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Performance Analysis of RIS-Assisted Cell-Free Massive MIMO Systems

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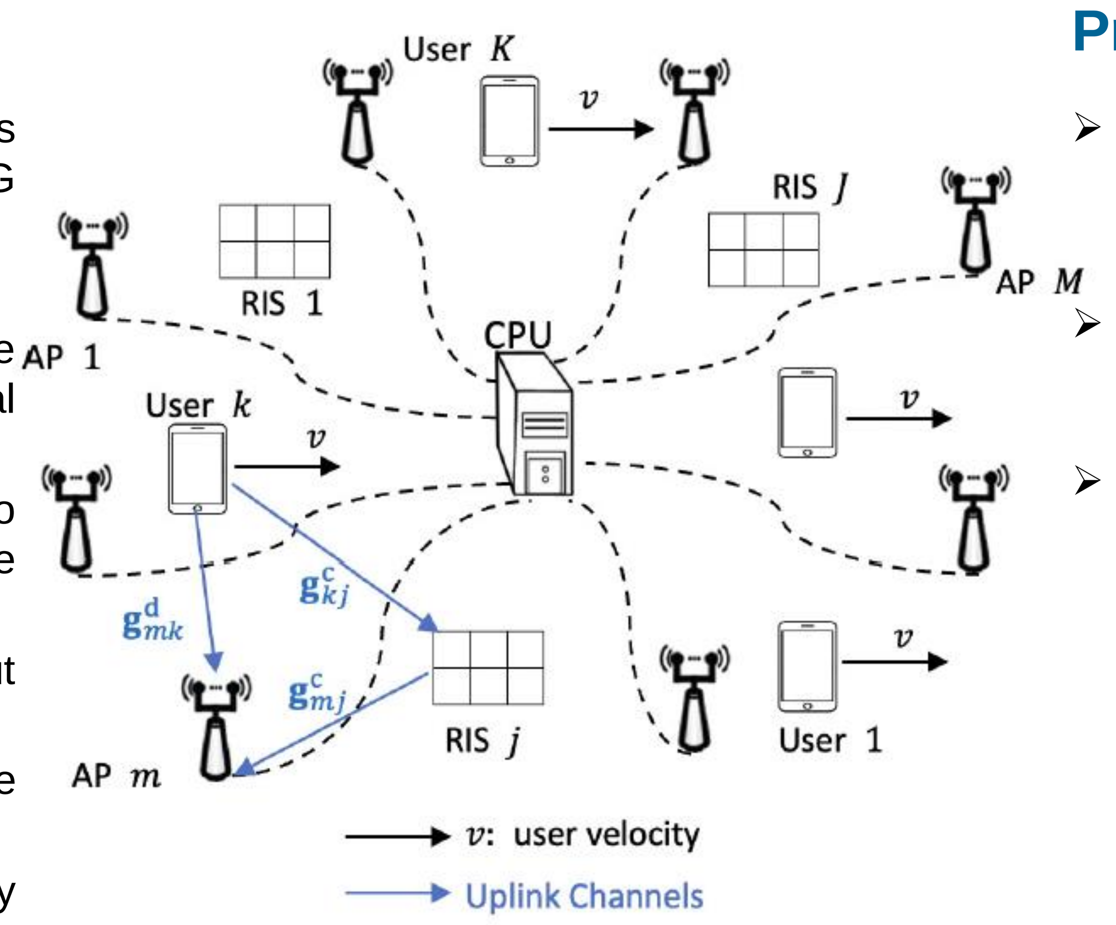
Abstract and Background

- Cell-free massive multiple-input multiple-out (MIMO) systems have been proposed as one of the key technologies of 6G wireless communication. Main advantages include:
  - Distributed networks and massive MIMO benefit integration
  - Achieve inter-cell interference mitigation, provide extensive transmission coverage and meet exponential communication requirement
- Reconfigurable intelligent surfaces (RISs) are proposed to assist conventional wireless networks for performance improvement with advantages:
  - Shape the electromagnetic-level radio waves without active power amplifiers or digital signal processing
  - Introduce additional controllable and reconfigurable cascaded links with low cost and power consumption
- Hence, cell-free massive MIMO and RISs are complementary and integrated to improve the wireless communication performance by exploiting the joint advantages. However, some challenging issues include:
  - External sources generate the electromagnetic interference (EMI) on RIS to cause performance loss
  - Mobile communication suffers from the channel aging which challenges the performance since each user is served by multiple APs, resulting in diverse angles of arrival



- Multi-RIS-Assisted Cell-Free Massive MIMO systems with user mobility
- EMI and channel aging can be non-negligible in RIS-aided cell-free massive MIMO systems with movable user
- The corresponding performance limits should be investigated.

Proposed System Model

- **The aggregate uplink channel matrix from the k-th user to the m-th AP:**

$$\mathbf{g}_{mk}[n] = \mathbf{g}^{d}_{mk}[n] + \sum_{j=1}^{J} \mathbf{g}^{c}_{mkj}[n]$$

- **Electromagnetic Interference Model:**

$$\mathbf{n}_j \sim \mathcal{CN}(0, A_j \sigma_j^2 \mathbf{R}_j)$$

- **Two-Phase Channel Estimation Scheme:**
  - **First sub-phase:** All RIS elements are OFF to estimate direct channels following the MMSE estimate
  - **Second sub-phase:** All RIS elements are ON to estimate RIS-aided cascaded channels following the MMSE estimate
  - **Fractional Power Control:** The pilot power of the k-th user is allocated as

$$p_k^{x} = \frac{\sum_{m=1}^{M} \mathrm{tr}(\boldsymbol{\Delta}^{x}_{mk})}{\sum_{k'=1}^{K}\sum_{m=1}^{M} \mathrm{tr}(\boldsymbol{\Delta}^{x}_{mk'})} P_{\mathrm{sum}}$$

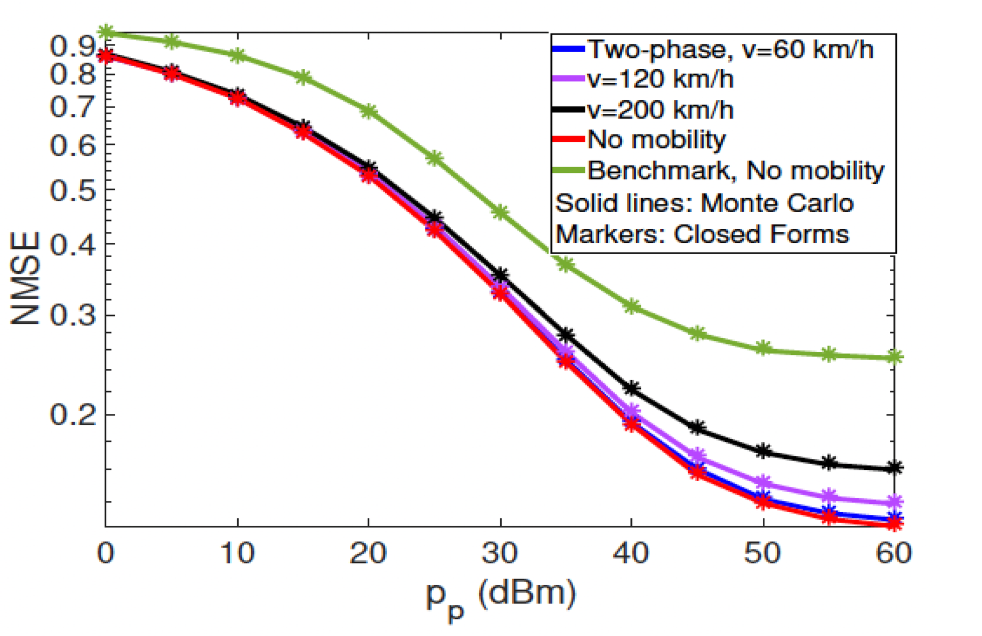
  - **Pilot Assignment:** The k-th user selects $m_k^{\max,x}$-th AP with the largest δ^{x}_{mk} as its prime AP and the pilot assignment for the k-th user follows

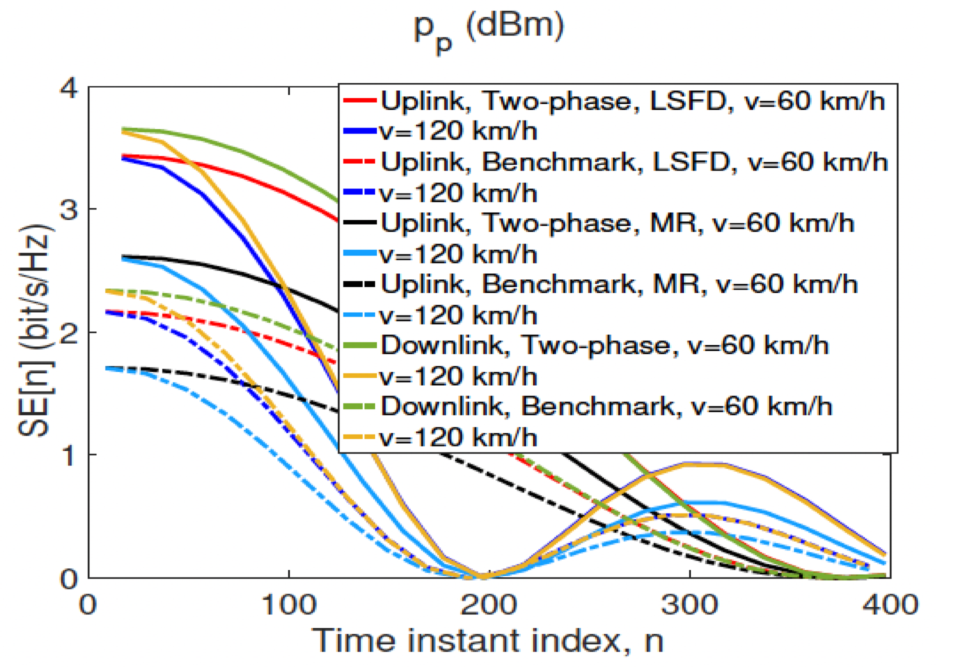
$$t_k = \arg\min_{t\in\{1,2,\ldots,\tau_p\}} \sum_{i\in S_t} p_i^{x}\,\mathrm{tr}(\boldsymbol{\Delta}^{x}_{m_k^{\max,x} i})$$

Performance Analysis and Simulation Results

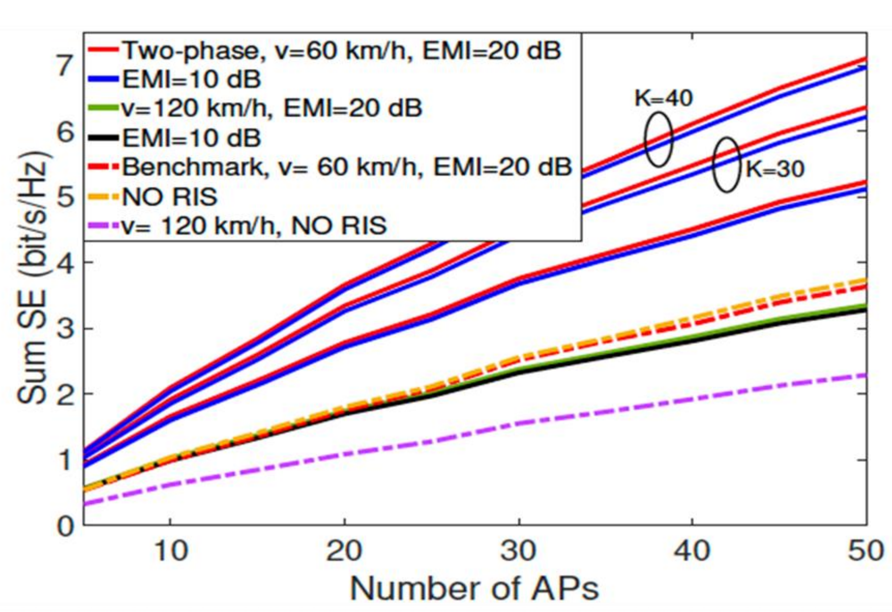
- **Channel estimation accuracy**: the normalised mean square error (NMSE) of the channel estimation is proposed as

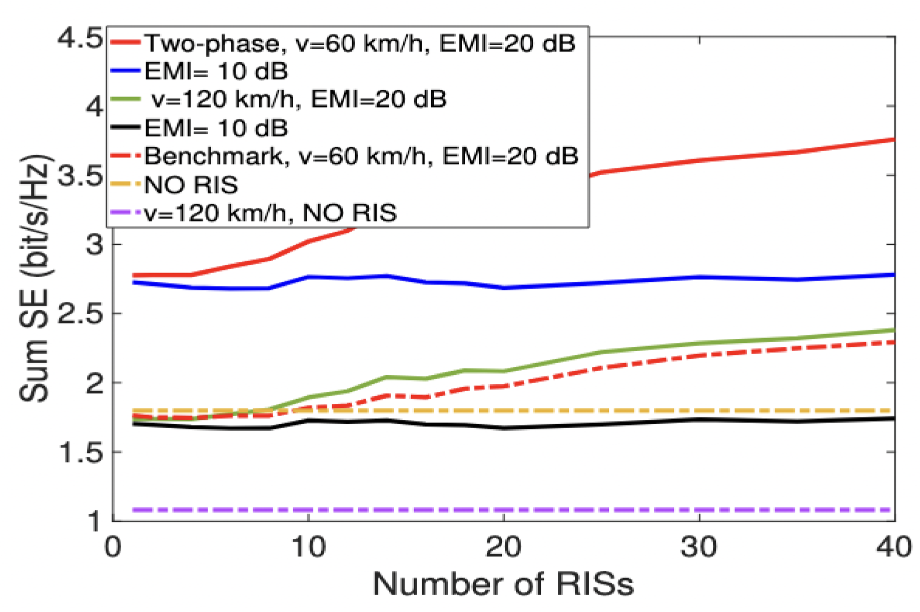
$$\mathrm{NMSE} = \frac{\sum_{m,k}\mathbb{E}\{\|\tilde{\mathbf{g}}_{mk}[\lambda]\|^2\}}{\sum_{m,k}\mathbb{E}\{\|\mathbf{g}_{mk}[\lambda]\|^2\}} = \frac{\sum_{m,k}\mathrm{tr}(\boldsymbol{\Delta}_{mk} - \mathbf{Q}^{d}_{mk} - \mathbf{Q}^{c}_{mk})}{\sum_{m,k}\mathrm{tr}(\boldsymbol{\Delta}_{mk})}$$

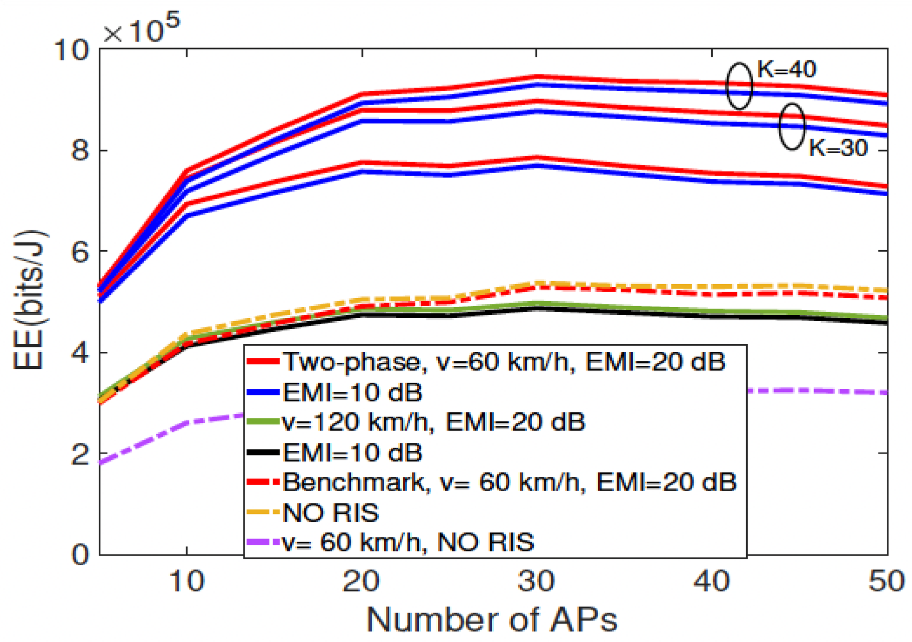


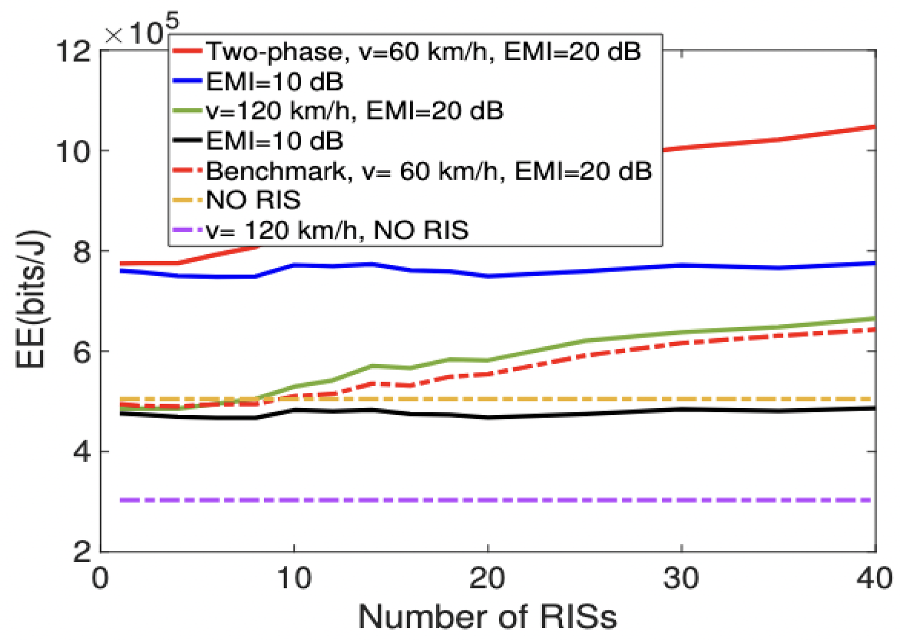


- **Sum SE**: the uplink SE and downlink SE based on the use-and-then-forget (UatF) bound are respectively lower-bounded by $\mathrm{SE}_k^{x} = \frac{1}{\tau_c}\sum_{n=\lambda}^{\tau_c}\log_2\left(1+\mathrm{SINR}_k^{x}[n]\right)$ with x=u, d and the sum rate follows $\mathrm{SE}_{\mathrm{sum}} = \frac{1}{2}\sum_{k=1}^{K}\left(\mathrm{SE}_k^{u}+\mathrm{SE}_k^{d}\right)$.
- **Total EE**: the total EE (bit/Joule) equals the sum throughput divided by the total power consumption (Watts) of the proposed system with $\epsilon = \frac{B\cdot\mathrm{SE}_{\mathrm{sum}}}{P_{\mathrm{total}}}$ and the the total power consumption is $P_{\mathrm{total}} = \frac{4\tau_p}{2\tau_c}P_{\mathrm{p}}^{\mathrm{ul}} + \frac{\tau_c-2\tau_p}{2\tau_c}P_{\mathrm{u}}^{\mathrm{ul}} + \frac{\tau_c-2\tau_p}{2\tau_c}P^{\mathrm{dl}} + P_{\mathrm{CP}}$









- NMSE as a function of p_p shows that the proposed two-phase channel estimation scheme can introduce additional estimation accuracy gain to lower the NMSE.
- The first zero position is shifted to the left side with higher user velocity and introduces an optimal resource block length to mitigate the channel aging effect.
- Increasing APs can introduce increasing spatial degrees of freedom to facilitate more efficient beamforming and compensate for the performance degradation caused by channel aging and EMI.
- Increasing APs can increase the total EE and then slowly decrease it because the sum SE and power consumption increase as a logarithmic function and a nearly linear function of APs, respectively.
- Increasing RISs is beneficial to improve the proposed system performance since passive beamforming can improve interference management and release the necessity of introducing RISs.
- Since RISs are passive without power consumption, the total EE experiences almost the same trend as the sum SE with increasing RISs.

Related Works

[1] J. Qian, C. Zhang, K. B. Letaief and R. Murch, "Two-Phase Channel Estimation for RIS-Aided Cell-Free Massive MIMO with Electromagnetic Interference," Proc. 2024 IEEE MeditCom, pp. 471-476, doi: 10.1109/MeditCom61057.2024.10621117.

[2] J. Qian, C. Zhang, R. Murch, & K. B. Letaief, (2024). Impact of Channel Aging and Electromagnetic Interference on RIS-Assisted Cell-Free Massive MIMO Systems. *ArXiv*. /abs/2407.03785

Acknowledgment

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