Uplink ISAC Receiver Designs

Receiver Design for Uplink ISAC

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Outline

Background

Uplink ISAC

Low-Altitude Economy

Emerging low-altitude application

- ➢ UAV video streaming and data uploading
- ➢ Environmental sensing and aerial monitoring
- ➢ Logistics, inspection, and airspace safety

Communication and sensing requirement

- ➢ Sustained **uplink transmission** for multimodal data

↕ Same time and frequency?

- ➢ **Continuous sensing** capability for surrounding targets

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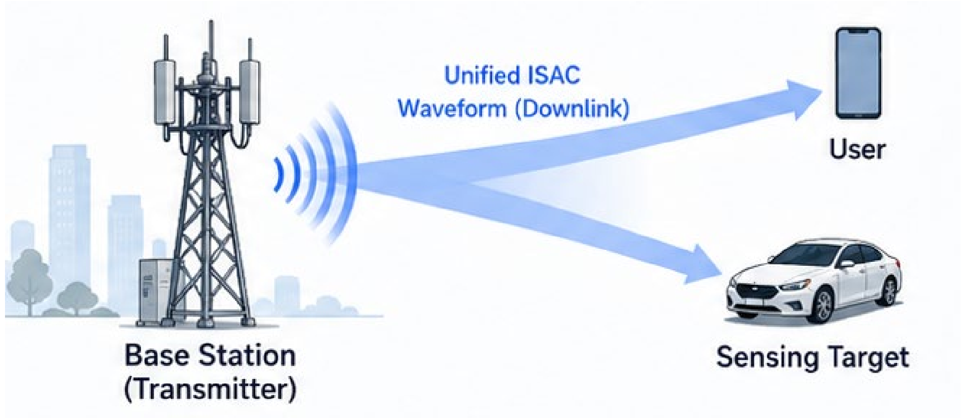
Comparison

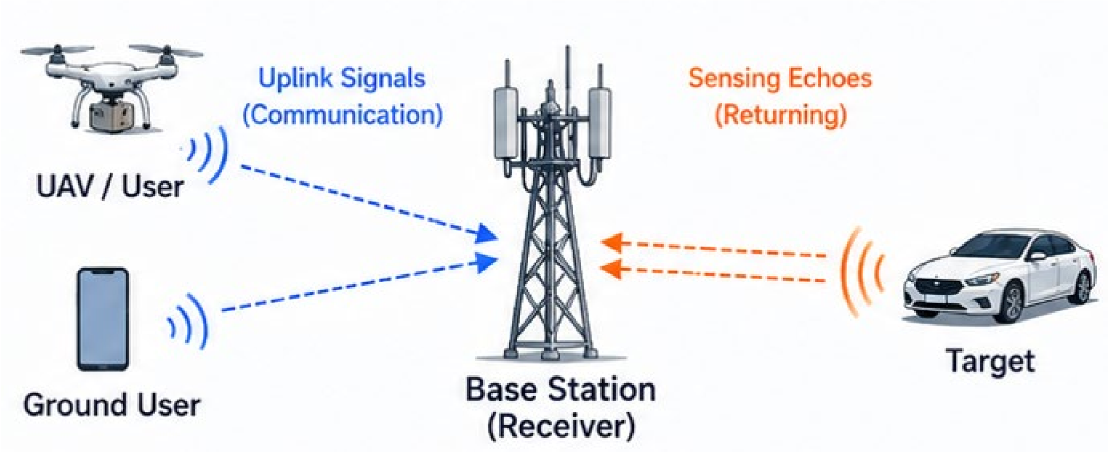
Downlink ISAC: Transmitter-side design



Research Focus:

- ➢ Unified Waveform Design
- ➢ Sensing and Communication (S&C) **tradeoff**

Uplink ISAC: Receiver-side Design



Research Focus:

- ➢ Signal Detection/ Parameter Estimation Algorithm
- ➢ S&C **mutual interference**

Key Point: How to decouple the S&C signal at the receiver in uplink ISAC?

Problem Formulation

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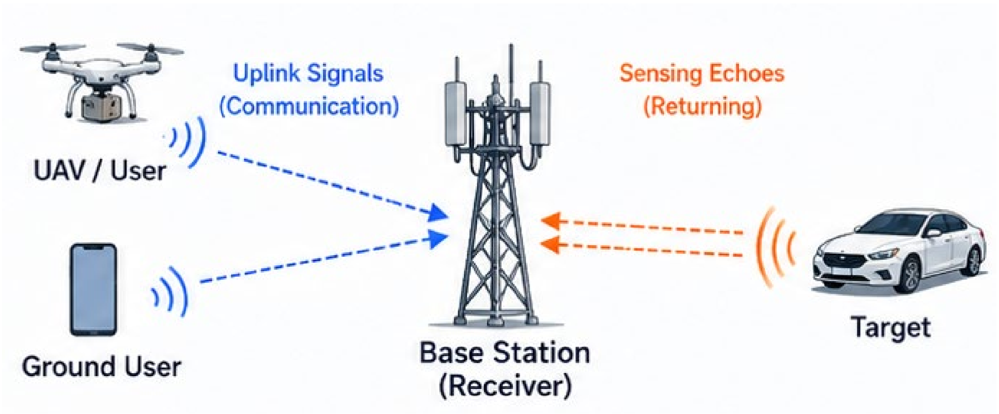
System Model



Sensing signal

Commun. signal

$$\mathbf{Y}=\mathbf{H}_{\mathrm{r}}\mathbf{X}_{\mathrm{r}}+\mathbf{H}_{\mathrm{c}}\mathbf{X}_{\mathrm{c}}+\tilde{\mathbf{N}} \leftarrow \text{Noise}$$

Sensing waveform:	$\mathbf{X}_{\mathrm{r}}=\left[\mathbf{x}_{\mathrm{r}}[1],\ldots,\mathbf{x}_{\mathrm{r}}[L]\right]$	Known
Target response matrix (TRM):	$\mathbf{H}_{\mathrm{r}}$	Unknown
Uplink data signal:	$\mathbf{X}_{\mathrm{c}}=\left[\mathbf{x}_{\mathrm{c}}[1],\ldots,\mathbf{x}_{\mathrm{c}}[L]\right]$	Unknown
Communication channel:	$\mathbf{H}_{\mathrm{c}}$	Known

ML Estimation

$$\underset{\underset{①}{\boxed{\mathbf{H}_{\mathrm{r}},\mathbf{X}_{\mathrm{c}}\in\mathcal{X}^{K\times L}}}}{\operatorname{argmin}}\left\|\mathbf{Y}-\overset{②}{\boxed{\mathbf{H}_{\mathrm{r}}}}\mathbf{X}_{\mathrm{r}}-\mathbf{H}_{\mathrm{c}}\overset{②}{\boxed{\mathbf{X}_{\mathrm{c}}}}\right\|_F^2$$

$$\Big\Downarrow \text{ Vectorized}$$

$$\underset{\mathbf{h}_{\mathrm{r}},\mathbf{x}_{\mathrm{c}}\in\mathcal{X}^{LK}}{\operatorname{argmin}}\left\|\mathbf{y}-\mathbf{A}_{\mathrm{c}}\mathbf{x}_{\mathrm{c}}-\mathbf{A}_{\mathrm{r}}\mathbf{h}_{\mathrm{r}}\right\|_2^2$$

Not a standard Least Square （LS） problem!

Main Challenges

① **Mixed integer Programming:** Discrete communication signal and continuous TRM

② **Undetermined Property:** $\mathbf{AX}+\mathbf{YB}=\mathbf{C}$ does not provide unique solution $\tilde{\mathbf{X}}$, $\tilde{\mathbf{Y}}$ without ① . [1]

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[1] A. Liao et.al., "Best approximate solution of matrix equation AXB + CYD = E," SIAM Journal on Matrix Analysis and Applications, 2005

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2. Conventional Receivers
3. Proposed Framework
4. Results and Outlook

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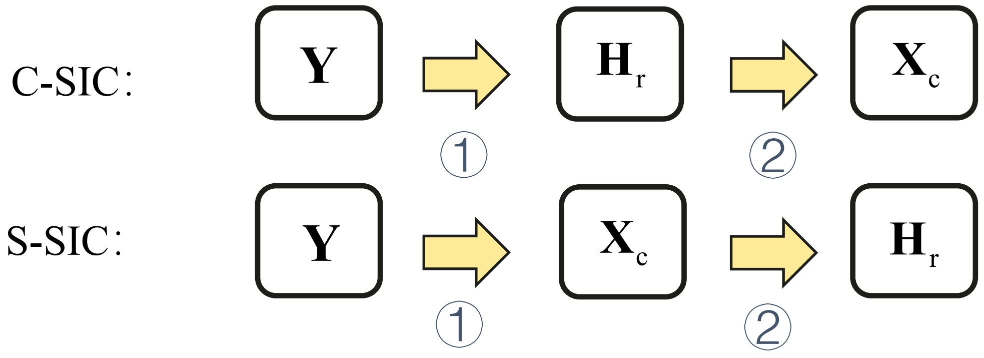
SIC-Type Receivers

SIC-Type Receivers[2]

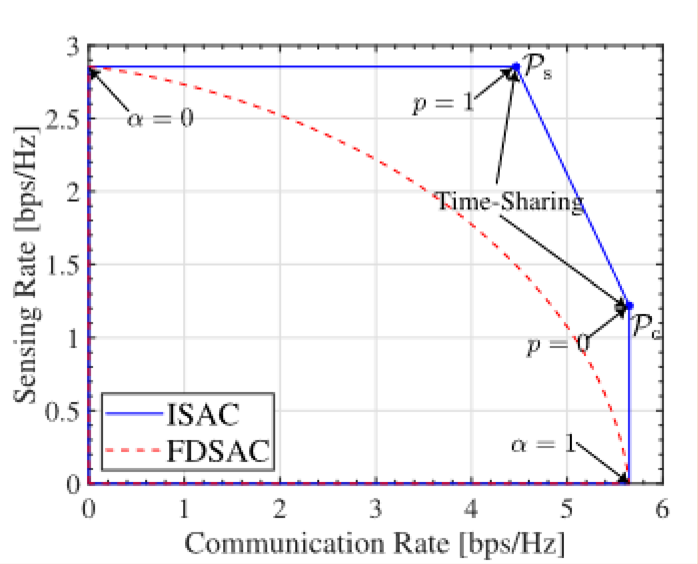


Take S-SIC as an example:

① The commun. signal is detected by **treating the sensing signal as AWGN.**

② The target response is estimated after subtracting the estimated commun. signal.

Pros and Cros



- Uplink ISAC **outperforms frequent-division ISAC**

Drawbacks:

- Ineffective **mutual interference** cancellation
- Potential **error propagation**

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[2] C. Ouyang, Y. Liu and H. Yang, "Revealing the Impact of SIC in NOMA-ISAC," in IEEE Wireless Communications Letters, vol. 12, no. 10, pp. 1707-1711, Oct. 2023

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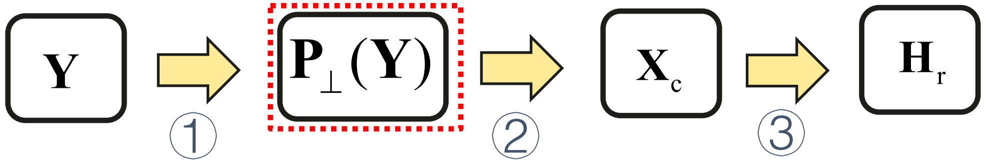
Projection-type Receivers

Projection-Type Receivers[2]

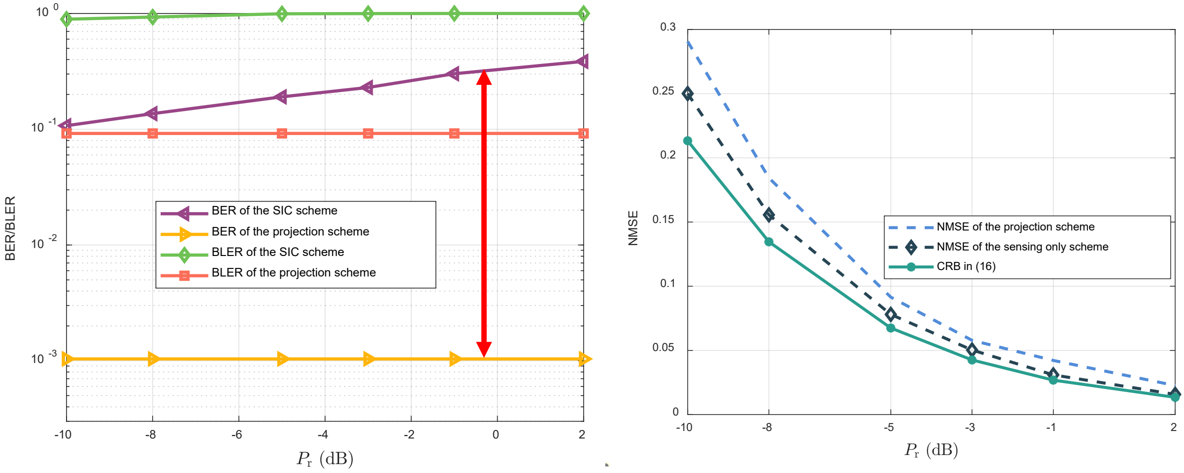
Design Pipeline


$\mathbf{Y} \xrightarrow{①} \mathbf{P}_{\perp}(\mathbf{Y}) \xrightarrow{②} \mathbf{X}_{\mathrm{c}} \xrightarrow{③} \mathbf{H}_{\mathrm{r}}$

Exploit the **structure of the sensing signal** to fully eliminate its interference to signal detection

- Achieve the same SNR as the commun. only systems $\mathrm{SNR}_{\mathrm{P}} \triangleq \frac{\mathbb{E}\left[\|\mathbf{\Gamma}\mathbf{A}_{\mathrm{c}}\mathbf{x}_{\mathrm{c}}\|_2^2\right]}{\mathbb{E}\left[\|\mathbf{\Gamma}\mathbf{n}\|_2^2\right]} = \frac{P_{\mathrm{c}}}{\sigma^2} = \mathrm{SNR}_{\mathrm{Com}}.$
- An **equivalent** formulation of ML estimation

Pros of the Projection-type receiver



- Lower BER due to the improved SNR
- Better Sensing performance due to the better communication signal detection in first stage

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[2] **Z. Yu** et.al., " Addressing the Mutual Interference in Uplink ISAC Receivers: A Projection Method," IEEE Wireless Commun. Lett., vol. 13, no. 11, pp. 3109–3113, Nov. 2024..

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Projection-type Receivers

Cros of the Projection-type receiver

- Consider the signal detection problem after projection

$$\underset{\mathbf{x}_{\mathrm{c}} \in \mathcal{X}^{LK}}{\operatorname{argmin}} \; \|\tilde{\mathbf{y}} - \mathbf{G}\mathbf{x}_{\mathrm{c}}\|_2^2 \qquad \mathbf{G} = \boxed{\mathbf{P}_\perp} \otimes \mathbf{H}_{\mathrm{c}}$$

Projection Matrix $\mathrm{Rank}(\mathbf{P}_\perp) = L - M_t$

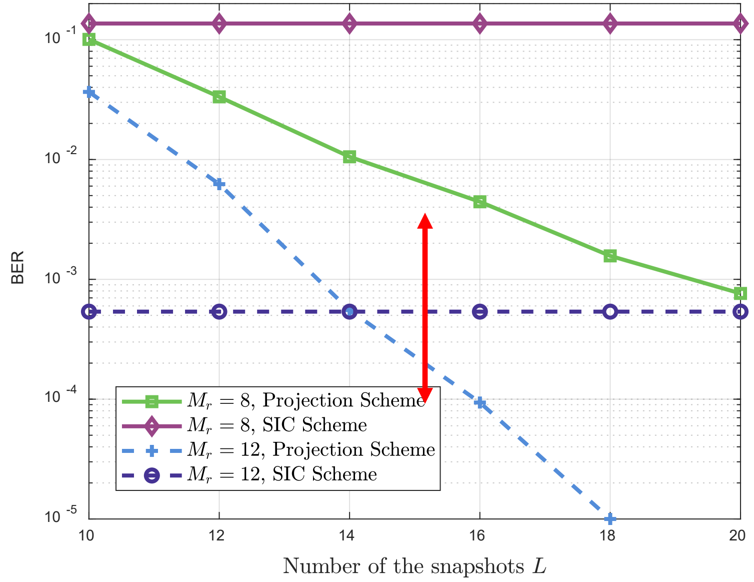
The rank of the observation matrix is given by

$$\mathrm{Rank}(\mathbf{G}) = (L - M_t)K < LK$$

- Signal Detection Algorithm

- Linear detectors, such as ZF, AMP, not applicable
- Other detectors, such as SDR, high complexity

Joint processing requirement



Jointly processing multiple snapshots is preferred, which leads to **higher computation complexity**.

Attractive in theory, constrained in practice

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3. **Proposed Framework**
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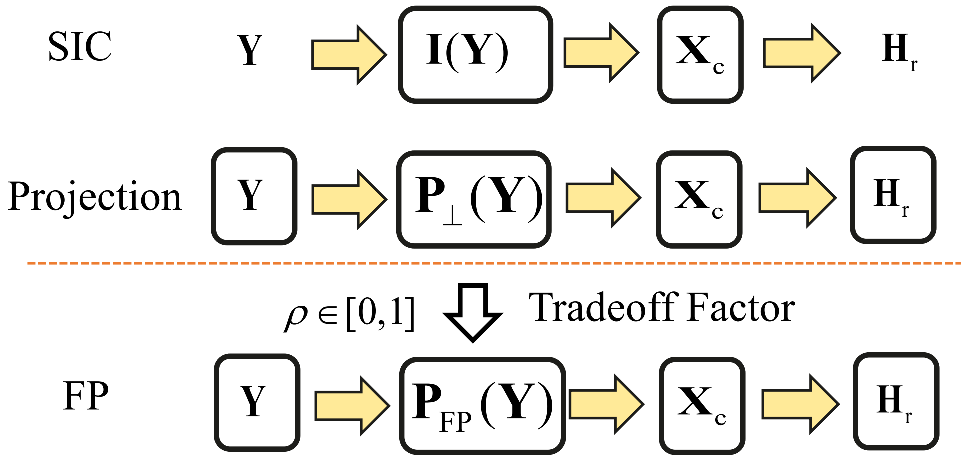
FP-type Receiver

Flexible Projection(FP): A framework



SIC $\mathbf{Y} \Rightarrow \boxed{\mathbf{I}(\mathbf{Y})} \Rightarrow \boxed{\mathbf{X}_c} \Rightarrow \mathbf{H}_r$

Projection $\boxed{\mathbf{Y}} \Rightarrow \boxed{\mathbf{P}_\perp(\mathbf{Y})} \Rightarrow \boxed{\mathbf{X}_c} \Rightarrow \boxed{\mathbf{H}_r}$

$\rho \in [0,1]$ ⇓ Tradeoff Factor

FP $\boxed{\mathbf{Y}} \Rightarrow \boxed{\mathbf{P}_{FP}(\mathbf{Y})} \Rightarrow \boxed{\mathbf{X}_c} \Rightarrow \boxed{\mathbf{H}_r}$

$$\mathbf{P}_{FP} = \boxed{\rho\mathbf{I} + (1-\rho)\mathbf{P}_\perp}$$
$$= \mathbf{P}_\perp + \rho\mathbf{P}_\parallel$$

FP Matrix

Projection matrix of the signal space

$\rho = 1$ $\mathbf{P}_{FP} = \mathbf{I}$ SIC

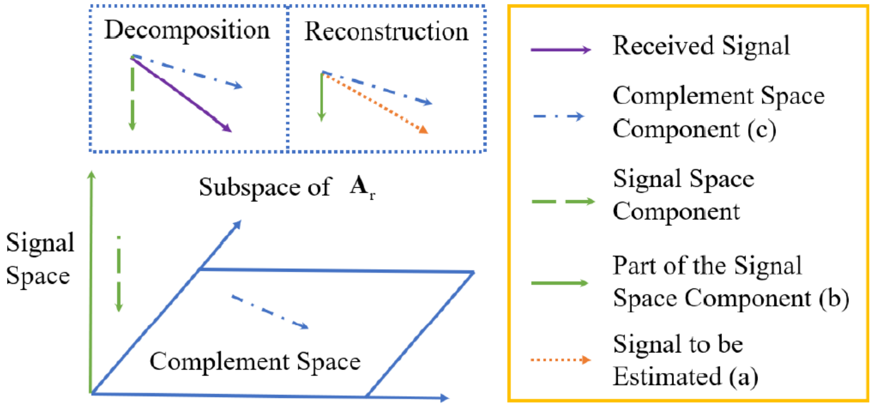
$\rho = 0$ $\mathbf{P}_{FP} = \mathbf{P}_\perp$ Projection

Physical Illustration

$$\hat{\mathbf{x}}_c = \underset{\mathbf{x}_c \in \mathcal{X}^{LK}}{\arg\min} \ \| \mathbf{\Gamma}_{FP}(\mathbf{y} - \mathbf{A}_c\mathbf{x}_c - \mathbf{A}_r\mathbf{h}_r)\|_2^2$$
$$= \underset{\mathbf{x}_c \in \mathcal{X}^{LK}}{\arg\min} \| \mathbf{\Gamma}(\mathbf{y} - \mathbf{A}_c\mathbf{x}_c) + \rho\mathbf{\Gamma}_{\parallel}(\mathbf{y} - \mathbf{A}_c\mathbf{x}_c - \mathbf{A}_r\mathbf{h}_r)\|_2^2$$

↑ Orthogonal space component

↑ Part of signal space component



Black or white is never optimal; balance is what we need

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FP-type Receiver

SINR & Correlation Tradeoff

✓ **SINR of the FP-type Receivers**

$$\mathrm{SINR}_{\mathrm{FP}} \triangleq \frac{\mathbb{E}\left[\| \mathbf{\Gamma}_{\mathrm{FP}}\mathbf{A}_{\mathrm{c}}\mathbf{x}_{\mathrm{c}}\|_2^2\right]}{\mathbb{E}\left[\| \mathbf{\Gamma}_{\mathrm{FP}}\mathbf{A}_{\mathrm{r}}\mathbf{h}_{\mathrm{r}}\|_2^2\right]+\mathbb{E}\left[\| \mathbf{\Gamma}_{\mathrm{FP}}\mathbf{n}\|_2^2\right]}$$

$$= \frac{P_{\mathrm{c}}(L-(1-\rho^2)M_t)KM_r}{\rho^2 LP_{\mathrm{s}}+(L-(1-\rho^2)M_t)M_rK\sigma^2},$$

Smaller ρ, larger SINR.

✓ **Condition Number of the FP-type Receivers**

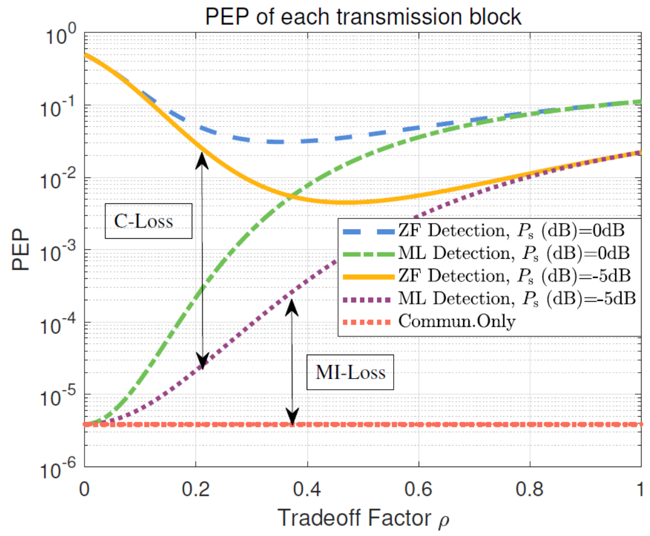
$$\mathrm{Cond}_{\mathrm{PT}}(\mathbf{G}_{\mathrm{T}}) \triangleq \frac{\omega_1(\mathbf{G}_{\mathrm{FP}})}{\omega_{LNt}(\mathbf{G}_{\mathrm{FP}})} = \sqrt{\frac{\lambda_1(\mathbf{G}_{\mathrm{FP}}^{\mathrm{H}}\mathbf{G}_{\mathrm{FP}})}{\lambda_{LNt}(\mathbf{G}_{\mathrm{FP}}^{\mathrm{H}}\mathbf{G}_{\mathrm{FP}})}}$$

$$= \frac{\lambda_1(\mathbf{P}_{\mathrm{FP}})}{\lambda_L(\mathbf{P}_{\mathrm{FP}})}\mathrm{Cond}(\mathbf{H}_{\mathrm{c}}) = \frac{1}{\rho}\mathrm{Cond}(\mathbf{H}_{\mathrm{c}})$$

Smaller ρ, smaller condition number, larger column correlations.

Pairwise Error Probability (PEP) Analysis

High-SNR approximation of BER curve



- ➢ ML Detector prefers small ρ, while ZF prefers larger.

⇩

Different ρ for different detection algorithm?

Finding the optimal tradeoff parameter is non-trivial

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DFP-type Receiver

Design Philosophy

- ➢ Homotopy Optimization

Easy Problem

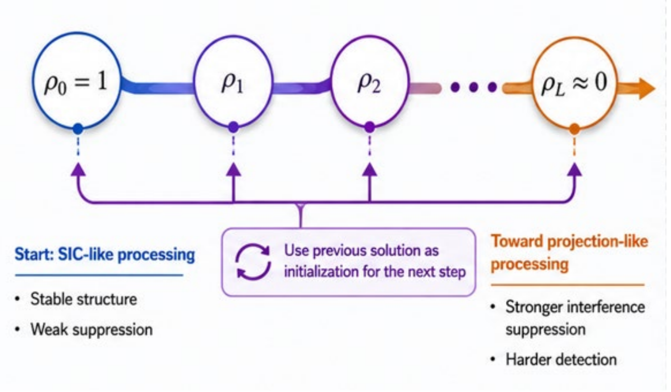
Construct a family of Homotopy function

$$h(\mathbf{z},\eta)=\begin{cases} f^{1}(\mathbf{z}),, & \text{if } \eta=1 \text{ and} \\ \cdots & \\ f(\mathbf{z}) & \text{if } \eta=0, \end{cases}$$

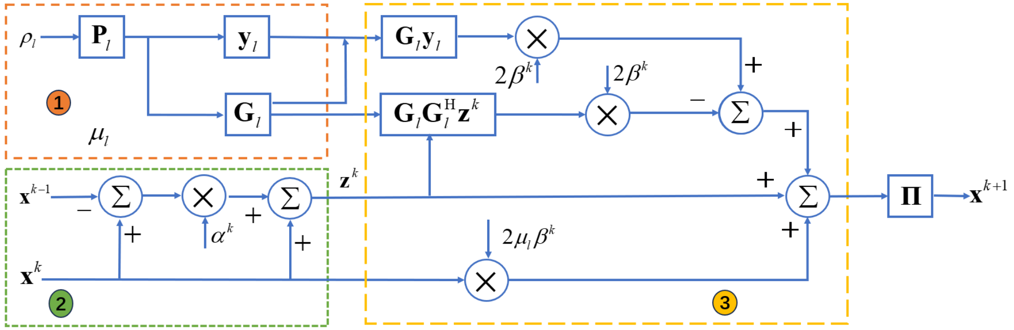
↑ Original Problem

Approximate the original problem with a sequence of problems

- ➢ Dynamic Projection



Implement Detail



✓ Outer Layer ①

Update penalty parameter μ and tradeoff factor ρ

✓ Inner Layer ② ③

Apply the gradient extrapolated majorization-minimization.

⇓

Only matrix multiplication evolved

Do the simple first, then do the right

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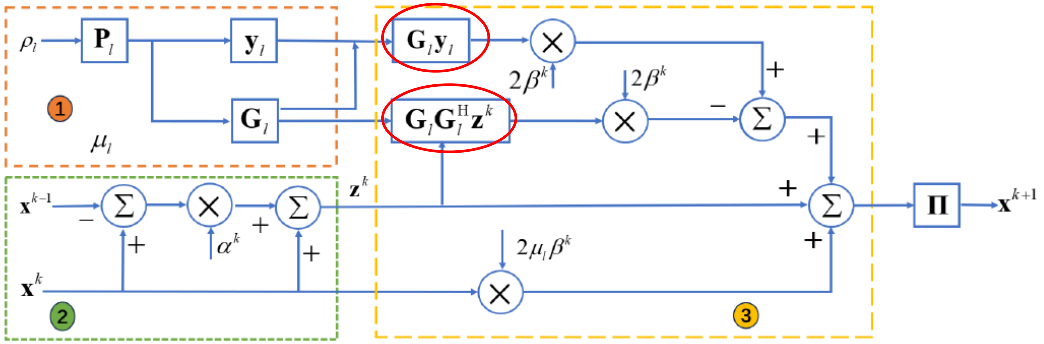
Complexity of DFP

Complexity Reduction

Calculating the gradient of DFP requires the update of observation matrix.



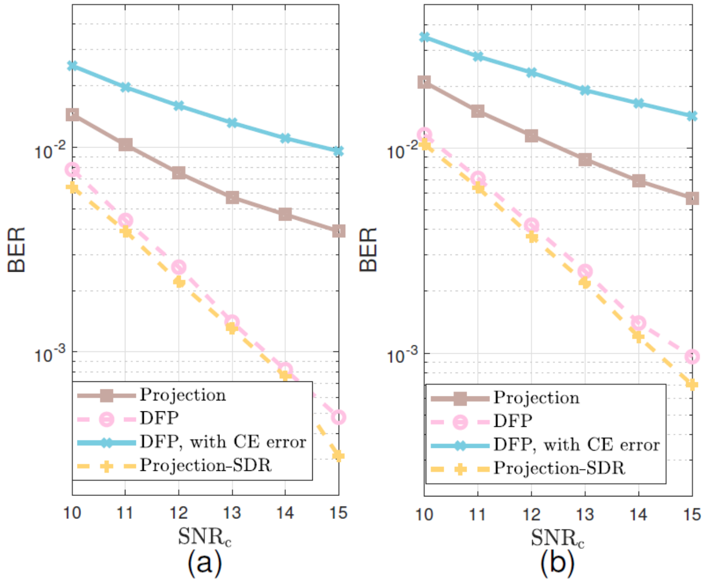
- Solution: pre-calculation

$$\mathbf{G}_l^{\mathrm{T}}\mathbf{G}_l = (1-\rho_l)^2\mathbf{M}_1 + \rho_l(1-\rho_l)\mathbf{M}_2 + \rho_l^2\mathbf{M}_3,$$
$$\mathbf{G}_l^{\mathrm{T}}\mathbf{y}_l = (1-\rho_l)^2\mathbf{u}_1 + \rho_l(1-\rho_l)\mathbf{u}_2 + \rho_l^2\mathbf{u}_3,$$

DFP-type receiver achieves the same complexity as conventional projection-type receiver via pre-calculation.

Performance Comparison

- Performance closes to projection-SDR
- CPU time **reduces 100x** than projection-SDR



(a)

(b)

(M_r, K, L)	**DFP receiver**	**SIC receiver**	**Projection-SDR**
(8, 8, 16)	0.0018	5.8×10^{-4}	0.55
(16, 16, 16)	0.0166	0.0025	2.52
(16, 16, 24)	0.0411	0.0025	Memory Limited

Performance Evaluation

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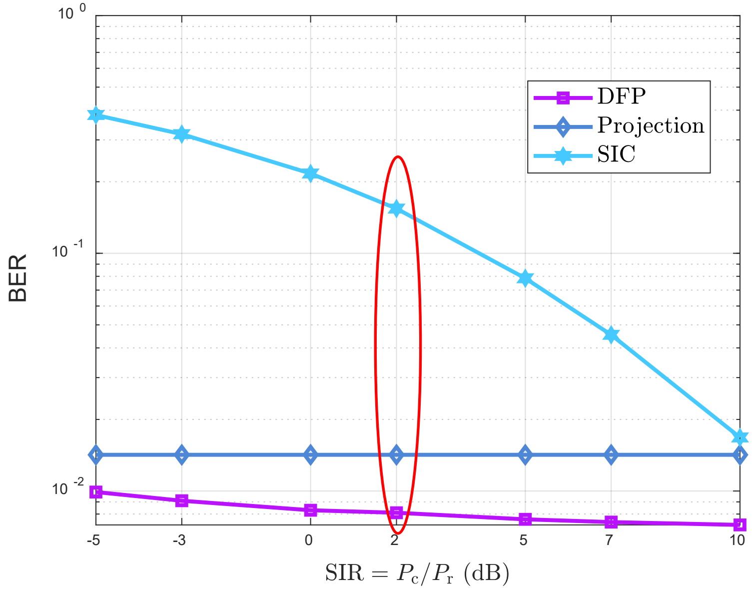
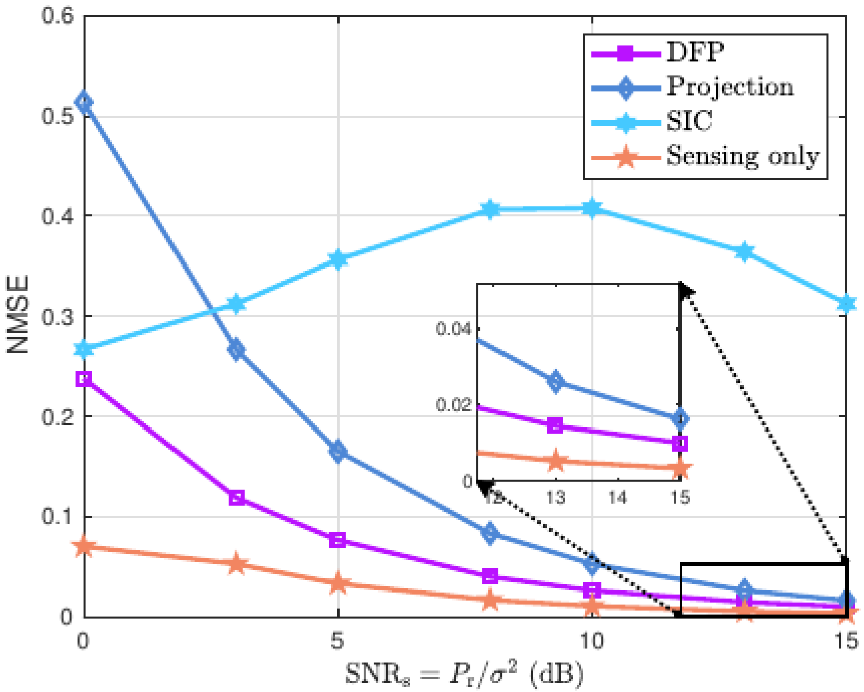
S&C Performance

BER of uplink transmission



DFP outperforms projection-type receiver and has much lower BER than SIC-type receiver.

NMSE of TRM Estimation



DFP has lower NMSE than benchmark, closes to the sensing-only systems in high SNR region.

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S&C Performance

Angle Estimation for Bistatic ISAC setup

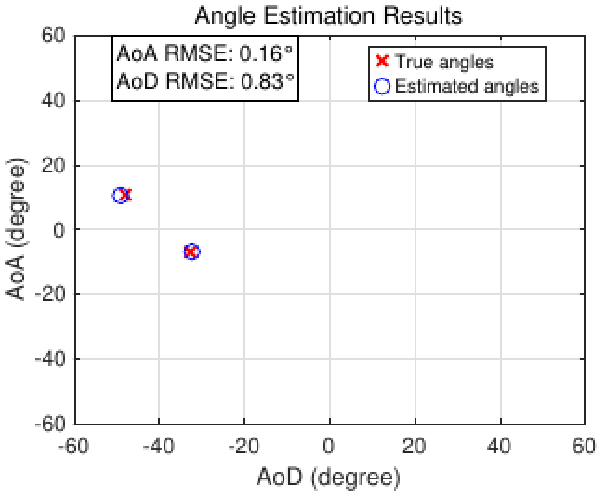


Fig. 9 (a): Sensing only, $M_t = N_r = K = 8$

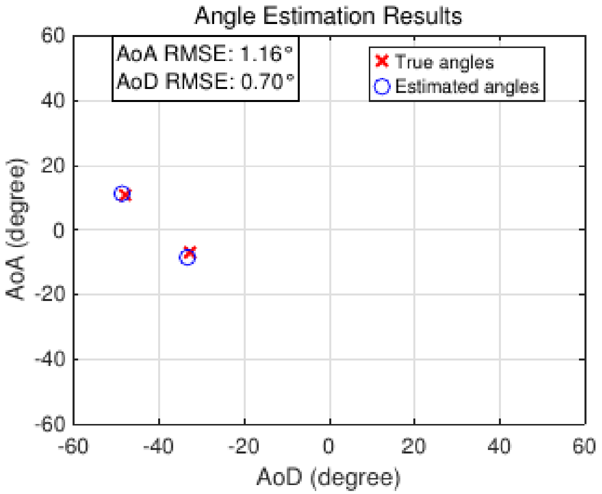


Fig. 9 (b): DFP, $M_t = N_r = K = 8$

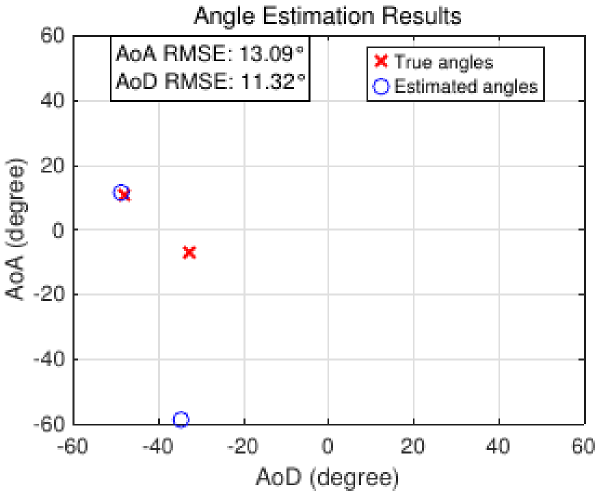


Fig. 9 (c): SIC, $M_t = N_r = K = 8$

	DFP-type	**SIC-type**	**Sensing-only**
RMSE	5.6°	8.2°	2.2°
Hit rate	71.3%	50.9%	90.2%

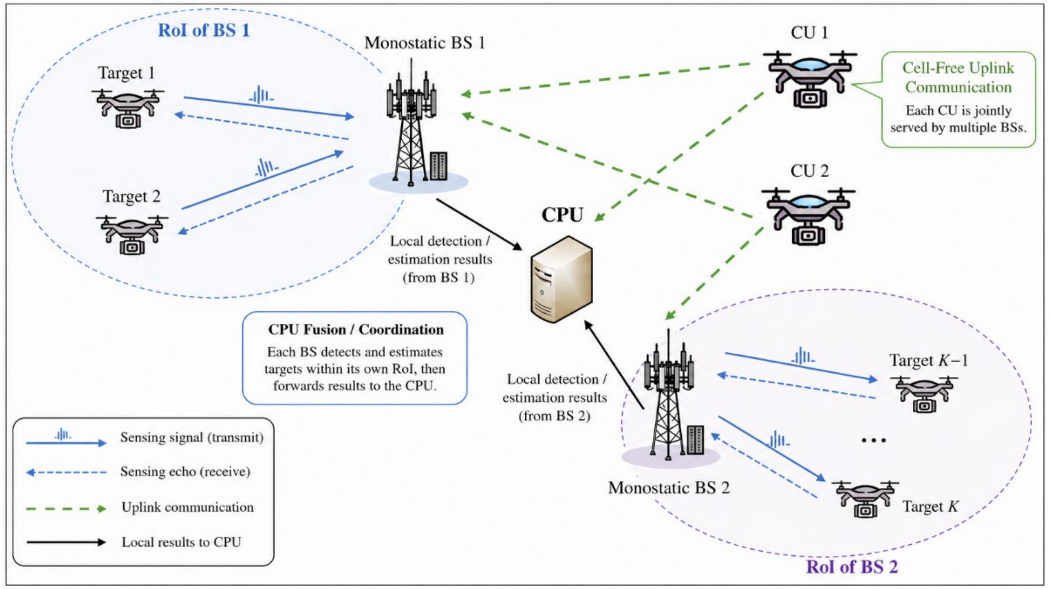
Error<2°

- Compared to the SIC receiver, the angle RMSE of DFP has reduced more than **40%**, and its hit rate has increased more than **20%**

Uplink ISAC

Cell-free Uplink ISAC systems

Gain from the diversity



- The rank-deficient issue can be addressed in cell-free uplink ISAC

Learn from the environment

- Design the structure of the DFP-receiver using detection theory

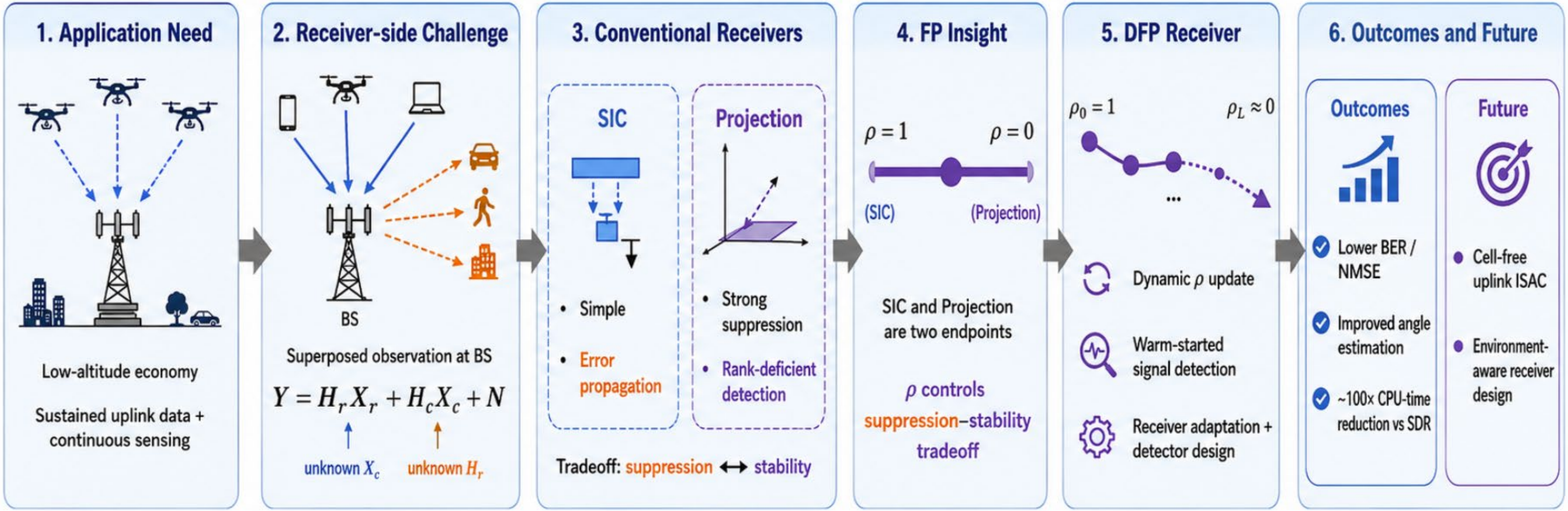
$$w_{1,k}^{(t)} = \frac{p(\mathbf{y}_k \mid z_k = 1, \mathbf{x}_{\mathrm{c}}^{(t-1)}) P(z_k = 1)}{p(\mathbf{y}_k \mid z_k = 1, \mathbf{x}_{\mathrm{c}}^{(t-1)}) P(z_k = 1) + p(\mathbf{y}_k \mid z_k = 0, \mathbf{x}_{\mathrm{c}}^{(t-1)}) P(z_k = 0)}$$

$$\boldsymbol{\Phi}_k^{(t)} = \frac{1}{\sigma_k^2}\left[(1 - w_{1,k}^{(t)})\mathbf{I} + w_{1,k}^{(t)}\boldsymbol{\Gamma}_k\right]$$

The receiver can be **adjusted according to the received signal**

Uplink ISAC

Take Away Message



➢ Related Paper

[1] **Z. Yu,** H. Ren, C. Pan, G. Zhou, R. Wang, M. Liu, J. Wang , " Addressing the Mutual Interference in Uplink ISAC Receivers: A Projection Method," IEEE Wireless Commun. Lett., vol. 13, no. 11, pp. 3109–3113, Nov. 2024.

[2] **Z. Yu,** H. Ren, C. Pan, G. Zhou, D. Wang, J. Wang , " A Framework for Uplink ISAC Receiver Designs: Performance Analysis and Algorithm Development," IEEE Trans. Wireless Commun., vol. 25, pp. 16628-16644, 2026.

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Thanks for your Listening!
Any Questions?

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