Super-Resolution Channel Estimation for MmWave Massive MIMO

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Outline

1 **System Model**

2 **Proposed 2D Unitary ESPRIT Based Channel Estimation Scheme**

a) Design of Training Signals
b) Modified 2D Unitary ESPRIT Algorithm
c) Reconstruct High-Dimensional mmWave MIMO Channel

3 **Simulation Results**

System Model

- The received signal $\boldsymbol{y}$ for the uplink:

$$\begin{aligned}\boldsymbol{y} &= \boldsymbol{W}^H \boldsymbol{H}\boldsymbol{F}\boldsymbol{s} + \boldsymbol{W}^H \boldsymbol{n} \\ &= \boldsymbol{W}_{\mathrm{BB}}^H \boldsymbol{W}_{\mathrm{RF}}^H \boldsymbol{H}\boldsymbol{F}_{\mathrm{RF}}\boldsymbol{F}_{\mathrm{BB}}\boldsymbol{s} + \boldsymbol{W}_{\mathrm{BB}}^H \boldsymbol{W}_{\mathrm{RF}}^H \boldsymbol{n}\end{aligned} \quad (1)$$

$$\begin{cases}\boldsymbol{W} = \boldsymbol{W}_{\mathrm{RF}}\boldsymbol{W}_{\mathrm{BB}} \\ \boldsymbol{F} = \boldsymbol{F}_{\mathrm{RF}}\boldsymbol{F}_{\mathrm{BB}}\end{cases}$$

N_{S}: number of data streams

N_{BS}, N_{MS}: number of antennas at the BS and MS

$N_{\mathrm{RF}}^{\mathrm{BS}}$, $N_{\mathrm{RF}}^{\mathrm{MS}}$: number of RF chains at the BS and MS

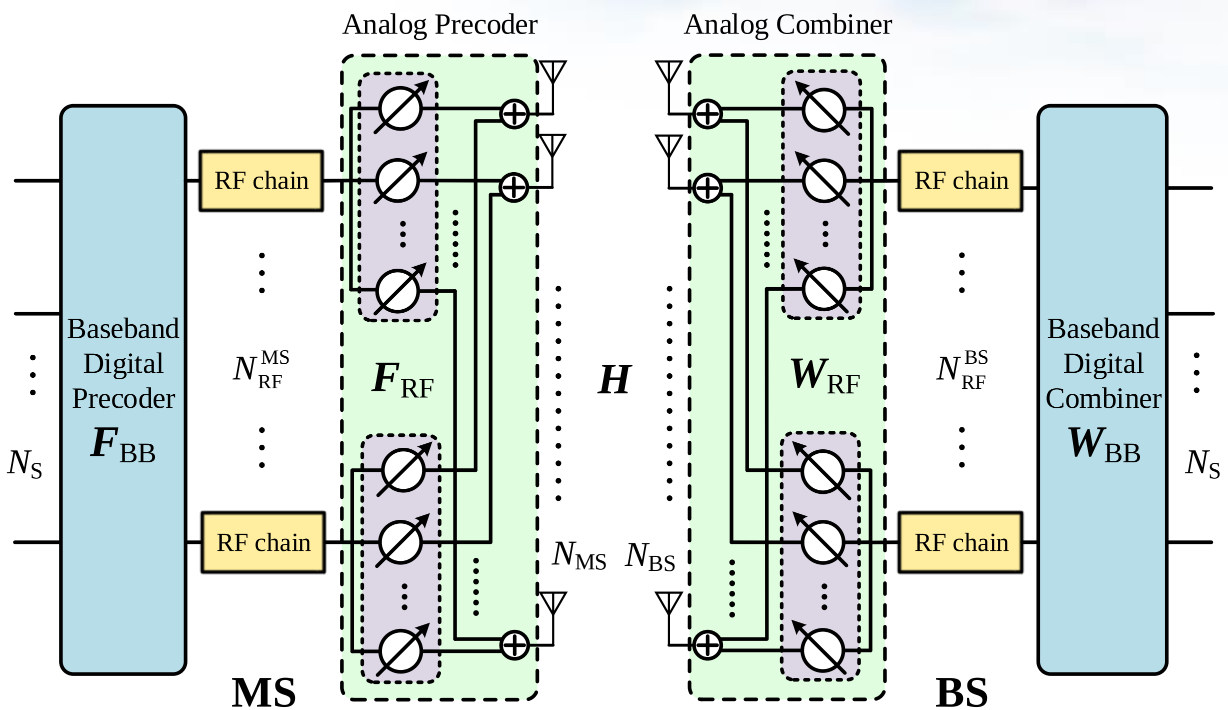

Fig. 1. Block diagram of transceiver for a typical mmWave massive MIMO system with hybrid precoding

System Model

- The geometric mmWave channel model with L dominated paths can be written as

$$\boldsymbol{H} = \sqrt{\frac{N_{\mathrm{BS}}N_{\mathrm{MS}}}{L}}\sum_{l=1}^{L}\alpha_l \boldsymbol{a}_{\mathrm{BS}}(\theta_l)\boldsymbol{a}_{\mathrm{MS}}^{H}(\varphi_l) \qquad (2)$$

$$\boldsymbol{H} = \boldsymbol{A}_{\mathrm{BS}}\boldsymbol{D}\boldsymbol{A}_{\mathrm{MS}}^{H} \qquad (4)$$

  - α_l is the complex gain of the l-th path
  - θ and φ are azimuth angles of AoA and AoD

$$\begin{cases} \boldsymbol{A}_{\mathrm{BS}} = \left[\boldsymbol{a}_{\mathrm{BS}}(\theta_1),\cdots,\boldsymbol{a}_{\mathrm{BS}}(\theta_L)\right] \\ \boldsymbol{A}_{\mathrm{MS}} = \left[\boldsymbol{a}_{\mathrm{MS}}(\varphi_1),\cdots,\boldsymbol{a}_{\mathrm{MS}}(\varphi_L)\right] \\ \boldsymbol{D} = \mathrm{diag}(\boldsymbol{d}) \\ \boldsymbol{d} = \sqrt{N_{\mathrm{BS}}N_{\mathrm{MS}} / L}\left[\alpha_1,\cdots,\alpha_L\right] \end{cases}$$

- The steering vectors with ULA:

$$\begin{aligned} \boldsymbol{a}_{\mathrm{BS}}(\theta_l) &= \frac{1}{\sqrt{N_{\mathrm{BS}}}}\left[1, e^{2\pi\Delta\sin(\theta_l)},\cdots,e^{2\pi(N_{\mathrm{BS}}-1)\Delta\sin(\theta_l)}\right]^T \\ \boldsymbol{a}_{\mathrm{MS}}(\varphi_l) &= \frac{1}{\sqrt{N_{\mathrm{MS}}}}\left[1, e^{2\pi\Delta\sin(\varphi_l)},\cdots,e^{2\pi(N_{\mathrm{MS}}-1)\Delta\sin(\varphi_l)}\right]^T \end{aligned} \qquad (3)$$

$\Delta = d/\lambda$ — the normalized spacing of adjacent antennas

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Design of Training Signals

- Each baseband observation mixes the signals from different antennas via the RF phase shift network;
- The shift-invariance of array response is destroyed by the RF phase shift network, which is the precondition of using the conventional ESPRIT algorithms;
- Solution:
  - Design the training signals to obtain a low-dimensional effective channel matrix with low pilot overhead;
  - This channel matrix has the same shift-invariance of array response as the high-dimensional MIMO channel matrix;
  - Obtain the paired super-resolution estimates of AoAs and AoDs.

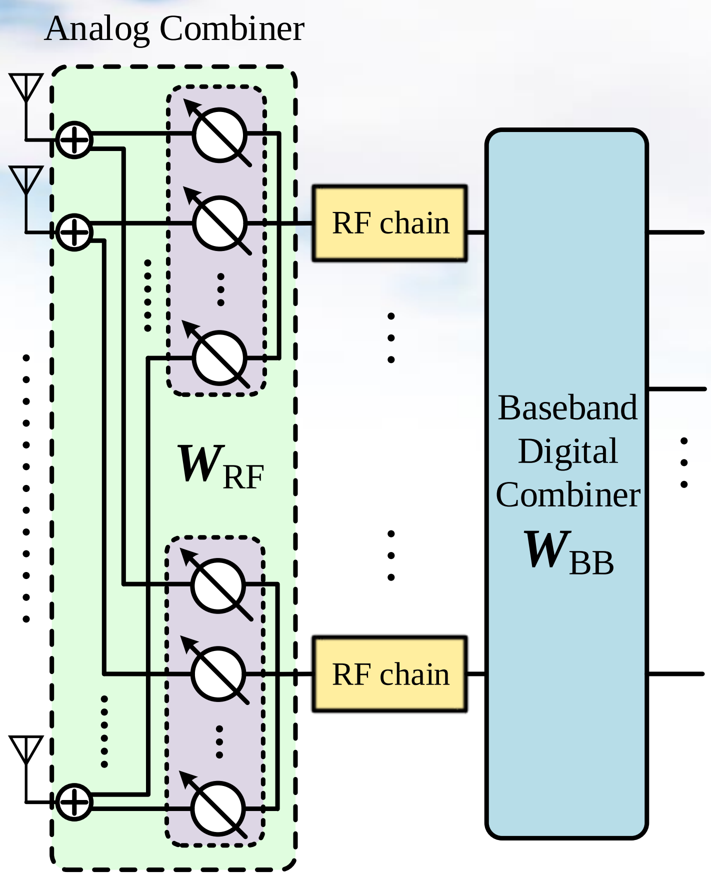

Fig. 2. Receiver with hybrid precoding

Design of Training Signals

- Consider T_{MS} time slots as a time-block, we have

$$\boldsymbol{y} = \boldsymbol{W}^H \boldsymbol{H} \boldsymbol{F} \boldsymbol{s} + \boldsymbol{W}^H \boldsymbol{n} \xRightarrow{T_{\mathrm{MS}}} \boldsymbol{Y} = \left[\boldsymbol{y}_1, \cdots, \boldsymbol{y}_{T_{\mathrm{MS}}} \right] = \boldsymbol{W}^H \boldsymbol{H} \boldsymbol{F} \boldsymbol{S} + \boldsymbol{W}^H \boldsymbol{N} \quad (5)$$

$\boldsymbol{S} = \left[\boldsymbol{s}_1, \cdots, \boldsymbol{s}_{T_{\mathrm{MS}}} \right]$ — the transmitted pilot signal block

- Furthermore, jointly consider $N_{\mathrm{b}}^{\mathrm{T}} N_{\mathrm{b}}^{\mathrm{R}}$ time-blocks, the aggregated received signal is

$$\tilde{\boldsymbol{Y}} = \begin{bmatrix} \boldsymbol{Y}_{1,1} & \cdots & \boldsymbol{Y}_{1,N_{\mathrm{b}}^{\mathrm{T}}} \\ \vdots & \ddots & \vdots \\ \boldsymbol{Y}_{N_{\mathrm{b}}^{\mathrm{R}},1} & \cdots & \boldsymbol{Y}_{N_{\mathrm{b}}^{\mathrm{R}},N_{\mathrm{b}}^{\mathrm{T}}} \end{bmatrix} = \tilde{\boldsymbol{W}}^H \boldsymbol{H} \tilde{\boldsymbol{F}} \bar{\boldsymbol{S}} + \bar{\boldsymbol{W}}^H \tilde{\boldsymbol{N}} \quad (6)$$

- $\tilde{\boldsymbol{F}} = [\boldsymbol{F}_1, \cdots, \boldsymbol{F}_{N_{\mathrm{b}}^{\mathrm{T}}}]$, $\tilde{\boldsymbol{W}} = [\boldsymbol{W}_1, \cdots, \boldsymbol{W}_{N_{\mathrm{b}}^{\mathrm{R}}}]$ — the aggregated hybrid combiner/precoder (need to design)
- $\bar{\boldsymbol{S}} = \mathrm{diag}\left[\boldsymbol{S}, \cdots, \boldsymbol{S} \right]$ — the aggregated pilot signal block (block diagonal matrix)
- $\bar{\boldsymbol{W}} = \mathrm{diag}[\boldsymbol{W}_1, \cdots, \boldsymbol{W}_{N_{\mathrm{b}}^{\mathrm{R}}}]$
- Thus, the total number of pilot overhead required for channel estimation is $T_{\mathrm{pilot}} = T_{\mathrm{MS}} N_{\mathrm{b}}^{\mathrm{R}} N_{\mathrm{b}}^{\mathrm{T}}$

Design of Training Signals

- To guarantee the same shift-invariance of array response in $\tilde{\boldsymbol{Y}}$, we can design the $\tilde{\boldsymbol{F}}$ and $\tilde{\boldsymbol{W}}$ as

$$\tilde{\boldsymbol{F}} = \alpha_f \begin{bmatrix} \boldsymbol{I}_{N_{\mathrm{b}}^{\mathrm{T}} N_{\mathrm{S}}} \\ \boldsymbol{O}_{\left(N_{\mathrm{MS}} - N_{\mathrm{b}}^{\mathrm{T}} N_{\mathrm{S}}\right) \times N_{\mathrm{b}}^{\mathrm{T}} N_{\mathrm{S}}} \end{bmatrix}, \quad \tilde{\boldsymbol{W}} = \alpha_w \begin{bmatrix} \boldsymbol{I}_{N_{\mathrm{b}}^{\mathrm{R}} N_{\mathrm{S}}} \\ \boldsymbol{O}_{\left(N_{\mathrm{BS}} - N_{\mathrm{b}}^{\mathrm{R}} N_{\mathrm{S}}\right) \times N_{\mathrm{b}}^{\mathrm{R}} N_{\mathrm{S}}} \end{bmatrix} \qquad (7)$$

- The low-dimensional effective channel matrix is

$$\bar{\boldsymbol{H}} = \tilde{\boldsymbol{W}}^H \boldsymbol{H} \tilde{\boldsymbol{F}} = \alpha_f \alpha_w \begin{bmatrix} \boldsymbol{H}_{1,1} & \cdots & \boldsymbol{H}_{1, N_{\mathrm{b}}^{\mathrm{T}} N_{\mathrm{S}}} \\ \vdots & \ddots & \vdots \\ \boldsymbol{H}_{N_{\mathrm{b}}^{\mathrm{R}} N_{\mathrm{S}}, 1} & \cdots & \boldsymbol{H}_{N_{\mathrm{b}}^{\mathrm{R}} N_{\mathrm{S}}, N_{\mathrm{b}}^{\mathrm{T}} N_{\mathrm{S}}} \end{bmatrix} \qquad (8)$$

- Next, design the aggregated hybrid combiner/precoder as

$$\left\{ \begin{aligned} \tilde{\boldsymbol{F}} &= [\boldsymbol{F}_1, \cdots, \boldsymbol{F}_{N_{\mathrm{b}}^{\mathrm{T}}}] \\ \tilde{\boldsymbol{W}} &= [\boldsymbol{W}_1, \cdots, \boldsymbol{W}_{N_{\mathrm{b}}^{\mathrm{R}}}] \\ \boldsymbol{F} &= \boldsymbol{F}_{\mathrm{RF}} \boldsymbol{F}_{\mathrm{BB}} \\ \boldsymbol{W} &= \boldsymbol{W}_{\mathrm{RF}} \boldsymbol{W}_{\mathrm{BB}} \end{aligned} \right\} \Rightarrow \left\{ \begin{aligned} &\left\{ \boldsymbol{F}_{\mathrm{RF},j} \right\}_{j=1}^{N_{\mathrm{b}}^{\mathrm{T}}} \\ &\left\{ \boldsymbol{F}_{\mathrm{BB},j} \right\}_{j=1}^{N_{\mathrm{b}}^{\mathrm{T}}} \\ &\left\{ \boldsymbol{W}_{\mathrm{RF},i} \right\}_{i=1}^{N_{\mathrm{b}}^{\mathrm{R}}} \\ &\left\{ \boldsymbol{W}_{\mathrm{BB},i} \right\}_{i=1}^{N_{\mathrm{b}}^{\mathrm{R}}} \end{aligned} \right\} \qquad (9)$$

Design of Training Signals

- The orthogonality of unitary matrix:

$$\boldsymbol{U}_{N_{\mathrm{RF}}^{\mathrm{MS}}} = [\boldsymbol{u}_1, \cdots, \boldsymbol{u}_{N_{\mathrm{RF}}^{\mathrm{MS}}}] \text{— as the set of the uplink training signals, orthogonality:} \begin{cases} \boldsymbol{u}_m^H \boldsymbol{u}_m = N_{\mathrm{RF}}^{\mathrm{MS}} \\ \boldsymbol{u}_m^H \boldsymbol{u}_n = 0, m \neq n \end{cases}$$

- For j-th digital/analog precoder,

$$\boldsymbol{F}_{\mathrm{BB},j} = [\boldsymbol{u}_1, \cdots, \boldsymbol{u}_{N_{\mathrm{S}}}]$$

$$\boldsymbol{F}_{\mathrm{RF},j} = \left[\boldsymbol{F}_{\mathrm{RF},j}^1, \boldsymbol{F}_{\mathrm{BB},j}, \boldsymbol{F}_{\mathrm{RF},j}^2 \right]^H \qquad (10)$$

$$\boldsymbol{F}_{\mathrm{RF},j}^1 = [\underbrace{\boldsymbol{u}_{N_{\mathrm{RF}}^{\mathrm{MS}}}, \cdots, \boldsymbol{u}_{N_{\mathrm{RF}}^{\mathrm{MS}}}}_{(j-1)N_{\mathrm{S}}}] \qquad \boldsymbol{F}_{\mathrm{RF},j}^2 = [\underbrace{\boldsymbol{u}_{N_{\mathrm{RF}}^{\mathrm{MS}}}, \cdots, \boldsymbol{u}_{N_{\mathrm{RF}}^{\mathrm{MS}}}}_{N_{\mathrm{MS}} - jN_{\mathrm{S}}}]$$

j-th hybrid precoder:

$$\boldsymbol{F}_j = \boldsymbol{F}_{\mathrm{RF},j} \boldsymbol{F}_{\mathrm{BB},j}, \ j = 1, \cdots, N_{\mathrm{b}}^{\mathrm{T}}$$

Similarly, i-th hybrid combiner:

$$\boldsymbol{W}_i = \boldsymbol{W}_{\mathrm{RF},i} \boldsymbol{W}_{\mathrm{BB},i}, \ i = 1, \cdots, N_{\mathrm{b}}^{\mathrm{R}}$$

$$\left[\left\{ \boldsymbol{F}_{\mathrm{RF},j} \right\}_{j=1}^{N_{\mathrm{b}}^{\mathrm{T}}}, \left\{ \boldsymbol{F}_{\mathrm{BB},j} \right\}_{j=1}^{N_{\mathrm{b}}^{\mathrm{T}}}, \left\{ \boldsymbol{W}_{\mathrm{RF},i} \right\}_{i=1}^{N_{\mathrm{b}}^{\mathrm{R}}}, \left\{ \boldsymbol{W}_{\mathrm{BB},i} \right\}_{i=1}^{N_{\mathrm{b}}^{\mathrm{R}}} \right]$$

$$\tilde{\boldsymbol{F}} = \left[\boldsymbol{F}_1, \cdots, \boldsymbol{F}_{N_{\mathrm{b}}^{\mathrm{T}}} \right], \ \tilde{\boldsymbol{W}} = \left[\boldsymbol{W}_1, \cdots, \boldsymbol{W}_{N_{\mathrm{b}}^{\mathrm{R}}} \right] \qquad (11)$$

[redacted] (12)

LS estimator

$$\bar{\boldsymbol{H}} = \tilde{\boldsymbol{Y}} \bar{\boldsymbol{S}}^{\dagger} = \tilde{\boldsymbol{Y}} \bar{\boldsymbol{S}}^H \left(\bar{\boldsymbol{S}} \bar{\boldsymbol{S}}^H \right)^{-1} \qquad (13)$$

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Modified 2D Unitary ESPRIT Algorith

$$\bar{\boldsymbol{H}} \in \mathbb{C}^{N_{\mathrm{R}}\times N_{\mathrm{T}}} \quad \begin{cases} R = N_{\mathrm{R}} - m_2 + 1 \\ T = N_{\mathrm{T}} - m_1 + 1 \end{cases}$$

- Step1: Spatial Smoothing Preprocessing

m_1 and m_2 are the smoothing parameters

$$\bar{\boldsymbol{H}}^{(i,j)} = \begin{bmatrix} \bar{\boldsymbol{H}}_{i,j} & \cdots & \bar{\boldsymbol{H}}_{i,N_{\mathrm{T}}-m_1+j} \\ \vdots & \ddots & \vdots \\ \bar{\boldsymbol{H}}_{N_{\mathrm{R}}-m_2+i,j} & \cdots & \bar{\boldsymbol{H}}_{N_{\mathrm{R}}-m_2+i,N_{\mathrm{T}}-m_1+j} \end{bmatrix} \Rightarrow \mathcal{H} = \begin{bmatrix} \bar{\boldsymbol{H}}^{(1,1)} & \cdots & \bar{\boldsymbol{H}}^{(m_2,1)} \\ \vdots & \ddots & \vdots \\ \bar{\boldsymbol{H}}^{(1,m_1)} & \cdots & \bar{\boldsymbol{H}}^{(m_2,m_1)} \end{bmatrix}$$

- Step2: Real Processing

$$\mathcal{H}_{\mathrm{R}} = \left(\boldsymbol{Q}_{m_1}^{H} \otimes \boldsymbol{Q}_{R}^{H}\right)\left[\mathcal{H} \quad \boldsymbol{J}_{m_1 R}\mathcal{H}^{*}\boldsymbol{J}_{m_2 T}\right]\boldsymbol{Q}_{2m_2 T}$$

$$\begin{cases} \boldsymbol{J}_n & \text{— the exchange matrix} \\ \boldsymbol{Q}_n & \text{— the left-real exchange matrix} \end{cases}$$

- Step3: Rank Reduction

$$\mathcal{H}_{\mathrm{R}} = \boldsymbol{U}\boldsymbol{\Sigma}\boldsymbol{V}^{H}, \; \hat{\boldsymbol{U}} = \boldsymbol{U}_{\{:,\,1:L\}}$$

- Step4: Joint Diagonalization

$$\mathfrak{Re}\{\boldsymbol{E}_{\theta}\}\hat{\boldsymbol{U}}\boldsymbol{T}\tilde{\boldsymbol{\Theta}} = \mathfrak{Im}\{\boldsymbol{E}_{\theta}\}\hat{\boldsymbol{U}}\boldsymbol{T}$$

$$\mathfrak{Re}\{\boldsymbol{E}_{\varphi}\}\hat{\boldsymbol{U}}\boldsymbol{T}\tilde{\boldsymbol{\Phi}} = \mathfrak{Im}\{\boldsymbol{E}_{\varphi}\}\hat{\boldsymbol{U}}\boldsymbol{T}$$

$$\boldsymbol{E}_{\theta} = \boldsymbol{I}_{m_1} \otimes \left(\boldsymbol{Q}_{R-1}^{H}\left[\boldsymbol{0} \quad \boldsymbol{I}_{R-1}\right]\boldsymbol{Q}_{R-1}\right)$$

$$\boldsymbol{E}_{\varphi} = \left(\boldsymbol{Q}_{m_1-1}^{H}\left[\boldsymbol{0} \quad \boldsymbol{I}_{m_1-1}\right]\boldsymbol{Q}_{m_1}\right) \otimes \boldsymbol{I}_{R}$$

LS

$$\boldsymbol{T}\tilde{\boldsymbol{\Theta}}\boldsymbol{T}^{-1} = \left(\boldsymbol{E}_{\theta,\mathrm{R}}\hat{\boldsymbol{U}}\right)^{\dagger}\boldsymbol{E}_{\theta,\mathrm{I}}\hat{\boldsymbol{U}}$$

$$\boldsymbol{T}\tilde{\boldsymbol{\Phi}}\boldsymbol{T}^{-1} = \left(\boldsymbol{E}_{\varphi,\mathrm{R}}\hat{\boldsymbol{U}}\right)^{\dagger}\boldsymbol{E}_{\varphi,\mathrm{I}}\hat{\boldsymbol{U}}$$

$$\begin{aligned} \boldsymbol{\Psi} &= \left(\boldsymbol{T}\tilde{\boldsymbol{\Phi}}\boldsymbol{T}^{-1}\right) + j\left(\boldsymbol{T}\tilde{\boldsymbol{\Theta}}\boldsymbol{T}^{-1}\right) = \boldsymbol{T}\left(\tilde{\boldsymbol{\Phi}} + j\tilde{\boldsymbol{\Theta}}\right)\boldsymbol{T}^{-1} \\ &= \left(\boldsymbol{E}_{\theta,\mathrm{R}}\hat{\boldsymbol{U}}\right)^{\dagger}\boldsymbol{E}_{\theta,\mathrm{I}}\hat{\boldsymbol{U}} + j\left(\left(\boldsymbol{E}_{\varphi,\mathrm{R}}\hat{\boldsymbol{U}}\right)^{\dagger}\boldsymbol{E}_{\varphi,\mathrm{I}}\hat{\boldsymbol{U}}\right) \end{aligned}$$

EVD

$$\boldsymbol{\Theta} = \mathrm{diag}\left(\tilde{\theta}_{\mathrm{BS},1},\cdots,\tilde{\theta}_{\mathrm{BS},L}\right), \; \tilde{\theta}_{\mathrm{BS},l} = \tan\left(\pi\Delta\sin\left(\hat{\theta}_{\mathrm{BS},l}\right)\right)$$

$$\boldsymbol{\Phi} = \mathrm{diag}\left(\tilde{\varphi}_{\mathrm{MS},1},\cdots,\tilde{\varphi}_{\mathrm{MS},L}\right), \; \tilde{\varphi}_{\mathrm{MS},l} = \tan\left(\pi\Delta\sin\left(\hat{\varphi}_{\mathrm{MS},l}\right)\right)$$

$$\Rightarrow \boxed{\left\{\hat{\theta}_l\right\}_{l=1}^{L}, \; \left\{\hat{\varphi}_l\right\}_{l=1}^{L}}$$

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Reconstruct High-Dimensional mmWave MIMO Channel

1. Based on obtained AoAs $\{\hat{\theta}_l\}_{l=1}^{L}$ and AoDs $\{\hat{\varphi}_l\}_{l=1}^{L}$, we can reconstruct the steering vector matrices

   $$\hat{\boldsymbol{A}}_{\text{BS}} = \left[\boldsymbol{a}\left(\hat{\theta}_1\right),\cdots,\boldsymbol{a}\left(\hat{\theta}_L\right)\right],\ \hat{\boldsymbol{A}}_{\text{MS}} = \left[\boldsymbol{a}\left(\hat{\varphi}_1\right),\cdots,\boldsymbol{a}\left(\hat{\varphi}_L\right)\right]$$

2. Vectorizing the low-dimensional effective channel matrix $\bar{\boldsymbol{H}} = \tilde{\boldsymbol{W}}^H \hat{\boldsymbol{A}}_{\text{BS}} \boldsymbol{D} \hat{\boldsymbol{A}}_{\text{MS}}^H \tilde{\boldsymbol{F}} + \bar{\boldsymbol{N}}$

   $$\bar{\boldsymbol{h}} = \text{vec}\left(\bar{\boldsymbol{H}}\right) = \underbrace{\left[\left(\hat{\boldsymbol{A}}_{\text{MS}}^H \tilde{\boldsymbol{F}}\right)^T \odot \left(\tilde{\boldsymbol{W}}^H \hat{\boldsymbol{A}}_{\text{BS}}\right)\right]}_{\boldsymbol{Z}} \boldsymbol{d} + \bar{\boldsymbol{n}} = \boldsymbol{Z}\boldsymbol{d} + \bar{\boldsymbol{n}}$$

3. Using the LS estimator, we can obtain the LS solution of associated path gain $\boldsymbol{d}$

   $$\hat{\boldsymbol{d}} = \arg\min_{\boldsymbol{d}} \left\|\bar{\boldsymbol{h}} - \boldsymbol{Z}\boldsymbol{d}\right\|_2^2 = \boldsymbol{Z}^{\dagger}\bar{\boldsymbol{h}} = \left(\boldsymbol{Z}^H\boldsymbol{Z}\right)^{-1}\boldsymbol{Z}^H\bar{\boldsymbol{h}}$$

4. Finally, we can reconstruct the high-dimensional mmWave MIMO channel as

   $$\hat{\boldsymbol{H}} = \hat{\boldsymbol{A}}_{\text{BS}} \text{diag}\left(\hat{\boldsymbol{d}}\right) \hat{\boldsymbol{A}}_{\text{MS}}^H$$

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Simulation Parameters and Comparison Schemes

Simulation Parameters

- $N_{\mathrm{BS}} = N_{\mathrm{MS}} = 64$
- $N_{\mathrm{RF}} = 4$
- $N_{\mathrm{S}} = T_{\mathrm{MS}} = 3$
- $N_{\mathrm{b}}^{\mathrm{T}} = N_{\mathrm{b}}^{\mathrm{R}} = 10$
- $L = 5$
- $m_1 = m_2 = 13$
- $\theta_l, \varphi_l \sim \mathcal{U}[-\pi/3, \pi/3]$

Comparison Schemes

① Adaptive Compressed Sensing (ACS) based channel estimation scheme:

A. Alkhateeb, O. El Ayach, G. Leus, and R. W. Heath, Jr., "Channel estimation and hybrid precoding for millimeter wave cellular systems," *IEEE J. Sel. Topics Signal Process.*, vol. 8, no. 5, pp. 831-846, Oct. 2014. [7]

② Orthogonal Matching Pursuit (OMP) based channel estimation scheme:

J. Lee, G. T. Gil, and Y. H. Lee, "Channel estimation via orthogonal matching pursuit for hybrid MIMO systems in millimeter wave communications," *IEEE Trans. Commun.*, vol. 64, no. 6, pp. 2370-2386, Jun. 2016. [8]

- **Pilot Overhead Comparison**

$$T_{\mathrm{Proposed}} = T_{\mathrm{MS}} N_{\mathrm{b}}^{\mathrm{R}} N_{\mathrm{b}}^{\mathrm{T}} = 300$$

$\boxed{\Downarrow 80\%}$ $$T_{\mathrm{ACS}} = KL^2 \left(KL / N_{\mathrm{RF}}\right) \log_K \left(G_{\mathrm{ACS}} / L\right) = 1500$$

$\boxed{\Downarrow 48\%}$ $$T_{\mathrm{OMP}} = N_{\mathrm{T}}^{\mathrm{Beam}} N_{\mathrm{R}}^{\mathrm{Beam}} / N_{\mathrm{RF}} = 576$$

Performance Evaluation Metrics

- normalized mean square error (NMSE): $\mathrm{NMSE} = 10\log_{10}\left(\mathbb{E}\left[\left\|\boldsymbol{H} - \hat{\boldsymbol{H}}\right\|_F^2 / \left\|\boldsymbol{H}\right\|_F^2\right]\right)$

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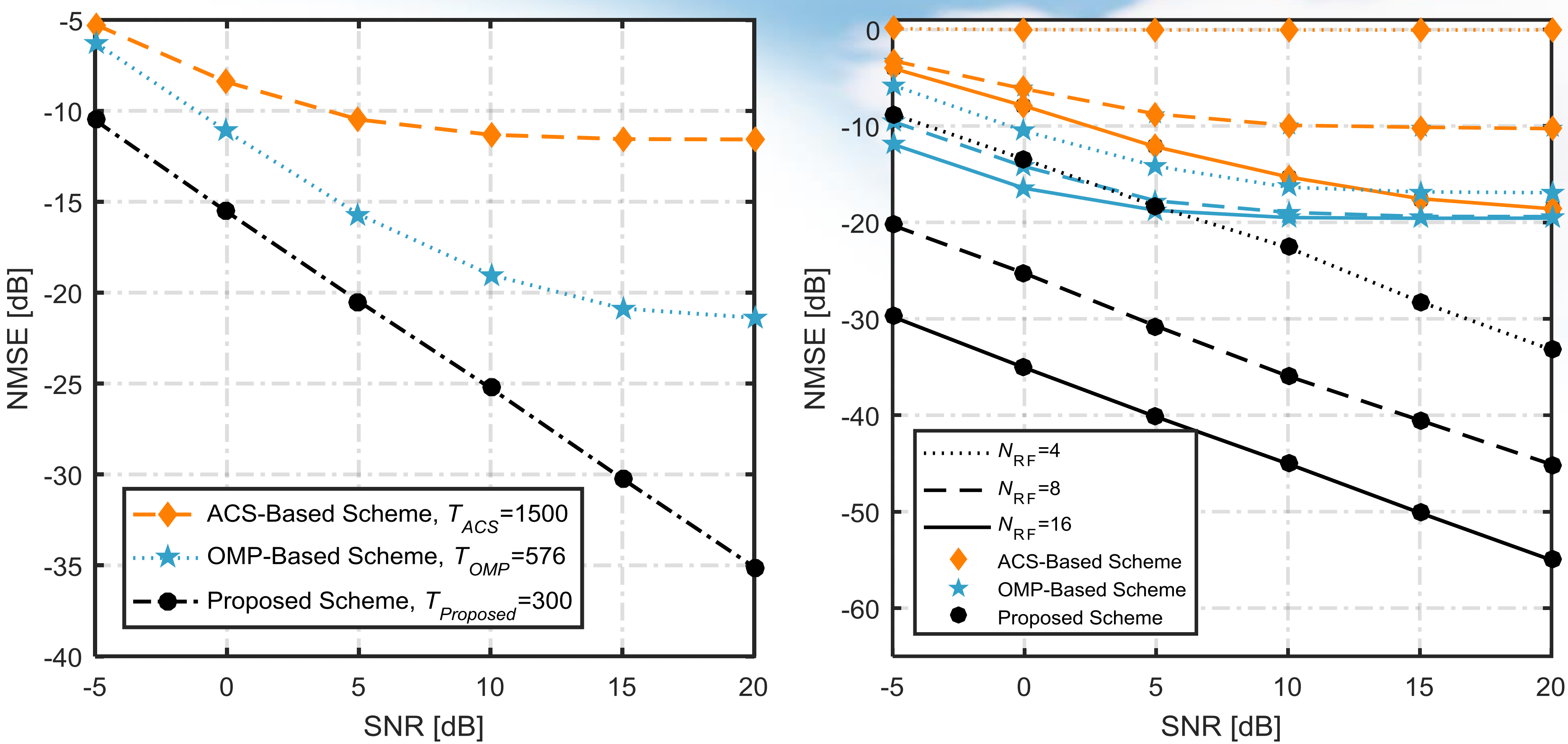

Fig. 1. NMSE performance comparison of different channel estimation schemes versus SNRs for $L = 5$.

Fig. 2. NMSE performance comparison of different schemes versus SNRs, where $N_{RF} = \{4, 8, 16\}$ are considered, respectively.

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THANKS!