Imperial College London

Beyond Diagonal Reconfigurable Intelligent Surfaces: The/A Next Frontier for Smart Radio Environment

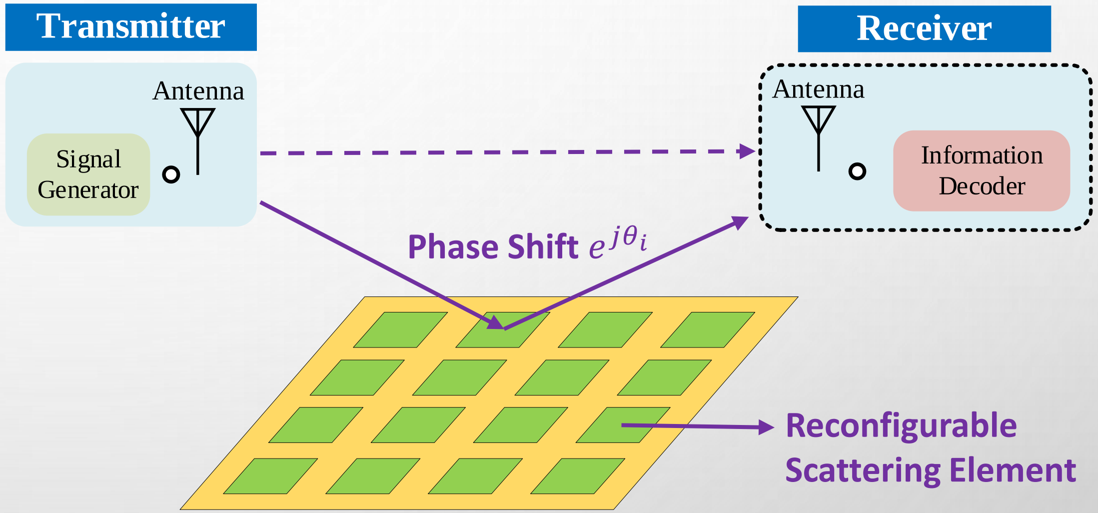
Prof. Bruno Clerckx
Communications and Signal Processing Group
Department of Electrical and Electronic Engineering
Imperial College London

COST INTERACT – Lisbon – January 2024

Special Thanks to Matteo Nerini (Imperial College London), Hongyu Li (Imperial College London),
Shanpu Shen (formerly Imperial College London, now University of Liverpool)

Reconfigurable Intelligent Surfaces (RIS)
Intelligent Reflecting Surfaces (IRS)

- Large number of passive reconfigurable scattering elements to "engineer the channel"
- Shape wavefront like smart mirrors
- Enabling spectrum efficient and "energy" efficient wireless (Communications, Sensing, Localization, Wireless Power Transfer), but also in Sound and Optics



Some important challenges:

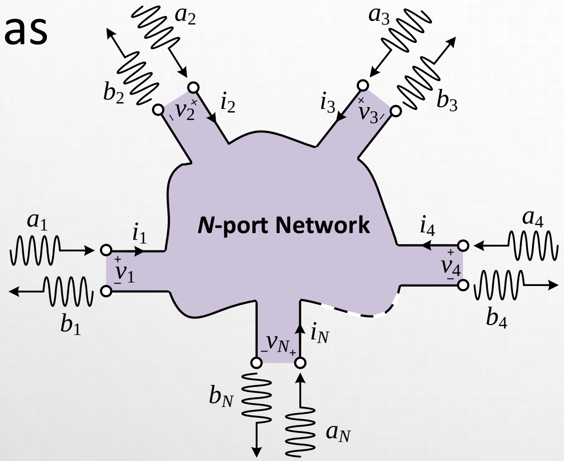
- Physical and electromagnetic compliant models of RIS
- Design and control of efficient RIS architectures

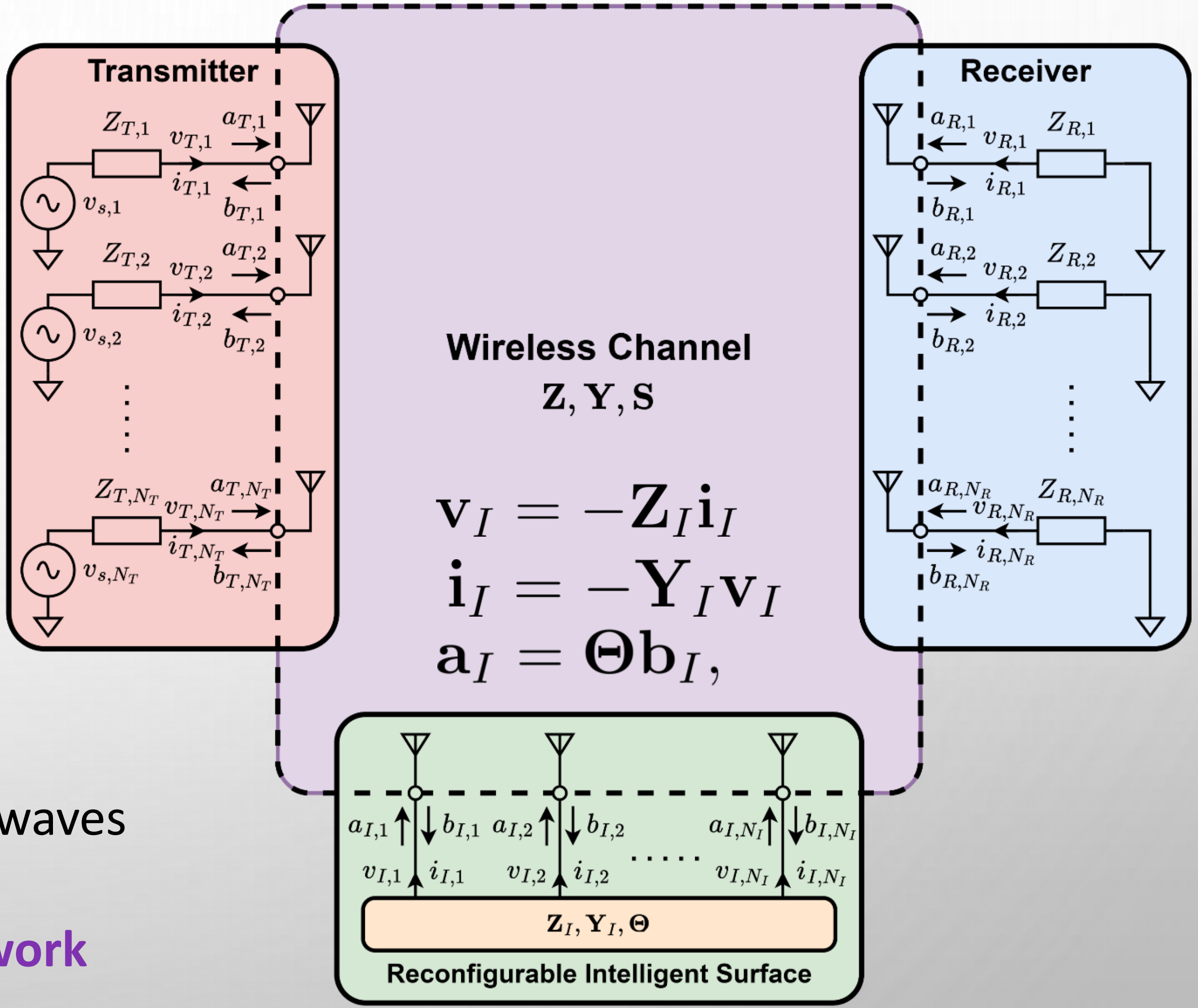
N. Kaina, M. Dupre, G. Lerosey, and M. Fink "Shaping complex microwave fields in reverberating media with binary tunable metasurfaces," Scientific Reports, 4 (1), 6693 (2014).

Q. Wu and R. Zhang, "Towards smart and reconfigurable environment: Intelligent reflecting surface aided wireless network," IEEE Commun. Mag., vol. 58, no. 1, pp. 106–112, 2019.

Multiport Network Analysis

- $N_T/N_R/N_I$ antennas at Tx/Rx/RIS
- $N = N_T + N_R + N_I$ antennas in wireless channel
  - Modeled as





$$\mathbf{v}_I = -\mathbf{Z}_I \mathbf{i}_I$$
$$\mathbf{i}_I = -\mathbf{Y}_I \mathbf{v}_I$$
$$\mathbf{a}_I = \boldsymbol{\Theta} \mathbf{b}_I,$$

- Z-parameters**,** Y-parameters, S-parameters to capture relationships between
  - $\boldsymbol{v}_T/\boldsymbol{v}_I/\boldsymbol{v}_R$ and $\boldsymbol{i}_T/\boldsymbol{i}_I/\boldsymbol{i}_R$: voltages and currents
  - $\mathbf{a}_T/\mathbf{a}_I/\mathbf{a}_R$ and $\mathbf{b}_T/\mathbf{b}_I/\mathbf{b}_R$: incident and reflected waves
- $\boldsymbol{Z}_I$ impedance matrix / $\boldsymbol{Y}_I$ admittance matrix / $\boldsymbol{\Theta}$ scattering matrix of **reconfigurable impedance network**
- **$\boldsymbol{Z}_I$ / $\boldsymbol{Y}_I$ / $\boldsymbol{\Theta}$ is reconfigurable and the key in RIS!**

M. Nerini, S. Shen, H. Li, M. Di Renzo, and B. Clerckx, “A Universal Framework for Multiport Network Analysis of Reconfigurable Intelligent Surfaces,” arXiv:2311.10561, 2023

Perfect Matching and No Mutual Coupling

$$\mathbf{v}_R = \mathbf{H}\,\mathbf{v}_T$$

Channel matrix H becomes an explicit function of Z_I / Y_I / Θ

- *Z*-parameters:

$$\mathbf{Z}=\begin{bmatrix} Z_0\mathbf{I} & \mathbf{0} & \mathbf{0}\\ \mathbf{Z}_{IT} & Z_0\mathbf{I} & \mathbf{0}\\ \mathbf{Z}_{RT} & \mathbf{Z}_{RI} & Z_0\mathbf{I}\end{bmatrix}\quad \overline{\mathbf{Z}}=\begin{bmatrix} Z_0\mathbf{I} & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{Z}_I & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & Z_0\mathbf{I}\end{bmatrix}$$

$$\mathbf{H}=\widetilde{\mathbf{Z}}_{RT}\widetilde{\mathbf{Z}}_{TT}^{-1}$$

$$\mathbf{H}=\frac{1}{2Z_0}\left(\mathbf{Z}_{RT}-\mathbf{Z}_{RI}\left(\underset{\uparrow}{\mathbf{Z}_I}+Z_0\mathbf{I}\right)^{-1}\mathbf{Z}_{IT}\right)$$

- *Y*-parameters:

$$\mathbf{Y}=\begin{bmatrix} \mathbf{I}/Z_0 & \mathbf{0} & \mathbf{0}\\ \mathbf{Y}_{IT} & \mathbf{I}/Z_0 & \mathbf{0}\\ \mathbf{Y}_{RT} & \mathbf{Y}_{RI} & \mathbf{I}/Z_0\end{bmatrix}\quad \overline{\mathbf{Y}}=\begin{bmatrix} \mathbf{I}/Z_0 & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{Y}_I & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{I}/Z_0\end{bmatrix}$$

$$\mathbf{H}=\mathbf{Y}_R^{-1}\widetilde{\mathbf{Y}}_{RT}\left(\widetilde{\mathbf{Y}}_{TT}-\mathbf{I}\right)^{-1}\mathbf{Y}_T$$

$$\mathbf{H}=\frac{Z_0}{2}\left(-\mathbf{Y}_{RT}+\mathbf{Y}_{RI}\left(\underset{\uparrow}{\mathbf{Y}_I}+\mathbf{I}/Z_0\right)^{-1}\mathbf{Y}_{IT}\right)$$

- *S*-parameters:

$$\mathbf{S}=\begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0}\\ \mathbf{S}_{IT} & \mathbf{0} & \mathbf{0}\\ \mathbf{S}_{RT} & \mathbf{S}_{RI} & \mathbf{0}\end{bmatrix}\quad \mathbf{\Gamma}=\begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{\Theta} & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{0}\end{bmatrix}$$

$$\mathbf{H}=\left(\mathbf{\Gamma}_R+\mathbf{I}\right)\widetilde{\mathbf{S}}_{RT}\left(\mathbf{I}+\mathbf{\Gamma}_T\widetilde{\mathbf{S}}_{TT}+\widetilde{\mathbf{S}}_{TT}\right)^{-1}$$

$$\mathbf{H}=\mathbf{S}_{RT}+\mathbf{S}_{RI}\underset{\uparrow}{\mathbf{\Theta}}\mathbf{S}_{IT}$$

All equivalent but S-parameters simplest and most intuitive.

M. Nerini, S. Shen, H. Li, M. Di Renzo, and B. Clerckx, “A Universal Framework for Multiport Network Analysis of Reconfigurable Intelligent Surfaces,” arXiv:2311.10561, 2023

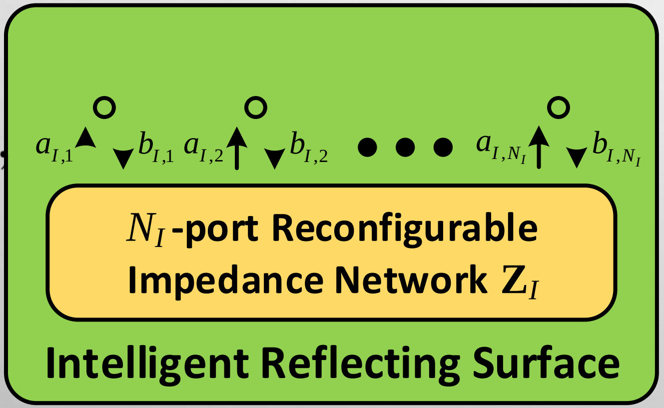
Simplified RIS Aided Communication Model

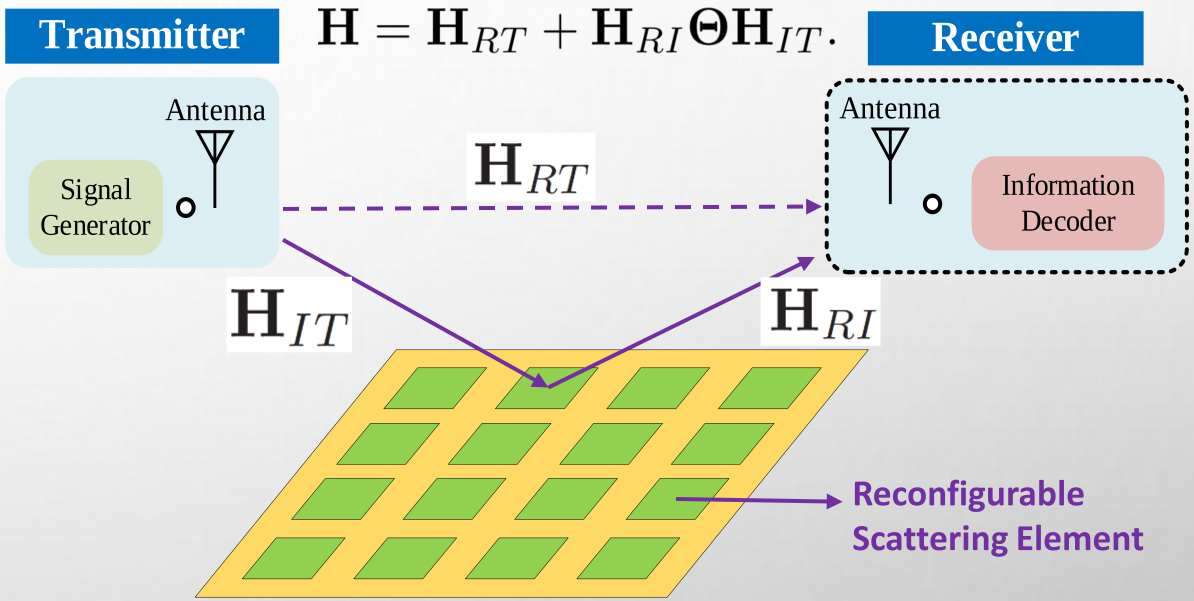
With perfect matching and no mutual coupling

$$\mathbf{H} = \mathbf{H}_{RT} + \mathbf{H}_{RI}\mathbf{\Theta}\mathbf{H}_{IT}.$$

- $\mathbf{\Theta}$ is the **scattering matrix** of **reconfigurable impedance network**
- **$\mathbf{\Theta}$ is reconfigurable and the key in RIS!**

$$\mathbf{a}_I = \mathbf{\Theta}\mathbf{b}_I,$$





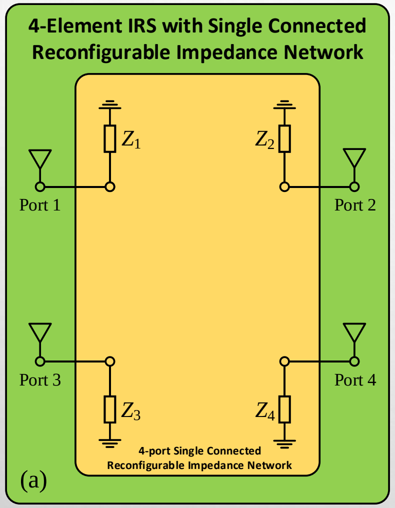
Question: $\mathbf{\Theta}$ and reconfigurable impedance network architectures?

S. Shen, B. Clerckx, and R. Murch, “Modeling and Architecture Design of Reconfigurable Intelligent Surfaces using Scattering Parameter Network Analysis,” IEEE Trans. on Wireless Commun, vol. 21, no. 2, pp. 1229-1243, Feb. 2022

From Diagonal to Beyond Diagonal RIS

Conventional (Diagonal) RIS

Physically: Each element is connected to a load disconnected from the other elements

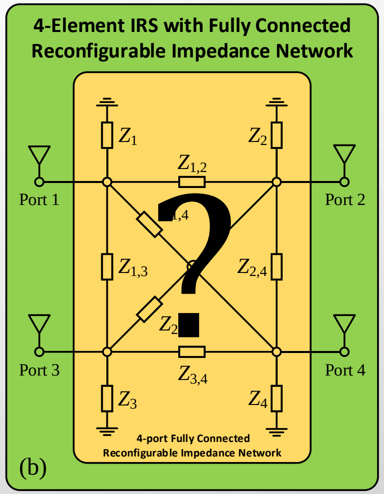


Mathematically: Control diagonal elements only

$$\mathbf{\Theta} = \begin{bmatrix} ? & 0 & 0 \\ 0 & ? & 0 \\ 0 & 0 & ? \end{bmatrix}$$

Beyond Diagonal RIS – BD-RIS

(Part of) elements are connected to each other via reconfigurable components

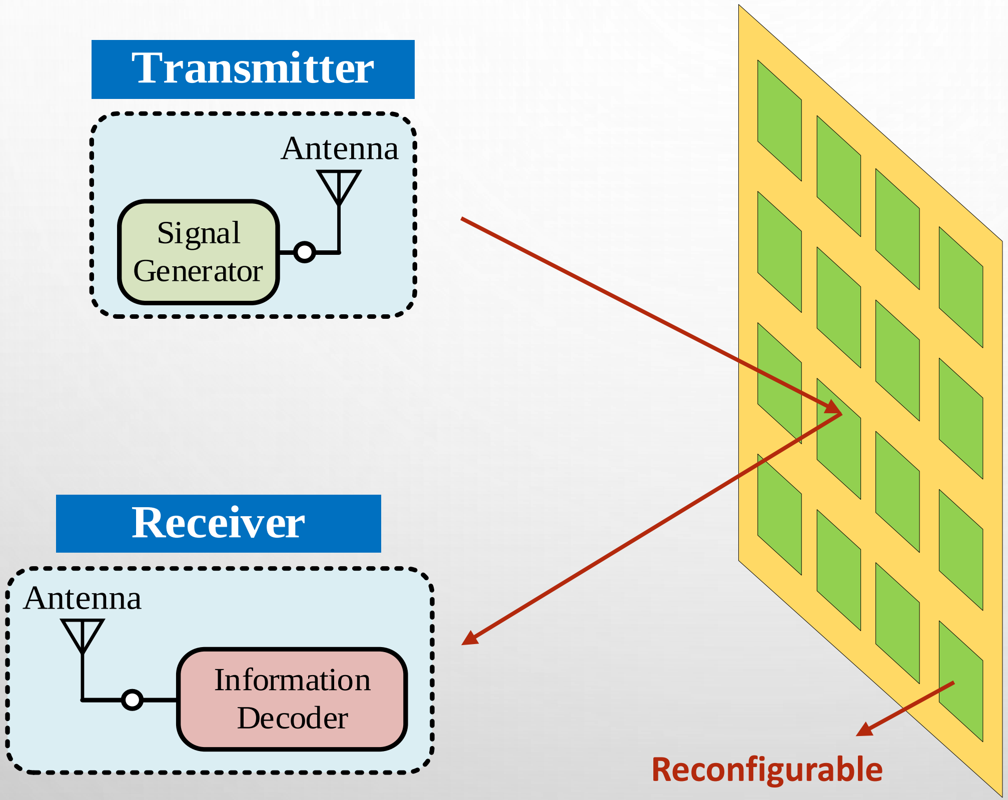


How? Why? When?

Control diagonal and off-diagonal elements

$$\mathbf{\Theta} = \begin{bmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & ? \end{bmatrix}$$

Reflective BD-RIS



Transmitter

Antenna

Signal Generator

Receiver

Antenna

Information Decoder

The other side of the RIS is blocked

Reconfigurable Scattering Element

Reflective mode: transmitter and receiver on the same side of the RIS

Conventional Reflective RIS

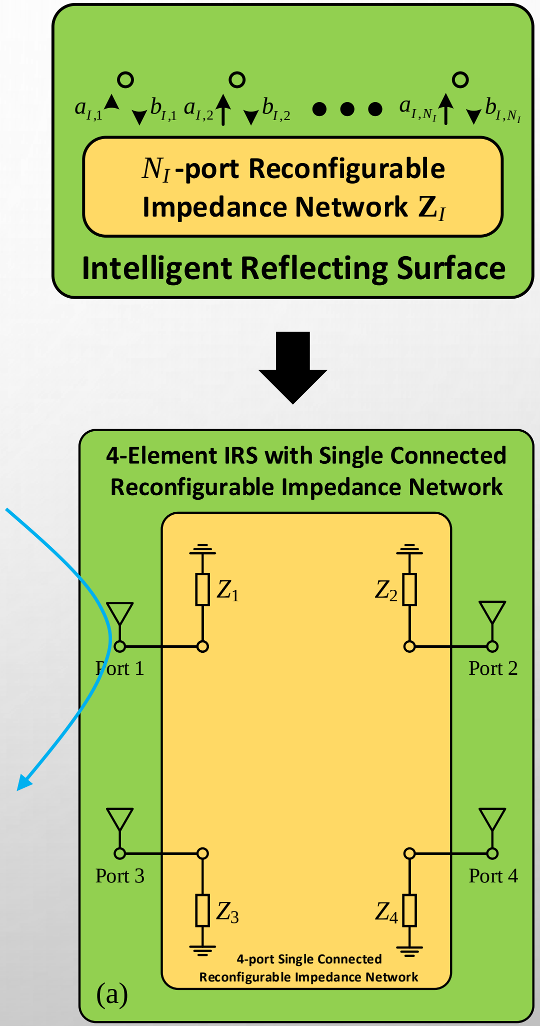
- **Conventional Single Connected Reconfigurable Impedance Network**
  - Each port is not connected to the other ports
  - Need N_I reconfigurable impedances for N_I-element RIS
  - Corresponding constraint (lossless)

$$\mathbf{\Theta} = \mathrm{diag}\left(e^{j\theta_1}, e^{j\theta_2}, \ldots, e^{j\theta_{N_I}}\right)$$

$$\boldsymbol{Y}_I = \mathrm{diag}\left(Y_1, Y_2, \ldots, Y_{N_I}\right)$$

$$\boldsymbol{Z}_I = \mathrm{diag}\left(Z_1, Z_2, \ldots, Z_{N_I}\right)$$

  - Only adjusts the phases of the impinging waves



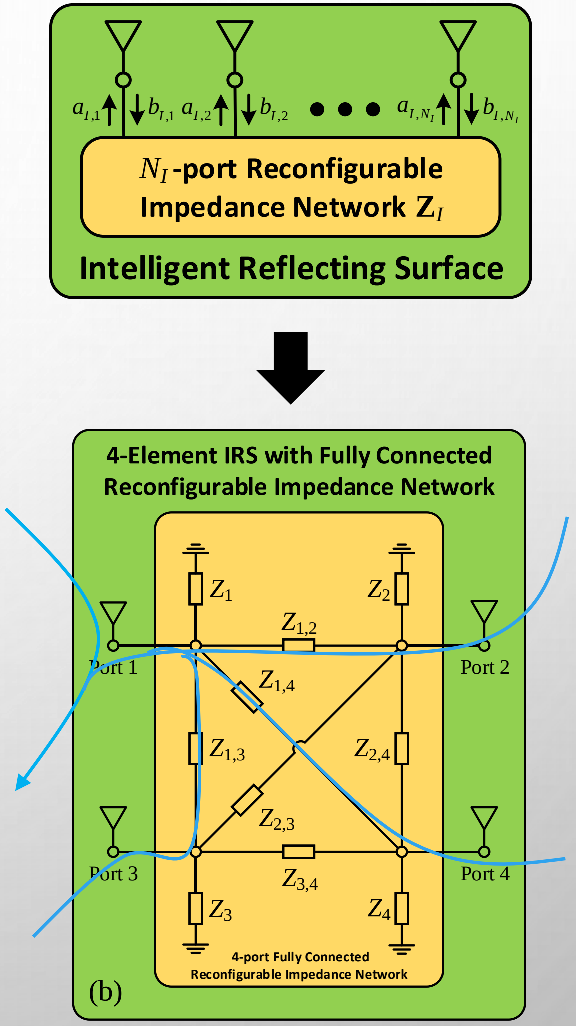
Signal impinging on Port 1 is entirely reflected by Port1 after phase shift adjustment

S. Shen, B. Clerckx, and R. Murch, "Modeling and Architecture Design of Reconfigurable Intelligent Surfaces using Scattering Parameter Network Analysis," IEEE Trans. on Wireless Commun, vol. 21, no. 2, pp. 1229-1243, Feb. 2022

Reflective BD-RIS using Fully Connected

- **Fully Connected Reconfigurable Impedance Network**
  - Each port is connected to the other ports
  - Need $N_I(N_I+1)/2$ reconfigurable impedances
  - Corresponding constraint $\boldsymbol{\Theta}=\boldsymbol{\Theta}^T,\ \boldsymbol{\Theta}^H\boldsymbol{\Theta}=\mathbf{I}$

  (symmetry due to reciprocal impedance network, unitary due to lossless)



Signal impinging on Port 1 is partially reflected by Port 1 and partially absorbed and reflected by other Ports

BD-RIS Benefit 1: Can adjust not only the phases but also the magnitudes of the impinging waves!

  - Become complicated when N_I is large
  - Need many more reconfigurable impedances

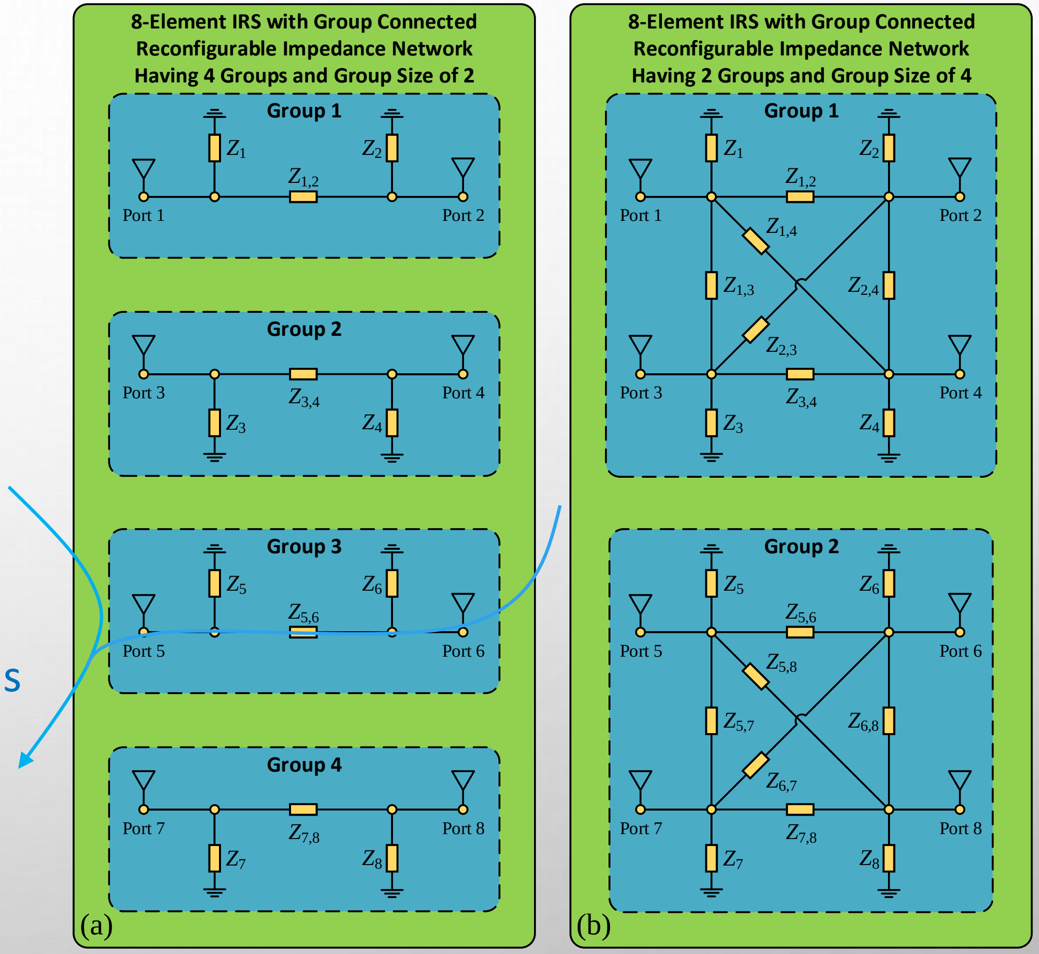
S. Shen, B. Clerckx, and R. Murch, "Modeling and Architecture Design of Reconfigurable Intelligent Surfaces using Scattering Parameter Network Analysis," IEEE Trans. on Wireless Commun, vol. 21, no. 2, pp. 1229-1243, Feb. 2022

Reflective BD-RIS using Group Connected

- **Group Connected Reconfigurable Impedance Network**
  - A tradeoff between single and fully connected cases
  - Divide RIS elements into G groups
  - Each group has $N_G = N_I/G$ elements and use fully connected reconfigurable impedance network
  - Corresponding constraint

$$\boldsymbol{\Theta} = \mathrm{diag}\left(\boldsymbol{\Theta}_1, \boldsymbol{\Theta}_2, ..., \boldsymbol{\Theta}_G\right),$$

$$\boldsymbol{\Theta}_g = \boldsymbol{\Theta}_g^T,\ \boldsymbol{\Theta}_g^H \boldsymbol{\Theta}_g = \mathbf{I},\ \forall g.$$



Signal impinging on a specific element is partially reflected by this element and by other elements in the group

S. Shen, B. Clerckx, and R. Murch, "Modeling and Architecture Design of Reconfigurable Intelligent Surfaces using Scattering Parameter Network Analysis," IEEE Trans. on Wireless Commun, vol. 21, no. 2, pp. 1229-1243, Feb. 2022

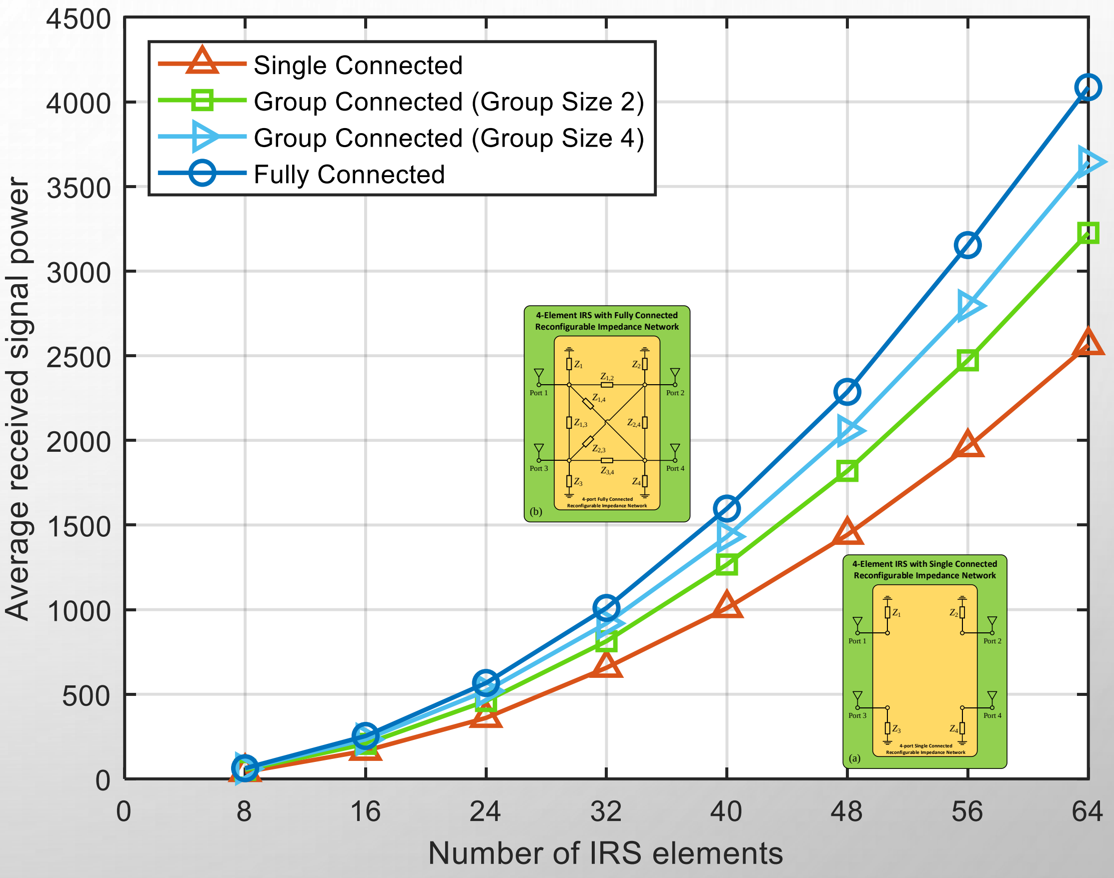
Power Gain

$$\begin{aligned} \max_{\boldsymbol{\Theta},\boldsymbol{\Theta}_g} \quad & \left\|\mathbf{h}_{RI}\boldsymbol{\Theta}\mathbf{h}_{IT}\right\|^2 \\ \text{s.t.} \quad & \boldsymbol{\Theta} = \operatorname{diag}\left(\boldsymbol{\Theta}_1, \boldsymbol{\Theta}_2, \ldots, \boldsymbol{\Theta}_G\right), \\ & \boldsymbol{\Theta}_g^H \boldsymbol{\Theta}_g = \mathbf{I}, \ \forall g, \\ & \boldsymbol{\Theta}_g = \boldsymbol{\Theta}_g^T, \ \forall g. \end{aligned}$$

	Group Size	Gain over Single Connected	Number of Impedances
Single connected	1	1	*N*
Group Connected	2	1.26	1.5*N*
Group Connected	4	1.43	2.5*N*
Fully Connected	*N*	1.60	*N*(*N*+1)/2

- Fully connected achieves highest power
- Group connected trades complexity and gain
- Single connected ⇔ EGC, Fully connected ⇔ MRC

i.i.d. Rayleigh fading

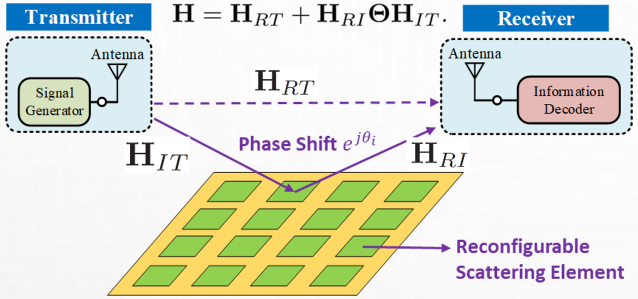


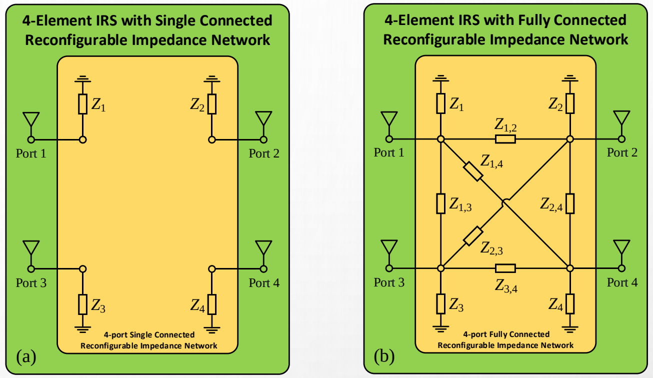
BD-RIS Benefit 2: Boost received power and therefore (sum-)rate

S. Shen, B. Clerckx, and R. Murch, “Modeling and Architecture Design of Reconfigurable Intelligent Surfaces using Scattering Parameter Network Analysis,” IEEE Trans. on Wireless Commun, vol. 21, no. 2, pp. 1229-1243, Feb. 2022

M. Nerini, S. Shen and B. Clerckx, “Closed-Form Global Optimization of Beyond Diagonal Reconfigurable Intelligent Surfaces,” IEEE Trans. Wireless Commun., 2023.

Propagation Conditions and Grouping Impacts Power Gain

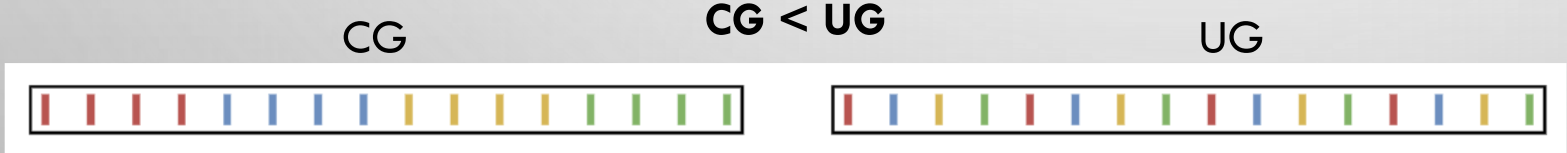


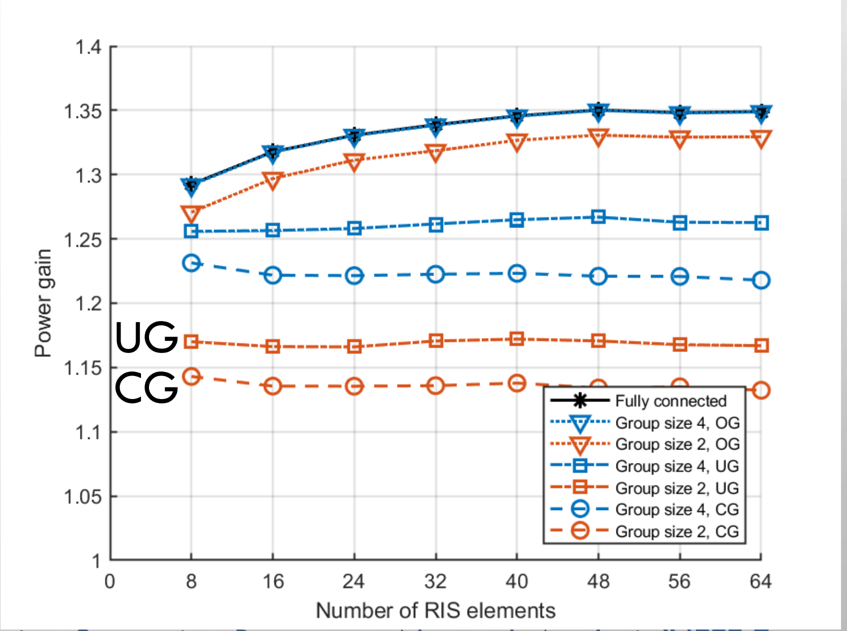


- $P_R^{\text{Single}} \leq \bar{P}_R^{\text{Fully}}$
  - Higher gains as we experience more i.i.d. fading
  - Equality for far-field LoS/free-space conditions

- Grouping strategy based on the channel statistics:

CG < UG



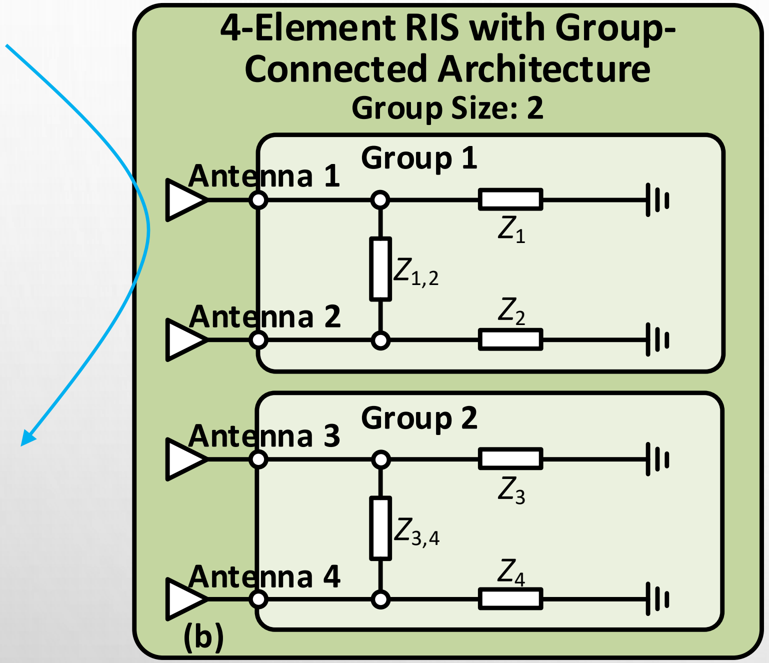


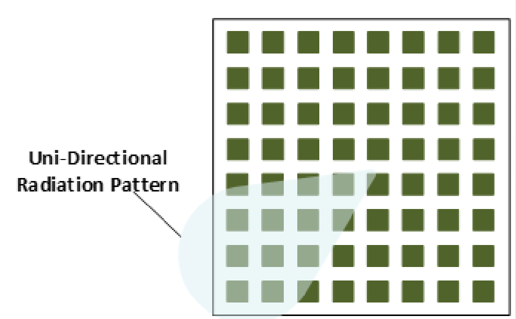
S. Shen, B. Clerckx, and R. Murch, “Modeling and Architecture Design of Reconfigurable Intelligent Surfaces using Scattering Parameter Network Analysis,” IEEE Trans. on Wireless Commun, vol. 21, no. 2, pp. 1229-1243, Feb. 2022

M. Nerini and B. Clerckx, “Reconfigurable Intelligent Surfaces Based on Single, Group and Fully Connected Discrete-Value Impedance Networks” arXiv:2110.00077

Hybrid BD-RIS

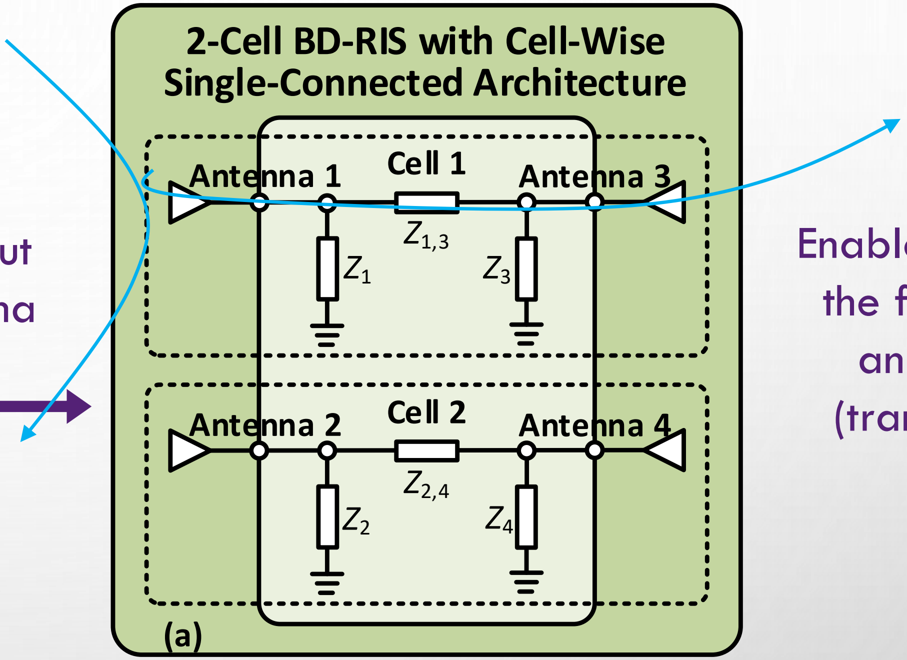
Reflective mode

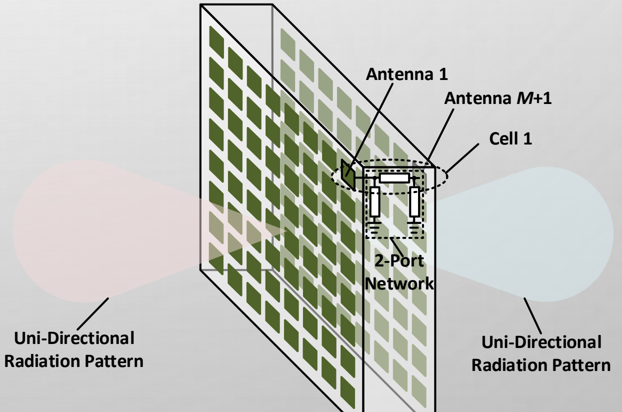




Keep circuit but change antenna orientation

Hybrid transmitting and reflecting mode

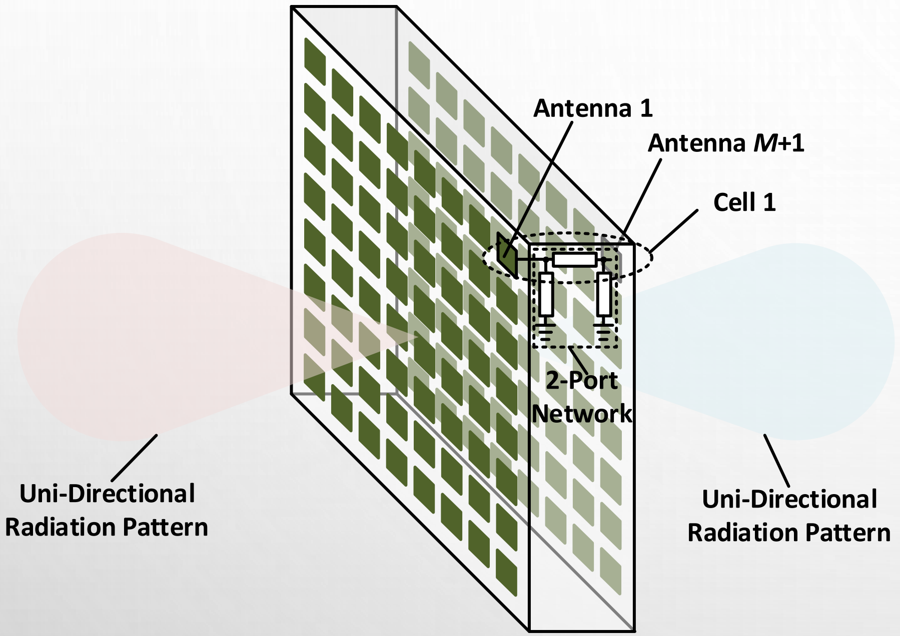


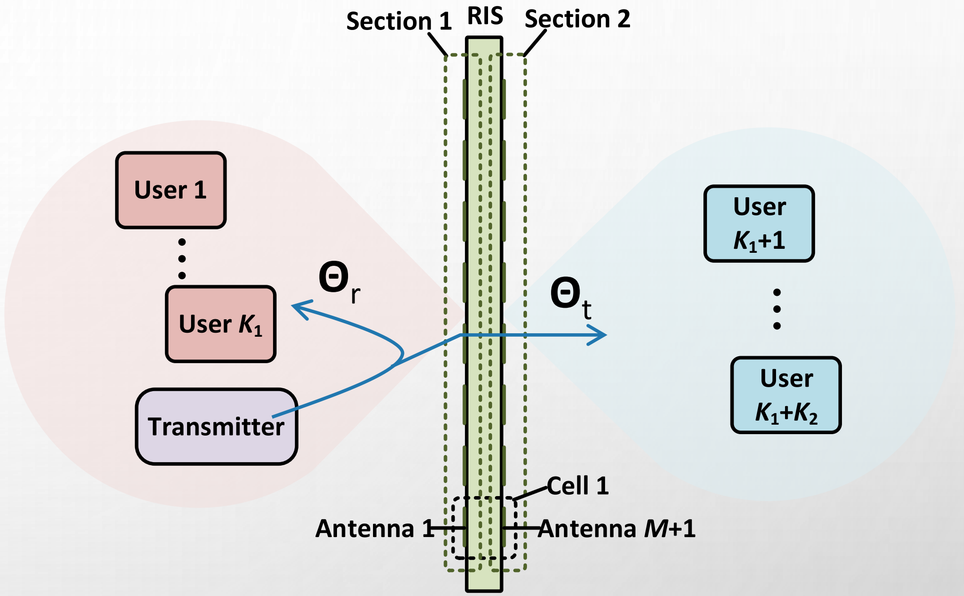


Enable coverage at the front (reflect) and the back (transmit) of RIS

H. Li, S. Shen, and B. Clerckx, “Beyond Diagonal Reconfigurable Intelligent Surface: From Transmitting and Reflecting Modes to Single-, Group-, and Fully-Connected Architectures,” IEEE Trans. Wireless Commun., vol. 22, no. 4, pp. 2311-2324, Apr. 2023.

Hybrid BD-RIS





An *M*-cell RIS, modelled as **2*M* antennas connected to a 2*M*-port reconfigurable impedance network**

$$\boxed{\boldsymbol{\Theta}^H \boldsymbol{\Theta} = \mathbf{I}_{2M}} \longrightarrow \boxed{\boldsymbol{\Theta}_r^H \boldsymbol{\Theta}_r + \boldsymbol{\Theta}_t^H \boldsymbol{\Theta}_t = \mathbf{I}_M}$$

H. Li, S. Shen, and B. Clerckx, "Beyond Diagonal Reconfigurable Intelligent Surface: From Transmitting and Reflecting Modes to Single-, Group-, and Fully-Connected Architectures," IEEE Trans. Wireless Commun., vol. 22, no. 4, pp. 2311-2324, Apr. 2023.

Hybrid BD-RIS Architectures

Single-Connected Architecture:

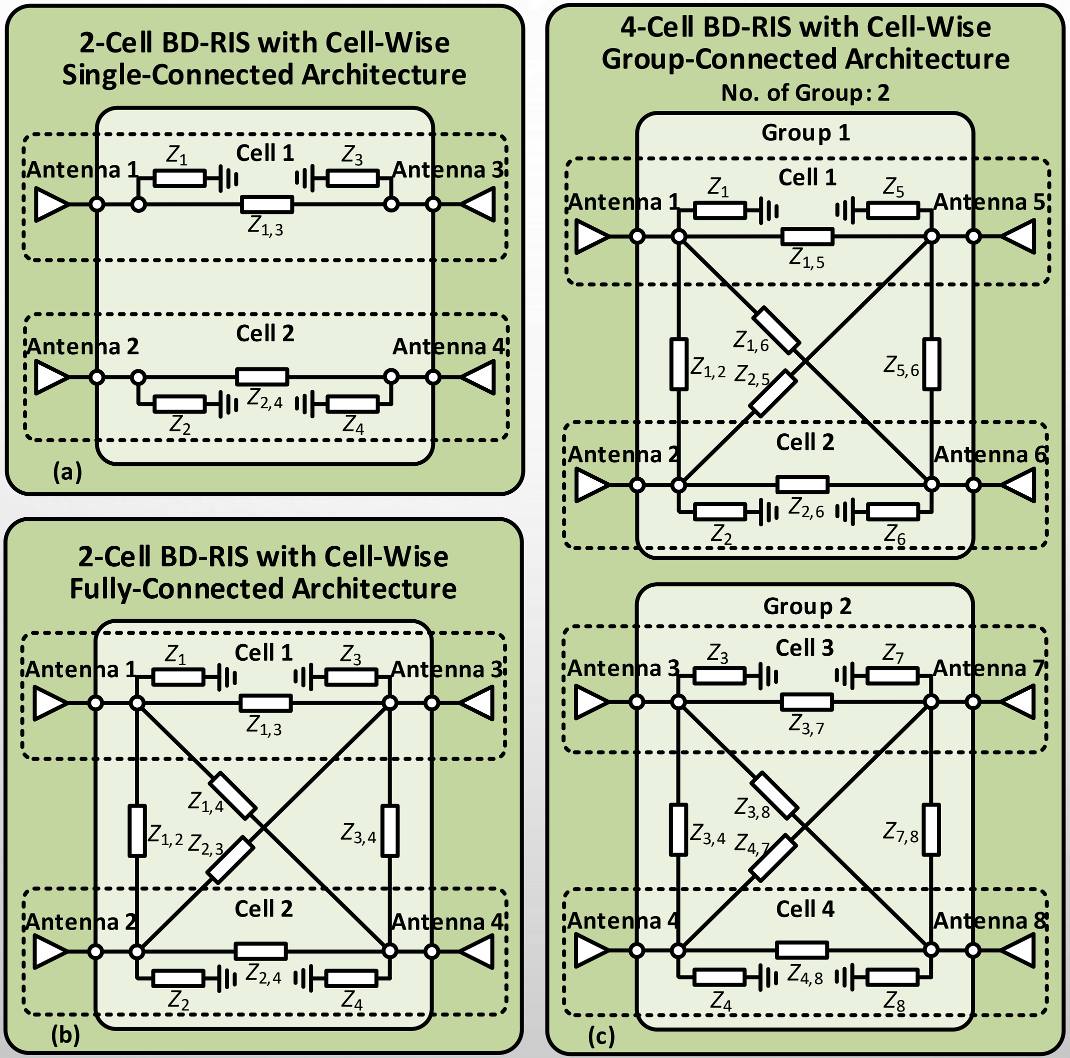
- RIS cells are not connected to each other
- Constraint:

$\boldsymbol{\Theta}_\mathrm{r} = \mathrm{diag}(\phi_{\mathrm{r},1},\dots,\phi_{\mathrm{r},M})$
$\boldsymbol{\Theta}_\mathrm{t} = \mathrm{diag}(\phi_{\mathrm{t},1},\dots,\ \phi_{\mathrm{t},M})$
$|\phi_{\mathrm{r},m}|^2 + |\phi_{\mathrm{r},m}|^2 = 1$, for all m

Fully-Connected Architecture:

- All cells are connected to each other
- Constraint:

$$\boldsymbol{\Theta}_\mathrm{r}^H\boldsymbol{\Theta}_\mathrm{r} + \boldsymbol{\Theta}_\mathrm{t}^H\boldsymbol{\Theta}_\mathrm{t} = \mathbf{I}_M$$



Group-Connected Architecture:

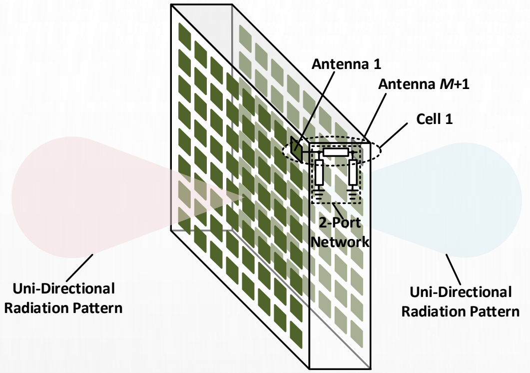
- M cells divided into G groups
- Each group utilize fully-connected architecture
- Constraint:

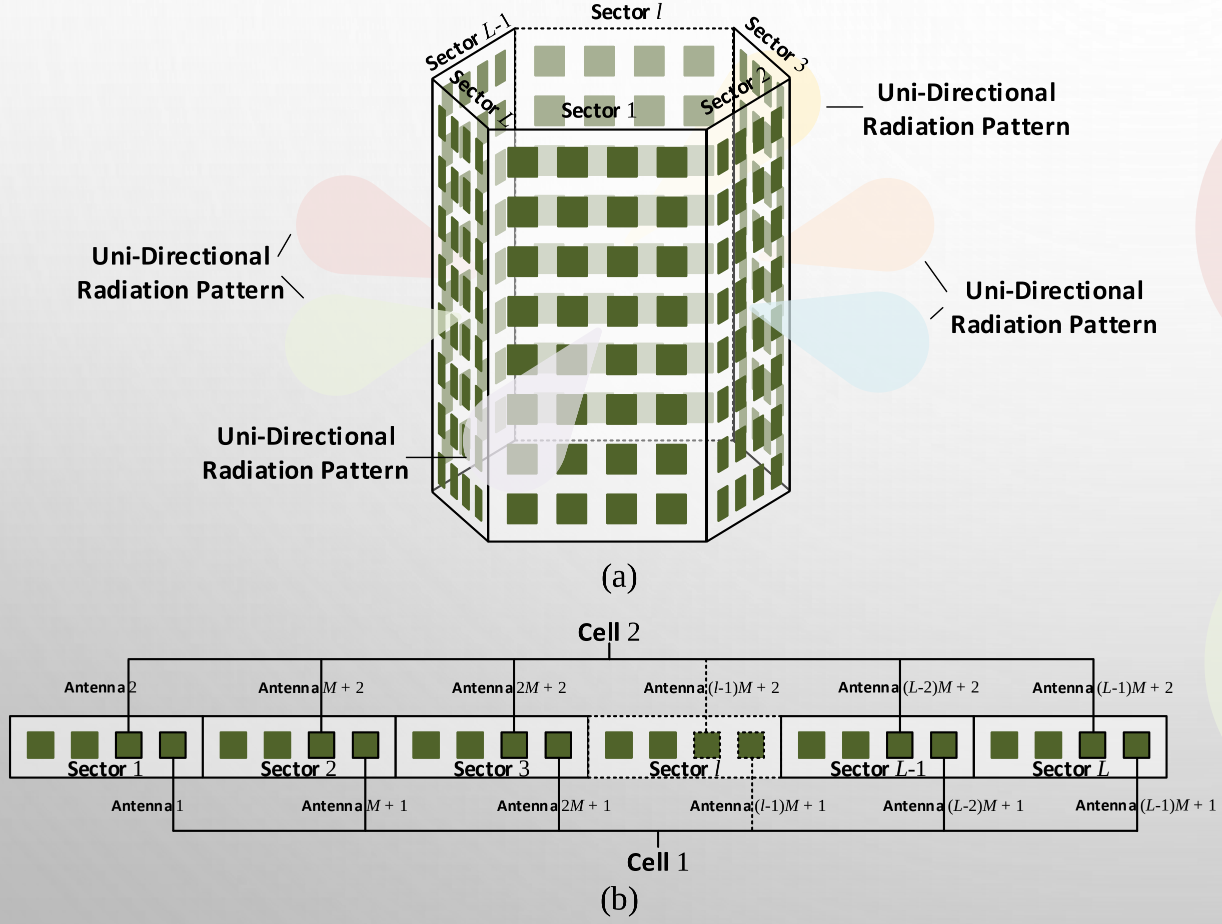
$\boldsymbol{\Theta}_\mathrm{r} = \mathrm{blkdiag}(\boldsymbol{\Theta}_{\mathrm{r},1},\dots,\ \boldsymbol{\Theta}_{\mathrm{r},G})$
$\boldsymbol{\Theta}_\mathrm{t} = \mathrm{blkdiag}(\boldsymbol{\Theta}_{\mathrm{t},1},\dots,\ \boldsymbol{\Theta}_{\mathrm{t},G})$
$\boldsymbol{\Theta}_{\mathrm{r},g}^H\boldsymbol{\Theta}_{\mathrm{r},g} + \boldsymbol{\Theta}_{\mathrm{t},g}^H\boldsymbol{\Theta}_{\mathrm{t},g} = \mathbf{I}_{M'}$
for all g

BD-RIS Benefit 3: Enable efficient and flexible hybrid (transmit and reflective) mode

H. Li, S. Shen, and B. Clerckx, "Beyond Diagonal Reconfigurable Intelligent Surface: From Transmitting and Reflecting Modes to Single-, Group-, and Fully-Connected Architectures," IEEE Trans. Wireless Commun., vol. 22, no. 4, pp. 2311-2324, Apr. 2023.

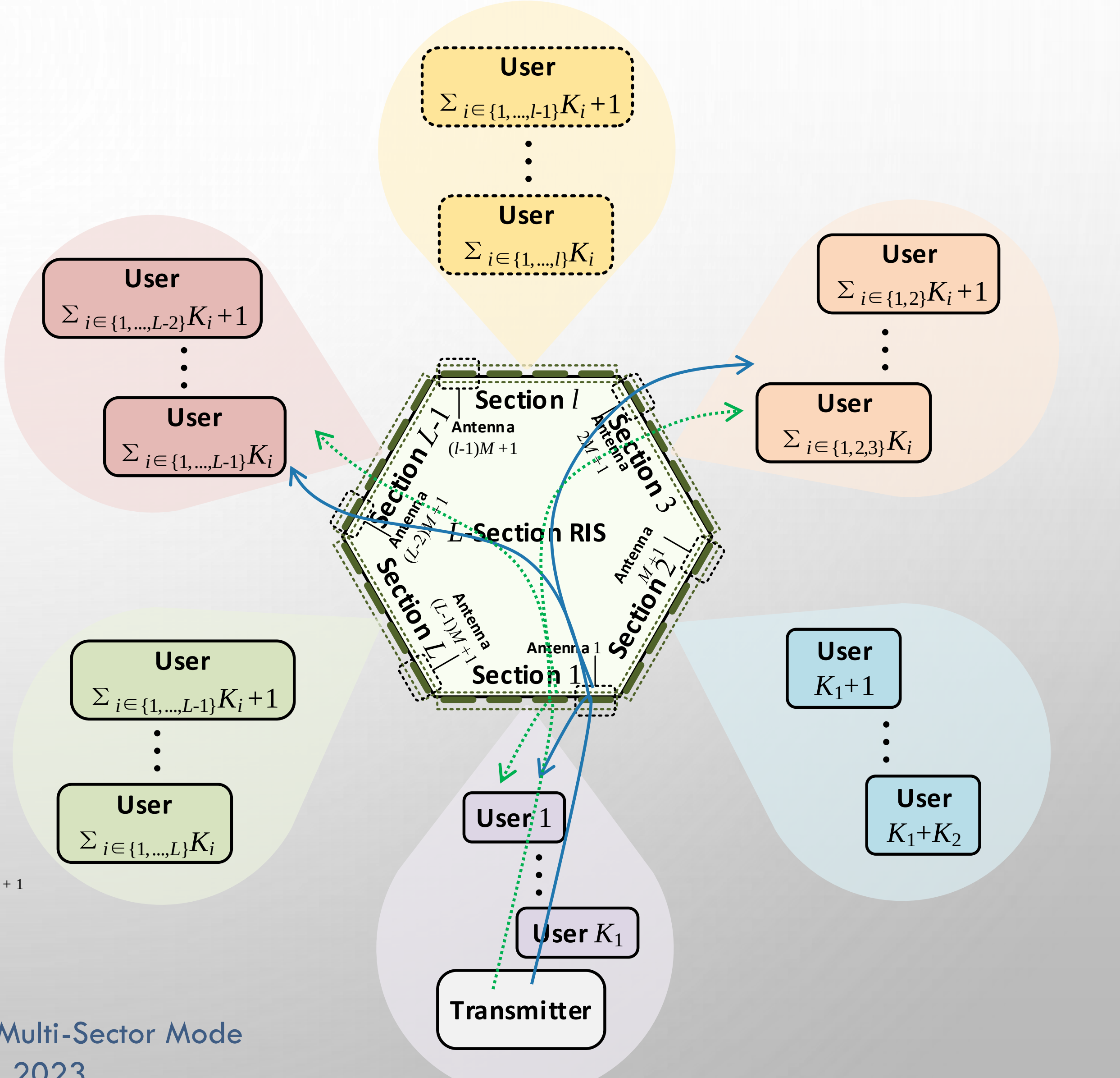
Multi-Sector BD-RIS





(a)

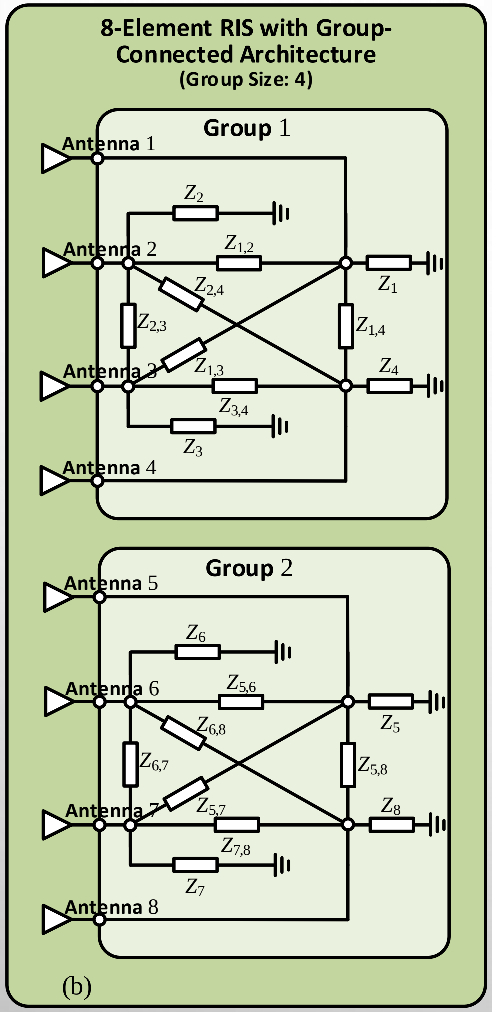
(b)



H. Li, S. Shen, and B. Clerckx, “Beyond Diagonal Reconfigurable Intelligent Surfaces: A Multi-Sector Mode Enabling Highly Directional Full-Space Wireless Coverage,” IEEE J. Sel. Areas Commun., 2023.

From Reflective to Multi-Sector BD-RIS

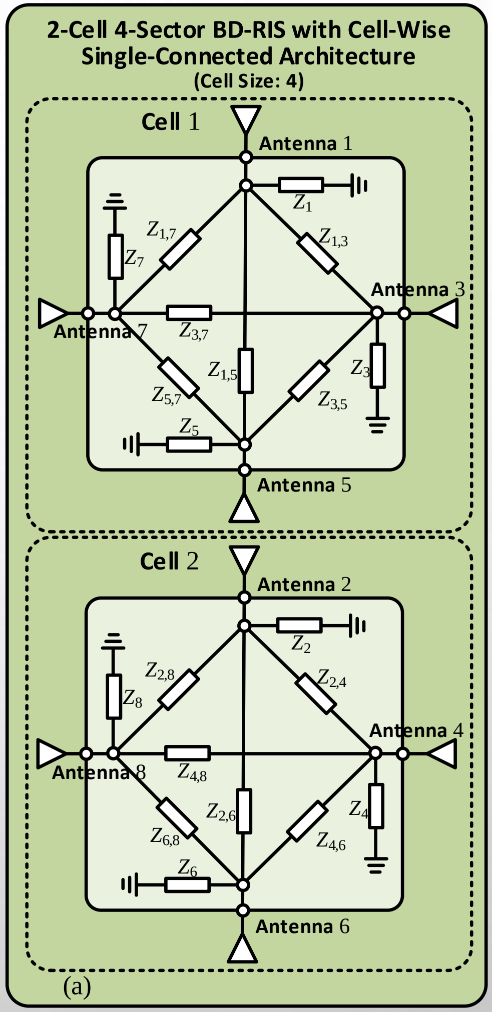
Reflective Mode



Keep circuit but change antenna orientation

Application of group-connected reconfigurable impedance network

Multi-Sector Mode



Enable highly directional full-space coverage

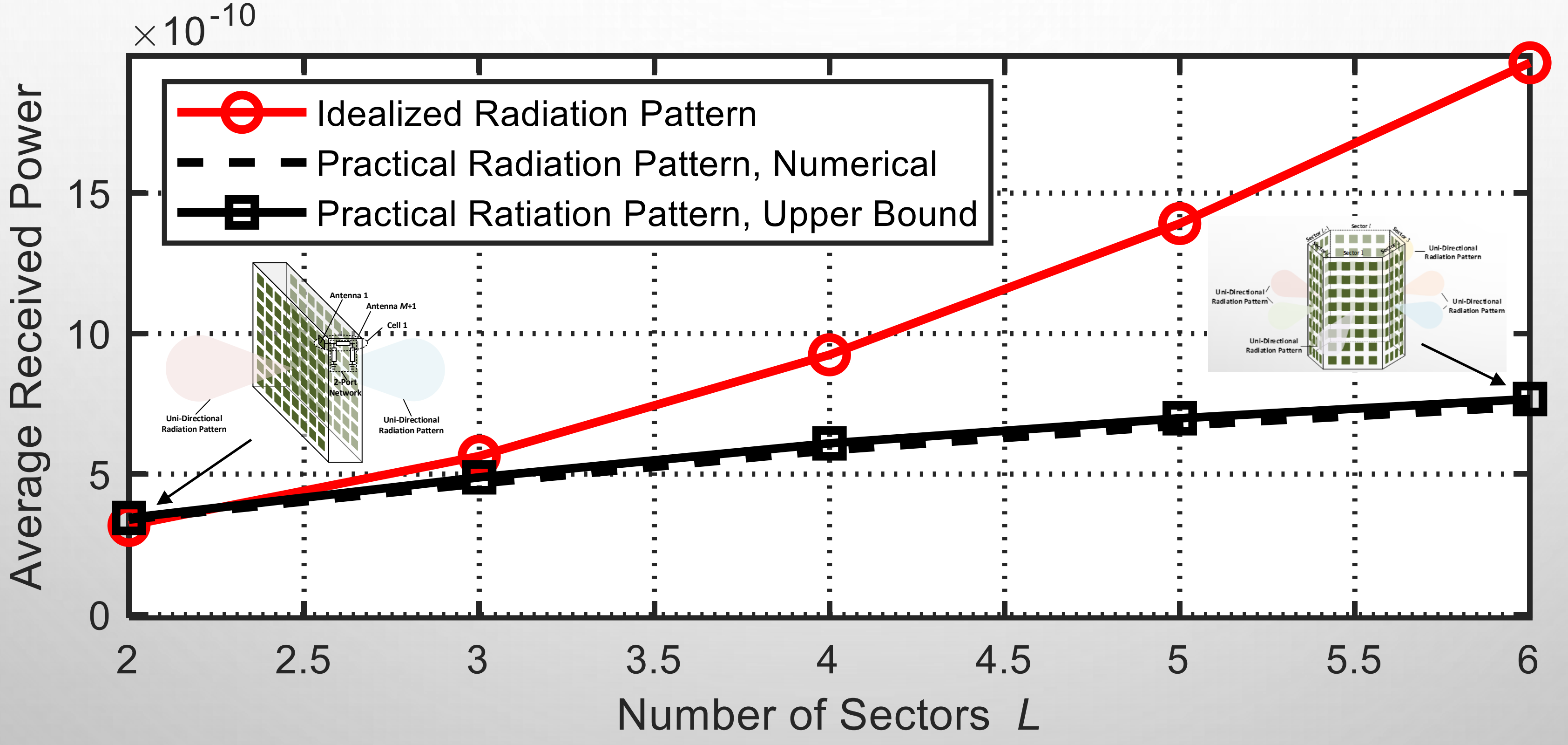
Constraint:

$$\sum_l \mathbf{\Theta}_l^H \mathbf{\Theta}_l = \mathbf{I}_M$$

H. Li, S. Shen, and B. Clerckx, "Beyond Diagonal Reconfigurable Intelligent Surfaces: A Multi-Sector Mode Enabling Highly Directional Full-Space Wireless Coverage," IEEE J. Sel. Areas Commun., 2023.

Multi-Sector BD-RIS

Average received power with practical radiation pattern



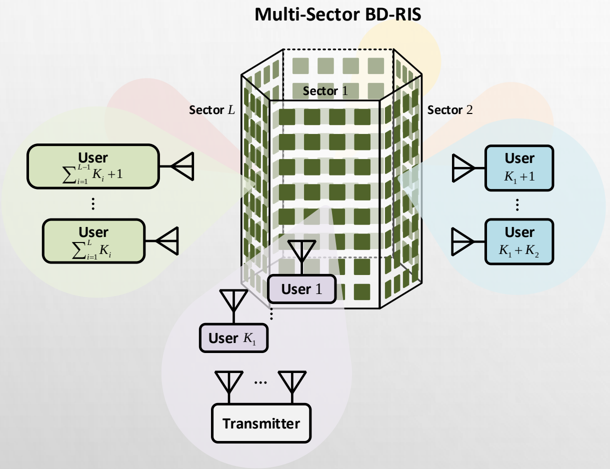
Number of antennas for whole RIS $LM = 180$

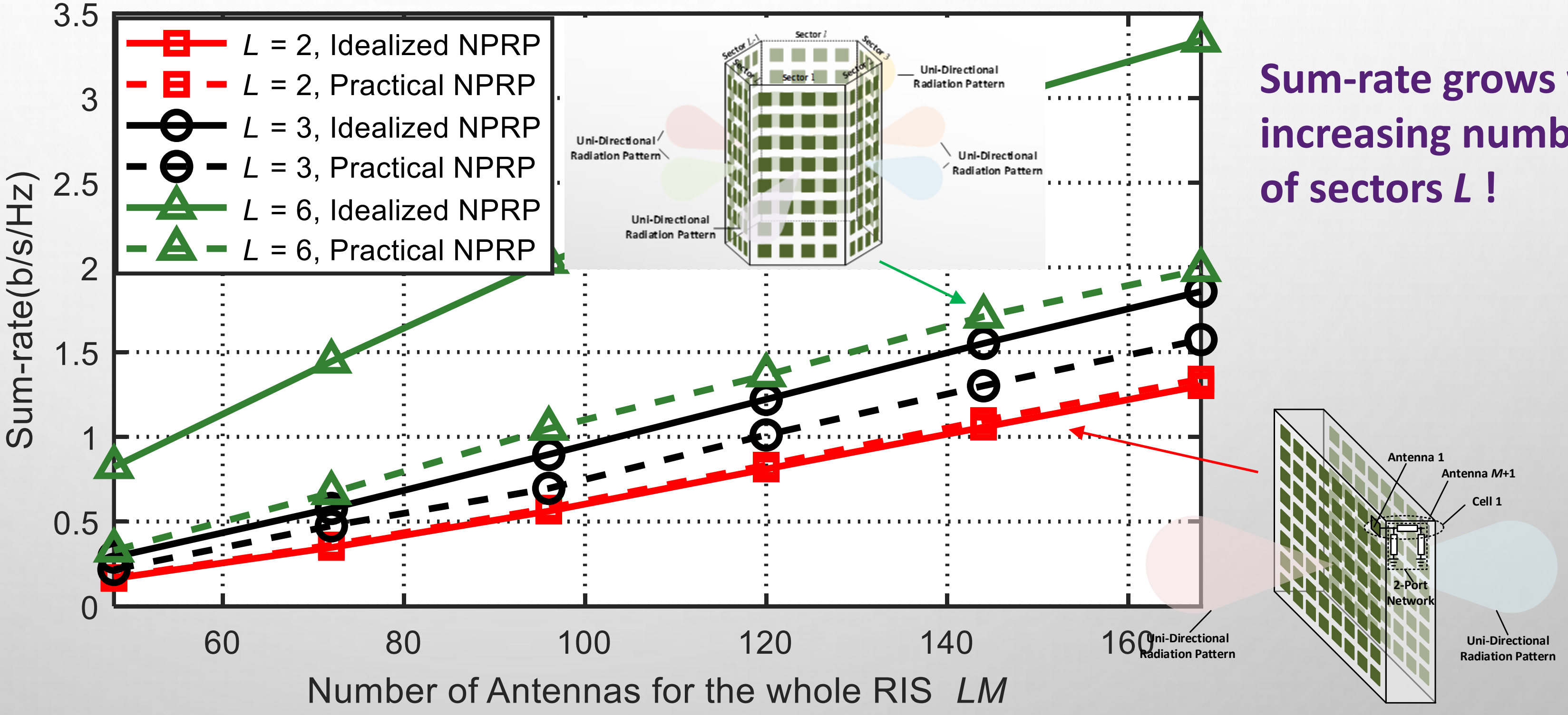
Received power grows with increasing number of sectors *L* !

H. Li, S. Shen, and B. Clerckx, “Beyond Diagonal Reconfigurable Intelligent Surfaces: A Multi-Sector Mode Enabling Highly Directional Full-Space Wireless Coverage,” IEEE J. Sel. Areas Commun., 2023.

Multi-Sector BD-RIS

Sum-rate enhancement





Sum-rate grows with increasing number of sectors *L* !

BD-RIS Benefit 4: Enable Highly Directional Full-Space Coverage

H. Li, S. Shen, and B. Clerckx, “Beyond Diagonal Reconfigurable Intelligent Surfaces: A Multi-Sector Mode Enabling Highly Directional Full-Space Wireless Coverage,” IEEE J. Sel. Areas Commun., 2023.

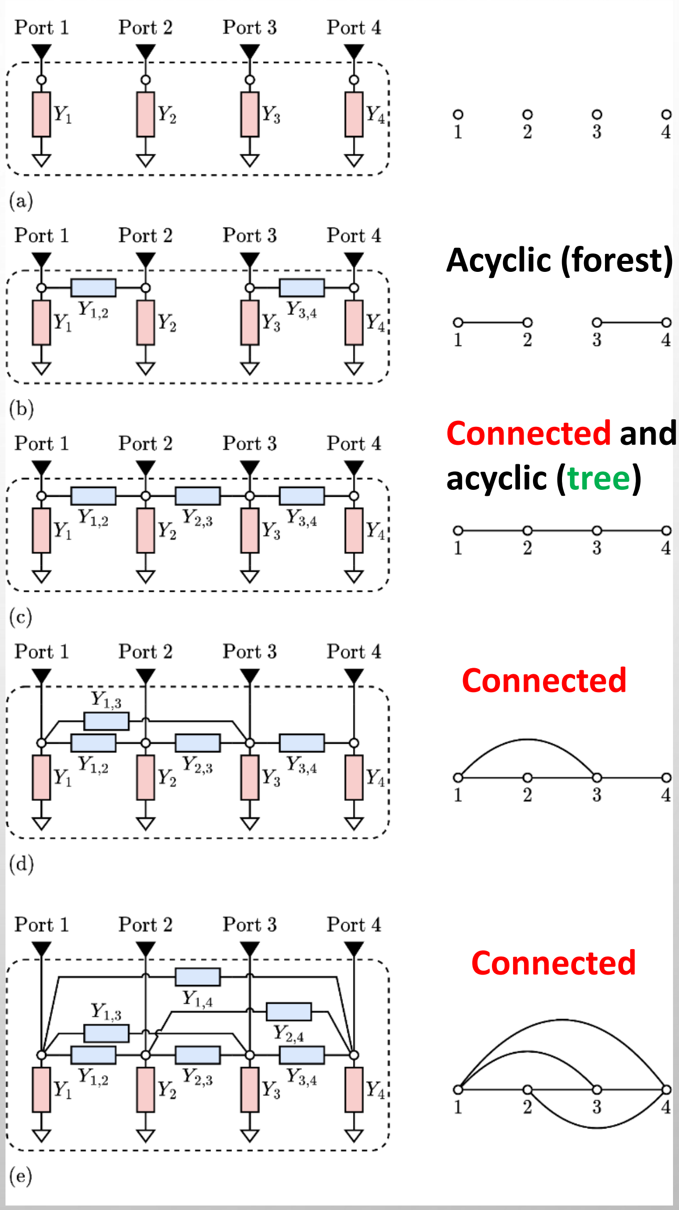
Graph Theoretical Modelling for BD-RIS

- A **BD-RIS architecture** is represented by a **graph**
  - Vertices: RIS elements
  - Edges: interconnections between RIS elements
  - Edge between vertices m and n ⇔ reconfigurable impedance between ports m and n

Which are the best architectures?

Proposition 1. A BD-RIS achieves performance of fully connected ⇔ its associated graph is **connected**.
Proposition 2. The minimum number of interconnections to achieve Prop. 1 is when its associated graph is a **tree**.

M. Nerini, S. Shen, H. Li, and B. Clerckx, "Beyond Diagonal Reconfigurable Intelligent Surfaces Utilizing Graph Theory: Modeling, Architecture Design, and Optimization", arXiv preprint arXiv:2305.05013, 2023.



Acyclic (forest)

Connected and acyclic (tree)

Connected

Connected

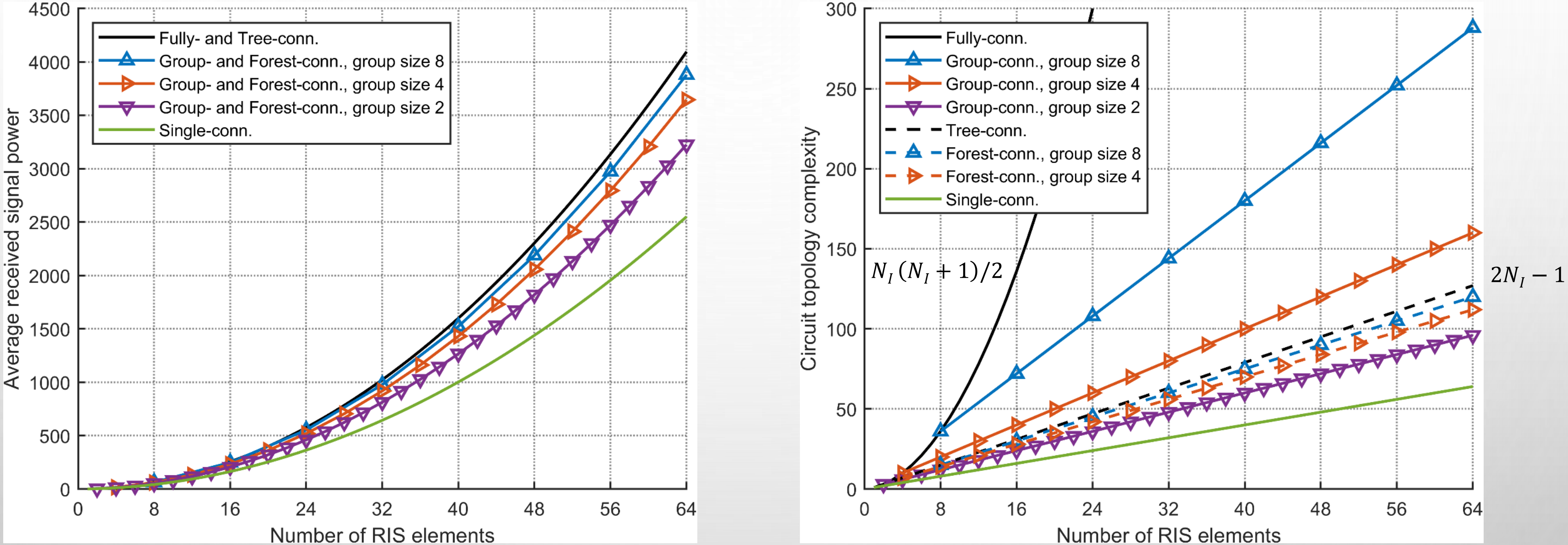
Single-connected RIS
Empty graph

Low performance
Low complexity

High performance
High complexity

Fully-connected RIS
Complete graph

Performance and Complexity Gain



Tree-connected performs as **fully-connected**, but with lower complexity: $2N_I - 1$ vs $N_I(N_I+1)/2$

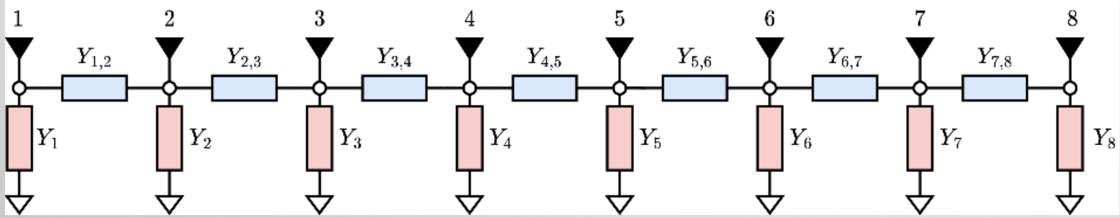
M. Nerini, S. Shen, H. Li, and B. Clerckx, “Beyond Diagonal Reconfigurable Intelligent Surfaces Utilizing Graph Theory: Modeling, Architecture Design, and Optimization”, arXiv preprint arXiv:2305.05013, 2023.

Tree-Connected BD-RIS

$$\boldsymbol{Y}_{\mathrm{I}} = j\boldsymbol{B}$$

Tridiagonal BD-RIS

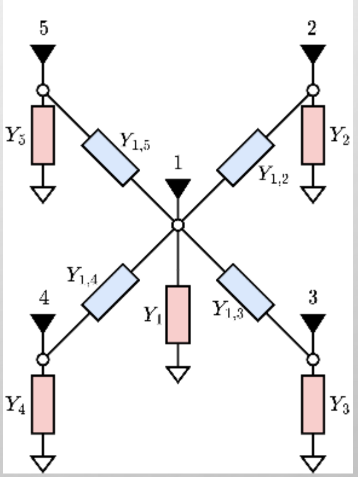
$$\mathbf{B} = \begin{bmatrix} [\mathbf{B}]_{1,1} & [\mathbf{B}]_{1,2} & \cdots & 0 \\ [\mathbf{B}]_{1,2} & [\mathbf{B}]_{2,2} & \ddots & \vdots \\ \vdots & \ddots & \ddots & [\mathbf{B}]_{N-1,N} \\ 0 & \cdots & [\mathbf{B}]_{N-1,N} & [\mathbf{B}]_{N,N} \end{bmatrix}$$



Path graph, with $N_I = 8$

Arrowhead BD-RIS

$$\mathbf{B} = \begin{bmatrix} [\mathbf{B}]_{1,1} & [\mathbf{B}]_{1,2} & \cdots & [\mathbf{B}]_{1,N} \\ [\mathbf{B}]_{1,2} & [\mathbf{B}]_{2,2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ [\mathbf{B}]_{1,N} & 0 & \cdots & [\mathbf{B}]_{N,N} \end{bmatrix}$$



Star graph, with $N_I = 5$

M. Nerini, S. Shen, H. Li, and B. Clerckx, "Beyond Diagonal Reconfigurable Intelligent Surfaces Utilizing Graph Theory: Modeling, Architecture Design, and Optimization", arXiv preprint arXiv:2305.05013, 2023.

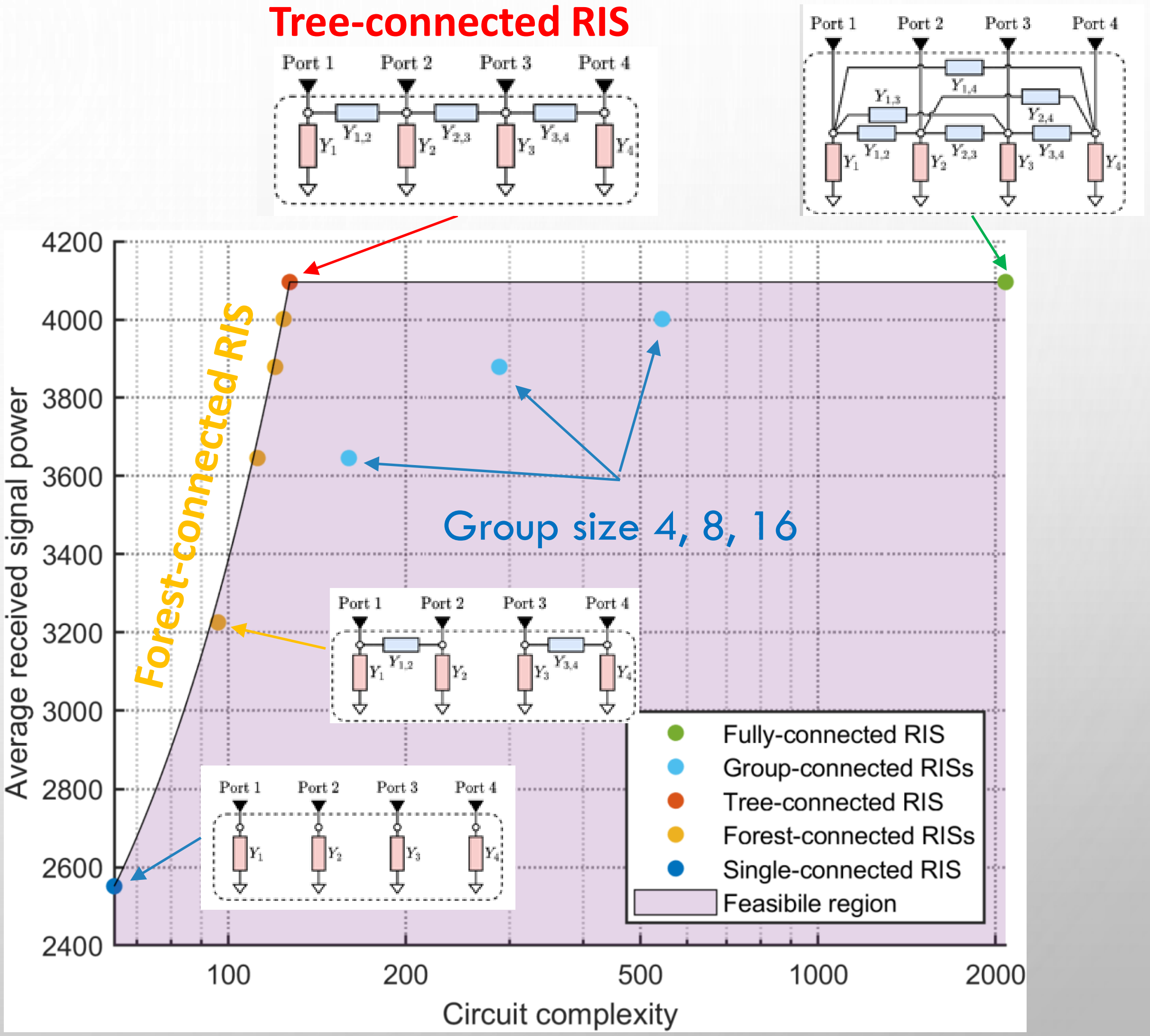
Pareto Frontier

What are the fundamental limits of the performance-complexity trade-off?

Pareto frontier of the performance-complexity trade-off with i.i.d. Rayleigh fading channels

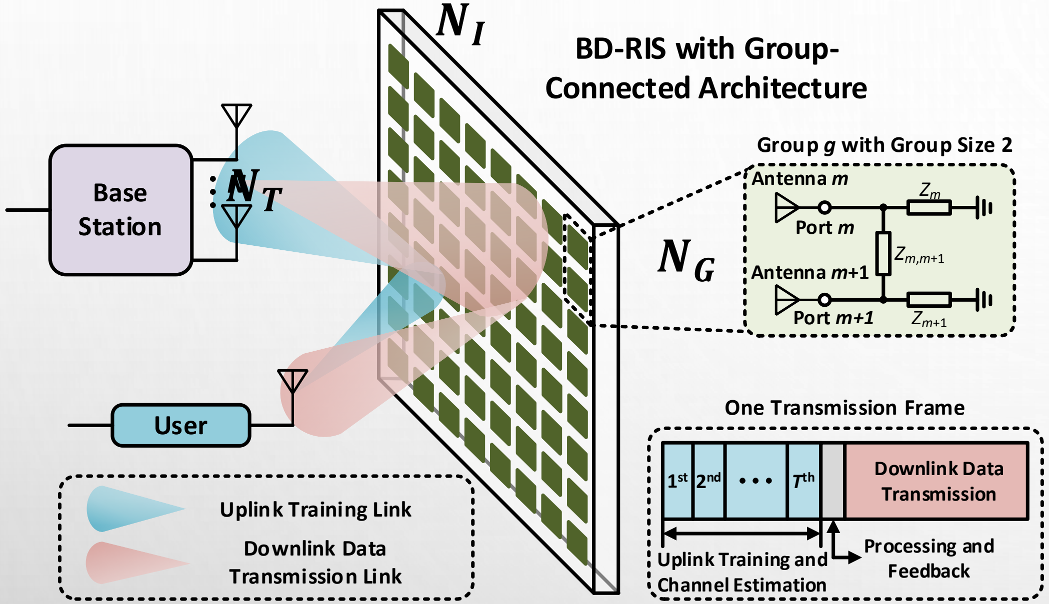
- $E[\bar{P}_R]$: Average received signal power (**performance**)
- C: Number of tunable components (**complexity**)
- N_I: Number of RIS elements (fixed to $N_I = 64$)

BD-RIS Benefit 5: Low complexity high performance architectures exist



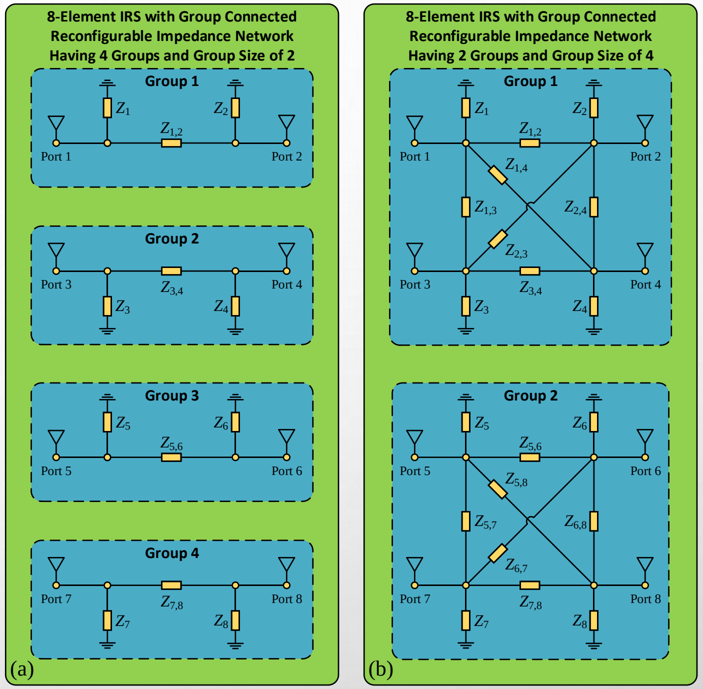
M. Nerini, and B. Clerckx, “Pareto Frontier for the Performance-Complexity Trade-off in Beyond Diagonal Reconfigurable Intelligent Surfaces”, IEEE Commun. Lett., 2023.

Channel Estimation for BD-RIS



$$\mathbf{H} = \mathbf{H}_{RT} + \mathbf{H}_{RI}\boldsymbol{\Theta}\mathbf{H}_{IT}.$$

- Purely passive channel estimation scheme to estimate cascaded user-RIS-BS channel
- Need to design new training for BD-RIS architectures capturing scattering matrix constraints and structure



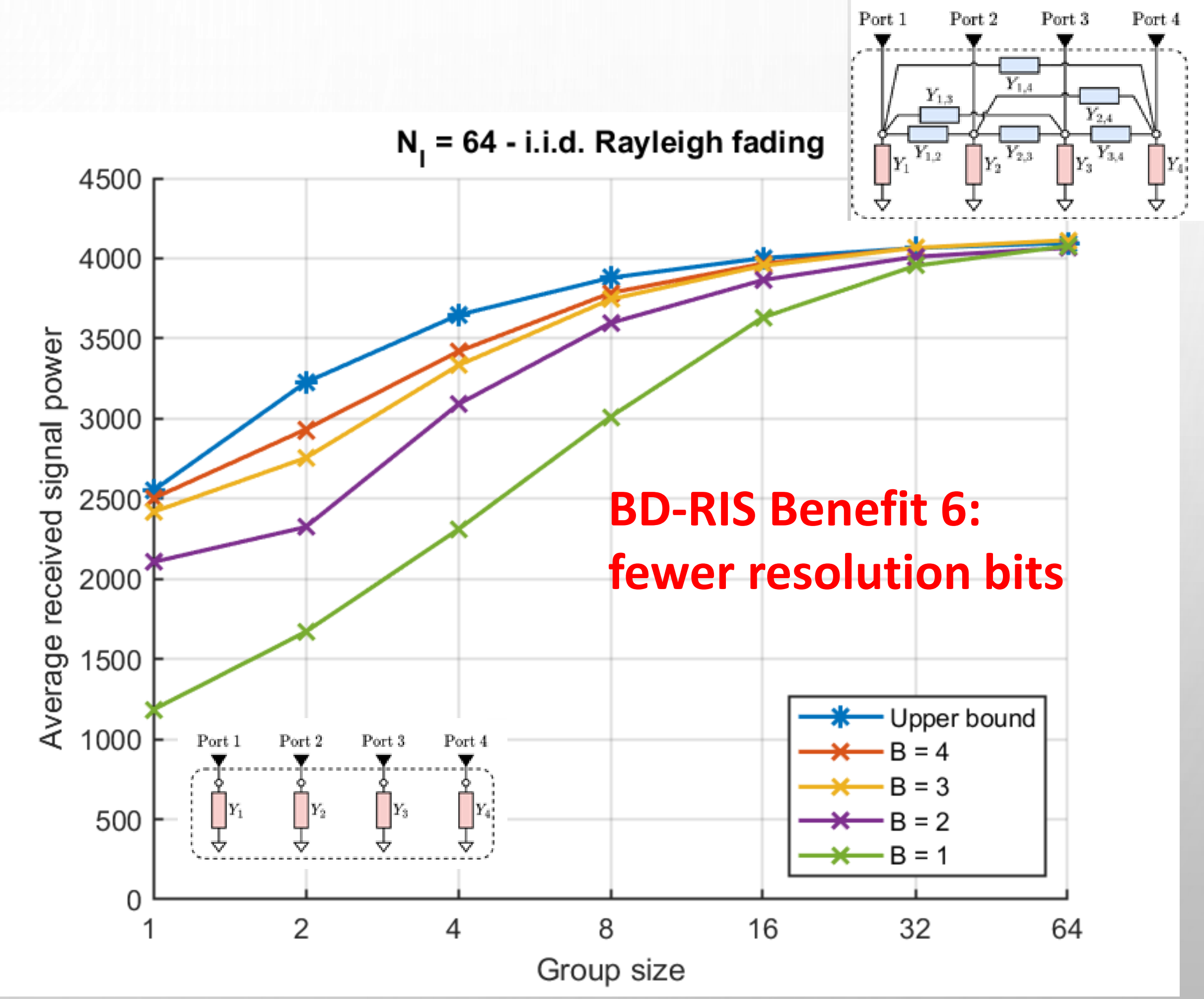
- Overhead of CE scales with group size N_G
- Higher N_G boosts received power at the cost of higher CE overhead

H. Li, Y. Zhang, and B. Clerckx, "Channel Estimation for Beyond Diagonal Reconfigurable Intelligent Surfaces with Group-Connected Architectures," arxiv:2307.06129, IEEE CAMSAP 2023.

BD-RIS with Discrete-Value Impedance Networks

- Codebook of Impedance
    - $\boldsymbol{Z}_I = j\boldsymbol{X}_I$ with $[\boldsymbol{X}_I]_{i,j} \in \mathbb{R}$ is not practical.
    - In practice $[\boldsymbol{X}_I]_{i,j} \in \{\pm X_1, \dots, \pm X_{2^B}\}$, where B is the number of resolution bits.

- Increase B achieves a higher received signal power - but more complicated hardware.
- Fewer resolution bits needed to achieve the upper bound as the group size increases.
- **1-bit resolution is sufficient** to achieve upper bound in fully connected case.



BD-RIS Benefit 6: fewer resolution bits

M. Nerini, S. Shen, and B. Clerckx, "Discrete-Value Group and Fully Connected Architectures for Beyond Diagonal Reconfigurable Intelligent Surfaces," IEEE Trans. Veh. Technol., 2023.

BD-RIS with Mutual Coupling

- Channel model with mutual coupling at the RIS (perfect matching w/o mutual coupling at Tx & Rx):
    - S-parameters: $\mathbf{H} = \mathbf{S}_{RT} + \mathbf{S}_{RI} \left(\mathbf{I} - \mathbf{\Theta}\mathbf{S}_{II}\right)^{-1} \mathbf{\Theta}\mathbf{S}_{IT}$
    - Z-parameters: $\mathbf{H} = \frac{1}{2Z_0} \left(\mathbf{Z}_{RT} - \mathbf{Z}_{RI} \left(\mathbf{Z}_I + \mathbf{Z}_{II}\right)^{-1} \mathbf{Z}_{IT}\right)$

Capture mismatching and mutual coupling

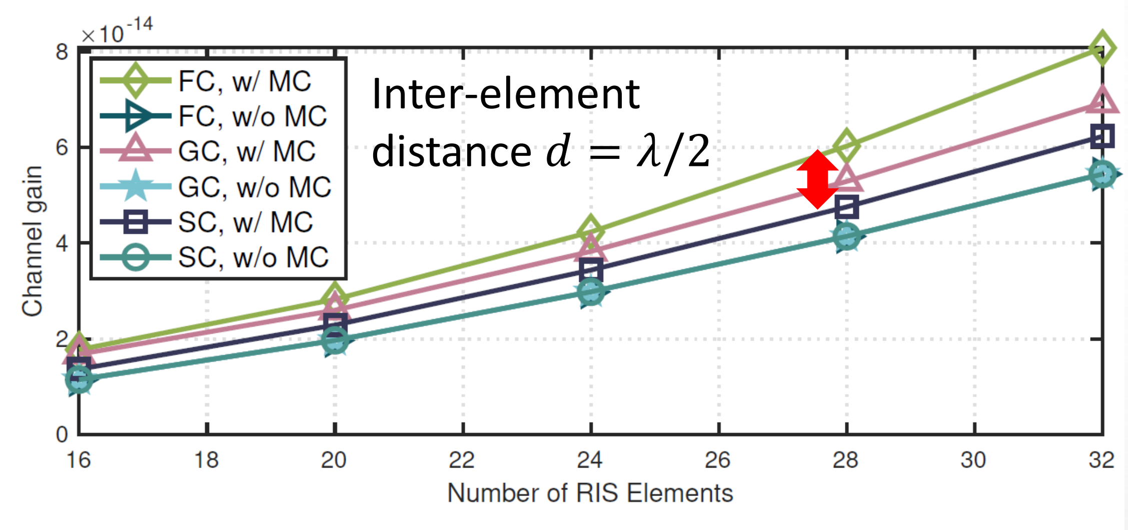
- Considering the Z-parameters, the channel gain maximization problems writes as

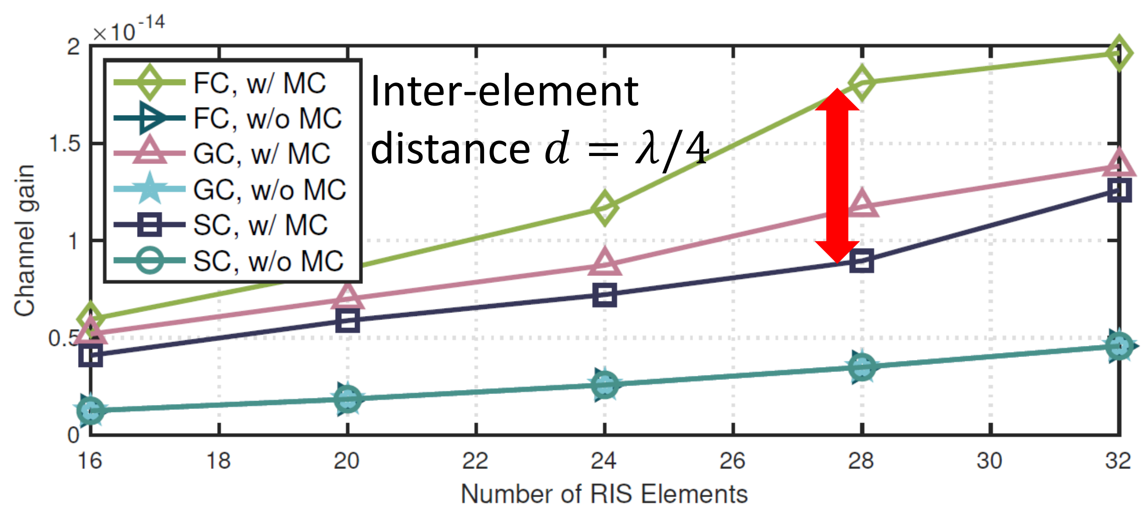
$$
\begin{aligned}
\max_{\mathbf{Z}_I} \quad & \left| z_{RT} - \mathbf{z}_{RI} \left(\mathbf{Z}_I + \mathbf{Z}_{II}\right)^{-1} \mathbf{z}_{IT} \right|^2 \\
\text{s.t.} \quad & \mathbf{Z}_I = \mathrm{diag}\left(\mathbf{Z}_{I,1}, \ldots, \mathbf{Z}_{I,G}\right), \\
& \underbrace{\mathbf{Z}_{I,g} = \mathbf{Z}_{I,g}^T}_{\text{reciprocal}}, \ \underbrace{\Re\{\mathbf{Z}_{I,g}\} = \mathbf{0}}_{\text{lossless}}, \ \forall g
\end{aligned}
$$

- $\boldsymbol{Z}_I$ can be iteratively updated by simplifying the objective until convergence.

H. Li, S. Shen, M. Nerini, M. Di Renzo, and B. Clerckx, "Beyond Diagonal Reconfigurable Intelligent Surfaces with Mutual Coupling: Modeling and Optimization", arXiv:2310.02708, 2023.

BD-RIS with Mutual Coupling





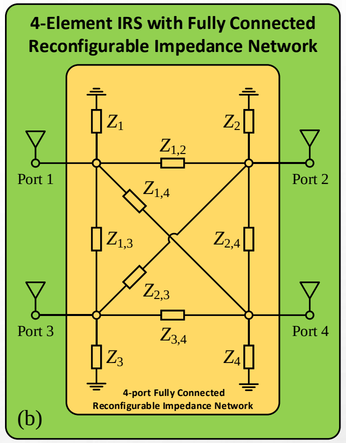
- Performance gain w/ mutual coupling even in far-field LoS.
- Performance gap between fully/group-connected BD-RIS and conventional RIS increases when decreasing the inter-element distance.
  - Mutual coupling results in larger values for off-diagonal entries of $\boldsymbol{Z}_{II}$

BD-RIS Benefit 7: Suitable for compact deployment with small inter-element spacing

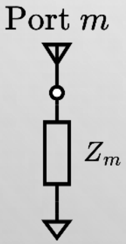
H. Li, S. Shen, M. Nerini, M. Di Renzo, and B. Clerckx, "Beyond Diagonal Reconfigurable Intelligent Surfaces with Mutual Coupling: Modeling and Optimization", arXiv:2310.02708, 2023.

BD-RIS with Lossy Interconnections

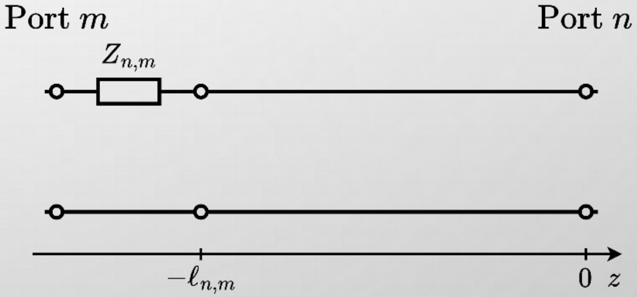
- The length of the interconnections in BD-RIS can be a considerable fraction of the wavelength, or many wavelengths



- To account for these effects, BD-RIS interconnections can be modelled as transmission lines



Port m connected to ground with Z_m

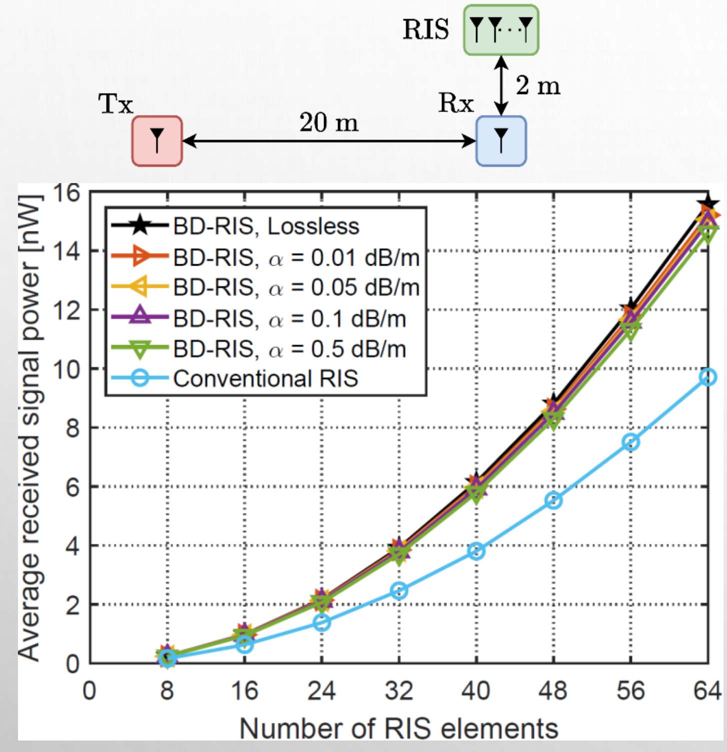


Ports m and n interconnected with $Z_{n,m}$ in series to a transmission line with length $\ell_{n,m}$ and propagation constant $\gamma = \alpha + j\beta$

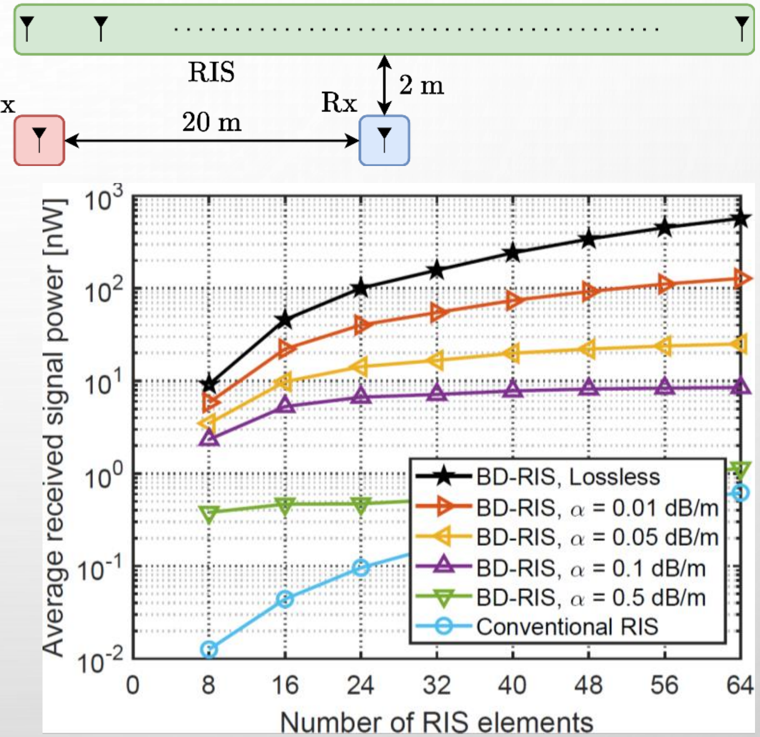
M. Nerini, G. Ghiaasi, and B. Clerckx, “Localized and Distributed Beyond Diagonal Reconfigurable Intelligent Surfaces with Lossy Interconnections: Modeling and Optimization”, arXiv:2402.05881.

BD-RIS with Lossy Interconnections

Localized RIS



Distributed RIS



BD-RIS Benefit 8: Orders of magnitude gains over conventional RIS in distributed deployments

- The performance of BD-RIS is only slightly impacted by losses given the short inter-element distance.

- The performance of BD-RIS is impacted by losses.
- Gain over conventional RIS when the TX (or the RX, or both) is not in the far-field of the RIS array, even under LoS conditions
- Gain of up to 1000 X since the signal can propagate inside the BD-RIS.

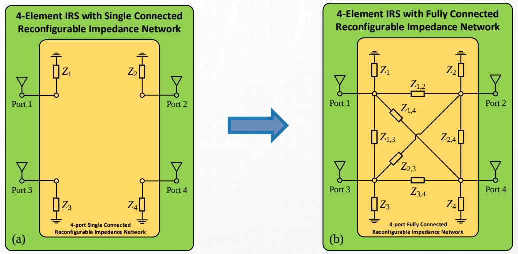
M. Nerini, G. Ghiaasi, and B. Clerckx, “Localized and Distributed Beyond Diagonal Reconfigurable Intelligent Surfaces with Lossy Interconnections: Modeling and Optimization”, arXiv:2402.05881.

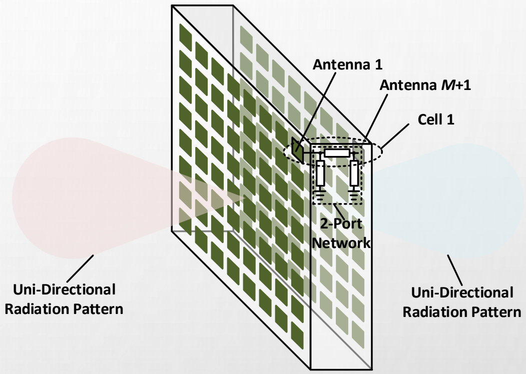
Beyond Diagonal RIS for RIS 2.0

Not restrict RIS to diagonal architectures – connect ports to each other

Why? How? When?

$$\boldsymbol{\Theta} = \begin{bmatrix} e^{j\theta_1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & e^{j\theta_N} \end{bmatrix} \Rightarrow \boldsymbol{\Theta} = \begin{bmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & ? \end{bmatrix}$$





Opens more questions than answers…so far, we see

Benefit 1: Adjust phases and magnitudes of the impinging waves

Benefit 2: Boost received power and sum-rate

gains higher in more iid-like deployments or when not in far-field

Benefit 3: Enable efficient and flexible hybrid mode

Benefit 4: Enable Full-Space (multi-sector) Coverage

Benefit 5: We do not need all connections, e.g. tree

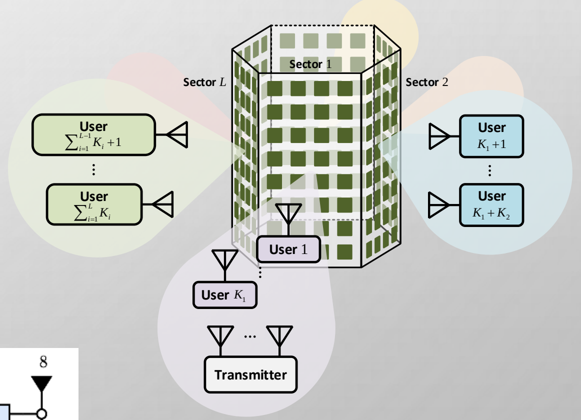
Benefit 6: Fewer resolution bits

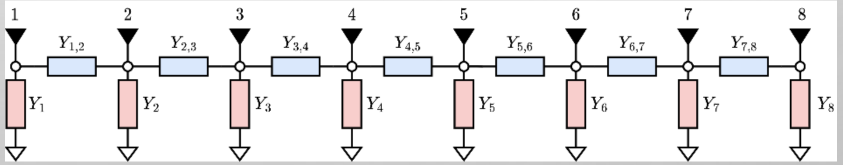
Benefit 7: Compact deployment with small inter-element spacing

Challenge 1: Careful about losses - gains in distributed lossy deployments

Challenge 2: CE overhead and accuracy

Multi-Sector BD-RIS





H. Li, S. Shen, M. Nerini, and B. Clerckx, “Reconfigurable Intelligent Surfaces 2.0: Beyond Diagonal Phase Shift Matrices,” IEEE Commun. Mag., 2023.

Future Works on BD-RIS

- Modeling of BD-RIS:
  - Wideband, mutual coupling, impedance mismatch, lossy impedance, RF impairments (non-linearity), quantized impedance, near-field propagation, active vs passive
- BD-RIS Design, Optimization, Signal Processing:
  - Learning optimal RIS architecture, fundamental tradeoff performance-complexity, channel estimation, BD-RIS optimization
- Wireless use cases:
  - How to exploit BD-RIS wave manipulation flexibility for communications, sensing, localization, power, security, channel attacks
  - Best use cases and deployments
- Prototyping/Experimentation

IEEE ComSoc Special Interest Group

IEEE ComSoc RCC Special Interest Group (SIG) on

Beyond Diagonal

Reconfigurable Intelligent Surface (BD-RIS)

Imperial College London

IEEE ComSoc IEEE Communications Society RCC SIG on BD-RIS

BD-RIS Webinar Series 2024

Jan 2024 - Apr 2024

Free and Open to the Public

Prof. Marco Di Renzo CentraleSupélec	Jan 10 12:00 pm UTC
Prof. Eduard A. Jorswieck Technical University of Braunschweig	Jan 24 12:00 pm UTC
Dr. Yijie (Lina) Mao ShanghaiTech University	Feb 07 12:00 pm UTC
Prof. Ross Murch The Hong Kong University of Science and Technology	Feb 21 12:00 pm UTC
Dr. Arman Shojaeifard InterDigital	Mar 06 12:00 pm UTC
Dr. Shanpu Shen University of Liverpool	Mar 20 12:00 pm UTC
Prof. Mohammed El-Hajjar University of Southampton	Apr 10 12:00 pm UTC
Prof. A. Lee Swindlehurst University of California, Irvine	Apr 24 4:00 pm UTC

Link & More Info.

Zoom Link: Here
Zoom Meeting ID: 922 7298 6094
Passcode: b$4iZc

For more information, visit: https://sites.google.com/view/ieee-comsoc-rcc-sig-bdris

Time & Duration

Please check the BD-RIS webinar series webpage for information on the scheduled time of the talks.

50 minutes per talk
10 minutes Q&A

Organizers

Prof. Bruno Clerckx
Imperial College London

Matteo Nerini
Imperial College London

Thank you for listening!

More information in https://youtu.be/x3VMQ-ZU0ek

H. Li, S. Shen, M. Nerini, and B. Clerckx, “Reconfigurable Intelligent Surfaces 2.0: Beyond Diagonal Phase Shift Matrices,” IEEE Commun. Mag., 2023.

S. Shen, B. Clerckx, and R. Murch, “Modeling and Architecture Design of Reconfigurable Intelligent Surfaces using Scattering Parameter Network Analysis,” IEEE Trans. Wireless Commun., 2022.

H. Li, S. Shen, and B. Clerckx, “Beyond Diagonal Reconfigurable Intelligent Surfaces: From Transmitting and Reflecting Modes to Single-, Group-, and Fully-Connected Architectures,” IEEE Trans. Wireless Commun., 2023.

H. Li, S. Shen, and B. Clerckx, “Beyond Diagonal Reconfigurable Intelligent Surfaces: A Multi-Sector Mode Enabling Highly Directional Full-Space Wireless Coverage,” IEEE J. Sel. Areas Commun., 2023.

H. Li, S. Shen, and B. Clerckx “A Dynamic Grouping Strategy for Beyond Diagonal Reconfigurable Intelligent Surfaces with Hybrid Transmitting and Reflecting Mode,” IEEE Trans. Veh. Technol., 2023.

H. Li, S. Shen, and B. Clerckx, “Synergizing Beyond Diagonal Reconfigurable Intelligent Surface and Rate-Splitting Multiple Access,” submitted to IEEE Trans. Wireless Commun., arXiv:2303.06912, 2023.

M. Nerini, S. Shen, and B. Clerckx, “Discrete-Value Group and Fully Connected Architectures for Beyond Diagonal Reconfigurable Intelligent Surfaces” IEEE Trans. Veh. Technol., 2023.

M. Nerini, S. Shen and B. Clerckx, “Optimal Group and Fully Connected Design for Beyond Diagonal Reconfigurable Intelligent Surfaces,” IEEE Trans. Wireless Commun., 2023.

Q. Li, M. El-Hajjar, I. Hemadeh, A. Shojaeifard, A. Mourad, B. Clerckx, L. Hanzo, “Reconfigurable Intelligent Surfaces Relying on Non-Diagonal Phase Shift Matrices,” IEEE Trans. Veh. Technol, 2022.

M. Nerini, and B. Clerckx, “Pareto Frontier for the Performance-Complexity Trade-off in Beyond Diagonal Reconfigurable Intelligent Surfaces”, IEEE Commun. Lett., 2023.

H. Li, Y. Zhang, and B. Clerckx, “Channel Estimation for Beyond Diagonal Reconfigurable Intelligent Surfaces with Group-Connected Architectures,” arXiv:2307.06129, 2023.

M. Nerini, S. Shen, H. Li, and B. Clerckx, “Beyond Diagonal Reconfigurable Intelligent Surfaces Utilizing Graph Theory: Modeling, Architecture Design, and Optimization”, submitted to IEEE Trans Wireless Commun., arXiv:2305.05013, 2023.

H. Li, S. Shen, M. Nerini, M. Di Renzo, and B. Clerckx, “Beyond Diagonal Reconfigurable Intelligent Surfaces with Mutual Coupling: Modeling and Optimization”, submitted to IEEE Commun. Lett., arXiv:2310.02708, 2023.

M. Nerini, S. Shen, H. Li, M. Di Renzo, and B. Clerckx, “A Universal Framework for Multiport Network Analysis of Reconfigurable Intelligent Surfaces,” submitted to IEEE Trans. Wireless Commun., arXiv:2311.10561, 2023.

M. Nerini, G. Ghiaasi, and B. Clerckx, “Localized and Distributed Beyond Diagonal Reconfigurable Intelligent Surfaces with Lossy Interconnections: Modeling and Optimization”, arXiv:2402.05881.

Questions - Comments - Collaboration

Prof. Bruno Clerckx

b.clerckx@imperial.ac.uk