RIBCE: RIS-BS virtual array based Channel Estimation for mm-Wave communication system

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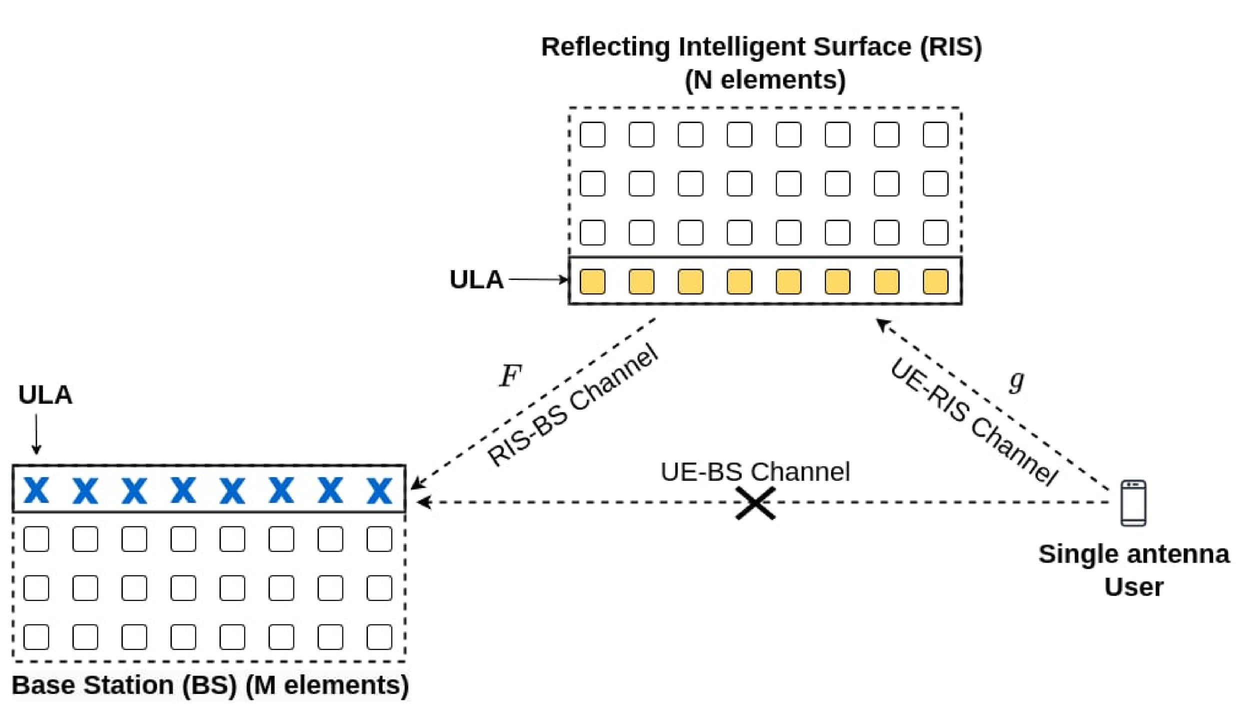
Abstract

- **Objective:** Propose an effective approach for cascaded channel estimation (CE) of RIS assisted mmWave communication system
- **Our Efficient approach and benefits:** By assuming a uniform linear array (ULA) structure for RIS and BS, we show that the RIS elements and BS antenna elements together can be visualized as a 2-D virtual array, and which we refer to as **RIS-BS virtual array**
- Leveraging the **RIS-BS virtual array**, and taking the advantage of the sparsity offered by mmWave channel, we propose i) **RIBCE-CS**, a CS based solution and ii) **RIBCE-ESPRIT**, an ESPRIT based approach to estimate the AoA's and AoD's jointly
- We provide a lower bound for the proposed algorithms and show that **the number of pilots required for CE reduces by** $\mathcal{O}(M)$ where M is the number of antenna elements at base station (BS)

Motivation

- Reconfigurable intelligent surface (RIS) has the ability to **intelligently steer the incident beam** and will be a key component in next generation communication systems
- Accurate channel state information (CSI) is required to induce desired phase-shift
- Cascaded CE is challenging and usually requires more pilot overhead
- **Problem addressed:** Effective cascaded CE with reduced pilot overhead

System Model



[†] Qingqing Wu and Rui Zhang. "Beamforming Optimization for Intelligent Reflecting Surface with Discrete Phase Shifts". In: IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP). 2019.

Song Noh et al. "Joint Direct and Indirect Channel Estimation for RIS-Assisted mm-Wave Systems Based on Array Signal Processing". In: IEEE Trans. Commun. (2023)

System Model

- RIS-BS channel matrix, $\mathbf{F}$ and UE-RIS channel, $\mathbf{g}$

$$\mathbf{F} = \sum_{r=1}^{L_f} \alpha_{f,r}\mathbf{u}_M(\psi_{f,r})\mathbf{u}_N^{\mathrm{H}}(\theta_{f,r})$$

$$\mathbf{g} = \sum_{s=1}^{L_g} \alpha_{g,s}\mathbf{u}_N(\theta_{g,s})$$

- Complex path gain: α
- AoA at RIS: $\theta_{g,s}$, AoD at RIS: $\theta_{f,r}$ and AoA at BS: $\psi_{f,r}$
- Array response vector of ULA for any angle $\delta \in [0,\pi]$ is

$$\mathbf{u}_P(\delta) = [1, e^{j\pi\cos(\delta)}, \ldots, e^{j\pi\cos(\delta)(P-1)}]^{\mathrm{T}}$$

- When pilot symbol x_k is transmitted by the user in slot k, the BS receives

$$\mathbf{y}_k = (\mathbf{F}\cdot \mathrm{diag}(\mathbf{w}_k)\cdot \mathbf{g})\, x_k + \mathbf{n}_k$$

- RIS reflection coefficients: $\mathbf{w}_k$
- Received signal at BS over K slots,

$$\mathbf{Y} = \left(\sum_{r=1}^{L_f} \alpha_{f,r}\mathbf{u}_M(\psi_{f,r})\mathbf{u}_N^{\mathrm{H}}(\theta_{f,r})\right) \times \mathrm{diag}\left(\sum_{s=1}^{L_g} \alpha_{g,s}\mathbf{u}_N(\theta_{g,s})\right)\mathbf{WX} + \mathbf{N}$$

$$= \left(\sum_{l=1}^{L} \alpha_l \mathbf{u}_M(\psi_l)\mathbf{u}_N^{\mathrm{H}}(\theta_l)\right)\mathbf{WX} + \mathbf{N}$$

- Here, $L = L_f L_g$ with $l = (r-1)L_g + s$
- $\alpha_l = \alpha_{f,r}\alpha_{g,s}$, $\theta_l = \theta_{f,r} - \theta_{g,s}$ and $\psi_l = \psi_{f,r}$

Contribution: RIS-BS virtual array

- mm-Wave channels are sparse $\implies K < \max\{M, N\}$
- Consider RIS reflection co-efficient matrix as [†]

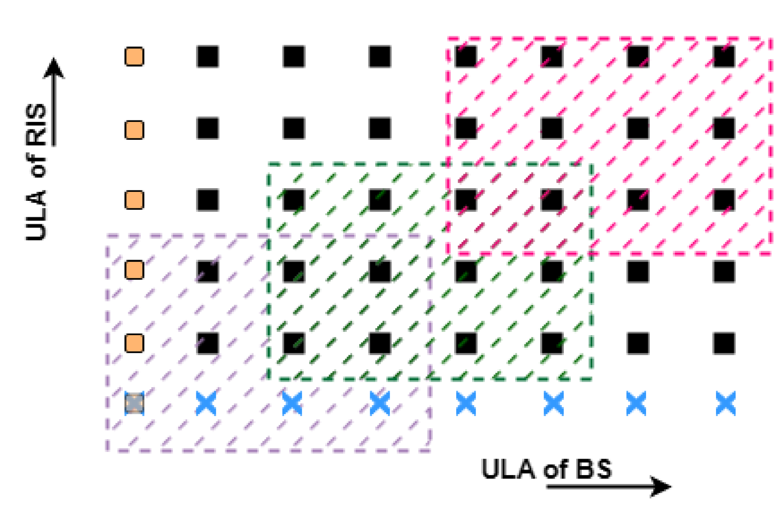
$$\mathbf{W} = \begin{bmatrix} \mathbf{I}_K \\ \mathbf{0}_{N-K}\mathbf{0}_K^T \end{bmatrix}$$

- Now,

$$\mathbf{Y} = \mathbf{U}_M(\boldsymbol{\psi})\mathrm{diag}(\boldsymbol{\alpha})\mathbf{U}_K^H(\boldsymbol{\theta})\mathbf{X} + \mathbf{N}$$

- With $\mathbf{X} = \mathbf{I}_K$ and using $\mathrm{vec}\{\mathbf{P}\mathrm{diag}(\mathbf{s})\mathbf{Q}^H\} = (\mathbf{Q} \odot \mathbf{P})\,\mathbf{s}$

$$\mathbf{y} = \mathrm{vec}(\mathbf{Y}) = (\mathbf{U}_K(\boldsymbol{\theta}) \odot \mathbf{U}_M(\boldsymbol{\psi}))\,\boldsymbol{\alpha} + \mathbf{n} \qquad (1)$$



- The Khatri-Rao product can be visualized as 2D array response of UPA and is referred as **RIS-BS virtual array**
- Proposed algorithms exploit the virtual array structure to **estimate the AoA and AoD pairs jointly**

RIBCE-Compressive Sensing Algorithm

- Utilizes dictionary matrices constructed for an angular resolution to estimate AoA's and AoD's
- For angular resolution of $\theta_{\mathrm{res}} = \frac{\pi}{D_1}$ and $\psi_{\mathrm{res}} = \frac{\pi}{D_2}$,

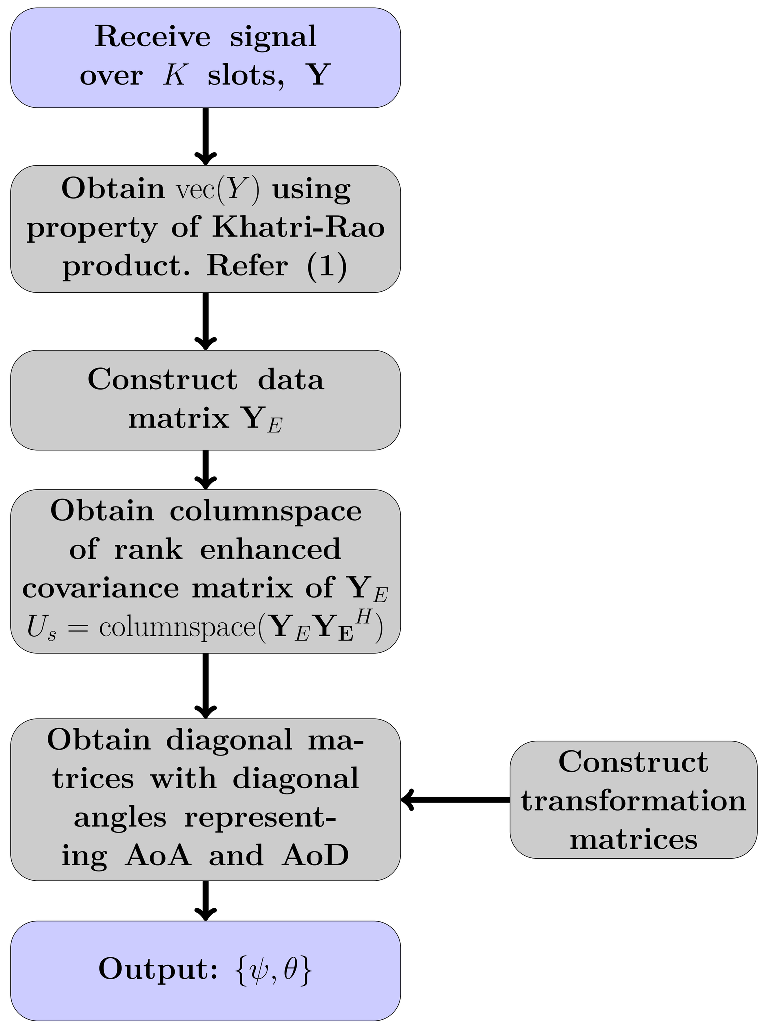
$$\mathbf{y} = \left(\mathbf{U}_K^{D_1}(\tilde{\boldsymbol{\theta}}) \otimes \mathbf{U}_M^{D_2}(\tilde{\boldsymbol{\psi}})\right)\boldsymbol{\alpha}_s + \mathbf{n}$$

- $\boldsymbol{\alpha}_s$: Sparse channel vector with $||\boldsymbol{\alpha}_s||_0 = L$
- Find the support of $\boldsymbol{\alpha}_s$ and estimate the $\{\boldsymbol{\psi}, \boldsymbol{\theta}\}$ angle pairs corresponding to the non-zero indices of $\boldsymbol{\alpha}_s$
- Formulate the optimization problem:

$$\min ||\boldsymbol{\alpha}_s||_1 \text{ s.t. } ||\mathbf{y} - \left(\mathbf{U}_K^{D_1}(\tilde{\boldsymbol{\theta}}) \otimes \mathbf{U}_M^{D_2}(\tilde{\boldsymbol{\psi}})\right)\boldsymbol{\alpha}_s||_2 < \epsilon$$

- Solve using compressive sensing algorithms such as Orthogonal Matching Pursuit (OMP)

RIBCE-ESPRIT Algorithm



- Each column of $\mathbf{Y}_E$ corresponds to 2D sub-array response of size $(K/2 \times M/2)$ and move the sub-array response over the entire RIS-BS virtual array to obtain $\mathbf{Y}_E$

Numerical Results

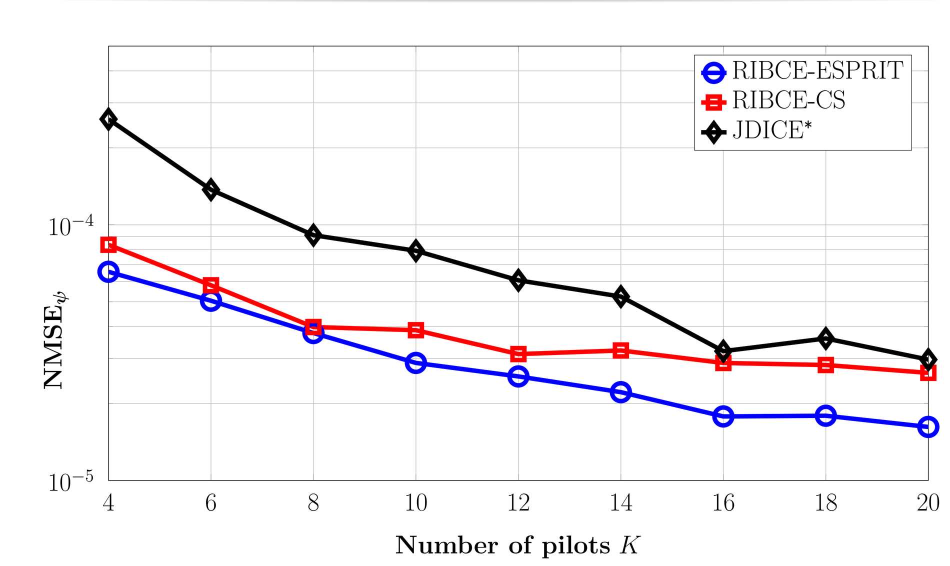


Figure 1: Performance of the proposed solutions in estimating $\boldsymbol{\psi}$

Numerical Results

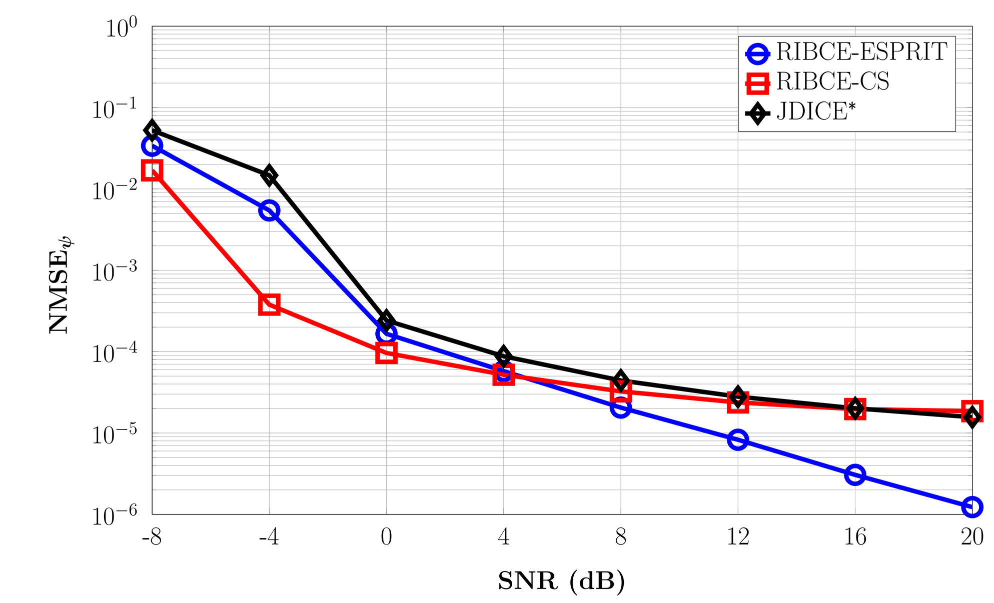


Figure 2: Performance of the proposed solutions in estimating $\boldsymbol{\psi}$

- Observe plateauing at high SNR by RIBCE-CS algorithm
- Due to the angular resolution $(\theta_{\mathrm{res}}, \psi_{\mathrm{res}})$ considered for dictionary matrices

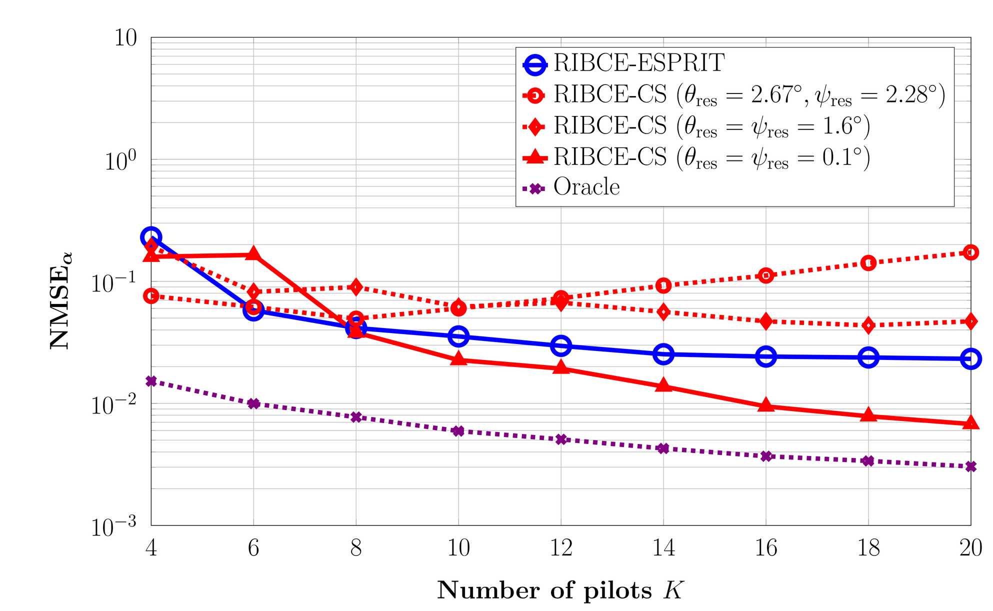


Figure 3: Performance of the proposed solutions in estimating the gains $\boldsymbol{\alpha}$

- The estimation **accuracy of angle pairs depends on the angle resolution**
- **Trade-off provides flexibility to choose between accuracy and computational complexity**

Conclusion & Future Work

- The proposed channel estimation algorithms exploits the RIS-BS virtual array
- Using the proposed algorithms results in reduced pilot overhead for CE by $\mathcal{O}$(# of antenna elements at BS)

Algorithms	Computational Complexity	Accuracy
RIBCE-CS	Tunable	
RIBCE-ESPRIT	High	High

- **Future Work:** Extend to the scenario with RIS and BS as uniform planar arrays