UCI Samueli School of Engineering

Joint Waveform and Beamforming Designs for RIS-ISAC Systems

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

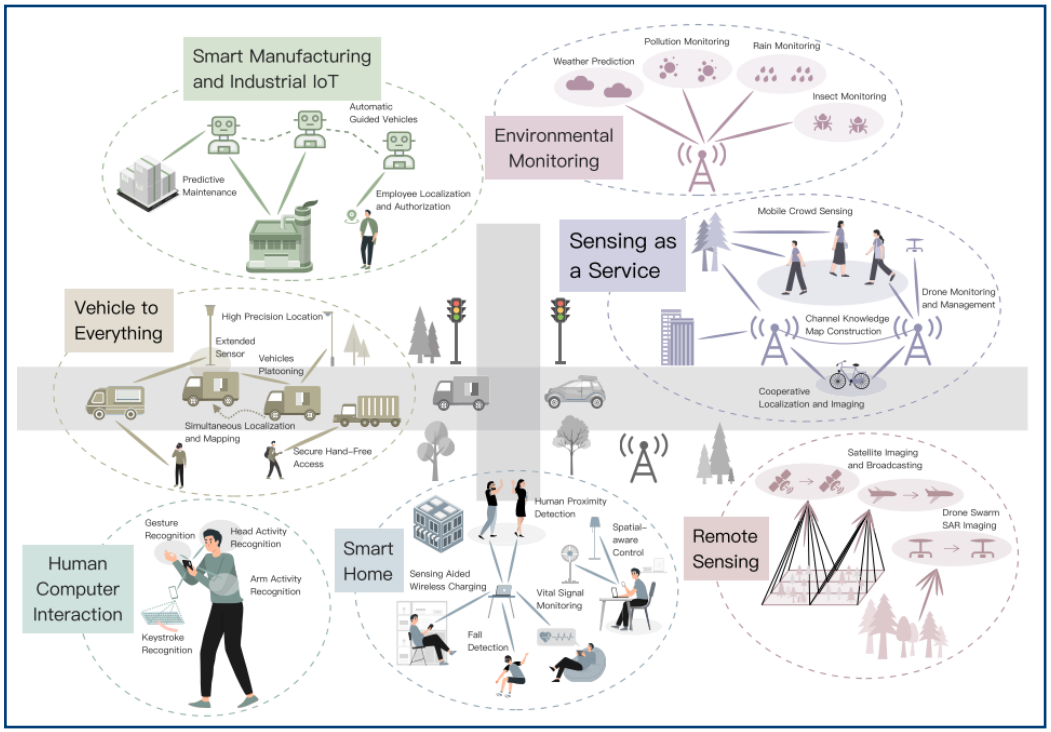


Fig. 1. ISAC technology for future wireless networks [1].

- 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)

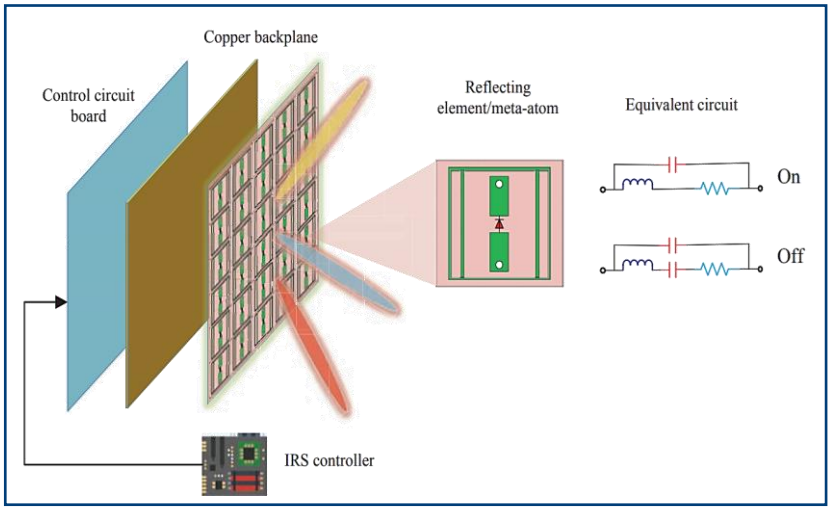


Fig. 2. Architecture of RIS [2].

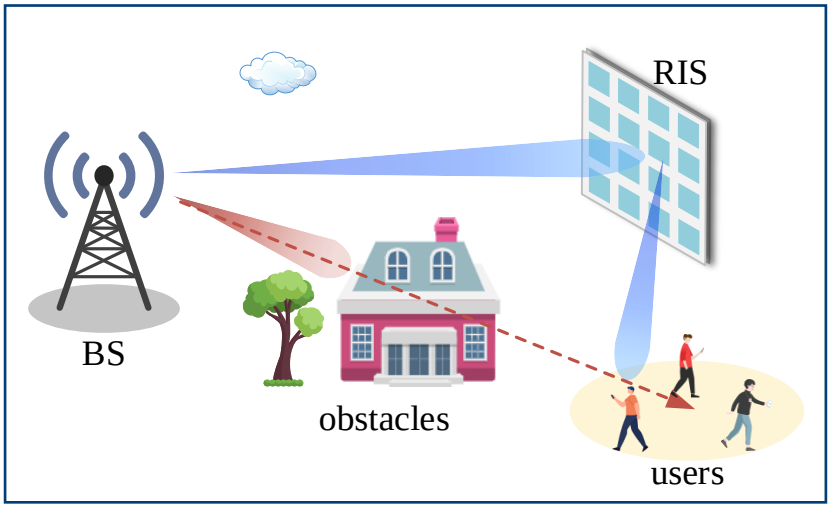


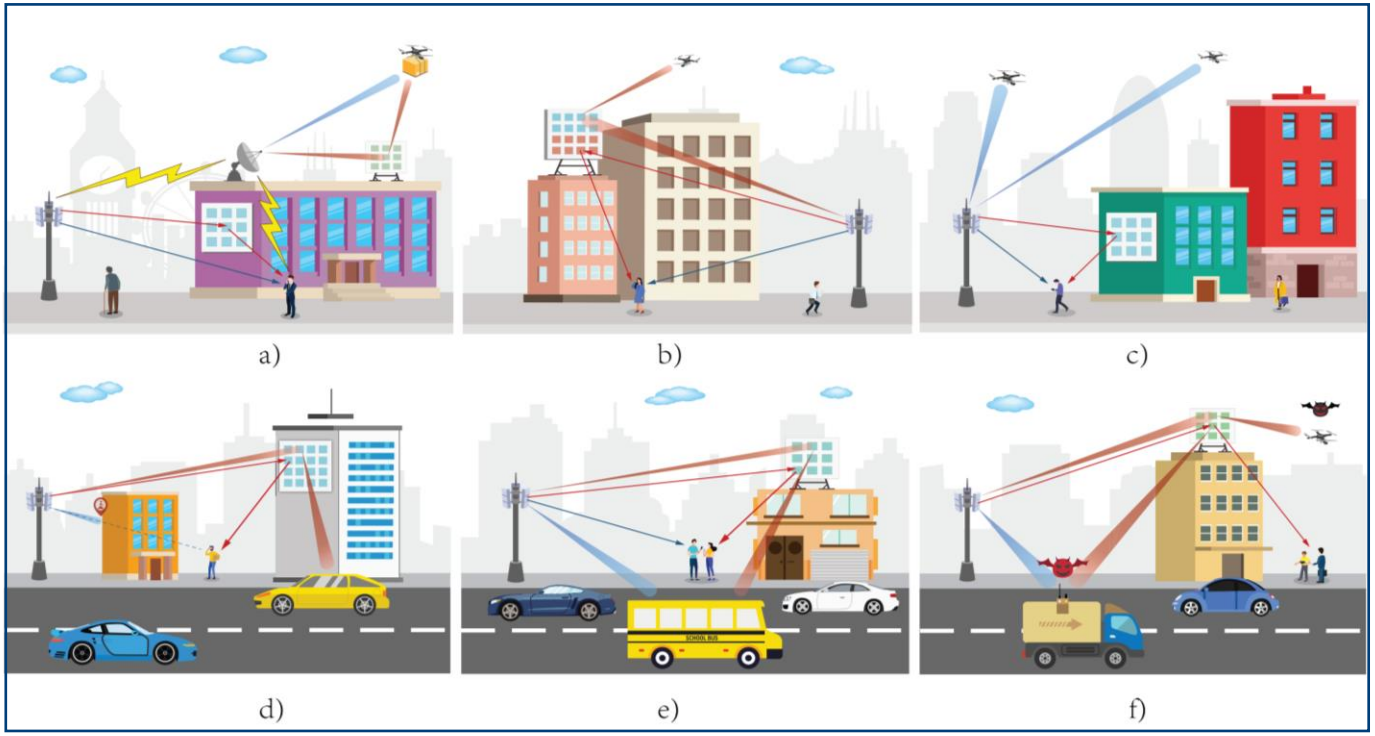
Fig. 3. A RIS-aided communication system.

- 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.

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.

Background of RIS-ISAC

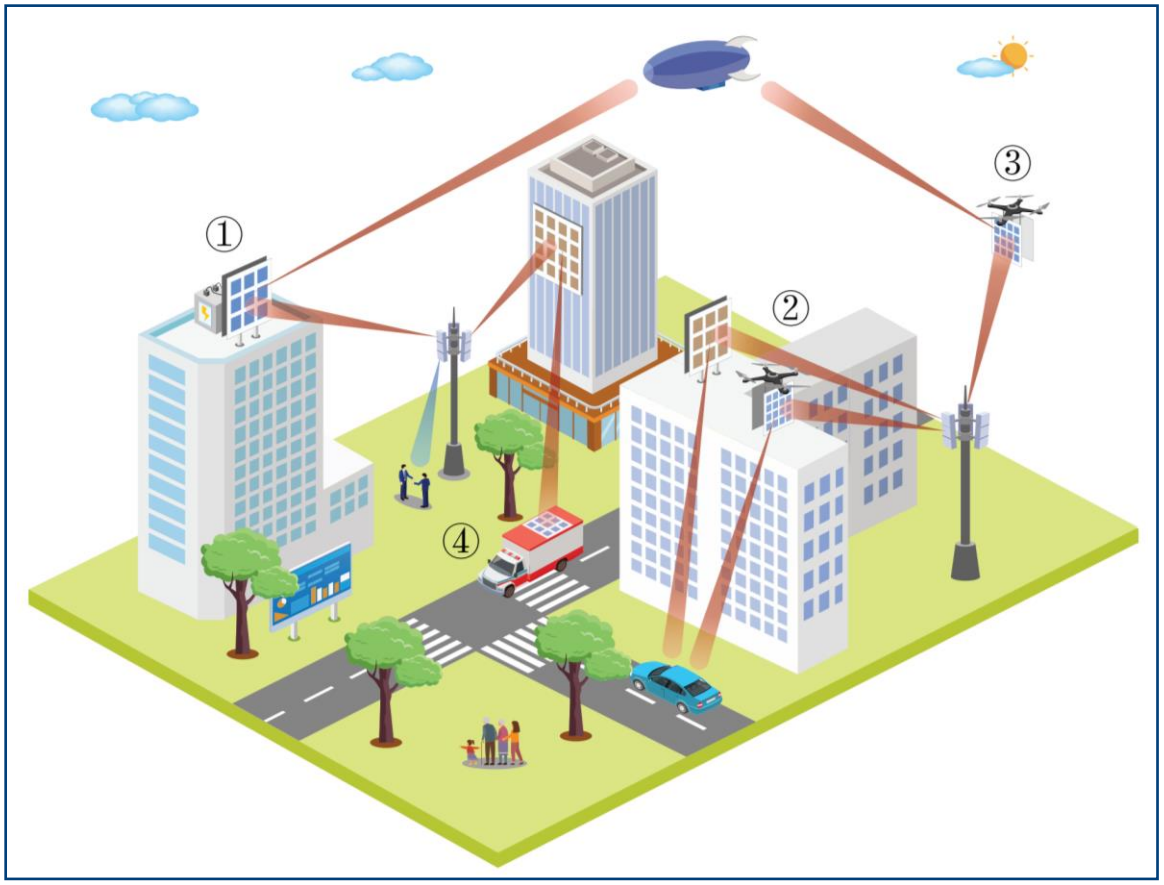


Fig. 5. Various RIS deployments in ISAC systems [3].

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

Background of RIS-ISAC

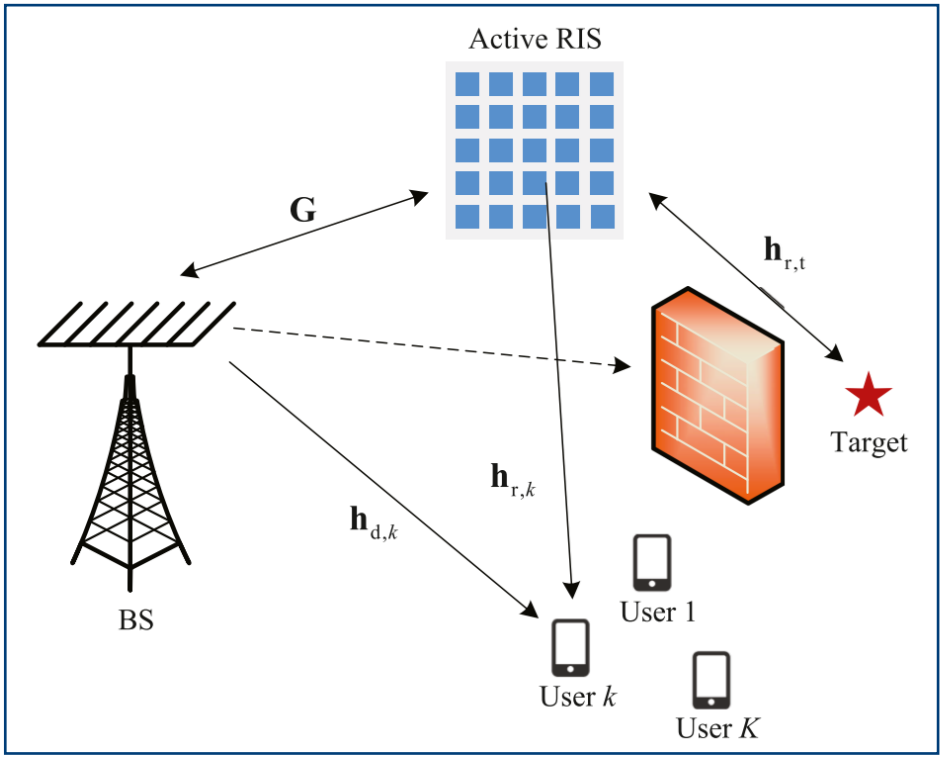


Fig. 6. An active RIS-assisted ISAC system [5].

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

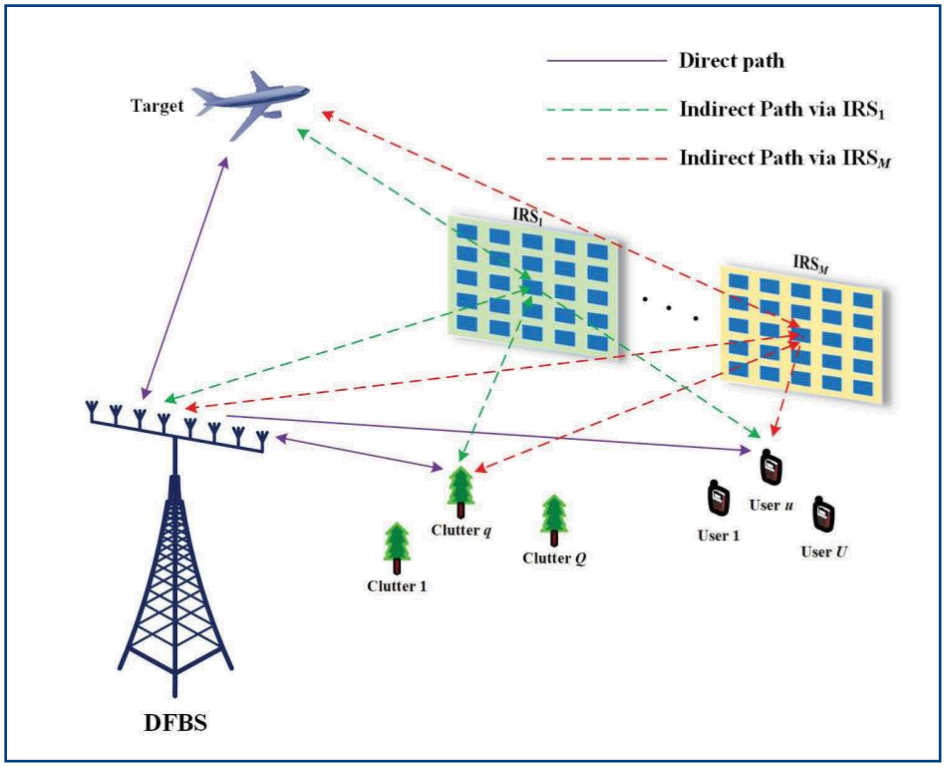


Fig. 7. A multi-RIS-aided ISAC system [6].

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

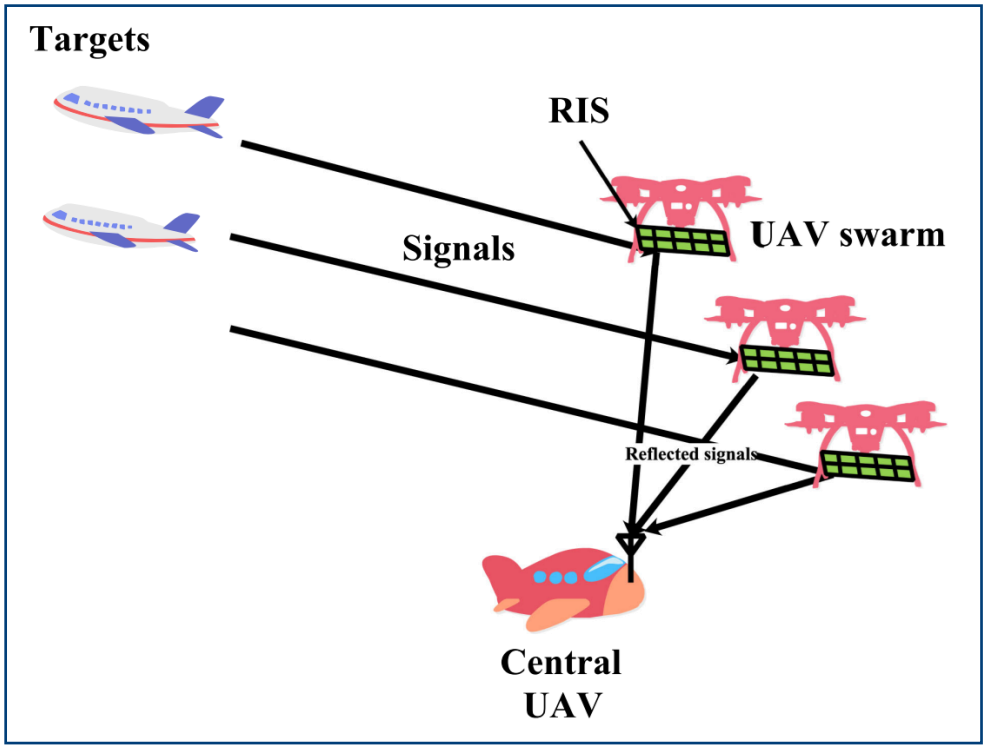


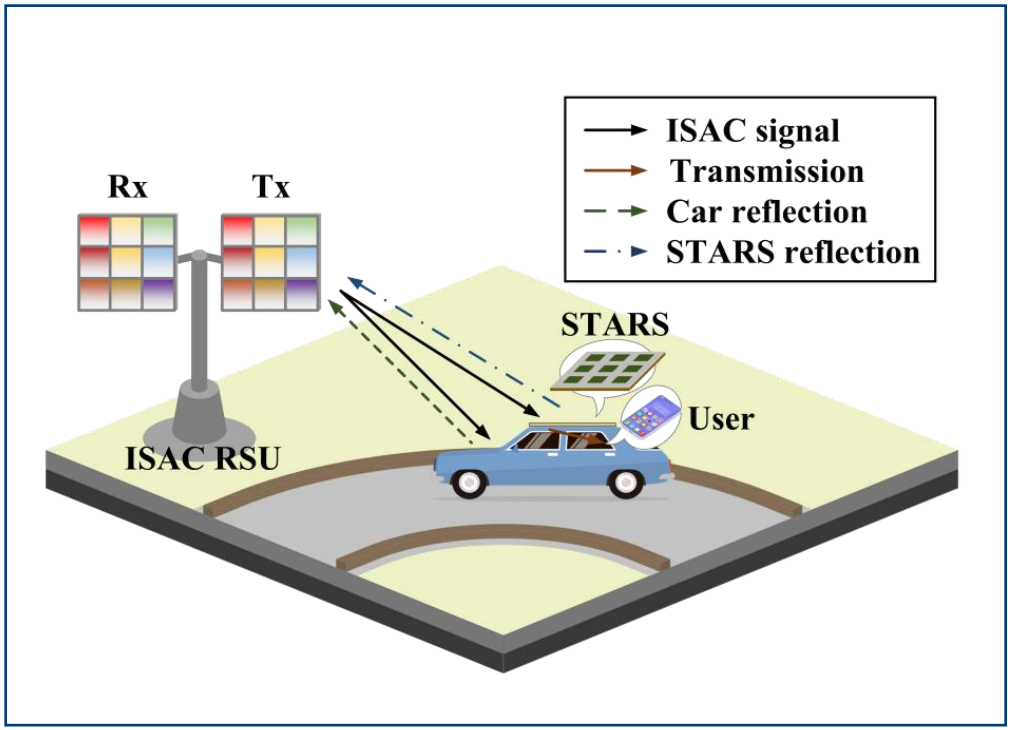
Fig. 8. An UAV-mounted RIS system [7].

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



Target-mounted RIS

- Cooperative target
- Improve backscatter signals
- Control mechanisms

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

[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.

General System Model

System Model

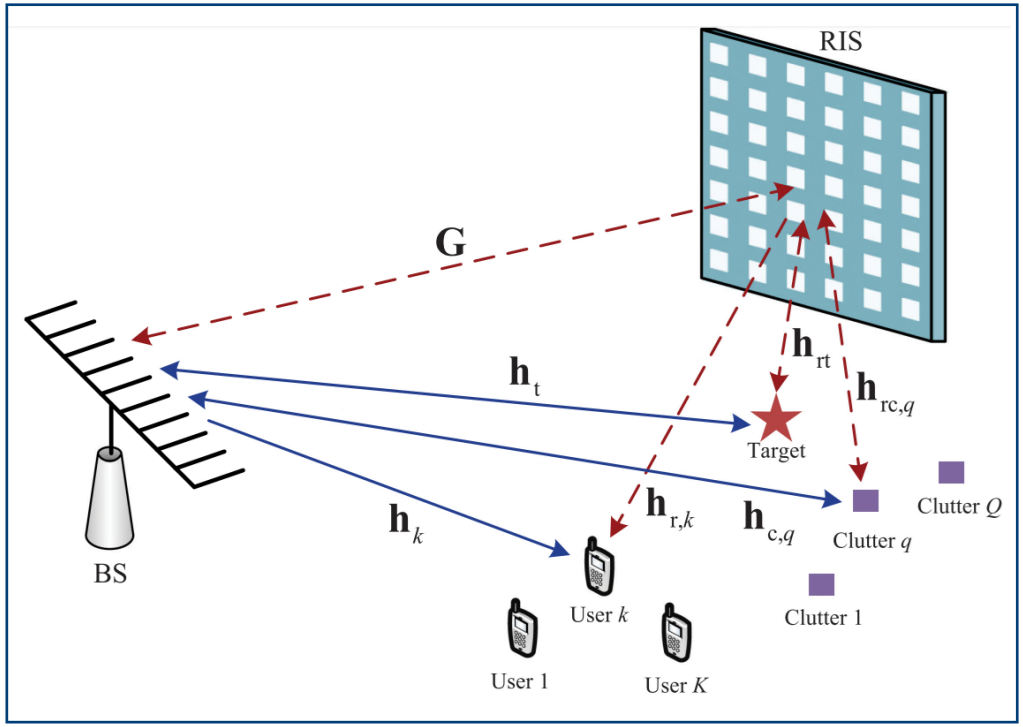


Fig. 10. A RIS-aided ISAC system.

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

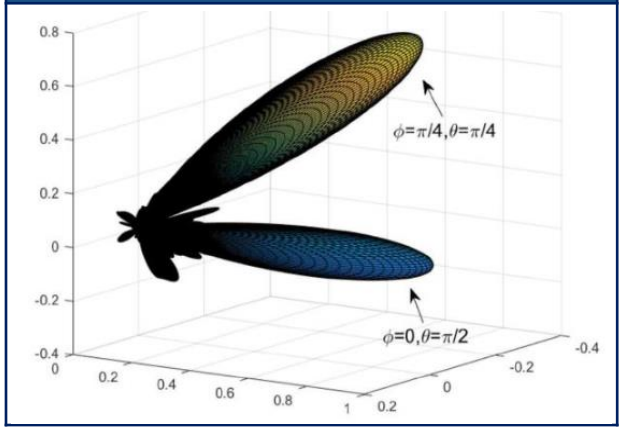
[9] Rang Liu, M. Li, Y. Liu, Q. Wu, and Q. Liu, "Joint transmit waveform and passive beamforming design for RIS-aided DFRC systems," *IEEE J. Sel. Topics Signal Process.*, vol. 16, no. 5, pp. 995-1010, Aug. 2022.

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

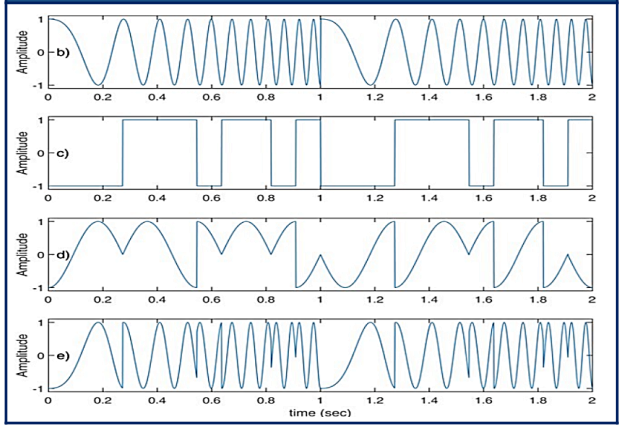
Dual-functional waveform & beamforming design

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

- Transmit signal: $\mathbf{x}_m = \mathbf{W}\mathbf{s}_m$

$$\mathbf{X} = \mathbf{W}\mathbf{S}$$

$$\mathbf{X} \triangleq [\mathbf{x}_1, \ldots, \mathbf{x}_L] \qquad \mathbf{S} \triangleq [\mathbf{s}_1, \ldots, \mathbf{s}_L]$$

- Receive signal:

$$y_{m,k} = \mathbf{h}_k^H \mathbf{W}\mathbf{s}_m + n_{m,k}$$

- Performance metric:

$$\mathrm{SINR}_k = \frac{|\mathbf{h}_k^H \mathbf{w}_k|^2}{\sum_{j=1, j\neq k}^{K} |\mathbf{h}_k^H \mathbf{w}_j|^2 + \sigma_k^2}$$

- statistical information
- MUI suppression

VS

Non-Linear SLP

- 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:

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

target RCS; 4 different paths; Doppler frequency

$$\mathbf{H}_0(\boldsymbol{\phi})$$

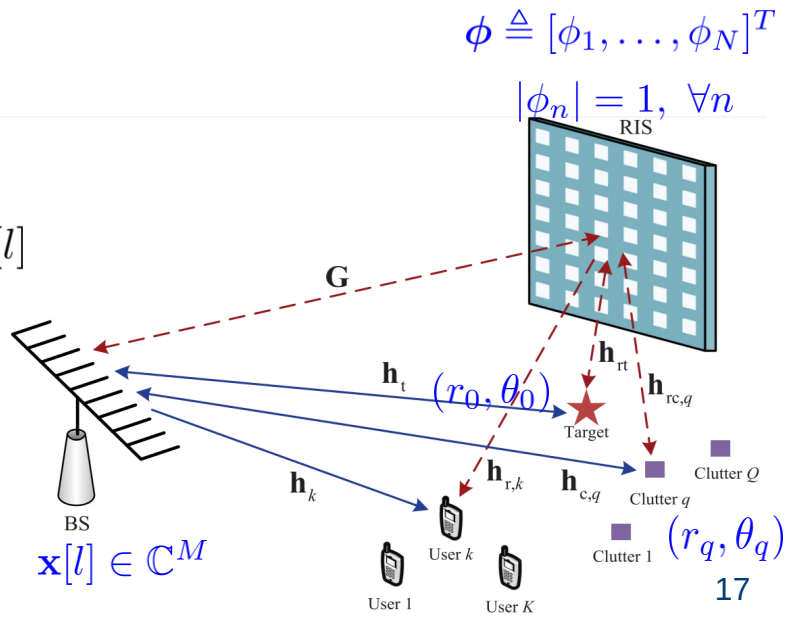
- Clutter returns:

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

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

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

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



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:

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

- 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:

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

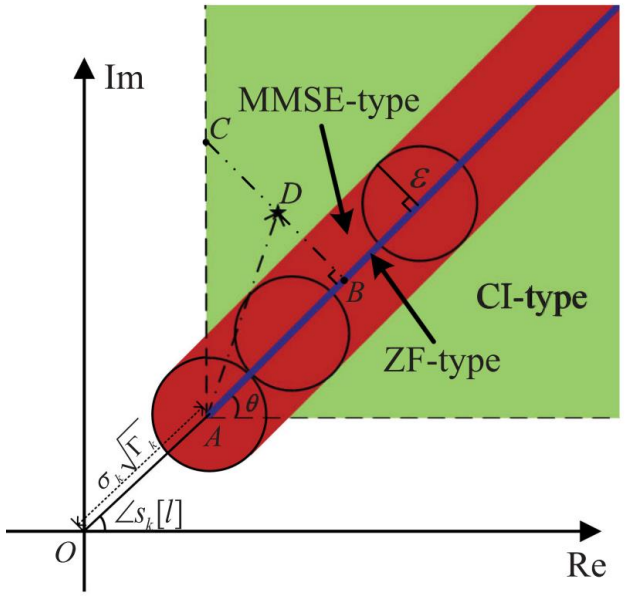


Fig. 11. Illustration of handling MUI.

Different strategies of handling MUI

- ZF-type communication metric:

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

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

scaling factor

- MMSE-type communication metric:

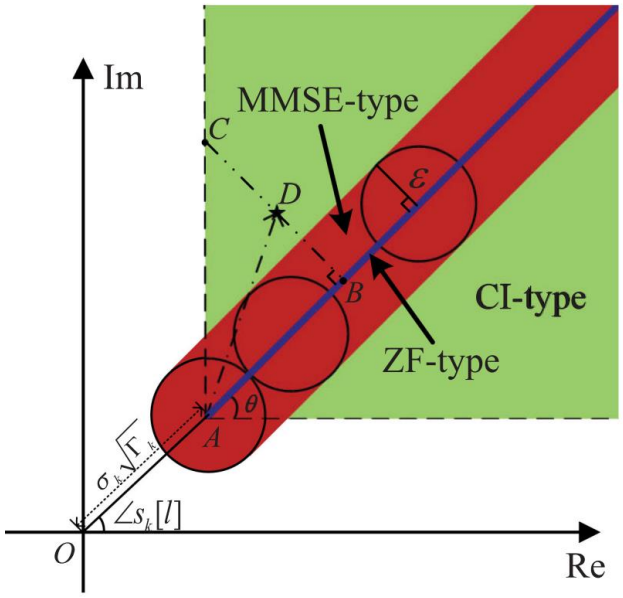
$$\left|(\mathbf{h}_k^H + \mathbf{h}_{\mathrm{r},k}^H \mathbf{\Phi} \mathbf{G})\mathbf{x}[l] - \alpha_{k,l} \sigma_k \sqrt{\Gamma_k} s_k[l]\right|^2 \leq \epsilon, \ \alpha_{k,l} \geq 1, \ \forall k, l$$

- CI-type communication metric:

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

- Reformulated as

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



Problem Formulation

$$\max_{\mathbf{x},\boldsymbol{\alpha},\mathbf{w},\boldsymbol{\phi}} \quad \frac{\varsigma_0^2|\mathbf{w}^H\widetilde{\mathbf{H}}_0(\boldsymbol{\phi})\mathbf{x}|^2}{\mathbf{w}^H\left[\sum_{q=1}^{Q}\varsigma_q^2\widetilde{\mathbf{H}}_q(\boldsymbol{\phi})\mathbf{x}\mathbf{x}^H\widetilde{\mathbf{H}}_q^H(\boldsymbol{\phi})+\varsigma_z^2\mathbf{I}_{ML}\right]\mathbf{w}}$$

$$\text{s.t.} \quad \text{communication QoS constraints}$$

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

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

- The optimal solution to the receive filter:

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

- The optimization problem is transformed into:

$$\min_{\mathbf{x},\boldsymbol{\alpha},\boldsymbol{\phi}} \quad -\mathbf{x}^H\widetilde{\mathbf{H}}_0^H(\boldsymbol{\phi})\left[\sum_{q=1}^{Q}\varsigma_q^2\widetilde{\mathbf{H}}_q(\boldsymbol{\phi})\mathbf{x}\mathbf{x}^H\widetilde{\mathbf{H}}_q^H(\boldsymbol{\phi})+\varsigma_z^2\mathbf{I}\right]^{-1}\widetilde{\mathbf{H}}_0(\boldsymbol{\phi})\mathbf{x}$$

$$\text{s.t.} \quad \text{communication QoS constraints}$$

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

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

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

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

- The augmented Lagrangian function:

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

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**

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

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**

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

$$
\mathbf{v} \triangleq \mathrm{vec}\{\boldsymbol{\phi}\boldsymbol{\phi}^T\} = \boldsymbol{\phi} \otimes \boldsymbol{\phi}
$$

- Construct a tractable surrogate function

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

- Solve for $\boldsymbol{\phi}$

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

Convex problem

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

G. Update the dual variables: $\quad \boldsymbol{\mu}_1 := \boldsymbol{\mu}_1 + \rho(\mathbf{x}_t - \mathbf{y}_t)$
$$\boldsymbol{\mu}_2 := \boldsymbol{\mu}_2 + \rho(\boldsymbol{\phi}_t - \boldsymbol{\varphi}_t)$$

H. Initialization

- The optimization problem of initializing **ϕ**

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

  - solved by manifold optimization algorithm, etc.

- The optimization problem of initializing **x**

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

Convex problems

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

Simulation Results

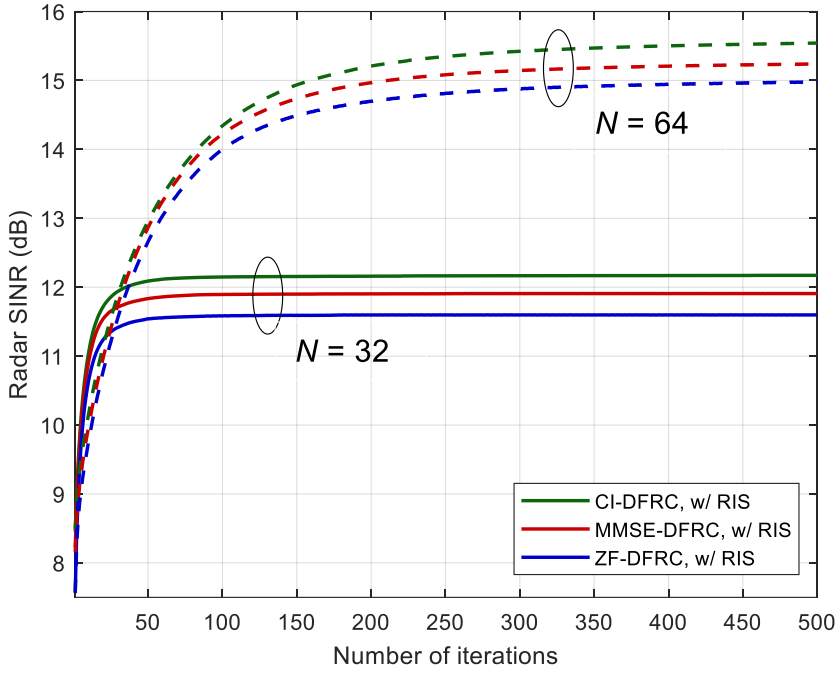


Fig. 12. Convergence illustration.

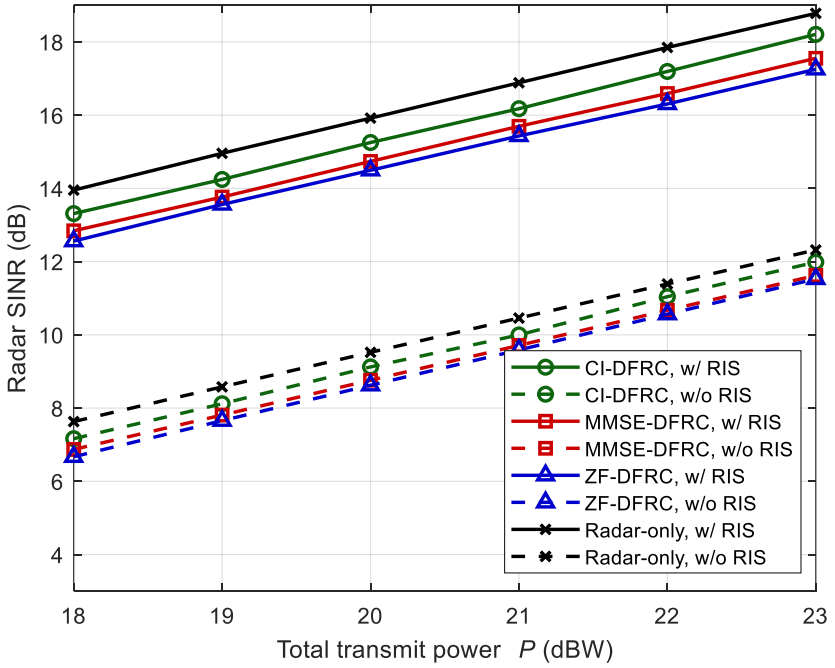


Fig. 13. Radar SINR versus total transmit power.

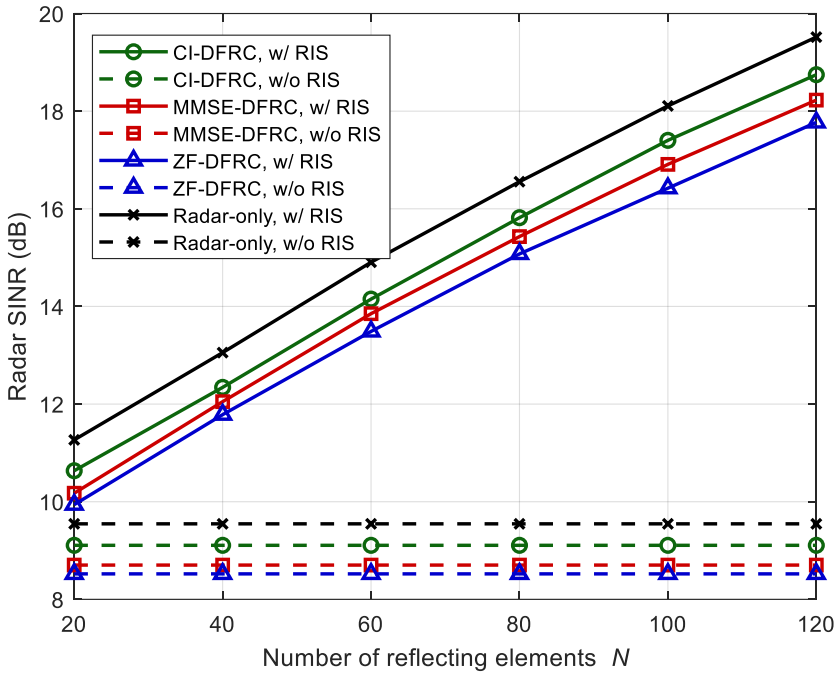


Fig. 14. Radar SINR versus N.

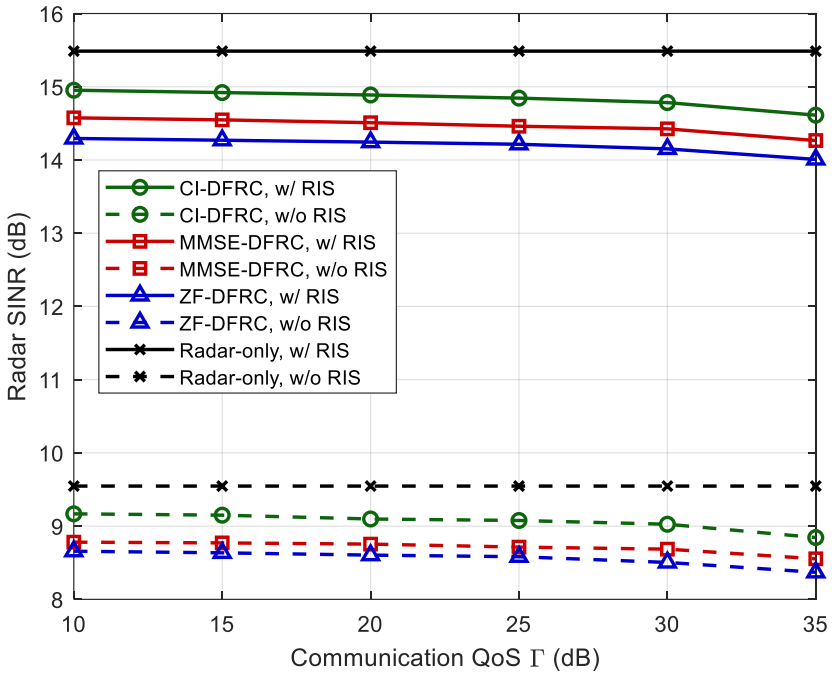


Fig. 15. Radar SINR versus communication QoS.

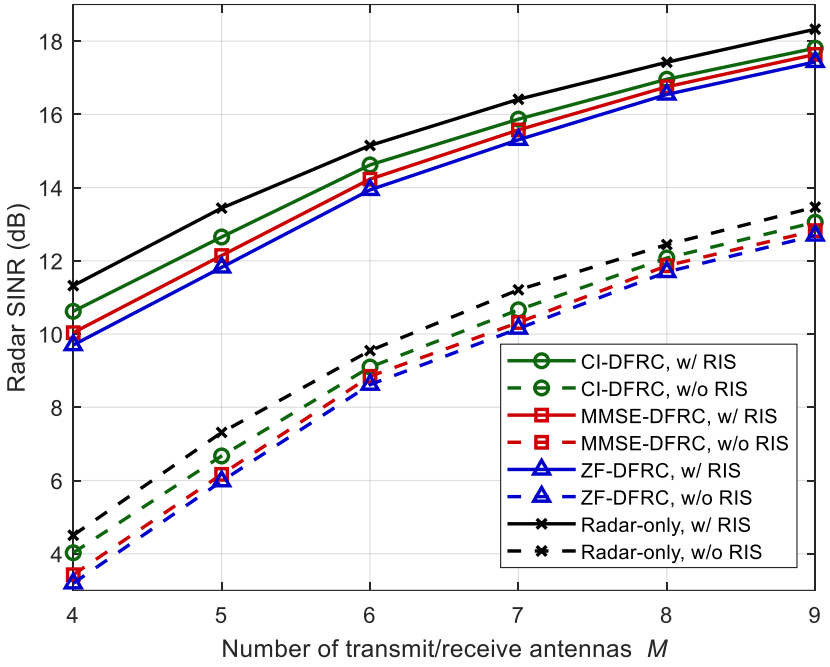


Fig. 16. Radar SINR versus *M*.

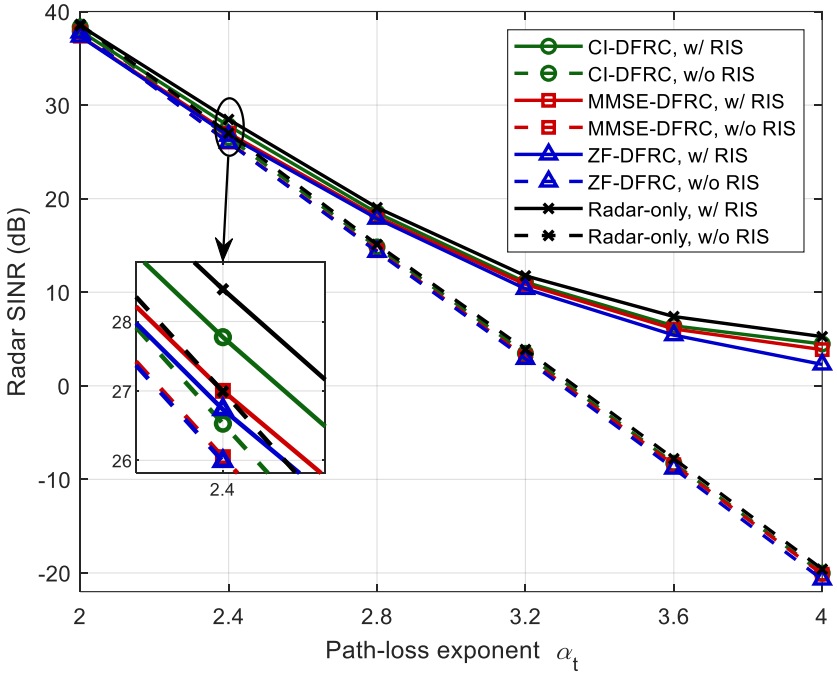


Fig. 17. Radar SINR versus path-loss exponent.

Joint Beamforming Designs for RIS-ISAC Systems

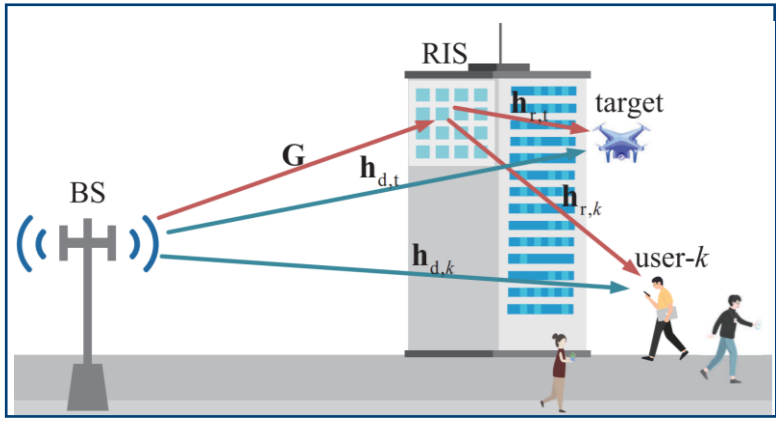


Fig. 18. An RIS-assisted ISAC system.

- **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: $y_k[l] = (\mathbf{h}_{\mathrm{d},k}^T + \mathbf{h}_{\mathrm{r},k}^T\boldsymbol{\Phi}\mathbf{G})\mathbf{x}[l] + n_k[l]$
- The received echo signals at the BS:

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

[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:

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

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

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

- 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:

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

Simulation Results

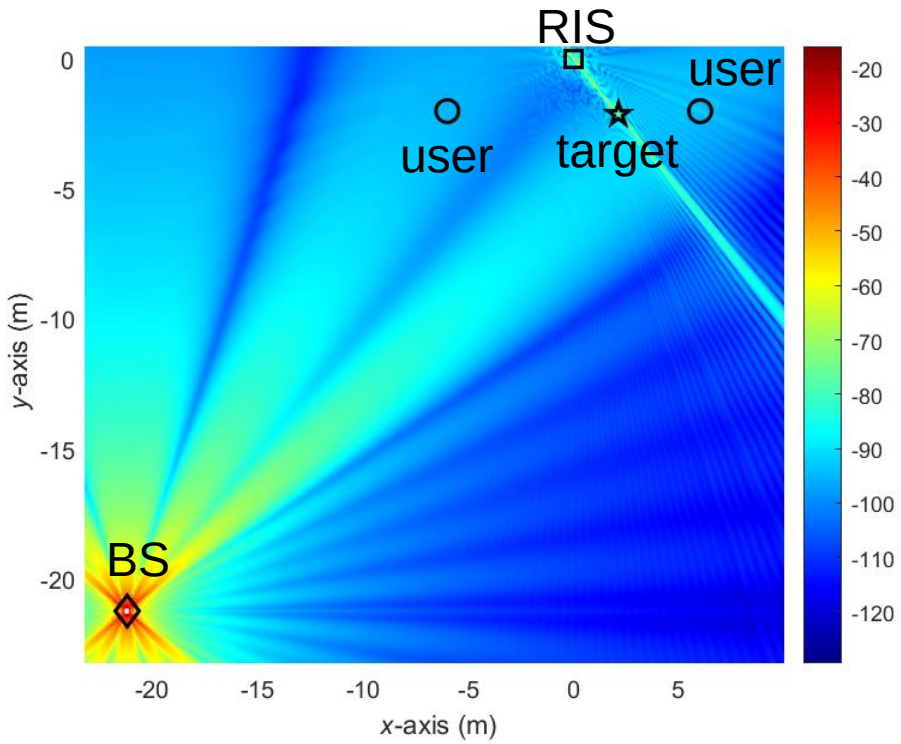
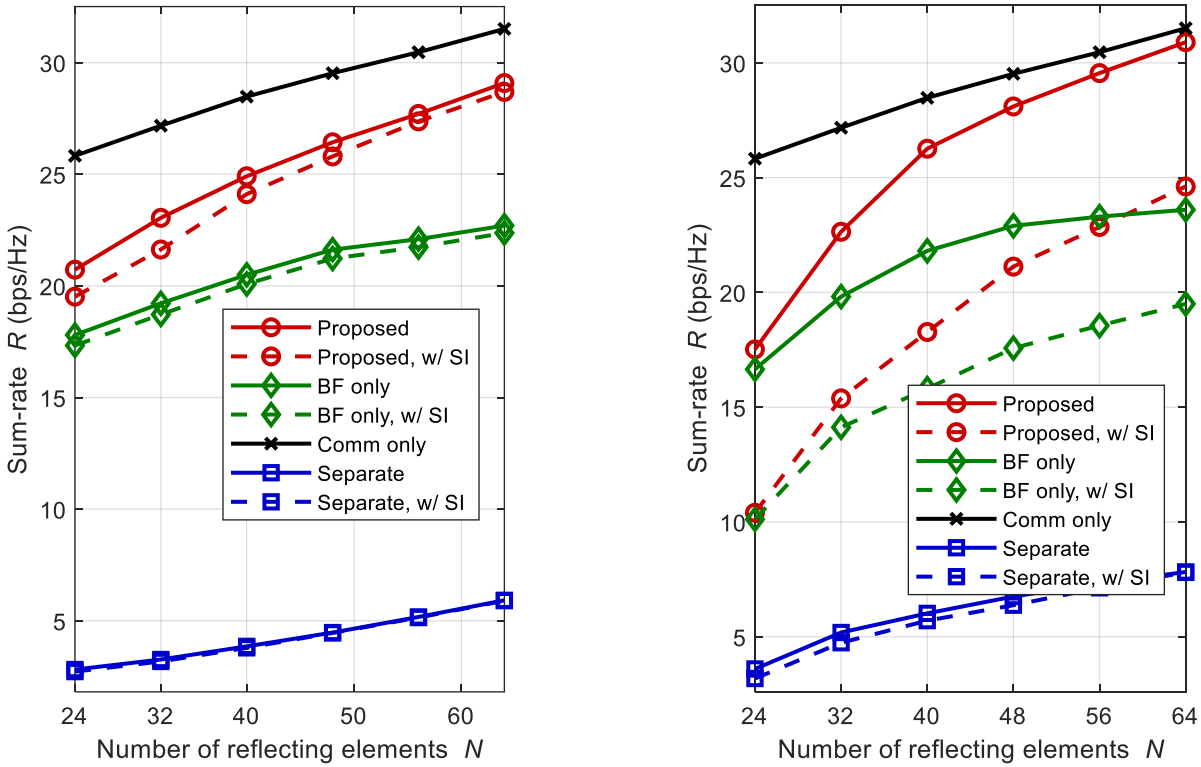
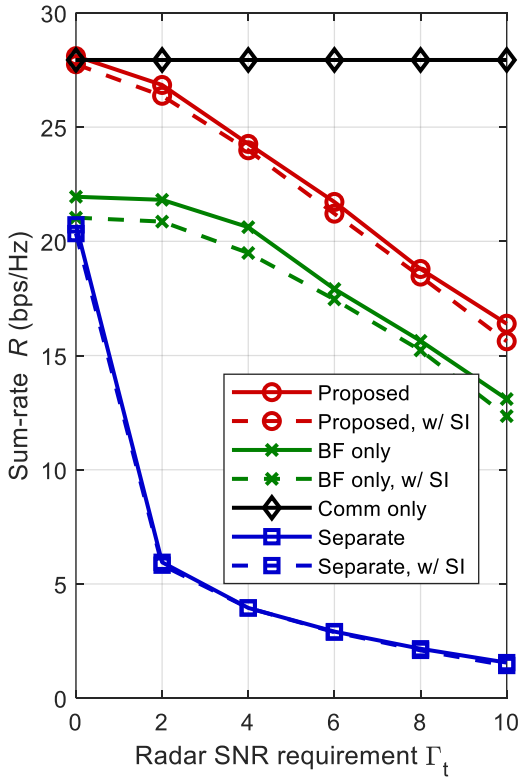


Fig. 19. Enhanced beampattern of the RIS-assisted system.

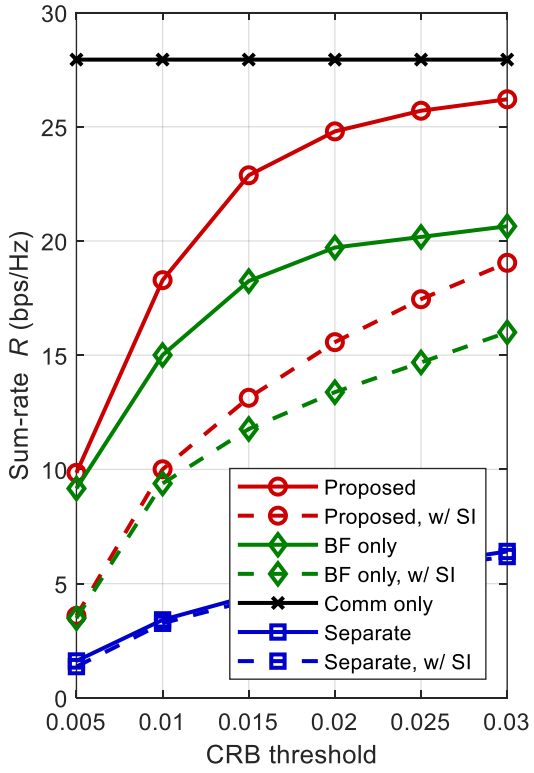


(a) SNR-constrained. (b) CRB-constrained.

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



(a) SNR-constrained.



(b) CRB-constrained.

Fig. 21. Impact of radar sensing performance.

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/