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Energy efficiency optimization for a RIS-assisted multi-cell communication system based on a practical RIS power consumption model

Key words: Reconfigurable intelligent surface (RIS); Energy efficiency; Multi-cell communication system

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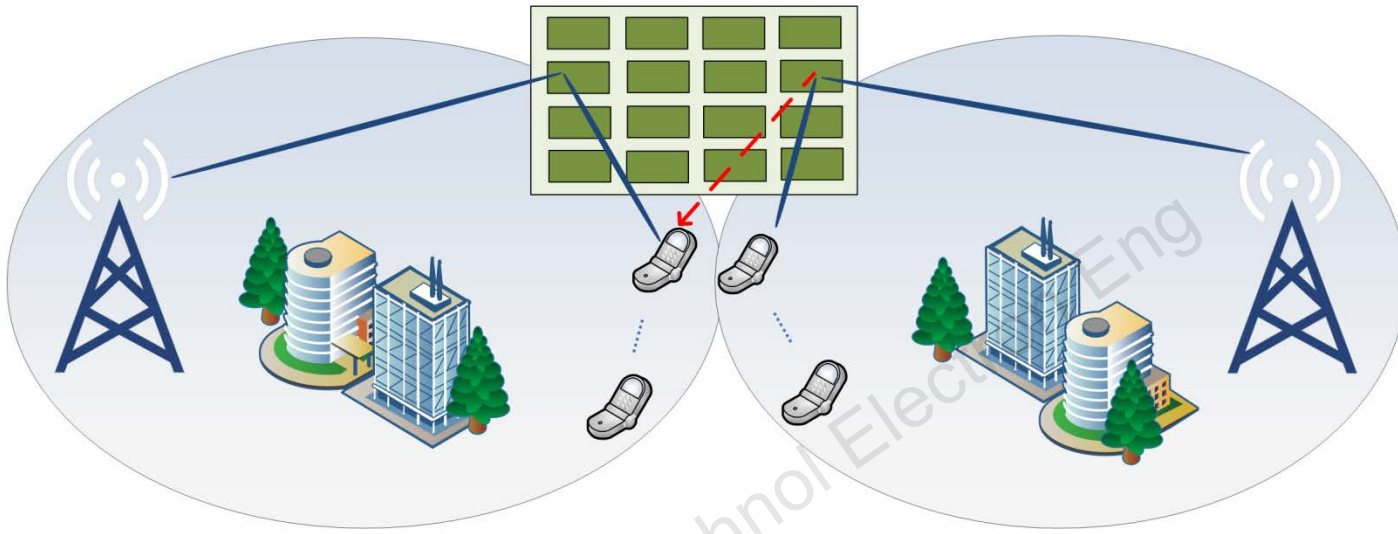
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Motivation

- ❑ To address the need for higher performance requirements, such as ultra-high data rates, ultra-lower latency, ultra-high reliability, and large-scale connection, the reconfigurable intelligent surface (RIS) has been identified as one of the most promising technologies.
- ❑ Energy efficiency is a crucial aspect of RIS-assisted communication systems because green communication is one of the primary demands for 6G. However, most existing works are based on hypothetical RIS power consumption models that have not been verified through measurement. In these works, the RIS power consumption is assumed to be a constant or even 0, and is independent of the phase shift value of each RIS reflecting unit.
- ❑ It is of practical significance to study RIS-assisted multi-cell communication information based on the practical RIS power consumption model.

System model



System model

□ System model

- Number of base station (BS) antennas: M
- Number of reflecting units: N
- Number of single-antenna users: K

□ Channel model

- the channel from the j^{th} BS to the RIS: $G_j \in \mathbb{C}^{N \times M}$
- the channel from the RIS to the k^{th} user in the j^{th} cell: $h_{j,k} \in \mathbb{C}^{N \times 1}$

System model

□ Signal model

□ The equivalent channel from the q^{th} BS to the k^{th} user in the j^{th} cell:

$$\mathbf{f}_{q,j,k}^{\text{H}} = \mathbf{h}_{j,k}^{\text{H}} \Phi \mathbf{G}_q$$

□ The achievable rate of the k^{th} user in the j^{th} cell:

$$R_{j,k} = \log_2 \left(1 + \frac{|\mathbf{f}_{j,j,k}^{\text{H}} \mathbf{w}_{j,k}|^2}{\sum_{l=1, l \neq k}^K |\mathbf{f}_{j,j,k}^{\text{H}} \mathbf{w}_{j,l}|^2 + \sum_{q=1, q \neq j}^J \sum_{l=1}^K |\mathbf{f}_{q,j,k}^{\text{H}} \mathbf{w}_{q,l}|^2 + \sigma_{j,k}^2} \right)$$

□ Power consumption model

□ The total power consumption of RIS: $P_{\text{RIS}} = P_{\text{static}} + P_{\text{dynamic}}$,

□ The dynamic power consumption: $P_{\text{dynamic}} = \sum_{n=1}^N b_n(\beta_n) \cdot P_{\text{PIN}}$,

□ The total power consumption of the system:

$$P_{\text{total}} = \nu^{-1} \sum_{j=1}^J \sum_{k=1}^K \|\mathbf{w}_{j,k}\|^2 + P_{\text{RIS}} + P_{\text{const}}, \quad P_{\text{const}} = J(P_{\text{BS}} + K P_{\text{user}})$$

Energy efficiency optimization

□ The optimization problem

$$\begin{aligned}
 & \max_{\mathbf{w}_{j,k}, \boldsymbol{\theta}} \delta \\
 \text{s.t.} \quad & \sum_{k=1}^K \|\mathbf{w}_{j,k}\|^2 \leq P_{\max,j}, \quad \forall j, \\
 & R_{j,k} \geq R_{\min,j,k}, \quad \forall j, k, \\
 & \theta_n \in \mathcal{F}, \quad \forall n = 1, 2, \dots, N,
 \end{aligned}
 \quad
 \delta = \frac{\sum_{j=1}^J \sum_{k=1}^K \log_2(1 + \gamma_{j,k})}{\nu^{-1} \sum_{j=1}^J \sum_{k=1}^K \|\mathbf{w}_{j,k}\|^2 + P_{\text{RIS}} + P_{\text{const}}}.$$

□ The weighted minimum mean square error transformation

$$\begin{aligned}
 & \min_{\mathbf{w}_{j,k}, \boldsymbol{\theta}, \chi_{j,k}, r_{j,k}} g(\mathbf{w}_{j,k}, \boldsymbol{\theta}, \chi_{j,k}, r_{j,k}) \\
 \text{s.t.} \quad & \sum_{k=1}^K \|\mathbf{w}_{j,k}\|^2 \leq P_{\max,j}, \quad \forall j, \\
 & \theta_n \in \mathcal{F}, \quad \forall n = 1, 2, \dots, N.
 \end{aligned}
 \quad
 \begin{aligned}
 & g(\mathbf{w}_{j,k}, \boldsymbol{\theta}, \chi_{j,k}, r_{j,k}) \\
 & = \sum_{j=1}^J \sum_{k=1}^K [\chi_{j,k} E_{j,k} - (1 + \rho_{j,k}) \ln((1 + \rho_{j,k})^{-1} \chi_{j,k})] \\
 & + \lambda P_{\text{total}}.
 \end{aligned}$$

Transmit beamforming optimization

□ The origin problem:

$$\begin{aligned} & \min_{\mathbf{w}_{j,k}, \chi_{j,k}, r_{j,k}} g(\mathbf{w}_{j,k}, \boldsymbol{\theta}, \chi_{j,k}, r_{j,k}) \\ & \text{s.t.} \quad \sum_{k=1}^K \|\mathbf{w}_{j,k}\|^2 \leq P_{\max,j}, \forall j. \end{aligned}$$

□ The Lagrange dual transformation

$$\begin{aligned} & \min_{\mathbf{w}_{j,k}} \mathcal{L}_j(\mathbf{w}_{j,k}) \\ & = \sum_{k=1}^K \left(\sum_{q=1}^J \sum_{l=1}^K \chi_{q,l} |r_{q,l}|^2 \mathbf{w}_{j,k}^H \mathbf{f}_{j,q,l} \mathbf{f}_{j,q,l}^H \mathbf{w}_{j,k} \right) \\ & \quad - \sum_{k=1}^K (\chi_{j,k} r_{j,k}^* \mathbf{f}_{j,j,k}^H \mathbf{w}_{j,k}) \\ & \quad - \sum_{k=1}^K (\chi_{j,k} r_{j,k} \mathbf{w}_{j,k}^H \mathbf{f}_{j,j,k}) \\ & \quad + (\lambda \nu^{-1} + \eta_j) \sum_{k=1}^K \|\mathbf{w}_{j,k}\|^2, \forall j. \end{aligned}$$

□ The optimum value of the auxiliary variable

$$\chi_{j,k}^{\text{opt}} = (1 + \rho_{j,k}) E_{j,k}^{-1}.$$

$$r_{j,k}^{\text{opt}} = \varpi^{-1} \mathbf{f}_{j,j,k}^H \mathbf{w}_{j,k},$$

where

$$\varpi = \sum_{q=1}^J \sum_{l=1}^K (\mathbf{f}_{q,j,k}^H \mathbf{w}_{q,l} \mathbf{w}_{q,l}^H \mathbf{f}_{q,j,k}) + \sigma_{j,k}^2.$$

□ The optimal solution of the transmit beamforming vector

$$\mathbf{w}_{j,k}^{\text{opt}} = \chi_{j,k} r_{j,k} \boldsymbol{\Pi}^{-1} \mathbf{f}_{j,j,k}, \quad (25)$$

where

$$\boldsymbol{\Pi} = \sum_{q=1}^J \sum_{l=1}^K \chi_{q,l} |r_{q,l}|^2 \mathbf{f}_{j,q,l} \mathbf{f}_{j,q,l}^H + (\lambda \nu^{-1} + \eta_j) \mathbf{I}_M.$$

Phase shift matrix optimization

□ The origin problem:

$$\begin{aligned} & \min_{\theta} y(\theta) + \lambda P_{\text{dynamic}} \\ & \text{s.t. } \theta_n \in \mathcal{F}, \forall n = 1, 2, \dots, N. \end{aligned}$$

$$y(\theta) = \sum_{j=1}^J \sum_{k=1}^K \chi_{j,k} \left(\sum_{q=1}^J \sum_{l=1}^K |r_{j,k}|^2 f_{q,j,k}^H w_{q,l} w_{q,l}^H f_{q,j,k} - r_{j,k}^* f_{j,j,k}^H w_{j,k} - w_{q,l}^H f_{q,j,k} r_{j,k} \right).$$

□ Simplify the original problem

$$\begin{aligned} & \min_{\theta} \boldsymbol{\varphi}^H \left(\mathbf{Y} \odot \mathbf{Z}^T \right) \boldsymbol{\varphi} - 2 \operatorname{Re} \left\{ \boldsymbol{\varphi}^H \mathbf{q}^* \right\} + \lambda P_{\text{dynamic}} \\ & \text{s.t. } \theta_n \in \mathcal{F}, \forall n = 1, 2, \dots, N \end{aligned}$$

□ Construct a continuous function to approximate the relationship between the continuous phase shift and dynamic power consumption

$$b_n(\beta_n) = -\frac{1}{2} \cos \theta_n + \frac{1}{2}$$

$$\begin{aligned} \mathbf{Y}_{j,k} &= \chi_{j,k} |r_{j,k}|^2 \mathbf{h}_{j,k} \mathbf{h}_{j,k}^H, \\ \mathbf{Y} &= \sum_{j=1}^J \sum_{k=1}^K \mathbf{Y}_{j,k}, \\ \mathbf{Z} &= \sum_{q=1}^J \sum_{l=1}^K \mathbf{G}_q w_{q,l} w_{q,l}^H \mathbf{G}_q^H, \\ \mathbf{Q}_{j,k} &= \chi_{j,k} r_{j,k}^* \mathbf{G}_j w_{j,k} \mathbf{h}_{j,k}^H, \\ \mathbf{Q} &= \sum_{j=1}^J \sum_{k=1}^K \mathbf{Q}_{j,k}. \end{aligned}$$

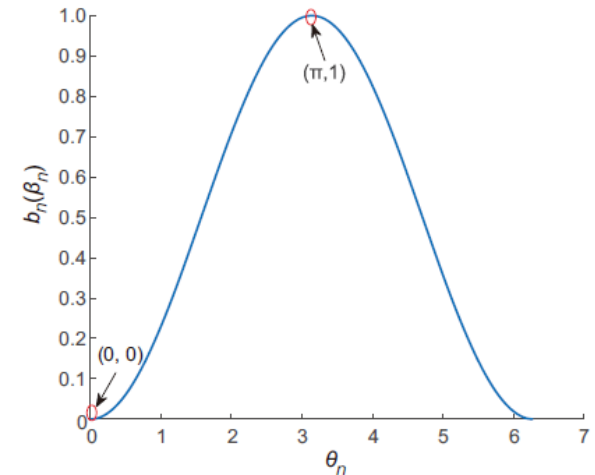


Fig. 2 $b_n(\beta_n)$ versus θ_n

Phase shift matrix optimization

□ The transformed problem:

$$\min_{\varphi} \left(\varphi^H (Y \odot Z^T) \varphi - 2\text{Re} \{ \varphi^H q^* \} - \frac{1}{2} \lambda P_{\text{PIN}} \text{Re} \{ \varphi^H \mathbf{1}_{N \times 1} \} \right)$$

s.t. $\theta_n \in [0, 2\pi), \forall n = 1, 2, \dots, N.$

□ Apply the MM algorithm to deal with the above non-convex optimization problem.

□ The upper bound of the objective function

$$\varphi^H \mathbf{W} \varphi - 2\text{Re} \{ \varphi^H (\mathbf{W} - Y \odot Z^T) \varphi^t \} + (\varphi^t)^H (\mathbf{W} - Y \odot Z^T) \varphi^t - \frac{1}{2} \lambda P_{\text{PIN}} \text{Re} \{ \varphi^H \mathbf{1}_{N \times 1} \}$$

□ The simplified problem:

$$\max_{\varphi} 2\text{Re} \{ \varphi^H \mathbf{x} \} \quad \mathbf{x} = (\mathbf{W} - Y \odot Z^T) \varphi^t + q^* + \frac{1}{4} \lambda P_{\text{PIN}} \mathbf{1}_{N \times 1}.$$

s.t. $\theta_n \in [0, 2\pi), \forall n = 1, 2, \dots, N,$

□ The optimal solution for RIS phase shift

$$\varphi^{\text{opt}} = e^{j \arg(\mathbf{x})}.$$

Simulation results

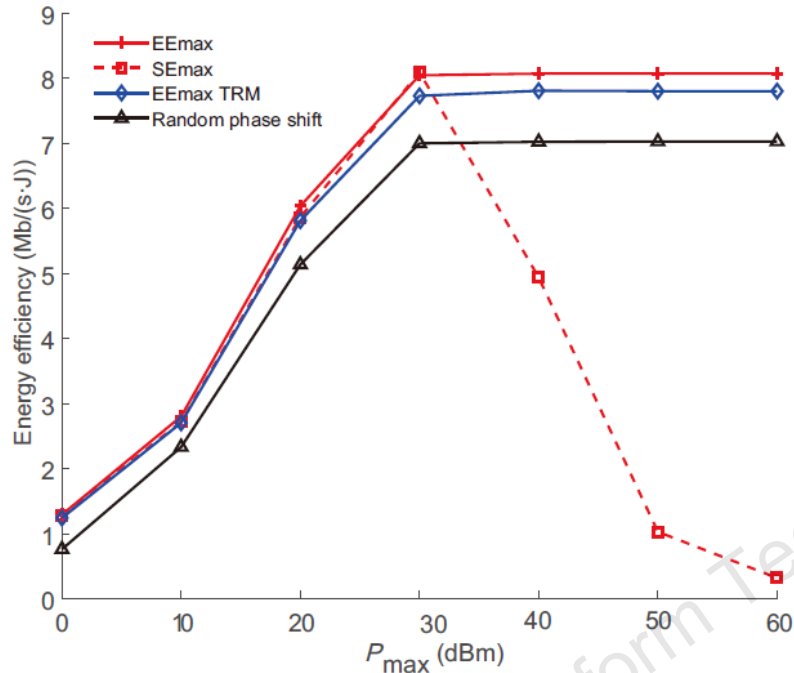


Fig. 3 Energy efficiency versus P_{\max} for our proposed algorithm and three benchmark algorithms

□ Comparing the EEmax and SEmax algorithms, for $P_{\max} > 30$ dBm, the energy efficiency of SEmax starts to degrade, which is due mainly to the larger power loss caused by the high transmit power.

□ It is observed that the impact of RIS phase shift on RIS power consumption is ignored in the theoretical RIS power consumption model. This leads to an increase in the total power consumption of the system, and thus a decrease in the energy efficiency of the system.

Simulation results

- Increasing the number of reflecting units is an effective way of improving the energy efficiency of the system
- The energy efficiency increases with the increase in the number of users.

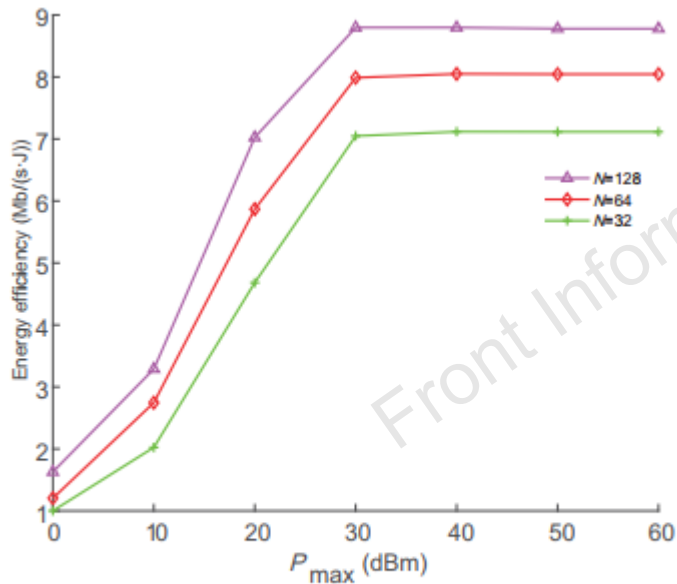


Fig. 4 Energy efficiency with different numbers of RIS reflecting units

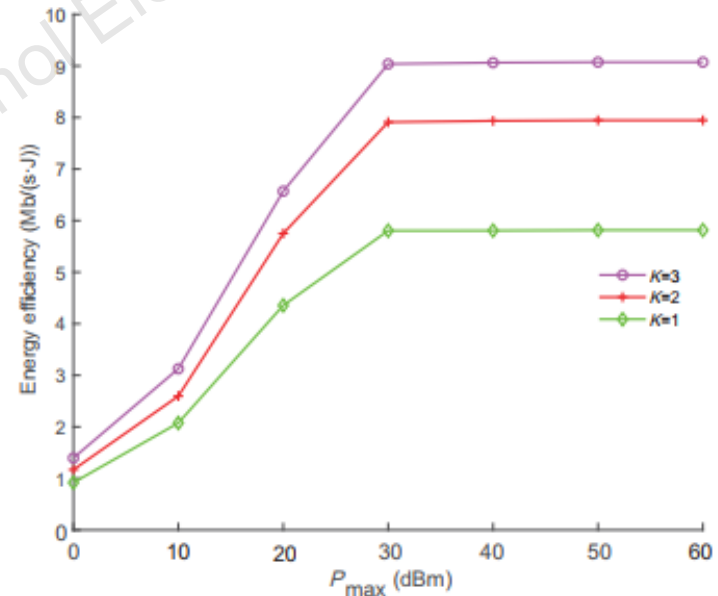


Fig. 5 Energy efficiency with different numbers of users

Simulation results

- ❑ The energy efficiency of the system is improved by increasing the number of BS antennas.
- ❑ As the user's minimum rate requirement increases, more BS power will be consumed to meet the requirement for users with rough channel conditions, which leads the energy efficiency of the system to decrease.

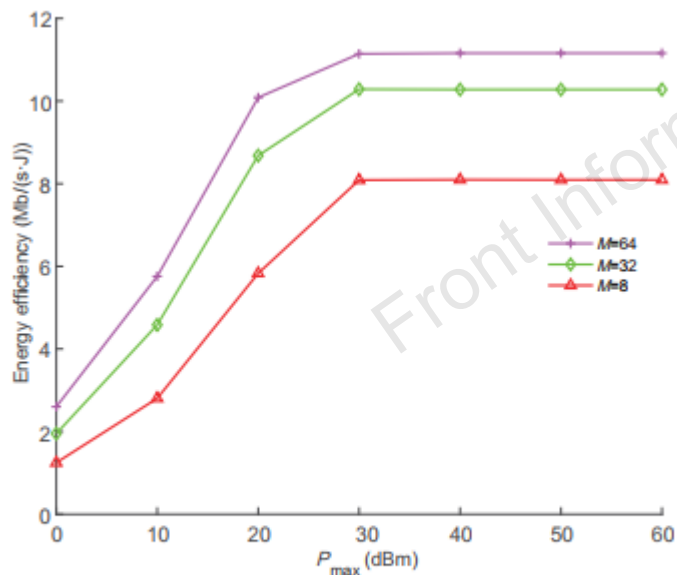


Fig. 6 Energy efficiency with different numbers of BS antennas

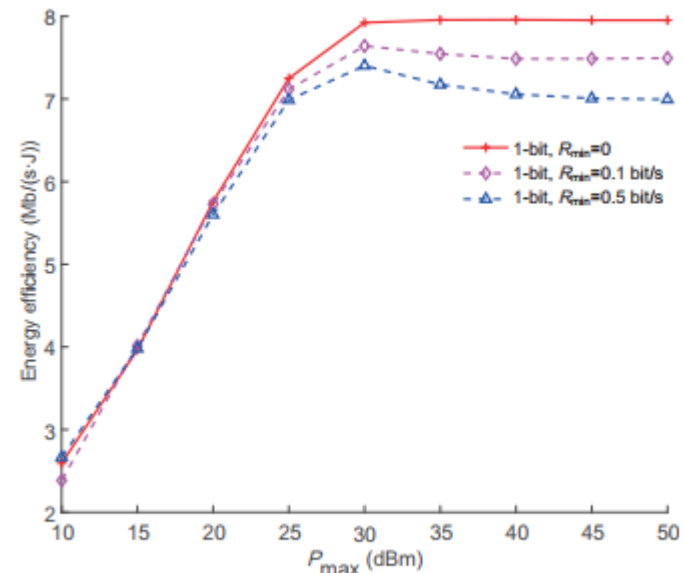


Fig. 7 Energy efficiency with different minimum rates

Conclusions

- ❑ The power consumption of practical RIS is closely related to the control circuit, bit resolution of RIS reflecting units, polarization direction, and encoding state of reflecting units, which cannot be ignored.
- ❑ To overcome the inconvenience of the discontinuity relationship between RIS power consumption and discrete phase shift, we establish a continuous alternative function.
- ❑ The proposed algorithm effectively optimizes the energy efficiency of the system as demonstrated by the simulation results.



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