

Drone Surveillance via Coordinated Beam Sweeping in MIMO-ISAC Networks

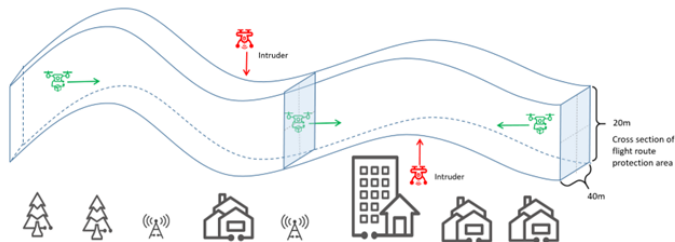
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Motivation and use cases

- 3GPP: Use case for sensing for UAV intrusion detection

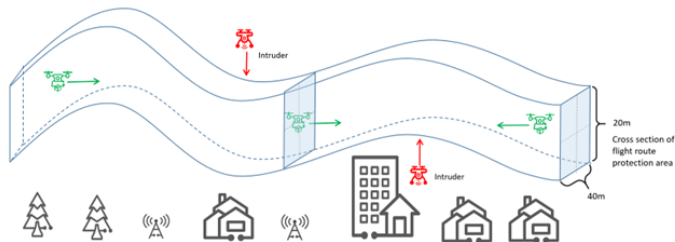
5G radio signals can be used to provide wireless access for communication, meanwhile the 5G radio signals can also be used to generate sensing data for object detection e.g. **sense presence or proximity of UAVs illegal flying in a specific area**. 5G System could provide sensing service by processing sensing data and output sensing information (e.g. relative position, altitude, distance, velocity, direction). In this case, 5G System could be used for sensing the UAV intrusion in



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- Drone surveillance (i.e., no-drone zone in airport, military base)



Motivation: Key challenges of drone detection in MIMO ISAC

Key challenges

- **Severe path loss**

Mono-static $L_{PL} \propto d^{-4}$

Bi-static $L_{PL} \propto d_1^{-2}d_2^{-2}$

RCS of a small drone ≈ -30 to -10 dBsm

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Radar system $P_{\max} \approx 0.6 - 2$ kW

Typical BS $P_{\max} \approx 20 - 200$ W

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- **CSI requirement (Precoder)**

Typically the communication precoder

Regularized zero-forcing $\mathbf{w}_i = \left(\sum_{j=1}^{N_{\text{UE}}} \hat{\mathbf{h}}_j \hat{\mathbf{h}}_j^H - \lambda \mathbf{I} \right)^{-1} \hat{\mathbf{h}}_i,$

and the **sensing precoder** $\mathbf{w}_s = \left(\mathbf{I} - \mathbf{U} \mathbf{U}^H \right) \hat{\mathbf{h}}_s$

Trade-off between communication-centric and sensing-centric

Challenges

- **Link-budget**

Proposed

- Multi-static (multiple AP coherent transmission)

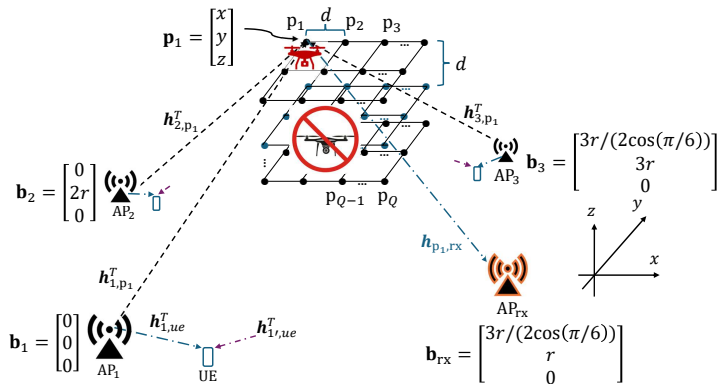
Challenges

- **Link-budget**
- **CSI requirement**

Proposed

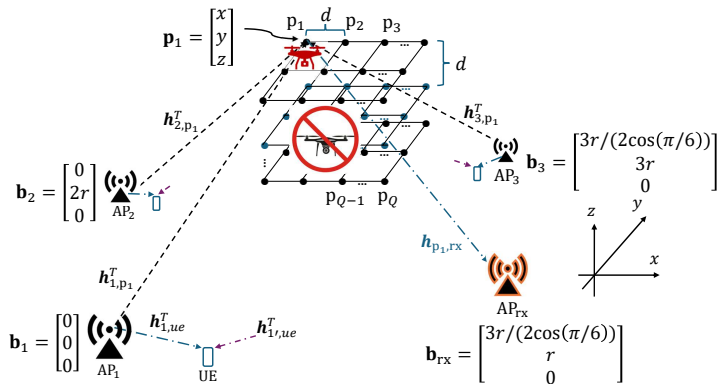
- Multi-static (multiple AP coherent transmission)
- **Codebook-based ISAC**
Joint design of sensing and communication reference signal, i.e., Synchronization Signal Block (SSB)
No CSI required!

System model



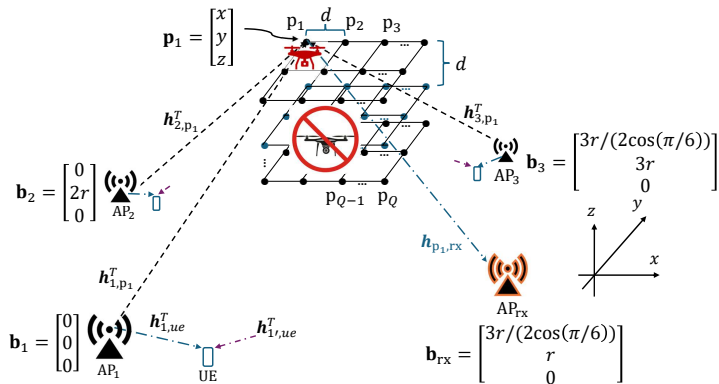
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- MIMO ISAC APs equipped with UPA, $M = M_V \times M_H$ antennas

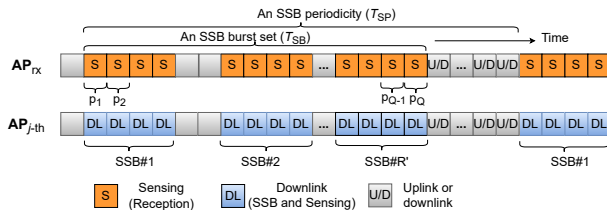
System model



- Surveillance region is a collection of equidistance Q voxels
- MIMO ISAC APs equipped with UPA, $M = M_V \times M_H$ antennas
- J transmitter APs, a receiver AP in hexagonal grid

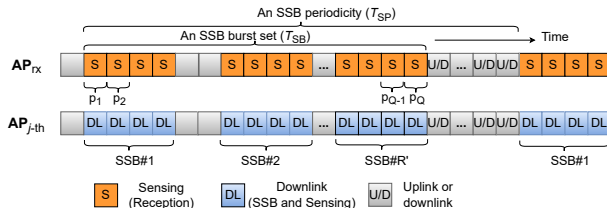
System model

The TDD flow

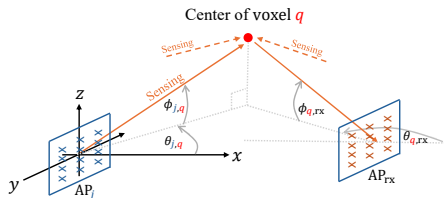


System model

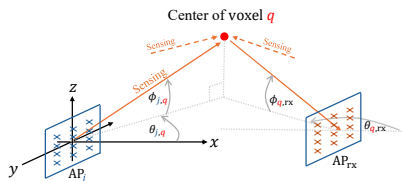
The TDD flow



Channel at voxel q



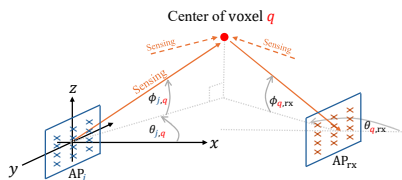
System model: Channels



The channel model

- Channel voxel q , LOS of $AP_{j-q}-AP_{rx}$

$$\mathbf{H}_{j,q} = \eta \sqrt{\beta_{j,q}} e^{-j2\pi f_c \tau_{j,q}} \tilde{\mathbf{H}}_{j,q}$$



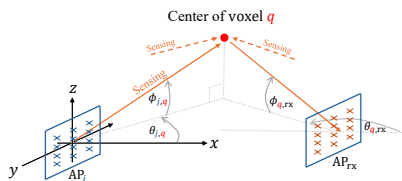
The channel model

- Channel voxel q , LOS of AP_j - q - AP_{rx}

$$\mathbf{H}_{j,q} = \eta \sqrt{\beta_{j,q}} e^{-j2\pi f_c \tau_{j,q}} \tilde{\mathbf{H}}_{j,q}$$

- The direct-link channel

$$\mathbf{H}_{0,j} = \sqrt{\beta_{0,j}} e^{-j2\pi f_c \tau_{0,j}} \tilde{\mathbf{H}}_{0,j}$$



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- User channel in at AP j th $\mathbf{h}_{j,ue} \sim \mathcal{CN}(0, \beta_{j,ue} \mathbf{I})$

System model: Tx, Rx signal

Transmitted signal

$$\mathbf{x}_j[q] = \underbrace{s[q]\mathbf{w}_{j,q}}_{\text{Sensing signal}} + \underbrace{\sqrt{\rho_{j,q}}c_j[q]\mathbf{f}_q^*}_{\text{SSB signal}} \quad (1)$$

System model: Tx, Rx signal

Transmitted signal

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The received signal at AP_{rx}

$$\mathbf{y}_{\text{ap}}[q] = \sum_{j=1}^J \alpha_j \mathbf{H}_{j,q} \mathbf{x}_j[q] + \sum_{j=1}^J \mathbf{H}_{0,j} \mathbf{x}_j[q] + \sum_{j=1}^J \mathbf{G}_{j,q} \mathbf{x}_j[q] + \mathbf{n}[q], \quad (3)$$

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$$\begin{aligned} \mathbf{y}_{\text{ap}}[q] = & \underbrace{s[q] \sum_{j=1}^J \alpha_j \mathbf{H}_{j,q} \mathbf{w}_{j,q}}_{\text{Sensing echoes}} + \underbrace{\sum_{j=1}^J \sqrt{\rho_{j,q}} c_j[q] \mathbf{G}_{j,q} \mathbf{f}_q^*}_{\text{SSB echoes (clutter)}} \\ & + \underbrace{\sum_{j=1}^J \mathbf{H}_{0,j} (s[q]\mathbf{w}_{j,q} + \sqrt{\rho_{j,q}}c_j[q]\mathbf{f}_q^*)}_{\text{Direct-link}} + \underbrace{\mathbf{n}[q]}_{\text{Noise}} \end{aligned} \quad (6)$$

Combining signal of voxel q th: $\mathbf{y}'_{\text{ap}}[q] = \mathbf{v}_q^H \mathbf{y}_{\text{ap}}[q]$

System model: UE and Sensing SINR

Average UE SINR

$$\gamma_{\text{ue},j,q} = \frac{\rho_{j,q}\beta_{j,\text{ue}}}{\sum_{i \in \mathcal{U}} \rho_{i,q}\beta_{i,\text{ue}} + \sigma_n^2} \quad (7)$$

System model: UE and Sensing SINR

Average UE SINR

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Average Sensing SINR

$$\gamma'_{\text{sen},q} = \frac{\sigma_{\text{rcs}}^2 |\mathbf{v}_q^H \mathbf{H}_q \mathbf{w}_q|^2}{\beta_{g,q} \sum_{j=1}^J \rho_{j,q} + \sigma_n^2}, \quad (9)$$

where $\mathbf{H}_q \in \mathbb{C}^{M \times JM}$ is $\mathbf{H}_q = [\mathbf{H}_{1,q}, \dots, \mathbf{H}_{J,q}]$ and $\mathbf{w}_q \in \mathbb{C}^{JM}$ is $\mathbf{w}_q = [\mathbf{w}_{1,q}^T, \dots, \mathbf{w}_{J,q}^T]^T$

Proposed coordinated precoder

Maximizing sensing SINR at voxel q w.r.t.

$$\arg \max_{\mathbf{w}_q, \rho_q} \gamma'_{\text{sen},q} = \frac{\mathbf{w}_q^H \mathbf{A} \mathbf{w}_q}{\xi(\rho_q)} \quad (10a)$$

$$\text{s.t. } \|\mathbf{w}_{j,q}\|^2 + \rho_{j,q} \leq P_{\max}, \quad \forall j, \quad (10b)$$

$$\mathbf{w}_{j,q}^H \mathbf{f}_q^* = 0, \quad \forall j, \quad (10c)$$

$$\gamma_{\text{ue},j,q} \geq \gamma_{\text{req}}, \quad \forall j, \quad (10d)$$

$$\mathbf{w}_{j,q}^H \mathbf{h}_{0,j,d}^* = 0, \quad \forall j, \quad (10e)$$

where $\rho_q = [\rho_{1,q}, \dots, \rho_{J,q}]^T$ $\mathbf{A} \in \mathbb{C}^{JM \times JM}$, $\mathbf{A} = \mathbf{H}_q^H \mathbf{v}_q \mathbf{v}_q^H \mathbf{H}_q$.

Proposed coordinated precoder

Maximizing sensing SINR at voxel q w.r.t. \mathbf{w}_q, ρ_q

$$\arg \max_{\mathbf{w}_q, \rho_q} \gamma'_{\text{sen},q} = \frac{\mathbf{w}_q^H \mathbf{A} \mathbf{w}_q}{\xi(\rho_q)} \quad (11a)$$

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Power constraint (11b), Comm/Sensing orthogonality (11c), Comm requirement (11d), Direct-link masking (11e).

Proposed coordinated precoder

Rewrite (11) as

$$\max_{\mathbf{W}_q, \rho_q} t \quad (12a)$$

$$\text{s.t. } \text{Tr}\{\mathbf{A}\mathbf{W}_q\} \geq t \cdot \xi(\rho_q) \quad (12b)$$

$$\text{Tr}\{[\cdot \mathbf{I} \cdot]_j \mathbf{W}_q [\cdot \mathbf{I} \cdot]_j^T\} + \rho_{j,q} \leq P_{\max}, \quad \forall j, \quad (12c)$$

$$\mathbf{f}_q^T [\cdot \mathbf{I} \cdot]_j \mathbf{W}_q [\cdot \mathbf{I} \cdot]_j^T \mathbf{f}_q^* = 0, \quad \forall j, \quad (12d)$$

$$\gamma_{\text{ue},j,q} \geq \gamma_{\text{req}}, \quad \forall j, \quad (12e)$$

$$\mathbf{h}_{0,j,d}^T [\cdot \mathbf{I} \cdot]_j \mathbf{W}_q [\cdot \mathbf{I} \cdot]_j^T \mathbf{h}_{0,j,d}^* = 0, \quad \forall j. \quad (12f)$$

Power constraint (12c), Comm/Sensing orthogonality (12d), Comm requirement (12e), Direct-link masking (12f).

Proposed coordinated precoder

The solution from optimizer is $\mathbf{W}_{\text{sol},q}$. The eigen-decomposition of $\mathbf{W}_{\text{sol},q}$

$$\mathbf{W}_{\text{sol},q} = \mathbf{Z}_q \Lambda_q \mathbf{Z}_q^H, \quad (13)$$

The optimized precoder is

$$\mathbf{w}_{\text{sol},q,j} = \sqrt{P_{\text{max}} - \rho_{\text{sol},q,j}} \mathbf{z}_{\text{dom},q,j}, \quad (14)$$

where $\mathbf{z}_{\text{dom},q,j} = [\cdot \ \mathbf{I} \cdot]_j \mathbf{z}_{\text{dom},q}$, $\mathbf{z}_{\text{dom},q} \in \mathbb{C}^{JM}$ is the dominant eigenvector of $\mathbf{W}_{\text{sol},q}$.

Non-coordinated precoder

A steering vector that projects onto the orthogonal complement of the column space span $\mathbf{U}_{j,q} = [\tilde{\mathbf{h}}_{0,j,d}, \mathbf{f}_q^*]$,

$$\mathbf{w}_{j,q} = e^{j2\pi\varphi_{j,q}} \sqrt{\tilde{\rho}_{j,q}} \tilde{\mathbf{w}}_{j,q} / \|\tilde{\mathbf{w}}_{j,q}\|,$$

$$\tilde{\mathbf{w}}_{j,q} = (\mathbf{I} - \mathbf{U}_{j,q}(\mathbf{U}_{j,q}^H \mathbf{U}_{j,q})^{-1} \mathbf{U}_{j,q}^H) \mathbf{h}_{j,q}, \quad (15)$$

where $\varphi_{j,q} = \frac{l_{j,q} - l_{1,q}}{\lambda}$ is the phase different between AP_j and AP₁ as a factor of wavelength λ .

Hypotheses

$$\begin{aligned}\mathcal{H}_0 &: \mathbf{y}_q = \mathbf{x}_{c,q} + \mathbf{n}_q, \\ \mathcal{H}_1 &: \mathbf{y}_q = \mathbf{x}_{s,q} + \mathbf{x}_{c,q} + \mathbf{n}_q.\end{aligned}\tag{16}$$

The likelihood function for both hypotheses are

$$\begin{aligned}p(\mathbf{y}_q|\mathcal{H}_0) &= \mathcal{CN}(0, \sigma^2\mathbf{I}) \\ &= \frac{1}{\pi^M \sigma^{2M}} \exp\left(-\sigma^{-2} \mathbf{y}_q^H \mathbf{y}_q\right), \\ p(\mathbf{y}_q|\mathcal{H}_1) &= \mathcal{CN}(0, \sigma^2\mathbf{I} + \sigma_{\text{rcsq}}^2) = \mathcal{CN}(0, \mathbf{C}_q) \\ &= \frac{1}{\pi^M \det(\mathbf{C}_q)} \exp\left(-\mathbf{y}_q^H \mathbf{C}_q^{-1} \mathbf{y}_q\right),\end{aligned}\tag{17}$$

where $\sigma^2 = \sigma_n^2 + \rho_q \beta_{g,q}$, $\mathbf{C}_q = \sigma^2\mathbf{I} + \sigma_{\text{rcsq}}^2$.

Detection rule

The log-likelihood ratio, $\text{LLR}(\mathbf{y}_q)$, is

$$\begin{aligned}\text{LLR}(\mathbf{y}_q) &= \ln \left(\frac{p(\mathbf{y}_q | \mathcal{H}_1)}{p(\mathbf{y}_q | \mathcal{H}_0)} \right) \\ &= \ln \left(\frac{\sigma^{2M}}{\det(\mathbf{C}_q)} \right) + \mathbf{y}_q^H (\sigma^{-2} \mathbf{I} - \mathbf{C}_q^{-1}) \mathbf{y}_q.\end{aligned}\tag{18}$$

The test statistic is

$$T(\mathbf{y}_q) = \mathbf{y}_q^H (\sigma^{-2} \mathbf{I} - \mathbf{C}_q^{-1}) \mathbf{y}_q \underset{\mathcal{H}_0}{\overset{\mathcal{H}_1}{\geq}} \gamma_{\text{th}},\tag{19}$$

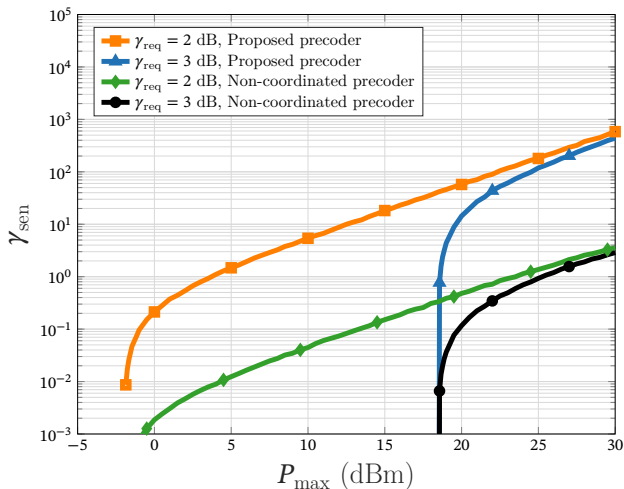
$$T(\mathbf{y}_q) = \mathbf{y}_q^H \Phi_q (\sigma^{-2} \mathbf{I} + \sigma_{\text{rcs}}^2 \Phi_q)^{-1} \mathbf{y}_q \underset{\mathcal{H}_0}{\overset{\mathcal{H}_1}{\geq}} \gamma'_{\text{th}}.\tag{20}$$

Table: Baseline parameters.

Parameter	Value	Parameter	Value
M_V, M_H	12	σ_{RCS}	-10 dBsm
f_c	15 GHz	z	10 m
$\beta_{g,q}$	-90dB	σ_n^2	-60 dBm
P_{max}	30 dBm	d	2 m
γ_{req}	3 dB	Volume	6x2x2 m^3
r	250 m		

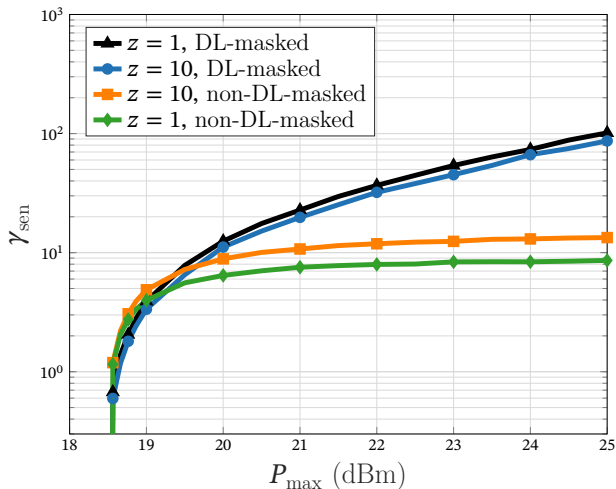
Simulation result

Evaluate the sensing performance via the averaged sensing SINR



Simulation result

Evaluate the sensing performance in altitudes



Simulation result

Coordination improves P_d

