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Joint Channel Estimation and Radar Sensing for UAV Networks with mmWave Massive MIMO

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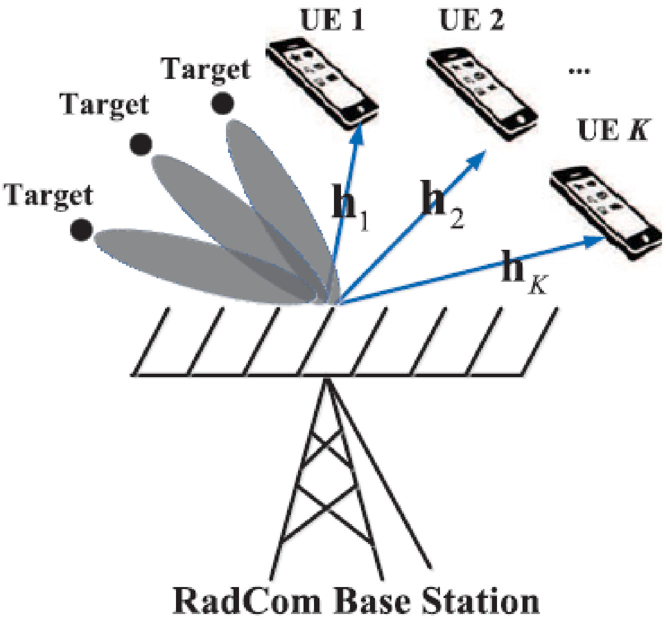
1 Introduction

- Integrated Sensing and Communication (ISAC) [R1]-[R2]
  - Integrate both functionalities of radar and communications, saving spectrum and hardware resources.
- Unmanned Aerial Vehicle (UAV) Networks [R3]
  - Play an important role in the non-terrestrial network (NTN)
  - Flexible deployment, fast response, line-of-sight (LoS) transmission, etc.
- It will be exciting to combine ISAC with UAV networks [R4].
- The state-of-the-art compressive sensing (CS) is applied to facilitate joint channel estimation (CE) and radar sensing.



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2 System Model

- A ground-to-air (G2A) ISAC scenario in UAV networks.
- At the terrestrial station, the full duplex (FD) [R5]-[R6] mmWave massive MIMO with hybrid beamforming (HBF) is deployed.

	Terrestrial Station	**UAV**
Array Form	Half-wavelength spaced uniform linear array (ULA)	
# of antennas	$\overline{N}$	N
# of Tx RF chains	$N_{\mathrm{RF}}<\overline{N}$	1
# of Rx RF chains	$\overline{N}$(Fully digital)	1

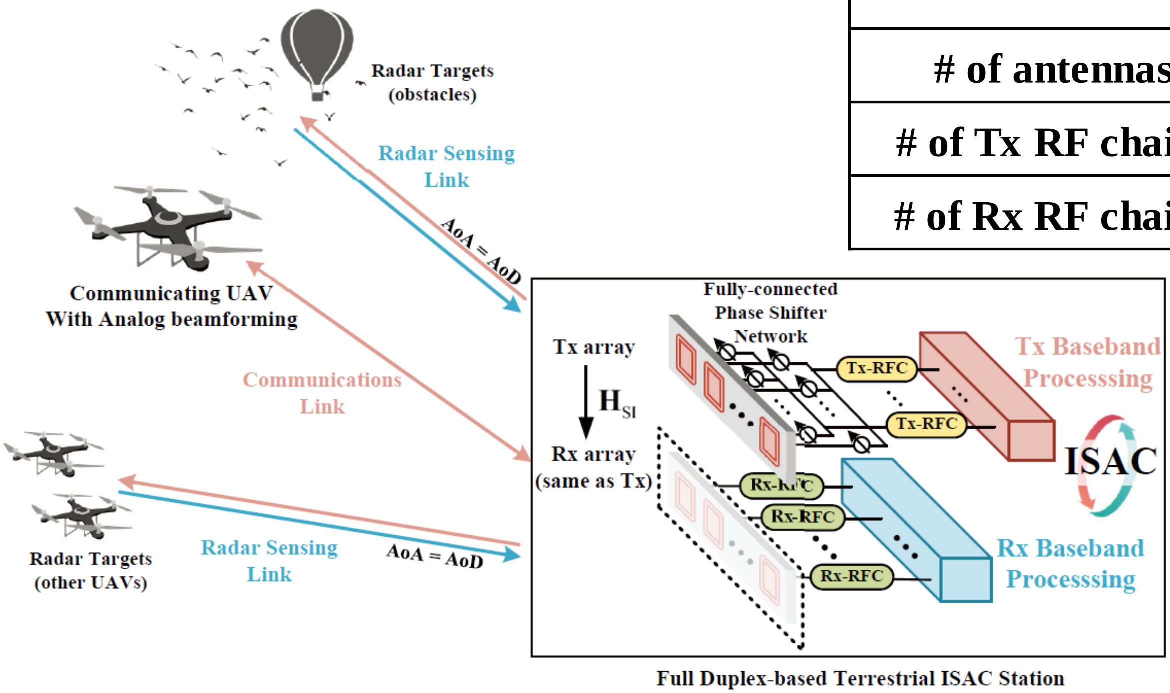

Fig. 1. The model of the considered UAV network, where the terrestrial ISAC station with FD mmWave mMIMO serves UAVs.

2 Channel Model

- The delay-domain **communication channel** with one LoS path and N_{C} NLoS clusters:

Pulse shaping filter with delay offset

$$\mathbf{H}(\tau) = \mathbf{H}_{\mathrm{LoS}} \boxed{p\left(\tau - \tau_{\mathrm{LoS}}\right)} + \sum_{c=1}^{N_{\mathrm{C}}} \sum_{l=1}^{N_{\mathrm{P}}} \mathbf{H}_{c,l}\, p\left(\tau - \tau_{c,l}\right), \quad (1)$$

with

$$\mathbf{H}_{\mathrm{LoS}} = \sqrt{N\overline{N}}\, g_{\mathrm{LoS}} \boxed{\mathbf{a}_N\left(\theta_{\mathrm{LoS}}\right) \mathbf{a}_{\overline{N}}^{\mathrm{H}}\left(\varphi_{\mathrm{LoS}}\right)}, \quad (2)$$

Steering vectors with AoA and AoD

$$\mathbf{H}_{c,l} = \sqrt{\frac{N\overline{N}}{K_{\mathrm{f}} N_{\mathrm{C}} N_{\mathrm{P}}}}\, g_{c,l} \mathbf{a}_N\left(\theta_{c,l}\right) \mathbf{a}_{\overline{N}}^{\mathrm{H}}\left(\varphi_{c,l}\right). \quad (3)$$

- The delay-domain **radar channel** (from the station to the targets and then back to station) with **spatial consistency** [Journal].

$$\overline{\mathbf{H}}(\tau) = \sum_{c=1}^{\overline{N}_{\mathrm{C}}} \sum_{l=1}^{\overline{N}_{\mathrm{P}}} \overline{\mathbf{H}}_{c,l}\, p\left(\tau - \overline{\tau}_{c,l}\right), \quad (5)$$

where

$$\overline{\mathbf{H}}_{c,l} = \sqrt{\frac{\overline{N}^2}{\overline{N}_{\mathrm{C}} \overline{N}_{\mathrm{P}}}}\, \overline{g}_{c,l} \boxed{\mathbf{a}_{\overline{N}}\left(\overline{\theta}_{c,l}\right) \mathbf{a}_{\overline{N}}^{\mathrm{H}}\left(\overline{\theta}_{c,l}\right)}. \quad (6)$$

Spatial Consistency, i.e., AoA=AoD for radar sensing

[Journal] Z. Gao, Z. Wan *et al.*, "Integrated Sensing and Communication with mmWave Massive MIMO: A Compressed Sampling Perspective ", submitted to ***IEEE TWC***, Major Revision. arXiv: 2201.05766

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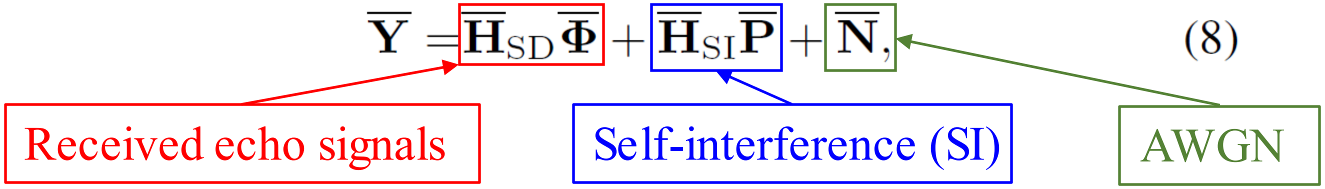
3.A Full-duplex and SI Cancellation

- To conduct the joint CE and radar sensing, the terrestrial station transmits the known pilot signals $\mathbf{p}_p \in \mathbb{C}^{\overline{N}\times 1}$ with $\|\mathbf{p}_p\|_2 = P_{\mathrm{Tx}}$.
- At the Rx part of terrestrial station, the received signals after reflection:



$$\overline{\mathbf{Y}} = \boxed{\overline{\mathbf{H}}_{\mathrm{SD}}\overline{\mathbf{\Phi}}} + \boxed{\overline{\mathbf{H}}_{\mathrm{SI}}\overline{\mathbf{P}}} + \boxed{\overline{\mathbf{N}},} \tag{8}$$

Received echo signals

Self-interference (SI)

AWGN

where $\overline{\mathbf{H}}_{\mathrm{SD}} \in \mathbb{C}^{\overline{N}\times L\overline{N}}$ is the effective radar CIR to be estimated, containing the information of delays (ranges) and angles of targets.

- At the UAV, the analog beamformer weight vectors $\mathbf{w}_q \in \mathbb{C}^{M\times 1}$, $q = 0, 1, \cdots, Q-1$ are used to receive the downlink pilot signals from terrestrial station. The received signals:

$$\mathbf{y} = \mathbf{\Phi}\,\mathrm{vec}\left(\mathbf{H}_{\mathrm{SD}}\right) + \mathbf{n}, \tag{10}$$

where $\mathbf{\Phi}$ is the known measurement matrix (consisting of pilot signals), and $\mathbf{H}_{\mathrm{SD}}$ is the effective communications CIR to be estimated.

- (8) and (10) are usually under-determined, which motivates us to resort to CS techniques.

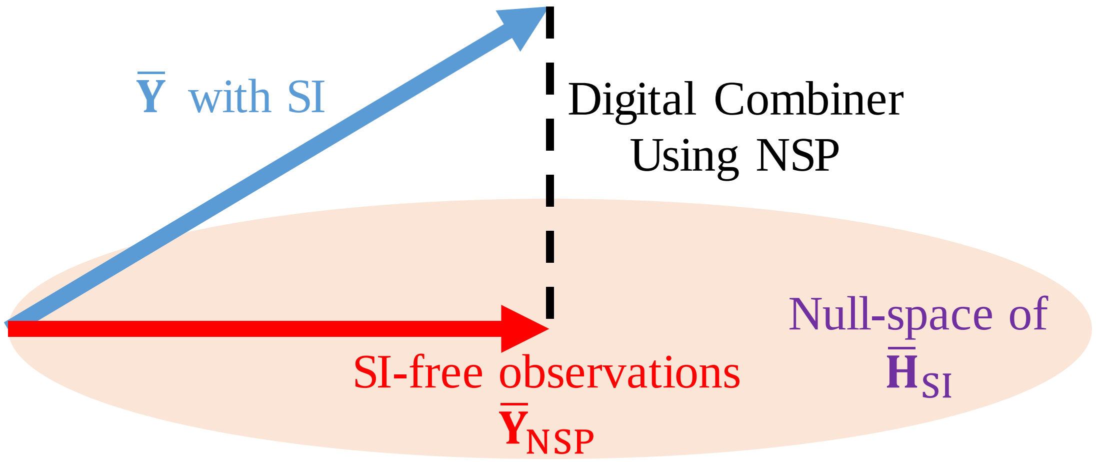
3.A Full-duplex and SI Cancellation

- Assume the SI channel $\overline{\mathbf{H}}_{\mathrm{SI}}$ is known [R5]-[R6]
- Since the same array are used for both Tx and Rx, the SI channel will be highly-correlated so that it will be rank-insufficient.
- We apply a digital combiner $\overline{\mathbf{W}} \in \mathbb{C}^{\overline{N}\times\overline{N}}$ to the receive signals $\overline{\mathbf{Y}}$ following the null-space projection (NSP) method [R6]:

$$\overline{\mathbf{W}} = \mathbf{I}_{\overline{N}} - \overline{\mathbf{H}}_{\mathrm{SI}}\overline{\mathbf{P}}\left(\overline{\mathbf{H}}_{\mathrm{SI}}\overline{\mathbf{P}}\right)^{\dagger}. \qquad (13)$$

- The SI-free received signals for radar sensing:

$$\overline{\mathbf{Y}}_{\mathrm{NSP}} \triangleq \overline{\mathbf{W}\mathbf{Y}} = \overline{\mathbf{W}\mathbf{H}}_{\mathrm{SD}}\overline{\mathbf{\Phi}} + \overline{\mathbf{W}\mathbf{N}} \qquad (14)$$



$\overline{\mathbf{Y}}$ with SI

Digital Combiner
Using NSP

Null-space of
$\overline{\mathbf{H}}_{\mathrm{SI}}$

SI-free observations
$\overline{\mathbf{Y}}_{\mathrm{NSP}}$

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3.B Waveform Design

- We note that in HBF architecture, the switch of phase shifter will take non-negligible reconfiguring time [R7], while this property is often sidestepped in previous works [R2] on waveform design.
- Given that, we propose to use a codebook of analog precoders (combiners) and to reserve sufficient idle time for reconfiguring RF circuits between two adjacent codewords, at the cost of loss of pilot diversity.

Analog Precoder Codebook

$$\left\{\mathbf{F}_n^{\mathrm{CB}} \in \mathbb{C}^{\overline{N}\times N_{\mathrm{RF}}}\right\}_{n=1}^{\overline{N}^{\mathrm{CB}}}$$

Analog Combiner Codebook

$$\left\{\mathbf{w}_n^{\mathrm{CB}} \in \mathbb{C}^{N\times 1}\right\}_{n=1}^{N^{\mathrm{CB}}}$$

Only $\overline{N}^{\mathrm{CB}}$ (N^{CB}) codewords are allocated to P (Q) pilot signals, reducing pilot diversity

$$\mathbf{F}_p = \begin{cases} \mathbf{F}^{\mathrm{CB}}_{\lceil (p+1)/\overline{T}_{\mathrm{RF}} \rceil}, & \mathrm{mod}\left(p, \overline{T}_{\mathrm{RF}}\right) < \overline{T}_{\mathrm{RF}} - T_{\mathrm{GI}}, \\ \boxed{\text{uncertain},} & \text{otherwise}, \end{cases} \tag{16}$$

Reconfiguring……

$$\mathbf{w}_n = \begin{cases} \mathbf{w}^{\mathrm{CB}}_{\lceil (n+1)/T_{\mathrm{RF}} \rceil}, & \mathrm{mod}\left(n, T_{\mathrm{RF}}\right) < T_{\mathrm{RF}} - T_{\mathrm{GI}}, \\ \boxed{\text{uncertain},} & \text{otherwise}. \end{cases} \tag{17}$$

3.B Waveform Design

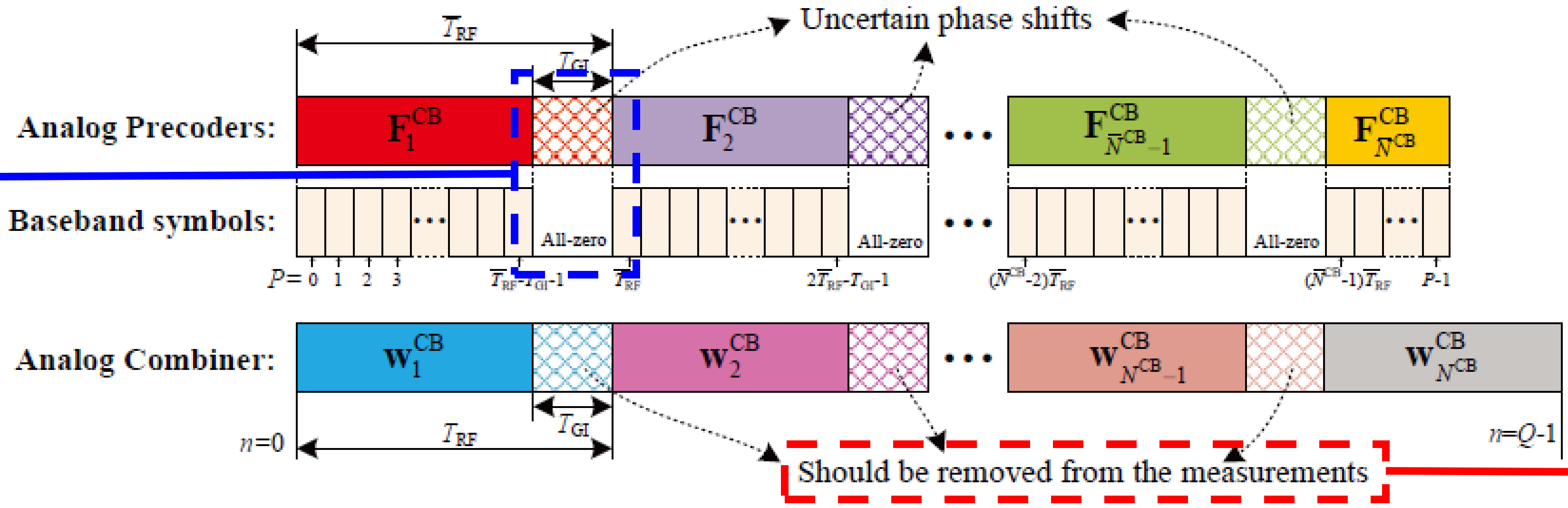

Fig. 2. The proposed waveform design which considers both the pilot diversity and the hardware feasibility.

- During the stage of uncertain analog precoders, zero baseband signals are transmitted, i.e., the actual transmit signals are also zeros:

$$\mathbf{s}_p = \mathbf{0}_{N_{\mathrm{RF}}\times 1} \text{ when } \mathrm{mod}\left(p, \overline{T}_{\mathrm{RF}}\right) \geq \overline{T}_{\mathrm{RF}} - T_{\mathrm{GI}}. \qquad (18)$$

- For the uncertain analog combiners, we remove them from the valid measurements:

$$\mathbf{y}_{\mathrm{v}} = \mathbf{\Phi}_{\mathrm{v}} \,\mathrm{vec}\left(\mathbf{H}_{\mathrm{SD}}\right) + \mathbf{n}_{\mathrm{v}}, \qquad (19)$$

where $\mathbf{y}_{\mathrm{v}} = [\mathbf{y}]_{\mathcal{I}_{\mathrm{v}}}$, $\mathbf{n}_{\mathrm{v}} = [\mathbf{n}]_{\mathcal{I}_{\mathrm{v}}}$, $\mathbf{\Phi}_{\mathrm{v}} = [\mathbf{\Phi}]_{\mathcal{I}_{\mathrm{v}}}$, and the ordered set for valid measurements $\mathcal{I}_{\mathrm{valid}} = \{i+1 \,|\, 0 \leq i < Q,\ \mathrm{mod}\left(i, T_{\mathrm{RF}}\right) < T_{\mathrm{RF}} - T_{\mathrm{GI}}\}$.

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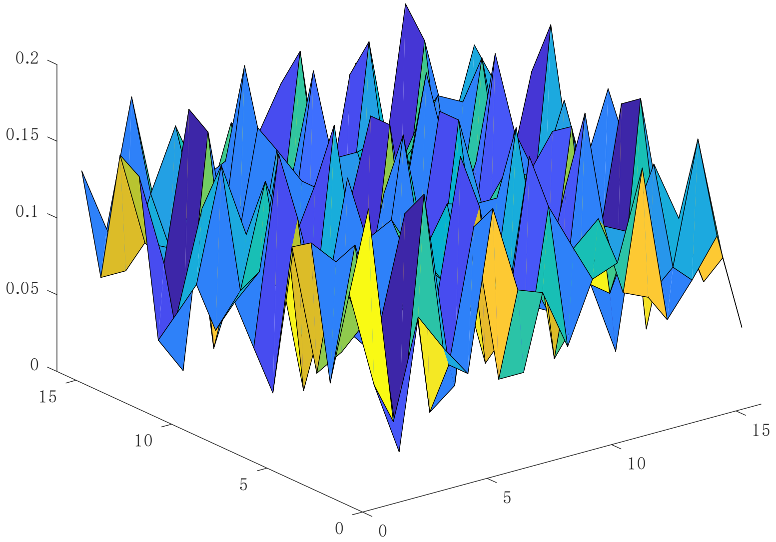
4.A Dictionary Design

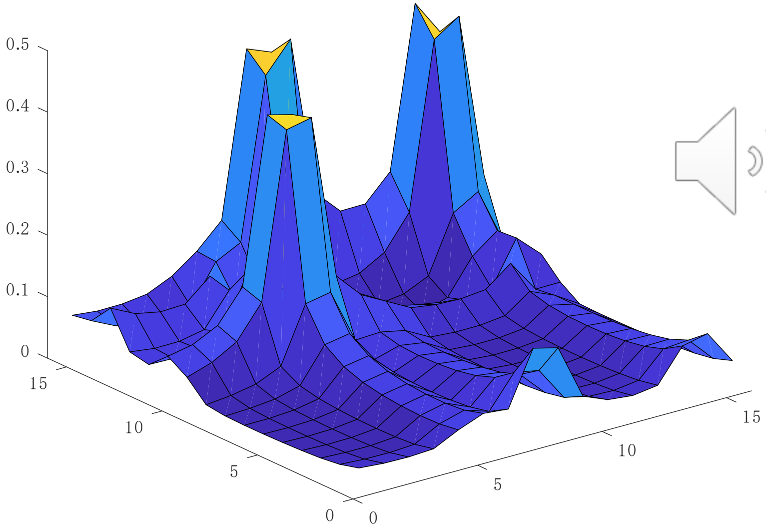
- Compressive sensing [R7]-[R8]: leveraging the sparsity of mmWave channels in many aspects to significantly reduce the pilot overhead in channel estimation and radar sensing.
- Re-represent the channels with the dictionaries $\mathbf{A}_{\mathrm{T}} \in \mathbb{C}^{\overline{N}\times G_{\mathrm{T}}}$, $\mathbf{A}_{\mathrm{R}} \in \mathbb{C}^{\overline{N}\times G_{\mathrm{R}}}$ and $\mathbf{A} \in \mathbb{C}^{N\times G}$

$$\boxed{\overline{\mathbf{H}}_l} \approx \mathbf{A}_{\mathrm{R}} \boxed{\overline{\mathbf{H}}_l^{\mathrm{Ad}}} \mathbf{A}_{\mathrm{T}}^{\mathrm{H}}, \tag{20}$$

$$\boxed{\mathbf{H}_l} \approx \mathbf{A} \boxed{\mathbf{H}_l^{\mathrm{Ad}}} \mathbf{A}_{\mathrm{T}}^{\mathrm{H}}, \tag{21}$$

Spatial-domain → Angular-domain (Sparse)



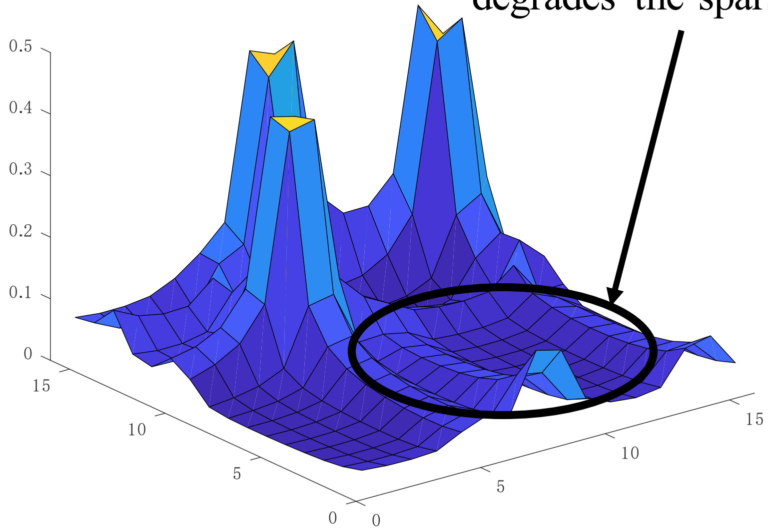


4.A Dictionary Design

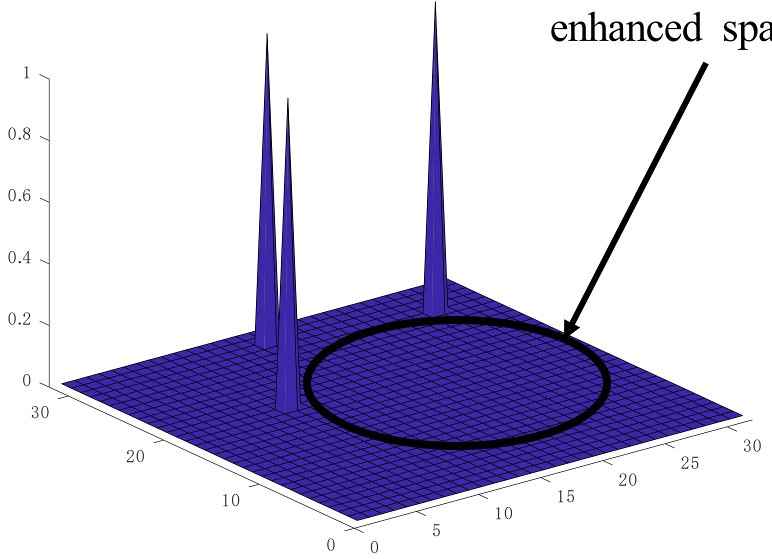
- Redundant dictionary [R8]: trading off the complexity and estimation performance.

Unitary dictionary 16×16 → Redundant dictionary 32×32

The power leakage that degrades the sparsity.



Larger dimension, enhanced sparsity



- Given the spatial consistency, i.e., AoA=AoD in radar sensing, we use multi-resolution (MR) dictionary design for radar sensing.
- Unitary dictionary for the Tx part, while redundant dictionary for the Rx part.

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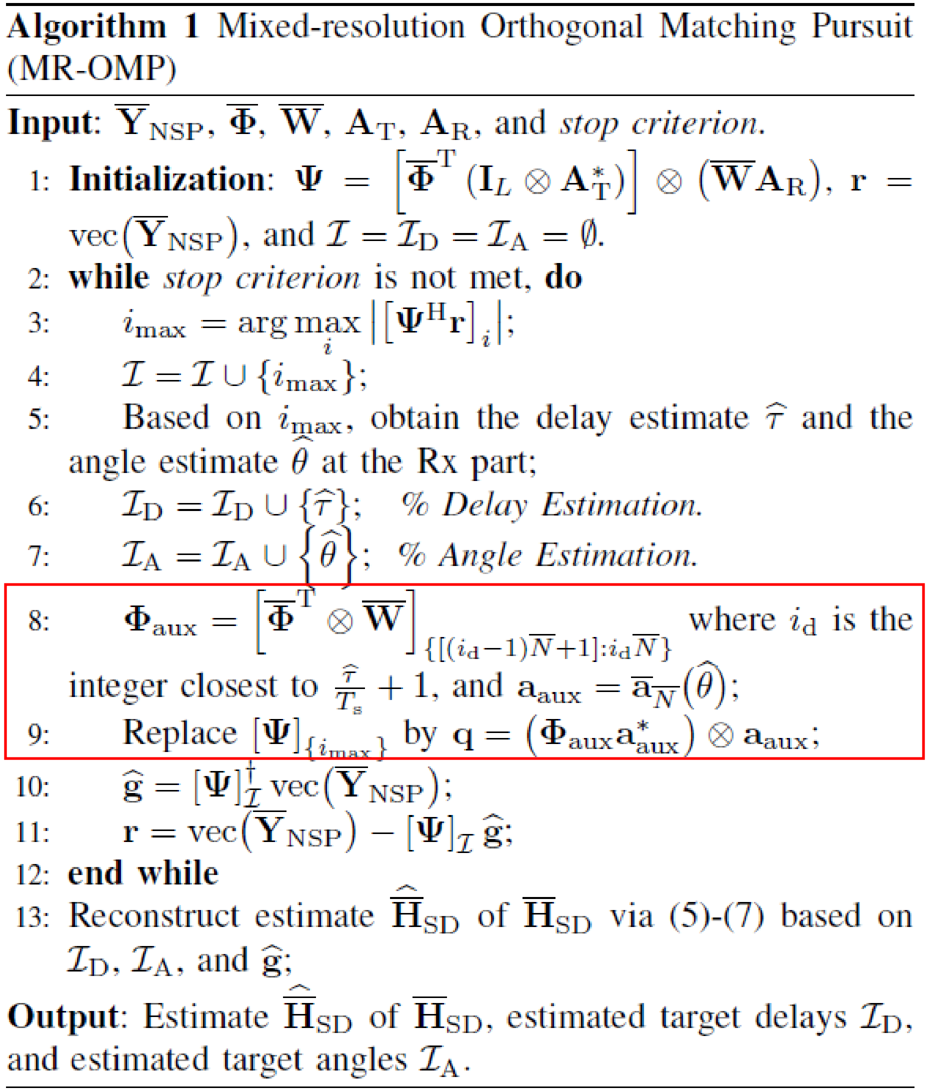
4.B Proposed CS-based Algorithms

- Multi-resolution Orthogonal Matching Pursuit (MR-OMP) to recover the radar CIR:



Algorithm 1 Mixed-resolution Orthogonal Matching Pursuit (MR-OMP)

```
Input: $\overline{\mathbf{Y}}_{\mathrm{NSP}}$, $\overline{\mathbf{\Phi}}$, $\overline{\mathbf{W}}$, $\mathbf{A}_{\mathrm{T}}$, $\mathbf{A}_{\mathrm{R}}$, and stop criterion.
Initialization: $\mathbf{\Psi} = \left[\overline{\mathbf{\Phi}}^{\mathrm{T}}(\mathbf{I}_L \otimes \mathbf{A}_{\mathrm{T}}^*)\right] \otimes (\overline{\mathbf{W}}\mathbf{A}_{\mathrm{R}})$, $\mathbf{r} = \mathrm{vec}(\overline{\mathbf{Y}}_{\mathrm{NSP}})$, and $\mathcal{I} = \mathcal{I}_{\mathrm{D}} = \mathcal{I}_{\mathrm{A}} = \emptyset$.
while stop criterion is not met, do
    $i_{\max} = \arg\max_i \left|[\mathbf{\Psi}^{\mathrm{H}}\mathbf{r}]_i\right|$;
    $\mathcal{I} = \mathcal{I} \cup \{i_{\max}\}$;
    Based on $i_{\max}$, obtain the delay estimate $\widehat{\tau}$ and the angle estimate $\widehat{\theta}$ at the Rx part;
    $\mathcal{I}_{\mathrm{D}} = \mathcal{I}_{\mathrm{D}} \cup \{\widehat{\tau}\}$;   % Delay Estimation.
    $\mathcal{I}_{\mathrm{A}} = \mathcal{I}_{\mathrm{A}} \cup \{\widehat{\theta}\}$;   % Angle Estimation.
    $\mathbf{\Phi}_{\mathrm{aux}} = \left[\overline{\mathbf{\Phi}}^{\mathrm{T}} \otimes \overline{\mathbf{W}}\right]_{\{[(i_{\mathrm{d}}-1)\overline{N}+1]:i_{\mathrm{d}}\overline{N}\}}$ where $i_{\mathrm{d}}$ is the integer closest to $\frac{\widehat{\tau}}{T_s}+1$, and $\mathbf{a}_{\mathrm{aux}} = \bar{\mathbf{a}}_{\overline{N}}(\widehat{\theta})$;
    Replace $[\mathbf{\Psi}]_{\{i_{\max}\}}$ by $\mathbf{q} = (\mathbf{\Phi}_{\mathrm{aux}}\mathbf{a}_{\mathrm{aux}}^*) \otimes \mathbf{a}_{\mathrm{aux}}$;
    $\widehat{\mathbf{g}} = [\mathbf{\Psi}]_{\mathcal{I}}^{\dagger}\mathrm{vec}(\overline{\mathbf{Y}}_{\mathrm{NSP}})$;
    $\mathbf{r} = \mathrm{vec}(\overline{\mathbf{Y}}_{\mathrm{NSP}}) - [\mathbf{\Psi}]_{\mathcal{I}}\widehat{\mathbf{g}}$;
end while
Reconstruct estimate $\widehat{\overline{\mathbf{H}}}_{\mathrm{SD}}$ of $\overline{\mathbf{H}}_{\mathrm{SD}}$ via (5)-(7) based on $\mathcal{I}_{\mathrm{D}}$, $\mathcal{I}_{\mathrm{A}}$, and $\widehat{\mathbf{g}}$;
Output: Estimate $\widehat{\overline{\mathbf{H}}}_{\mathrm{SD}}$ of $\overline{\mathbf{H}}_{\mathrm{SD}}$, estimated target delays $\mathcal{I}_{\mathrm{D}}$, and estimated target angles $\mathcal{I}_{\mathrm{A}}$.
```

An extension of OMP algorithm considering the spatial consistency and the MR dictionaries

The measurement matrix will be refined by replacing the lower-resolution angle estimate at the Tx part by the higher-resolution angle estimate at the Rx part

4.B CS-based ISAC Solutions

- Low-complexity CE scheme for energy-constraint UAVs to recover the LoS component of communication channels:

$$i_{\mathrm{LoS}} = \arg\max_{i} \left| \left[\left(\left(\mathbf{I}_L \otimes \mathbf{A}_{\mathrm{T}}^{\mathrm{T}} \right) \otimes \mathbf{A}^{\mathrm{H}} \right) \mathbf{\Phi}_{\mathrm{V}}^{\mathrm{H}} \mathbf{y}_{\mathrm{V}} \right]_i \right|, \qquad (24)$$

A single correlation step of the OMP framework

The estimate of LoS component will be fed back to the terrestrial station to conduct beamforming for payload data transmission.

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5 Simulation Results

Simulation Parameters

- Carrier frequency 77 GHz (λ=3.9 mm)
- $\overline{N}$ =16, N = 8, N_{RF} = 4
- $\overline{N}_{\mathrm{C}} = N_{\mathrm{C}} = 6$, $\overline{N}_{\mathrm{P}} = N_{\mathrm{P}} = 15$
- The maximum path-delay is LT_{S} with L=32 and sampling period T_{S}=5 ns

The average spectral efficiency (ASE) performance v.s. the sizes of codebooks for waveform design

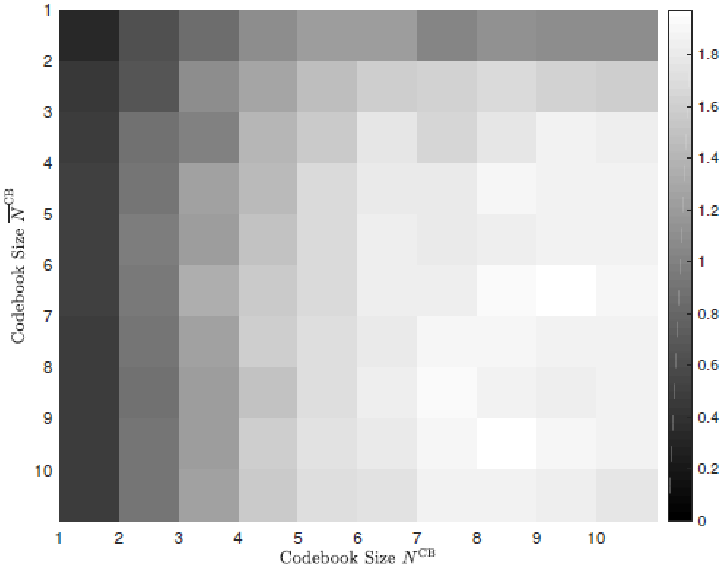

Fig. 3. Phase transition in ASE performance versus the codebook sizes $\overline{N}^{\mathrm{CB}}$ and N^{CB}.

◆ **Small size of codebook brings poor ASE performance due to the lack of pilot diversity**

◆ **Choosing appropriate codebook size trades off the system performance and storage burden**

5 Simulation Results

Simulation Parameters

- Carrier frequency 77 GHz (λ=3.9 mm)
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- The maximum path-delay is LT_{S} with L=32 and sampling period T_{S}=5 ns

Benchmark 1: Cramér-Rao bound (CRB) of Well-determined LS;
Benchmark 2: Original OMP algorithm[R8] ignoring spatial consistency
Benchmark 3: The proposed MR-OMP algorithm without SI cancellation

The normalized mean-square-error (NMSE) performance v.s. signal-to-noise ratio (SNR)

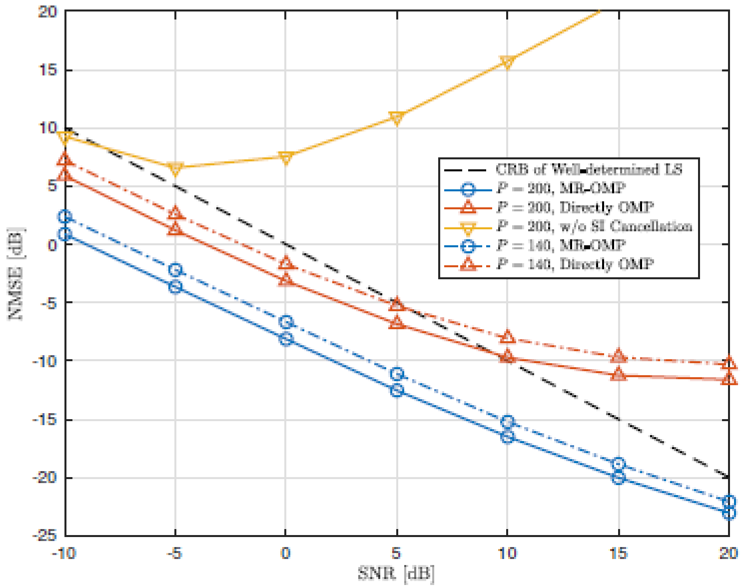


Fig. 4. Performance comparison of different radar CIR recovery algorithms. The impact of SI is also presented.

- ◆ **It indicates the necessity of SI cancellation for FD ISAC systems.**
- ◆ **The proposed MR-OMP outperforms the benchmarks significantly.**

Simulation Results

Simulation Parameters

- Carrier frequency 77 GHz (λ=3.9 mm)
- $\bar{N}$ =16, N = 8, N_{RF} = 4
- $\bar{N}_{\mathrm{C}} = N_{\mathrm{C}} = 6$, $\bar{N}_{\mathrm{P}} = N_{\mathrm{P}} = 15$
- The maximum path-delay is LT_{S} with L=32 and sampling period T_{S}=5 ns

Benchmark 1: Perfect LoS recovery

Benchmark 2: Unitary dictionary for channel estimation

The average spectral efficiency (ASE) performance v.s. signal-to-noise ratio (SNR)

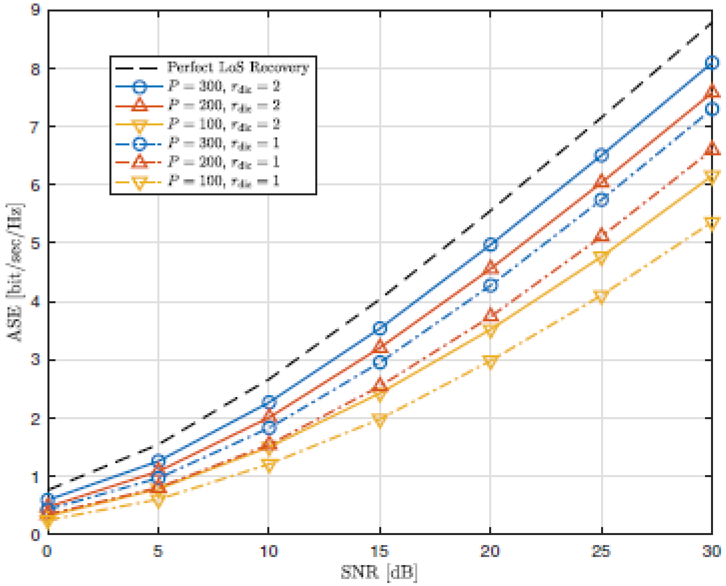


Fig. 5. ASE performance versus SNR. Different values of P and r_{dic} are considered.

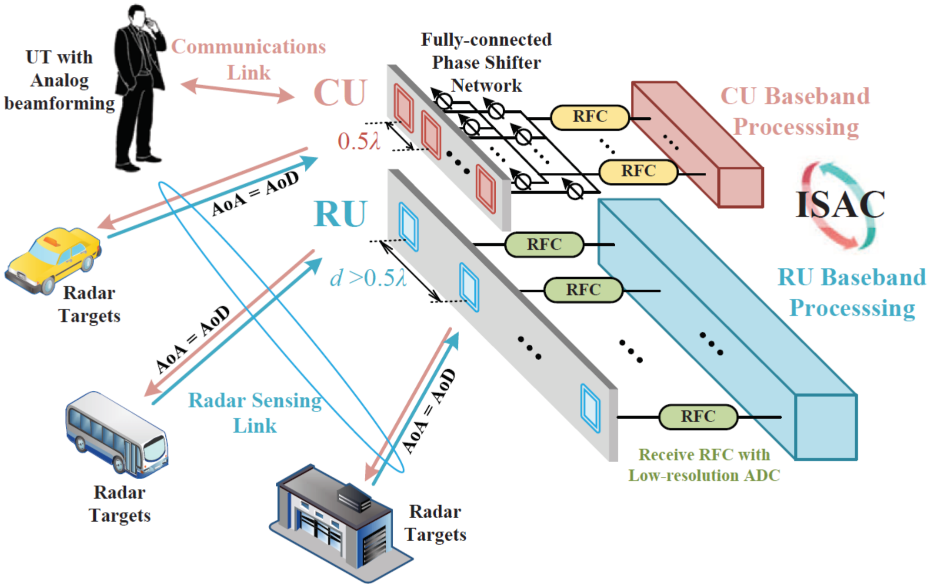
◆ **The performance of the proposed low-complexity CE scheme can approach that of the perfect channel recovery**

◆ **Redundant dictionary can effectively improve the performance**

CONTENTS

6 Future Works

- Use two separated arrays as the transceiver, respectively, to avoid the difficult full-duplexing. The arrays can be judiciously designed to enhance system performance [Journal].



- The analysis of near-field effect
- Reconfigurable intelligent surface (RIS)-aided ISAC systems
- Orthogonal time frequency space (OTFS) technique to support high-speed ISAC scenario
- ……

[Journal] Z. Gao, Z. Wan *et al.*, “Integrated Sensing and Communication with mmWave Massive MIMO: A Compressed Sampling Perspective ”, submitted to ***IEEE TWC***, Major Revision. arXiv: 2201.05766

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[Journal] Z. Gao, Z. Wan *et al.*, "Integrated Sensing and Communication with mmWave Massive MIMO: A Compressed Sampling Perspective ", submitted to *IEEE Trans. Wireless Commun.*, Major Revision. arXiv: 2201.05766

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Thanks for your listening

Any questions are welcome