Reconfigurable Intelligent Surfaces: An Overview

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Outline

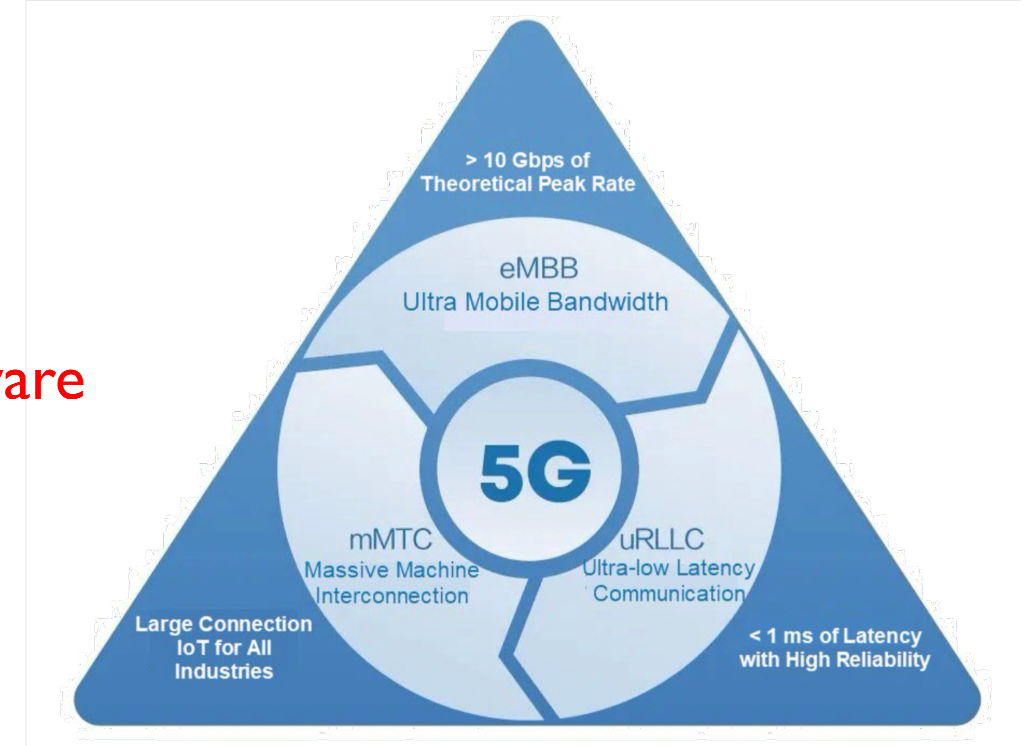
- Motivation
- Introduction to RIS
- RIS Deployment Location
- Practical RIS Modeling
- Optimizing of RIS reflection coefficients
- Conclusion

5G and Beyond

- **Enabling Technologies**
  - Massive MIMO
  - mmWave Communication

- **Current challenges regarding 5G**
  - High spatial resolution requires expensive hardware
    - High frequencies (mmWave)
    - Massive MIMO
    - Ultra-Dense Networking

Enable Internet of Everything network



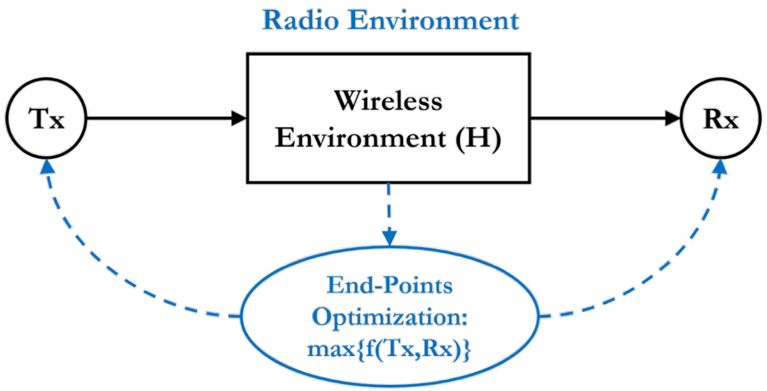
W. Saad, M. Bennis and M. Chen, "A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems," in IEEE Network, vol. 34, no. 3, pp. 134-142, May/June 2020

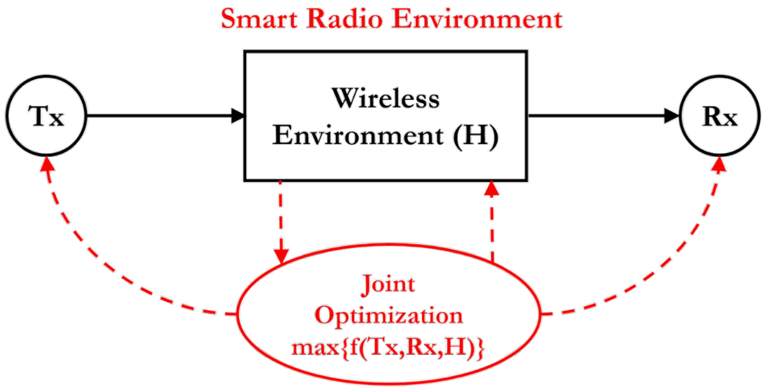
Smart Environments

- New IoE services being developed
  - Virtual reality, telemedicine, brain-computer interfaces, and connected autonomous systems, etc.

- Transforming wireless systems into a self-sufficient, software-based, smart radio environment

- Smart radio environment
  - Convert wireless channel into an optimization variable





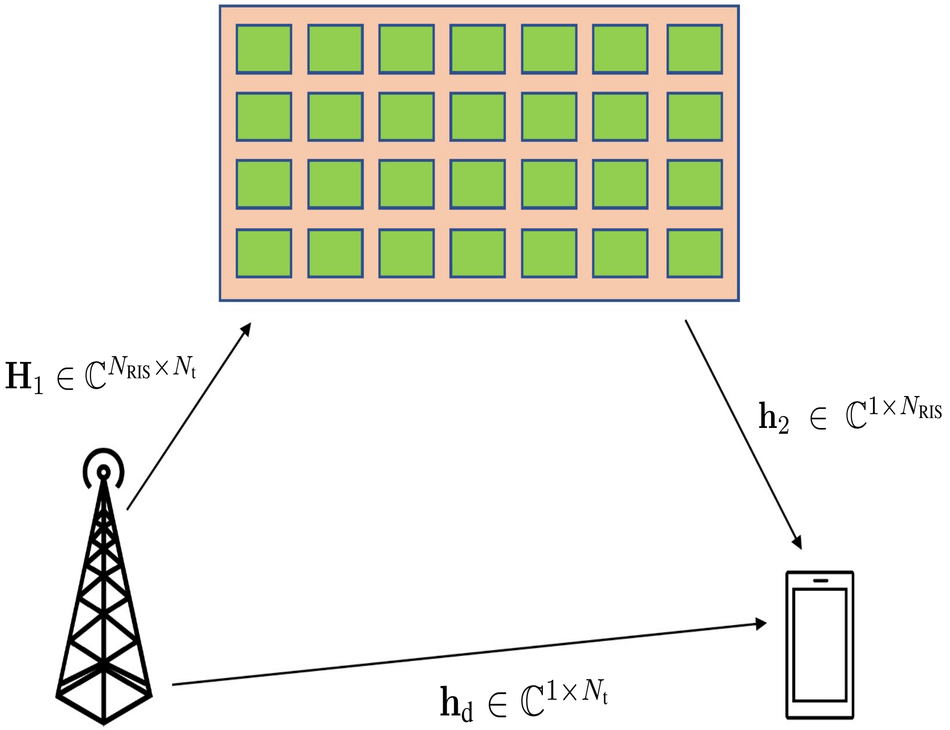
[1] M. Di Renzo et al., "Smart Radio Environments Empowered by Reconfigurable Intelligent Surfaces: How It Works, State of Research, and The Road Ahead," in IEEE Journal on Selected Areas in Communications, vol. 38, no. 11, pp. 2450-2525, Nov. 2020
[2] W. Saad, M. Bennis and M. Chen, "A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems," in IEEE Network, vol. 34, no. 3, pp. 134-142, May/June 2020

Large Arrays

Many names in literature regarding intelligent surfaces

- Active Arrays
  - Large intelligent surfaces
  - Reconfigurable reflectarrays
- Semi-passive arrays
  - Reconfigurable intelligent surfaces
  - Intelligent reflecting surfaces
  - Software-controlled metasurfaces

$$\mathbf{\Phi} = \mathrm{diag}\{e^{\mathrm{j}\phi_1}, \ldots, e^{\mathrm{j}\phi_{N_{\mathrm{RIS}}}}\}$$



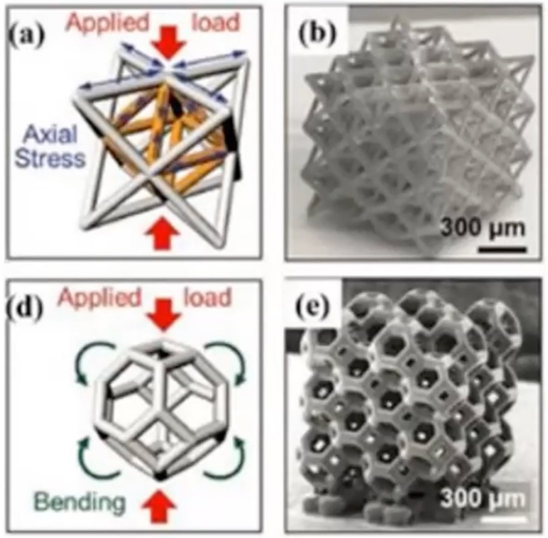
[1] E. Bjornson, Reconfigurable Intelligent Surfaces And Holographic Massive MIMO: Vision, Fundamentals, And Key Open Problems, IEEE ICC 2021 Tutorial

Metamaterials/surfaces

- Initial metamaterials
  - 3D synthetic materials engineered to achieve unique properties not found naturally
  - Double-negative material
    - $\epsilon < 0,\ \mu < 0$, ϵ permittivity μ permeability
  - Comprised of set of small scatterers in array to obtain a net behavior

- Metasurfaces
  - Metafilm or single-layer metamaterials
  - Used in place of metamaterials
    - Easier to implement
    - Occupy less space
    - Additional use cases:
      - Controllable "smart" surfaces

Metamaterial



Metasurface

C. L. Holloway, E. F. Kuester, J. A. Gordon, J. O'Hara, J. Booth and D. R. Smith, "An Overview of the Theory and Applications of Metasurfaces: The Two-Dimensional Equivalents of Metamaterials," in IEEE Antennas and Propagation Magazine, vol. 54, no. 2, pp. 10-35, April 2012, doi: 10.1109/MAP.2012.6230714.

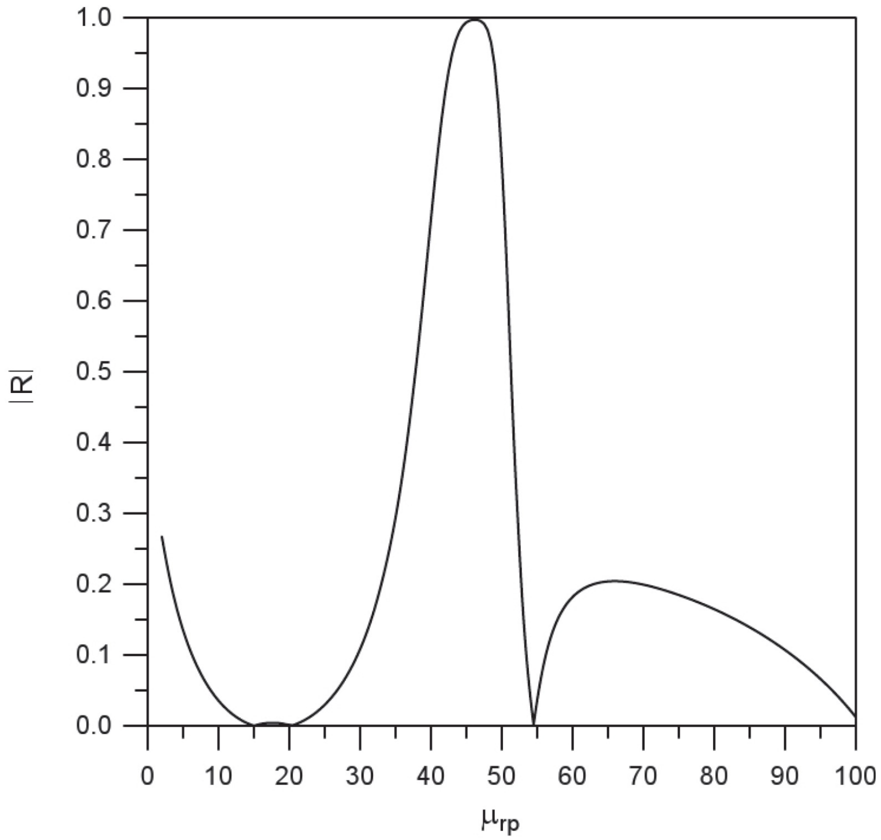
RIS: Controllable Metasurfaces

- Comprised of subwavelength cells
  - $\in [\frac{\lambda}{10}, \frac{\lambda}{2}]$ size

- RIS controller can change the electrical or magnetic properties of elements through the tunable component
  - Reducing the amplitude
  - Time delays
  - Polarization Change

- General Implementation
  - RIS Controller
  - PIN diodes
  - Varactor-diode based programmable metasurface
  - Aim: Enabling large phase shifts from each cell while minimizing amplitude shifts
    - Passive elements

Reflection coefficient of scatterers vs scatterers' permeability



[1] Reconfigurable Intelligent Surfaces: A Signal Processing Perspective With Wireless Applications

[2] C. L. Holloway, E. F. Kuester, J. A. Gordon, J. O'Hara, J. Booth and D. R. Smith, "An Overview of the Theory and Applications of Metasurfaces: The Two-Dimensional Equivalents of Metamaterials," in IEEE Antennas and Propagation Magazine, vol. 54, no. 2, pp. 10-35, April 2012, doi: 10.1109/MAP.2012.6230714.

Practical Modeling of the RIS

General Modeling

Reflection coefficient

$$\boldsymbol{\Theta} = \beta \mathrm{diag}(e^{j\varphi_1}, \cdots, e^{j\varphi_M}) \in \mathbb{C}^{M \times M}$$

Amplitude reflection coefficient

$\beta \in [0, 1]$ Prior work mostly assumes ideal RIS ($\beta = 1$)

Phase shift of m-th reflecting element

$$\varphi_m \in [0, 2\pi)$$

Practical Modeling

Reflection coefficient

$$\Gamma_{n,m} = A_{n,m} e^{j\varphi_{n,m}}$$

$$\Gamma_{n,m} = \frac{Z_{n,m} - Z_0}{Z_{n,m} + Z_0}$$

Impedance for (n,m) RIS element: $Z_{n,m}$

Source impedance: Z_0

Amplitude reflection coefficient

$$A_{n,m} = \left| \frac{Z_{n,m} - Z_0}{Z_{n,m} + Z_0} \right|$$

Phase shift of reflecting element

$$\varphi_{n,m} = \arctan \left(\frac{\mathrm{Im}\left(\frac{Z_{n,m} - Z_0}{Z_{n,m} + Z_0}\right)}{\mathrm{Re}\left(\frac{Z_{n,m} - Z_0}{Z_{n,m} + Z_0}\right)} \right)$$

[1] W. Tang et al., "MIMO Transmission Through Reconfigurable Intelligent Surface: System Design, Analysis, and Implementation," in IEEE Journal on Selected Areas in Communications, vol. 38, no. 11, pp. 2683-2699, Nov. 2020.

RIS Location/Number of Elements

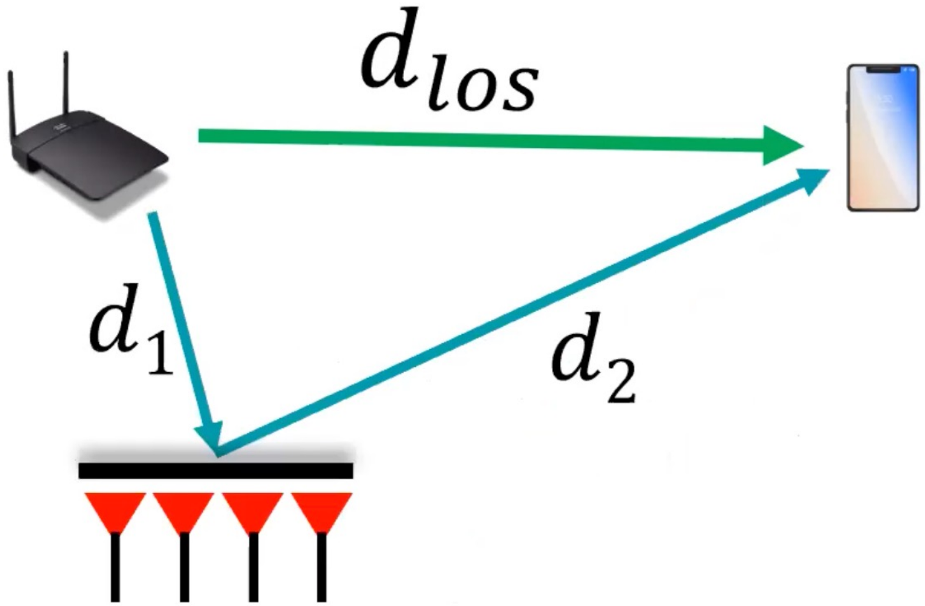
RIS should be deployed near BS based on Friis pathloss

- Pathloss on LOS path:

$$P_{los} \propto \frac{1}{(d_{los})^2}$$

- Pathloss on NLOS path

$$P_{refl} \propto \frac{1}{(d_1)^2}\frac{1}{(d_2)^2} \times N^2$$



Configure number of RIS elements to compensate for pathloss on path with RIS

Figures taken from ICC Workshop 2021 on RIS Presentation by Dinesh Bharadia

M. Dunna, C. Zhang, D. Sievenpiper, and D. Bharadia, "ScatterMIMO: Enabling Virtual MIMO with Smart Surfaces," in 2020 IEEE MobiCom, 2020, pp. 14.

MISO RIS Optimization: SDP by CVX Solver

- Evaluate transmit beamformer $\boldsymbol{w}$ using maximum ratio transmission MRT
- Assumes an IRS controller which carries out computations
  - Feedback $\boldsymbol{w}$ to BS
- Obtain higher rank solution then obtain rank-1 matrix containing optimized RIS phases
- CVX solver can be used to optimize $\boldsymbol{V}$ in the standard SDP

$$\max_{\boldsymbol{w},\boldsymbol{\theta}} \quad |(\boldsymbol{h}_r^H \Theta \boldsymbol{G} + \boldsymbol{h}_d^H)\boldsymbol{w}|^2$$
$$\text{s.t.} \quad \|\boldsymbol{w}\|^2 \leq \bar{p},$$
$$0 \leq \theta_n \leq 2\pi, \forall n = 1, \cdots, N.$$

Standard SDP

$$\max_{\boldsymbol{V}} \quad \text{tr}(\boldsymbol{R}\boldsymbol{V})$$
$$\text{s.t.} \quad \boldsymbol{V}_{n,n} = 1, \forall n = 1, \cdots, N+1,$$
$$\boldsymbol{V} \succeq 0.$$

$$\boldsymbol{V} = \bar{\boldsymbol{v}}\bar{\boldsymbol{v}}^H \quad \boldsymbol{R} = \begin{bmatrix} \boldsymbol{\Phi}\boldsymbol{\Phi}^H & \boldsymbol{\Phi}\boldsymbol{h}_d \\ \boldsymbol{h}_d^H \boldsymbol{\Phi}^H & 0 \end{bmatrix}, \quad \bar{\boldsymbol{v}} = \begin{bmatrix} \boldsymbol{v} \\ t \end{bmatrix}$$

$$\bar{\boldsymbol{v}} = \boldsymbol{U}\boldsymbol{\Sigma}^{1/2}\boldsymbol{r} \quad \boldsymbol{r} \in \mathcal{CN}(\boldsymbol{0}, \boldsymbol{I}_{N+1})$$

$$\boldsymbol{v} = e^{j \arg([\frac{\bar{\boldsymbol{v}}}{\bar{v}_{N+1}}]_{(1:N)})}$$

Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network: Joint active and passive beamforming design," in 2018 IEEE Global Commun. Conf., 2018, pp. 1–6.

MISO RIS Optimization: Fixed Point Iteration

- Semidefinite relaxation on the quadratically constrained quadratic problem (QCQP) in $\mathcal{P}_1$
- **Fixed point iteration used to solve $\mathcal{P}_2$**
- Precoder designed by maximum ratio transmission (MRT) after RIS phases are $\mathcal{P}_2$ optimized
- Initialization:

$$\tilde{\mathbf{v}}^\star = \sqrt{M+1}\boldsymbol{\lambda}_{\max}(\mathbf{R})$$

$$\mathbf{v}^{(0)} = \operatorname{unt}(\tilde{\mathbf{v}}^\star)$$

- Update Rule:

$$\mathbf{v}^{(t+1)} = \operatorname{unt}\left(\mathbf{R}\mathbf{v}^{(t)}\right)$$

$$R = \log\left(1 + \frac{\left|(\mathbf{h}_\mathrm{r}^H \boldsymbol{\Phi}\mathbf{G} + \mathbf{h}^H)\mathbf{f}\right|^2}{\sigma^2}\right)$$

$$\begin{aligned}\mathcal{P}_1 : \underset{\mathbf{f},\boldsymbol{\Phi}}{\text{maximize}} \quad & \left|\left(\mathbf{h}_\mathrm{r}^H \boldsymbol{\Phi}\mathbf{G} + \mathbf{h}^H\right)\mathbf{f}\right|^2 \\ \text{subject to} \quad & \|\mathbf{f}\|^2 \leq P \\ & \boldsymbol{\Phi} = \operatorname{diag}\left(e^{\jmath\theta_1}, e^{\jmath\theta_2}, \cdots, e^{\jmath\theta_M}\right)\end{aligned}$$

Reformulation of optimization problem

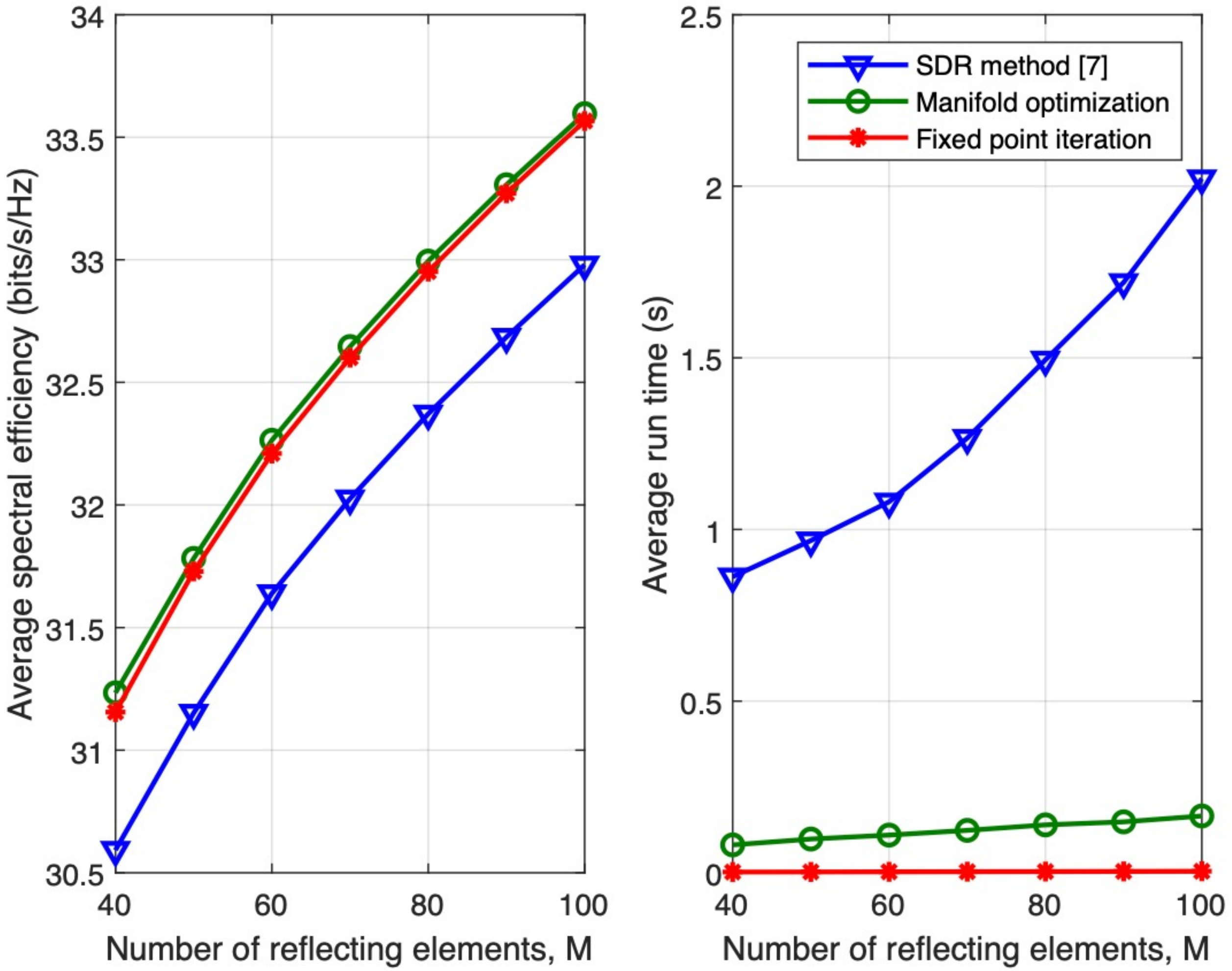
$$\begin{aligned}\mathcal{P}_2 : \underset{\mathbf{v}\in\mathbb{C}^{M+1}}{\text{maximize}} \quad & \mathbf{v}^H\mathbf{R}\mathbf{v} \\ \text{subject to} \quad & |v_i| = 1, \quad i \in \{1, 2, \cdots, M+1\}\end{aligned}$$

$$\mathbf{v} = [\mathbf{x}^T, t]^T \quad \mathbf{x} = \left[e^{\jmath\theta_1}, e^{\jmath\theta_2}, \cdots, e^{\jmath\theta_M}\right]^H$$

$$t \in \mathbb{R} \quad \mathbf{R} = \begin{bmatrix}\operatorname{diag}\left(\mathbf{h}_\mathrm{r}^H\right)\mathbf{G}\mathbf{G}^H\operatorname{diag}(\mathbf{h}_\mathrm{r}) & \operatorname{diag}\left(\mathbf{h}_\mathrm{r}^H\right)\mathbf{G}\mathbf{h} \\ \mathbf{h}^H\mathbf{G}^H\operatorname{diag}(\mathbf{h}_\mathrm{r}) & 0\end{bmatrix}$$

X. Yu, D. Xu, and R. Schober, "MISO wireless communication systems via intelligent reflecting surfaces : (invited paper)," in 2019 IEEE/CIC Intl. Conf. on Commun. China, 2019, pp. 735–740.

MISO RIS Optimization: Fixed Point Iteration



X. Yu, D. Xu, and R. Schober, "MISO wireless communication systems via intelligent reflecting surfaces : (invited paper)," in 2019 IEEE/CIC Intl. Conf. on Commun. China, 2019, pp. 735–740.

MIMO RIS Optimization: Alternating Optimization

- Narrowband case
- Optimization of Q with reflection coefficients $\{\alpha_m\}_{m=1}^{M}$ held constant by waterfilling
- Optimization of α_m given fixed Q and $\{\alpha_i, i \neq m\}_{i=1}^{M}$
  - Rewrite spectral efficiency as a function of α_m

$$\max_{\alpha_m} \ \log_2 \det(\boldsymbol{A}_m + \alpha_m \boldsymbol{B}_m + \alpha_m^* \boldsymbol{B}_m^H)$$
$$\text{s.t.} \quad |\alpha_m| = 1.$$

  - Exploit structure of problem to obtain optimal solution to each subproblem.

$$(\text{P1}) \quad \max_{\boldsymbol{\phi}, \boldsymbol{Q}} \ \log_2 \det\left(\boldsymbol{I}_{N_r} + \frac{1}{\sigma^2} \tilde{\boldsymbol{H}} \boldsymbol{Q} \tilde{\boldsymbol{H}}^H\right)$$
$$\text{s.t.} \quad \boldsymbol{\phi} = \text{diag}\{\alpha_1, ..., \alpha_M\}$$
$$|\alpha_m| = 1, \quad m = 1, ..., M$$
$$\text{tr}(\boldsymbol{Q}) \leq P$$
$$\boldsymbol{Q} \succeq \boldsymbol{0}.$$

Obtain more tractable problem by rewriting the capacity with the following change:

$$\tilde{\boldsymbol{H}} = \boldsymbol{H} + \boldsymbol{R} \boldsymbol{\phi} \boldsymbol{T}$$

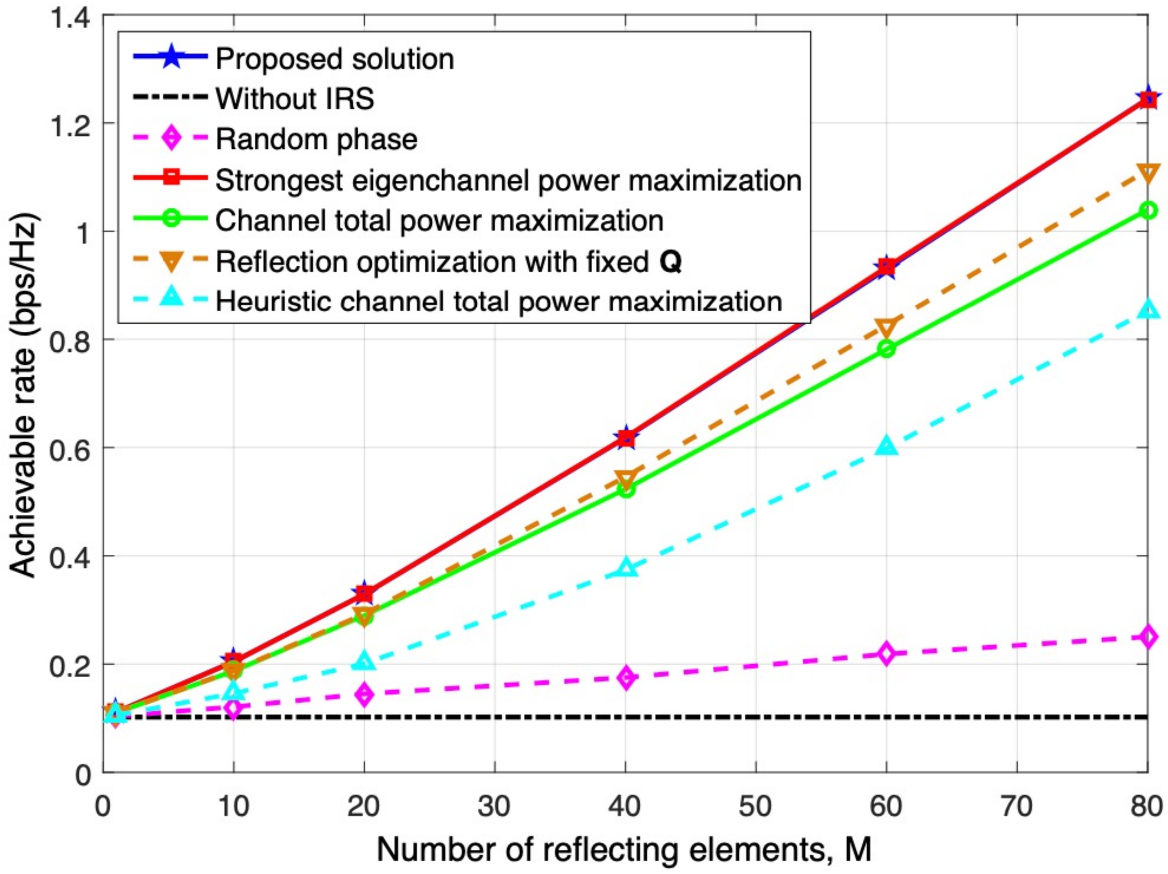
↓

$$\tilde{\boldsymbol{H}} = \boldsymbol{H} + \sum_{m=1}^{M} \alpha_m \boldsymbol{r}_m \boldsymbol{t}_m^H$$

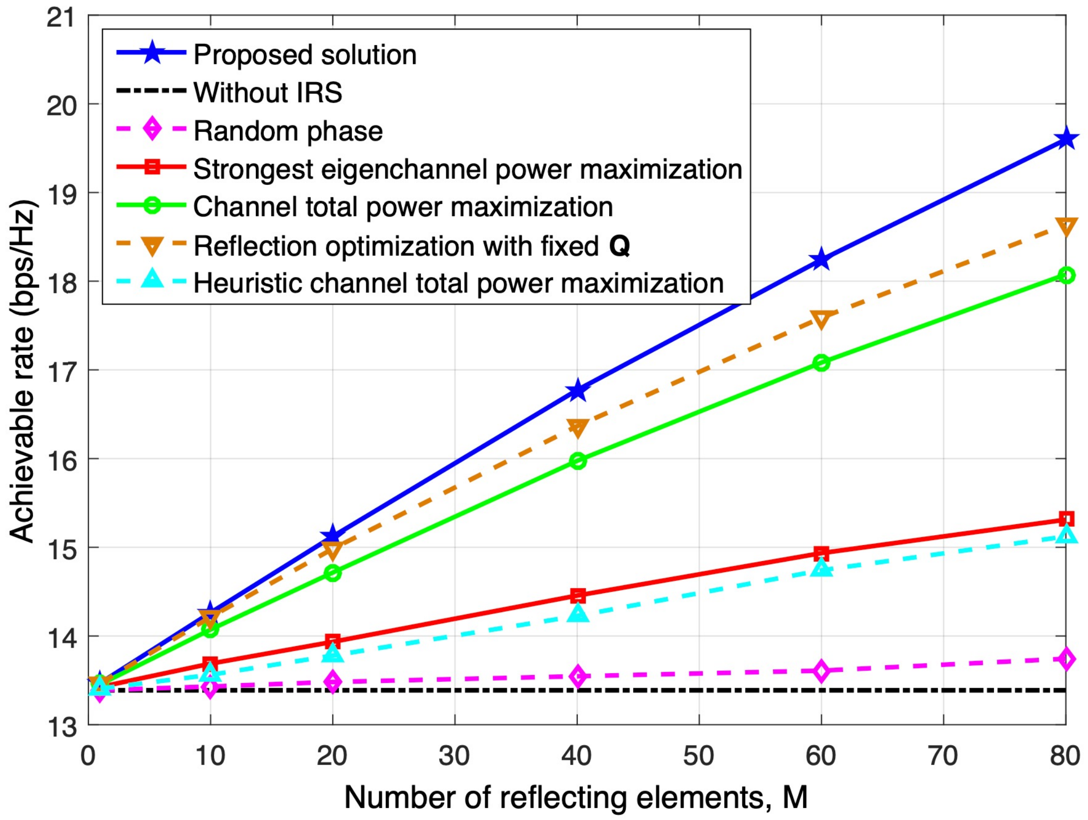
[1] S. Zhang and R. Zhang, "Capacity Characterization for Intelligent Reflecting Surface Aided MIMO Communication," in IEEE Journal on Selected Areas in Communications, vol. 38, no. 8, pp. 1823-1838, Aug. 2020.

MIMO RIS Optimization: Alternating Optimization

Low SNR



High SNR

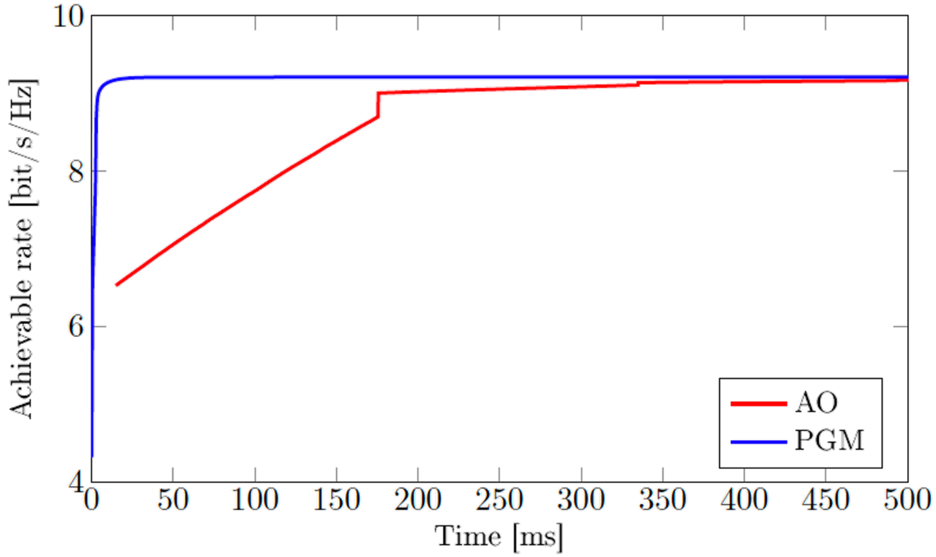


Achievable rate versus M

[1] S. Zhang and R. Zhang, "Capacity Characterization for Intelligent Reflecting Surface Aided MIMO Communication," in IEEE Journal on Selected Areas in Communications, vol. 38, no. 8, pp. 1823-1838, Aug. 2020.

MIMO RIS Optimization: Projected Gradient Ascent (PGA)

- Until convergence
  - Optimization over RIS elements Θ
  - Optimization over $\mathcal{Q}$
- Comparison of PGA to AO method



Optimization Problem

$$\underset{\boldsymbol{\theta},\mathbf{Q}}{\text{maximize}}\ f(\boldsymbol{\theta},\mathbf{Q}) = \ln\det\left(\mathbf{I}+\mathbf{Z}(\boldsymbol{\theta})\mathbf{Q}\mathbf{Z}^H(\boldsymbol{\theta})\right)$$
$$\text{subject to}\ \operatorname{Tr}(\mathbf{Q}) \le P_t;\ \mathbf{Q}\succeq \mathbf{0};$$
$$|\theta_l| = 1, l = 1,2,\ldots,N_{\text{ris}}.$$

where

$$\mathbf{Z}(\boldsymbol{\theta}) = \bar{\mathbf{H}}_{\text{DIR}} + \mathbf{H}_2\mathbf{F}(\boldsymbol{\theta})\bar{\mathbf{H}}_1$$
$$\bar{\mathbf{H}}_{\text{DIR}} = \mathbf{H}_{\text{DIR}}/\sqrt{N_0}$$
$$\bar{\mathbf{H}}_1 = \mathbf{H}_1\sqrt{\beta_{\text{INDIR}}^{-1}/N_0}.$$

Optimization variables

$$\Theta = \{\boldsymbol{\theta}\in\mathbb{C}^{N_{\text{ris}}\times 1} : |\theta_l| = 1, l = 1,2,\ldots,N_{\text{ris}}\}$$
$$\mathcal{Q} = \{\mathbf{Q}\in\mathbb{C}^{N_t\times N_t} : \operatorname{Tr}(\mathbf{Q})\le P_t; \mathbf{Q}\succeq\mathbf{0}\}$$

N. S. Perović, L. -N. Tran, M. Di Renzo and M. F. Flanagan, "Achievable Rate Optimization for MIMO Systems With Reconfigurable Intelligent Surfaces," in IEEE Transactions on Wireless Communications, vol. 20, no. 6, pp. 3865-3882, June 2021, doi: 10.1109/TWC.2021.3054121.

MISO RIS Channel Estimation

$$\boldsymbol{\Theta} \triangleq \mathrm{diag}\left\{\alpha_1 \mathrm{e}^{j\theta_1}\ \alpha_2 \mathrm{e}^{j\theta_2} \ldots \alpha_M \mathrm{e}^{j\theta_M}\right\} \in \mathbb{C}^{M\times M}$$

$$\alpha_i \in (0,1)$$

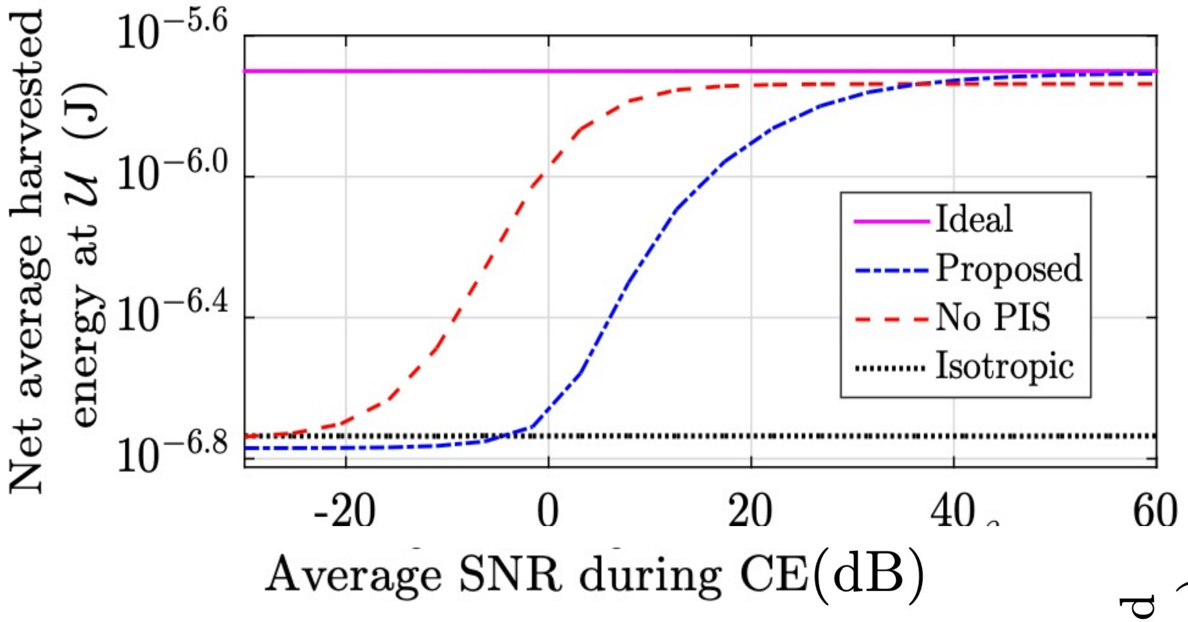
$$\theta_i \in (0,2\pi)$$

- Stage 1: Uplink Channel Estimate time: $(M+1)\,\tau_c$
  - LS Estimate of each channel
  - Binary setting for each RIS element ON/OFF control

- Stage 2: Downlink Active/Passive beamforming design
  - Active beamforming from BS designed using maximum ratio transmission (MRT)
  - Optimal: Passive beamforming designed by SDR-based solution using CVX
  - Suboptimal: Passive beamforming with closed-form solution for RIS phase shifts

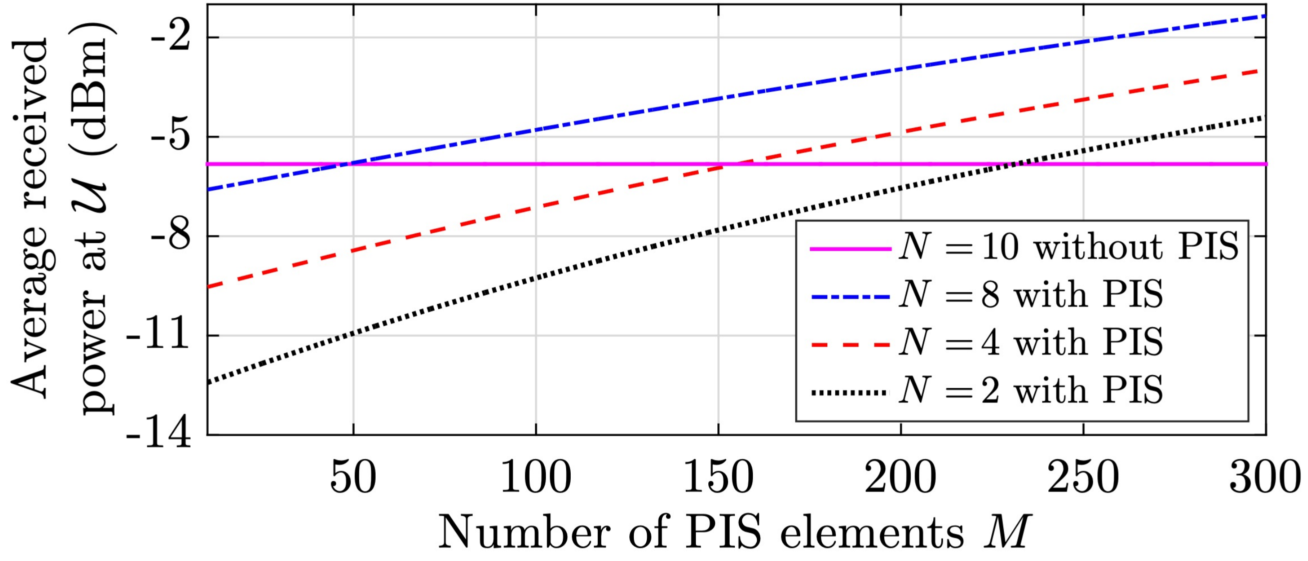
D. Mishra and H. Johansson, "Channel Estimation and Low-complexity Beamforming Design for Passive Intelligent Surface Assisted MISO Wireless Energy Transfer," ICASSP 2019 - 2019 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), 2019, pp. 4659-4663.

RIS Channel Estimation



Performance of proposed least squared estimator for different SNRS

RIS size needed to reduce active array size at BS



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Some RIS Use Cases

- Physical layer security
  - IRS to enhance secrecy rate of wireless networks
- Wireless Power Transfer
  - Deploying RIS in vicinity of IoT devices to improve the received power level of IoT devices
- mmWave/terahertz Communications
  - Improve the channel conditions of the mmWave MIMO channel