RIS Energy Efficiency Optimization with Practical Power Model

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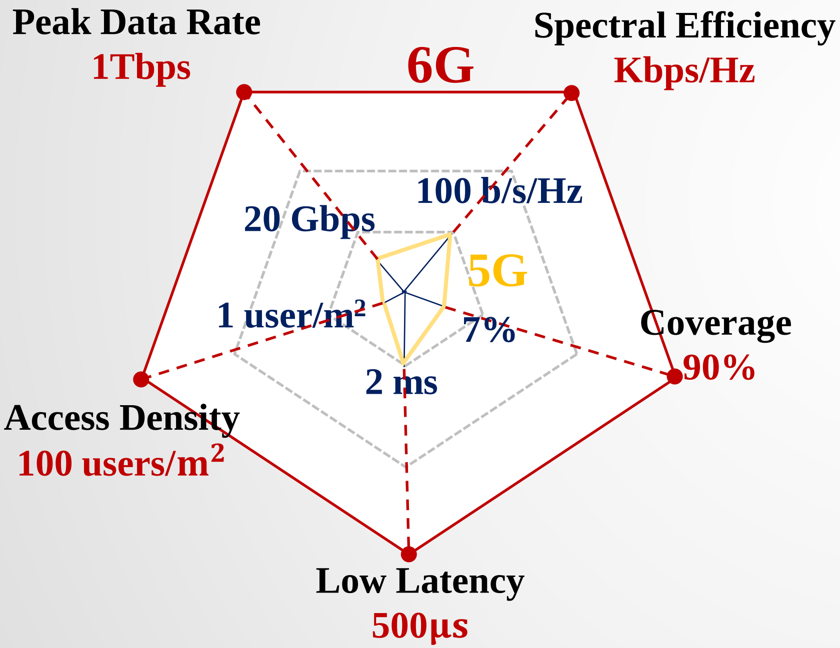
2 **Practical Power Model**

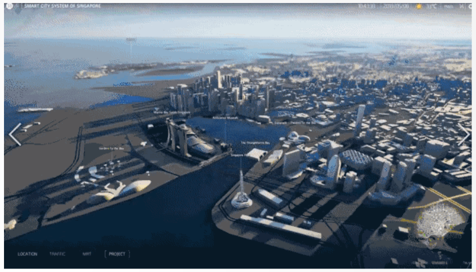
3 **Algorithms and Simulations**

4 **Conclusions**

Background: 6G Requirements

- **Key Performance Indicators of 6G communication**





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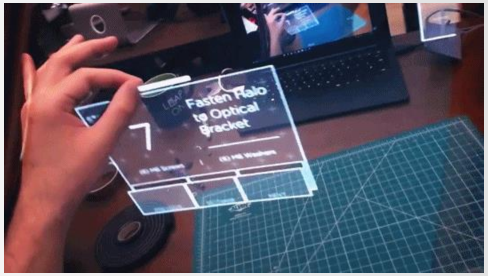
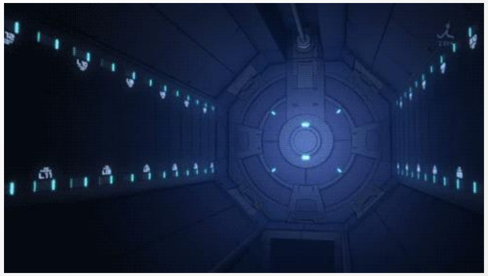
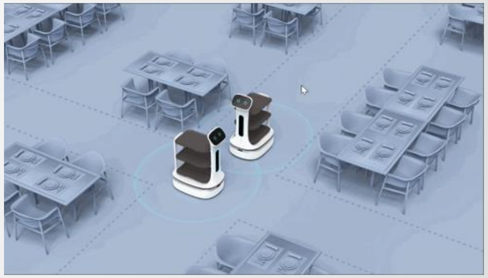


Extended Reality



Holographic Video



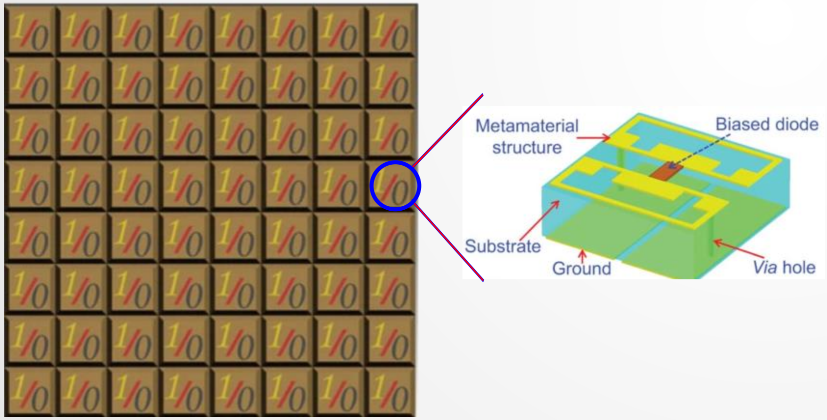
Intelligent Transport

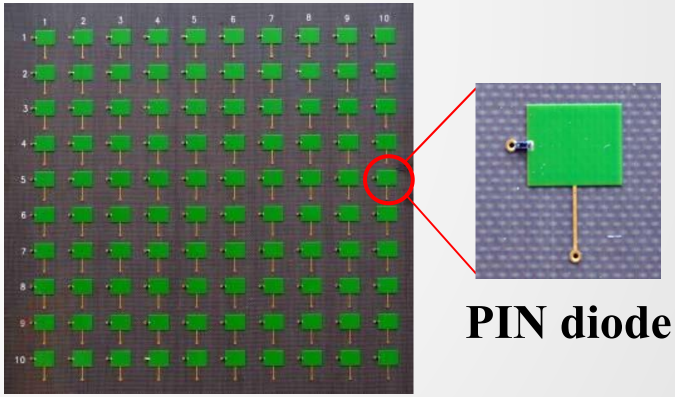
[1] ITU FG-NET-2030, "Network 2030-A Blueprint of Technology, Applications and Market Drivers towards the Year 2030 and Beyond," *https://www.itu.int/en/ITU-T/focusgroups/net2030/Documents/White_Paper.pdf*, ITU, Geneva, Switzerland, May 2019.

Background: RIS

- **Reconfigurable Intelligent Surface (RIS)**
  - **A surface of reconfigurable metamaterial**
  - **Control the propagation of electromagnetic wave**
  - **Manipulate the channel to improve the signal quailty**

Overcome blockage
Increase SE
Power-saving





PIN diode

[1] T. Cui, M. Qi, X. Wan, J. Zhao, and Q. Cheng, "Coding metamaterials, digital metamaterials and programmable metamaterials," *Light: Science & Applications*, vol. 3, p. e218, Oct. 2014.
[2] H. Yang, X. Cao, F. Yang, J. Gao, S. Xu, M. Li, X. Chen, Y. Zhao, Y. Zheng, and S. Li, "A programmable metasurface with dynamic polarization, scattering and focusing control," *Scientific Reports*, vol. 6, p. 35692 EP, Oct. 2016.

Background: RIS

- **Reconfigurable Intelligent Surface (RIS)**
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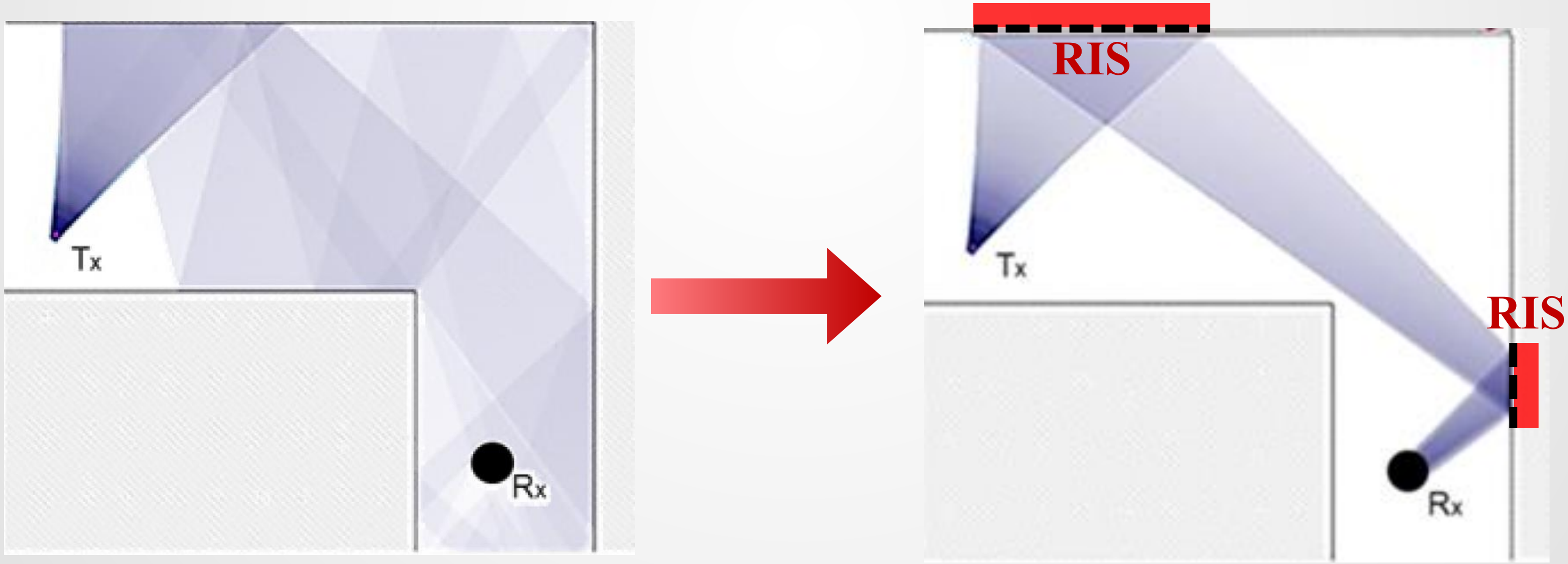


[1] E. Basar, M. Di Renzo, J. De Rosny, M. Debbah, M. Alouini, and R. Zhang, “Wireless communications through reconfigurable intelligent surfaces,” *IEEE Access*, vol. 7, pp. 116753-116773, Jul. 2019.

Background: Energy Efficiency (EE)

- **An important indicator: Energy Efficiency (EE)**
  - **Growing attention with green and sustainable requirements**

$$\mathrm{EE} = \frac{K \times B \times N \times \log_2\big(1 + \mathrm{SINR}(d)\big)}{P_I + P_c}$$

- **Modeling EE in RIS-assisted communication systems**

$$\mathrm{EE}_{\mathrm{RIS}} = \frac{BW \overbrace{\times \sum_{k=1}^{K} \log_2(1 + \gamma_k)}^{\text{Spectral Efficiency (bps/Hz)}}}{\xi \sum_{k=1}^{K} p_k + P_{\mathrm{BS}} + K P_{\mathrm{UE}} + N P_n(b)}$$

p_k: **BS transmit power**

P_{BS}: **BS static power**

P_{UE}: **UE static power**

$P_n(b)$: **Power consumption for each RIS element**

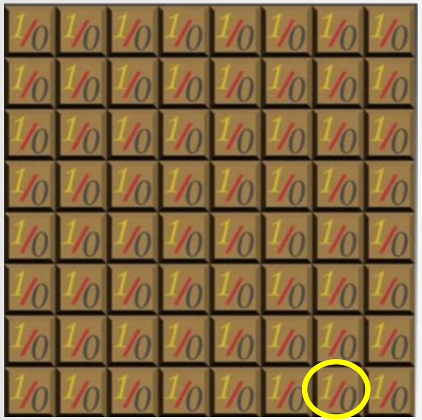
Power consumption of each element is assumed to be same

[1] Q. Wu, G. Y. Li, W. Chen, D. W. K. Ng and R. Schober, "An Overview of Sustainable Green 5G Networks," *IEEE Wireless Communications*, vol. 24, no. 4, pp. 72-80, Aug. 2017.

[2] C. Huang, A. Zappone, G. C. Alexandropoulos, M. Debbah and C. Yuen, "Reconfigurable Intelligent Surfaces for Energy Efficiency in Wireless Communication," *IEEE Transactions on Wireless Communications*, vol. 18, no. 8, pp. 4157-4170, Aug. 2019.

Background: RIS Power Model

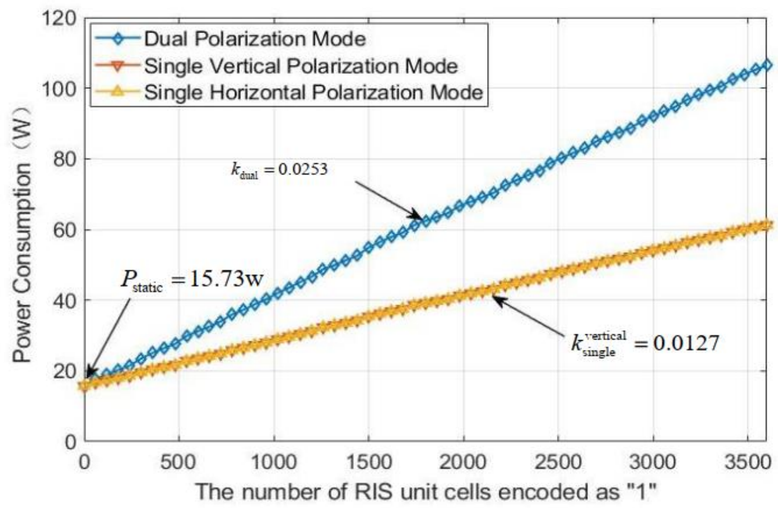
- **Dynamic power consumption of each RIS elements**
  - **Varies with the configuration of RIS**



$$\xcancel{P_{\text{RIS}} = N P_n(b)}$$

Encode as "1" (ON state): $P \approx 10$ mW

Encode as "0" (OFF state): $P \approx 0$



ON/OFF-state power difference should be taken into consideration

[1] J. Wang, W. Tang, J. C. Liang, L. Zhang, J. Y. Dai, X. Li, S. Jin, Q. Cheng, and T. J. Cui, "Reconfigurable intelligent surface: Power consumption modeling and practical measurement validation," *arXiv preprint arXiv:2211.00323*, Nov. 2022.

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4 Conclusions

Practical Power Model

- **Total power model for RIS-assisted systems**

$$P_{\text{total}} = P_{\text{static}} + \boxed{P_{\text{RIS}}} + P_{\text{transmit}}$$

$$P_{\text{RIS}} = \|\boldsymbol{\theta}\|_0 P_0, \qquad \theta_n \in \{0, \pi\}$$

$$\begin{cases} \text{ON-state: } P_{\text{RIS},n} = P_0 \\ \text{OFF-state: } P_{\text{RIS},n} = 0 \end{cases}$$

- **Energy Efficiency (EE) for RIS-assisted systems**

$$\text{EE}_{\text{RIS}} = \frac{BW \times \text{SE}_{\text{RIS}}(\boldsymbol{\Theta}, \boldsymbol{W})}{P_{\text{static}} + \|\boldsymbol{\theta}\|_0 P_0 + \text{trace}(\boldsymbol{W}^{\text{H}}\boldsymbol{W})}$$

EE is related to the number of ON-state RIS elements

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[1] J. Wang, W. Tang, J. C. Liang, L. Zhang, J. Y. Dai, X. Li, S. Jin, Q. Cheng, and T. J. Cui, "Reconfigurable intelligent surface: Power consumption modeling and practical measurement validation," *arXiv preprint arXiv:2211.00323*, Nov. 2022.

EE Optimization Formulation

- **Formulation of EE Optimization problem**
  - **Downlink Multi-user Multiple-Input Single-Output (MU-MISO) systems**
  - **ON/OFF-state power difference is taken into consideration**

$$\mathrm{SE}(\boldsymbol{\Theta},\mathbf{W}) = \sum_{k=1}^{K} \log_2\left(1 + \frac{\left|\boldsymbol{f}_k^{\mathrm{H}}\boldsymbol{\Theta}\mathbf{G}\mathbf{w}_k\right|^2}{\sum_{k'\neq k}\left|\boldsymbol{f}_k^{\mathrm{H}}\boldsymbol{\Theta}\mathbf{G}\mathbf{w}_{k'}\right|^2 + \sigma_n^2}\right) \quad [\mathrm{bps/Hz}]$$

$$\mathrm{EE}(\boldsymbol{\Theta},\mathbf{W}) = \frac{\mathrm{BW}\times\mathrm{SE}(\boldsymbol{\Theta},\mathbf{W})}{P_{\mathrm{static}} + P_0\|\boldsymbol{\theta}\|_0 + \mathrm{tr}(\boldsymbol{W}^{\mathrm{H}}\boldsymbol{W})} \quad [\mathrm{bit/Joule}]$$

$$\underset{\boldsymbol{\Theta},\mathbf{W}}{\text{maximize}} \ \mathrm{EE}(\boldsymbol{\Theta},\boldsymbol{W}) \quad \text{subject to} \ \mathrm{tr}\left(\boldsymbol{W}^{\mathrm{H}}\boldsymbol{W}\right) \leq P_{\max}$$

$$\mathrm{SE}_k \geq \mathrm{SE}_{\min}, \quad \forall k \in \mathcal{K}$$

$$\theta_n \in \{0,\pi\}, \quad \forall n \in \mathcal{N}$$

Non-Convex!

Mixed-Integer!

How to solve the Non-Convex Mixed-Integer Problem?

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AO Framework

- **Alternating Optimization (AO) framework**
  - **Optimize the BS precoder and RIS coding matrix separately**
  - **Using Zero-Forcing (ZF) precoder**
  - **Iterative steps utill the target function converges**

Original Problem

$$\begin{aligned} \underset{\boldsymbol{\Theta},\mathbf{W}}{\text{maximize}}\ & \mathrm{EE}(\boldsymbol{\Theta}, \boldsymbol{W}) \\ \text{subject to}\ & \mathrm{tr}\left(\boldsymbol{W}^{\mathrm{H}}\boldsymbol{W}\right) \le P_{\max} \\ & \mathrm{SE}_k \ge \mathrm{SE}_{\min}, \qquad \forall k \in \mathcal{K} \\ & \theta_n \in \{0, \pi\}, \qquad \forall n \in \mathcal{N} \end{aligned}$$

$$\begin{aligned} \underset{\boldsymbol{\Theta},\mathbf{W}}{\text{maximize}}\ & \frac{1}{P_1 + \sum_{k=1}^{K} p_k t_k} \sum \log_2\left(1 + \frac{p_k}{\sigma_n^2}\right) \\ \text{subject to}\ & \sum p_k t_k \le P_{\max} \\ & p_k \ge p_{\min}, \qquad \forall k \in \mathcal{K} \end{aligned}$$

Power Allocation Problem

$$\begin{aligned} \underset{\boldsymbol{\Theta},\mathbf{W}}{\text{maximize}}\ & P_0 \|\boldsymbol{\theta}\|_0 + \sum p_k t_k \\ \text{subject to}\ & \sum_{k=1}^{K} p_k t_k \le P_{\max} \\ & \theta_n \in \{0, \pi\}, \qquad \forall n \in \mathcal{N} \end{aligned}$$

RIS Beamforming Problem

Power Allocation Problem

- **Dinkelbach's Method**
  - **Iteratively update the power allocation *P* and target function**

Power Allocation Problem

$$\begin{aligned} \underset{\boldsymbol{\Theta},\mathbf{W}}{\text{maximize}} \ & \frac{1}{P_1 + \sum_{k=1}^{K} p_k t_k} \sum \log_2\left(1 + \frac{p_k}{\sigma_n^2}\right) \\ \text{subject to} \ & \sum p_k t_k \le P_{\max} \\ & p_k \ge p_{\min}, \qquad \forall k \in \mathcal{K} \end{aligned}$$

$$\boldsymbol{P}^{(i)} = \arg\max_{\boldsymbol{P}} \sum_{k=1}^{K} \log_2\left(1 + \frac{p_k}{\sigma_n^2}\right) - \lambda^{(i-1)}\left(P_1 + \sum_{k=1}^{K} p_k t_k\right)$$

$$\text{subject to} \ \sum_{k=1}^{K} p_k t_k \le P_{\max}, \qquad p_k \ge p_{\min}$$

$$\lambda^{(i)} = \frac{1}{P_1 + \sum_{k=1}^{K} p_k^{(i)} t_k} \sum_{k=1}^{K} \log_2\left(1 + \frac{p_k^{(i)}}{\sigma_n^2}\right)$$

$$\lambda^{(i-1)} \Downarrow \boldsymbol{P}^{(i)} \Downarrow \lambda^{(i)} \Downarrow \boldsymbol{P}^{(i+1)}$$

[1] C. Huang, A. Zappone, G. C. Alexandropoulos, M. Debbah and C. Yuen, "Reconfigurable Intelligent Surfaces for Energy Efficiency in Wireless Communication," *IEEE Transactions on Wireless Communications*, vol. 18, no. 8, pp. 4157-4170, Aug. 2019.

Analytical solution to the subproblem

- **Water-filling-like Solution to the subproblem**

$$\boldsymbol{P}^{(i)} = \arg\max_{\boldsymbol{P}} \sum_{k=1}^{K} \log_2\left(1+\frac{p_k}{\sigma_n^2}\right) - \lambda^{(i-1)}\left(P_1 + \sum_{k=1}^{K} p_k t_k\right)$$

$$\text{subject to } \sum_{k=1}^{K} p_k t_k \le P_{\max}, \qquad p_k \ge p_{\min}$$

Step 1: **Find ζ such that:** $\sum_k\{\zeta - t_k\sigma_n^2, t_k P_{\min}\} = P_{\max}$

Step 2: $\xi^{(i)} = \min\{\zeta, 1/\left(\lambda^{(i-1)}\log 2\right)\}$

Step 3: $p_k^{(i)} = \max\{\left(\xi^{(i)} - t_k\sigma_n^2\right)/t_k, p_{\min}\}$

Power Allocation Problem has been solved up to now

RIS Beamforming Problem

- **Equally transformed to the original RIS Beamforming Problem**
  - **Express it as standard SDP as nearly as possible**
  - **Using matrix $\boldsymbol{X} = \boldsymbol{x}\boldsymbol{x}^{\mathrm{H}}$ to avoid the square term**

Non-Convex!

$$\begin{aligned} \underset{\boldsymbol{\Theta},\mathbf{W}}{\text{maximize}}\ & P_0\|\boldsymbol{\theta}\|_0 + \sum p_k t_k \\ \text{subject to}\ & \sum_{k=1}^{K} p_k t_k \le P_{\max} \\ & \theta_n \in \{0,\pi\}, \qquad \forall n \in \mathcal{N} \end{aligned}$$

Mixed-Integer!

Original RIS Beamforming Problem

$$\begin{aligned} \underset{\boldsymbol{X}}{\text{minimize}}\ & -\frac{1}{4}P_0 \operatorname{tr}(\boldsymbol{E}_0\boldsymbol{X}) + \operatorname{tr}\left(\boldsymbol{F}_0^{\mathrm{H}}(\boldsymbol{X} \odot \boldsymbol{G}_0)\boldsymbol{F}_0\boldsymbol{P}^{-1}\right)^{-1} \\ \text{subject to}\ & \operatorname{tr}\left(\boldsymbol{F}_0^{\mathrm{H}}(\boldsymbol{X} \odot \boldsymbol{G}_0)\boldsymbol{F}_0\boldsymbol{P}^{-1}\right)^{-1} \le P_{\max} \\ & \operatorname{tr}\left(\boldsymbol{E}_{i,i}\boldsymbol{X}\right) = 1, \qquad \forall i \in \{1,2,\dots,N+1\} \\ & \boldsymbol{X} \succcurlyeq 0 \ \text{(Matrix } \boldsymbol{X} \text{ is positive semidefinite)} \\ & \operatorname{rank}(\boldsymbol{X}) = 1 \end{aligned}$$

Still Non-Convex!

How to deal with the only non-convex constrain?

SDP Relaxation

- **SDP Relaxation**
  - **Relax the Rank-1 Constrain to acquire a standard SDP**
  - **Randomly projection to achieve the original approximate solution**

$$\begin{aligned}
\underset{\boldsymbol{X}}{\text{minimize}}\; & -\frac{1}{4}P_0\mathrm{tr}(\boldsymbol{E}_{\boldsymbol{0}}\boldsymbol{X}) + \mathrm{tr}\left(\boldsymbol{F}_{\boldsymbol{0}}^{\mathrm{H}}(\boldsymbol{X}\odot\boldsymbol{G}_{\boldsymbol{0}})\boldsymbol{F}_{\boldsymbol{0}}\boldsymbol{P}^{-1}\right)^{-1} \\
\text{subject to}\; & \mathrm{tr}\left(\boldsymbol{F}_{\boldsymbol{0}}^{\mathrm{H}}(\boldsymbol{X}\odot\boldsymbol{G}_{\boldsymbol{0}})\boldsymbol{F}_{\boldsymbol{0}}\boldsymbol{P}^{-1}\right)^{-1} \le P_{\max} \\
& \mathrm{tr}\left(\boldsymbol{E}_{\boldsymbol{i},\boldsymbol{i}}\boldsymbol{X}\right) = 1, \qquad \forall i \in \{1,2,\dots,N+1\} \\
& \boldsymbol{X} \succcurlyeq 0 \;\; (\text{Matrix } \boldsymbol{X} \text{ is positive semidefinite}) \\
& \xcancel{\mathrm{rank}(\boldsymbol{X}) = 1}
\end{aligned}$$

Standard Semidefinite Programming (SDP)

Optimal solution $\widetilde{\boldsymbol{X}}$ to the SDP

↓ **Randomly Project**

Approximate solution $\widehat{\boldsymbol{X}}$

[1] S. P. Boyd and L. Vandenberghe, *Convex optimization*. Cambridge,U.K.: Cambridge University Press, 2004.

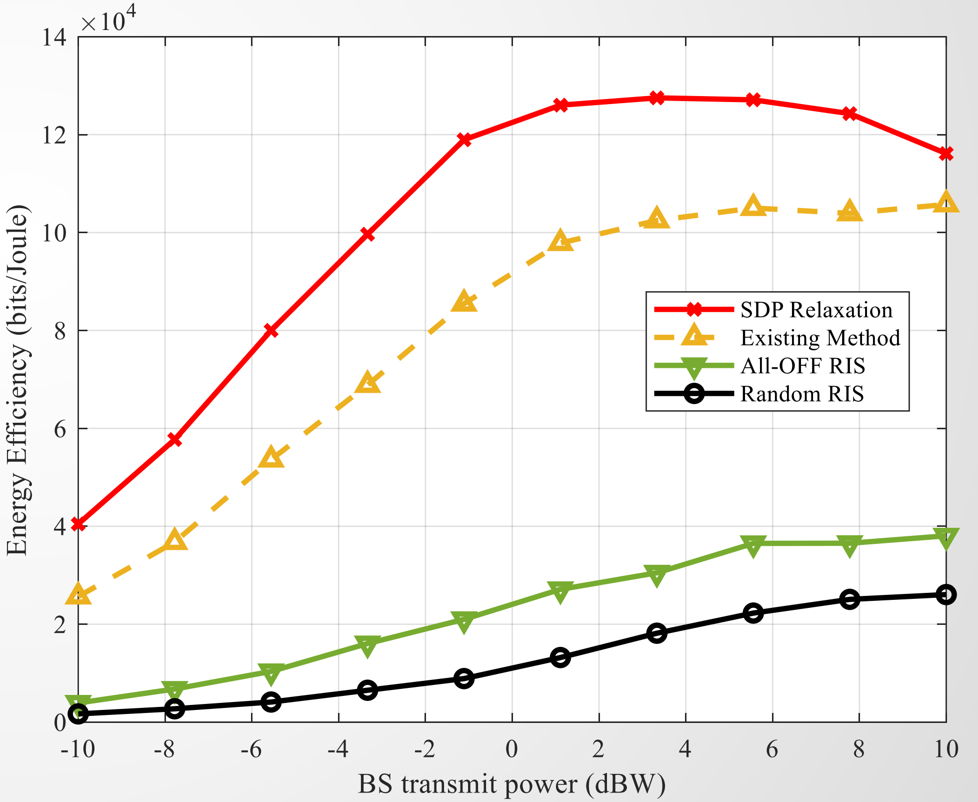
[2] A. M.-C. So, J. Zhang, and Y. Ye, "On approximating complex quadraticoptimization problems via semidefinite programming relaxations," *Math. Program.*, vol. 110, no. 1, pp. 93–110, June 2007.

Simulations

- **Impact of the Base Station Transmit Power**

RIS Elements	**64= 8 × 8**
BS Antennas	**8**
Number of Users	**4**
P_{static}	**4 W**
P_0	**1 mW**
Carrier Frequency	**3.5 GHz**
Subcarrier Spacing	**180 kHz**
Thermo Noise	**-174 dBm/Hz**

Simulation Parameters

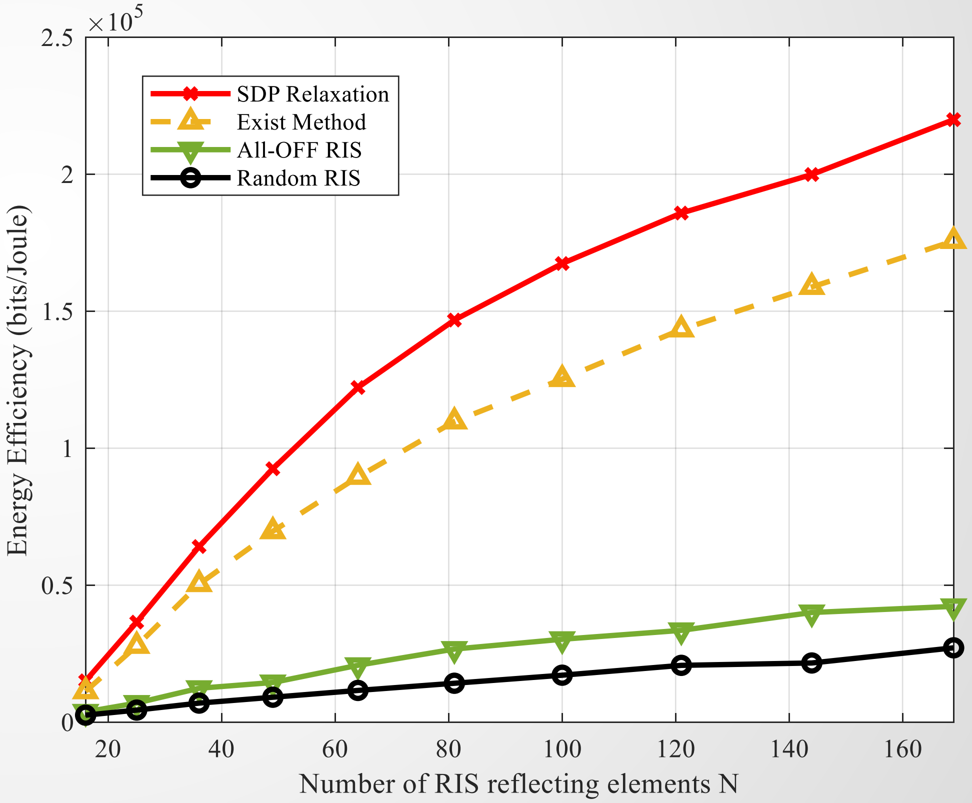


Simulations

- **Impact of the Number of RIS Elements**

P_{transmit}	1 W
BS Antennas	8
Number of Users	4
P_{static}	4 W
P_0	1 mW
Carrier Frequency	3.5 GHz
Subcarrier Spacing	180 kHz
Thermo Noise	-174 dBm/Hz

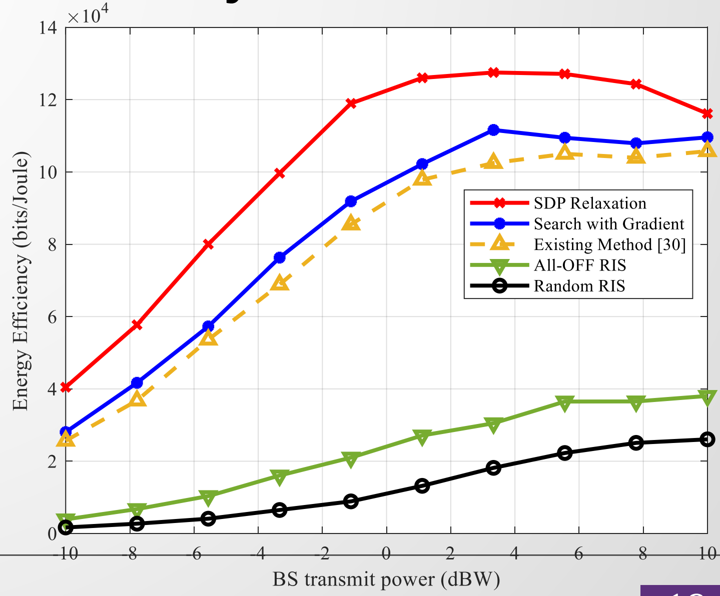
Simulation Parameters



Conclusion

- Construct a Practical Power Model for RIS-assisted systems
  - Consider the power difference between ON/OFF states
- Design an Effective Algorithm to the EE Optimization problem
  - Design a polynomial computational algorithm for the Non-Convex Mixed-Integer problem
- Verify the efficiency of the proposed algorithm by simulations

$$
\begin{aligned}
\underset{\boldsymbol{\Theta},\mathbf{W}}{\text{maximize}}\quad & \mathrm{EE}(\boldsymbol{\Theta},\boldsymbol{W}) \\
\text{subject to}\quad & \mathrm{tr}\left(\boldsymbol{W}^{\mathrm{H}}\boldsymbol{W}\right) \le P_{\max} \\
& \mathrm{SE}_k \ge \mathrm{SE}_{\min}, \qquad \forall k \in \mathcal{K} \\
& \theta_n \in \{0,\pi\}, \qquad \forall n \in \mathcal{N}
\end{aligned}
$$



Thanks for Listening

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