Design and Optimization of Cell-Free Systems: Channel Estimation, Duplexing Scheme, and Synchronization

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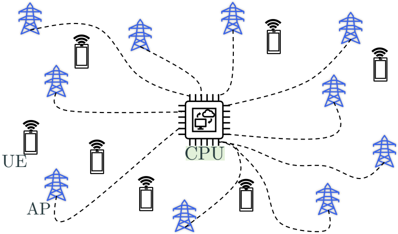
Introduction to Cell-Free

Cellular to Cell-Free: A Paradigm Shift

- Mitigates effects of path loss
- Improved **macro-diversity**
- Improved **link reliability**
- Uniform **QoS**
- 10× **SE** compared to cellular†



A typical CF-mMIMO setup

† G. Interdonato et al., "Ubiquitous cell-free massive MIMO communications," EURASIP J. Wireless Commun. Netw., vol. 2019, no. 1, p. 197, Dec. 2019

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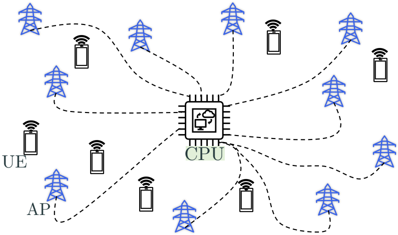

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Key Idea

Multi-cell/multi-user interference of cellular mMIMO is treated as useful information-bearing signals

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Signal Processing Challenges

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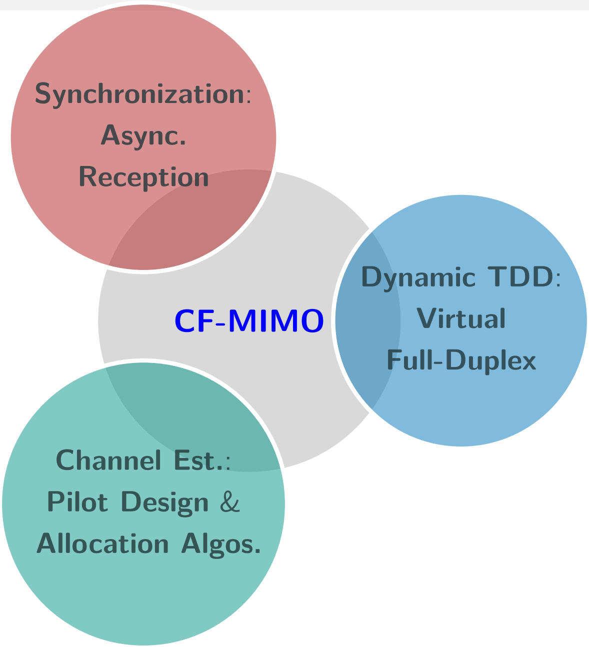
- **Synchronization**: Effects of slowness of the speed of light

... so on...

We addressed



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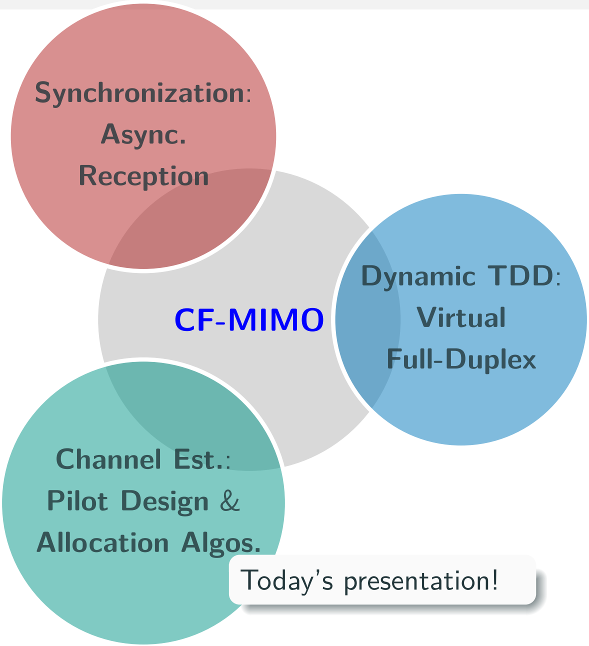
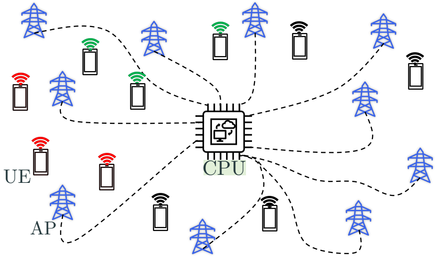


Today's presentation!

Channel Estimation

Challenge in Joint Estimation

- There is no inherent UE grouping/clustering
- All the APs in the vicinity of a UE need to obtain good channel estimates



Color code for orthogonal pilots.

- Random allocation: Huge pilot contamination

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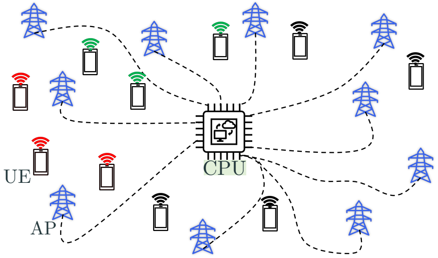

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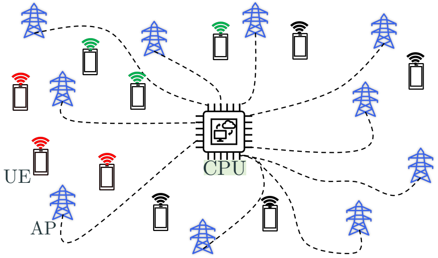

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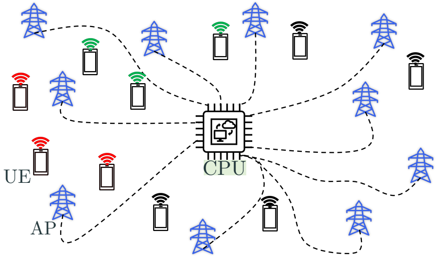

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- Random allocation: Huge pilot contamination
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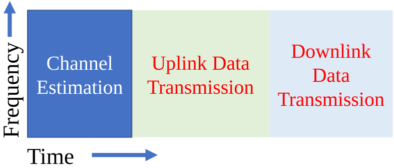
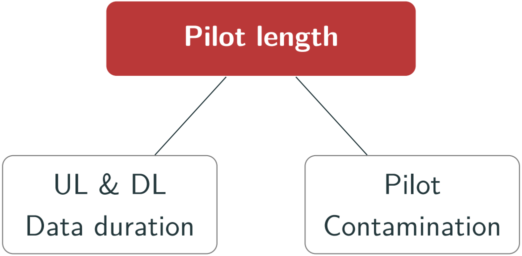
- No pilot contamination: $\tau_p \geq K$
  - Proportionally reduces data transmission duration

Our Aim



Typical TDD frame structure



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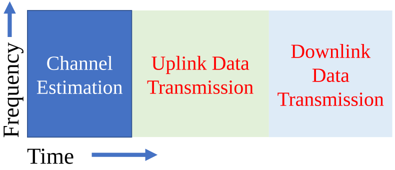

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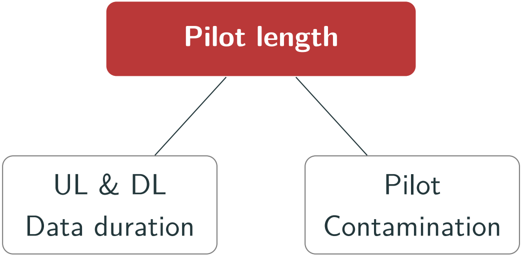

Optimize the pilot length

- Reduce pilot contamination using least length pilot
- Maximize data duration

MMSE Channel Estimator

Local estimate of kth UE's channel at the mth AP

Received signal at the mth AP

$$\hat{\mathbf{f}}_{mk} = \sqrt{\tau_p \mathcal{E}_{p,k}} \beta_{mk} c_{mk} \mathbf{y}_{p,m}$$

$$c_{mk} \triangleq \left(\tau_p \mathcal{E}_{p,k} \beta_{mk} + \tau_p \sum_{n \in \mathcal{P}_{l(k)} \setminus k} \mathcal{E}_{p,n} \beta_{mn} + N_0\right)^{-1}$$

Pilot reusing UEs

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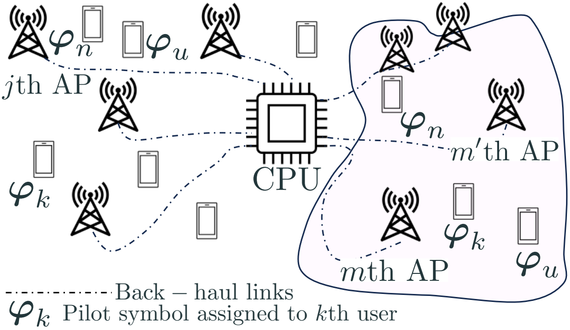
Pilot reusing UEs

Key Observation

If pilot reusing UEs are far apart, then pilot contamination will be considerably lower

Clustering & Pilot Allocation

Clustering: Motivation



Orthogonality within the shaded region

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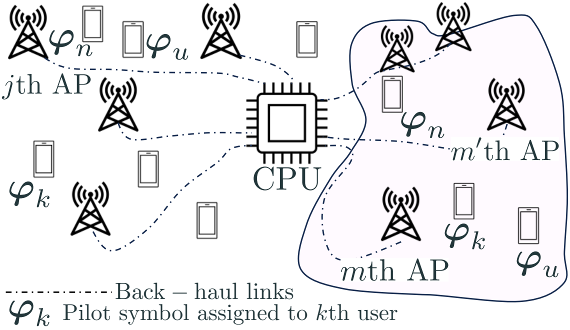

Orthogonality within the shaded region

Key Observation

Only a **subset of APs** within the vicinity of a UE receives a signal with **sufficient strength** for decodability

- Define the **shaded region**:

$$r_o \triangleq \max\left\{\max_{k\in\mathcal{U}} d_{m_k k}, d_{\mathrm{SNR}_o}\right\}$$

① $d_{m_k k} = \min\{d_{mk}, \forall m \in \mathcal{A}\}$: Max of all nearest APs' distances
② $d_{\mathrm{SNR}_o} = \max_d \left\{\frac{N\mathcal{E}_p\beta(d)}{N_0} \geq \gamma_{\min}\right\}$: ***Sufficient strength***

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- **Case 1**: ① > ②: There is no UE that is not connected to any AP
- **Case 2**: ① < ②: Every UE is connected to all APs where the received signal strength is at least $\gamma_{\min}$

Formed Clusters

Set of AP indices $(\forall k \in \mathcal{U})$

$$\mathcal{U}_k \triangleq \{m \text{ s.t. } \|\mathbf{u}_k - \mathbf{a}_m\| \leq r_o, \forall m \in \mathcal{A}\}$$

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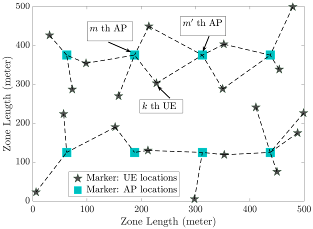

AP-UE connections

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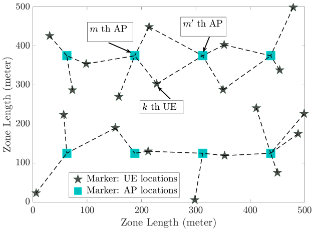

AP-UE connections

Problem

$$\min \ \tau_p$$

$$\text{subject to } \langle \boldsymbol{\varphi}_{l(k)}, \boldsymbol{\varphi}_{l(k')} \rangle = 0, \quad \forall k, k' \in \mathcal{A}_m, \forall m \in \mathcal{U}_k$$

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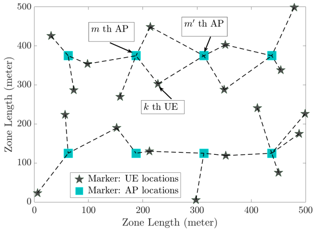

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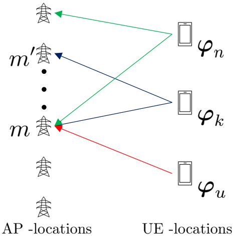
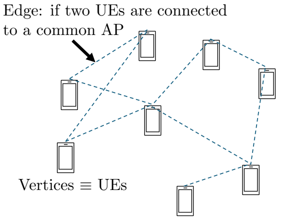
Any **two UEs** that are connected to **a common AP** are assigned **orthogonal** pilot sequences

Two Views

Bipartite Graph Coloring



Vertex Coloring



Edges from each UE: same color
Edges into each AP: distinct color

Any two vertices (UEs) connected by an edge (AP) must have distinct colors

Solve using **minimum** number of colors (orthogonal pilots)

How to color/assign pilots?

- **Recall**: Color is equivalent to orthogonal pilots
- Two questions:
  - Which vertex (UE) do we choose at a given iteration?
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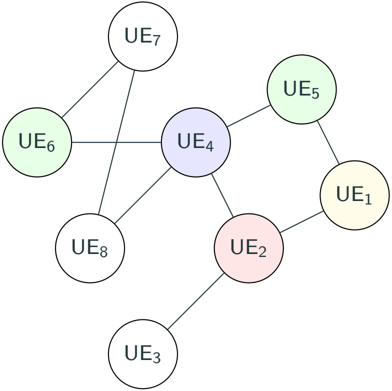
☞ Enumerate for each vertex:

- # distinct colored vertices connected to it
- # of vertices connected to it

☞ Tabulate color (pilot) set:

Color	Repetition factor
	1
	2



At some point in time

Algorithm

Input : $\bar{\mathcal{U}} = \{1, 2, \ldots, K\}$, $\mathcal{C} = \emptyset$ (**colors**)

while $\bar{\mathcal{U}} \neq \emptyset$ **do**

  Select $k \in \bar{\mathcal{U}}$: the **maximum** number of **distinct colored vertices** connected to it.

  Tie-break: Choose $k \in \bar{\mathcal{U}}$ with the **maximum number of vertices** connected to it.

  Tie-break: Choose any $k \in \bar{\mathcal{U}}$ at random

  Assign color:

$$c(k) = \min \quad c(p) \in \mathcal{C}$$

$$\text{subject to } c(k') \neq c(p), \forall k' \in \{l \text{ s.t. } e_{kl} \in \mathcal{E}\}.$$

  if $c(k) = \emptyset$ **then**

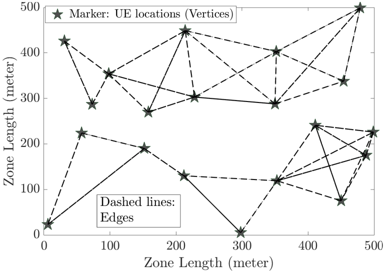
    Assign a new color $c(k)$ to vertex k

    Update Color Set: $\mathcal{C} \leftarrow \mathcal{C} \cup c(k)$

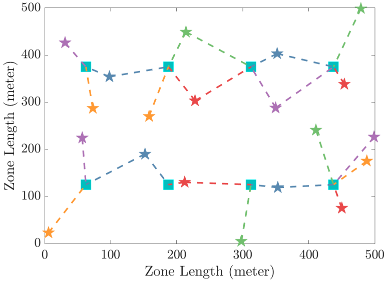
  end

end

Illustration

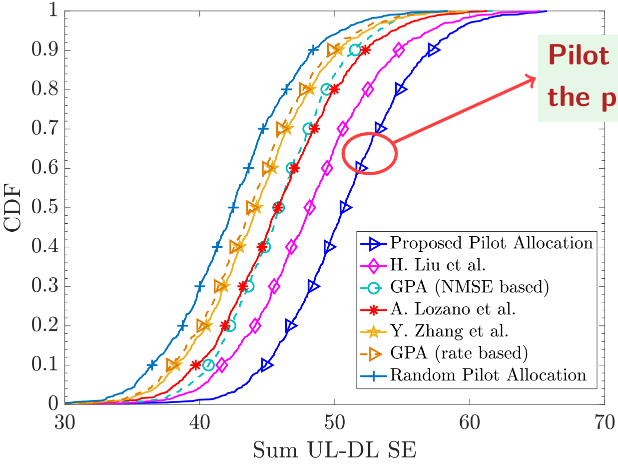


Graph formed by connecting UEs (vertices) that share common AP(s)



Colored AP-UE connections: Distinct colors correspond to distinct orthonormal pilot sequences

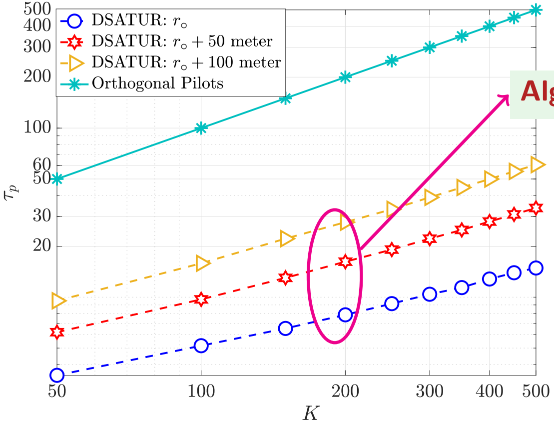
Comparative Study



Pilot allocation using the proposed algorithm

Comparison with existing schemes

Pilot Length



Algorithm: $\tau_p << K$

Scaling of pilot length with number of UEs (K)

Key Message

- **Minimizes the pilot length** at the same time ensures no contamination among the clustered APs
- **Low complexity** solution for pilot allocation: does not require SINR exchange
- Algorithm is known to be **optimal** for all **bipartite** graph

Reference

A. Chowdhury and C. R. Murthy, "Pilot Length Minimization via AP-UE Clustering in Cell-Free Systems," ICASSP 2024, Seoul, Republic of Korea, Apr. 2024, pp. 9216-9220.

Virtual FD & Synchronization: A Quick Look

Question

Can we achieve **FD performance** with **HD hardware**, thus avoiding self-interference?

Virtual FD: DTDD & CF

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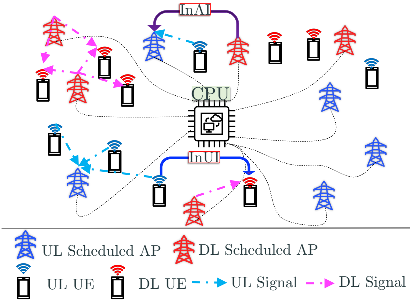

Virtual FD

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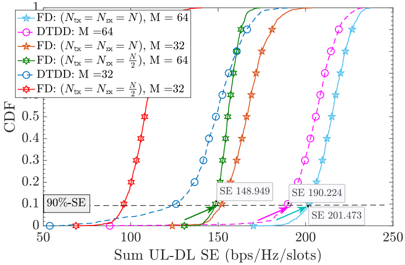
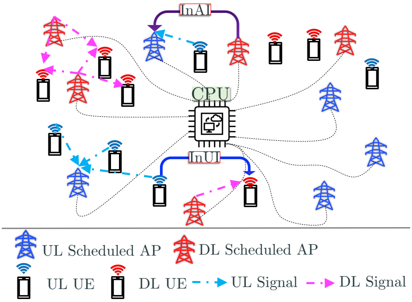


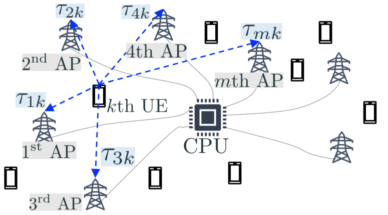
Promise of DTDD HD CF



Virtual FD

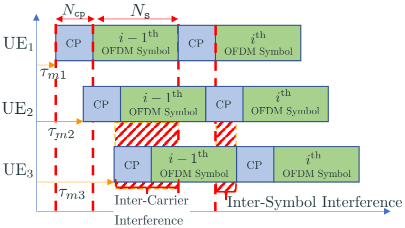
[Anubhab & Chandra: TCOM, Jul. 2022, WCL Mar. 2023, TCOM Jan. 2024]

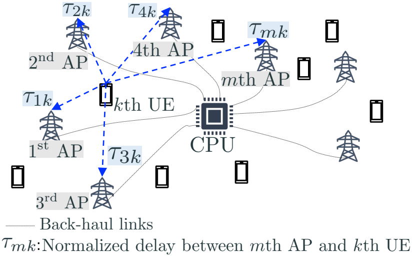
Uplink Synchronization

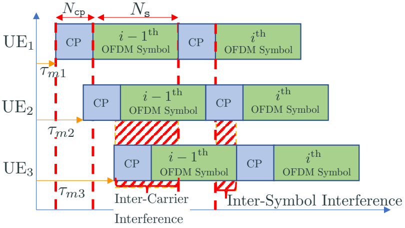


Back-haul links

τ_{mk}:Normalized delay between mth AP and kth UE



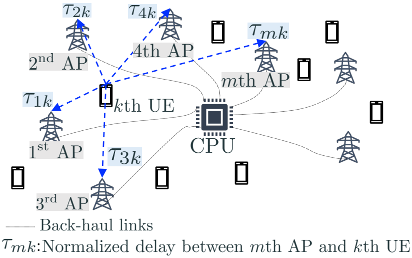


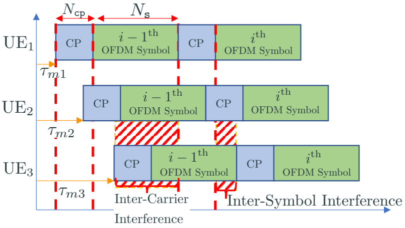


Key Observation

CF-MIMO systems can not be synchronous!

Uplink Synchronization





Key Observation

CF-MIMO systems can not be synchronous!

- Mathematical framework to analyze UL asynchrony and SE
- Interference aware combining to combat ICI and ISI

[Anubhab & Chandra: SPAWC, Sep. 2023]

Overall Publications

[J1] A. Chowdhury and C. R. Murthy, Half-Duplex APs with Dynamic TDD vs. Full-Duplex APs in Cell-Free Systems, accepted in IEEE *Transactions on Communications*, Jan. 2024

[J2] A. Chowdhury and C. R. Murthy, On the Sum Spectral Efficiency of Dynamic TDD Enabled Cell-Free Massive MIMO Systems, *IEEE Wireless Communications Letters*, vol. 12, no. 3, pp. 481-485, Mar. 2023

[J3] A. Chowdhury, R. Chopra, and C. R. Murthy, Can Dynamic TDD Enabled Half-Duplex Cell-Free Massive MIMO Outperform Full-Duplex Cellular Massive MIMO?, *IEEE Transactions on Communications*, vol. 70, no. 7, pp. 4867-4883, Jul. 2022

[J4] A. Chowdhury, P. Sasmal, C. R. Murthy, and R. Chopra, On the Performance of Distributed Antenna Array Systems with Quasi-Orthogonal Pilots, *IEEE Transactions on Vehicular Technology*, vol. 71, no. 3, pp. 3326-3331, Mar. 2022

Continued

[C1] A. Chowdhury and C. R. Murthy, Pilot Length Minimization via AP-UE Clustering in Cell-Free Systems, accepted in *IEEE ICASSP*, Seoul, Korea, Apr. 2024

[C2] A. Chowdhury and C. R. Murthy, How Resilient are Cell-Free Massive MIMO OFDM Systems to Propagation Delays?, *Proc. IEEE SPAWC*, Shanghai, China, Sep. 2023.

[C3] A. Chowdhury and C. R. Murthy, Comparative Study of Dynamic TDD with Full-Duplex in Cell-Free Massive MIMO Systems, *NCC*, Guwahati, India, Feb. 2023.

[C4] A. Chowdhury, C. R. Murthy, and R. Chopra, Dynamic TDD Enabled Distributed Antenna Array Massive MIMO System, *Proc. IEEE SAM*, Trondheim, Norway, Jun. 2022.

[C5] A. Chowdhury, P. Sasmal, and C. R. Murthy, Comparison of Orthogonal vs. Union of Subspace Based Pilots for Multi-Cell Massive MIMO Systems, *Proc. IEEE SPAWC*, Atlanta, Georgia, USA, May 2020.

Thank You... Questions?

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