One Target, Many Views
Multi-User Fusion for Collaborative Uplink ISAC

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Outline

1. Motivation & Scenario
2. System Model
3. Collaborative ISAC Framework
4. Numerical Results
5. Conclusion & Future Directions

Why Collaborative Uplink ISAC?

- Emerging XR and autonomous driving $\Rightarrow$ need for **environment-aware links**.
- Spectrum congestion $\Rightarrow$ reuse communication waveforms for radar.
- Uplink signals provide multiple illumination sources. Each user = a new sensing angle.

Key Question

How to exploit *multi-user diversity* to jointly sense & decode *without pilots*?

System Scenario

- R single-antenna users $\rightarrow$ mmWave BS with N_r-element ULA.
- Orthogonal Frequency Division Multiplexing (**OFDM**).
- **Pilot-free** uplink: data symbols only.
- Sparse multipath (s_i paths): delays τ, Dopplers ν, AoAs θ.
- Two clasess: shared target vs. user-specific.



Multi-user perspective enriches sensing.

Unified Time–Frequency–Space Observation

Signal Model

$$y_n = \sum_{i=1}^{R} \sum_{\ell=1}^{s_i} c_{\ell,i}\, \mathbf{e}_n^\top \mathbf{a}_{3D}(\tau_\ell^i, \nu_\ell^i, \theta_\ell^i)\, x_n^i + \varepsilon_n$$

$$n = \underbrace{p + Pq}_{\triangleq \tilde{n}} + PQr \quad \text{(Unified Index)}$$

Parameters:

- P OFDM blocks
- Q Subcarriers
- N_r Antennas
- $L \triangleq PQN_r$ time-freq.-space samples

Transmitted Signal:

- $x_n^i \triangleq \mathbf{d}_{\tilde{n}}^\top \mathbf{f}_i$
- $\mathbf{f}_i \in \mathbb{C}^{k_i \times 1}$: message of user i
- $\widetilde{\mathbf{D}}_i \triangleq [\mathbf{d}_0^\top, ..., \mathbf{d}_{PQ-1}^\top]^\top \in \mathbb{C}^{PQ \times k_i}$: codebook matrix

Jointly recover $\mathbf{f}_i$ and **continuous parameters** $\zeta^i \triangleq (\tau^i, \nu^i, \theta^i)$.

3D Super-Resolution via Atomic Norm

Primal Formulation

$$\min_{\boldsymbol{\mathcal{Z}}} \sum_{i=1}^{R} \|\mathbf{Z}_i\|_{\mathcal{A}_{3D}}$$
$$\text{s.t.} \quad \|\mathbf{y} - \mathcal{B}(\boldsymbol{\mathcal{Z}})\|_2 \leq \eta$$

Measurement Operator

$$[\mathcal{B}(\boldsymbol{\mathcal{Z}})]_n \triangleq \sum_{i=1}^{R} \langle \mathbf{B}_n^i, \mathbf{Z}_i \rangle, \quad \mathbf{B}_n^i \triangleq \mathbf{d}_n^i \mathbf{e}_n^\top$$

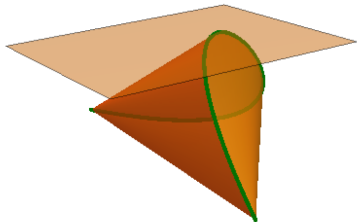


Figure: Atomic norm optimization when $\eta = 0$

Dual Formulation

$$\max_{\mathbf{q}, \zeta_i} \quad \text{Re}\langle \mathbf{q}, \mathbf{y} \rangle - \eta \|\mathbf{q}\|_2$$
$$\text{s.t.} \quad \left\| \sum_{n=0}^{L-1} q_n \mathbf{B}_n^i \, \mathbf{a}_{3D}^*(\zeta^i) \right\|_2 \leq 1, \ \forall i$$

- **Primal Approach**: 3-level Toeplitz SDP, Vandermonde
- **Dual Approach**: Dual polynomial peak-finding

Dual Polynomial Definition

$$f_i(\zeta) \triangleq \left\| \sum_{n=0}^{L-1} q_n \, \mathbf{B}_n^i \, \mathbf{a}^*(\zeta) \right\|_2, \quad i = 1, \ldots, R$$

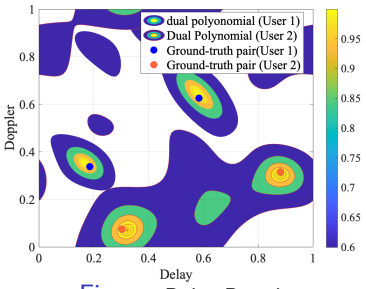


Figure: Delay-Doppler

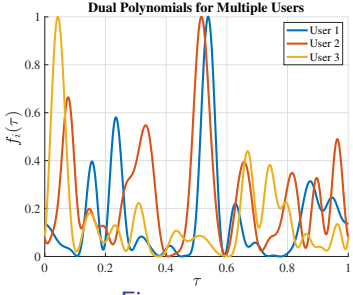


Figure: Delay

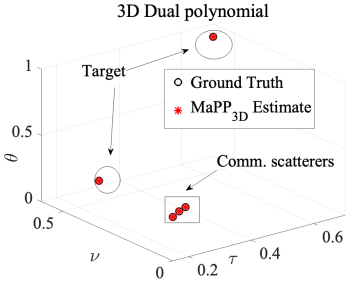


Figure: Delay-Doppler-Angle

Key Idea: *The peaks of the dual polynomial $f_i(\zeta)$ directly reveal the continuous Delay, Doppler, and Angle parameters.*

Shared vs. User-Specific?

Step 1: Angle-of-Arrival (AoA)

Cluster estimated AoAs:

$$\Delta_\theta = \max_{i,j} |\widehat{\theta}^i_T - \widehat{\theta}^j_T| \leq \delta_\theta$$

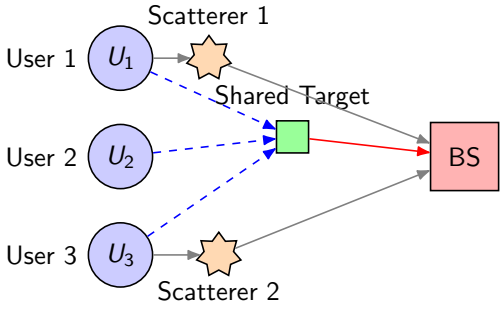
If violated, classify as user-specific

Step 2: Range Consistency

Solve bistatic ellipsoid equation:

$$\left\| \mathbf{x}_i - \mathbf{x}_{BS} - \widehat{d}^i_{TB} \begin{bmatrix} \cos\widehat{\theta}_T \\ \sin\widehat{\theta}_T \end{bmatrix} \right\| + \widehat{d}^i_{TB} = c\widehat{\tau}_i$$

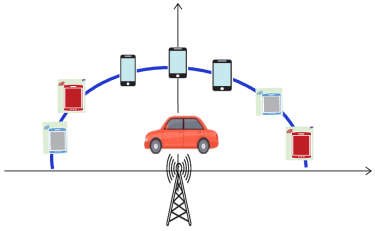
$$\Delta_{d_{TB}} = \max_{i,j} |\widehat{d}^i_{TB} - \widehat{d}^j_{TB}| \leq \delta_{d_{TB}}$$

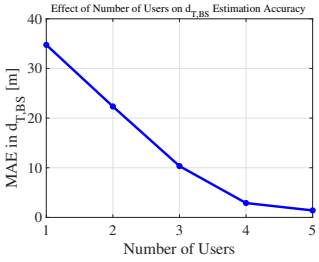


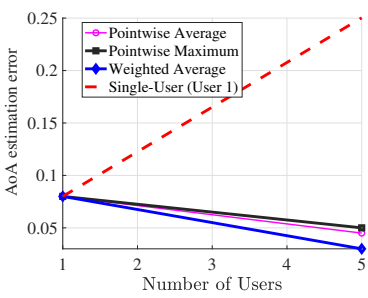
Decision Rule:
If $\Delta_\theta \leq \delta_\theta$ and $\Delta_{d_{TB}} \leq \delta_{d_{TB}}$:
Shared Target else **User-Specific**

Collaborative Target Fusion

- **Pointwise Average:**
  $\hat{\zeta} = \arg\max_{\zeta} \frac{1}{R} \sum_i f_i(\zeta)$
- **Weighted Average:**
  $\hat{\zeta} = \arg\max_{\zeta} \frac{\sum_i w_i f_i(\zeta)}{\sum_i w_i}$
- **Maximum Voting:**
  $\hat{\zeta} = \arg\max_{\zeta} \max_i f_i(\zeta)$







- Significant improvement in range localization and AoA estimation.
- Gains scale with number of users until a limit point which depends on the amount of resources.

Communication Performance (SER)

Aggregate Symbol Error Rate (SER)

$$\mathrm{SER} \triangleq \frac{\#\text{erroneously decoded symbols}}{\#\text{transmitted symbols of all users}}$$

Key Insights

- **Collaboration** significantly reduces SER.
- **Fusion methods** outperform independent user decoding.

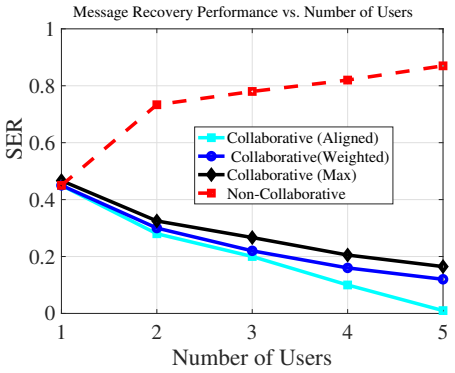


Figure: Settings: **0 dB SNR**.

Multi-user fusion substantially enhances communication reliability in noisy ISAC environments.

Summary & Future Work

- Proposed pilot-free collaborative uplink ISAC.
- Joint 3D parameter estimation via atomic norm.
- Demonstrated benefits of user diversity & collaboration.

Future Directions

- Real-time implementations
- Dynamic user scenarios & mobility
- Theoretical limits for the maximum number of collaborators

Thank you!

Questions?