one6G Summit 2022

Pilot Decontamination and User Scheduling in Cell-Free User-Centric Networks

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Some Key 6G Concepts

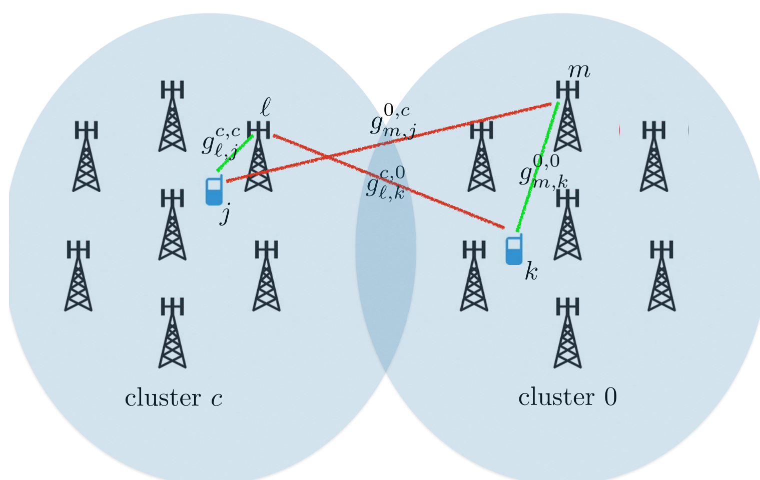
- Opening to new frequency bands, higher carrier frequencies (150 GHz, so-called "sub-THz"), for very large channel bandwidths.
- Beyond cellular: "cell-free" massive MIMO.
- Integrated sensing and communications (ISAC).

In this talk

- Beyond cellular: “cell-free” massive MIMO.
- “Conventional” frequency bands (below 11GHz).
- Scenarios: campus networks, ultra-dense deployments, super-high spectral efficiency (≥ 50 bit/s/Hz per 10$\times$10 m^2).

Joint Processing of “Radio Units”

- [Wyner, TIT 1994]: centralized processing of all antennas in the uplink, Vector Gaussian MAC, capacity region was already known.
- [GC, Shamai, TIT 2003 – Weingarten, Steinberg, Shamai, TIT 2006]: Vector Gaussian BC, sum capacity and capacity region, downlink.
- Some past attempts: Coordinated MultiPoint (CoMP) ....
- Some successes: C-RAN, distributed antenna systems with joint processing, virtualization of the PHY/MAC in the CP.

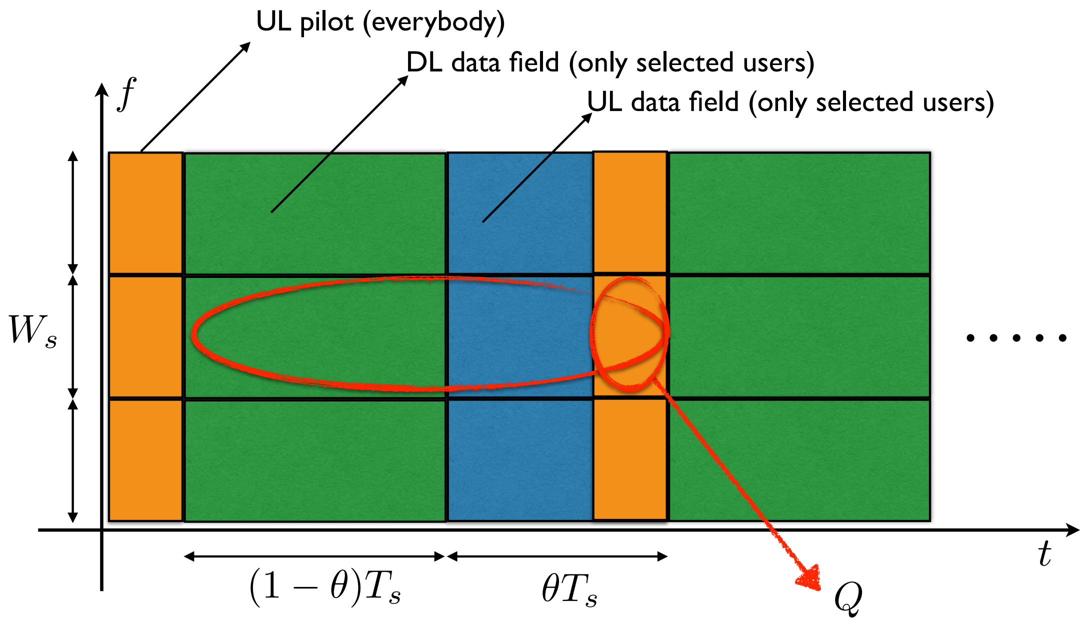


Massive MIMO and TDD Reciprocity

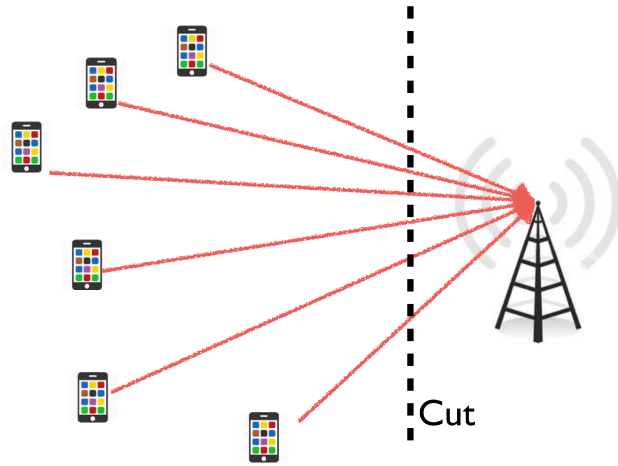
- channel reciprocity:

$$\text{UL: } \mathbf{r} = \mathbf{H}\mathbf{s} + \mathbf{w}, \quad \text{DL: } \mathbf{y} = \mathbf{H}^{\mathsf{H}}\mathbf{x} + \mathbf{z}.$$

- Block-fading channel model: coherence block $T \approx \lceil W_c T_c \rceil$.



Pre-Log Cost of Channel Estimation



- Zheng and Tse "Grassmannian packing" result. For i.i.d. fading, in the high-SNR regime:

$$C_{\text{sum}} \leq M^*(1 - M^*/T) \log \text{SNR} + O(1)$$

where

$$M^* = \min\{M, K, T/2\}$$

- This bound is tight: use UL training and DL precoding (e.g., ZFBF), with M^* orthogonal pilots over M^* dimensions per block.

The massive MIMO idea: $M \gg K$

- Suppose M and K very large.
- The system multiplexing gain is maximized by

$$\max_{M^*} M^*(1 - M^*/T) = T/4, \quad \text{for } \; M^* = T/2$$

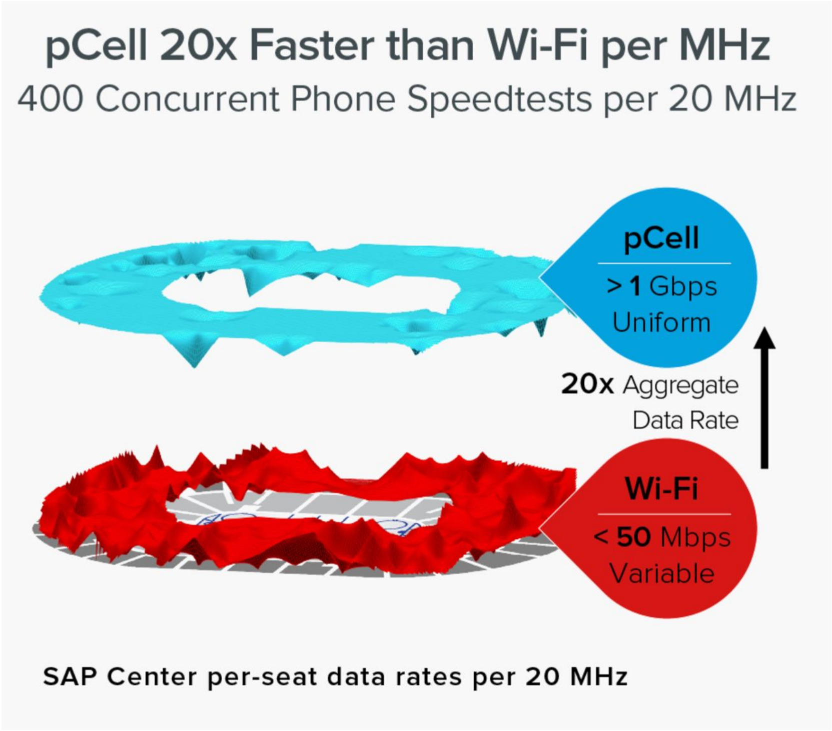
- Consequence: half of the coherence block ($T/2$ dimensions) should be dedicated to UL training, and groups of $T/2$ users should be served simultaneously.
- Consequence: the number of antennas M become a free commodity, as long as $M \geq T/2$.
- **Letting $M \gg T/2 \geq K$ yields significant advantages (energy efficiency, simplicity, deterministic limits (channel hardening), latency ...).**

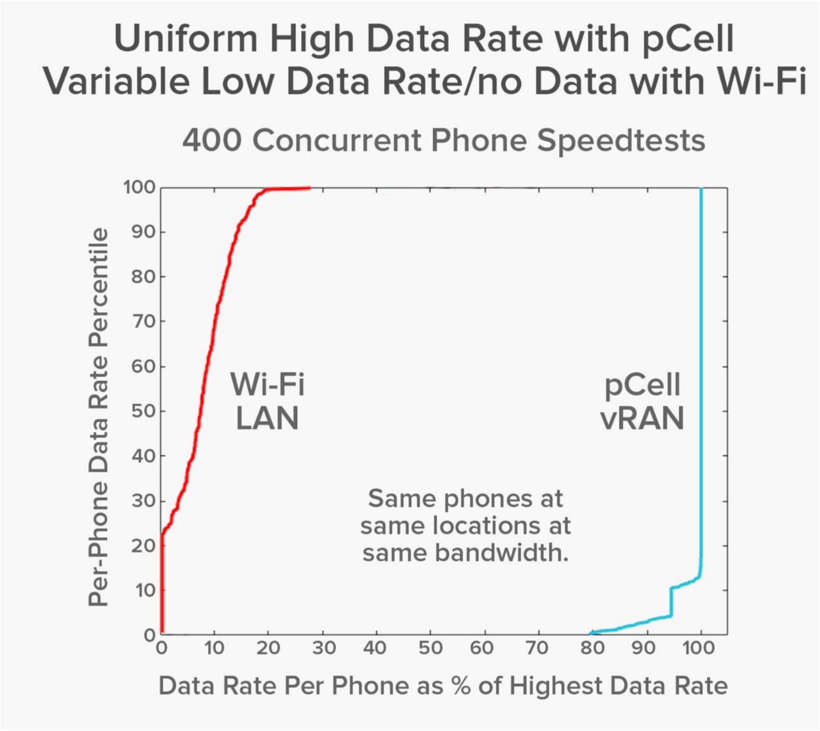
A Motivating Example in Favor of Cell-Free

- Artemis Networks (startup based in the Bay Area, USA), has implemented a LTE/5G TDD based cell-free network (called “pCell”).
- The system is limited to 20 MHz bandwidth, is based on TDD reciprocity and baseband MU-MIMO precoding.
- They run a field trial based on 400 legacy smartphones distributed in the SAP Center Arena in San Jose, CA.

A Motivating Example in Favor of Cell-Free

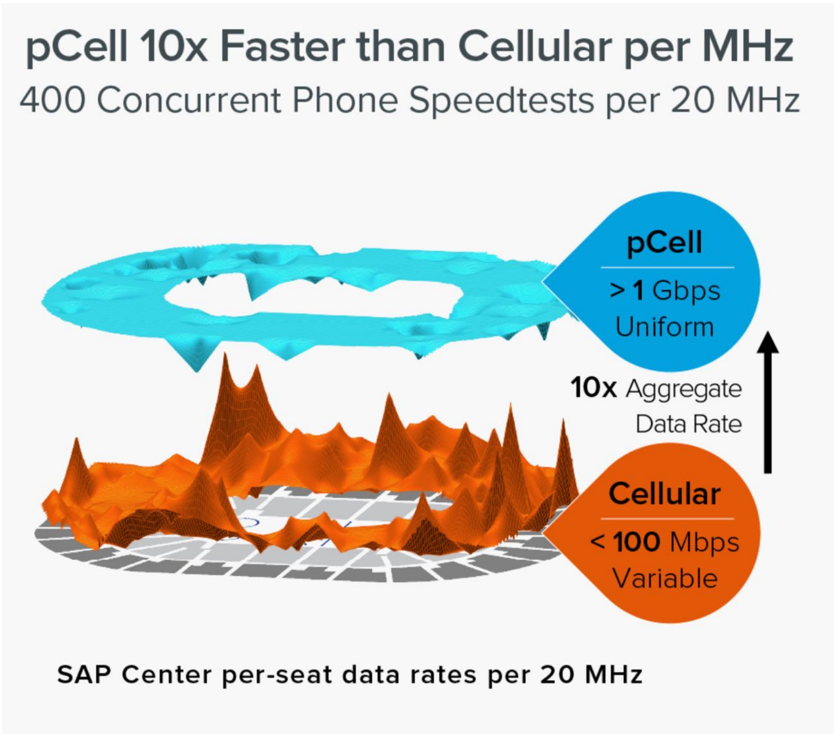
- Rate comparison with deployed WiFi (the WiFi LAN uses a total bandwidth of 400 MHz).

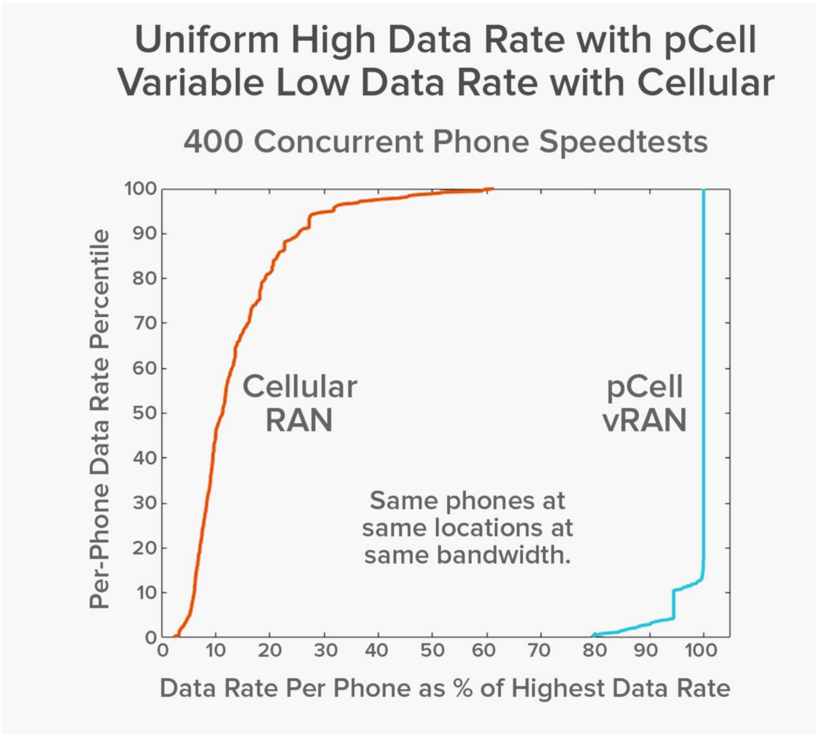




A Motivating Example in Favor of Cell-Free

- Rate comparison with deployed LTE/DAS (the LTE/DAS uses a total bandwidth of 55 MHz).

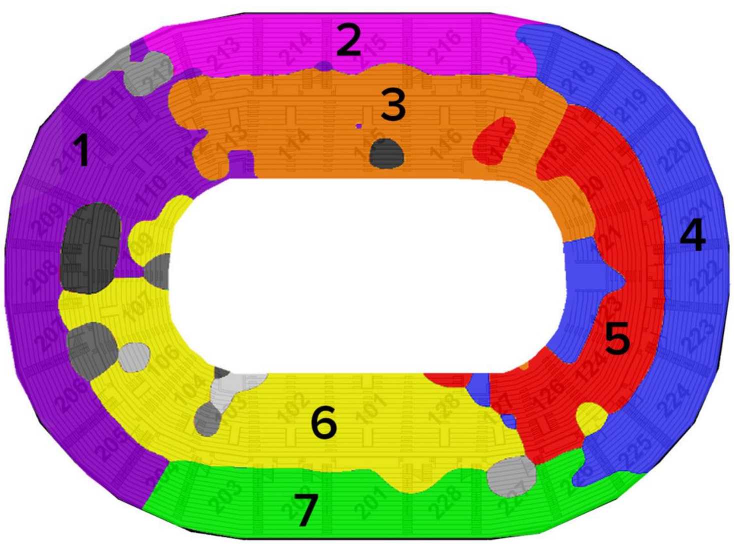




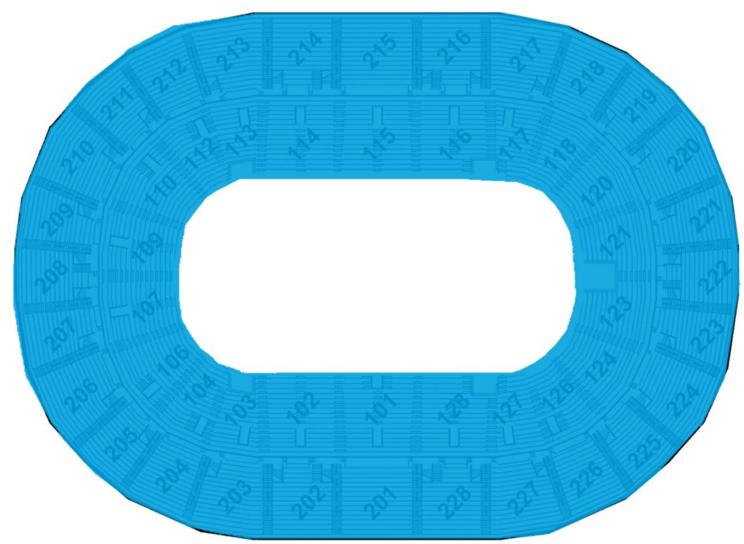
A Motivating Example in Favor of Cell-Free

- Unique RU-UE association yields a "cellular" system with some inter-RU coordination for interference avoidance.
- The full joint processing of all RUs turns interference into useful signal, via PHY baseband precoding.

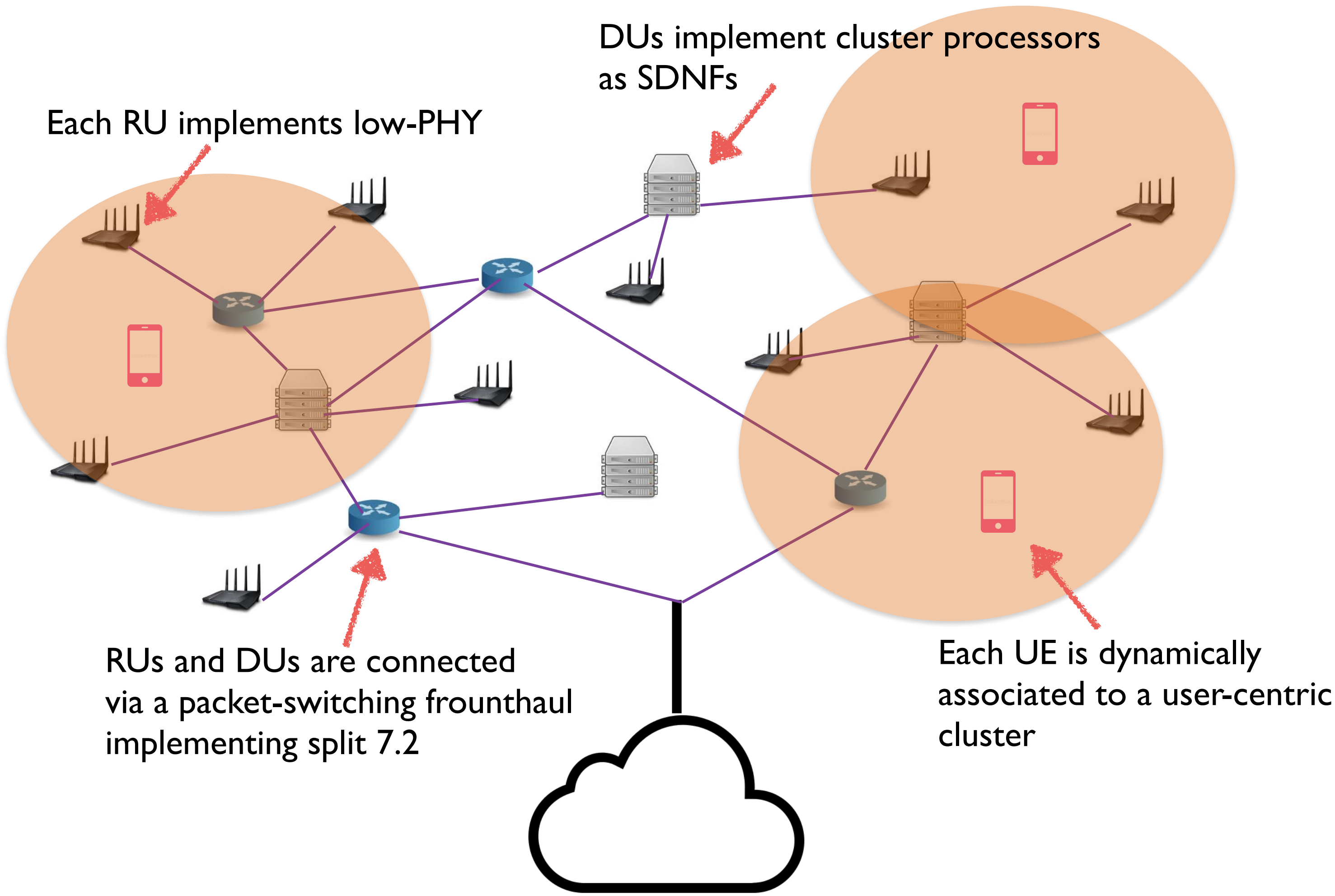
Cellular



pCell



Cell-Free User-Centric Architectures (1)



Cell-Free User-Centric Architectures (2)

- Central concept: Scalability.

  As the coverage area $A \to \infty$, with given RU density λ_a, DU density λ_d, and UE density λ_u, the load of the fronthaul at any node and the computational load at any processor remain finite.

- Some interesting design challenges:

1. Dynamic user-centric formation (including initial access, discovery).
2. Handling mobility (roaming, migration of the clusters).
3. UL pilot allocation.
4. UL and DL (linear) processing, cluster-level receive and precoding vectors (asymmetric and “local” CSI).
5. Pilot (de)contamination.
6. Scheduling for delay and fairness.
7. Energy efficiency (smart switch-off of network components).

Energy Efficiency: the more distributed the better

- Good rule of thumb for operating regime: $\lambda_a < \lambda_u < M\lambda_a$.
- Given a total number of antennas $LM = \lambda_a AM = N_{\rm tot}$, how should they be distributed?
- Array gain:

$$G \propto M = \frac{N_{\rm tot}}{\lambda_a A}$$

- Pathloss coefficient

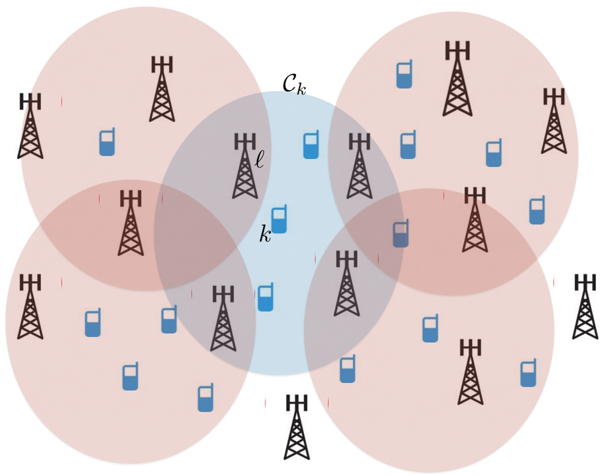
$$\mathcal{L} \propto d^{-\nu}, \quad \text{where } d \propto \sqrt{\frac{A}{L}} = \sqrt{\frac{1}{\lambda_a}}$$

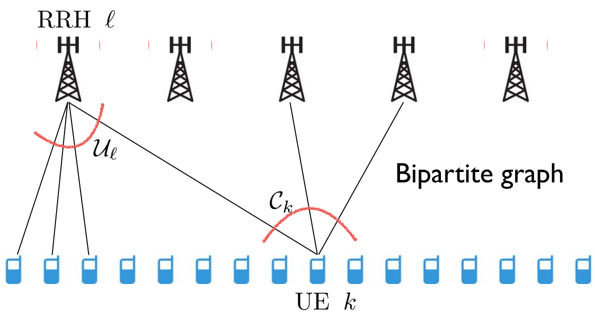
- Product antenna gain $\times$ pathloss coefficient

$$G \times \mathcal{L} \propto \frac{N_{\rm tot}}{A} \cdot \lambda_a^{(\nu/2-1)}$$

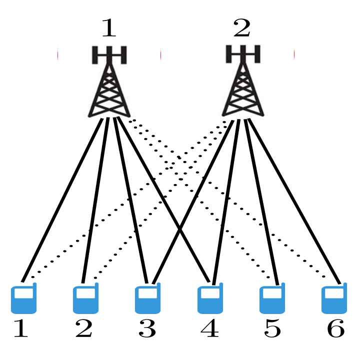
- Since $\nu > 2$, it is convenient to distribute the antennas (large L, moderate M).

Reference model: ideal partial CSI





- Each cluster processor has a “partial view” of the full CSI



Example 1: Consider the simple case of $L = 2$ and $K = 6$ in Fig. 2. Let’s focus on user $k = 3$, for which $\mathcal{C}_3 = \{1, 2\}$. We have $\mathcal{U}_1 = \{1, 2, 3, 4\}$ and $\mathcal{U}_2 = \{3, 4, 5, 6\}$, therefore $\mathcal{U}(\mathcal{C}_3) = \{1, 2, 3, 4, 5, 6\}$. The complete channel matrix is given by

$$\mathbb{H} = \begin{bmatrix} \mathbf{h}_{1,1} & \mathbf{h}_{1,2} & \mathbf{h}_{1,3} & \mathbf{h}_{1,4} & \mathbf{h}_{1,5} & \mathbf{h}_{1,6} \\ \mathbf{h}_{2,1} & \mathbf{h}_{2,2} & \mathbf{h}_{2,3} & \mathbf{h}_{2,4} & \mathbf{h}_{2,5} & \mathbf{h}_{2,6} \end{bmatrix},$$

while the *partial* cluster-centric channel matrix $\mathbb{H}(\mathcal{C}_3)$ is given by

$$\mathbb{H}(\mathcal{C}_3) = \begin{bmatrix} \mathbf{h}_{1,1} & \mathbf{h}_{1,2} & \mathbf{h}_{1,3} & \mathbf{h}_{1,4} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{h}_{2,3} & \mathbf{h}_{2,4} & \mathbf{h}_{2,5} & \mathbf{h}_{2,6} \end{bmatrix}.$$

◊

Some recent relevant references

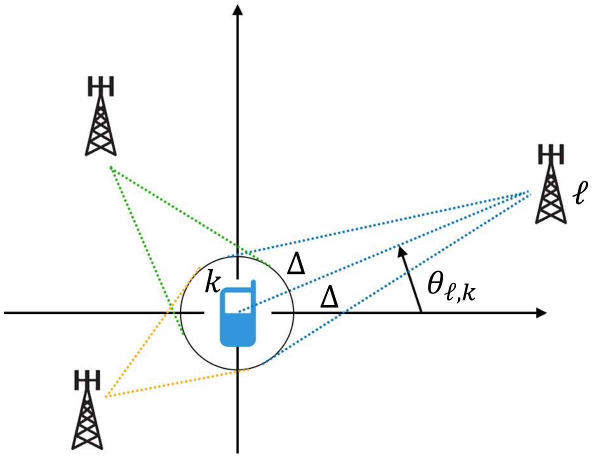
- E. Björnson and L. Sanguinetti, "Scalable Cell-Free Massive MIMO Systems," in IEEE Transactions on Communications, vol. 68, no. 7, pp. 4247-4261, July 2020.
- Ö. T. Demir, E. Björnson, L. Sanguinetti, "Foundations of UserCentric Cell-Free Massive MIMO," Foundations and Trends in Signal Processing, vol. 14, no. 3-4, pp. 162472, 2021.
- F. Göttsch, N. Osawa, T. Ohseki, K. Yamazaki and G. Caire, "The Impact of Subspace-Based Pilot Decontamination in User-Centric Scalable Cell-Free Wireless Networks," 2021 IEEE 22nd International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), 2021.
- Miretti L, Björnson E, Gesbert D. "Team MMSE precoding with applications to cell-free massive MIMO," IEEE Transactions on Wireless Communications. 2022 Feb 8.
- Göttsch F, Osawa N, Ohseki T, Yamazaki K, Caire G. "Subspace-Based Pilot Decontamination in User-Centric Scalable Cell-Free Wireless Networks," arXiv preprint arXiv:2203.00714. 2022 Mar 1.

Spatially consistent correlated channels

- K single-antenna UEs, L RUs with M antennas randomly placed on a squared region with torus topology
  - Each UE k is connected to a RU cluster $\mathcal{C}_k$, each RU ℓ is associated with a UE cluster $\mathcal{U}_\ell$
  - UE-RU association described by a bipartite graph such that the graph contains a UE-RU edge (k,ℓ) if $k \in \mathcal{U}_\ell$ and $\ell \in \mathcal{C}_k$; the set of associations is denoted by $\mathcal{E}$
- Single ring local scattering model [6] for the individual RU-UE channels

$$\mathbf{h}_{\ell,k} = \sqrt{\frac{\beta_{\ell,k} M}{|\mathcal{S}_{\ell,k}|}} \mathbf{F}_{\ell,k} \boldsymbol{\nu}_{\ell,k},$$

$\mathbf{F}_{\ell,k}$: subspace defined by $\theta_{\ell,k} \pm \Delta$
$\mathcal{S}_{\ell,k}$: set of column indices of the DFT matrix
$\beta_{\ell,k}$: large scale fading coefficient (LSFC)
$\boldsymbol{\nu}_{\ell,k}$: Gaussian random vector



[6] A. Adhikary, J. Nam, J. Ahn and G. Caire, "Joint Spatial Division and Multiplexing—The Large-Scale Array Regime," in IEEE Transactions on Information Theory, vol. 59, no. 10, pp. 6441-6463, Oct. 2013, doi: 10.1109/TIT.2013.2269476.

UL receiver/DL precoder (by reciprocity)

- Overall $LM \times 1$-dimensional signal vector received at the RU antennas after scaling with $\mathrm{SNR} = P^{\mathrm{UE}}/N_0$

$$\mathbb{y}^{\mathrm{ul}} = \sqrt{\mathsf{SNR}}\,\mathbb{H}\mathbb{s}^{\mathrm{ul}} + \mathbb{z}^{\mathrm{ul}}$$

i.i.d. noise vector $\sim \mathcal{CN}(0,1)$

Global $LM \times K$ channel matrix of all LM RU antennas and K UEs

$K \times 1$ vector of UEs' UL symbols

- The UL SINR and ergodic optimistic rate are given by

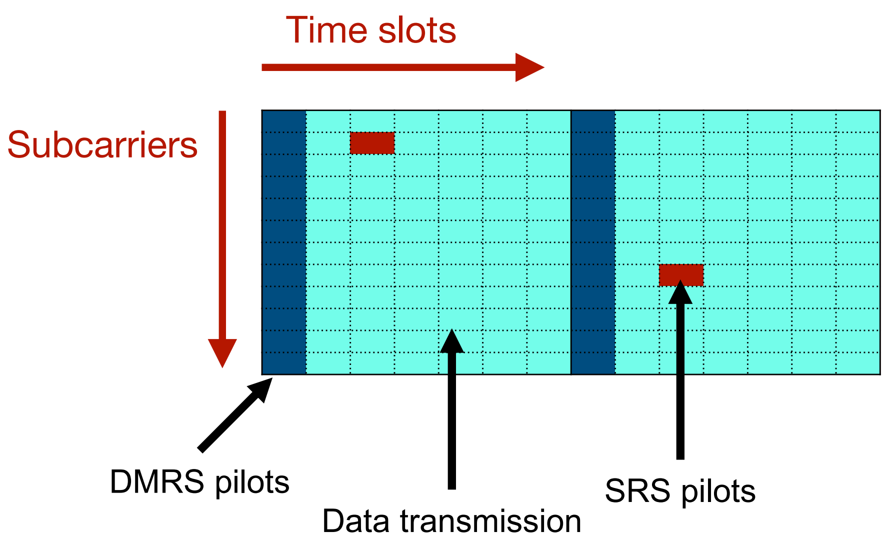
$$\mathrm{SINR}_k^{\mathrm{ul}} = \frac{\left|\mathbb{v}_k^{\mathrm{H}}\mathbb{h}_k\right|^2}{\mathrm{SNR}^{-1} + \sum_{j \neq k}\left|\mathbb{v}_k^{\mathrm{H}}\mathbb{h}_j\right|^2} \qquad R_k^{\mathrm{ul}} = \mathbb{E}\left[\log\left(1 + \mathrm{SINR}_k^{\mathrm{ul}}\right)\right]$$

where $\mathbb{h}_j$ is the j-th column of $\mathbb{H}$, the channel vector of UE j to all LM RU antennas

- Combining vector $\mathbb{v}_k = \left[w_{1,k}\mathbf{v}_{1,k}^{\mathrm{T}}, w_{2,k}\mathbf{v}_{2,k}^{\mathrm{T}}, \dots, w_{L,k}\mathbf{v}_{L,k}^{\mathrm{T}}\right]^{\mathrm{T}}$
  - Weighted local Linear MMSE (LMMSE) receiver $w_{\ell,k}\mathbf{v}_{\ell,k}$ for $(\ell, k) \in \mathcal{E}$
  - $\mathbf{v}_{\ell,k} = \mathbf{0}$ otherwise if $(\ell, k) \notin \mathcal{E}$

UL pilot strategy

- Sounding reference signal (SRS) and demodulation reference signal (DMRS) pilots for subspace and instantaneous channel estimation, respectively
  - Latin squares-based SRS pilot assignment (see [4])
- Robust Principle Component Analysis (R-PCA) algorithm from [5] for subspace estimation



$$\begin{bmatrix} \boxed{1} & 2 & 3 & 4 & 5 \\ 2 & 3 & 4 & 5 & \boxed{1} \\ 3 & 4 & 5 & \boxed{1} & 2 \\ 4 & 5 & \boxed{1} & 2 & 3 \\ 5 & \boxed{1} & 2 & 3 & 4 \end{bmatrix}$$

A latin square used for SRS pilot assignment

[4] G. J. Pottie and A. R. Calderbank, "Channel coding strategies for cellular radio," in IEEE Transactions on Vehicular Technology, vol. 44, no. 4, pp. 763-770, Nov. 1995.
[5] H. Xu, C. Caramanis and S. Sanghavi, "Robust PCA via Outlier Pursuit," in IEEE Transactions on Information Theory, vol. 58, no. 5, pp. 3047-3064, May 2012.

UL channel estimation

- The UL DMRS pilot signal at RU ℓ is $\mathbf{Y}_\ell^{\text{pilot}} = \sum_{i=1}^{K} \frac{1}{\tau_p \text{SNR}} \mathbf{h}_{\ell,i} \phi_{t_i}^{\text{H}} + \mathbf{Z}_\ell^{\text{pilot}}$, where ϕ_{t_i} is the UL DMRS pilot signal of UE i with total energy $\|\phi_{t_i}\|^2 = \tau_p \text{SNR}$, and $\mathbf{Z}_\ell^{\text{pilot}}$ is AWGN i.i.d $\sim \mathcal{CN}(0, \mathbf{I})$
- "Pilot matching" channel estimation
  - $\hat{\mathbf{h}}_{\ell,k}^{\text{pm}} = \frac{1}{\tau_p \text{SNR}} \mathbf{Y}_\ell^{\text{pilot}} \phi_{t_k} = \mathbf{h}_{\ell,k} + \sum_{\substack{i: t_i = t_k \\ i \neq k}} \mathbf{h}_{\ell,i} + \tilde{\mathbf{z}}_{t_k,\ell}$, where $\tilde{\mathbf{z}}_{t_k,\ell}$ is i.i.d. $\sim \mathcal{CN}\left(0, \frac{1}{\tau_p \text{SNR}}\right)$
- "Subspace projection" channel estimation

$$\hat{\mathbf{h}}_{\ell,k}^{\text{sp}} = \mathbf{F}_{\ell,k} \mathbf{F}_{\ell,k}^{\text{H}} \hat{\mathbf{h}}_{\ell,k}^{\text{pm}}$$

  - The pilot contamination term is now a Gaussian vector with mean zero and covariance matrix

$$\Sigma_{\ell,k}^{\text{co}} = \sum_{\substack{i: t_i = t_k \\ i \neq k}} \frac{\beta_{\ell,i} M}{|\mathcal{S}_{\ell,i}|} \mathbf{F}_{\ell,k} \mathbf{F}_{\ell,k}^{\text{H}} \, \mathbf{F}_{\ell,i} \mathbf{F}_{\ell,i}^{\text{H}} \, \mathbf{F}_{\ell,k} \mathbf{F}_{\ell,k}^{\text{H}}$$

  - If $\mathbf{F}_{\ell,k}$ and $\mathbf{F}_{\ell,i}$ are nearly orthogonal, i.e., $\mathbf{F}_{\ell,k}^{\text{H}} \mathbf{F}_{\ell,i} \approx \mathbf{0}$, the DMRS pilot contamination of UE i can be removed to a significant extent

SRS orthogonal latin squares

Example for SRS pilot assignment:

Time slots →

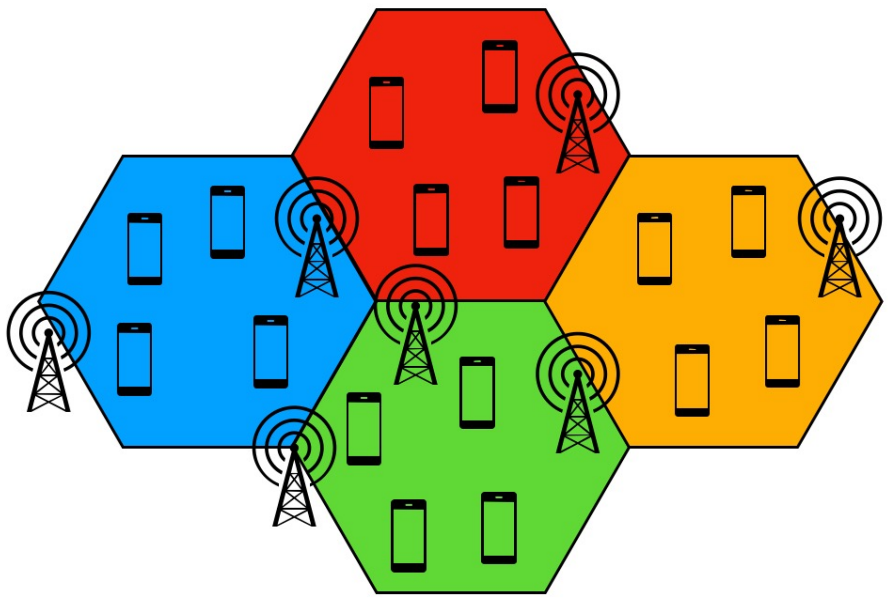
$$\mathbf{A} = \begin{bmatrix} \boxed{1} & 2 & 3 & 4 & 5 \\ 2 & 3 & 4 & 5 & \boxed{1} \\ 3 & 4 & 5 & \boxed{1} & 2 \\ 4 & 5 & \boxed{1} & 2 & 3 \\ 5 & \boxed{1} & 2 & 3 & 4 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} \boxed{1} & 2 & 3 & 4 & 5 \\ 3 & 4 & 5 & 1 & \boxed{2} \\ 5 & 1 & 2 & \boxed{3} & 4 \\ 2 & 3 & \boxed{4} & 5 & 1 \\ 4 & \boxed{5} & 1 & 2 & 3 \end{bmatrix}$$

↓ Subcarriers

- $\mathbf{A}$ and $\mathbf{B}$ are mutually orthogonal Latin squares
  - The UE $k_1(\mathbf{A})$ associated to Latin square $\mathbf{A}$ has SRS pilot sequence $\{1,5,4,3,2\}$
  - $k_1(\mathbf{A})$ „collides“ in each time slot with another UE associated to Latin square $\mathbf{B}$, specifically with the UEs $\{k_1(\mathbf{B}), k_5(\mathbf{B}), k_4(\mathbf{B}), k_3(\mathbf{B}), k_2(\mathbf{B})\}$
  - $k_1(\mathbf{A})$ does not collide with another UE associated to Latin square $\mathbf{A}$ in any time slot

Latin squares geographic assignment

- Orthogonal latin squares-based SRS pilot hopping scheme based on UE locations
  - Independent of RU locations
- UEs in the same area/group use sequences from the same latin square
  - No SRS pilot contamination from UEs in the same area



R-PCA channel subspace estimation (1)

- The received SRS pilot sample at RU ℓ used for subspace estimation of UE k in time slot s is given by

Hopping sequences of user i that collide with user k in slot s

i.i.d. noise vector $\sim \mathcal{CN}(0, \frac{1}{\mathrm{SNR}})$

$$
\begin{aligned}
\mathbf{y}_{\ell,k}^{\mathrm{SRS}}(s) &= \mathbf{h}_{\ell,k}(s) + \sum_{i \neq k : t_i^{\mathrm{SRS}}(s) = t_k^{\mathrm{SRS}}(s)} \mathbf{h}_{\ell,i}(s) + \tilde{\mathbf{z}}_{\ell,k}(s) \\
&= \mathbf{h}_{\ell,k}(s) + \sum_{\substack{i \neq k: \\ i \in \mathcal{I}_k^s(s)}} \mathbf{h}_{\ell,i}(s) + \sum_{\substack{i \neq k: \\ i \in \mathcal{I}_k^w(s)}} \mathbf{h}_{\ell,i}(s) + \tilde{\mathbf{z}}_{\ell,k}(s) \\
&= \mathbf{h}_{\ell,k}(s) + \mathbf{e}_{\ell,k}(s) + \mathbf{n}_{\ell,k}(s)
\end{aligned}
$$

- $\mathbf{e}_{\ell,k} = \sum_{i \neq k : i \in \mathcal{I}_k^s(s)} \mathbf{h}_{\ell,i}(s)$ and $\mathbf{n}_{\ell,k} = \sum_{i \neq k : i \in \mathcal{I}_k^w(s)} \mathbf{h}_{\ell,i}(s) + \tilde{z}_{\ell,k}(s)$ are the strong undesired signals (the so-called outliers), and noise plus weak undesired signals, respectively
- The sets $\mathcal{I}_k^s(s)$ and $\mathcal{I}_k^w(s)$ contain the UEs colliding with UE k with strong and weak LSFCs with respect to RU ℓ, respectively

R-PCA channel subspace estimation (2)

- Fixing some λ and ϵ, the following convex optimization problem is posed

$$\begin{aligned} \underset{\mathbf{H}_{\ell,k},\mathbf{E}_{\ell,k}}{\text{minimize}} \quad & \|\mathbf{H}_{\ell,k}\|_* + \lambda\|\mathbf{E}_{\ell,k}\|_{2,1} \\ \text{subject to:} \quad & \|\mathbf{Y}_{\ell,k}^{\text{SRS}} - \mathbf{H}_{\ell,k} - \mathbf{E}_{\ell,k}\|_F \leqslant \epsilon \end{aligned}$$

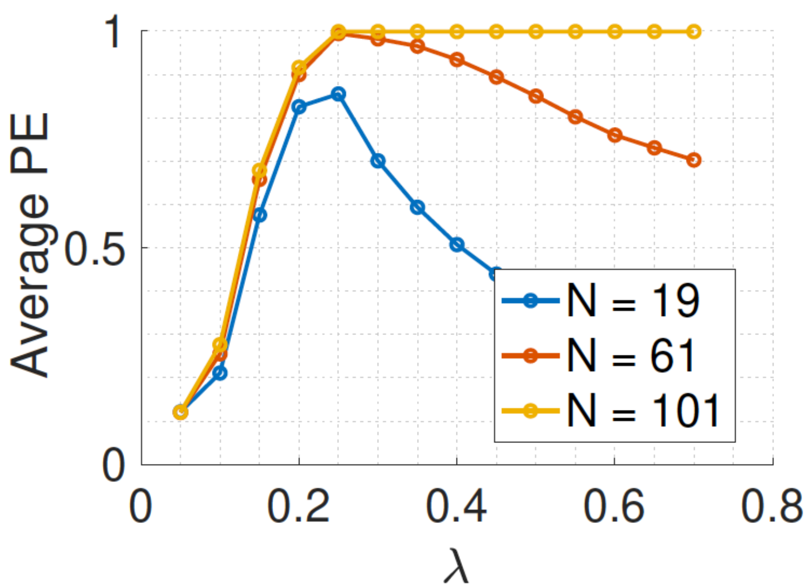
  and approached with the R-PCA algorithm, which returns estimates $\widehat{\mathbf{H}}_{\ell,k}$ and $\widehat{\mathbf{E}}_{\ell,k}$ of the channel and outlier matrix, respectively
- $\|\cdot\|_*$, $\|\cdot\|_F$ and $\|\cdot\|_{2,1}$ denote the nuclear norm, the Frobenius norm, and and the sum of the ℓ_2 column norms of a matrix, respectively
- From the SVD $\widehat{\mathbf{H}}_{\ell,k} = \widehat{\mathbf{U}}\widehat{\mathbf{S}}\widehat{\mathbf{V}}^{\mathrm{H}}$, we estimate the subspace by considering the left singular vectors (columns of $\widehat{\mathbf{U}}$) corresponding to the dominant singular values
  - One approach to find the number of dominant singular values is to find the index at which there is the largest difference (gap) between consecutive singular values (diagonal entries of $\widehat{\mathbf{S}}$)

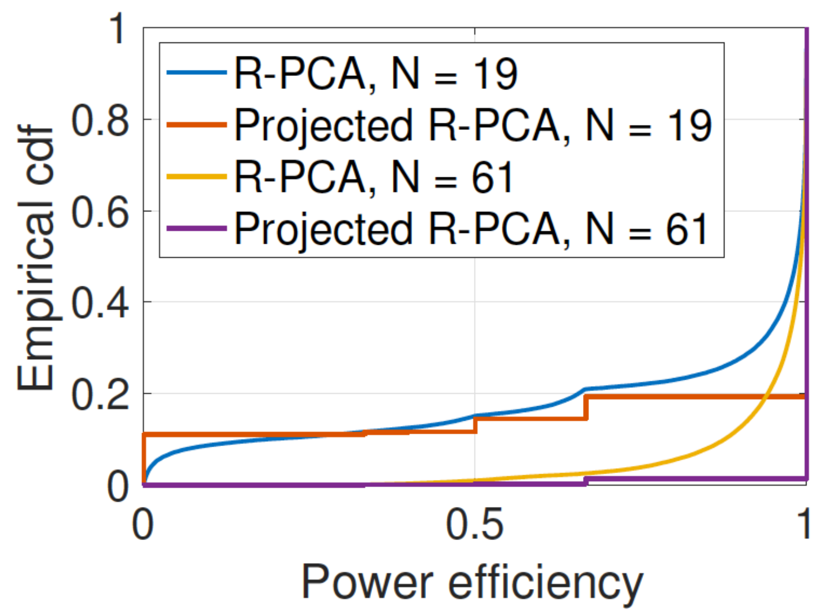
R-PCA channel subspace estimation (3)

- With $\hat{\mathbf{F}}_{\ell,k} = \hat{\mathbf{F}}_{\ell,k}^{\mathrm{PCA}}$ or $\hat{\mathbf{F}}_{\ell,k} = \hat{\mathbf{F}}_{\ell,k}^{\mathrm{PP}}$, the subspace estimation accuracy is evaluated in terms of power efficiency (PE), given by

$$E_{PE}\left(\hat{\mathbf{F}}_{\ell,k}\right) = \frac{\mathrm{tr}\left(\Sigma_{\mathbf{h}}(\mathbf{F}_{\ell,k})\Sigma_{\mathbf{h}}(\hat{\mathbf{F}}_{\ell,k})\right)}{\mathrm{tr}\left(\Sigma_{\mathbf{h}}(\mathbf{F}_{\ell,k})\Sigma_{\mathbf{h}}(\mathbf{F}_{\ell,k})\right)},$$

where $\Sigma_{\mathbf{h}}\left(\mathbf{F}_{\ell,k}\right) = \frac{\beta_{\ell,k}M}{|\mathcal{S}_{\ell,k}|}\mathbf{F}_{\ell,k}\left(\mathbf{F}_{\ell,k}\right)^{\mathrm{H}}$ and $\Sigma_{\mathbf{h}}\left(\hat{\mathbf{F}}_{\ell,k}\right) = \frac{\beta_{\ell,k}M}{r^{\mathrm{PCA}}}\hat{\mathbf{F}}_{\ell,k}\left(\hat{\mathbf{F}}_{\ell,k}\right)^{\mathrm{H}}$





R-PCA channel subspace estimation (4)

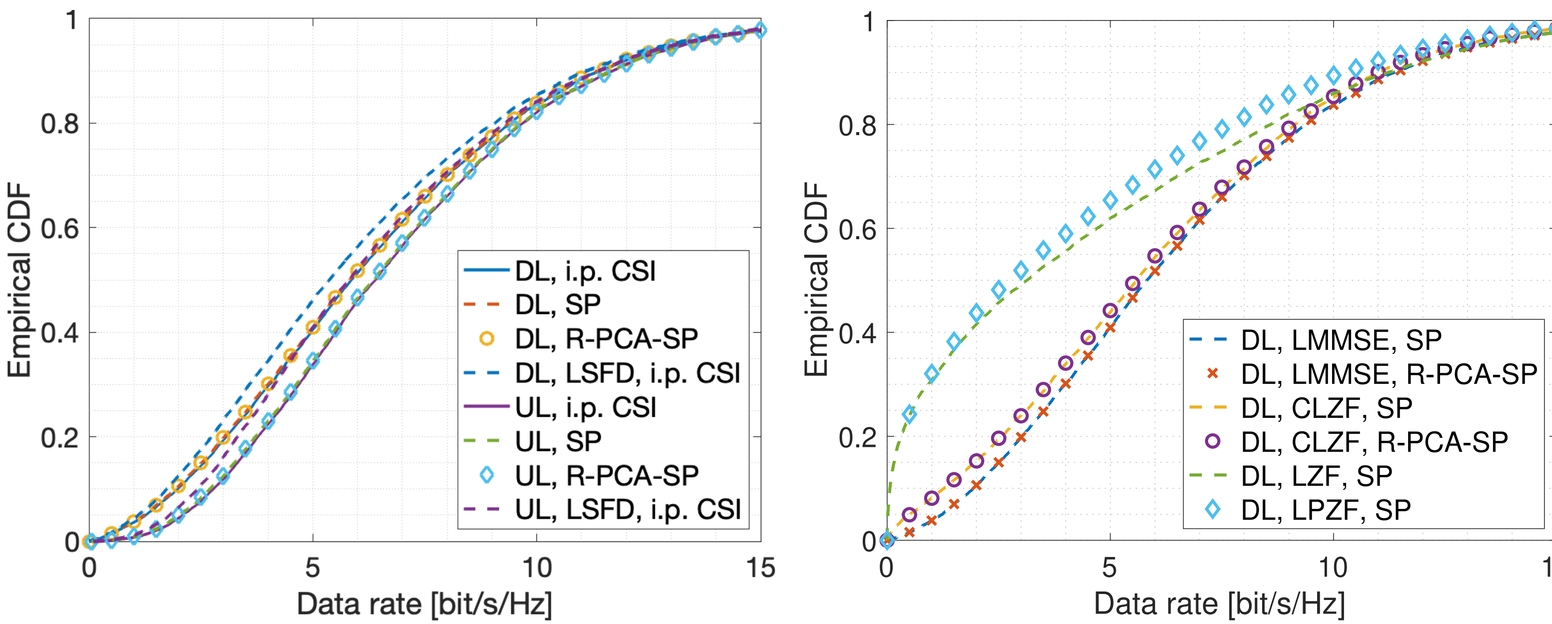


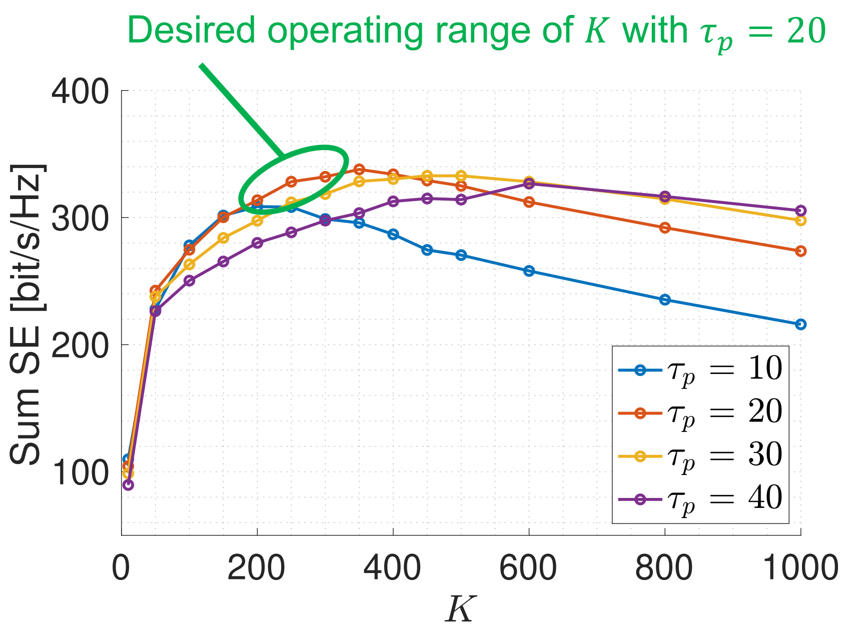
Fig. 5. The UL and DL data rates for LMMSE combining with DL power allocation from UL-DL duality (left). The DL data rates for different precoding schemes, where LMMSE/CLZF do power allocation from duality and LZF/LPZF use PPA (right).

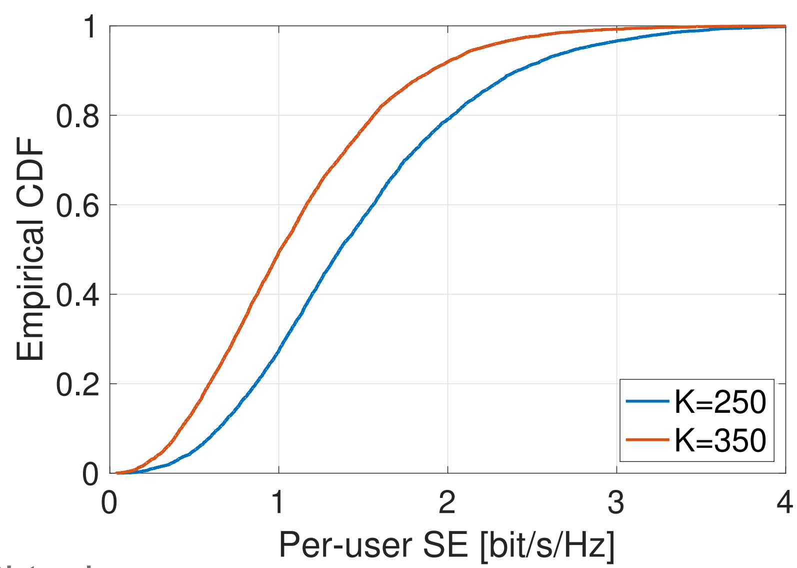
- Thanks to the UL-DL duality result, the DL precoding vectors are identical to the UL multiuser detection vectors.

- The performance with actual CSI estimation (SP-based pilot decontamination, with estimated channel subspace via R-PCA) is almost identical to the ideal partial CSI case.

Total spectral efficiency and scheduling (1)

- Squared network with area $A = 100 \times 100\ \mathrm{m}^2$
  - $L = 25$ RUs with fixed locations and $M = 16$ antennas
  - $Q = 10$, maximal cluster size of RUs serving a UE
- Here, we consider optimistic ergodic rates for multiple setups and channel realizations
- The sum SE does not grow linearly with K, and the per-user SE is approximately in the range [.1, 4] bit/s/Hz for 250-350 simultaneously active UEs, i.e., SE is not “fairly distributed”





Optimal User Load in Dense User-Centric Cell-Free Massive MIMO Networks

Total spectral efficiency and scheduling (2)

- Network Utility Maximization (e.g., max-min Fairness, proportional fairness):

$$\overline{R}_k = \lim_{T\to\infty} \frac{1}{T} \sum_{t=1}^{T} R_k(t), \quad \Rightarrow \ \max \ G(\overline{\mathbf{R}})$$

for a suitable $G(\cdot)$, concave componentwise non-decreasing utility function.

- Given a scheduled rate r_k, the actual rate is

$$R_k(t) = r_k \times 1\{r_k < \log(1 + \mathsf{SINR}_k(t))\}$$

- The corresponding maximum expected "outage rate" is given by

$$\widehat{r}_k = \max_{r\geq 0} \ r \times (1 - F_k(r))$$

where we define the CDF $F_k(r) = \mathbb{P}(\log(1 + \mathsf{SINR}_k) \leq r)$.

Fairness scheduling

- Scheduler (1): update virtual arrival processes: let $\{A_k(t)\}$ the solution of the convex problem

$$\max \quad VG(\mathbf{a}) - \sum_k a_k Q_k(t), \quad \text{s.t. } \mathbf{a} \in [0, A_{\max}]^K$$

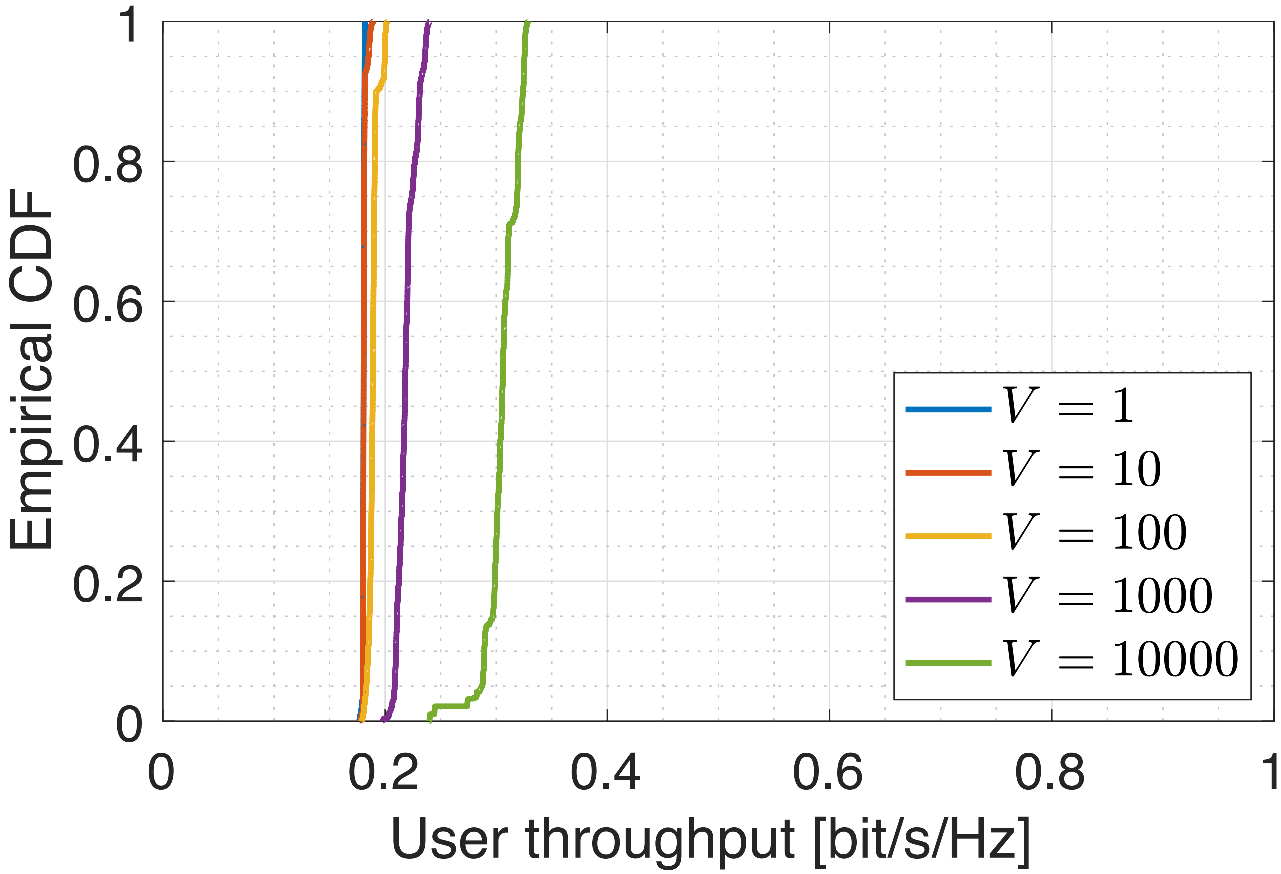
- Scheduler (2): select active users: let $\{x_k\} \in \{0,1\}^K$ be the solution of the linear integer program

$$\max \quad \sum_k x_k Q_k(t) \widehat{r}_k (1 - F_k(\widehat{r}_k)), \quad \text{s.t. } \sum_k x_k \leq K_{\text{opt}}$$

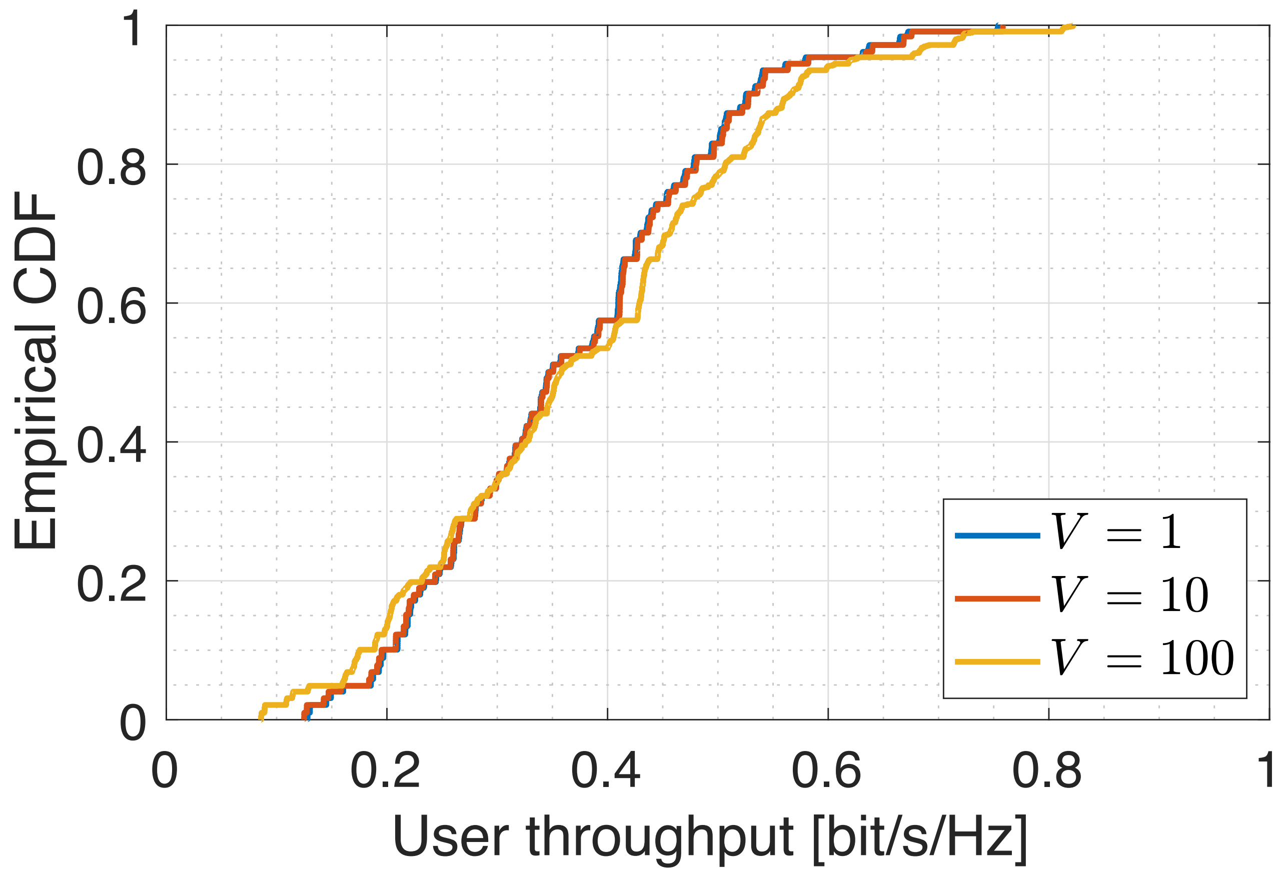
- Scheduler (3): update the virtual queues as

$$Q_k(t+1) = \max\{Q_k(t) + A_k(t) - R_k(t), 0\}$$

Example for Max-Min Fairness



Example for Proportional Fairness

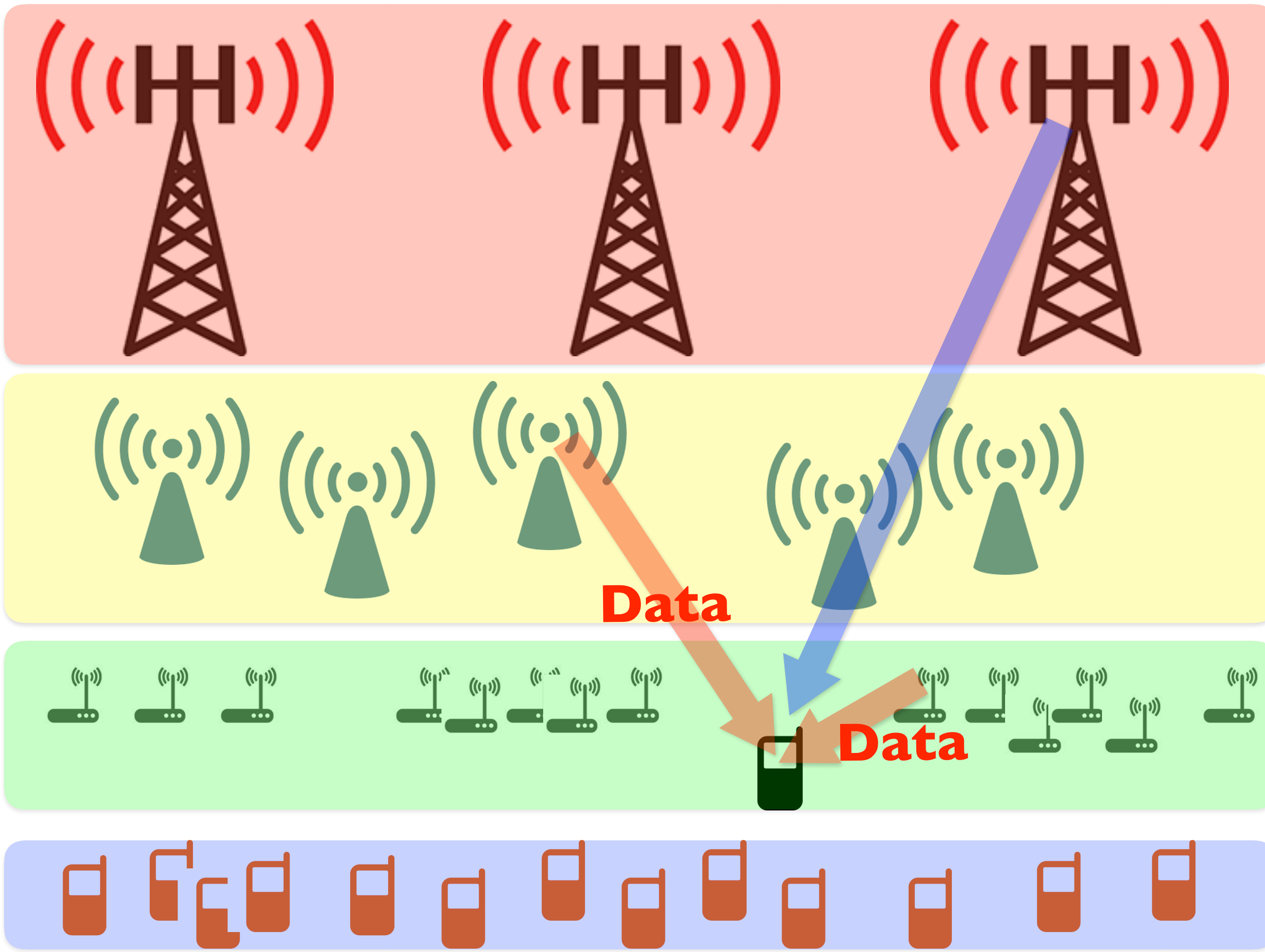


Technische Universität Berlin

The Future:

Cell-Free User-Centric at mmWave/sub-THz ???

Multifrequency heterogeneous networks



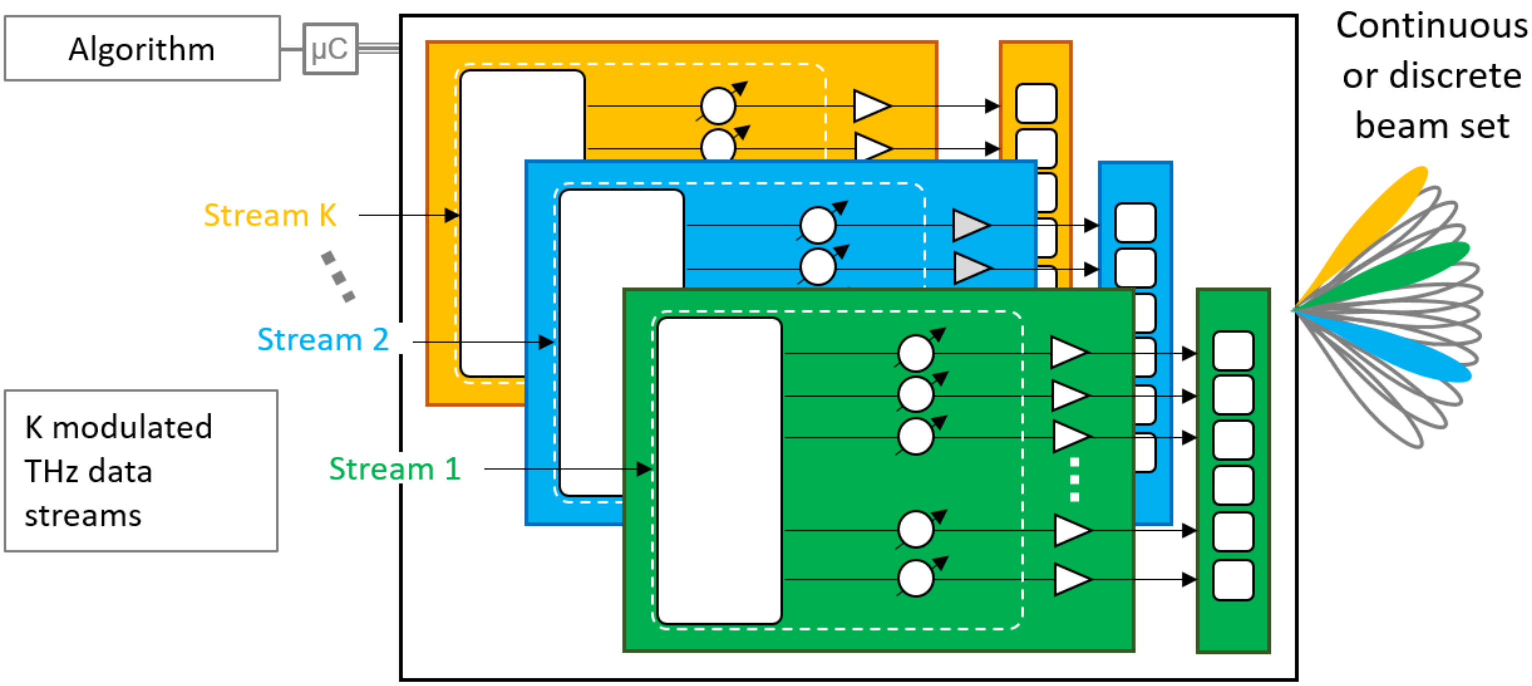
- Made possible by the decoupling of data and control planes.

Problems at very high carrier frequencies

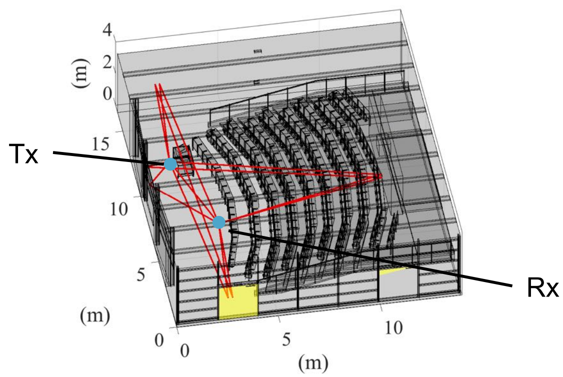
- Isotropic pathloss: it requires very large antenna array gains.
- Difficulty of fully digital BB processing: HDA beamforming.
- Blocking effects rather than multipath fading: essentially LoS communication.

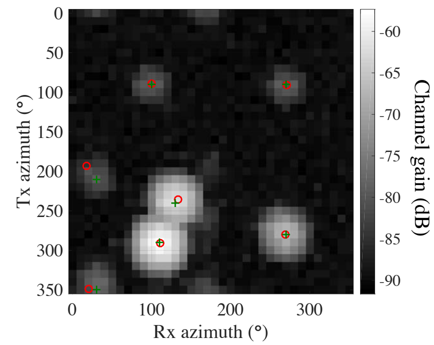
One-Stream Per-Subarray HDA

- We consider RUs with OSPS HDA beamforming: in general, $N_{\rm rf} \ll M$. What counts is the number of RF chains (subarrays).

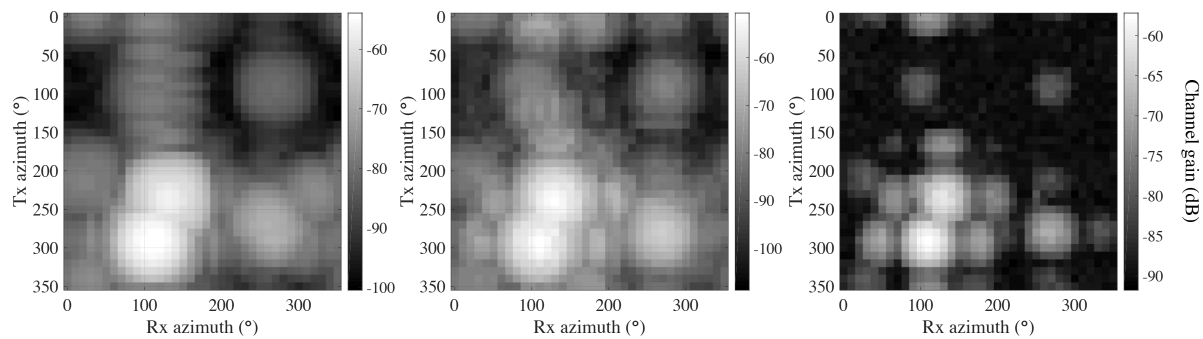


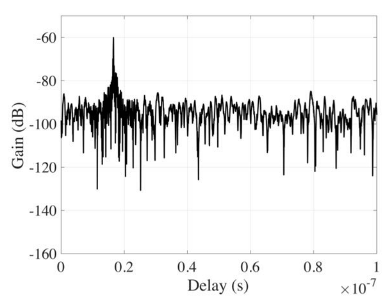
Sparsity in the Angle-Doppler-Delay Domain



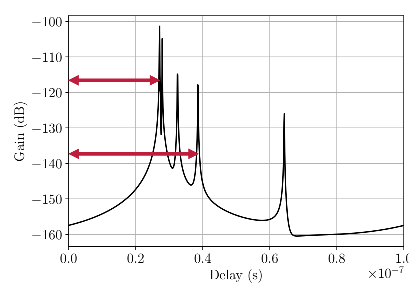


Measured power-angular spectrum

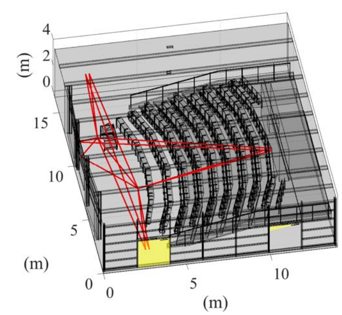




Measured CIR with channel sounder



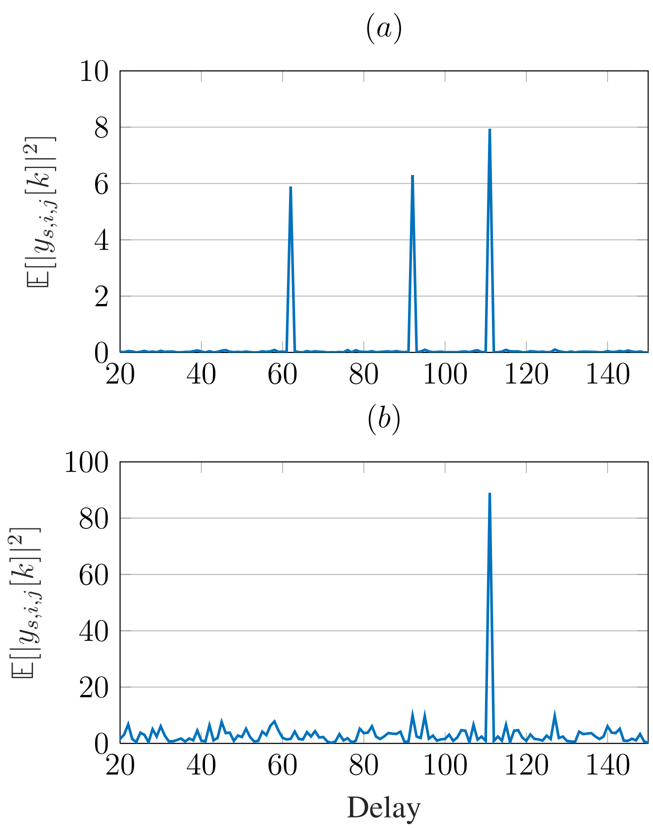
Simulated CIR



Propagation paths

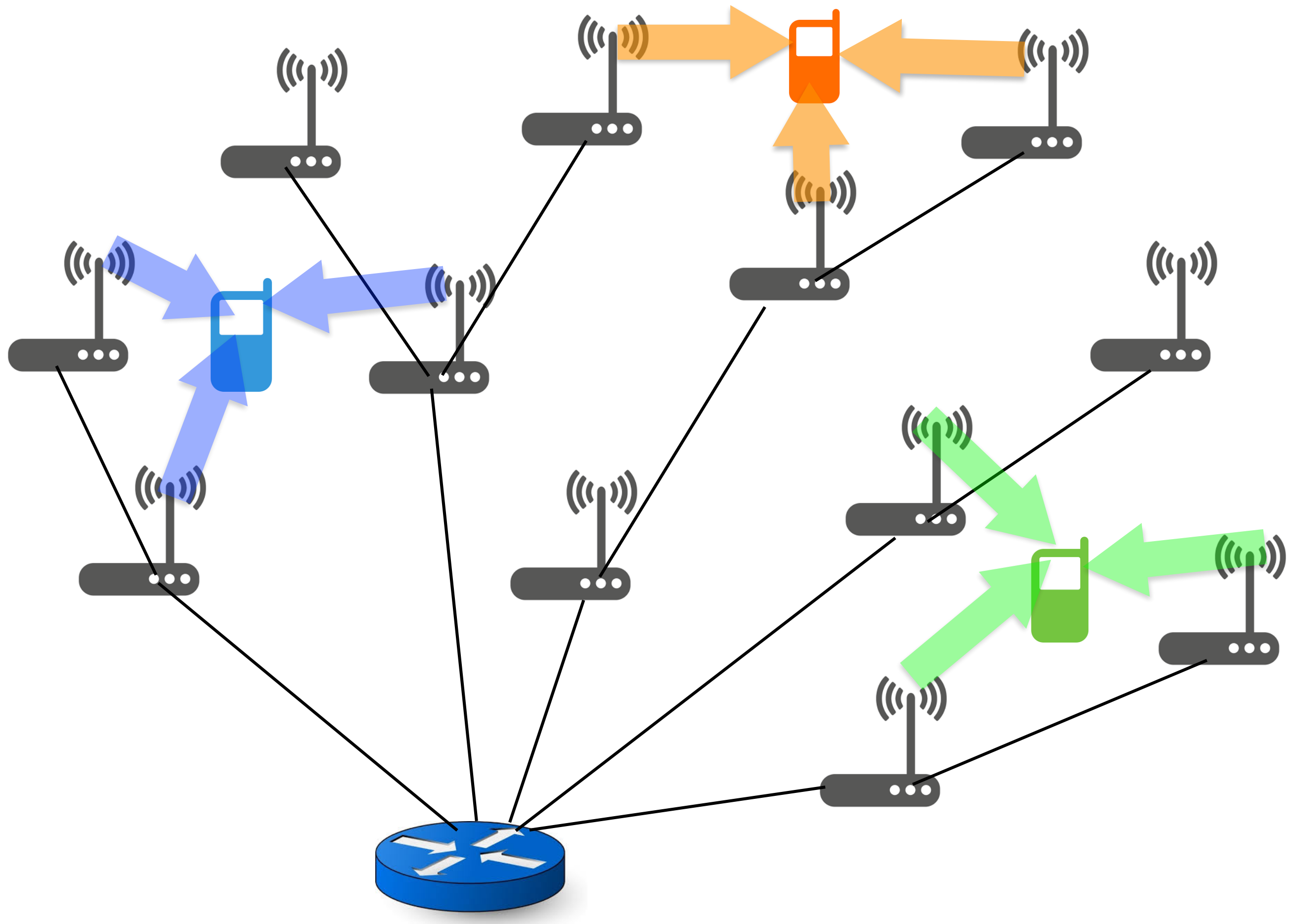
Before and after Beam Alignment

- With enough bidirectional gain, the channel reduces to a single delay and phase/frequency shift.



Cell-Free User-Centric to combat LoS blocking

- Each user is served by multiple concurrent beams in macro-diversity.



Routing with packet replication

Challenges

- Each user “sees” the superposition of multiple beamformed signals: each arrives with a different delay, and frequency offset.
- The resulting channel is frequency-selective and (potentially) rapidly varying.
- How to recombine/equalize?
- Are there modulation formats better suited than OFDM for this case?
- How to achieve “beam alignment” in a cell-free user-centric scenario? UE-driven?
- Can ISAC help for beam alignment/tracking? Can we use backscatter signals and full-duplex radar to extract environment/position information in real time and adapt beam allocation?

Thank You