W02: 2nd Workshop on "Integrating UAVs into 5G and Beyond"

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Multi-User Wideband Sparse Channel Estimation for Aerial BS with Hybrid Full-Dimensional MIMO

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May 20, 2019

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System Model

- Consider TDD based hybrid FD-MIMO-OFDM system[1]
- An aerial BS equipped with UPA adopts K subcarriers to serve U single-antenna UEs
- $N_{\mathrm{BS}} = N_{\mathrm{BS}}^{\mathrm{h}} N_{\mathrm{BS}}^{\mathrm{v}}$ antennas, N_{RF} RF chains, N_{s} data streams ($U = N_{\mathrm{s}} \le N_{\mathrm{RF}} \ll N_{\mathrm{BS}}$)
- Uplink received signal $\boldsymbol{y}_k$ at k-th subcarrier:

$$\boldsymbol{y}_k = \boldsymbol{P}_k^H \sum_{u=1}^{U} \boldsymbol{h}_{k,u} s_{k,u} + \boldsymbol{P}_k^H \boldsymbol{n}_k = \boldsymbol{P}_{\mathrm{BB},k}^H \boldsymbol{P}_{\mathrm{RF}}^H \boldsymbol{H}_k \boldsymbol{s}_k + \boldsymbol{P}_{\mathrm{BB},k}^H \boldsymbol{P}_{\mathrm{RF}}^H \boldsymbol{n}_k \quad \boxed{(1)}$$

$$\begin{cases} \boldsymbol{P}_k = \boldsymbol{P}_{\mathrm{RF}} \boldsymbol{P}_{\mathrm{BB},k} \\ \boldsymbol{H}_k = [\boldsymbol{h}_{k,1}, \cdots, \boldsymbol{h}_{k,U}] \\ \boldsymbol{s}_k = [s_{k,1}, \cdots, s_{k,U}]^T \\ \boldsymbol{n}_k \sim \mathcal{CN}(\boldsymbol{0}, \sigma_n^2 \boldsymbol{I}) \end{cases}$$

- Each entry in $\boldsymbol{P}_{\mathrm{RF}}$ satisfies the constant modulus constraint
- Quantized phase set: $\mathcal{A} = \left\{-\pi, -\pi + \frac{2\pi}{2^Q}, \cdots, \pi - \frac{2\pi}{2^Q}\right\}$

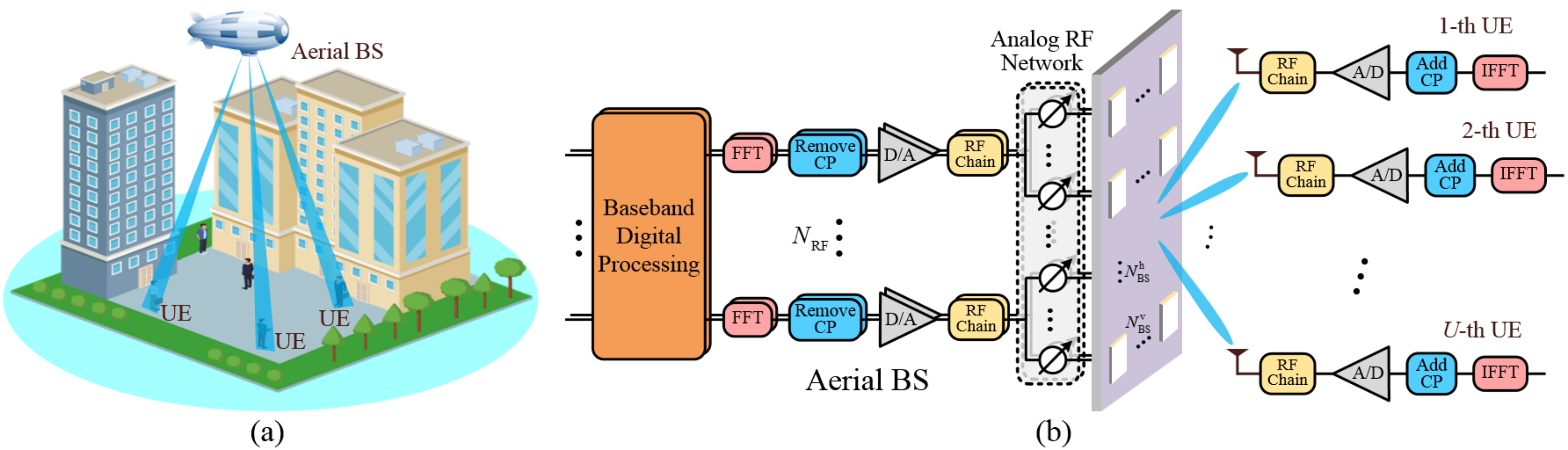

Fig. 1. (a) The air-ground mmWave channels between the aerial BS and multiple UEs; and (b) transceiver diagram of a typical uplink hybrid FD-MIMO-OFDM system.

Channel model

- The air-ground mmWave channels generated by the LoS paths exhibit inherent sparsity[1,2]
- Uplink delay-domain channel $\boldsymbol{h}_u(\tau)$ between BS and u-th UE can be modeled as

$$\boldsymbol{h}_u(\tau)=\sqrt{\frac{N_{\mathrm{BS}}}{U}}\alpha_u \boldsymbol{a}_{\mathrm{BS}}(\mu_u,\nu_u)p(\tau-\tau_u) \quad \boxed{(2)}$$

$$\begin{cases} \alpha_u \sim \mathcal{CN}(0,1) \text{ — path gain} \\ \boldsymbol{a}_{\mathrm{BS}}(\mu_u,\nu_u)=\boldsymbol{a}_\nu(\nu_u)\otimes \boldsymbol{a}_\mu(\mu_u) \text{ — array response vector} \\ \left.\begin{aligned} \mu_u &= \pi\sin(\theta_u)\cos(\varphi_u) \\ \nu_u &= \pi\sin(\varphi_u) \end{aligned}\right\} \text{ — spatial frequencies} \\ \theta_u / \varphi_u \text{ — horizontal/vertical AoA} \end{cases}$$

- Frequency-domain channel $\boldsymbol{h}_{k,u}$ at the k-th subcarrier[3]

$$\boldsymbol{h}_{k,u}=\sqrt{\frac{N_{\mathrm{BS}}}{U}}\alpha_u \boldsymbol{a}_{\mathrm{BS}}(\mu_u,\nu_u)e^{-j2\pi\frac{kf_s}{K}\tau_u} \quad \boxed{(4)}$$

$$\boldsymbol{H}_k=[\boldsymbol{h}_{k,1},\cdots,\boldsymbol{h}_{k,U}]=\boldsymbol{A}_{\mathrm{BS}}\boldsymbol{D}_k \quad \boxed{(5)}$$

$$\begin{cases} \boldsymbol{A}_{\mathrm{BS}}=[\boldsymbol{a}_{\mathrm{BS}}(\mu_1,\nu_1),\cdots,\boldsymbol{a}_{\mathrm{BS}}(\mu_U,\nu_U)]=\boldsymbol{A}_{\mathrm{BS}}^{\nu}\odot \boldsymbol{A}_{\mathrm{BS}}^{\mu} \\ \boldsymbol{D}_k=\mathrm{diag}(\boldsymbol{d}_k),\ \boldsymbol{d}_k=\mathrm{diag}(\boldsymbol{\alpha})\boldsymbol{\tau}_k \end{cases}$$

- $\{\alpha_u,\ \theta_u,\ \varphi_u,\ \tau_u\}_{u=1}^{U}$ — channel parameters

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Multi-user Wideband Sparse Channel Estimation

A. Problem Formulation

- Digital UPA ($M_{\mathrm{BS}}^{\mathrm{h}} \times M_{\mathrm{BS}}^{\mathrm{v}}$) is visualized from hybrid UPA ($N_{\mathrm{BS}}^{\mathrm{h}} \times N_{\mathrm{BS}}^{\mathrm{v}}$)
- $\boldsymbol{s}_k = \boldsymbol{s},\ \boldsymbol{P}_{\mathrm{BB},k} = \boldsymbol{P}_{\mathrm{BB}} \Rightarrow \boldsymbol{P}_k = \boldsymbol{P},\ 0 \le k \le K-1$
- $N_t = \left\lceil M_{\mathrm{BS}}^{\mathrm{h}} M_{\mathrm{BS}}^{\mathrm{v}} / N_{\mathrm{s}} \right\rceil$ time-blocks, N_{o} OFDM symbols → $T_{\mathrm{CE}} = N_t N_{\mathrm{o}}$
- $\boldsymbol{y}_{k,n_t}^{(n_{\mathrm{o}})} = \boldsymbol{P}_{n_t}^H \boldsymbol{H}_k \boldsymbol{s}_{n_{\mathrm{o}}} + \boldsymbol{P}_{n_t}^H \boldsymbol{n}_{n_{\mathrm{o}}}$ $\boxed{(1)}$

↓ N_{o} OFDM

- $\boldsymbol{Y}_{k,n_t} = [\boldsymbol{y}_{k,n_t}^{(1)}, \cdots, \boldsymbol{y}_{k,n_t}^{(N_{\mathrm{o}})}] = \boldsymbol{P}_{n_t}^H \boldsymbol{H}_k \boldsymbol{S} + \boldsymbol{N}_{k,n_t}$ $\boxed{(6)}$ $\boldsymbol{P}_{n_t}$ — n_t-th hybrid combiner

↓ N_t time-blocks

- $\tilde{\boldsymbol{Y}}_k = [\boldsymbol{Y}_{k,1}^T, \cdots, \boldsymbol{Y}_{k,N_t}^T]^T = \tilde{\boldsymbol{P}}^H \boldsymbol{H}_k \boldsymbol{S} + \mathrm{Blkdiag}(\tilde{\boldsymbol{P}}^H) \tilde{\boldsymbol{N}}_k$ $\boxed{(7)}$ $\tilde{\boldsymbol{P}} = [\boldsymbol{P}_1, \cdots, \boldsymbol{P}_{N_t}]$ — aggregated hybrid combiner

↓ $\boldsymbol{J}_s = \left[\boldsymbol{I}_{N_{\mathrm{BS}}^{\mathrm{sub}}}, \cdots, \boldsymbol{O}_{N_{\mathrm{BS}}^{\mathrm{sub}} \times (N_t N_{\mathrm{s}} - N_{\mathrm{BS}}^{\mathrm{sub}})} \right]$

- $\tilde{\boldsymbol{y}}_k = \mathrm{vec}\left((\boldsymbol{J}_s \tilde{\boldsymbol{Y}}_k)^T \right) = \left((\boldsymbol{J}_s \tilde{\boldsymbol{P}}^H \boldsymbol{A}_{\mathrm{BS}}) \odot \boldsymbol{S}^T \right) \mathrm{diag}(\boldsymbol{\alpha}) \boldsymbol{\tau}_k + \tilde{\boldsymbol{n}}_k$ $\boxed{(8)}$

↓ $\{\tilde{\boldsymbol{y}}_k\}_{k=0}^{K-1}$

A. Problem Formulation

- $\tilde{\boldsymbol{Y}} = [\tilde{\boldsymbol{y}}_0, \tilde{\boldsymbol{y}}_1, \cdots, \tilde{\boldsymbol{y}}_{K-1}] = (\bar{\boldsymbol{A}}_{\text{BS}} \odot \boldsymbol{S}^T)\text{diag}(\boldsymbol{\alpha})\boldsymbol{A}_\tau^T + \tilde{\boldsymbol{N}}$ (9)

$$\begin{cases} \bar{\boldsymbol{A}}_{\text{BS}} = \boldsymbol{J}_s \tilde{\boldsymbol{P}}^H \boldsymbol{A}_{\text{BS}} \\ \boldsymbol{A}_\tau = [\boldsymbol{a}_\gamma(\gamma_1), \cdots, \boldsymbol{a}_\gamma(\gamma_U)] \\ \gamma_u = -2\pi f_s \tau_u / K \end{cases}$$

vec

- $\tilde{\boldsymbol{y}} = \text{vec}(\tilde{\boldsymbol{Y}}) = (\boldsymbol{A}_\tau \odot \bar{\boldsymbol{A}}_{\text{BS}} \odot \boldsymbol{S}^T)\boldsymbol{\alpha} + \tilde{\boldsymbol{n}}$ (10)

mat

- $\bar{\boldsymbol{Y}} = \text{mat}(\tilde{\boldsymbol{y}})^T = (\boldsymbol{A}_\tau \odot \bar{\boldsymbol{A}}_{\text{BS}})\text{diag}(\boldsymbol{\alpha})\boldsymbol{S} + \bar{\boldsymbol{N}}^T$ (11)

- Our objective is to estimate the $\{\theta_u, \varphi_u, \tau_u\}_{u=1}^U$ from $\bar{\boldsymbol{Y}}$
- However, $\bar{\boldsymbol{A}}_{\text{BS}} = \boldsymbol{J}_s \tilde{\boldsymbol{P}}^H \boldsymbol{A}_{\text{BS}} \rightarrow \tilde{\boldsymbol{P}}$ destroys the shift-invariance structure of $\boldsymbol{A}_{\text{BS}}$
- Design appropriate hybrid combiners $\{\boldsymbol{P}_{n_t}\}_{n_t=1}^{N_t}$

B. Design Hybrid Combiner at BS

- Based on Algorithm 1 → $\{\boldsymbol{P}_{\mathrm{RF},n_t}\}_{n_t=1}^{N_t}$ → $\tilde{\boldsymbol{P}}$ → (11) to yield

$$\bar{\boldsymbol{Y}} = \boldsymbol{A}_{\tau\mathrm{BS}}\bar{\boldsymbol{S}} + \bar{\boldsymbol{N}}^T \qquad \boxed{(13)}$$

- $\boldsymbol{A}_{\tau\mathrm{BS}}$ can be further written as

$$\begin{aligned}\boldsymbol{A}_{\tau\mathrm{BS}} &= \boldsymbol{A}_{\tau} \odot \left(\boldsymbol{J}_s\tilde{\boldsymbol{P}}^H(\boldsymbol{A}_{\mathrm{BS}}^{\nu} \odot \boldsymbol{A}_{\mathrm{BS}}^{\mu})\right) \\ &= \boldsymbol{A}_{\tau} \odot \bar{\boldsymbol{A}}_{\mathrm{BS}}^{\nu} \odot \bar{\boldsymbol{A}}_{\mathrm{BS}}^{\mu}\end{aligned} \qquad \boxed{(14)}$$

- $\bar{\boldsymbol{A}}_{\mathrm{BS}}^{\mu}$ takes from first $M_{\mathrm{BS}}^{\mathrm{h}}$ rows of $\boldsymbol{A}_{\mathrm{BS}}^{\mu}$
- $\bar{\boldsymbol{A}}_{\mathrm{BS}}^{\nu}$ takes from first $M_{\mathrm{BS}}^{\mathrm{v}}$ rows of $\boldsymbol{A}_{\mathrm{BS}}^{\nu}$
- $\boldsymbol{A}_{\tau\mathrm{BS}}$ holds triple invariance structure
- Using 3-D unitary ESPRIT algorithm

$$\Downarrow$$

$$\{\theta_u,\ \varphi_u,\ \tau_u\}_{u=1}^{U}$$

Algorithm 1 Hybrid Combiner Design

Input: N_t, N_{s}, N_{RF}, $N_{\mathrm{BS}}^{\mathrm{h}}$, $N_{\mathrm{BS}}^{\mathrm{v}}$, $M_{\mathrm{BS}}^{\mathrm{h}}$, and $M_{\mathrm{BS}}^{\mathrm{v}}$
Output: $\widetilde{\boldsymbol{P}}$

Generate unitary matrix $\boldsymbol{U}_{N_{\mathrm{RF}}} = [\boldsymbol{u}_1, \cdots, \boldsymbol{u}_{N_{\mathrm{RF}}}]$
Construct index matrix $\boldsymbol{\Xi}$ based on (12)
for $n_t = 1, 2, \cdots, N_t$ **do**
  $\boldsymbol{P}_{\mathrm{BB},n_t} = \boldsymbol{U}_{N_{\mathrm{RF}}\{:,\,1:N_{\mathrm{s}}\}}$
  Initialize $\boldsymbol{P}_{\mathrm{RF},n_t} = \boldsymbol{1}_{N_{\mathrm{BS}}}^T \otimes \boldsymbol{u}_{N_{\mathrm{RF}}}^H$
  Extract $\boldsymbol{\Xi}_{n_t}^{\mathrm{sub}} = \boldsymbol{\Xi}_{\{:,(n_t-1)N_{\mathrm{s}}+1:n_t N_{\mathrm{s}}\}}$ and $\boldsymbol{p} = \mathrm{vec}(\boldsymbol{\Xi}_{n_t}^{\mathrm{sub}})$
  Get index set $\mathcal{I}_{n_t} = \mathrm{mod}\left(\mathrm{find}\left(\boldsymbol{p} \neq 0\right), N_{\mathrm{BS}}\right)$
  Replace $\boldsymbol{P}_{\mathrm{RF},n_t\{\mathcal{I}_{n_t},:\}} \leftarrow \boldsymbol{P}_{\mathrm{BB},n_t}^H$
  Quantize phase values of $\boldsymbol{P}_{\mathrm{RF},n_t}$
  $\boldsymbol{P}_{n_t} = \boldsymbol{P}_{\mathrm{RF},n_t}\boldsymbol{P}_{\mathrm{BB},n_t}$
end for
return $\widetilde{\boldsymbol{P}} = [\boldsymbol{P}_1, \cdots, \boldsymbol{P}_{N_t}]$

C. 3-D Unitary ESPRIT Algorithm[4,5,6]

- Step 1. 3-D spatial smoothing preprocessing

$$\Downarrow \bar{\boldsymbol{Y}}_{\mathrm{s}}$$

- Step 2. Forward backward averaging

$$\Downarrow \bar{\boldsymbol{Y}}_{\mathrm{re}}$$

- Step 3. Signal subspace approximation

$$\Downarrow \boldsymbol{E}_{\mathrm{s}}$$

- Step 4. Solve shift-invariance equations

$$\Downarrow \hat{\boldsymbol{\Phi}}_{\mu},\ \hat{\boldsymbol{\Phi}}_{\nu},\ \hat{\boldsymbol{\Phi}}_{\gamma}$$

- Step 5. SSD algorithm pairing

$$\Downarrow \boldsymbol{\Gamma}_{\mu},\ \boldsymbol{\Gamma}_{\nu},\ \boldsymbol{\Gamma}_{\gamma}$$

$$\{\widehat{\mu}_u, \widehat{\nu}_u, \widehat{\gamma}_u\}_{u=1}^{U}$$

$$\Downarrow$$

$$\{\hat{\theta}_u,\ \hat{\varphi}_u,\ \hat{\tau}_u\}_{u=1}^{U}$$

Algorithm 2 3-D Unitary ESPRIT Algorithm

Input: $\bar{\boldsymbol{Y}}$, U, $M_{\mathrm{BS}}^{\mathrm{h}}$, $M_{\mathrm{BS}}^{\mathrm{v}}$, K, G_{μ}, G_{ν}, and G_{γ}.
Output: $\{\widehat{\mu}_u, \widehat{\nu}_u, \widehat{\gamma}_u\}_{u=1}^{U}$.

1: Obtain smoothed matrix $\bar{\boldsymbol{Y}}_{\mathrm{s}}$ in (16) using 3-D spatial smoothing preprocessing.
2: Obtain real-valued matrix $\bar{\boldsymbol{Y}}_{\mathrm{re}}$ in (17) using forward backward averaging.
3: Extract approximate signal subspace matrix $\boldsymbol{E}_{\mathrm{s}}$ through SVD.
4: Solve three shift-invariance equations in (18) to obtain $\widehat{\boldsymbol{\Phi}}_{\mu}$, $\widehat{\boldsymbol{\Phi}}_{\nu}$, and $\widehat{\boldsymbol{\Phi}}_{\gamma}$ using LS or total LS estimator.
5: Yield three approximate upper triangular matrices $\boldsymbol{\Gamma}_{\mu}$, $\boldsymbol{\Gamma}_{\nu}$, and $\boldsymbol{\Gamma}_{\gamma}$ using SSD algorithm.
6: Extract main diagonal elements of these matrices and calculate $\{\widehat{\mu}_u, \widehat{\nu}_u, \widehat{\gamma}_u\}_{u=1}^{U}$ based on (20).

- ***D. Reconstruct MIMO Channel***

- Based on $\{\hat{\theta}_u,\ \hat{\varphi}_u,\ \hat{\tau}_u\}_{u=1}^{U} \rightarrow \hat{\boldsymbol{A}}_{\mathrm{BS}},\ \hat{\boldsymbol{A}}_{\tau} \rightarrow \hat{\boldsymbol{A}} = \left(\hat{\boldsymbol{A}}_{\tau} \odot (\boldsymbol{J}_s \tilde{\boldsymbol{P}}^H \hat{\boldsymbol{A}}_{\mathrm{BS}})\right) \odot \boldsymbol{S}^T$

(10)

- $\hat{\boldsymbol{\alpha}} = \sqrt{N_{\mathrm{BS}}/U}\,[\hat{\alpha}_1,\cdots,\hat{\alpha}_U]^T = \arg\min_{\boldsymbol{\alpha}} \|\tilde{\boldsymbol{y}} - \hat{\boldsymbol{A}}\boldsymbol{\alpha}\|_2^2 = (\hat{\boldsymbol{A}}^H\hat{\boldsymbol{A}})^{-1}\hat{\boldsymbol{A}}^H\tilde{\boldsymbol{y}}$ $\boxed{(21)}$

$$\hat{\boldsymbol{H}}_k = [\hat{\boldsymbol{h}}_{k,1},\cdots,\hat{\boldsymbol{h}}_{k,U}] \qquad \boxed{(22)}$$

- where $\hat{\boldsymbol{h}}_{k,u} = \sqrt{\frac{N_{\mathrm{BS}}}{U}}\hat{\alpha}_u \boldsymbol{a}_{\mathrm{BS}}(\hat{\mu}_u,\hat{\nu}_u)e^{j\hat{\gamma}_u},\ u = 1,\cdots,U$

$$\begin{cases} \hat{\mu}_u = \pi\sin(\hat{\theta}_u)\cos(\hat{\varphi}_u) \\ \hat{\nu}_u = \pi\sin(\hat{\varphi}_u) \\ \hat{\gamma}_u = -2\pi k f_s \hat{\tau}_u / K \end{cases}$$

TABLE I. Computational Complexity

3-D Unitary ESPRIT Algorith

Operation	Complexity
Step 1	$\mathcal{O}(M_{\mathrm{sub}} N_{\mathrm{BS}}^{\mathrm{sub}} N_o G)$
Step 2	$\mathcal{O}(8 M_{\mathrm{sub}} N_o G)$
Step 3	$\mathcal{O}(\frac{1}{4} M_{\mathrm{sub}} U^2)$
Step 4	$\mathcal{O}(\frac{3}{4}(U^3 + 2U^2 M_{\mathrm{sub}}) + \frac{1}{2}(M_\mu + M_\nu + M_\tau) M_{\mathrm{sub}} U)$
Step 5	$\mathcal{O}(\frac{3}{4} U^4)$
(21)	$\mathcal{O}(U^3 + 2U^2 K N_{\mathrm{BS}}^{\mathrm{sub}} N_o)$
(22)	$\mathcal{O}(K U N_{\mathrm{BS}})$

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Simulation Results

- **Simulation Parameters**

- $f_c = 30$ GHz, $f_s = 200$ MHz, $N_{\rm BS} = N_{\rm BS}^{\rm h} \times N_{\rm BS}^{\rm v} = 10 \times 10 = 100$, $N_{\rm RF} = 4$, $Q = 1$ bit
- $K = 128$, θ_u, $\varphi_u \sim \mathcal{U}[-\pi/3, \pi/3]$, $\tau_u \sim \mathcal{U}[0, \tau_{\max}]$, $\tau_{\max} = 16/f_s$
- $M_{\rm BS}^{\rm h} = M_{\rm BS}^{\rm v} = 6$, $G_\mu = G_\nu = 2$, $G_\gamma = K/2$

- Normalized Mean Square Error (NMSE) of channel estimation
- Achievable sum-rate of downlink data transmission

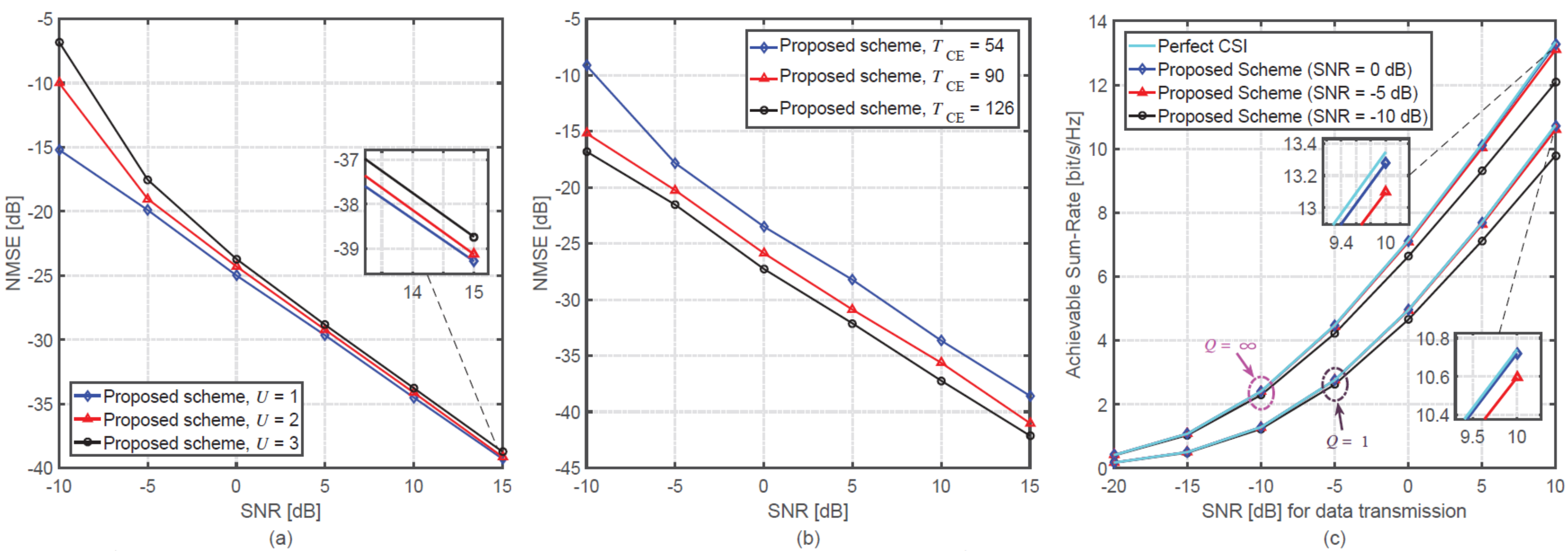

Fig. 2. NMSE and achievable sum-rate performance comparison of the proposed scheme versus SNRs: (a) $T_{\rm CE}$ =72; (b) U =2; and (c) $T_{\rm CE}$ =54 and U =2.

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Thanks for your listening!