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Joint Waveform and Beamforming Designs for RIS-ISAC Systems

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Education:

Ph.D. Dalian University of Technology, Dalian, China 2018 - 2023

B.S. Dalian University of Technology, Dalian, China 2014 - 2018

Research:

Integrated sensing and communications (ISAC)

Reconfigurable intelligent surfaces (RIS)

Symbol-level precoding

Physical layer security

CONTENT

01

PART ONE

Introduction of RIS-ISAC

Integrated Sensing and Communications (ISAC)

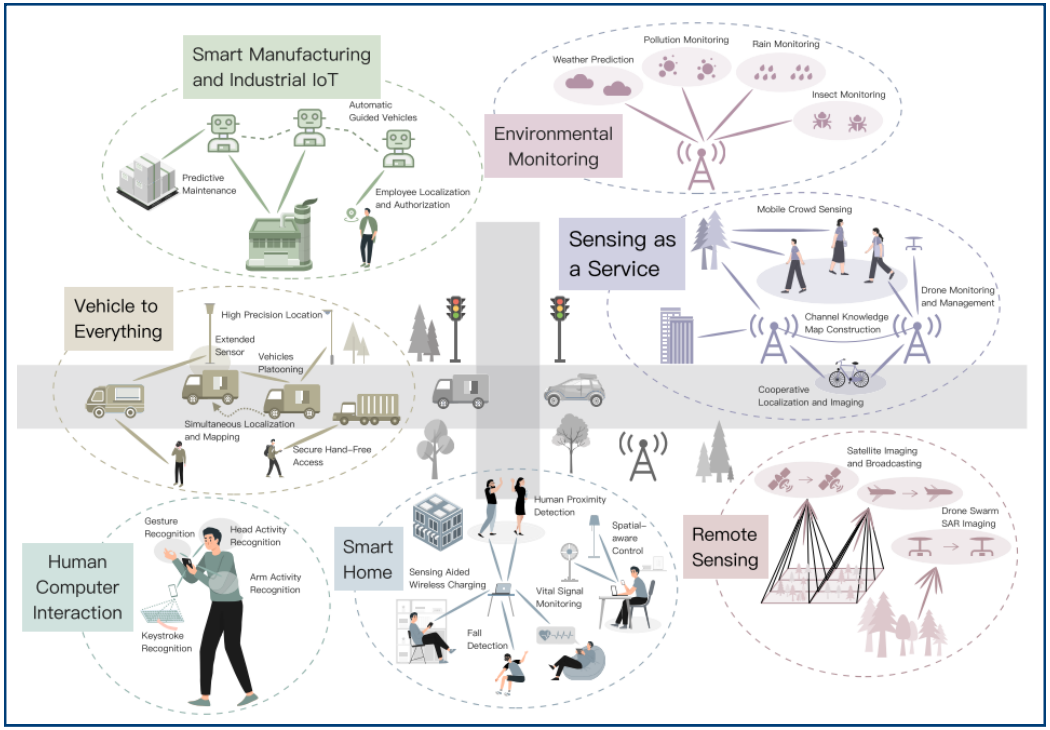

Fig. 1. ISAC technology for future wireless networks [1].

- Spectrum sharing
- Colocated hardware
- Unified waveform
- Joint signal processing

- High efficiencies
- Performance trade-off

High-quality ubiquitous communications and high-accuracy sensing!

[1] F. Liu, et al., "Integrated sensing and communications: Toward dual-functional wireless networks for 6G and beyond," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1728-1767, Jun. 2022.

Reconfigurable Intelligent Surfaces (RIS)

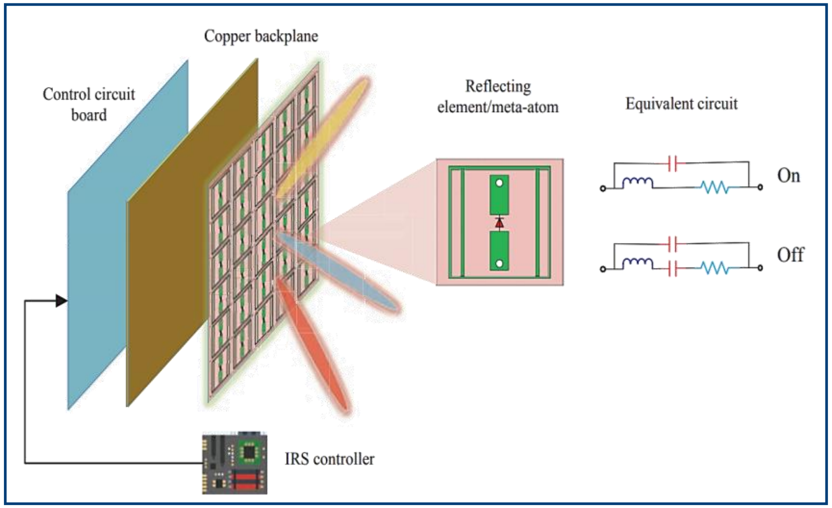

Fig. 2. Architecture of RIS [2].

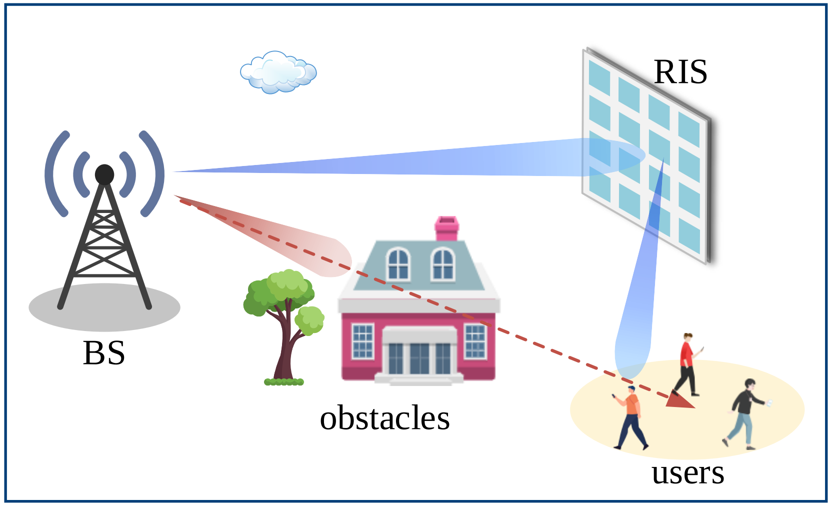

Fig. 3. A RIS-aided communication system.

- Passive reflection elements
- Adjusting the parameters of EM waves
- Cost-effective and hardware-efficient
- Reshaping radio environment

Low-cost, wide-coverage, and high-quality wireless networks!

[2] 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, Jan. 2020.

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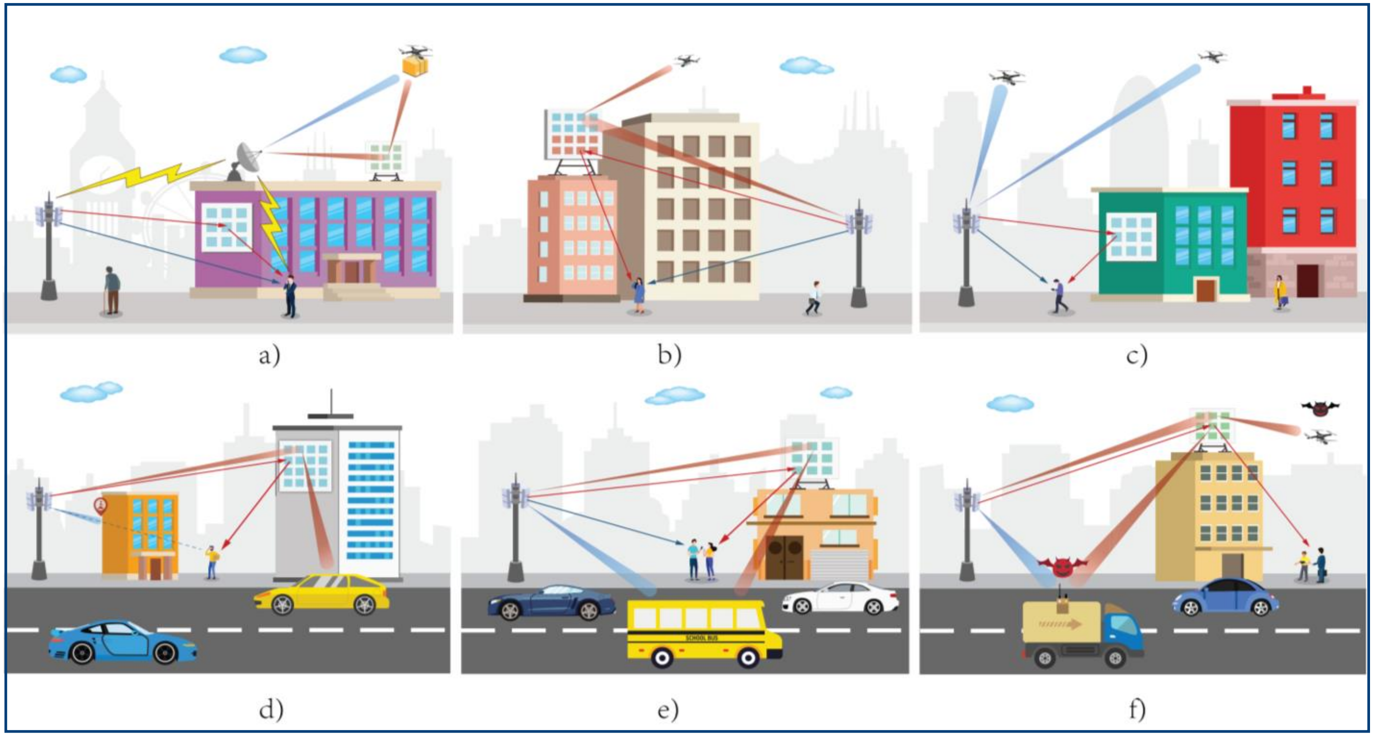
Background of RIS-ISAC



Virtual LoS link

New dimension

Fig. 4. Typical applications of RIS in ISAC systems [3].

[3] Rang Liu, M. Li, H. Luo, Q. Liu, and A. L. Swindlehurst, "Integrated sensing and communication with reconfigurable intelligent surfaces: Opportunities, applications, and future directions," *IEEE Wireless Commun.*, vol. 30, no. 1, pp. 50-57, Feb. 2023.

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Background of RIS-ISAC

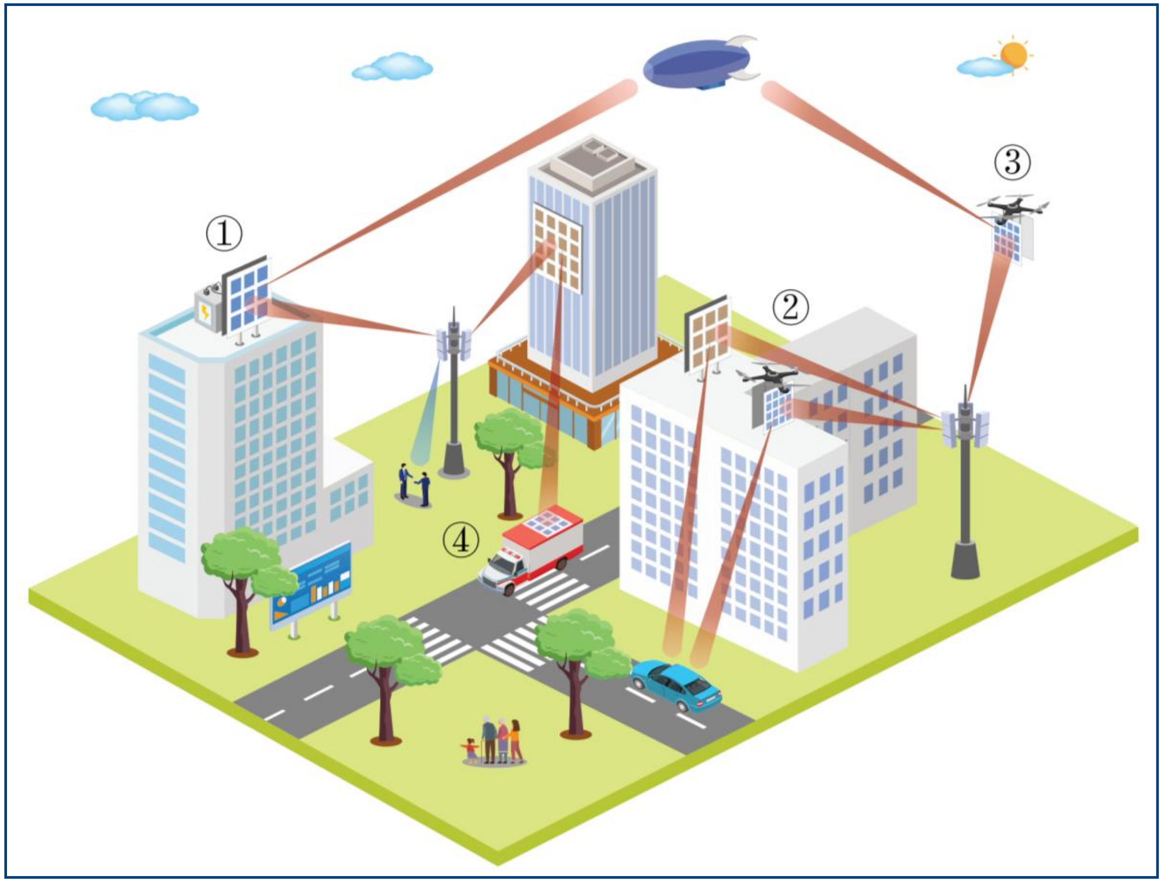


Fig. 5. Various RIS deployments in ISAC systems [3].

- active RIS
- multiple RISs
- UAV-mounted RIS
- target-mounted RIS

Background of RIS-ISAC

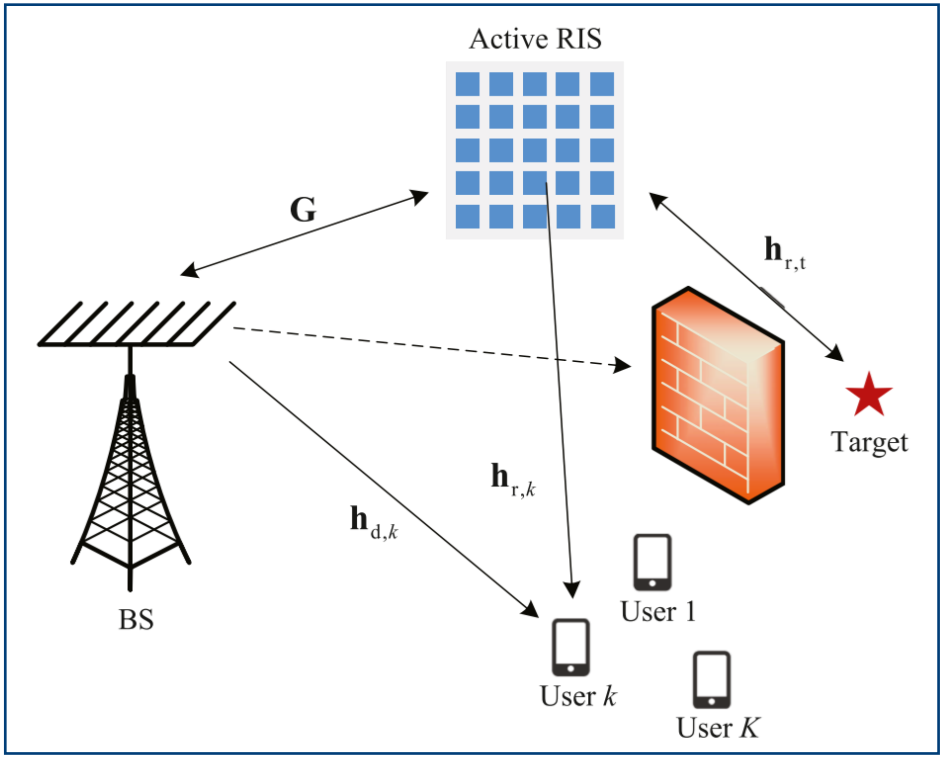


Fig. 6. An active RIS-assisted ISAC system [5].

Active RIS

- Multiplicative fading effect
- Reflection-type amplifiers
- Enhanced S&C performance
- Dynamic noise

[4] Q. Zhu, M. Li, Rang Liu, and Q. Liu, "Cramer-Rao bound optimization for active RIS-empowered ISAC systems," *IEEE Trans. Wireless Commun.*, major revision.

[5] Q. Zhu, M. Li, Rang Liu, and Q. Liu, "Joint transceiver beamforming and reflecting design for active RIS-aided ISAC systems," *IEEE Trans. Veh. Technol.*, vol. 72, no. 7, pp. 9636-9640, Jul. 2023.

Background of RIS-ISAC

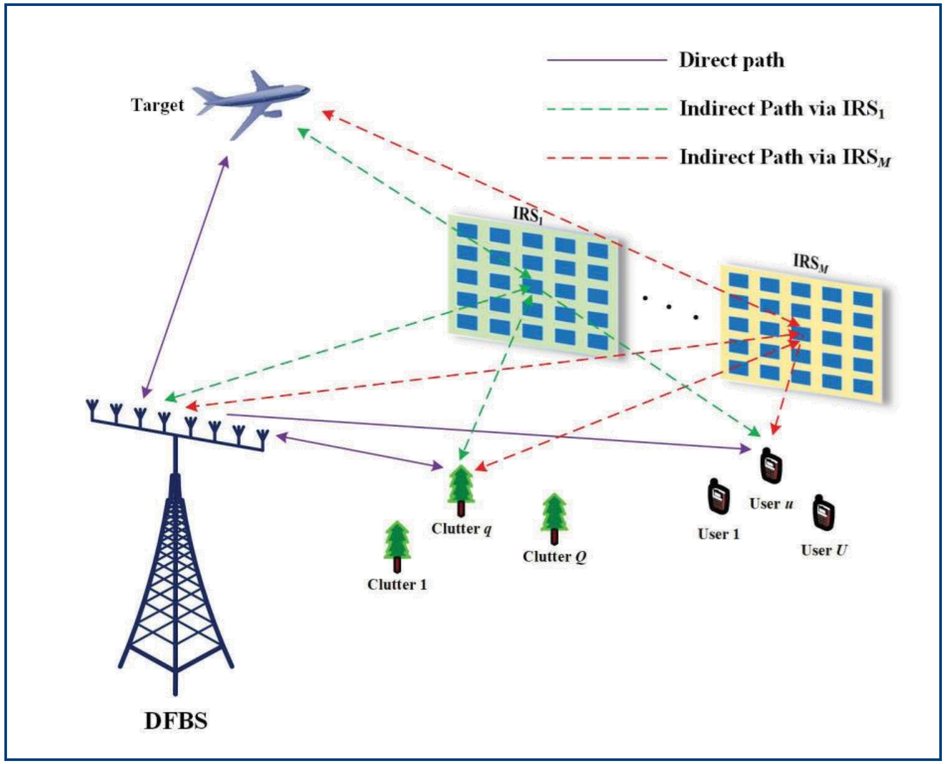


Fig. 7. A multi-RIS-aided ISAC system [6].

Multiple RISs

- Geographic diversity
- Hotspots/edge/blind areas
- High-dimensional optimization
- Deployment and control

[6] T. Wei, L. Wu, K. V. Mishra, and M. R. B. Shankar, "Multi-IRS-aided Doppler-tolerant wideband DFRC system," *IEEE Trans. Commun.*, vol. 71, no. 11, pp. 6561-6577, Nov. 2023.

Background of RIS-ISAC

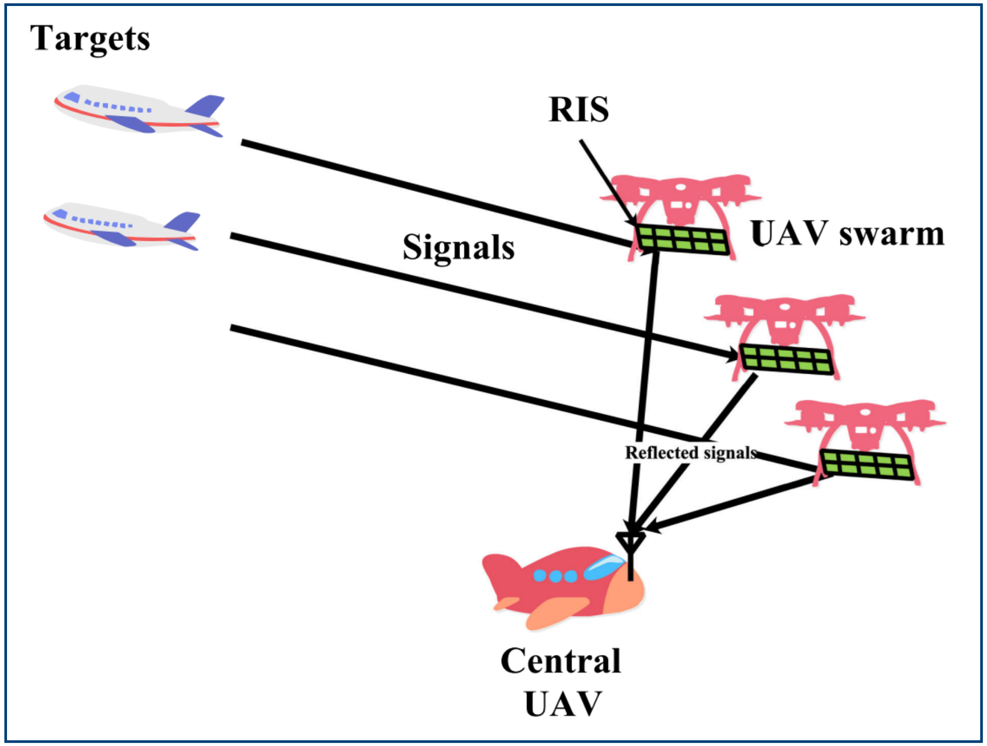


Fig. 8. An UAV-mounted RIS system [7].

UAV-mounted RIS

- High mobility and flexibility
- Wide coverage
- Joint UAV trajectory design

[7] P. Chen, Z. Chen, B. Zheng, and X. Wang, "Efficient DOA estimation method for reconfigurable intelligent surfaces aided UAV swarm," *IEEE Trans. Signal Process.*, vol. 70, pp. 743-755, 2022.

Background of RIS-ISAC

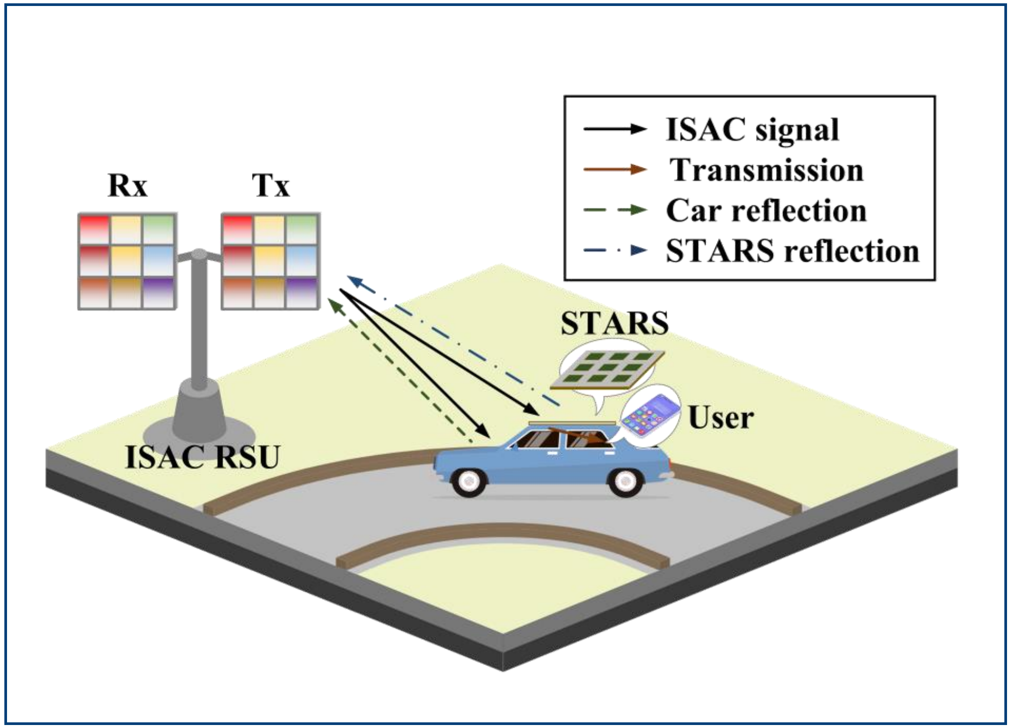


Fig. 9. The ISAC target-mounted STARS-assisted vehicular network [8].

Target-mounted RIS

- Cooperative target
- Improve backscatter signals
- Control mechanisms

[8] H. Zhang, Rang Liu, et al., “Joint sensing and communication optimization in target-mounted STARS-assisted vehicular networks: A MADRL approach,” *IEEE Trans. Veh. Technol*., to appear.

02

PART TWO

General System Model

System Model

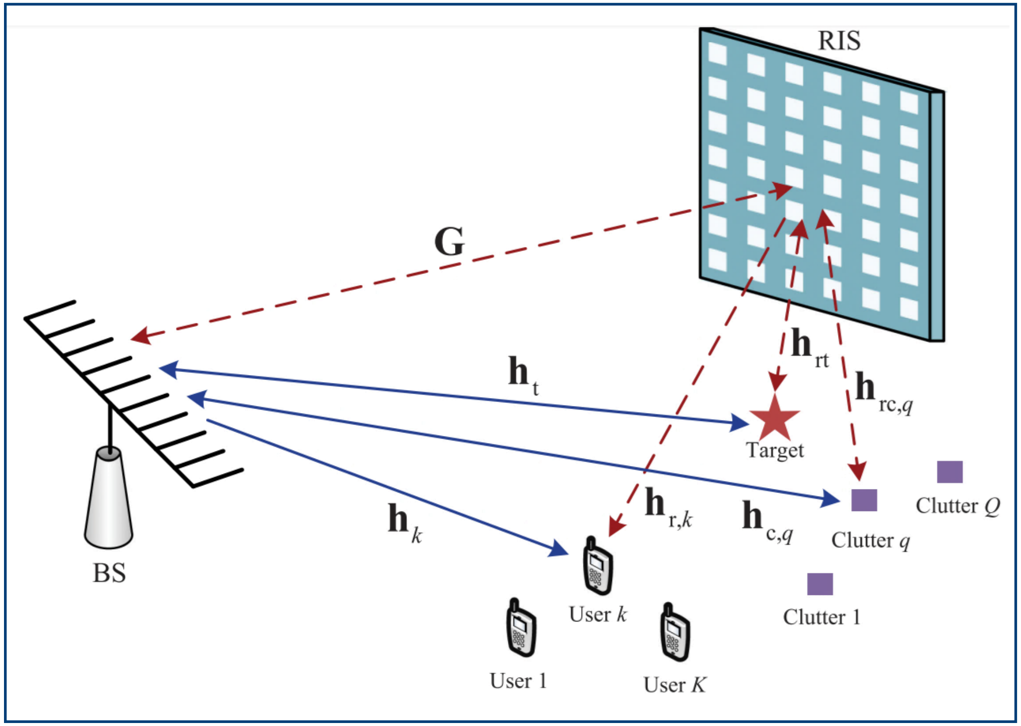


Fig. 10. A RIS-aided ISAC system.

- **Motivations**
  - new optimization dimension
  - wide-coverage service
- **Contributions**
  - general system model
  - better S&C performance
- **Techniques**
  - space-time adaptive processing
  - symbol-level precoding

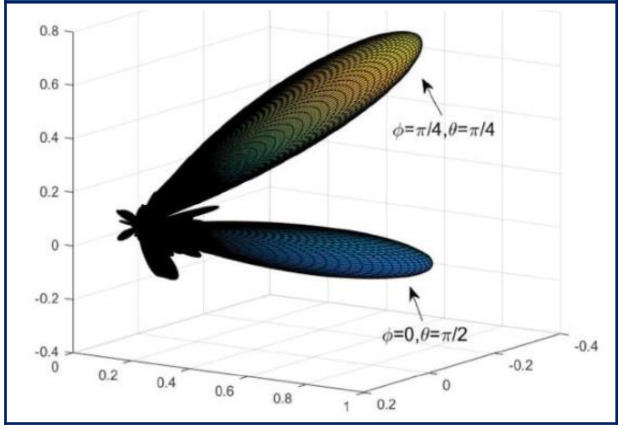
[9] Rang Liu, M. Li, Y. Liu, Q. Wu, and Q. Liu, "Joint transmit waveform and passive beamforming design for RIS-aided DFRC systems," *IEEE J. Sel. Topics Signal Process.*, vol. 16, no. 5, pp. 995-1010, Aug. 2022.

Performance metrics for sensing

- Target detection： identify the presence or absence of a target
  - **SNR**/**SINR**/detection probability
- Parameter estimation： estimate target azimuth angle/distance/velocity
  - **CRB**: the lower bound for any unbiased estimator
- General cases： favorable beampattern/waveform
  - beampattern, waveform similarity, mutual information, sidelobe level

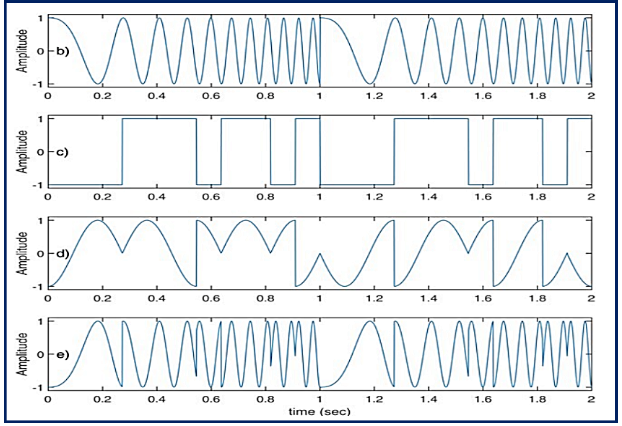
Dual-functional waveform & beamforming design

Spatial domain



VS

Time domain



Performance metrics for communications

- reliability: SNR/SINR, rate/**sum-rate**, **SER**
- efficiency: power/spectral efficiency

Block-level precoding & symbol-level precoding

Linear BLP		Non-Linear SLP
• Transmit signal: $\mathbf{x}_m = \mathbf{W}\mathbf{s}_m$ $\mathbf{X} = \mathbf{W}\mathbf{S}$ $\mathbf{X} \triangleq [\mathbf{x}_1, \ldots, \mathbf{x}_L]$ $\quad \mathbf{S} \triangleq [\mathbf{s}_1, \ldots, \mathbf{s}_L]$ • Receive signal: $y_{m,k} = \mathbf{h}_k^H \mathbf{W}\mathbf{s}_m + n_{m,k}$ • Performance metric: $\mathrm{SINR}_k = \frac{\lvert \mathbf{h}_k^H \mathbf{w}_k \rvert^2}{\boxed{\sum_{j=1, j\neq k}^{K} \lvert \mathbf{h}_k^H \mathbf{w}_j \rvert^2} + \sigma_k^2}$ - statistical information - MUI suppression	**VS**	• Transmit signal: $\mathbf{s}_m \rightarrow \mathbf{x}_m$ • Receive signal: $r_{m,k} = \mathbf{h}_k^H \mathbf{x}_m + n_{m,k}$ • Performance metric: safety margin - symbol-dependent - MUI exploitation symbol inform. ⇨ temporal DoFs

Radar Sensing Model

- The received signal at the BS:

$$\mathbf{r}[l] = \alpha_0(\mathbf{h}_{\mathrm{t}}+\mathbf{G}^H\boldsymbol{\Phi}\mathbf{h}_{\mathrm{rt}})(\mathbf{h}_{\mathrm{t}}^H+\mathbf{h}_{\mathrm{rt}}^H\boldsymbol{\Phi}\mathbf{G})\mathbf{x}[l]e^{\jmath 2\pi(l-1)\nu_0}+\mathbf{c}[l]+\mathbf{z}[l]$$

target RCS — 4 different paths $\mathbf{H}_0(\boldsymbol{\phi})$ — Doppler frequency

- Clutter returns:

$$\mathbf{c}[l] = \sum_{q=1}^{Q}\alpha_q(\mathbf{h}_{\mathrm{c},q}+\mathbf{G}^H\boldsymbol{\Phi}\mathbf{h}_{\mathrm{rc},q})(\mathbf{h}_{\mathrm{c},q}^H+\mathbf{h}_{\mathrm{rc},q}^H\boldsymbol{\Phi}\mathbf{G})\mathbf{x}[l-r_q]e^{\jmath 2\pi(l-1)\nu_q}$$

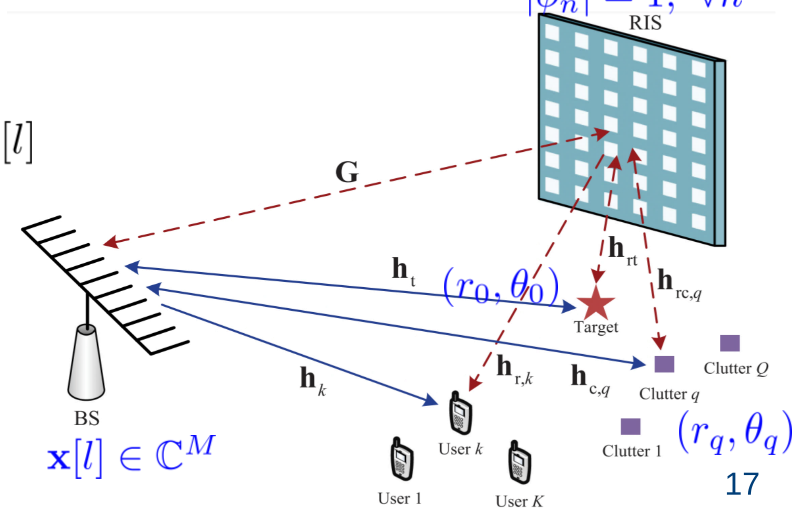
$\mathbf{H}_q(\boldsymbol{\phi})$

- The received signal in the *l*-th time slot:

$$\mathbf{r}[l] = \alpha_0\mathbf{H}_0(\boldsymbol{\phi})\mathbf{x}[l] + \sum_{q=1}^{Q}\alpha_q\mathbf{H}_q(\boldsymbol{\phi})\mathbf{x}[l-r_q] + \mathbf{z}[l]$$

$\boldsymbol{\phi} \triangleq [\phi_1, \ldots, \phi_N]^T$

$|\phi_n| = 1, \ \forall n$



Sensing Performance Metrics

- The received signal during one CPI:

$$\mathbf{r} = \alpha_0 \widetilde{\mathbf{H}}_0(\boldsymbol{\phi})\mathbf{x} + \sum_{q=1}^{Q} \alpha_q \widetilde{\mathbf{H}}_q(\boldsymbol{\phi})\mathbf{x} + \mathbf{z}$$

$$\widetilde{\mathbf{H}}_0(\boldsymbol{\phi}) \triangleq \mathbf{I}_L \otimes \mathbf{H}_0(\boldsymbol{\phi}), \qquad \widetilde{\mathbf{H}}_q(\boldsymbol{\phi}) \triangleq [\mathbf{I}_L \otimes \mathbf{H}_q(\boldsymbol{\phi})]\mathbf{J}_{r_q}, \qquad \mathbf{J}_{r_q}(i,j) = \begin{cases} 1, & i-j = Mr_q \\ 0, & \text{otherwise} \end{cases}$$

- The output after the linear space-time receive filter:

$$\mathbf{w}^H\mathbf{r} = \alpha_0 \mathbf{w}^H \widetilde{\mathbf{H}}_0(\boldsymbol{\phi})\mathbf{x} + \mathbf{w}^H \sum_{q=1}^{Q} \alpha_q \widetilde{\mathbf{H}}_q(\boldsymbol{\phi})\mathbf{x} + \mathbf{w}^H\mathbf{z}$$

- The radar output SINR:

$$\boxed{\gamma_{\mathrm{r}} = \frac{\varsigma_0^2 |\mathbf{w}^H \widetilde{\mathbf{H}}_0(\boldsymbol{\phi})\mathbf{x}|^2}{\mathbf{w}^H \left[\sum_{q=1}^{Q} \varsigma_q^2 \widetilde{\mathbf{H}}_q(\boldsymbol{\phi})\mathbf{x}\mathbf{x}^H \widetilde{\mathbf{H}}_q^H(\boldsymbol{\phi}) + \varsigma_{\mathrm{z}}^2 \mathbf{I}_{ML}\right]\mathbf{w}}}$$

- The constant-modulus waveform:

$$|x_i| = \sqrt{P/M}, \quad \forall i = 1, \ldots, ML$$

Communication Model

- The communication symbols in the l-th time slot:

$$\mathbf{s}[l] \triangleq [s_1[l], \ldots, s_K[l]]^T$$

- The received signal of the k-th user:

$$r_k[l] = (\mathbf{h}_k^H + \mathbf{h}_{\mathrm{r},k}^H \mathbf{\Phi} \mathbf{G})\mathbf{x}[l] + n_k[l], \quad \forall l$$

- The received noise-free signal:

$$\overrightarrow{OD} = \widetilde{r}_k[l] = (\mathbf{h}_k^H + \mathbf{h}_{\mathrm{r},k}^H \mathbf{\Phi} \mathbf{G})\mathbf{x}[l]$$

$$\widetilde{r}_k[l] = \left[\mathbf{e}_l^T \otimes \left(\mathbf{h}_k^H + \boldsymbol{\phi}^T \mathrm{diag}\{\mathbf{h}_{\mathrm{r},k}^H\}\mathbf{G}\right)\right]\mathbf{x}$$

- The desired symbol with the required SNR:

$$\overrightarrow{OA} = \sigma_k \sqrt{\Gamma_k} s_k[l]$$

- The multiuser interference:

$$\overrightarrow{OD} - \overrightarrow{OA} = (\mathbf{h}_k^H + \mathbf{h}_{\mathrm{r},k}^H \mathbf{\Phi} \mathbf{G})\mathbf{x}[l] - \sigma_k \sqrt{\Gamma_k} s_k[l]$$

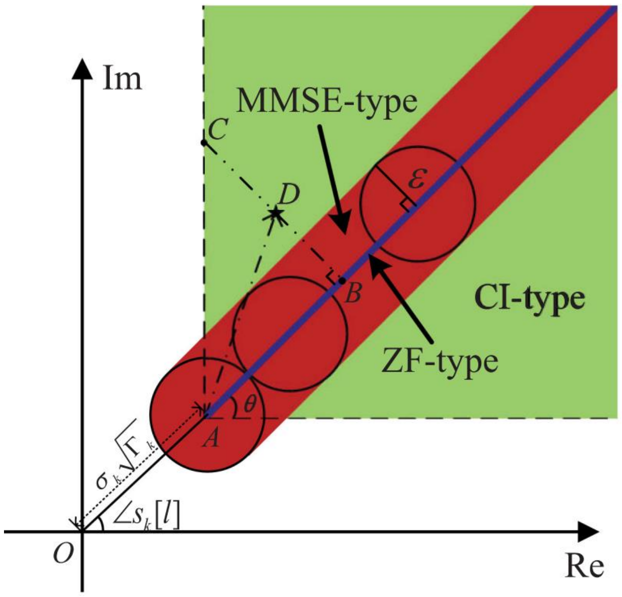


Fig. 11. Illustration of handling MUI.

- ZF-type communication metric:

$$(\mathbf{h}_k^H + \mathbf{h}_{\mathrm{r},k}^H \mathbf{\Phi}\mathbf{G})\mathbf{x}[l] = \sigma_k \sqrt{\Gamma_k} s_k[l]$$

$$\Downarrow$$

$$(\mathbf{h}_k^H + \mathbf{h}_{\mathrm{r},k}^H \mathbf{\Phi}\mathbf{G})\mathbf{x}[l] = \underbrace{\alpha_{k,l}}_{\text{scaling factor}} \sigma_k \sqrt{\Gamma_k} s_k[l], \ \alpha_{k,l} \geq 1, \ \forall k, l$$

- MMSE-type communication metric:

$$\left|(\mathbf{h}_k^H + \mathbf{h}_{\mathrm{r},k}^H \mathbf{\Phi}\mathbf{G})\mathbf{x}[l] - \alpha_{k,l}\sigma_k \sqrt{\Gamma_k} s_k[l]\right|^2 \leq \epsilon, \ \alpha_{k,l} \geq 1, \ \forall k, l$$

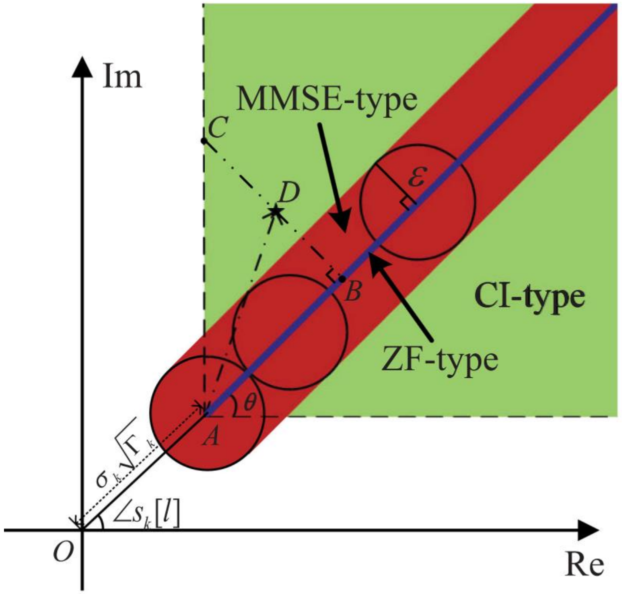
- CI-type communication metric:

$$\Re\{(\mathbf{h}_k^H + \mathbf{h}_{\mathrm{r},k}^H \mathbf{\Phi}\mathbf{G})\mathbf{x}[l] e^{-\jmath \angle s_k[l]} - \sigma_k \sqrt{\Gamma_k}\} \sin\theta - \left|\Im\{(\mathbf{h}_k^H + \mathbf{h}_{\mathrm{r},k}^H \mathbf{\Phi}\mathbf{G})\mathbf{x}[l] e^{-\jmath \angle s_k[l]}\}\right| \cos\theta \geq 0, \ \forall k, l$$

- Reformulated as

$$\boxed{\begin{aligned} &[\mathbf{h}_{k,l}^H + (\mathbf{e}_l^T \otimes \boldsymbol{\phi}^T)\mathbf{G}_k]\mathbf{x} = \alpha_{k,l}\gamma_{k,l}^{\mathrm{ZF}}, \quad \alpha_{k,l} \geq 1, \ \forall k, l \\ &\left|[\mathbf{h}_{k,l}^H + (\mathbf{e}_l^T \otimes \boldsymbol{\phi}^T)\mathbf{G}_k]\mathbf{x} - \alpha_{k,l}\gamma_{k,l}^{\mathrm{ZF}}\right|^2 \leq \epsilon, \ \alpha_{k,l} \geq 1, \ \forall k, l \\ &\Re\{\gamma_{k,l}^{\mathrm{CI}}[\mathbf{h}_{k,l}^H + (\mathbf{e}_l^T \otimes \boldsymbol{\phi}^T)\mathbf{G}_k]\mathbf{x}\} \geq 1, \quad \forall k, l \end{aligned}}$$

Different strategies of handling MUI



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Problem Formulation

$$\begin{aligned}\max_{\mathbf{x},\boldsymbol{\alpha},\mathbf{w},\boldsymbol{\phi}} \quad & \frac{\varsigma_0^2|\mathbf{w}^H\widetilde{\mathbf{H}}_0(\boldsymbol{\phi})\mathbf{x}|^2}{\mathbf{w}^H\left[\sum_{q=1}^{Q}\varsigma_q^2\widetilde{\mathbf{H}}_q(\boldsymbol{\phi})\mathbf{x}\mathbf{x}^H\widetilde{\mathbf{H}}_q^H(\boldsymbol{\phi})+\varsigma_{\mathrm{z}}^2\mathbf{I}_{ML}\right]\mathbf{w}} \\ \text{s.t.} \quad & \text{communication QoS constraints} \\ & |x_i| = \sqrt{P/M}, \quad \forall i \\ & |\phi_n| = 1, \quad \forall n\end{aligned}$$

- The optimal solution to the receive filter:

$$\mathbf{w}^\star = \frac{\left[\sum_{q=1}^{Q}\varsigma_q^2\widetilde{\mathbf{H}}_q(\boldsymbol{\phi})\mathbf{x}\mathbf{x}^H\widetilde{\mathbf{H}}_q^H(\boldsymbol{\phi})+\varsigma_{\mathrm{z}}^2\mathbf{I}\right]^{-1}\widetilde{\mathbf{H}}_0(\boldsymbol{\phi})\mathbf{x}}{\mathbf{x}^H\widetilde{\mathbf{H}}_0^H(\boldsymbol{\phi})\left[\sum_{q=1}^{Q}\varsigma_q^2\widetilde{\mathbf{H}}_q(\boldsymbol{\phi})\mathbf{x}\mathbf{x}^H\widetilde{\mathbf{H}}_q^H(\boldsymbol{\phi})+\varsigma_{\mathrm{z}}^2\mathbf{I}\right]^{-1}\widetilde{\mathbf{H}}_0(\boldsymbol{\phi})\mathbf{x}}$$

- The optimization problem is transformed into:

$$\begin{aligned}\min_{\mathbf{x},\boldsymbol{\alpha},\boldsymbol{\phi}} \quad & -\mathbf{x}^H\widetilde{\mathbf{H}}_0^H(\boldsymbol{\phi})\left[\sum_{q=1}^{Q}\varsigma_q^2\widetilde{\mathbf{H}}_q(\boldsymbol{\phi})\mathbf{x}\mathbf{x}^H\widetilde{\mathbf{H}}_q^H(\boldsymbol{\phi})+\varsigma_{\mathrm{z}}^2\mathbf{I}\right]^{-1}\widetilde{\mathbf{H}}_0(\boldsymbol{\phi})\mathbf{x} \\ \text{s.t.} \quad & \text{communication QoS constraints} \\ & |x_i| = \sqrt{P/M}, \quad \forall i \\ & |\phi_n| = 1, \quad \forall n\end{aligned}$$

03 PART THREE

Joint Designs for RIS-ISAC

Joint Transmit Waveform and Beamforming Design

A. ADMM-based transformation

$$\min_{\mathbf{x},\boldsymbol{\alpha},\mathbf{y},\boldsymbol{\varphi},\boldsymbol{\phi}} \; f_1(\mathbf{x},\boldsymbol{\phi}) \triangleq -\mathbf{x}^H\widetilde{\mathbf{H}}_0^H(\boldsymbol{\phi})\Big[\sum_{q=1}^{Q}\varsigma_q^2\widetilde{\mathbf{H}}_q(\boldsymbol{\phi})\mathbf{x}\mathbf{x}^H\widetilde{\mathbf{H}}_q^H(\boldsymbol{\phi})+\varsigma_z^2\mathbf{I}\Big]^{-1}\widetilde{\mathbf{H}}_0(\boldsymbol{\phi})\mathbf{x}$$

s.t. communication QoS constraints

$$|x_i| \le \sqrt{P/M}, \quad \forall i$$
$$|\phi_n| \le 1, \quad \forall n$$
$$|y_i| = \sqrt{P/M}, \quad \forall i$$
$$|\varphi_n| = 1, \quad \forall n$$

indicator function $\mathbb{I}(\mathbf{x},\boldsymbol{\alpha},\mathbf{y},\boldsymbol{\phi},\boldsymbol{\varphi})$

$$\mathbf{y} = \mathbf{x}$$
$$\boldsymbol{\varphi} = \boldsymbol{\phi}$$

auxiliary variables

$$\begin{aligned}\min_{\mathbf{x},\boldsymbol{\alpha},\mathbf{y},\boldsymbol{\varphi},\boldsymbol{\phi}} \quad & f_1(\mathbf{x},\boldsymbol{\phi}) + \mathbb{I}(\mathbf{x},\boldsymbol{\alpha},\mathbf{y},\boldsymbol{\phi},\boldsymbol{\varphi}) \\ \text{s.t.} \quad & \mathbf{y} = \mathbf{x} \\ & \boldsymbol{\varphi} = \boldsymbol{\phi}\end{aligned}$$

- The augmented Lagrangian function:

$$\begin{aligned}\mathcal{L}(\mathbf{x},\boldsymbol{\alpha},\mathbf{y},\boldsymbol{\phi},\boldsymbol{\varphi},\boldsymbol{\mu}_1,\boldsymbol{\mu}_2) \triangleq\; & f_1(\mathbf{x},\boldsymbol{\phi}) + \mathbb{I}(\mathbf{x},\boldsymbol{\alpha},\mathbf{y},\boldsymbol{\phi},\boldsymbol{\varphi}) \\ & + \frac{\rho}{2}\Big\|\mathbf{x}-\mathbf{y}+\frac{\boldsymbol{\mu}_1}{\rho}\Big\|^2 + \frac{\rho}{2}\Big\|\boldsymbol{\phi}-\boldsymbol{\varphi}+\frac{\boldsymbol{\mu}_2}{\rho}\Big\|^2\end{aligned}$$

B. MM-based transformation

- A surrogate function constructed by using the first-order Taylor expansion:

$$\mathbf{s}^H\mathbf{M}^{-1}\mathbf{s} \geq 2\Re\{\mathbf{s}_t^H\mathbf{M}_t^{-1}\mathbf{s}\} - \mathrm{Tr}\{\mathbf{M}_t^{-1}\mathbf{s}_t\mathbf{s}_t^H\mathbf{M}_t^{-1}\mathbf{M}\} + c$$

$$\Downarrow$$

$$f_1(\mathbf{x},\boldsymbol{\phi}) \leq \mathrm{Tr}\Big\{\mathbf{M}_t^{-1}\mathbf{s}_t\mathbf{s}_t^H\mathbf{M}_t^{-1}\Big[\sum_{q=1}^{Q}\varsigma_q^2\widetilde{\mathbf{H}}_q(\boldsymbol{\phi})\mathbf{x}\mathbf{x}^H\widetilde{\mathbf{H}}_q^H(\boldsymbol{\phi})\Big]\Big\} - 2\Re\{\mathbf{s}_t^H\mathbf{M}_t^{-1}\widetilde{\mathbf{H}}_0(\boldsymbol{\phi})\mathbf{x}\} + c_1$$

$$\Downarrow$$

- The surrogate AL function:

$$\begin{aligned}\mathcal{L}(\mathbf{x},\boldsymbol{\alpha},\mathbf{y},\boldsymbol{\phi},\boldsymbol{\varphi},\boldsymbol{\mu}_1,\boldsymbol{\mu}_2) \leq\ & \mathrm{Tr}\Big\{\mathbf{M}_t^{-1}\mathbf{s}_t\mathbf{s}_t^H\mathbf{M}_t^{-1}\Big[\sum_{q=1}^{Q}\varsigma_q^2\widetilde{\mathbf{H}}_q(\boldsymbol{\phi})\mathbf{x}\mathbf{x}^H\widetilde{\mathbf{H}}_q^H(\boldsymbol{\phi})\Big]\Big\} \\ & - 2\Re\{\mathbf{s}_t^H\mathbf{M}_t^{-1}\widetilde{\mathbf{H}}_0(\boldsymbol{\phi})\mathbf{x}\} + c_1 + \mathbb{I}(\mathbf{x},\boldsymbol{\alpha},\mathbf{y},\boldsymbol{\phi},\boldsymbol{\varphi}) \\ & + \frac{\rho}{2}\Big\|\mathbf{x}-\mathbf{y}+\frac{\boldsymbol{\mu}_1}{\rho}\Big\|^2 + \frac{\rho}{2}\Big\|\boldsymbol{\phi}-\boldsymbol{\varphi}+\frac{\boldsymbol{\mu}_2}{\rho}\Big\|^2\end{aligned}$$

$$\Downarrow$$

Block update

C. Update **x** and **α**

$$\begin{aligned}
\min_{\mathbf{x},\boldsymbol{\alpha}} \quad & \mathbf{x}^H \mathbf{D}_t \mathbf{x} + \Re\{\mathbf{d}_t^H \mathbf{x}\} \\
\text{s.t.} \quad & \widetilde{\mathbf{h}}_{k,l}^H \mathbf{x} = \alpha_{k,l}\gamma_{k,l}^{\text{ZF}}, \quad \alpha_{k,l} \geq 1, \quad \forall k,l \\
& \text{or} \quad \left|\widetilde{\mathbf{h}}_{k,l}^H \mathbf{x} - \alpha_{k,l}\gamma_{k,l}^{\text{ZF}}\right|^2 \leq \epsilon, \quad \alpha_{k,l} \geq 1, \quad \forall k,l \\
& \text{or} \quad \Re\{\gamma_{k,l}^{\text{CI}} \widetilde{\mathbf{h}}_{k,l}^H \mathbf{x}\} \geq 1, \quad \forall k,l \\
& |x_i| \leq \sqrt{P/M}, \quad \forall i
\end{aligned}$$

Convex problem

D. Update **y**

$$\begin{aligned}
\min_{\mathbf{y}} \quad & \left\|\mathbf{x}_t - \mathbf{y} + \frac{\boldsymbol{\mu}_1}{\rho}\right\|^2 \\
\text{s.t.} \quad & |y_i| = \sqrt{P/M}, \quad \forall i
\end{aligned}
\quad \Rightarrow \quad \mathbf{y}^\star = \sqrt{P/M} e^{\jmath \angle(\rho \mathbf{x}_t + \boldsymbol{\mu}_1)}$$

E. Update **ϕ**

$$\begin{aligned}
\min_{\boldsymbol{\phi}} \; f_2(\boldsymbol{\phi}) = & \boldsymbol{\phi}^H \mathbf{F}_t \boldsymbol{\phi} + \Re\{\boldsymbol{\phi}^H \mathbf{f}_t\} + \mathbf{v}^H \mathbf{F}_{\text{v},t} \mathbf{v} + \Re\{\mathbf{v}^H \mathbf{f}_{\text{v},t}\} \\
& + \Re\{\mathbf{v}^H \mathbf{L}_t \boldsymbol{\phi}\} + c_2 + \frac{\rho}{2}\left\|\boldsymbol{\phi} - \boldsymbol{\varphi}_t + \frac{\boldsymbol{\mu}_2}{\rho}\right\|^2 \\
\text{s.t.} \quad & \text{communication QoS constraints} \\
& |\phi_n| \leq 1, \quad \forall n
\end{aligned}$$

$$\boxed{\begin{aligned} \mathbf{v} & \triangleq \text{vec}\{\boldsymbol{\phi}\boldsymbol{\phi}^T\} \\ & = \boldsymbol{\phi} \otimes \boldsymbol{\phi} \end{aligned}}$$

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- Construct a tractable surrogate function

$$
\begin{aligned}
f_2(\boldsymbol{\phi}) \leq\ & \boldsymbol{\phi}^H \mathbf{F}_t \boldsymbol{\phi} + \Re\{\boldsymbol{\phi}^H \mathbf{f}_t\} + \frac{\lambda_2}{2}\boldsymbol{\phi}^H\boldsymbol{\phi} + \Re\{\boldsymbol{\phi}^H \mathbf{U}\bar{\mathbf{f}}_{\mathrm{v},t}\} + c_3 \\
& + c_4 + \frac{\lambda_3}{2}\boldsymbol{\phi}^H\boldsymbol{\phi} + \Re\{\boldsymbol{\phi}^H \mathbf{U}\bar{\boldsymbol{\ell}}_t\} + c_5 + c_2 + \frac{\rho}{2}\left\|\boldsymbol{\phi} - \boldsymbol{\varphi}_t + \frac{\boldsymbol{\mu}_2}{\rho}\right\|^2 \\
=\ & \boldsymbol{\phi}^H \widetilde{\mathbf{F}}_t \boldsymbol{\phi} + \Re\{\boldsymbol{\phi}^H \widetilde{\mathbf{f}}_t\} + c_6
\end{aligned}
$$

- Solve for **ϕ**

$$
\begin{aligned}
\min_{\boldsymbol{\phi}} \quad & \boldsymbol{\phi}^H \widetilde{\mathbf{F}}_t \boldsymbol{\phi} + \Re\{\boldsymbol{\phi}^H \widetilde{\mathbf{f}}_t\} \\
\text{s.t.} \quad & \mathbf{h}_{k,l}^H \mathbf{x} + \widetilde{\mathbf{g}}_{k,l}^T \boldsymbol{\phi} = \alpha_{k,l}\gamma_{k,l}^{\mathrm{ZF}}, \quad \alpha_{k,l} \geq 1, \quad \forall k,l \\
& \text{or} \quad \left|\mathbf{h}_{k,l}^H \mathbf{x} + \widetilde{\mathbf{g}}_{k,l}^T \boldsymbol{\phi} - \alpha_{k,l}\gamma_{k,l}^{\mathrm{ZF}}\right|^2 \leq \epsilon, \ \alpha_{k,l} \geq 1, \ \forall k,l \\
& \text{or} \quad \Re\left\{\gamma_{k,l}^{\mathrm{CI}}(\mathbf{h}_{k,l}^H \mathbf{x} + \widetilde{\mathbf{g}}_{k,l}^T \boldsymbol{\phi})\right\} \geq 1, \quad \forall k,l \\
& |\phi_n| \leq 1, \quad \forall n
\end{aligned}
$$

Convex problem

F. Update **φ** $\boldsymbol{\varphi}^\star = e^{\jmath\angle(\rho\boldsymbol{\phi}_t + \boldsymbol{\mu}_2)}$

G. Update the dual variables:

$$
\begin{aligned}
\boldsymbol{\mu}_1 &:= \boldsymbol{\mu}_1 + \rho(\mathbf{x}_t - \mathbf{y}_t) \\
\boldsymbol{\mu}_2 &:= \boldsymbol{\mu}_2 + \rho(\boldsymbol{\phi}_t - \boldsymbol{\varphi}_t)
\end{aligned}
$$

H. Initialization

- The optimization problem of initializing **ϕ**

$$\max_{\boldsymbol{\phi}} \ \left\|\mathbf{h}_{\mathrm{t}}^{H}+\mathbf{h}_{\mathrm{rt}}^{H}\mathbf{\Phi}\mathbf{G}\right\|^{2}+\sum_{k=1}^{K}\left\|\mathbf{h}_{k}^{H}+\mathbf{h}_{\mathrm{r},k}^{H}\mathbf{\Phi}\mathbf{G}\right\|^{2}-\sum_{q=1}^{Q}\left\|\mathbf{h}_{\mathrm{c},q}^{H}+\mathbf{h}_{\mathrm{rc},q}^{H}\mathbf{\Phi}\mathbf{G}\right\|^{2}$$
$$\text{s.t.} \quad |\phi_n|=1, \quad \forall n$$

  - solved by manifold optimization algorithm, etc.

- The optimization problem of initializing **x**

$$\max_{\mathbf{x}} \ \min_{k,l} \ \alpha_{k,l}$$
$$\text{s.t.} \ \left[\mathbf{h}_{k,l}^{H}+(\mathbf{e}_{l}^{T}\otimes\boldsymbol{\phi}^{T})\mathbf{G}_{k}\right]\mathbf{x}=\alpha_{k,l}\gamma_{k,l}^{\mathrm{ZF}}, \ \forall k,l,$$
$$\text{or} \ \left|[\mathbf{h}_{k,l}^{H}+(\mathbf{e}_{l}^{T}\otimes\boldsymbol{\phi}^{T})\mathbf{G}_{k}]\mathbf{x}-\alpha_{k,l}\gamma_{k,l}^{\mathrm{ZF}}\right|^{2}\leq\epsilon, \ \forall k,l$$
$$|x_i|\leq\sqrt{P/M}, \quad \forall i$$

Convex problems

$$\max_{\mathbf{x}} \ \min_{k,l} \ \Re\{\widetilde{\mathbf{h}}_{k,l}^{H}\mathbf{x}\}$$
$$\text{s.t.} \quad |x_i|\leq\sqrt{P/M}, \quad \forall i$$

Simulation Results

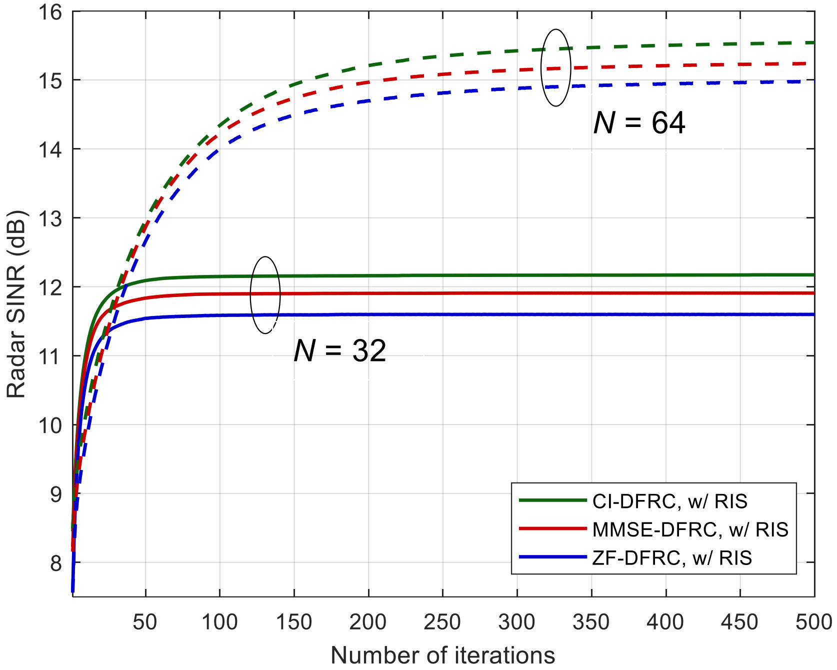

Fig. 12. Convergence illustration.

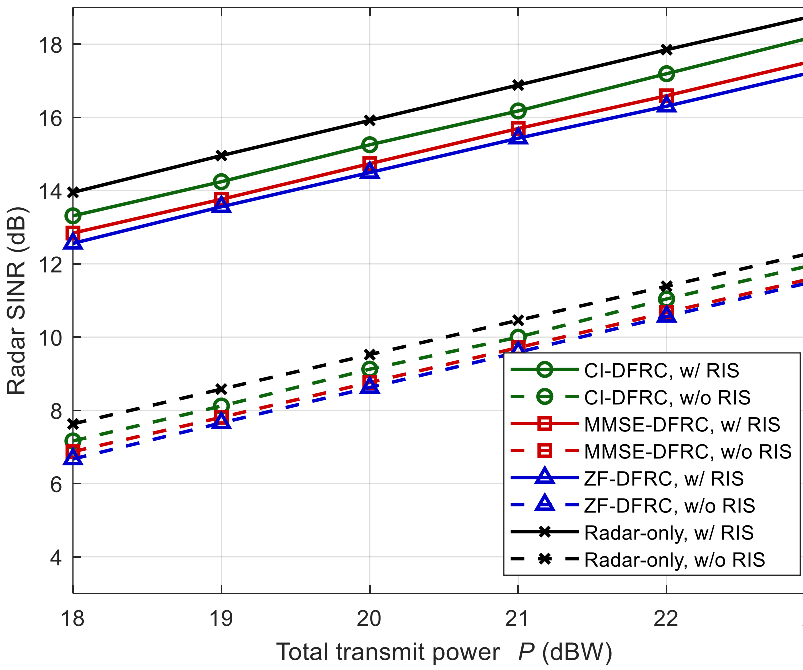

Fig. 13. Radar SINR versus total transmit power.

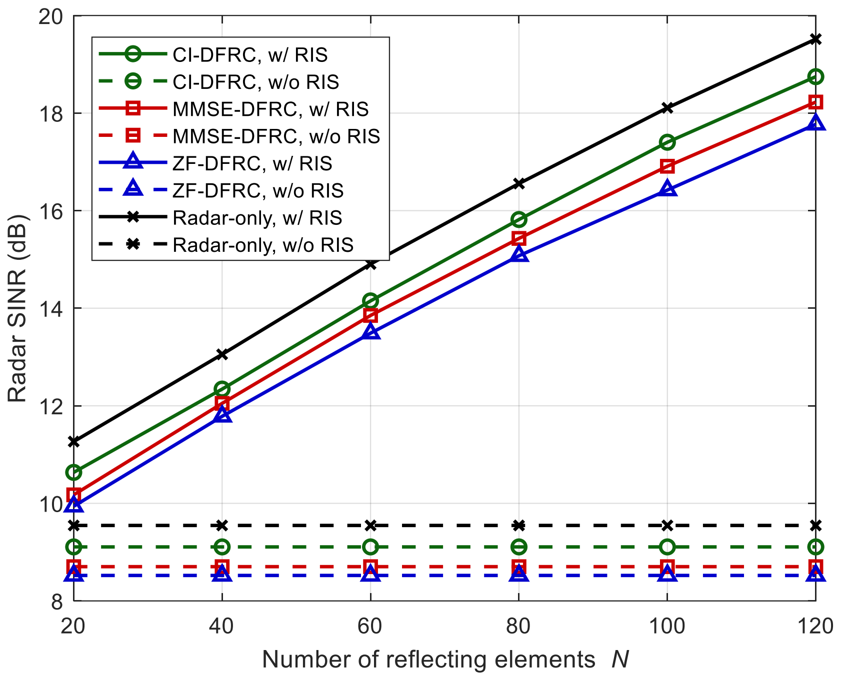

Fig. 14. Radar SINR versus *N*.

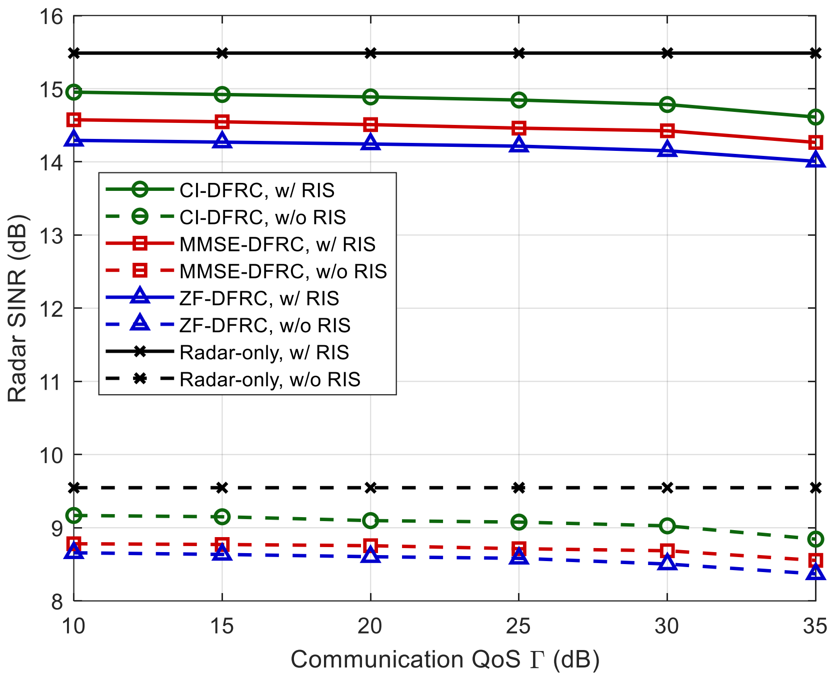

Fig. 15. Radar SINR versus communication QoS.

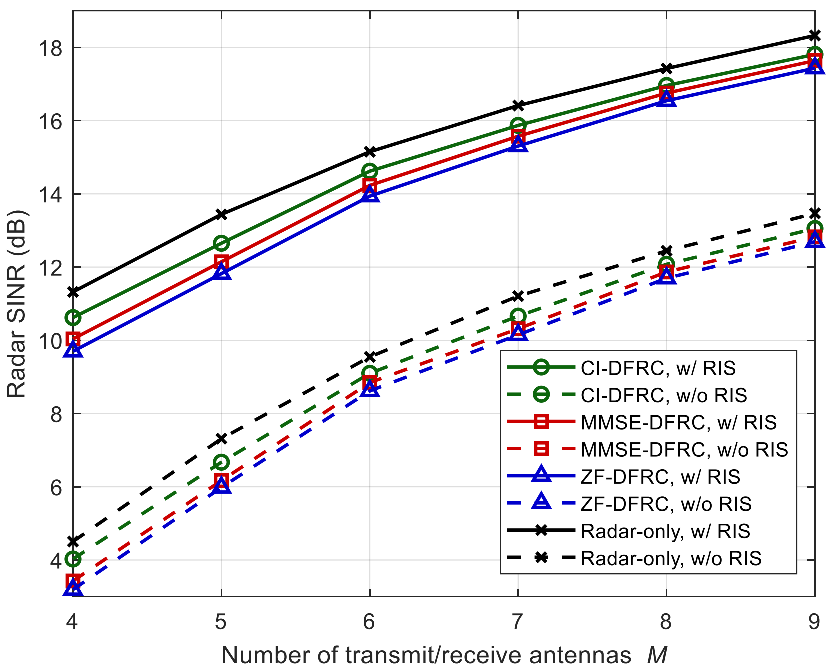

Fig. 16. Radar SINR versus *M*.

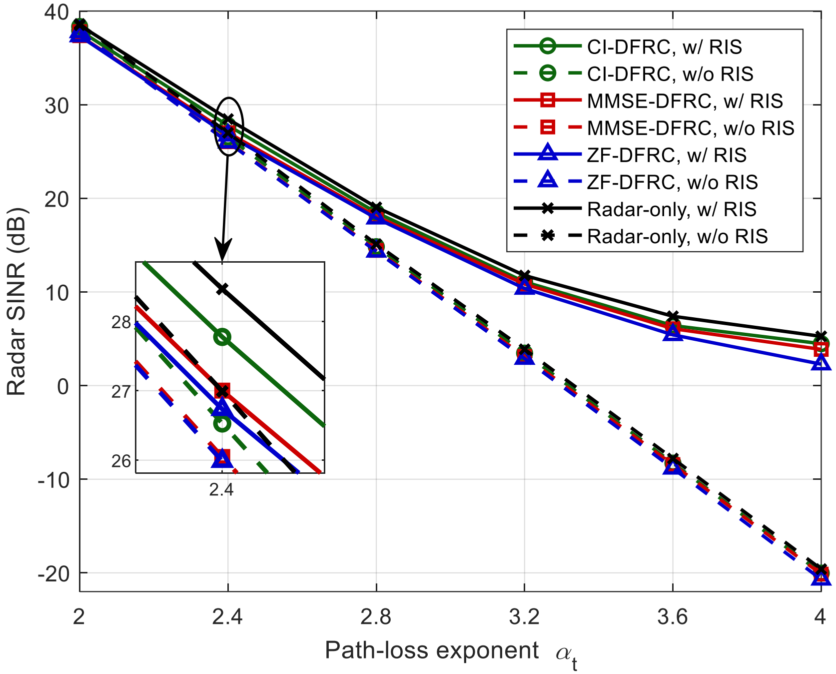

Fig. 17. Radar SINR versus path-loss exponent.

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Joint Beamforming Designs for RIS-ISAC Systems

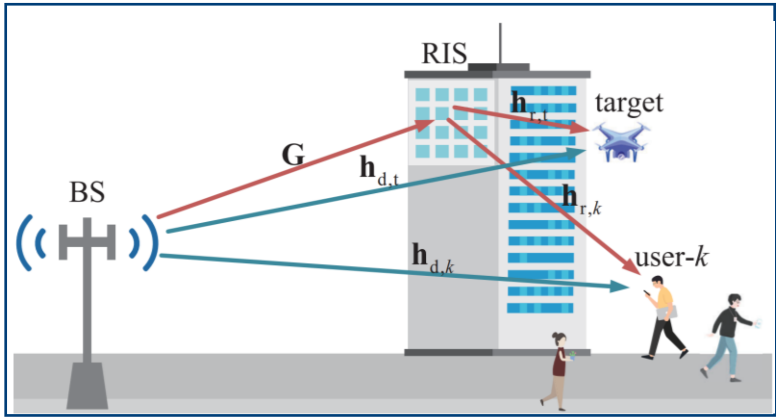


Fig. 18. An RIS-assisted ISAC system.

- **Contributions**
  - joint beamforming designs
  - detection & estimation
  - sum-rate maximization

- Transmitted dual-functional signal: $\mathbf{x}[l] = \mathbf{W}_{\mathrm{c}}\mathbf{s}_{\mathrm{c}}[l] + \mathbf{W}_{\mathrm{r}}\mathbf{s}_{\mathrm{r}}[l] = \mathbf{W}\mathbf{s}[l]$
- The received signal at the *k*-th user: $y_k[l] = (\mathbf{h}_{\mathrm{d},k}^T + \mathbf{h}_{\mathrm{r},k}^T \mathbf{\Phi}\mathbf{G})\mathbf{x}[l] + n_k[l]$
- The received echo signals at the BS:

$$\mathbf{y}_{\mathrm{r}}[l] = \alpha_{\mathrm{t}}(\mathbf{h}_{\mathrm{d,t}} + \mathbf{G}^T\mathbf{\Phi}\mathbf{h}_{\mathrm{r,t}})(\mathbf{h}_{\mathrm{d,t}}^T + \mathbf{h}_{\mathrm{r,t}}^T\mathbf{\Phi}\mathbf{G})\mathbf{W}\mathbf{s}[l] + \mathbf{n}_{\mathrm{r}}[l]$$

[10] Rang Liu, M. Li, Q. Liu, and A. L. Swindlehurst, “SNR/CRB-constrained joint beamforming and reflection designs for RIS-ISAC systems,” *IEEE Trans. Wireless Commun.*, to appear.

Target detection

- Matched-filtering: $\widetilde{\mathbf{Y}}_\mathrm{r} = \alpha_\mathrm{t}\mathbf{H}_\mathrm{t}(\boldsymbol{\phi})\mathbf{W}\mathbf{S}\mathbf{S}^H + \mathbf{N}_\mathrm{r}\mathbf{S}^H$
- Vectorized output: $\widetilde{\mathbf{y}}_\mathrm{r} = \alpha_\mathrm{t}(\mathbf{S}\mathbf{S}^H \otimes \mathbf{H}_\mathrm{t}(\boldsymbol{\phi}))\mathbf{w} + \widetilde{\mathbf{n}}_\mathrm{r}$
- Receive beamformer: $\mathbf{u}^H\widetilde{\mathbf{y}}_\mathrm{r} = \alpha_\mathrm{t}\mathbf{u}^H(\mathbf{S}\mathbf{S}^H \otimes \mathbf{H}_\mathrm{t}(\boldsymbol{\phi}))\mathbf{w} + \mathbf{u}^H\widetilde{\mathbf{n}}_\mathrm{r}$
- Detection probability: $P_\mathrm{D} \propto \eta_1/\eta_0 = \dfrac{\sigma_\mathrm{t}^2\mathbb{E}\{|\mathbf{u}^H(\mathbf{S}\mathbf{S}^H \otimes \mathbf{H}_\mathrm{t}(\boldsymbol{\phi}))\mathbf{w}|^2\}}{L\sigma_\mathrm{r}^2\mathbf{u}^H\mathbf{u}} + 1$

$$\mathbb{E}\{f(x)\} \geq f(\mathbb{E}\{x\}) \Downarrow \mathbb{E}\{\mathbf{S}\mathbf{S}^H\} = L\mathbf{I}_{K+M}$$

- Worst-case radar SNR: $\mathrm{SNR}_\mathrm{t} \geq \dfrac{L\sigma_\mathrm{t}^2|\mathbf{u}^H(\mathbf{I}_{K+M} \otimes \mathbf{H}_\mathrm{t}(\boldsymbol{\phi}))\mathbf{w}|^2}{\sigma_\mathrm{r}^2\mathbf{u}^H\mathbf{u}}$
- SNR-constrained joint design:

$$\begin{aligned}
\max_{\mathbf{W},\mathbf{u},\boldsymbol{\phi}} \quad & \sum_{k=1}^{K}\log_2(1+\mathrm{SINR}_k) \\
\text{s.t.} \quad & \frac{L\sigma_\mathrm{t}^2|\mathbf{u}^H(\mathbf{I}_{K+M} \otimes \mathbf{H}_\mathrm{t}(\boldsymbol{\phi}))\mathbf{w}|^2}{\sigma_\mathrm{r}^2\mathbf{u}^H\mathbf{u}} \geq \Gamma_\mathrm{t} \\
& \|\mathbf{W}\|_F^2 \leq P_\mathrm{t} \\
& |\phi_n| = 1, \quad \forall n
\end{aligned}$$

DoA Estimation

- Unknown target parameter: $\boldsymbol{\xi} \triangleq [\boldsymbol{\theta}^T, \boldsymbol{\alpha}^T]^T$

$$\boldsymbol{\theta} \triangleq [\theta_1, \theta_2]^T \quad \boldsymbol{\alpha} \triangleq [\Re\{\alpha_\mathrm{t}\}, \Im\{\alpha_\mathrm{t}\}]^T$$

- Vectorized received signal: $\mathbf{y}_\mathrm{r} = \alpha_\mathrm{t} \mathrm{vec}\{\mathbf{H}_\mathrm{t}(\boldsymbol{\phi})\mathbf{W}\mathbf{S}\} + \mathbf{n}_\mathrm{r}$

- Fisher information matrix: $\mathbf{F}_\mathrm{IM}(i,j) = \frac{2}{\sigma_\mathrm{r}^2}\Re\left\{\frac{\partial^H \boldsymbol{\eta}}{\partial \xi_i}\frac{\partial \boldsymbol{\eta}}{\partial \xi_j}\right\}$

$$\mathbf{F}_\mathrm{IM} = \begin{bmatrix} \mathbf{F}_{\boldsymbol{\theta}\boldsymbol{\theta}^T} & \mathbf{F}_{\boldsymbol{\theta}\boldsymbol{\alpha}^T} \\ \mathbf{F}_{\boldsymbol{\theta}\boldsymbol{\alpha}^T}^T & \mathbf{F}_{\boldsymbol{\alpha}\boldsymbol{\alpha}^T} \end{bmatrix} = \begin{bmatrix} \mathbf{C}_{\boldsymbol{\theta}\boldsymbol{\theta}^T} & \mathbf{C}_{\boldsymbol{\theta}\boldsymbol{\alpha}^T} \\ \mathbf{C}_{\boldsymbol{\alpha}\boldsymbol{\theta}^T} & \mathbf{C}_{\boldsymbol{\alpha}\boldsymbol{\alpha}^T} \end{bmatrix}^{-1} = \mathbf{C}^{-1}$$

- The CRB for estimating DoAs:

$$\mathrm{CRB}_{\theta_1} + \mathrm{CRB}_{\theta_2} = \mathrm{Tr}\{\mathbf{C}_{\boldsymbol{\theta}\boldsymbol{\theta}^T}\} = \mathrm{Tr}\{(\mathbf{F}_{\boldsymbol{\theta}\boldsymbol{\theta}^T} - \mathbf{F}_{\boldsymbol{\theta}\boldsymbol{\alpha}^T}\mathbf{F}_{\boldsymbol{\alpha}\boldsymbol{\alpha}^T}^{-1}\mathbf{F}_{\boldsymbol{\theta}\boldsymbol{\alpha}^T}^T)^{-1}\}$$

- CRB-constrained joint design:

$$\begin{aligned} \max_{\mathbf{W},\boldsymbol{\phi}} \quad & \sum_{k=1}^{K} \log_2(1+\mathrm{SINR}_k) \\ \text{s.t.} \quad & \mathrm{Tr}\{(\mathbf{F}_{\boldsymbol{\theta}\boldsymbol{\theta}^T} - \mathbf{F}_{\boldsymbol{\theta}\boldsymbol{\alpha}^T}\mathbf{F}_{\boldsymbol{\alpha}\boldsymbol{\alpha}^T}^{-1}\mathbf{F}_{\boldsymbol{\theta}\boldsymbol{\alpha}^T}^T)^{-1}\} \le \varepsilon \\ & \|\mathbf{W}\|_F^2 \le P_\mathrm{t} \\ & |\phi_n| = 1, \quad \forall n \end{aligned}$$

Simulation Results

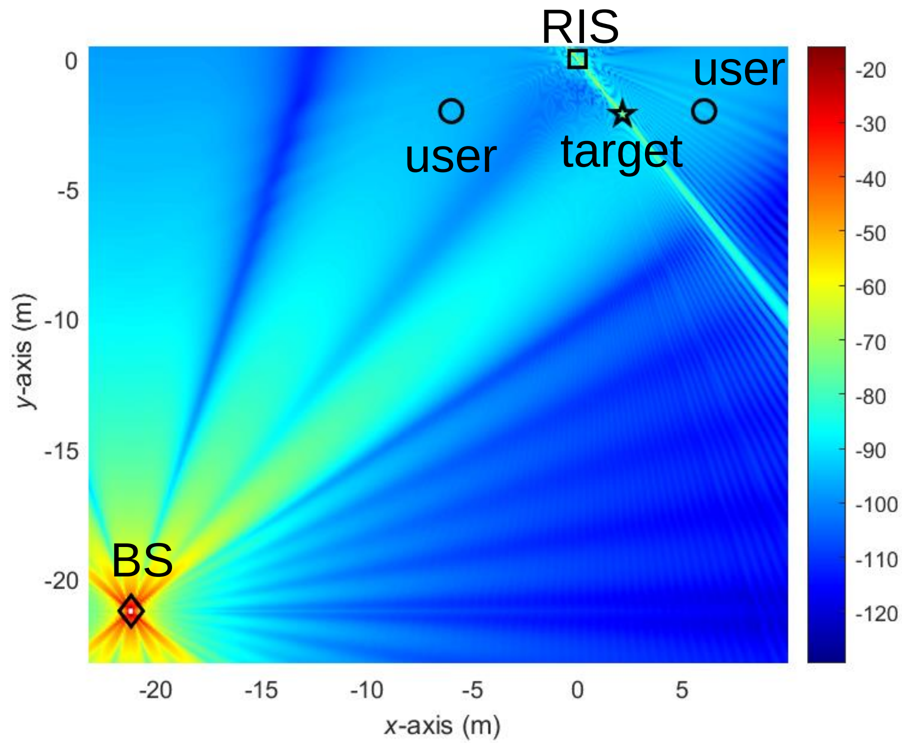
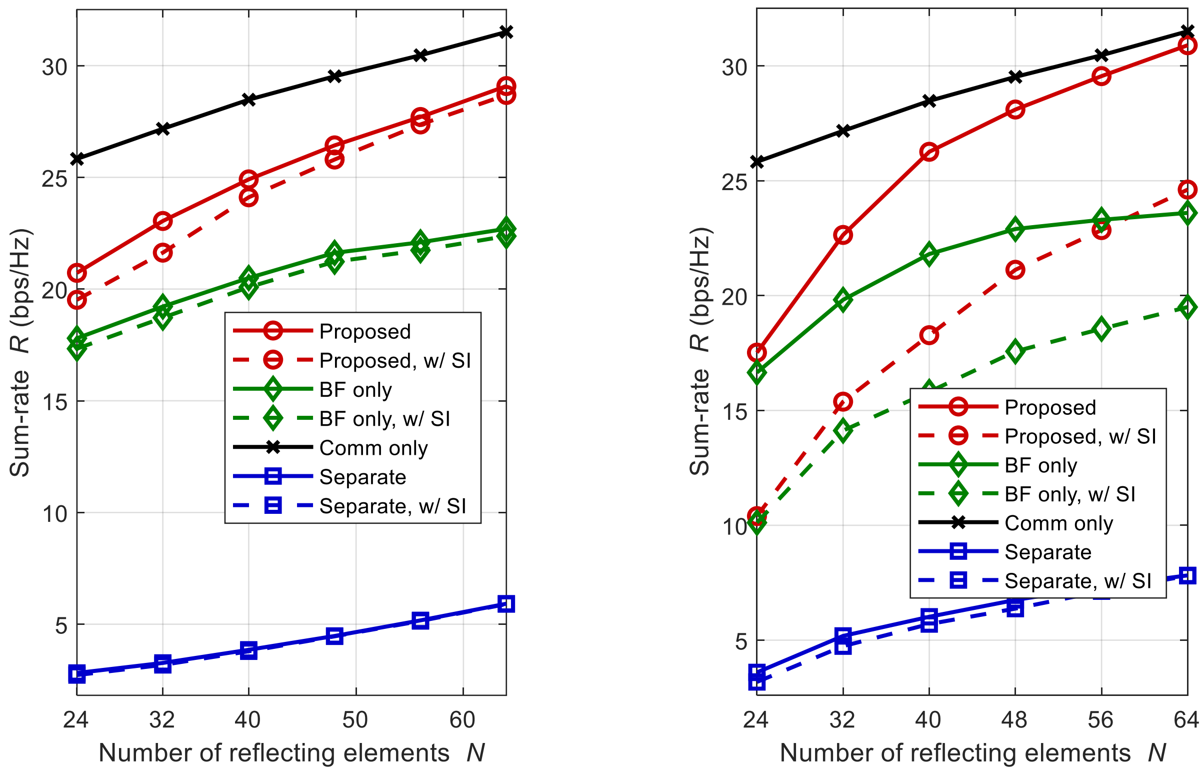
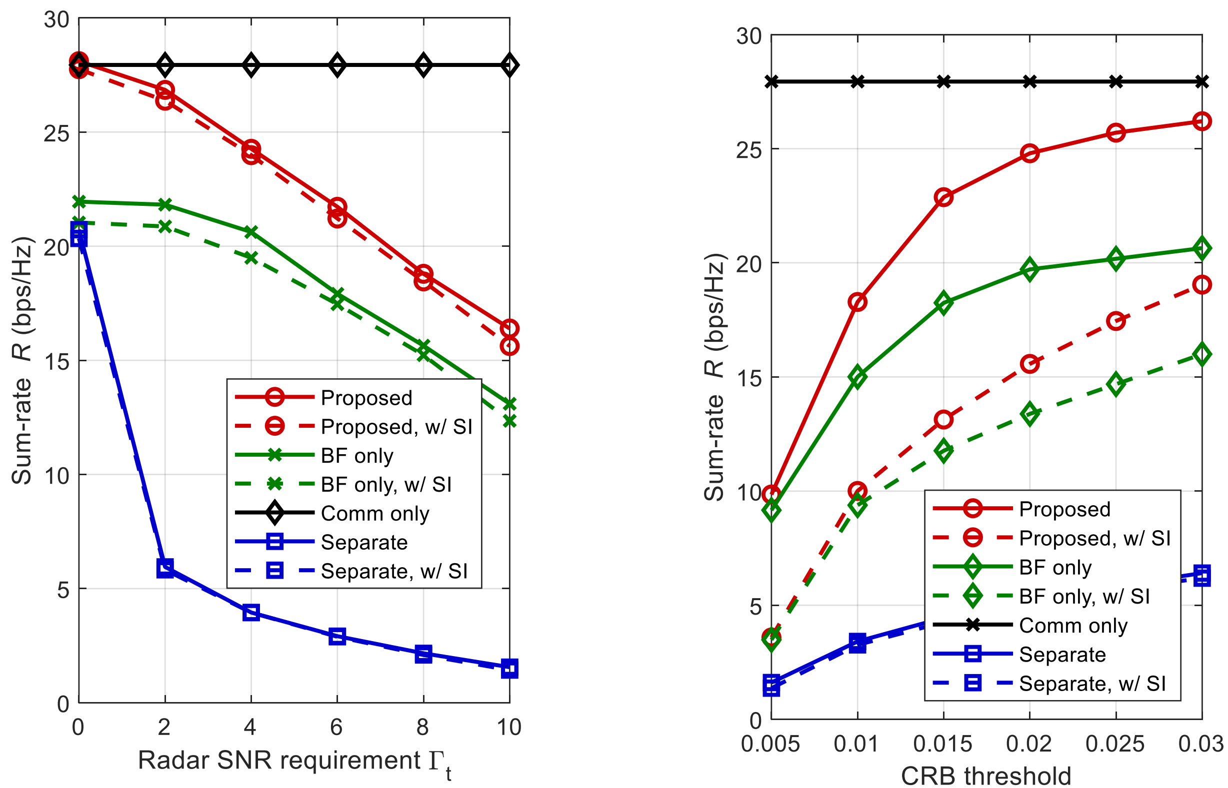


Fig. 19. Enhanced beampattern of the RIS-assisted system.



(a) SNR-constrained. (b) CRB-constrained.

Fig. 20. Sum-rate versus the number of reflecting elements.



(a) SNR-constrained. (b) CRB-constrained.

Fig. 21. Impact of radar sensing performance.

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04 PART FOUR

Conclusions

Future Directions

☐ Conclusions

- A general system model for RIS-ISAC systems
- Joint transmit waveform and passive beamforming design
- SNR/CRB-constrained joint beamforming designs

☐ Future Directions

- Sensing algorithms based on multipath exploitation
- Near-field communication and sensing
- Wideband waveform design for RIS-ISAC

Related Publications

[1] **Rang Liu**, M. Li, Y. Liu, Q. Wu, and Q. Liu, “Joint transmit waveform and passive beamforming design for RIS-aided DFRC systems,” *IEEE J. Sel. Topics Signal Process.*, vol. 16, no. 5, pp. 995-1010, Aug. 2022.

[2] **Rang Liu**, M. Li, H. Luo, Q. Liu, and A. L. Swindlehurst, “Integrated sensing and communication with reconfigurable intelligent surfaces: Opportunities, applications, and future directions,” *IEEE Wireless Commun.*, vol. 30, no. 1, pp. 50-57, Feb. 2023.

[3] **Rang Liu**, M. Li, Q. Liu, and A. L. Swindlehurst, “SNR/CRB-constrained joint beamforming and reflection designs for RIS-ISAC systems,” *IEEE Trans. Wireless Commun.*, to appear.

[4] H. Luo, **Rang Liu**, M. Li, and Q. Liu, “RIS-aided integrated sensing and communication: Joint beamforming and reflection design,” *IEEE Trans. Veh. Technol.*, vol. 72, no. 7, pp. 9626-9630, Jul. 2023.

[5] H. Luo, **Rang Liu**, M. Li, Y. Liu, and Q. Liu, “Joint beamforming design for RIS-assisted integrated sensing and communication systems,” *IEEE Trans. Veh. Technol.*, vol. 71, no. 12, pp. 13393-13397, Dec. 2022.

[6] H. Zhang, **Rang Liu**, M. Li, W. Wang, and Q. Liu, “Joint sensing and communication optimization in target-mounted STARS-assisted vehicular networks: A MADRL approach,” *IEEE Trans. Veh. Technol.*, to appear.

[7] Q. Zhu, M. Li, **Rang Liu**, and Q. Liu, “Cramer-Rao bound optimization for active RIS-empowered ISAC systems,” *IEEE Trans. Wireless Commun.*, major revision.

[8] Q. Zhu, M. Li, **Rang Liu**, and Q. Liu, “Joint transceiver beamforming and reflecting design for active RIS-aided ISAC systems,” *IEEE Trans. Veh. Technol.*, vol. 72, no. 7, pp. 9636-9640, Jul. 2023.

[9] J. Chu, Z. Lu, **Rang Liu**, M. Li, and Q. Liu, “Joint beamforming and reflection design for secure RIS-ISAC systems,” *IEEE Trans. Veh. Technol.*, to appear.

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THANK YOU!

Q & A

The source codes can be found at https://rangliu0706.github.io/