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2023 IEEE Virtual Conference on Communications

Channel Estimation using In-Band Pilots for Cell-Free Massive MIMO

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Outline

- ☐ Part 1: Introduction and Major Contributions
- ☐ Part 2: System Model
- ☐ Part 3: Channel Estimation Using In-Band Pilots
- ☐ Part 4: Simulation Results
- ☐ Part 5: Conclusion and Future Works

Part 1: Introduction and Major Contributions

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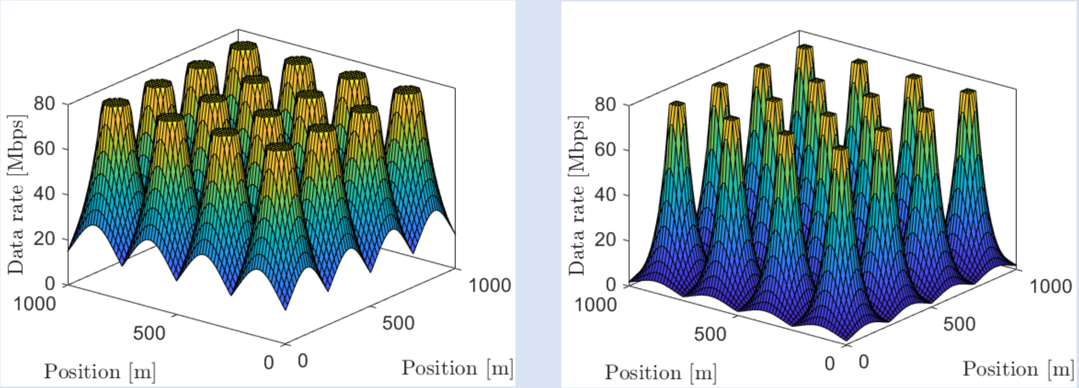
Cell-Free Massive MIMO: A Promising Technology in B5G/6G

- Cell-free (CF) massive multiple-input multiple-output (mMIMO) systems have been envisioned as a promising solution to enhance wireless transmission qualities and provide a larger coverage.

- The CF mMIMO system has a large number of individually controllable access points (APs) distributed over a wide area for simultaneously serving a small number of user equipment (UE).

- By using the CF system, it is possible to achieve a promising transmission rate for users since the inter-cell interference can be mitigated.



Özlem Tugfe Demir; Emil Björnson; Luca Sanguinetti, Foundations of User-Centric Cell-Free Massive MIMO, 2021.

Pilot Contamination in the CF mMIMO System

- Some early CF mMIMO studies assumed that all pilot signals are transmitted at full power during the training phase. This may, however, increase pilot contamination especially when a UE has poor channel quality.
- Thus, the most appropriate pilot power should be distributed to corresponding UEs. Besides, opportunistic AP selections can also bring a significant performance boost.
- Moreover, we can also superimpose pilot signals on data signals to enhance transmission performance, at the expense of data interference.

So what can we do to further reduce pilot contamination and increase performance of the CF mMIMO system?

Major Contributions in This Work

In this work, we bring a novel pilot design, named in-band pilots (IBPs). The IBP scheme aims to superimpose the pilot and the signal in frequency domain.

- ☐ **Firstly, we introduce a new system model of the CF mMIMO network, which includes the IBP design for releasing the capability of the CF system.**
- ☐ **Then, we derive analytical expressions for mean square error (MSE) and normalized mean square error (NMSE) of the channel estimation using the proposed IBP scheme in the CF network.**
- ☐ **Moreover, we obtain an analytical expression for the estimated data frequency for the UE, and we also numerically compare the NMSE performance of the regular, the conventional superimposed, and the in-band pilots.**

Part 2: System Model

- ☐ Part 1: Introduction and Major Contributions
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An uplink CF mMIMO System

- We consider an uplink CF mMIMO system with K single-antenna UEs and L APs, each equipped with N antennas. Both UEs and APs are arbitrarily distributed over the coverage area. Dynamic cooperation clustering technique is used, i.e. each UE is served by a subset of the APs, depending on the UE's needs.

- During the uplink data (or pilot) transmission, all APs will receive a superposition of the signals sent from all UEs. Similarly, all UEs will receive signals from all other UEs.

ρ is the scaling factor for the data

λ is the scaling factor for the pilot

$$\mathbf{Y}_l' = \sum_{k=0}^{K-1} \sqrt{\mu_k}\, \mathbf{h}_{l,k} \mathbf{s}_{l,k}^{\mathsf{T}} + \mathbf{W}_l$$

Using the SP

$$\mathbf{Y}_l = \sum_{k=0}^{K-1} \sqrt{\mu_k}\, \mathbf{h}_{l,k} \left(\rho_k \mathbf{x}_k + \lambda_k \mathbf{p}_k\right)^{\mathsf{T}} + \mathbf{W}_l$$

Insert In-Band Pilot to the System

- **For the k-th user, the pilots can be superimposed in the frequency domain onto its data frequencies as $\mathbb{S}_k = \mathbf{Q}_k \mathbb{X}_k + \lambda_k \mathbb{P}_k$.**

- **$\mathbf{Q}_k$ can be defined as a square diagonal matrix with the main diagonal element as $\mathbf{q}_k = [\gamma_k \quad \cdots \quad \gamma_k \quad \rho_k \quad \gamma_k \quad \cdots \quad \gamma_k]$.**

$$\boxed{\mathbf{Y}_l = \sum_{k=0}^{K-1} \sqrt{\mu_k}\, \mathbf{h}_{l,k} (\rho_k \mathbf{x}_k + \lambda_k \mathbf{p}_k)^{\mathsf{T}} + \mathbf{W}_l}$$

After FT

$$\boxed{\mathbb{Y}_l = \sum_{k=0}^{K-1} \sqrt{\mu_k}\, \mathbf{h}_{l,k} (\mathbf{Q}_k \mathbb{X}_k + \lambda_k \mathbb{P}_k)^{\mathsf{T}} + \mathbb{W}_l}$$

ρ is the scaling factor for the power of the data frequency where the pilot frequency is superimposed

$$\boxed{\frac{C_u - 1}{C_u}\gamma_k^2 + \frac{1}{C_u}\rho_k^2 + \lambda_k^2 = 1}$$

γ is the scaling factor for the remaining data frequencies.

Part 3: Channel Estimation Using In-Band Pilots

☐ Part 1: Introduction and Major Contributions

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☐ **Part 3: Channel Estimation Using In-Band Pilots**

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Least Square and Linear Minimum Mean Square Error Estimation

LS

$$\begin{aligned}\hat{\mathbf{h}}_{l,k} &\triangleq \frac{1}{C_u\sqrt{\mu_k}\,\lambda_k}\mathbb{Y}_l\mathbb{P}_k^* \\ &= \frac{1}{C_u\sqrt{\mu_k}\,\lambda_k}\Bigg(\sum_{m=0}^{K-1}\sqrt{\mu_m}\,\mathbf{h}_{l,m}\lambda_m\mathbb{P}_m^{\mathsf{T}}\mathbb{P}_k^* \\ &\quad + \sum_{m=0}^{K-1}\sqrt{\mu_m}\,\mathbf{h}_{l,m}(\mathbf{Q}_m\mathbb{X}_m)^{\mathsf{T}}\mathbb{P}_m^* + \mathbb{W}_l\mathbb{P}_m^*\Bigg) \\ &= \mathbf{h}_{l,k} + \frac{\rho_k}{C_u\lambda_k}\chi_k^{(k)}P_k^{(k)\,*}\mathbf{h}_{l,k} \\ &\quad + \frac{\gamma_k P_k^{(k)\,*}}{C_u\lambda_k\sqrt{\mu_k}}\sum_{\substack{m=0\\ m\neq k}}^{K-1}\sqrt{\mu_m}\,\chi_m^{(k)}\mathbf{h}_{l,m} + \frac{\mathbb{W}_l\mathbb{P}_k^*}{C_u\lambda_k\sqrt{\mu_k}}\end{aligned}$$

LMMSE

$$\begin{aligned}\tilde{\mathbf{h}}_{l,k} &\triangleq \mathbf{R}_{\mathbf{h}\hat{\mathbf{h}}}\boldsymbol{\Psi}_{\hat{\mathbf{h}}\hat{\mathbf{h}}}^{-1}\hat{\mathbf{h}}_{l,k} \\ &= A_{l,k}\Bigg(\mathbf{h}_{l,k} + \frac{\rho_k}{C_u\lambda_k}\chi_k^{(k)}P_k^{(k)\,*}\mathbf{h}_{l,k} + \\ &\quad \frac{\gamma_k P_k^{(k)\,*}}{C_u\lambda_k\sqrt{\mu_k}}\sum_{\substack{m=0\\ m\neq k}}^{K-1}\sqrt{\mu_m}\,\chi_m^{(k)}\mathbf{h}_{l,m} + \frac{\mathbb{W}_l\mathbb{P}_k^*}{C_u\lambda_k\sqrt{\mu_k}})\end{aligned}$$

$$\mathbf{R}_{\mathbf{h}\hat{\mathbf{h}}} = \mathbb{E}\{\hat{\mathbf{h}}_{l,k}\mathbf{h}_{l,k}^{\mathsf{H}}\} \qquad \boldsymbol{\Psi}_{\hat{\mathbf{h}}\hat{\mathbf{h}}} = \mathbb{E}\{\hat{\mathbf{h}}_{l,k}\hat{\mathbf{h}}_{l,k}^{\mathsf{H}}\}$$

$$\begin{aligned}A_{l,k} &\triangleq \mathbf{R}_{\mathbf{h}\hat{\mathbf{h}}}\boldsymbol{\Psi}_{\hat{\mathbf{h}}\hat{\mathbf{h}}}^{-1} \\ &= \frac{\beta_{l,k}}{\beta_{l,k} + \frac{\rho_k^2}{C_u\lambda_k^2}\beta_{l,k} + \frac{\gamma_k^2}{C_u\lambda_k^2}\sum_{\substack{m=0\\ m\neq k}}^{K-1}\mu_m\beta_{l,m} + \frac{\sigma^2}{C_u\lambda_k^2\mu_k}}\end{aligned}$$

MSE and NMSE

MSE

$$\begin{aligned}\mathrm{MSE}_{l,k} &\triangleq \frac{1}{N}\mathbb{E}\{\|\Delta\mathbf{h}_{l,k}\|^2\}\\ &= \frac{1}{N}\mathbb{E}\left\{(\tilde{\mathbf{h}}_{l,k}-\mathbf{h}_{l,k})^{\mathsf{H}}(\tilde{\mathbf{h}}_{l,k}-\mathbf{h}_{l,k})\right\}\\ &= \frac{1}{N}\mathbb{E}\left\{\tilde{\mathbf{h}}_{l,k}^{\mathsf{H}}\tilde{\mathbf{h}}_{l,k}-\tilde{\mathbf{h}}_{l,k}^{\mathsf{H}}\mathbf{h}_{l,k}-\mathbf{h}_{l,k}^{\mathsf{H}}\tilde{\mathbf{h}}_{l,k}+\mathbf{h}_{l,k}^{\mathsf{H}}\mathbf{h}_{l,k}\right\}\\ &= A_{l,k}^2\left(\beta_{l,k}+\frac{\rho_k^2}{C_u\lambda_k^2}\beta_{l,k}+\frac{\gamma_k^2}{C_u\lambda_k^2}\sum_{\substack{m=0\\ m\neq k}}^{K-1}\mu_m\beta_{l,m}+\frac{\sigma^2}{\lambda_{j,m}^2C_u}\right)\\ &\quad -2A_{l,k}\left(\beta_{l,k}+\frac{\rho_k}{\sqrt{C_u}\,\lambda_k}\beta_{l,k}\right)+\beta_{l,k}\\ &= A_{l,k}\beta_{l,k}-2A_{l,k}\beta_{l,k}-2A_{l,k}\frac{\rho_k}{\sqrt{C_u}\,\lambda_k}\beta_{l,k}+\beta_{l,k}\\ &= \left(1-A_{l,k}-2A_{l,k}\frac{\rho_k}{\sqrt{C_u}\,\lambda_k}\right)\beta_{l,k}\\ &= \beta_{l,k}-A_{l,k}\left(1+\frac{2\rho_k}{\sqrt{C_u}\,\lambda_k}\right)\beta_{l,k}\end{aligned}$$

$$\Delta\mathbf{h}_{l,k}\triangleq\tilde{\mathbf{h}}_{l,k}-\mathbf{h}_{l,k}$$

NMSE

$$\begin{aligned}\mathrm{NMSE} &= \frac{\sum_{l,k}\mathbb{E}\{\|\Delta\mathbf{h}_{l,k}\|^2\}}{\sum_{l,k}\mathbb{E}\{\|\mathbf{h}_{l,k}\|^2\}}\\ &= \frac{\sum_{l,k}\beta_{l,k}-A_{l,k}\left(1+\frac{2\rho_k}{\sqrt{C_u}\lambda_k}\right)\beta_{l,k}}{\sum_{l,k}\beta_{l,k}}\end{aligned}$$

$$\begin{aligned}A_{l,k} &\triangleq \mathbf{R}_{\mathbf{h}\hat{\mathbf{h}}}\boldsymbol{\Psi}_{\hat{\mathbf{h}}\hat{\mathbf{h}}}^{-1}\\ &= \frac{\beta_{l,k}}{\beta_{l,k}+\frac{\rho_k^2}{C_u\lambda_k^2}\beta_{l,k}+\frac{\gamma_k^2}{C_u\lambda_k^2}\sum_{\substack{m=0\\ m\neq k}}^{K-1}\mu_m\beta_{l,m}+\frac{\sigma^2}{C_u\lambda_k^2\mu_k}}\end{aligned}$$

Simulation Results

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Parameters Setting

- **A square area of $D \times D$ is considered as the main cell and the wrap-around technique is applied to mimic a large network deployment without edges. Unless otherwise stated, we assume that all APs are deployed uniformly at random in the coverage area. The large-scale fading coefficient can be expressed as**

$$\beta_{l,k} \triangleq \begin{cases} -L - 35\log_{10}(d_{l,k}) + \sigma_1, & \text{if } d_{l,k} > d_1 \\ -L - 15\log_{10}(d_1) - 20\log_{10}(d_{l,k}) + \sigma_2, & \\ \qquad \text{if } d_0 < d_{l,k} \le d_1 & \\ -L - 15\log_{10}(d_1) - 20\log_{10}(d_0), & \text{if } d_{l,k} \le d_0, \end{cases}$$

$$\begin{aligned} L \triangleq\ & 46.3 + 33.9\log_{10}(f) - 13.82\log_{10}(h_{\mathrm{AP}}) \\ & - (1.1\log_{10}(f) - 0.7)h_{\mathrm{UE}} + (1.56\log_{10}(f) - 0.8) \end{aligned}$$

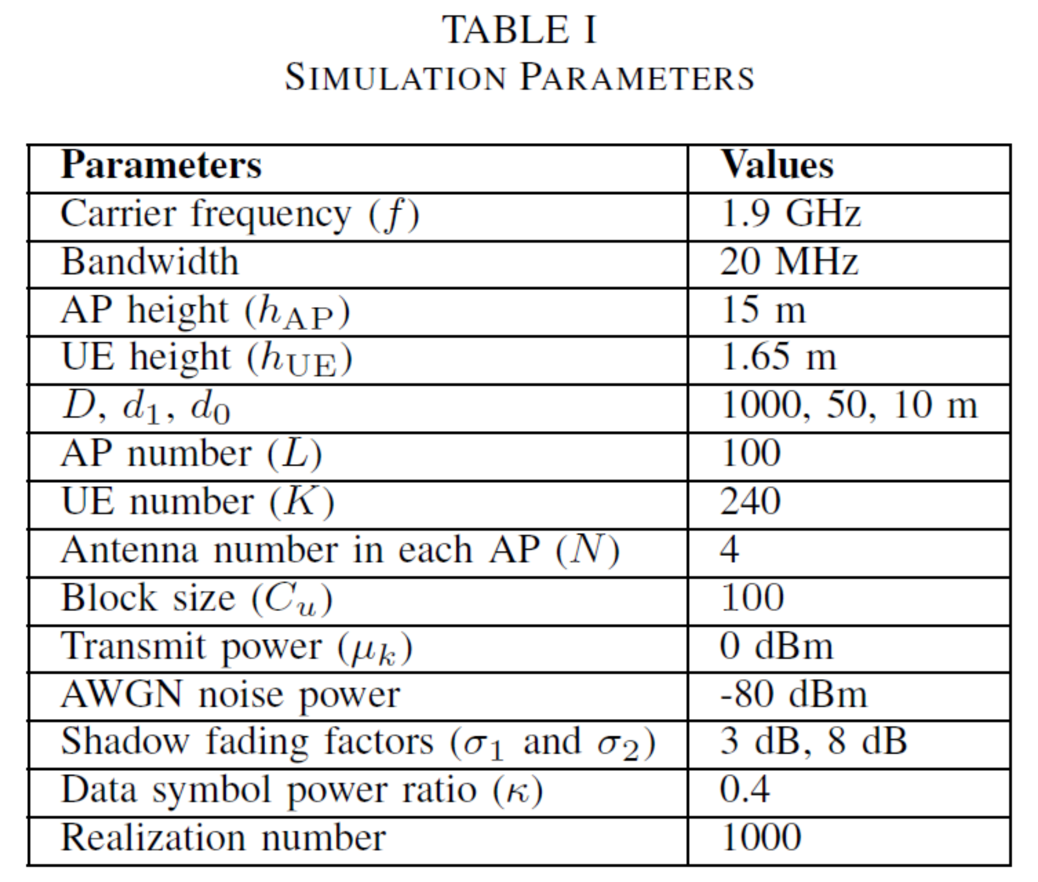

TABLE I
SIMULATION PARAMETERS

Parameters	**Values**
Carrier frequency (f)	1.9 GHz
Bandwidth	20 MHz
AP height (h_{AP})	15 m
UE height (h_{UE})	1.65 m
D, d_1, d_0	1000, 50, 10 m
AP number (L)	100
UE number (K)	240
Antenna number in each AP (N)	4
Block size (C_u)	100
Transmit power (μ_k)	0 dBm
AWGN noise power	-80 dBm
Shadow fading factors (σ_1 and σ_2)	3 dB, 8 dB
Data symbol power ratio (κ)	0.4
Realization number	1000

Simulation Results

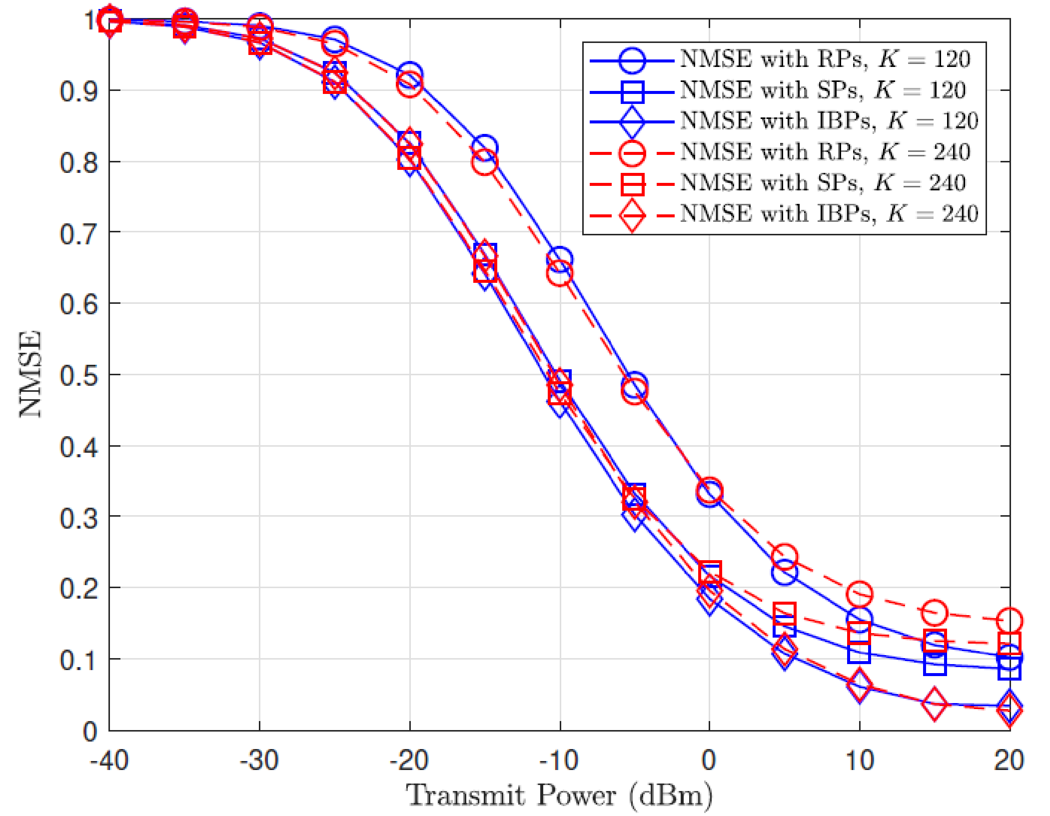

Fig. 1. NMSE vs. transmit power against different numbers of UEs K.

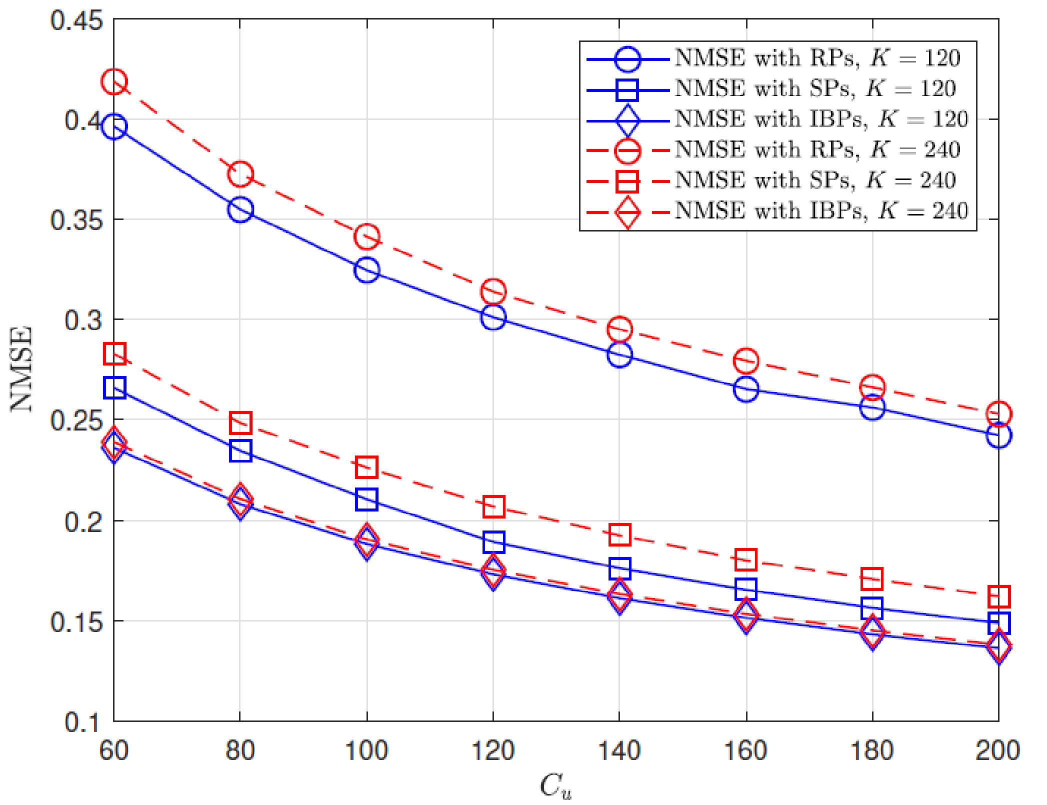

Fig. 2. NMSE vs. block sizes C_u against different numbers of UEs K.

Conclusion and Future Works

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Conclusion and Future Works

- ☐ A channel estimation approach using the IBP scheme has been proposed in this paper. The proposed strategy works in the frequency domain, as opposed to other conventional approaches that function in the time domain.
- ☐ Analytical and simulated results have confirmed that the IBP scheme is more effective and robust in enhancing performance and reducing pilot contamination.
- ☐ Future research directions: 1) achievable spectral efficiency analysis and power control designs for the IBP; 2) reconfigurable intelligent surfaces – aided CF system with the IBP; and 3) channel codes, such as low density parity check codes, can be incorporated into the proposed scheme.

Thank You

Q&A?