Angle Estimation for Terahertz Ultra-Massive MIMO-Based Space-to-Air Communications

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1 Introduction

- Terahertz (THz) communication
  - Tens of GHz ultra-broad band
  - Tbps ultra-high peak data rate
- Ultra-Massive (UM)-MIMO
  - Tens of thousands of antennas
- THz UM-MIMO technique
  - Reliable CSI acquisition
- THz UM-MIMO based satellite communication systems
  - Ultra-large array aperture
  - Ultra-broad band
  - Ultra-high velocity
- THz UM-MIMO based space-to-air channel
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- Angle estimation for space-to-air LoS links
  - Low earth orbit (LEO) satellite serves multiple UAVs
  - Dual delay-beam squint effects (Doppler compensation)

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Space-to-Air Communication Scenario

- L UAVs communicate with a LEO satellite
  - UAV antenna array
    - Analog beamforming
    - $N_{\mathrm{U}} = N_{\mathrm{U}}^{\mathrm{h}} N_{\mathrm{U}}^{\mathrm{v}}$
  - Satellite antenna array
    - Sub-connected PSN
    - $N_{\mathrm{S}} = N_{\mathrm{S}}^{\mathrm{h}} N_{\mathrm{S}}^{\mathrm{v}}$
    - $N_{\mathrm{S}}^{\mathrm{h}} = \widetilde{I}_{\mathrm{S}}^{\mathrm{h}} M_{\mathrm{S}}^{\mathrm{h}}$
    - $N_{\mathrm{S}}^{\mathrm{v}} = \widetilde{I}_{\mathrm{S}}^{\mathrm{v}} M_{\mathrm{S}}^{\mathrm{v}}$
    - $M_{\mathrm{S}} = M_{\mathrm{S}}^{\mathrm{h}} M_{\mathrm{S}}^{\mathrm{v}}$
    - $L = \widetilde{I}_{\mathrm{S}}^{\mathrm{h}} \widetilde{I}_{\mathrm{S}}^{\mathrm{v}}$ RF chains at satellite

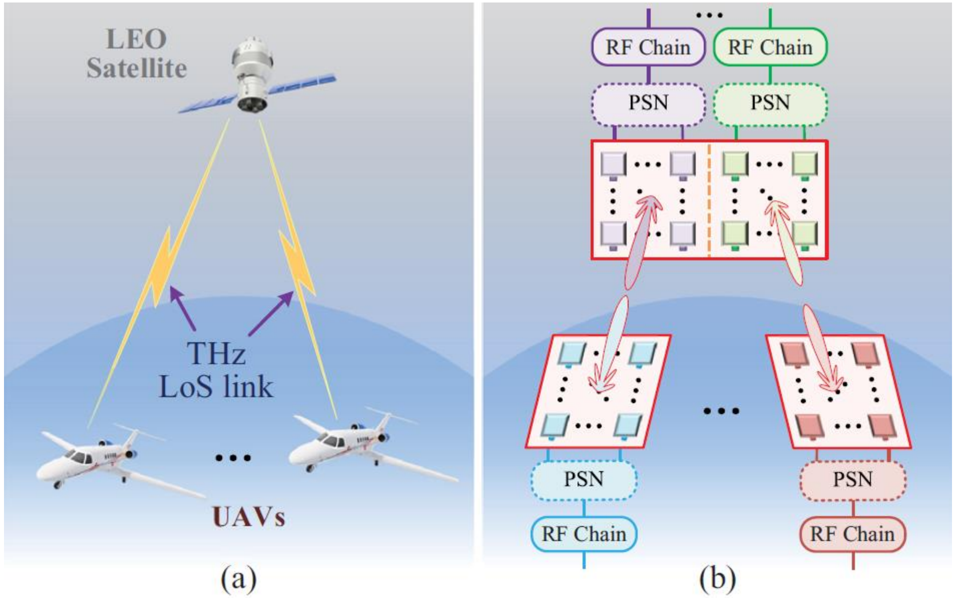

Fig. 1. (a) Typical space-to-air communication scenario; and (b) structure diagram of antenna arrays at transceiver.

THz UM-MIMO Channel Model

- DL *spatial-delay* channel matrix (channel reciprocity in TDD)

$$[\bar{\boldsymbol{H}}^{(t)}_{\mathrm{DL},l}(\tau)]_{n_\mathrm{U},n_\mathrm{S}} = \sqrt{G_l}\alpha_l e^{\mathrm{j}2\pi\psi_l t}\delta\Big(\tau-\tau_l-\underbrace{(\tau_l^{[n_\mathrm{U}]}+\tau_l^{[n_\mathrm{S}]})}_{\textit{Delay squint}}\Big), \quad (1)$$

- DL *spatial-frequency* channel matrix

$$\boldsymbol{H}^{[m]}_{\mathrm{DL},l}[k] = \sqrt{G_l}\alpha_l e^{\mathrm{j}2\pi\psi_l(m-1)T_{\mathrm{sym}}} e^{-\mathrm{j}2\pi\left(\frac{k-1}{K}-\frac{1}{2}\right)f_s\tau_l}\boldsymbol{A}_{\mathrm{DL},l}[k], \quad (2)$$

  - Duration time of OFDM symbol T_{sym}, system bandwidth f_s
  - DL array response matrix

$$\boldsymbol{A}_{\mathrm{DL},l}[k] = \underbrace{\left(\boldsymbol{a}_\mathrm{U}(\mu_l^\mathrm{U},\nu_l^\mathrm{U})\boldsymbol{a}_\mathrm{S}^\mathrm{H}(\mu_l^\mathrm{S},\nu_l^\mathrm{S})\right)}_{\boldsymbol{A}_{\mathrm{DL},l}} \circ \underbrace{\left(\bar{\boldsymbol{a}}_\mathrm{U}(\mu_l^\mathrm{U},\nu_l^\mathrm{U},k)\bar{\boldsymbol{a}}_\mathrm{S}^\mathrm{H}(\mu_l^\mathrm{S},\nu_l^\mathrm{S},k)\right)}_{\bar{\boldsymbol{A}}_{\mathrm{DL},l}[k]\ (\textit{Beam squint component})}, \quad (3)$$

  - Define virtual angles $\mu_l^\mathrm{U} = \pi\sin(\theta_l^\mathrm{U})\cos(\varphi_l^\mathrm{U})$, $\nu_l^\mathrm{U} = \pi\sin(\varphi_l^\mathrm{U})$
  - General array response vector $\boldsymbol{a}_\mathrm{U}(\mu_l^\mathrm{U},\nu_l^\mathrm{U}) = \boldsymbol{a}_\mathrm{v}(\nu_l^\mathrm{U},N_\mathrm{U}^\mathrm{v})\otimes\boldsymbol{a}_\mathrm{h}(\mu_l^\mathrm{U},N_\mathrm{U}^\mathrm{h})$
  - Frequency-dependent array response *squint* vector

$$\bar{\boldsymbol{a}}_\mathrm{U}(\mu_l^\mathrm{U},\nu_l^\mathrm{U},k) = \bar{\boldsymbol{a}}_\mathrm{v}(\nu_l^\mathrm{U},N_\mathrm{U}^\mathrm{v},k)\otimes\bar{\boldsymbol{a}}_\mathrm{h}(\mu_l^\mathrm{U},N_\mathrm{U}^\mathrm{h},k)$$

- Horizontal/vertical steering (squint) vectors

$$\boldsymbol{a}_{\mathrm{h}}(\mu_l^{\mathrm{U}}, N_{\mathrm{U}}^{\mathrm{h}}) = \left[1 \ e^{\mathrm{j}\mu_l^{\mathrm{U}}} \ \cdots \ e^{\mathrm{j}(N_{\mathrm{U}}^{\mathrm{h}}-1)\mu_l^{\mathrm{U}}}\right]^{\mathrm{T}},$$

$$\boldsymbol{a}_{\mathrm{v}}(\nu_l^{\mathrm{U}}, N_{\mathrm{U}}^{\mathrm{v}}) = \left[1 \ e^{\mathrm{j}\nu_l^{\mathrm{U}}} \ \cdots \ e^{\mathrm{j}(N_{\mathrm{U}}^{\mathrm{v}}-1)\nu_l^{\mathrm{U}}}\right]^{\mathrm{T}},$$

$$\bar{\boldsymbol{a}}_{\mathrm{h}}(\mu_l^{\mathrm{U}}, N_{\mathrm{U}}^{\mathrm{h}}, k) = \left[1 \ e^{\mathrm{j}\left(\frac{k-1}{K}-\frac{1}{2}\right)\frac{f_s}{f_z}\mu_l^{\mathrm{U}}} \ \cdots \ e^{\mathrm{j}\left(\frac{k-1}{K}-\frac{1}{2}\right)\frac{f_s}{f_z}(N_{\mathrm{U}}^{\mathrm{h}}-1)\mu_l^{\mathrm{U}}}\right]^{\mathrm{T}},$$

$$\bar{\boldsymbol{a}}_{\mathrm{v}}(\nu_l^{\mathrm{U}}, N_{\mathrm{U}}^{\mathrm{v}}, k) = \left[1 \ e^{\mathrm{j}\left(\frac{k-1}{K}-\frac{1}{2}\right)\frac{f_s}{f_z}\nu_l^{\mathrm{U}}} \ \cdots \ e^{\mathrm{j}\left(\frac{k-1}{K}-\frac{1}{2}\right)\frac{f_s}{f_z}(N_{\mathrm{U}}^{\mathrm{v}}-1)\nu_l^{\mathrm{U}}}\right]^{\mathrm{T}}.$$

- UL *spatial-frequency* channel matrix

$$\boldsymbol{H}_{\mathrm{UL},l}^{[n]}[k] = \sqrt{G_l}\alpha_l e^{\mathrm{j}2\pi\psi_l(n-1)T_{\mathrm{sym}}}\boldsymbol{A}_{\mathrm{UL},l}[k]. \quad (4)$$

3 CONTENTS

GTTDU Module Based Transceiver

- Establish reliable THz communication link
  - Attenuate the impact of delay-beam squint effects
- Common treatment
  - Tunable true-time delay unit (TTDU)
  - High hardware complexity and cost
- Grouping TTDU (GTTDU) based transceiver
  - GTTDU module
  - Reconfigurable RF selection network (PSN and ASN)

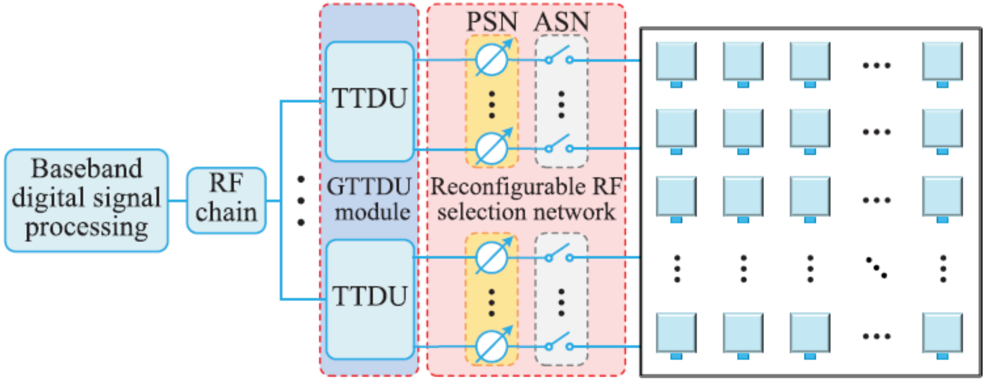

Fig. 2. GTTDU module based transceiver structure corresponding to one RF

3 Compensated role of GTTDU module

- Prior information acquired from positioning systems
  - $\{\widetilde{\mu}_l^{\mathrm{U}}\}_{l=1}^{L}$, $\{\widetilde{\nu}_l^{\mathrm{U}}\}_{l=1}^{L}$, $\{\widetilde{\mu}_l^{\mathrm{S}}\}_{l=1}^{L}$, and $\{\widetilde{\nu}_l^{\mathrm{S}}\}_{l=1}^{L}$
- *Lemma 1*: (consider ideal TTDU module)
  - The compensated DL spatial-frequency channel matrix

$$\widetilde{\boldsymbol{H}}_{\mathrm{DL},l}^{[m]}[k] = \sqrt{G_l}\alpha_l e^{\mathrm{j}2\pi\psi_l(m-1)T_{\mathrm{sym}}} e^{-\mathrm{j}2\pi\left(\frac{k-1}{K}-\frac{1}{2}\right)f_s\tau_l}\,\widetilde{\boldsymbol{A}}_{\mathrm{DL},l}[k], \quad (5)$$

$$\widetilde{\boldsymbol{A}}_{\mathrm{DL},l}[k] = \boldsymbol{A}_{\mathrm{DL},l}[k] \circ \underbrace{\left(\bar{\boldsymbol{a}}_{\mathrm{U}}(\widetilde{\mu}_l^{\mathrm{U}}, \widetilde{\nu}_l^{\mathrm{U}}, k)\bar{\boldsymbol{a}}_{\mathrm{S}}^{\mathrm{H}}(\widetilde{\mu}_l^{\mathrm{S}}, \widetilde{\nu}_l^{\mathrm{S}}, k)\right)^*}_{\widetilde{\bar{\boldsymbol{A}}}_{\mathrm{DL},l}[k]}. \quad (6)$$

$$\boldsymbol{A}_{\mathrm{DL},l}[k] = \underbrace{\left(\boldsymbol{a}_{\mathrm{U}}(\mu_l^{\mathrm{U}}, \nu_l^{\mathrm{U}})\boldsymbol{a}_{\mathrm{S}}^{\mathrm{H}}(\mu_l^{\mathrm{S}}, \nu_l^{\mathrm{S}})\right)}_{\boldsymbol{A}_{\mathrm{DL},l}} \circ \underbrace{\left(\bar{\boldsymbol{a}}_{\mathrm{U}}(\mu_l^{\mathrm{U}}, \nu_l^{\mathrm{U}}, k)\bar{\boldsymbol{a}}_{\mathrm{S}}^{\mathrm{H}}(\mu_l^{\mathrm{S}}, \nu_l^{\mathrm{S}}, k)\right)}_{\bar{\boldsymbol{A}}_{\mathrm{DL},l}[k]\ (\textbf{\textit{Beam squint component}})}, \quad (3)$$

- Ideal TTDU module provides a performance upper-bound
  - Practical DL/UL channel matrices compensated by the GTTDU module can be derived from (5) and (6)

Proposed Angle Estimation Solution

- OFDMA
  - K subcarriers can be equally assigned to L UAVs
- Frame structure
  - Fine azimuth/elevation angles at UAVs in DL
  - Fine azimuth/elevation angles at satellite in UL
  - Accumulate multiple OFDM symbols
  - Doppler compensation

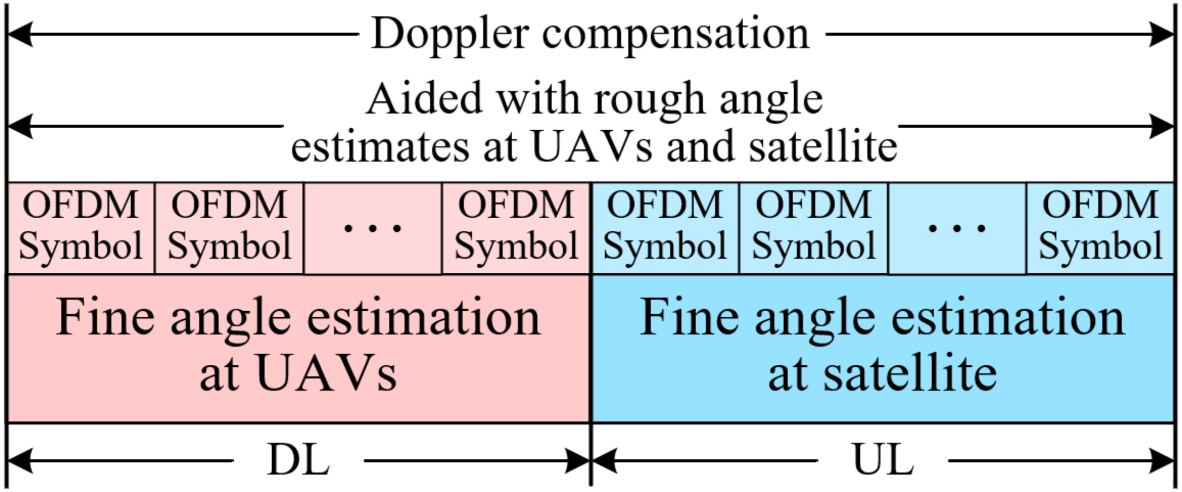

Fig. 3. Frame structure of the proposed angle estimation solution

3 Subarray selection scheme

- *Remark*
  - For different selected subarrays, received signals differ by one envisaged phase
  - These regular phase differences construct array response vector of low-dimensional fully-digital array
- UPA of size 5×5 → 4 subarrays of size 4×4 in 4 successive OFDM symbols → equivalent fully-digital array with size of 2×2 with critical d

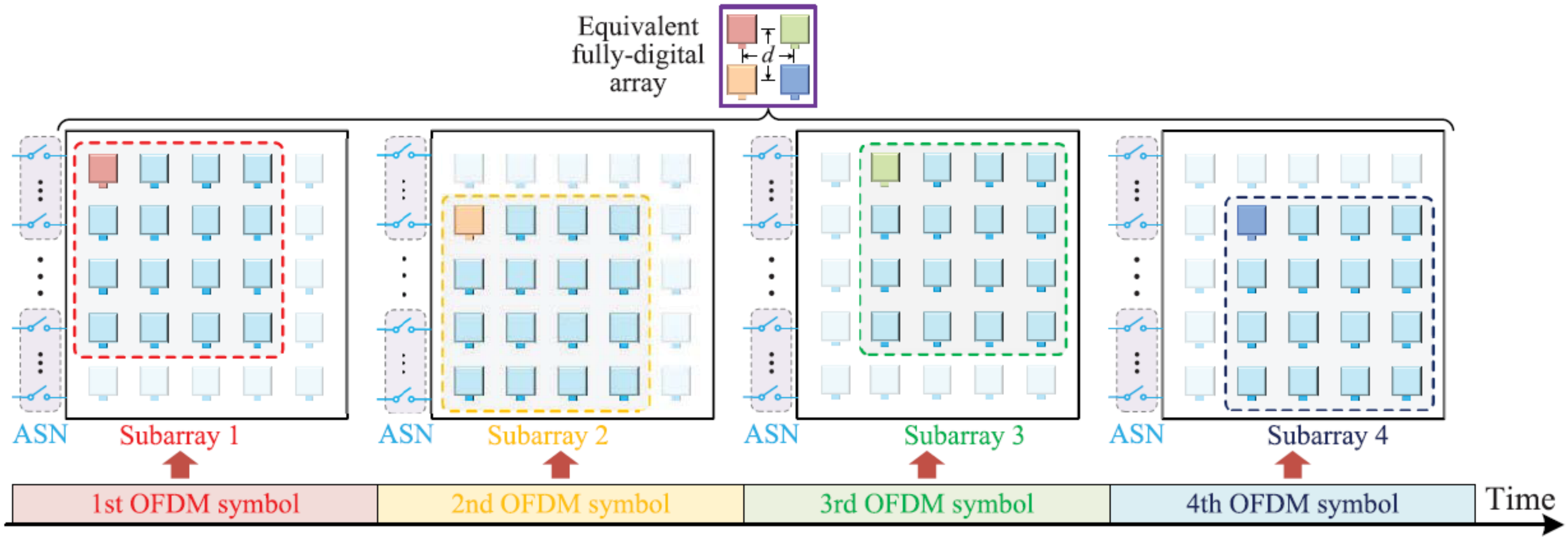

Fig. 4. Schematic diagram of subarray selection scheme

Fine Angle Estimation at UAVs

- Design analog precoding and combining vectors
  - $I_{\mathrm{U}} = I_{\mathrm{U}}^{\mathrm{h}} I_{\mathrm{U}}^{\mathrm{v}}$ OFDM symbols (I_{U} selected subarray pattern)
  - Initialize $\boldsymbol{p}_{\mathrm{RF},l} = \boldsymbol{0}_{N_{\mathrm{S}}}$, and then let $[\boldsymbol{p}_{\mathrm{RF},l}]_{\mathcal{I}_{\mathrm{S},l}} = \frac{1}{\sqrt{\bar{M}_{\mathrm{S}}}}[\boldsymbol{a}_{\mathrm{S}}(\widetilde{\mu}_l^{\mathrm{S}}, \widetilde{\nu}_l^{\mathrm{S}})]_{\mathcal{I}_{\mathrm{S},l}}$
  - Initialize $\boldsymbol{q}_{\mathrm{RF},l}^{[m]} = \boldsymbol{0}_{N_{\mathrm{U}}}$, and then let $[\boldsymbol{q}_{\mathrm{RF},l}^{[m]}]_{\mathcal{I}_{\mathrm{U}}^{[m]}} = \frac{1}{\sqrt{\bar{M}_{\mathrm{U}}}}[\boldsymbol{a}_{\mathrm{U}}(\widetilde{\mu}_l^{\mathrm{U}}, \widetilde{\nu}_l^{\mathrm{U}})]_{\mathcal{I}_{\mathrm{U}}^{[1]}}$, $1 \le m \le I_{\mathrm{U}}$
- UL received signal formulation
  - Collect K_l subcarriers of I_{U} OFDM symbols

$$\boldsymbol{Y}_{\mathrm{DL},l} = \sqrt{P_l G_l}\alpha_l \left(\boldsymbol{Q}_{\mathrm{RF},l}^{\mathrm{H}} \boldsymbol{A}_{\mathrm{DL},l} \boldsymbol{p}_{\mathrm{RF},l} \boldsymbol{s}_{\mathrm{DL},l}^{\mathrm{T}}\right) \circ \widetilde{\boldsymbol{Y}}_{\mathrm{DL},l} + \boldsymbol{N}_{\mathrm{DL},l}, \quad (7)$$

$$\boldsymbol{Q}_{\mathrm{RF},l} = \left[\boldsymbol{q}_{\mathrm{RF},l}^{[1]} \cdots \boldsymbol{q}_{\mathrm{RF},l}^{[I_{\mathrm{U}}]}\right]$$

Residual beam squint matrix

  - Compared with $(\boldsymbol{q}_{\mathrm{RF},l}^{[1]})^{\mathrm{H}} \boldsymbol{a}_{\mathrm{U}}(\mu_l^{\mathrm{U}}, \nu_l^{\mathrm{U}})$, $(\boldsymbol{q}_{\mathrm{RF},l}^{[m]})^{\mathrm{H}} \boldsymbol{a}_{\mathrm{U}}(\mu_l^{\mathrm{U}}, \nu_l^{\mathrm{U}})$ is multiplied by an extra phase shift $e^{\mathrm{j}\left((i_{\mathrm{U}}^{\mathrm{h}}-1)\mu_l^{\mathrm{U}} + (i_{\mathrm{U}}^{\mathrm{v}}-1)\nu_l^{\mathrm{U}}\right)}$ for $m = (i_{\mathrm{U}}^{\mathrm{v}} - 1) I_{\mathrm{U}}^{\mathrm{h}} + i_{\mathrm{U}}^{\mathrm{h}}$
  - Effective array response vector of fully-digital array with size $I_{\mathrm{U}}^{\mathrm{h}} \times I_{\mathrm{U}}^{\mathrm{v}}$

$$\bar{\bar{\boldsymbol{a}}}_{\mathrm{U}}(\mu_l^{\mathrm{U}}, \nu_l^{\mathrm{U}}) = \boldsymbol{a}_{\mathrm{v}}(\nu_l^{\mathrm{U}}, I_{\mathrm{U}}^{\mathrm{v}}) \otimes \boldsymbol{a}_{\mathrm{h}}(\mu_l^{\mathrm{U}}, I_{\mathrm{U}}^{\mathrm{h}}) \in \mathbb{C}^{I_{\mathrm{U}}}$$

  - (7) can be rewritten as $\boldsymbol{Y}_{\mathrm{DL},l} = \gamma_{\mathrm{DL},l} \left(\bar{\bar{\boldsymbol{a}}}_{\mathrm{U}}(\mu_l^{\mathrm{U}}, \nu_l^{\mathrm{U}}) \boldsymbol{s}_{\mathrm{DL},l}^{\mathrm{T}}\right) \circ \widetilde{\boldsymbol{Y}}_{\mathrm{DL},l} + \boldsymbol{N}_{\mathrm{DL},l}$, (8)

3 Fine Angle Estimation at UAVs

Algorithm 1: Prior-Aided Iterative Angle Estimation

Input: Rough virtual angles $\{\widetilde{\mu}_l^{\mathrm{U}}, \widetilde{\nu}_l^{\mathrm{U}}, \widetilde{\mu}_l^{\mathrm{S}}, \widetilde{\nu}_l^{\mathrm{S}}\}_{l=1}^{L}$, received signal $\boldsymbol{Y}_{\mathrm{DL},l}$, and maximum iterations $i_{\mathrm{U}}^{\max}$

Output: Estimated azimuth/elevation angles $\{\widehat{\theta}_l^{\mathrm{U}}, \widehat{\varphi}_l^{\mathrm{U}}\}$ and virtual angles $\{\widehat{\mu}_l^{\mathrm{U}}, \widehat{\nu}_l^{\mathrm{U}}\}$ for $1 \le l \le L$

```
for i_U = 1, ..., i_U^max do
    if i_U = 1 then
        Apply TDU-ESPRIT algorithm to Y_DL,l;
        Obtain angle estimates of first iteration as
        {θ̂_l^(i_U), φ̂_l^(i_U)} and {μ̂_l^(i_U), ν̂_l^(i_U)};
    else
        Design compensation matrix Ỹ_DL,l^(i_U−1), whose k_l th
        column ỹ_DL,l^(i_U−1)[k_l] is shown in (10);
        Obtain compensated matrix
        Y_DL,l^(i_U) = (Ỹ_DL,l^(i_U−1))^* ∘ Y_DL,l in (11);
        Apply TDU-ESPRIT algorithm to Y_DL,l^(i_U);
        Obtain angle estimates of i_U th iteration as
        {θ̂_l^(i_U), φ̂_l^(i_U)} and {μ̂_l^(i_U), ν̂_l^(i_U)};
    end
end
Return: θ̂_l^U = θ̂_l^(i_U^max), φ̂_l^U = φ̂_l^(i_U^max), μ̂_l^U = μ̂_l^(i_U^max), and
ν̂_l^U = ν̂_l^(i_U^max) for 1 ≤ l ≤ L
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$$\boldsymbol{Y}_{\mathrm{DL},l} = \gamma_{\mathrm{DL},l}\left(\bar{\bar{\boldsymbol{a}}}_{\mathrm{U}}(\mu_l^{\mathrm{U}}, \nu_l^{\mathrm{U}})\boldsymbol{s}_{\mathrm{DL},l}^{\mathrm{T}}\right) \circ \widetilde{\boldsymbol{Y}}_{\mathrm{DL},l} + \boldsymbol{N}_{\mathrm{DL},l}, \quad (8)$$

$$\widetilde{\boldsymbol{Y}}_{\mathrm{DL},l}^{(i_{\mathrm{U}}-1)} = \left[\widetilde{\boldsymbol{y}}_{\mathrm{DL},l}^{(i_{\mathrm{U}}-1)}[\{\mathcal{K}_l\}_1] \cdots \widetilde{\boldsymbol{y}}_{\mathrm{DL},l}^{(i_{\mathrm{U}}-1)}[\{\mathcal{K}_l\}_{K_l}]\right]$$

$$\widetilde{\boldsymbol{y}}_{\mathrm{DL},l}^{(i_{\mathrm{U}}-1)}[k_l] = \left(\bar{\boldsymbol{a}}_{\mathrm{v}}(\widetilde{\nu}_l^{\mathrm{U}}, I_{\mathrm{U}}^{\mathrm{v}}, k_l) \otimes \bar{\boldsymbol{a}}_{\mathrm{h}}(\widetilde{\mu}_l^{\mathrm{U}}, I_{\mathrm{U}}^{\mathrm{h}}, k_l)\right)^* \circ \left(\bar{\boldsymbol{a}}_{\mathrm{v}}(\widehat{\nu}_l^{(i_{\mathrm{U}}-1)}, I_{\mathrm{U}}^{\mathrm{v}}, k_l) \otimes \bar{\boldsymbol{a}}_{\mathrm{h}}(\widehat{\mu}_l^{(i_{\mathrm{U}}-1)}, I_{\mathrm{U}}^{\mathrm{h}}, k_l)\right). \quad (10)$$

$$\boldsymbol{Y}_{\mathrm{DL},l}^{(i_{\mathrm{U}})} = \gamma_{\mathrm{DL},l}\left(\bar{\bar{\boldsymbol{a}}}_{\mathrm{U}}(\mu_l^{\mathrm{U}}, \nu_l^{\mathrm{U}})\boldsymbol{s}_{\mathrm{DL},l}^{\mathrm{T}}\right) \circ \left(\widetilde{\boldsymbol{Y}}_{\mathrm{DL},l} \circ \left(\widetilde{\boldsymbol{Y}}_{\mathrm{DL},l}^{(i_{\mathrm{U}}-1)}\right)^*\right) + \boldsymbol{N}_{\mathrm{DL},l}^{(i_{\mathrm{U}})}. \quad (11)$$

3 Fine Angle Estimation at Satellite

- Design analog precoding and combining vectors
  - $I_{\rm S} = I_{\rm S}^{\rm h} I_{\rm S}^{\rm v}$ OFDM symbols
  - Utilize the estimated $\{\widehat{\mu}_l^{\rm U}, \widehat{\nu}_l^{\rm U}\}_{l=1}^{L}$ to design $\boldsymbol{f}_{{\rm RF},l} = \boldsymbol{a}_{\rm U}(\widehat{\mu}_l^{\rm U}, \widehat{\nu}_l^{\rm U})$
  - Initialize $\boldsymbol{w}_{{\rm RF},l}^{[n]} = \boldsymbol{0}_{N_{\rm S}}$, and then let $[\boldsymbol{w}_{{\rm RF},l}^{[n]}]_{\mathcal{I}_{{\rm S},l}^{[n]}} = \frac{1}{\sqrt{\bar{M}_{\rm S}}}[\boldsymbol{a}_{\rm S}(\widetilde{\mu}_l^{\rm S}, \widetilde{\nu}_l^{\rm S})]_{\mathcal{I}_{{\rm S},l}^{[1]}}$
- Obtain the UL received signal $\boldsymbol{Y}_{{\rm UL},l}$
- Utilize the proposed **Algorithm 1**
  - Replace the input parameters
  - Obtain $\widehat{\theta}_l^{\rm S} = \widehat{\theta}_l^{(i_{\rm S}^{\max})}$, $\widehat{\varphi}_l^{\rm S} = \widehat{\varphi}_l^{(i_{\rm S}^{\max})}$, $\widehat{\mu}_l^{\rm S} = \widehat{\mu}_l^{(i_{\rm S}^{\max})}$, and $\widehat{\nu}_l^{\rm S} = \widehat{\nu}_l^{(i_{\rm S}^{\max})}$ for $1 \leq l \leq L$.

3 Computational Complexity Analysis

- Total computational complexity is $\mathcal{O}\left(i_{\mathrm{U}}^{\max} L I_{\mathrm{U}} K_l + i_{\mathrm{S}}^{\max} L I_{\mathrm{S}} K_l\right)$
- Computational complexity of the proposed angle estimation solution is in polynomial time
  - Effective low-dimensional signals at the receiver are utilized to estimate angles

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Simulation Parameters

- LEO satellite serves L = 2 UAVs
- Vertical distance between satellite and UAVs is 200 kilometer
- Relative radial velocity 200 m/s

TABLE I. Simulation Parameter Settings

Parameter	Value
f_z (f_s)	0.1 THz (1 GHz)
$N_{\mathrm{U}}^{\mathrm{h}}$, $N_{\mathrm{U}}^{\mathrm{v}}$, $M_{\mathrm{S}}^{\mathrm{h}}$, $M_{\mathrm{S}}^{\mathrm{v}}$	200
$\widetilde{I}_{\mathrm{S}}^{\mathrm{h}}$ $(\widetilde{I}_{\mathrm{S}}^{\mathrm{v}})$	1 (2)
$I_{\mathrm{U}}^{\mathrm{h}}$, $I_{\mathrm{U}}^{\mathrm{v}}$, $I_{\mathrm{S}}^{\mathrm{h}}$, $I_{\mathrm{S}}^{\mathrm{v}}$	5
$\widetilde{M}_{\mathrm{U}}^{\mathrm{h}}$, $\widetilde{M}_{\mathrm{U}}^{\mathrm{v}}$, $\widetilde{M}_{\mathrm{S}}^{\mathrm{h}}$, $\widetilde{M}_{\mathrm{S}}^{\mathrm{v}}$	5
K (cyclic prefix N_{cp})	2048 (128)
$\{\theta_l^{\mathrm{U}},\varphi_l^{\mathrm{U}},\theta_l^{\mathrm{S}},\varphi_l^{\mathrm{S}}\}_{l=1}^{L}$	$-60^\circ - 60^\circ$
$\{\tau_l\}_{l=1}^{L}$ $(\{\alpha_l\}_{l=1}^{L})$	$\mathcal{U}[0, N_{\mathrm{cp}}T_s]$ $(\mathcal{CN}(0,1))$
Maximum offset of rough angle estimates	$\pm 5^\circ$

- Root mean square error (RMSE) metric

$$\mathrm{RMSE}_{\boldsymbol{x}} = \sqrt{\mathbb{E}\left(\frac{1}{L}\|\boldsymbol{x}-\widehat{\boldsymbol{x}}\|_2^2\right)}$$ with $[\boldsymbol{x}]_l$ being θ_l^{U}, φ_l^{U}, θ_l^{S}, or φ_l^{S}

- CRLBs serve as the *lower bounds* of angle estimation
- $i_{\mathrm{U}}^{\max} = 2$ and $i_{\mathrm{S}}^{\max} = 2$ iterations

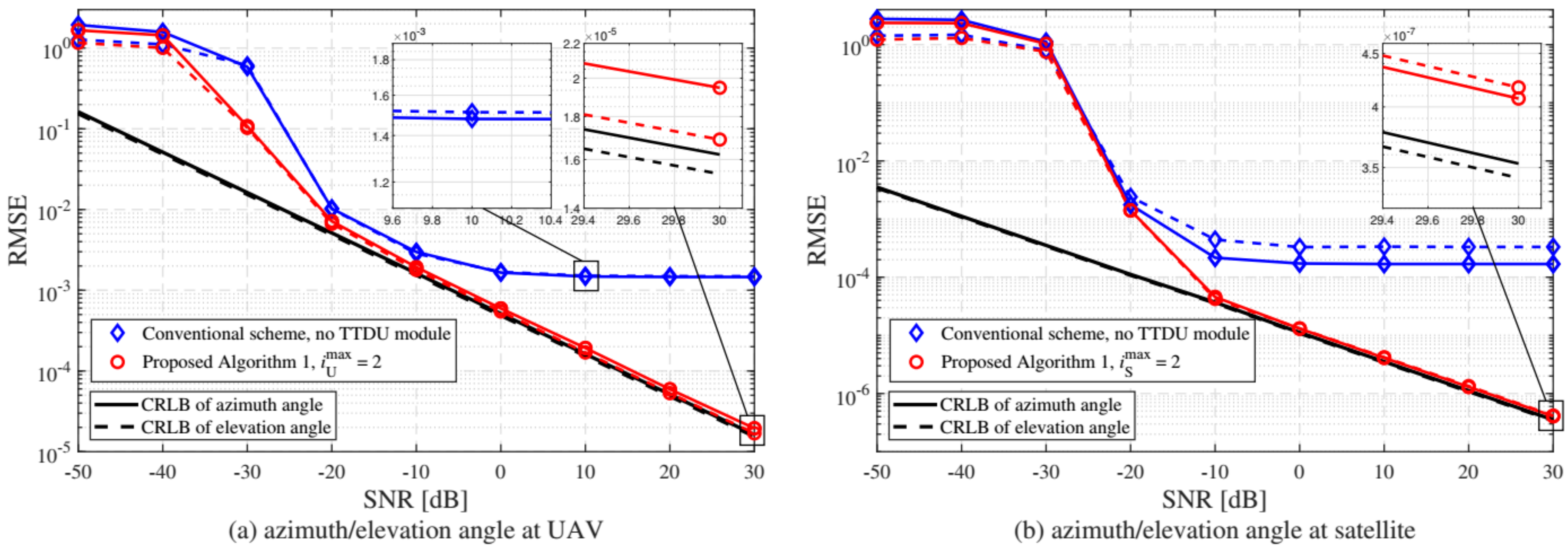

Fig. 5. RMSE comparison of azimuth/elevation angles $\{\theta_l^{\mathrm{U}}, \varphi_l^{\mathrm{U}}, \theta_l^{\mathrm{S}}, \varphi_l^{\mathrm{S}}\}_{l=1}^{L}$ at the UAVs and satellite.

Thanks for your listening!

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