal, unit-modulus

$$\mathbf{H} = \mathbf{H}_{\mathrm{R,M}}\boldsymbol{\Omega}\mathbf{H}_{\mathrm{B,R}}$$

Tandem channels via RIS

Proposed Channel Sounding [He-21]

- CE and DT

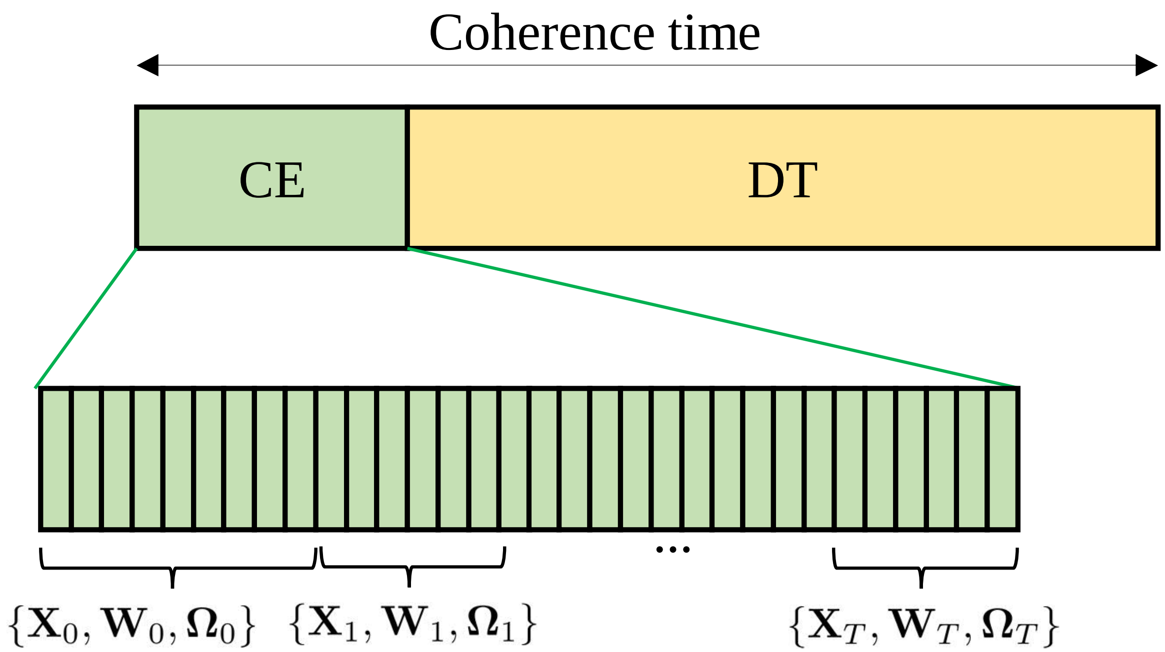
- CE divided multi-sub-blocks

Stage 1 sounding

$$\mathbf{Y}_0 = \mathbf{W}_t^{\mathsf{H}}\mathbf{H}(\mathbf{\Omega}_0)\mathbf{X}_t + \mathbf{W}_t^{\mathsf{H}}\mathbf{Z}_0,\ t = 0$$

Stage 2 sounding

$$\mathbf{Y}_t = \mathbf{W}_t^{\mathsf{H}}\mathbf{H}(\mathbf{\Omega}_t)\mathbf{X}_t + \mathbf{W}_t^{\mathsf{H}}\mathbf{Z}_t,\ t = 1, \cdots, T$$



Note that we try different phase control matrices

[He-21] J. He, H. Wymeersch & M. Juntti, "Channel estimation for RIS-aided mmWave MIMO systems via atomic norm minimization". IEEE Trans. Wirel. Commun. DOI: 10.1109/TWC.2021.3070064

Two-Stage Channel Estimation

- Stage 1 CE

To be estimated

$$\mathbf{H} = \mathbf{A}(\phi_{\mathrm{R,M}})\mathbf{G}_0\mathbf{A}^{\mathsf{H}}(\boldsymbol{\theta}_{\mathrm{B,R}})$$

$$\mathbf{G}_0 = \mathrm{diag}(\boldsymbol{\rho}_{\mathrm{R,M}})\mathbf{A}^{\mathsf{H}}(\boldsymbol{\theta}_{\mathrm{R,M}})\boldsymbol{\Omega}_0\mathbf{A}(\boldsymbol{\phi}_{\mathrm{B,R}})\mathrm{diag}(\boldsymbol{\rho}_{\mathrm{B,R}}),$$

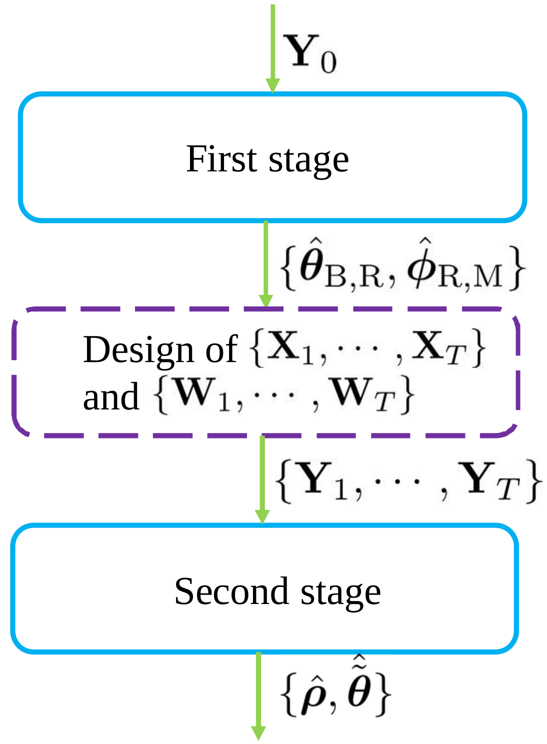
- Stage 2 CE

$$\mathbf{X}_t = \frac{1}{\sqrt{N_{\mathrm{B}}}}\mathbf{A}(\hat{\boldsymbol{\theta}}_{\mathrm{B,R}}), \qquad \mathbf{W}_t = \frac{1}{\sqrt{N_{\mathrm{M}}}}\mathbf{A}(\hat{\boldsymbol{\phi}}_{\mathrm{R,M}})$$

$$\Rightarrow \quad \mathbf{A}^{\mathsf{H}}(\boldsymbol{\theta}_{\mathrm{B,R}})\mathbf{X}_t \approx \sqrt{N_{\mathrm{B}}}\mathbf{I}, \qquad \mathbf{W}_t^{\mathsf{H}}\mathbf{A}(\boldsymbol{\phi}_{\mathrm{R,M}}) \approx \sqrt{N_{\mathrm{M}}}\mathbf{I}.$$

For $t = 1, \cdots, T$

Usually $L_{\mathrm{B,R}}$ and $L_{\mathrm{R,M}}$ are quite small!



Atomic Norm Minimization (AMN)

- Stage 1: $\phi_{\mathrm{R,M}}\ \min \frac{\mu}{2}\|\bar{\mathbf{U}}\|_{\mathcal{A}_M} + \frac{1}{2}\|\mathbf{Y}_0 - \mathbf{W}_0^{\mathsf{H}}\bar{\mathbf{U}}\|_{\mathrm{F}}^2,$ $\quad \boldsymbol{\theta}_{\mathrm{B,R}}\ \min \frac{\eta}{2}\|\tilde{\mathbf{U}}\|_{\mathcal{A}_M} + \frac{1}{2}\|\mathbf{Y}_0^{\mathsf{H}} - \mathbf{X}_0^{\mathsf{H}}\tilde{\mathbf{U}}\|_{\mathrm{F}}^2;$

$$\bar{\mathbf{U}} = \mathbf{A}(\phi_{\mathrm{R,M}})\mathbf{G}_0\mathbf{A}^{\mathsf{H}}(\boldsymbol{\theta}_{\mathrm{B,R}})\mathbf{X}_0 = \mathbf{A}(\phi_{\mathrm{R,M}})\bar{\mathbf{C}} \quad \tilde{\mathbf{U}} = \mathbf{A}(\boldsymbol{\theta}_{\mathrm{B,R}})\mathbf{G}_0^{\mathsf{H}}\mathbf{A}^{\mathsf{H}}(\phi_{\mathrm{R,M}})\mathbf{W}_0 = \mathbf{A}(\boldsymbol{\theta}_{\mathrm{B,R}})\tilde{\mathbf{C}}$$

$$\bar{\mathbf{C}} = \mathbf{G}_0\mathbf{A}_t^{\mathsf{H}}(\boldsymbol{\theta}_{\mathrm{B,R}})\mathbf{X}_0$$

$$\tilde{\mathbf{C}} = \mathbf{G}_0^{\mathsf{H}}\mathbf{A}^{\mathsf{H}}(\phi_{\mathrm{R,M}})\mathbf{W}_0$$

- Stage 2:

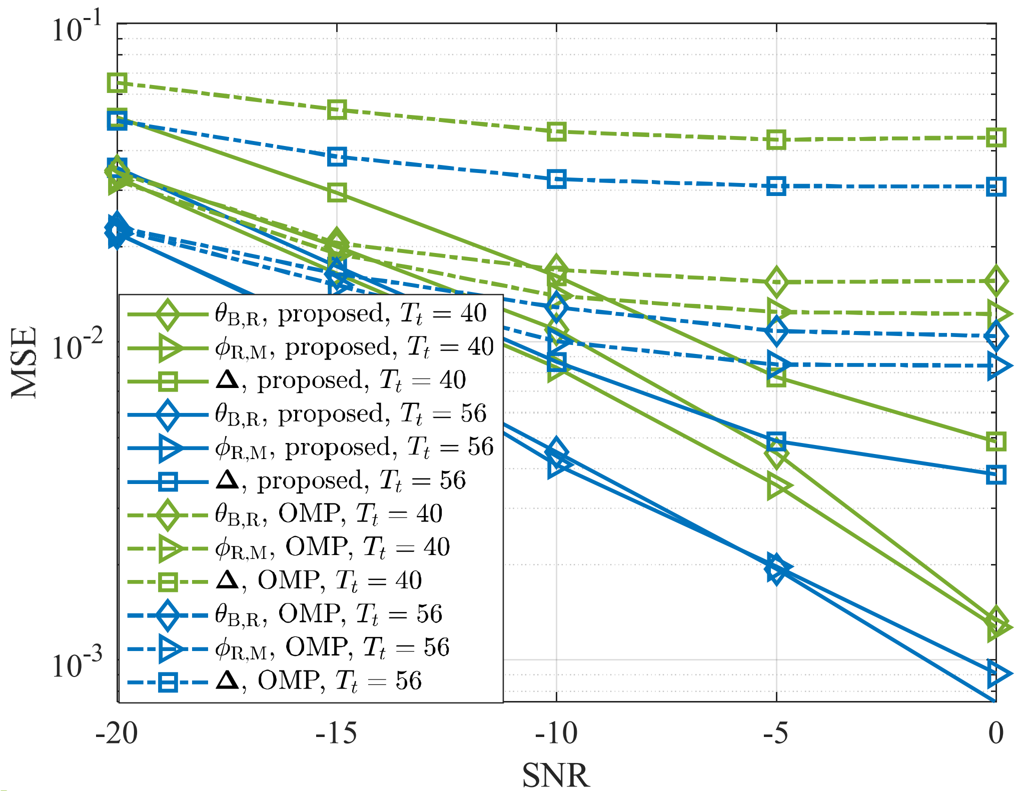
$\tilde{\theta}_i$

$$\{\hat{\mathbf{v}}, \hat{\mathbf{h}}_i, \hat{z}\} = \arg\min_{\mathbf{v},\mathbf{h}_i,z} 0.5\nu_i z + \frac{\nu_i}{2N_{\mathrm{R}}}\mathrm{Tr}(\mathrm{Toep}(\mathbf{v})) + \frac{1}{2}\|[\mathbf{Y}]_{i,:}^{\mathsf{T}} - \sqrt{N_{\mathrm{B}}N_{\mathrm{M}}}\bar{\boldsymbol{\Omega}}\mathbf{h}_i\|_2^2$$
$$\text{s.t.} \begin{bmatrix} \mathrm{Toep}(\mathbf{v}) & \mathbf{h}_i \\ \mathbf{h}_i^{\mathsf{H}} & z \end{bmatrix} \succeq \mathbf{0},\ \text{for } i = 1, \cdots, L_{\mathrm{B,R}}L_{\mathrm{R,M}},$$

$$\mathbf{h}_i = \rho_i\boldsymbol{\alpha}(\tilde{\theta}_i)$$

$$\hat{\rho}_i = \left(\boldsymbol{\alpha}(\hat{\tilde{\theta}}_i)\right)^{\dagger}\hat{\mathbf{h}}_i,$$

Estimation Performance



$$\mathrm{MSE}\big(\sin(\boldsymbol{\theta}_{\mathrm{B,R}})\big) = \mathbb{E}\Big[\frac{\|\sin(\boldsymbol{\theta}_{\mathrm{B,R}}) - \sin(\hat{\boldsymbol{\theta}}_{\mathrm{B,R}})\|_2^2}{L_{\mathrm{B,R}}}\Big],$$

$$\mathrm{MSE}\big(\sin(\boldsymbol{\phi}_{\mathrm{R,M}})\big) = \mathbb{E}\Big[\frac{\|\sin(\boldsymbol{\phi}_{\mathrm{R,M}}) - \sin(\hat{\boldsymbol{\phi}}_{\mathrm{R,M}})\|_2^2}{L_{\mathrm{R,M}}}\Big],$$

$$\mathrm{MSE}\big(\sin(\boldsymbol{\Delta})\big) = \mathbb{E}\Big[\frac{\|\sin(\boldsymbol{\Delta}) - \sin(\hat{\boldsymbol{\Delta}})\|_{\mathrm{F}}^2}{L_{\mathrm{B,R}}L_{\mathrm{R,M}}}\Big],$$

$$[\boldsymbol{\Delta}]_{mn} = \mathrm{asin}\big(\sin([\boldsymbol{\phi}_{\mathrm{B,R}}]_n) - \sin([\boldsymbol{\theta}_{\mathrm{R,M}}]_m)\big)$$

$$N_{\mathrm{B}} = N_{\mathrm{M}} = 16,\ N_{\mathrm{R}} = 32$$
$$L_{\mathrm{B,R}} = L_{\mathrm{R,M}} = 2$$

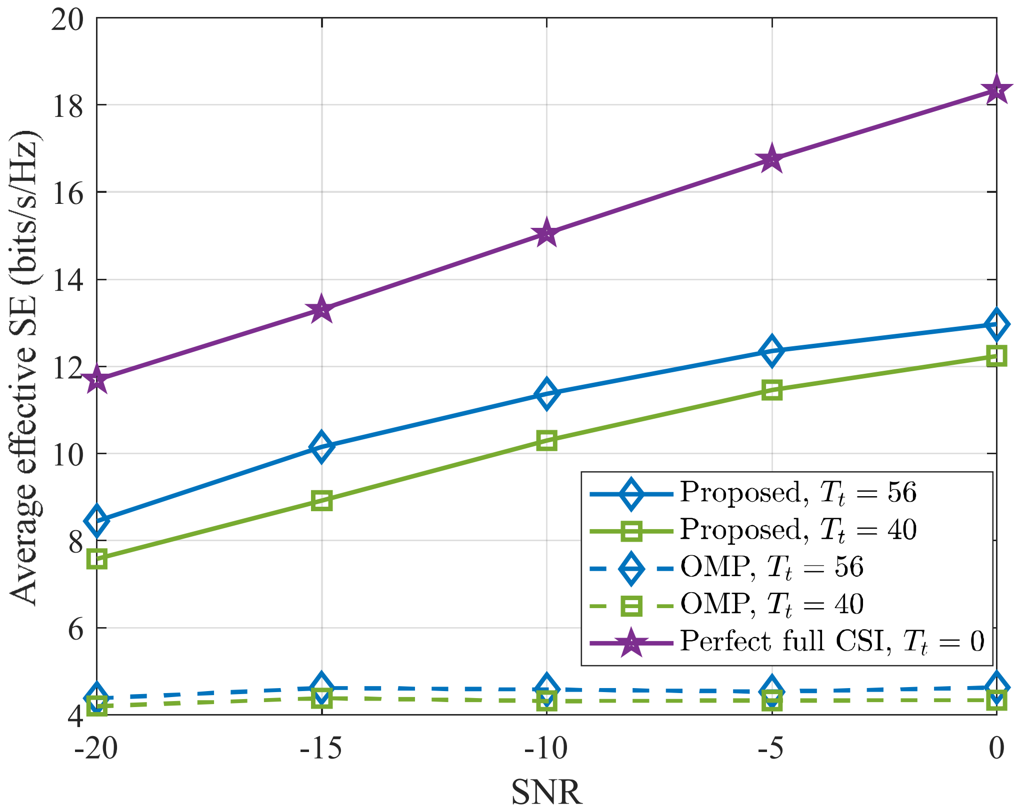
Training overhead 1

$$N_0 = M_0 = T = 10 \text{ with } T_t = 40$$

Training overhead 2

$$N_0 = M_0 = T = 14 \text{ with } T_t = 56$$

Spectral Efficiency Performance



$$R = \mathbb{E}\left[\frac{T_c - T_t}{T_c}\log_2\left(1 + \frac{|\mathbf{w}^{\mathsf{H}}\hat{\mathbf{H}}\mathbf{f}|^2}{\sigma^2 + \mathrm{var}\left(\mathbf{w}^{\mathsf{H}}\mathbf{H}_{\mathrm{e}}(\boldsymbol{\Omega}^{\star})\mathbf{f}\right)}\right)\right]$$

$$N_{\mathrm{B}} = N_{\mathrm{M}} = 16,\ N_{\mathrm{R}} = 32$$

$$L_{\mathrm{B,R}} = L_{\mathrm{R,M}} = 2$$

Training overhead 1

$$N_0 = M_0 = T = 10 \text{ with } T_t = 40$$

Training overhead 2

$$N_0 = M_0 = T = 14 \text{ with } T_t = 56$$

CWC Oulu
CENTRE FOR WIRELESS COMMUNICATIONS
University of Oulu

ARIADNE University of Oulu

Summary and Conclusions

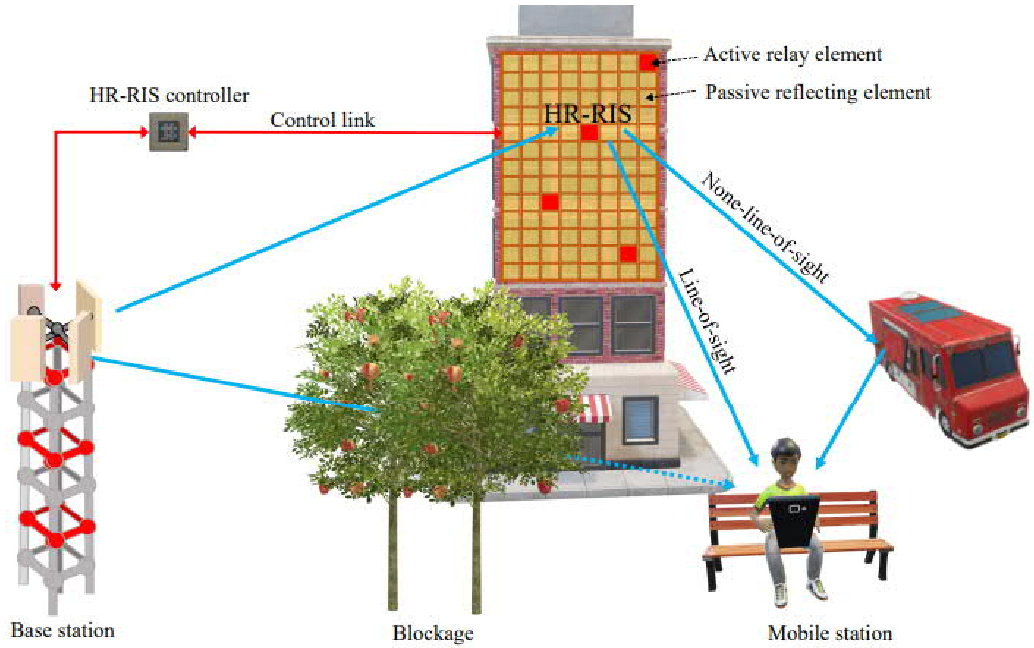
- RIS channel estimation is challenging and not always feasible
- We assumed known *sparse channel* structure to derive a superresolution algorithm based on ANM.
- Two-stage optimization problems.
- RIS phase control matrix designed to maximize the power of effective channel based on the estimates in the second stage.
- Joint beamforming at BS and MS
- Active receiver at RIS could enhance and simplify CE.

Hybrid Relay – RIS [Nguyen-21]

- Very large RISs are required [1], [2].
- A few more elements only provide small gain.

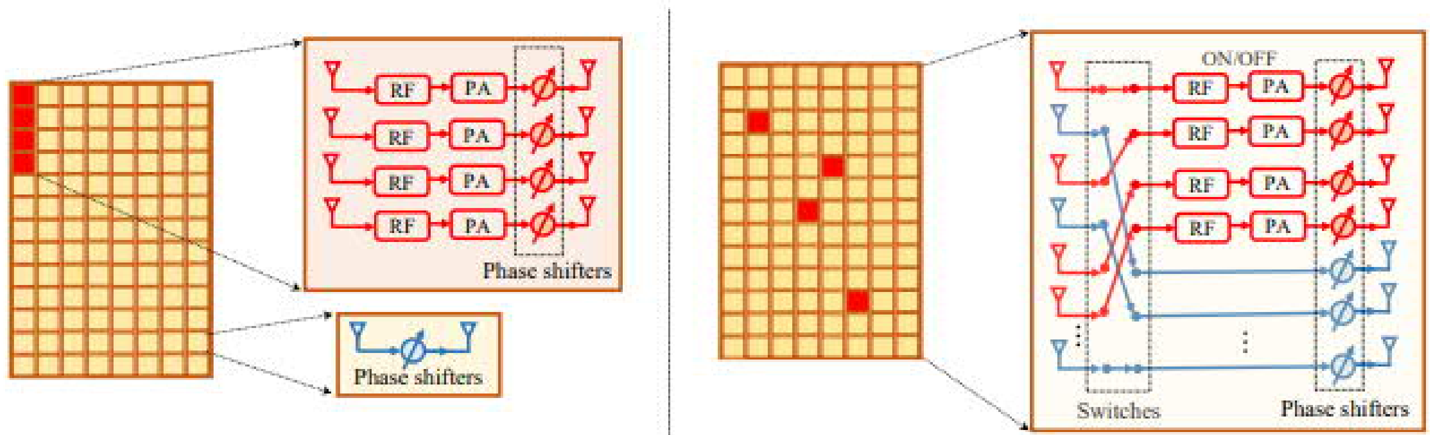
Replacing a few passive elements by relays:
⇒ Small loss in passive BF gains
⇒ Significant active relaying gains

Hybrid relay-reflecting intelligent surface (HR-RIS)



[1] Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming," *IEEE Trans. Wireless Commun.*, vol. 18, no. 11, pp. 5394–5409, Aug. 2019.
[2] E. Bjornson, O. Ozdogan, and E. G. Larsson, "Intelligent reflecting ¨ surface versus decode-and-forward: How large surfaces are needed to beat relaying?" *IEEE Wireless Commun. Lett.*, vol. 9, no. 2, pp. 244– 248, Oct. 2020.
T. N. Nguyen, Q.-D. Vu, K. C. Lee & M. Juntti, "Hybrid relay-reflecting intelligent surface-assisted wireless communication". IEEE Transactions on Signal Processing, submitted February 2021. https://arxiv.org/abs/2103.03900

HR-RIS Architectures



(a) Fixed HR-RIS architecture.

(b) Dynamic HR-RIS architecture.

- Configure and fix in advance during manufacturing ⇒ fixed HR-RIS architecture [3]
- Dynamically optimize based on CSI ⇒ dynamic HR-RIS architecture [3]
- Active element: RF, power amp., phase shifter
- Passive element: only phase shifter

[3] N. T. Nguyen, J. He, V.-D. Nguyen, H. Wymeersch, D. W. K. Ng, R. Schober, S. Chatzinotas, and M. Juntti, “Hybrid Relay-Reflecting Intelligent Surface-Aided Wireless Communications: Opportunities, Challenges, and Future Perspectives,” *arXiv:2104.02039, 2021.*

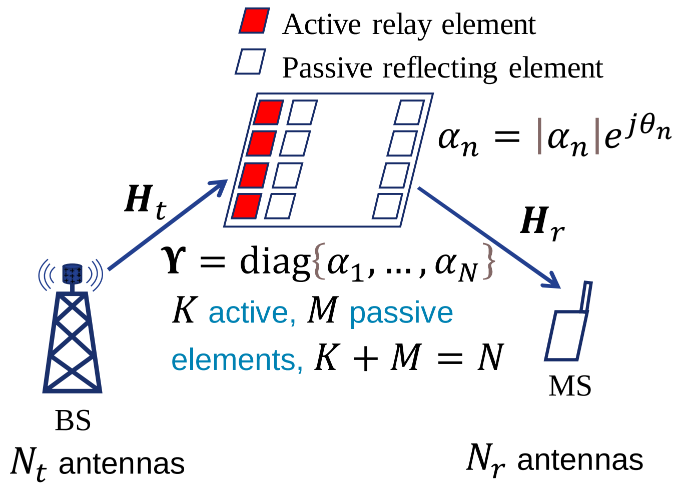
System Model

– The received signal at the MS:

$$\boldsymbol{y} = \underbrace{\boldsymbol{H}_r\boldsymbol{\Phi}\boldsymbol{H}_t\boldsymbol{x}}_{\text{reflected signal}} + \underbrace{\boldsymbol{H}_r\boldsymbol{\Psi}\boldsymbol{H}_t\boldsymbol{x}}_{\text{relayed signal}} + \underbrace{\boldsymbol{H}_r\boldsymbol{\Psi}\boldsymbol{n}_H}_{\text{amplified noise}} + \underbrace{\boldsymbol{n}_{\text{MS}}}_{\text{noise at MS}} \quad (1)$$

- $\boldsymbol{H}_r\boldsymbol{\Psi}\boldsymbol{n}_H \sim \mathcal{CN}\left(\boldsymbol{0}, \sigma^2\boldsymbol{H}_r\boldsymbol{\Psi}\boldsymbol{\Psi}^H\boldsymbol{H}_r^H\right)$
- $\boldsymbol{n}_{\text{MS}} \sim \mathcal{CN}\left(\boldsymbol{0}, \sigma^2\boldsymbol{I}_{N_r}\right)$
- $\boldsymbol{n} \triangleq \boldsymbol{H}_r\boldsymbol{\Psi}\boldsymbol{n}_H + \boldsymbol{n}_{\text{MS}} \sim \mathcal{CN}\left(\boldsymbol{0}, \sigma^2\left(\boldsymbol{I}_{N_r} + \boldsymbol{H}_r\boldsymbol{\Psi}\boldsymbol{\Psi}^H\boldsymbol{H}_r^H\right)\right)$

$$\Rightarrow \boldsymbol{y} = \boldsymbol{H}_r\boldsymbol{\Upsilon}\boldsymbol{H}_t\boldsymbol{x} + \boldsymbol{n} \quad (2)$$



$\mathbb{A}$: positions of K active elements

$\boldsymbol{\Upsilon} = \boldsymbol{\Phi} + \boldsymbol{\Psi}$

$\boldsymbol{\Psi}$ contains only active coefficients

$\boldsymbol{\Phi}$ contains only passive coefficients

SE Maximization

- Spectral efficiency (SE)

$$f_0(\{\alpha_n\}) = \log_2\left|\boldsymbol{I}_{N_r} + \rho \boldsymbol{H}_r \boldsymbol{\Upsilon} \boldsymbol{H}_t \boldsymbol{H}_t^H \boldsymbol{\Upsilon}^H \boldsymbol{H}_r^H \boldsymbol{R}^{-1}\right| \quad (3)$$

$$\leq \log_2\left|\boldsymbol{R} + \rho \boldsymbol{H}_r \boldsymbol{\Upsilon} \boldsymbol{H}_t \boldsymbol{H}_t^H \boldsymbol{\Upsilon}^H \boldsymbol{H}_r^H\right| \triangleq f(\{\alpha_n\}) \quad (4)$$

$\boldsymbol{R} = \boldsymbol{I}_{N_r} + \boldsymbol{H}_r \boldsymbol{\Psi} \boldsymbol{\Psi}^H \boldsymbol{H}_r^H$, $\rho = P_{\mathrm{BS}}/\sigma^2$

- Transmit power of active elements: $P_a = trace\left(\boldsymbol{\Psi}(P_{\mathrm{BS}} \boldsymbol{H}_t \boldsymbol{H}_t^H + \sigma^2 \boldsymbol{I}_{N_r})\boldsymbol{\Psi}^H\right)$ (5)
- HR-RIS is designed to maximize the SE

$$(\mathrm{P0}) \begin{cases} \underset{\{\alpha_n\}}{\text{maximize}} & f(\{\alpha_n\}) \\ \text{subject to} & |\alpha_n| = 1, \forall n \notin \mathbb{A} \\ & P_a \leq P_a^{max} \end{cases}$$

CWC Oulu
CENTRE FOR WIRELESS COMMUNICATIONS
University of Oulu

ARIADNE University of Oulu

Alternating Optmization Approach

- Let $\boldsymbol{r}_n$ be the nth column of $\boldsymbol{H}_r$, $\boldsymbol{t}_n^H$ be the nth row of $\boldsymbol{H}_t$.
- $\boldsymbol{\Upsilon}$ and $\boldsymbol{\Psi}$ are diagonal $\Rightarrow \boldsymbol{H}_r\boldsymbol{\Upsilon}\boldsymbol{H}_t = \sum_{n=1}^{N} \alpha_n \boldsymbol{r}_n \boldsymbol{t}_n^H$, $\boldsymbol{H}_r\boldsymbol{\Psi} = \sum_{n=1}^{N} \alpha_n \boldsymbol{r}_n$. (6)

$$\Rightarrow f(\alpha_n) = \log_2\left|\boldsymbol{A}_n + |\alpha_n|^2\boldsymbol{B}_n + \alpha_n\boldsymbol{C}_n + \alpha_n^*\boldsymbol{C}_n^H\right| \quad (7)$$

$P_a = \sum_{n\in\mathbb{A}} |\alpha_n|^2 \xi_n$, where $\xi_n = \sigma^2 + P_{\mathrm{BS}}\|\boldsymbol{t}_n\|^2$

($\boldsymbol{A}_n$, $\boldsymbol{B}_n$, and $\boldsymbol{C}_n$ are all independent of α_n.)

$$(\mathrm{P}) \quad \begin{cases} \underset{\alpha_n}{\text{maximize}} & f(\alpha_n) \\ \text{subject to} & |\alpha_n| = 1, n \notin \mathbb{A} \\ & |\alpha_n|^2 \le \dfrac{P_a^{max} - \sum_{i\in\mathbb{A}, i\neq n} |\alpha_i|^2 \xi_i}{\xi_n}, n \in \mathbb{A} \end{cases}$$

NN1 Optmization -> Optimization
Nhan Nguyen, 20/04/2021

Alternating Optimization (2)

$$f(\alpha_n) = \log_2|\boldsymbol{A}_n + |\alpha_n|^2\boldsymbol{B}_n + \alpha_n\boldsymbol{C}_n + \alpha_n^*\boldsymbol{C}_n^H|$$

$$= \log_2|\boldsymbol{A}_n| + \log_2|\underbrace{\boldsymbol{I}_{N_r} + |\alpha_n|^2\boldsymbol{A}_n^{-1}\boldsymbol{B}_n}_{\triangleq \boldsymbol{D}_n} + \alpha_n\boldsymbol{A}_n^{-1}\boldsymbol{C}_n + \alpha_n^*\boldsymbol{A}_n^{-1}\boldsymbol{C}_n^H|$$

$$= \log_2|\boldsymbol{A}_n| + \log_2|\boldsymbol{D}_n| + \log_2|\boldsymbol{I}_{N_r} + \alpha_n\boldsymbol{E}_n^{-1}\boldsymbol{C}_n + \alpha_n^*\boldsymbol{E}_n^{-1}\boldsymbol{C}_n^H| \qquad (\boldsymbol{E}_n \triangleq \boldsymbol{A}_n\boldsymbol{D}_n)$$

$$= \log_2|\boldsymbol{A}_n| + \log_2(1 + |\alpha_n|^2\underbrace{\gamma_n}) + \log_2(1 + |\alpha_n|^2|\underbrace{\lambda_n}|^2 + 2\Re(\alpha_n\lambda_n) + c_n) \quad [4] \qquad (8)$$

sole non-zero eigenvalue of $\boldsymbol{A}_n^{-1}\boldsymbol{B}_n$ sole non-zero eigenvalue of $\boldsymbol{E}_n^{-1}\boldsymbol{C}_n$

- Phase of $\alpha_n^\star$ is $-\arg\{\lambda_n\}$
- $f(\alpha_n^\star)$ monotonically increases with $|\alpha_n^\star|$

$$\alpha_n^\star = \begin{cases} \sqrt{\frac{P_a^{max} - \tilde{P}_a}{\xi_n}}\, e^{-j\arg\{\lambda_n\}}, n \in \mathbb{A} \\ e^{-j\arg\{\lambda_n\}}, \ \text{otherwise} \end{cases} \qquad (9)$$

[4] S. Zhang and R. Zhang, "Capacity characterization for intelligent reflecting surface aided MIMO communication," IEEE J. Sel. Areas Commun., vol. 38, no. 8, pp. 1823–1838, 2020.

Alternating Optimization Algorithm

$$|\alpha_n^\star|^2 = \frac{P_a^{max} - \sum_{i\in\mathbb{A}, i\neq n}|\alpha_i|^2\xi_i}{\sigma^2 + P_{\mathrm{BS}}||\boldsymbol{t}_n||^2}, n \in \mathbb{A} \quad (10)$$

→ With a limited power budget P_a^{max}, the HR-RIS with a small number of active elements is easider to attain SE gains.

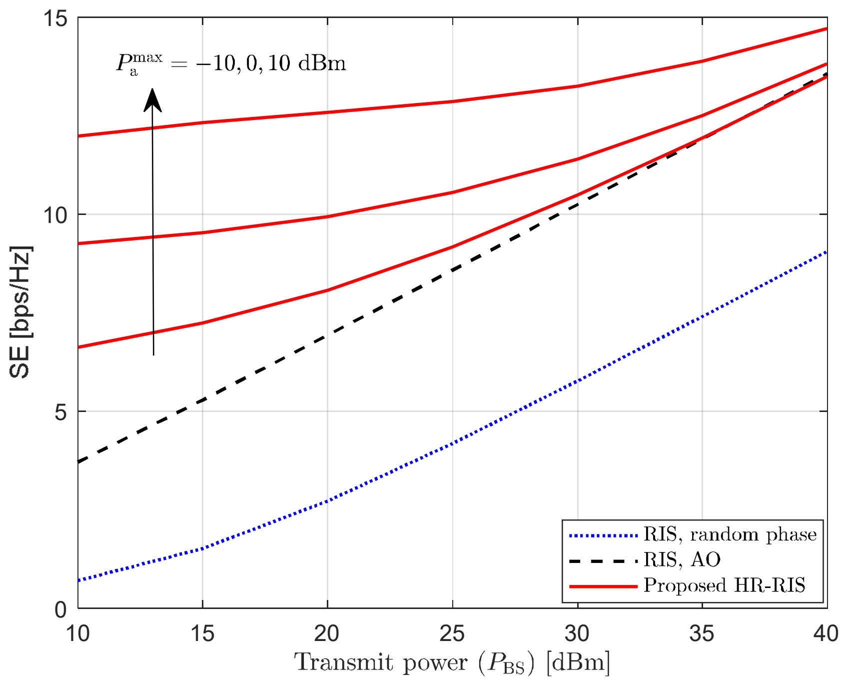
→ With a fixed P_a^{max}, a lower P_{BS} and/or smaller $||\boldsymbol{t}_n||^2$ (caused by severe path loss) can result in a higher $|\alpha_n^\star|^2$, and thus, provide a higher SE gains.

Algorithm 1 Find $\boldsymbol{\Upsilon}^\star$ for HR-RIS

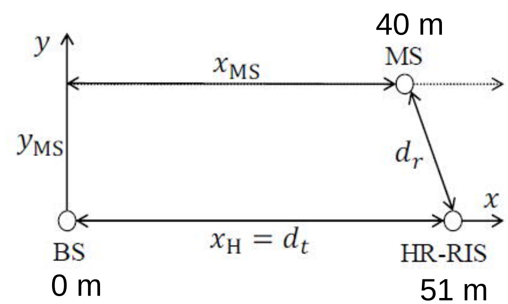
Input: $\boldsymbol{H}_t, \boldsymbol{H}_r, \mathbb{A}$.
Output: $\boldsymbol{\Upsilon}^\star$.

Randomly generate $\{\alpha_n\}$ with $|\alpha_n| = 1$ for $n \notin \mathbb{A}$ and $\sum_{n\in\mathbb{A}} |\alpha_n|^2 \xi_n = P_{\mathrm{a}}^{\max}$ for $n \in \mathbb{A}$.
while not converge **do**
  for $n = 1 \to N$ **do**
    Compute $\boldsymbol{A}_n, \boldsymbol{B}_n$, and $\boldsymbol{C}_n$ based on (9)-(14).
    $\boldsymbol{D}_n = \boldsymbol{I}_{N_r} + |\alpha_n|^2 \boldsymbol{A}_n^{-1}\boldsymbol{B}_n$, $\boldsymbol{E}_n = \boldsymbol{A}_n\boldsymbol{D}_n$.
    Find λ_n as the sole non-zero eigenvalue of $\boldsymbol{E}_n^{-1}\boldsymbol{C}_n$.
    Compute $\alpha_n^\star$ based on (23).
  end for
  Check convergence.
end while
$\boldsymbol{\Upsilon}^\star = \mathrm{diag}\{\alpha_1^\star, \ldots, \alpha_N^\star\}$.

Example: SE vs. TX Power



$$N_t = 32, N_r = 2, N = 50, K = 4$$



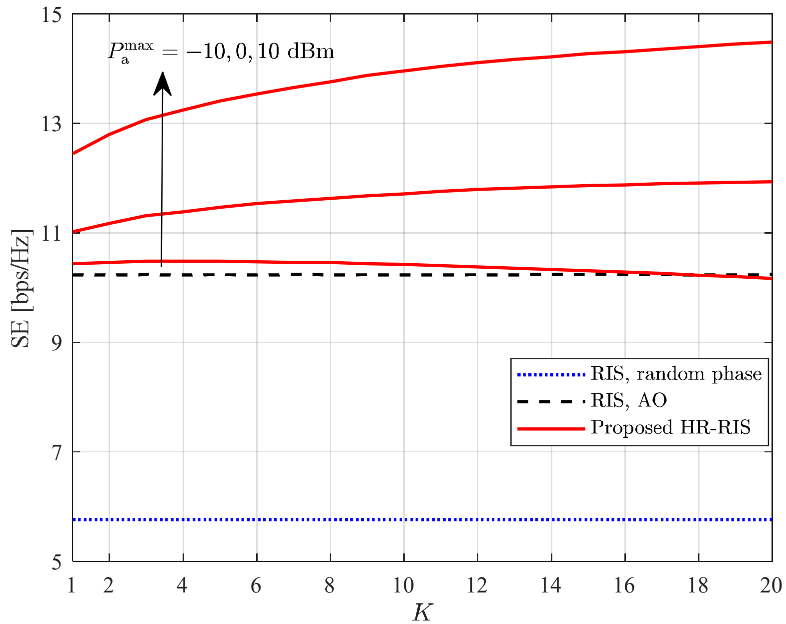
- The proposed HR-RIS scheme can provide significant improvement in SE compared with the conventional RIS.
- The SE improvement is more significant at low P_{BS}.

CWC Oulu
CENTRE FOR WIRELESS COMMUNICATIONS
University of Oulu

ARIADNE University of Oulu

6G FLAGSHIP UNIVERSITY OF OULU

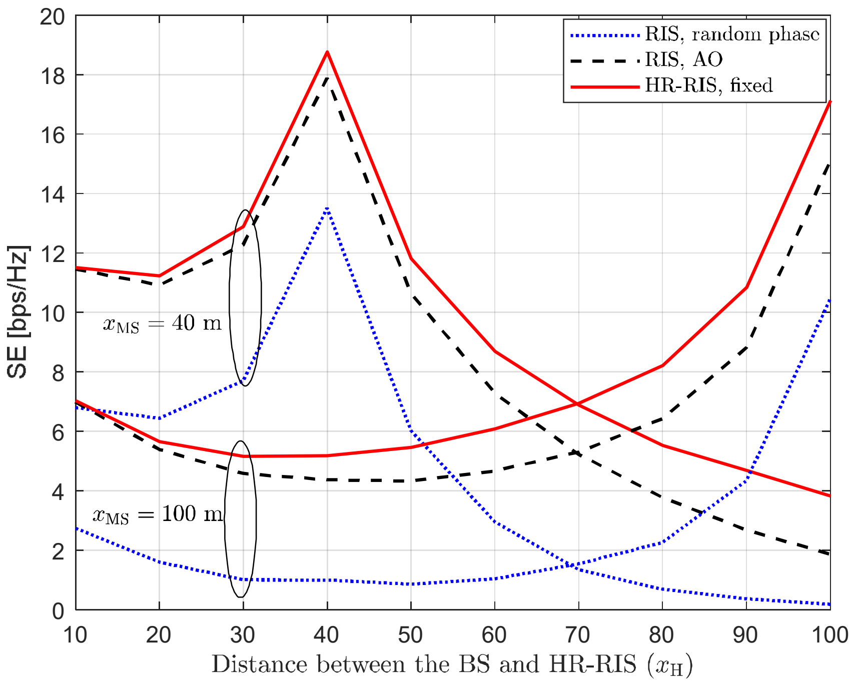
Example: SE vs. No. Active Elements



$N_t = 32, N_r = 2, N = 50, P_{BS} = 30$ dBm

- Deploying more active elements at the HR-RIS does not always provide a higher SE.
- For low P_a^{max}, HR-RIS with a large number of active elements can have performance loss.

Example: SE vs. Distance



$N_t = 32, N_r = 2, N = 50, P_{\mathrm{BS}} = 30$ dBm, and $P_a^{max} = 0$ dBm

- Both RIS and HR-RIS performs the best when they are close to the MS.
- When the RIS/HR-RIS moves far away from the BS, HR-RIS attains more significant active beamforming gains (due to more severe path loss).

Summary and Conclusions

- HR-RIS can provide semi-passive beamforming gains to achieve higher SE compared to the conventional RIS.
- Only a few elements are connected to PA to serve as active relays, while the other sever as passive reflection elements.
- HR-RIS can be designed and optimized by alternating optimization:
  - A small number of active elements is sufficient for a satisfying SE gain. Deploying many active elements does not always provide higher SE.
  - HR-RIS can attain a more significant SE gain when the transmit power at the BS is small and/or when the BS-HR-RIS distance is large.

Future Research

- Hybrid receive architectures can enhance the CE and positioning
- Position aware beamforming can enhance CE and communications
- SE and energy efficiency optimization of HR-RIS
- Implementation aspects