Cell-free massive MIMO Networks

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Important concepts of wireless channels

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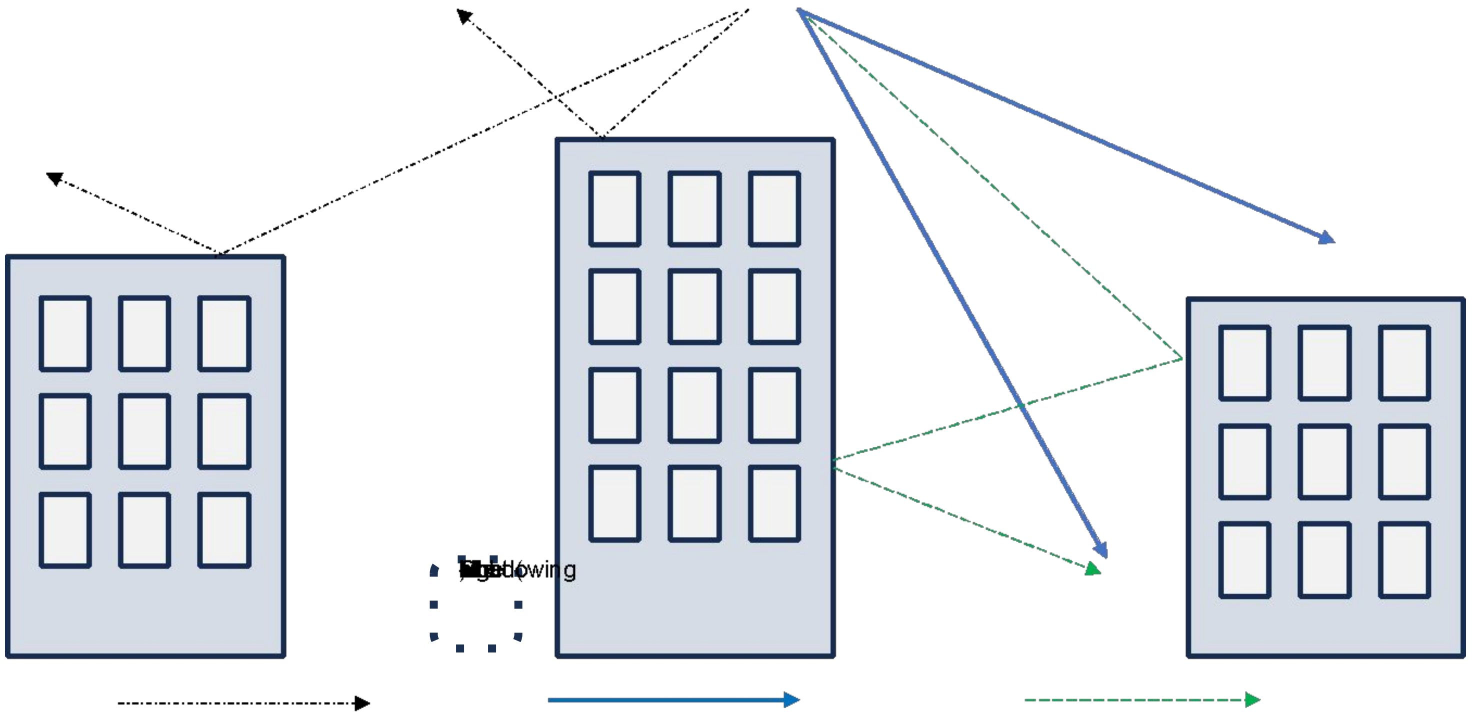
Channel propagation

Line-of-sight (LoS) propagation

Non-Line-of-Sight (NLoS) propagation (multipath)

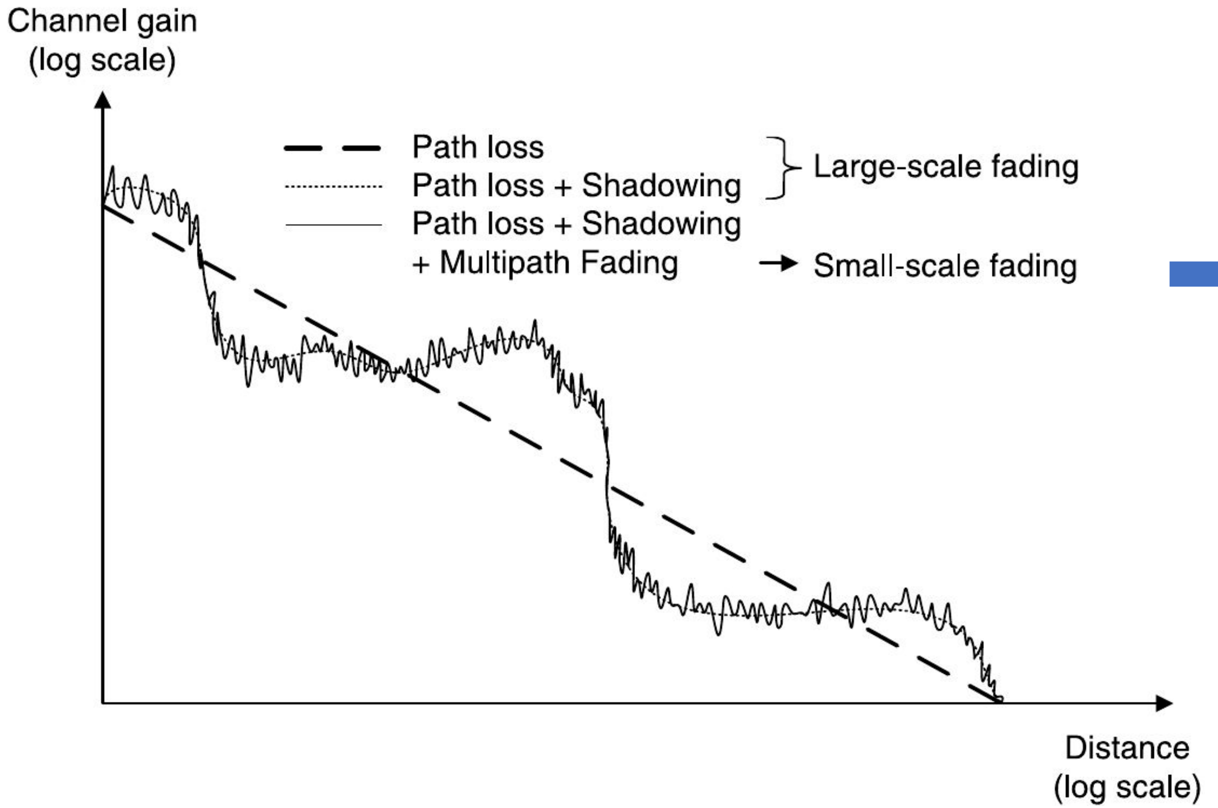
Shadowing



Channel fading

Fading

- Small-Scale Fading: rapid fluctuations in signal strength over short distances and short periods of time
- Large-Scale Fading: variations in signal strength over longer distances and time periods



A typical model

Rayleigh fading:
I.I.D random variables

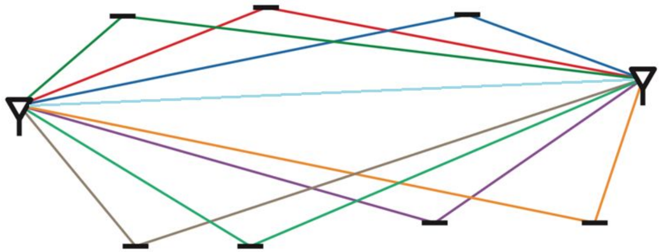
$$\mathbf{h}_{lk}^{j} \sim \mathcal{N}_{\mathbb{C}}\left(\mathbf{0}_{M_j}, \mathbf{R}_{lk}^{j}\right)$$

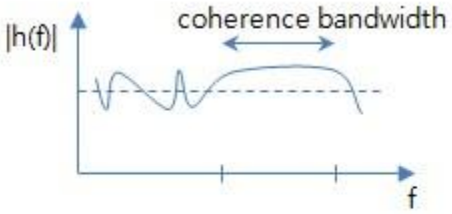
Coherence Time and Bandwidth

Coherence Block

- Coherence bandwidth

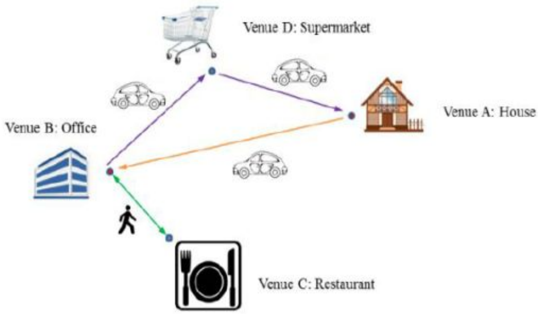
Multipath Delays → phase shifts in frequency → channel changes in frequency (→ coherence bandwidth)

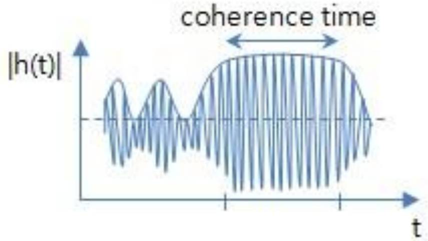




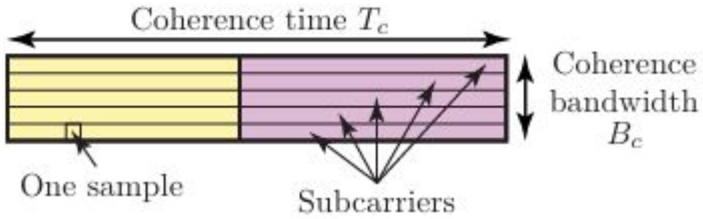
- Coherence time

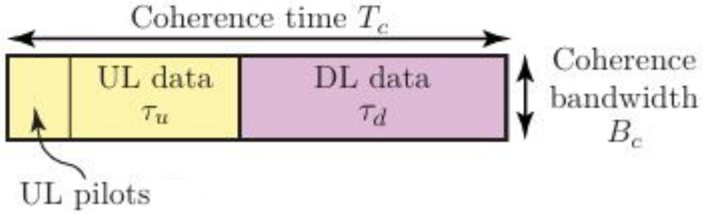
Doppler shift→ phase shift in time → channel changes in time (→ coherence time)





- Coherence block





Cellular networks, MIMO and co-located massive MIMO

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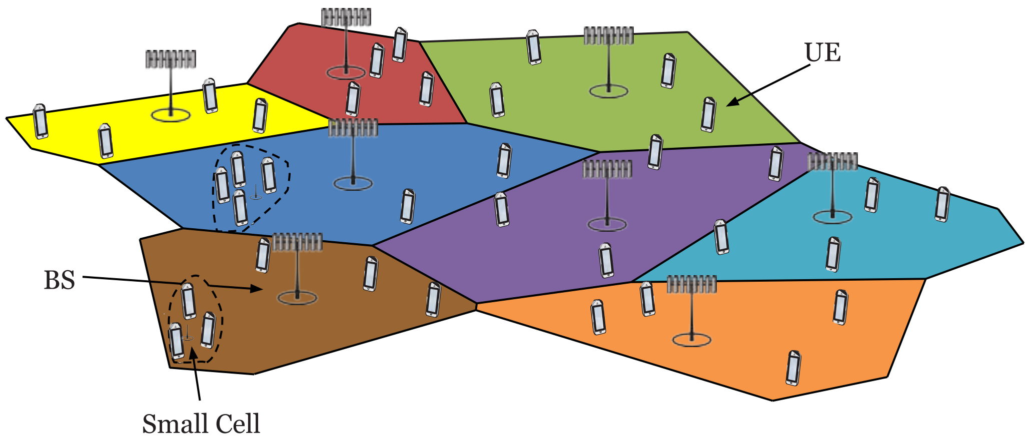
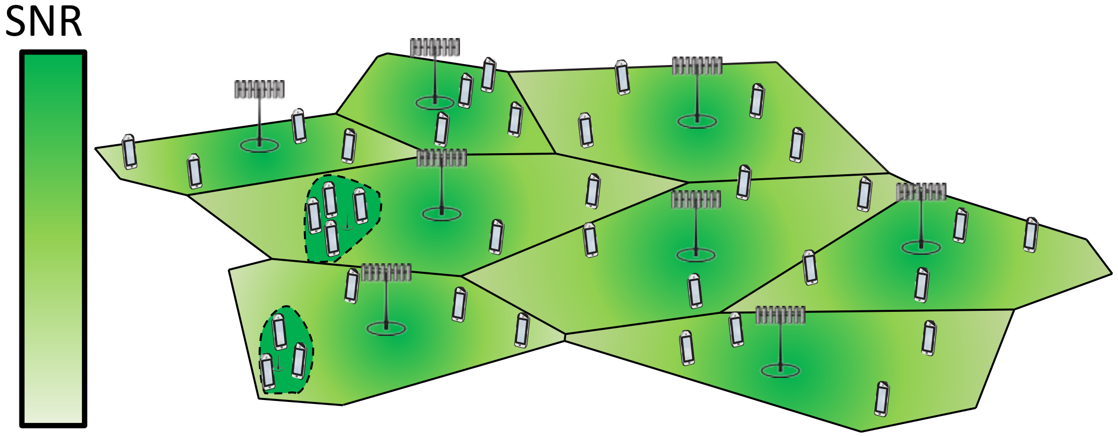
Cellular Networks

Definition

- The coverage area is called cell
- A base station (BS) serves a set of user equipment (UE)





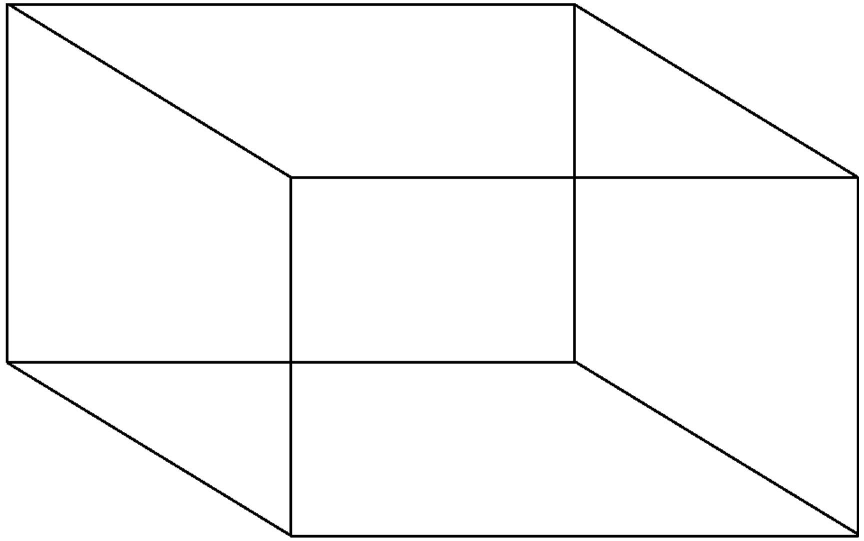
Main tiers

- Coverage tier: outdoor
- Hotspot tier: indoor and limited area outdoor service

Cellular Networks

The concept of area throughput

- Modeled as the volume of a rectangular box
- Measured in bit/s/Km^2



A question arises

- What should we improve? CD, BW or SE?
- What are the impacts of improving CD, BW or SE?

Increasing BW

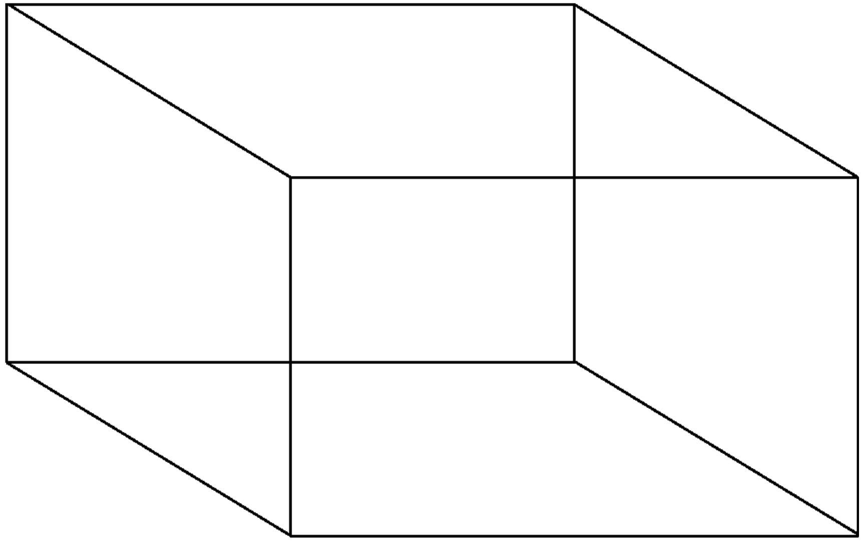
- Impaired by license and spectrum sharing
- Very hard to do for the coverage tier

Increasing CD

- There are some challenges…

Increasing SE

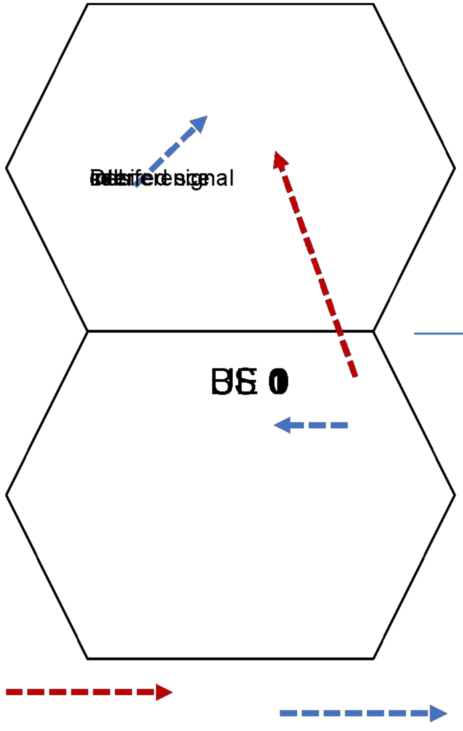
- Allows to use the BSs and bandwidth more effectively



Ways to improve the Spectral Efficiency (SE)

Increasing the transmit power

- Pushes the network into an interference-limited regime
- Example, a Line-of-Sight (LOS) case. Two cells and two UEs



Two cell Wyner model

$$\mathsf{SE}_0^{\mathrm{LoS}} = \log_2\left(1 + \frac{1}{\bar{\beta} + \frac{1}{\mathsf{SNR}_0}}\right),$$

where $\bar{\beta} = \dfrac{\beta_1^0}{\beta_0^0}$

- β_1^0: Channel gain of interfering UE 1
- β_0^0: Channel gain of UE 0

$$\frac{1}{\bar{\beta} + \frac{1}{\mathsf{SNR}_0}} = \frac{\overbrace{p\beta_0^0}^{\text{Signal power}}}{\underbrace{p\beta_1^0}_{\text{Interference power}} + \underbrace{\sigma^2}_{\text{Noise power}}}$$

$$\mathsf{SE}_0^{\mathrm{LoS}} \to \log_2\left(1 + \frac{1}{\bar{\beta}}\right) \quad \text{as} \quad p \to \infty$$

Ways to improve the Spectral Efficiency (SE)

Array gain

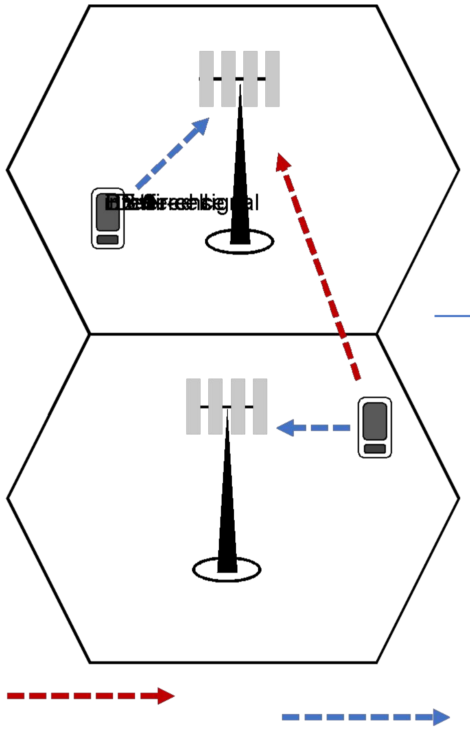
- Increase the SE by using multiple transmitting antennas (M)
- Example: Non-Line-Of-Sight (NLOS) case. Two cells and two UEs

$$\mathsf{SE}_0^{\mathrm{NLoS}} \geq \log_2\left(1 + \frac{M-1}{\bar{\beta} + \frac{1}{\mathsf{SNR}_0}}\right),$$

Array gain (M) → $M-1$

where $\bar{\beta} = \frac{\beta_1^0}{\beta_0^0}$

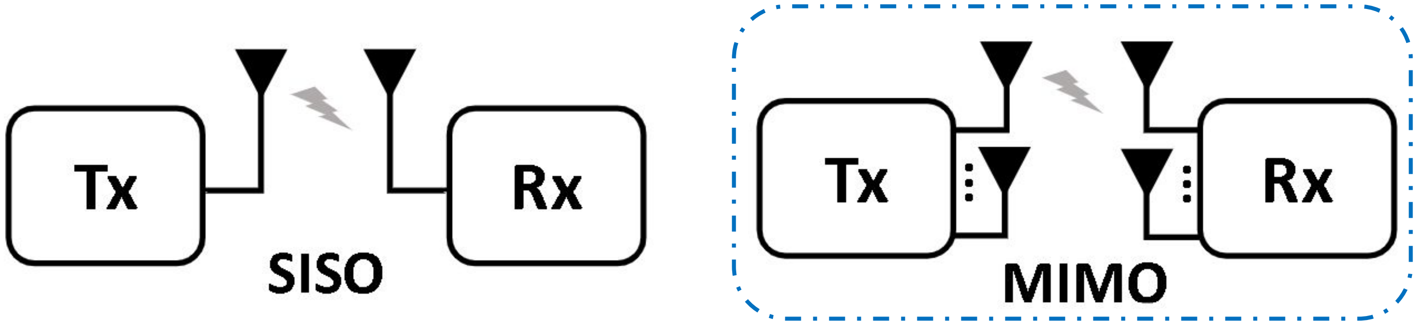
- β_1^0: Channel gain of interfering UE 1
- β_0^0: Channel gain of UE 0

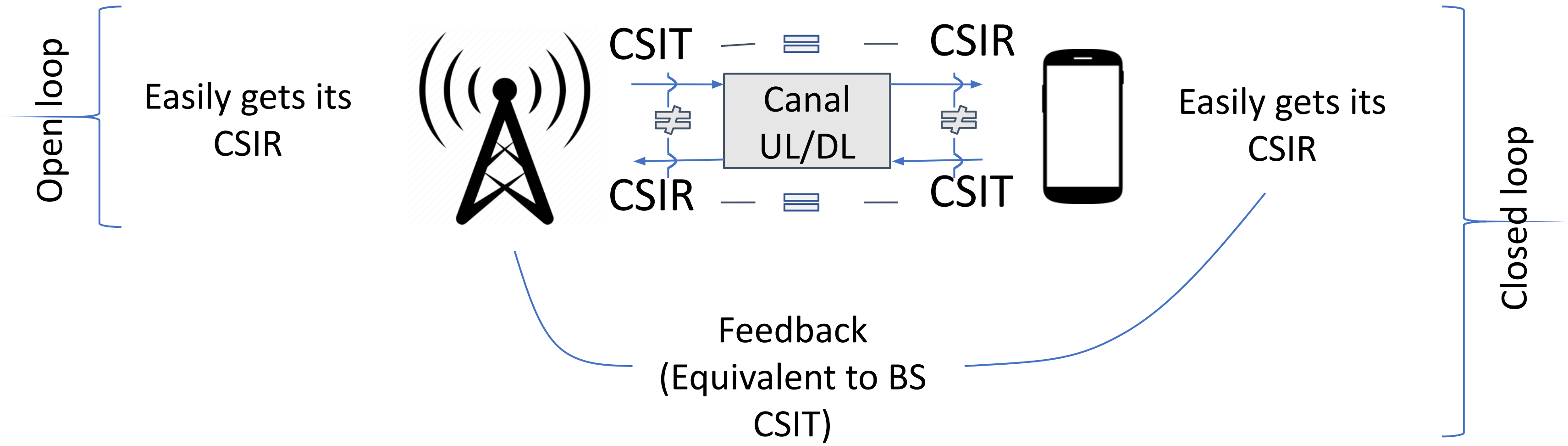


Two cell Wyner model

Basics of multi antenna communication

- Increase the SE by exploiting the array gain

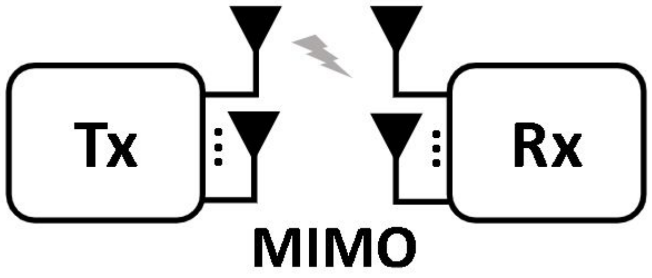




MIMO

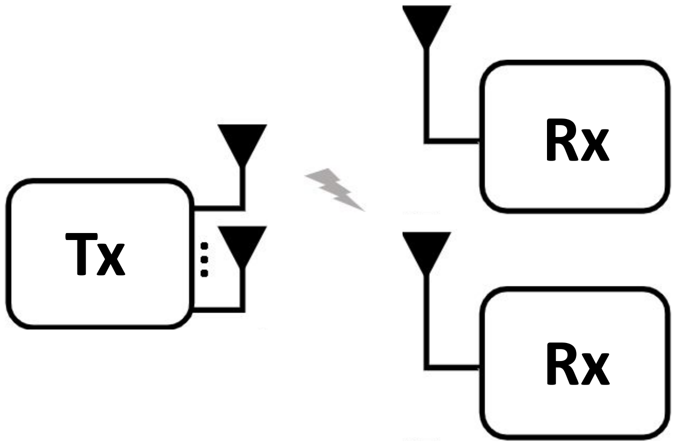
Single-user (SU) MIMO

- There is only one UE and one BS (or AP)
- Both are equipped with multiple antennas

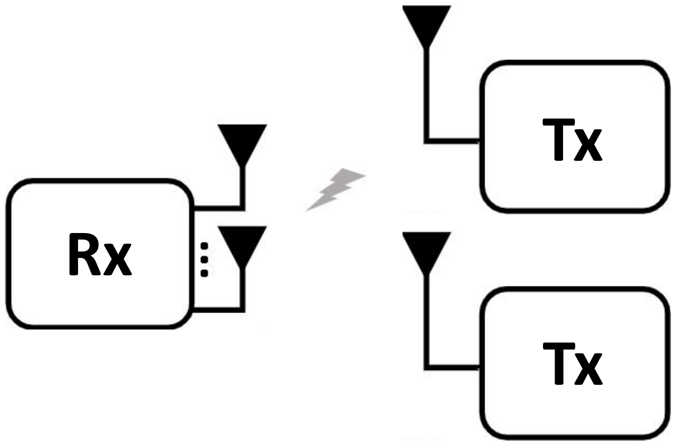


Multi-user (MU) MIMO

- BSs are equipped with multiple antennas and serve multiple UEs (single or multi antenna)

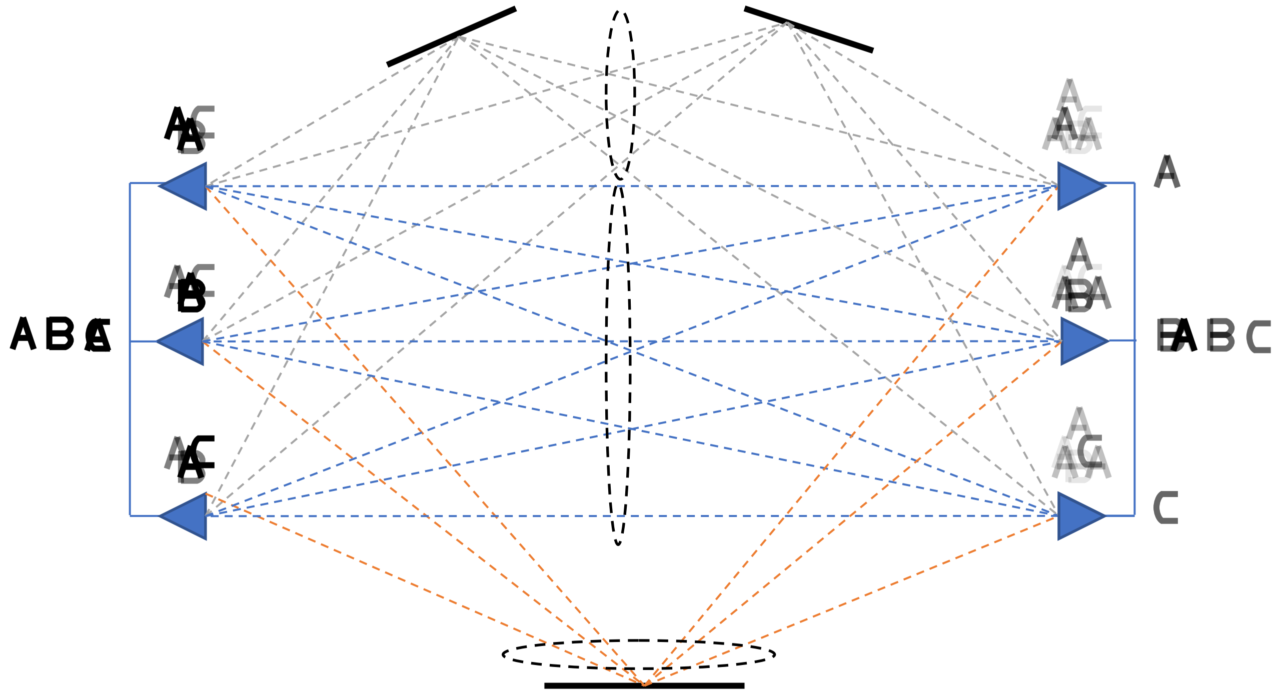


Downlink

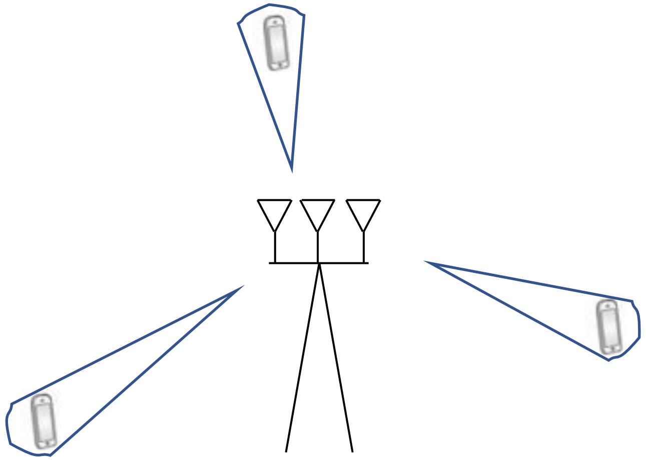


Uplink

MIMO operation types



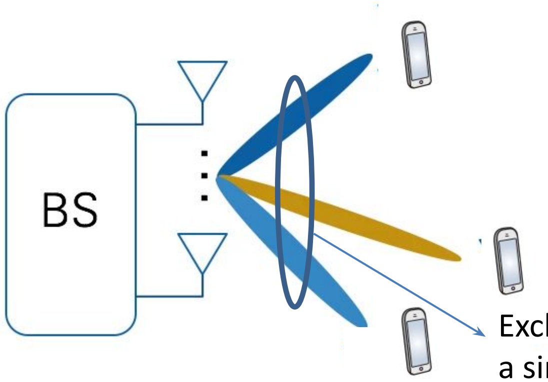
- Diversity
  - Combiner
  - Space time code
- Multiplexing
  - Precoder
  - Combiner
- Multiple Acess
  - Precoder
  - Combiner



Massive MIMO

Basics of massive MIMO

- Base stations (BSs) equipped with several antennas (64, 128 or more)
- Number of users (K) smaller than M



Exclusive channels for users in a simple way (enables linear processing)

Favorable propagation

- The channel directions become asymptotically orthogonal as *M*→

$$\frac{(\mathbf{h}_i^0)^{\mathrm{H}}\mathbf{h}_k^0}{\sqrt{\mathbb{E}\{\|\mathbf{h}_i^0\|^2\}\mathbb{E}\{\|\mathbf{h}_k^0\|^2\}}} \to 0 \quad \text{as} \quad M \to \infty$$

Channel directions $\mathbf{h}_i^0/\sqrt{\mathbb{E}\{\|\mathbf{h}_i^0\|^2\}}$ and $\mathbf{h}_k^0/\sqrt{\mathbb{E}\{\|\mathbf{h}_k^0\|^2\}}$

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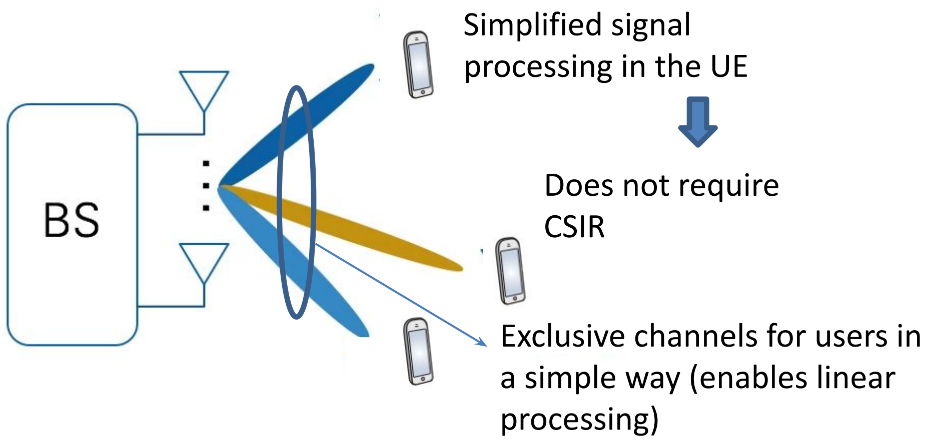

Channel Hardening

- A fast fading channel behaves almost deterministically due to spatial diversity

$$\frac{\|\mathbf{h}_i^0\|^2}{\mathbb{E}\{\|\mathbf{h}_i^0\|^2\}} = \frac{\|\mathbf{h}_i^0\|^2}{M\beta_i^0} \rightarrow 1 \quad \text{for} \quad M \rightarrow \infty$$

Massive MIMO

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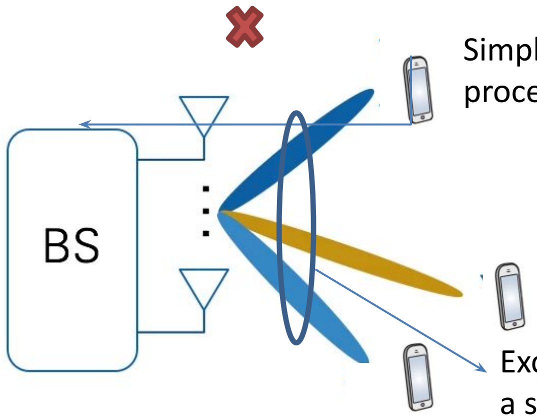
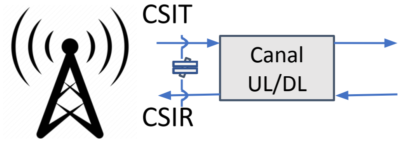
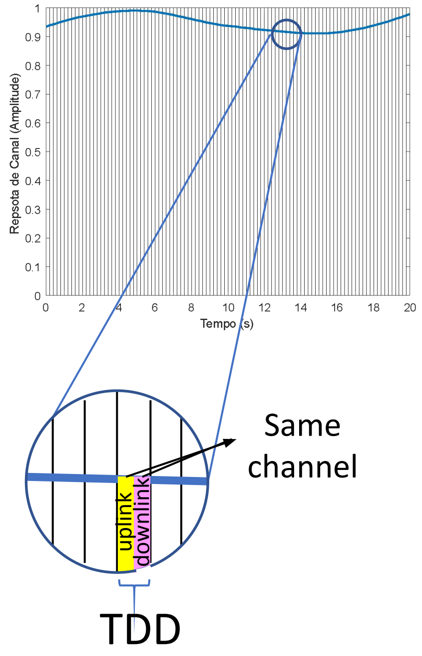


TDD coherent operation

- Reciprocal channels





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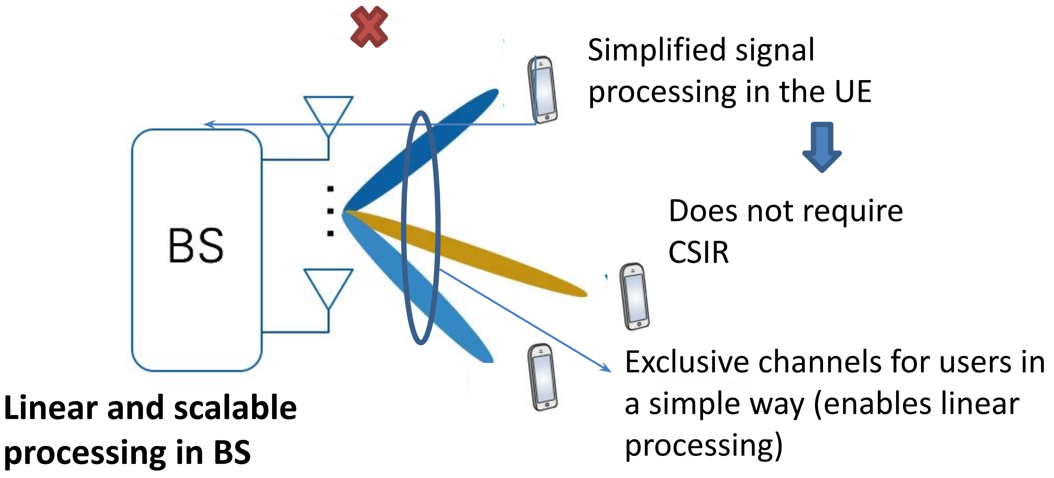

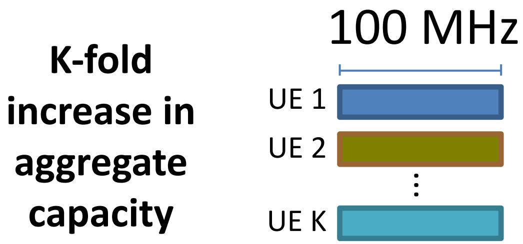

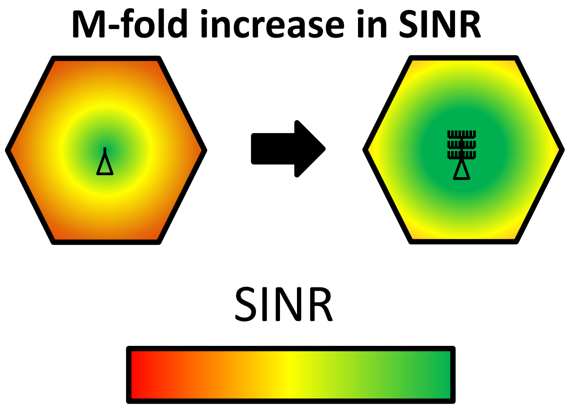

Distributed MIMO and Cell-free massive MIMO networks

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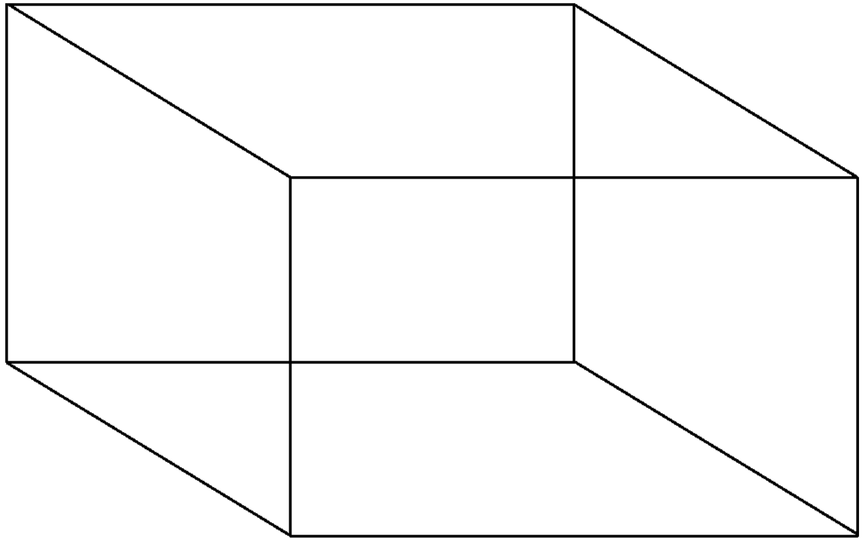
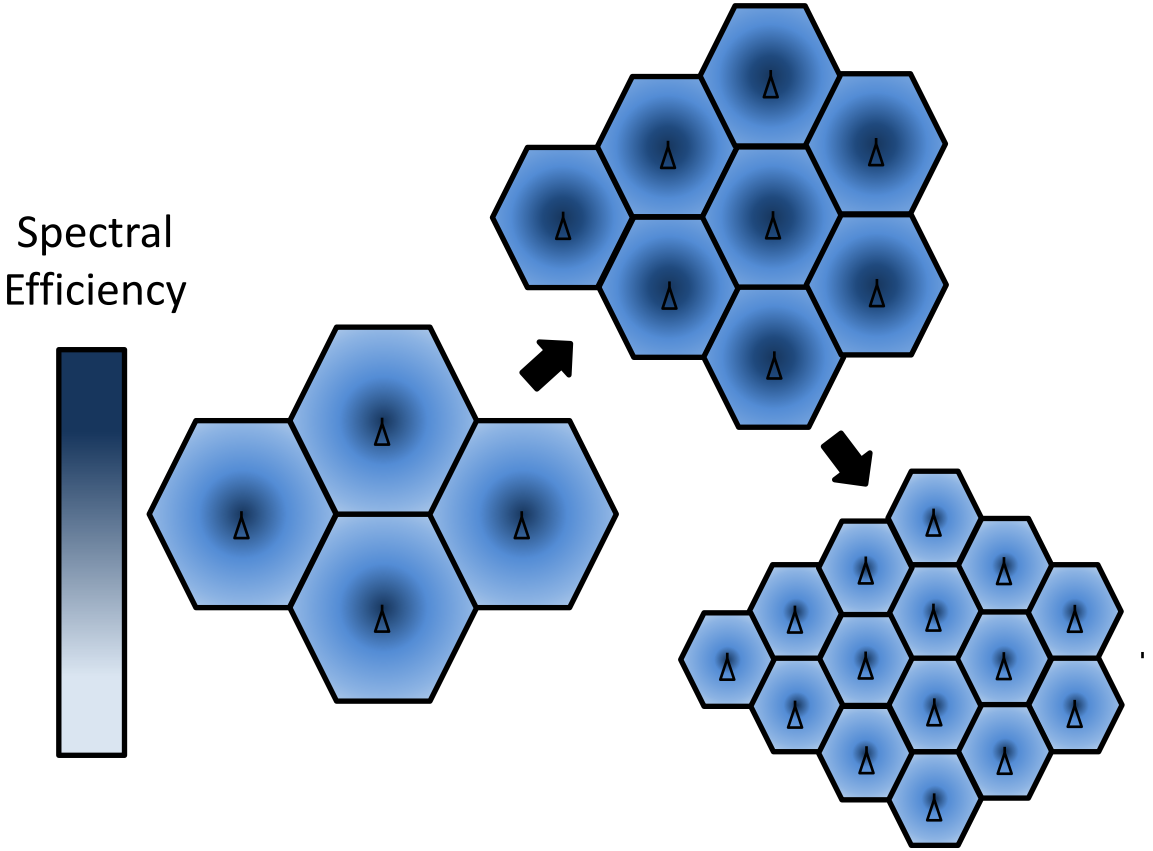
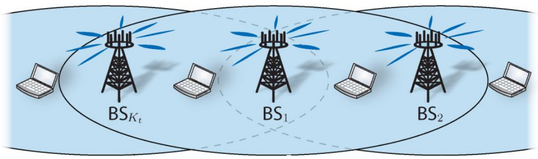


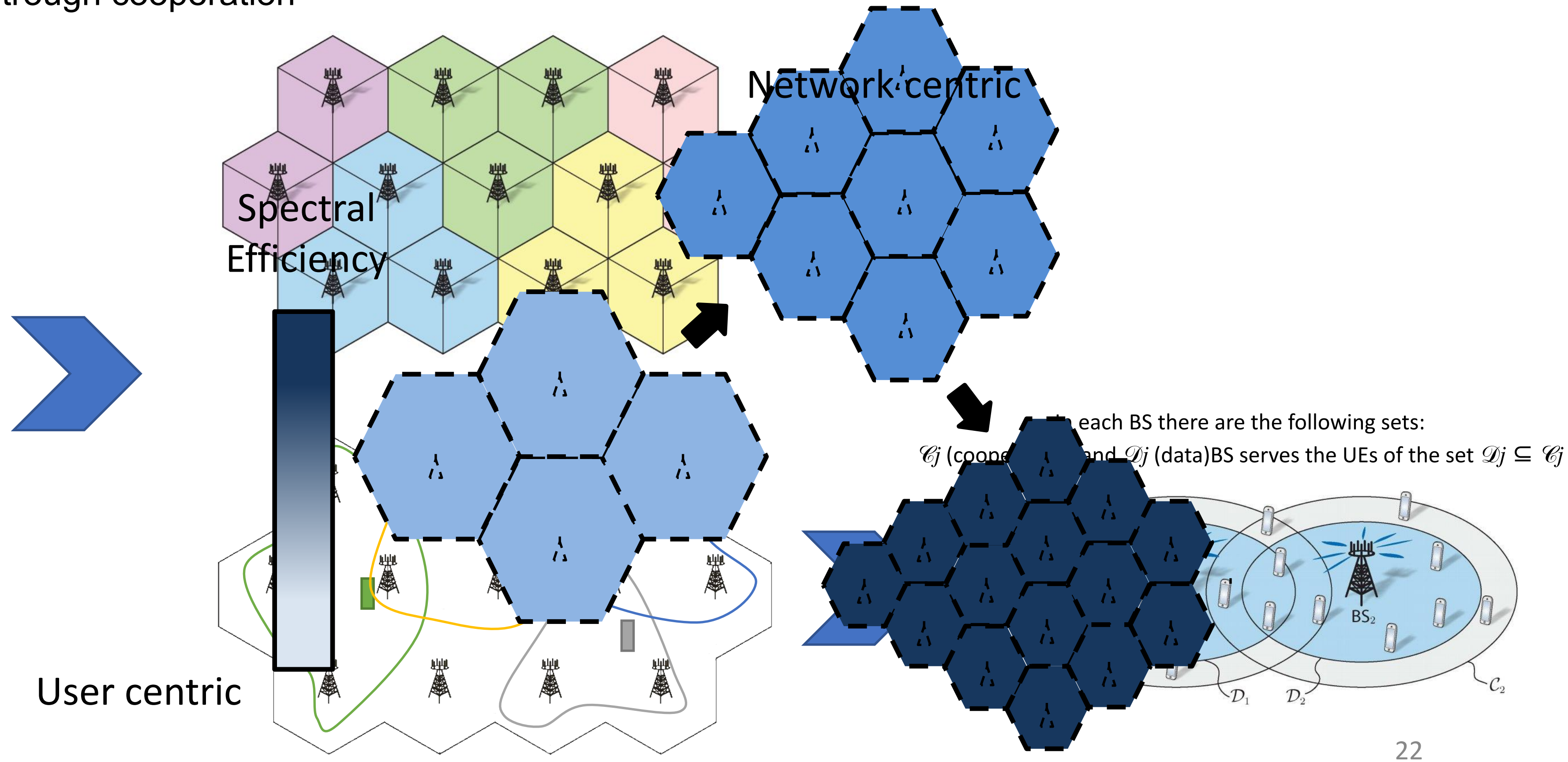

Spectral
Efficiency

Distributed MIMO systems, network MIMO

- A user is connected to more than one BS at the same time
- Target: Minimize interference trough cooperation

Macrodiversity





Why is distributed MIMO not implemented yet

MIMO distribuído vs massive MIMO

Distributed MIMO VS Massive MIMO

- Formal definition (Standardization)
- TDD
- Signal processing definition

Cell-Free

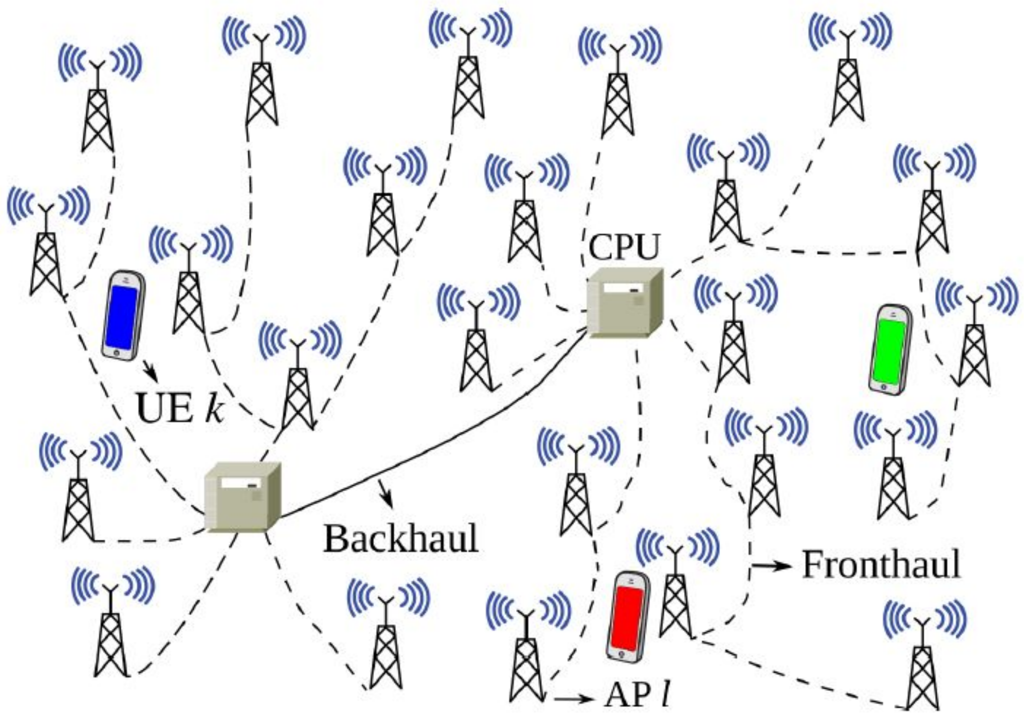
Cell-Free Massive MIMO Networks

A particular case of distributed MIMO

- The antennas are spread out in the coverage area in terminals called access points (APs)
- Benefits of massive MIMO and distributed MIMO
- Better coverage probability

Canonical cell-free

- All APs serve all UEs
- Infeasible in terms of processing and data sharing



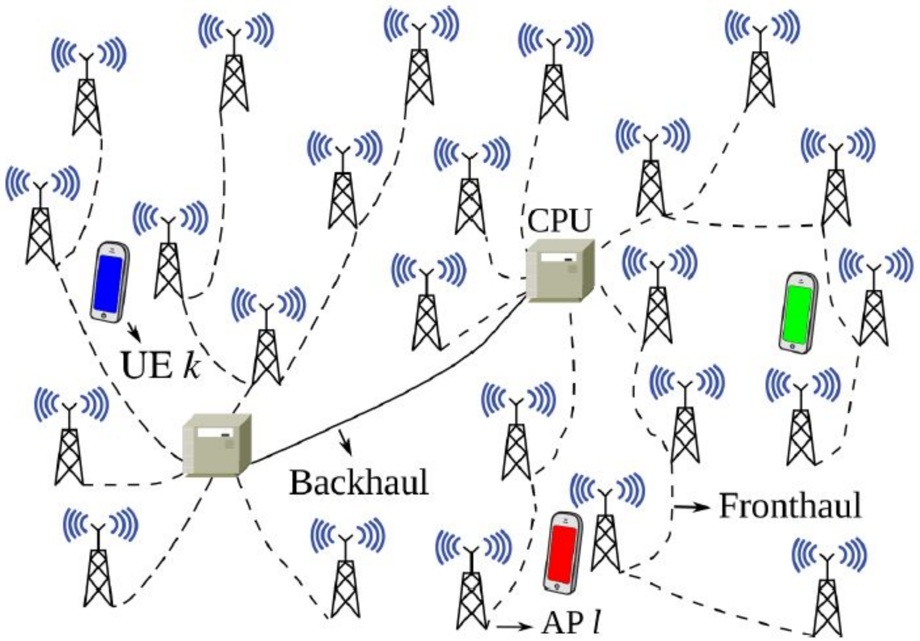
Timeline

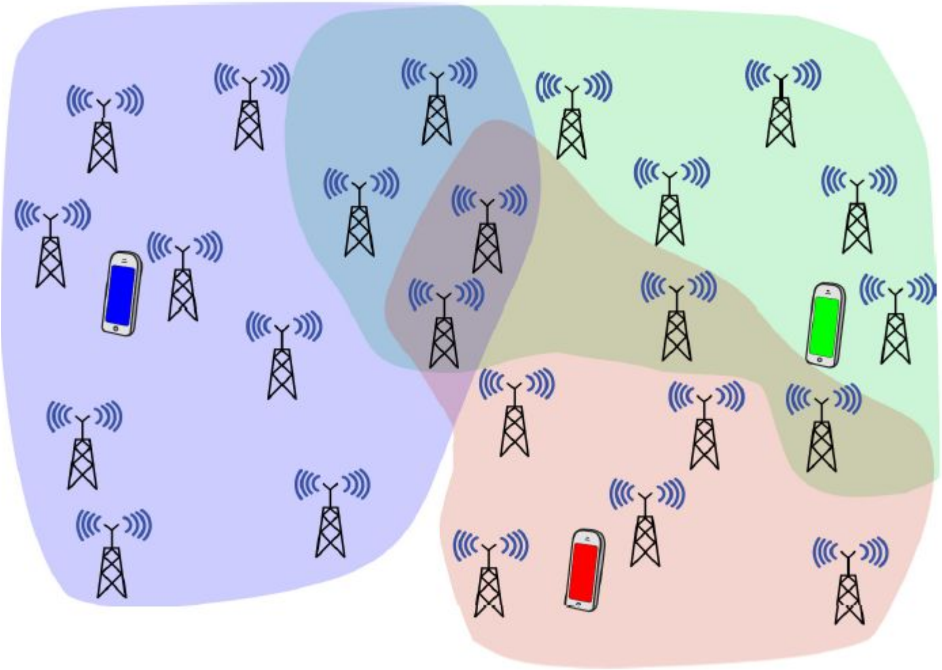
- Distributed MIMO
- Canonical cell-free massive MIMO
- User-centric cell-free massive MIMO ⟵
- Scalable user-centric cell free massive MIMO

User-Centric Cell-Free Massive MIMO Networks

User centric approach

- The UEs connect to a subset of APs called AP cluster
- Reduction of processing demands and data sharing



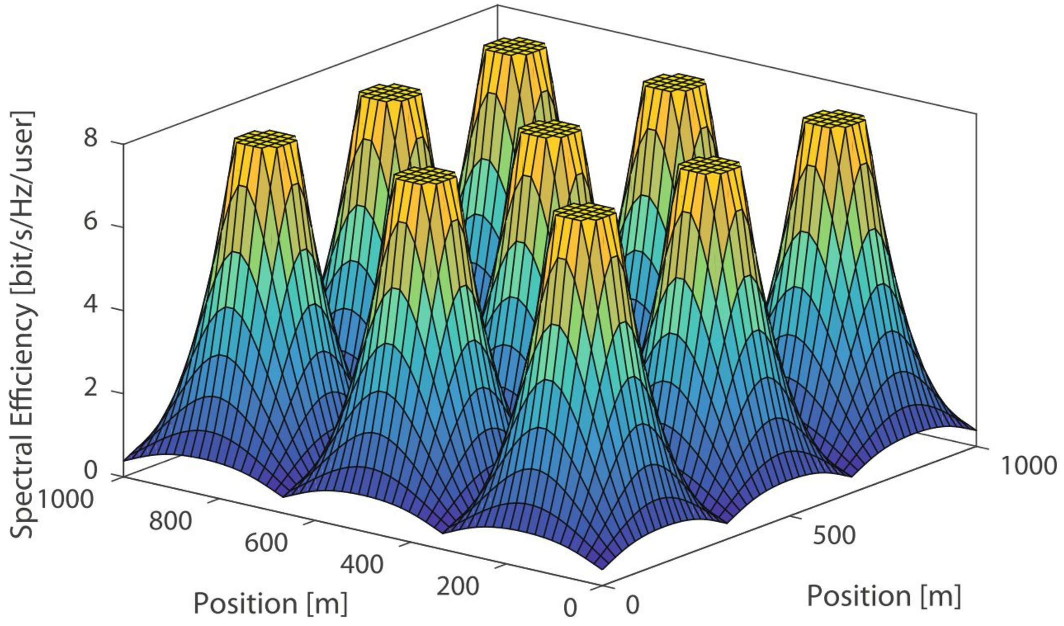


User-Centric Cell-Free Massive MIMO Networks

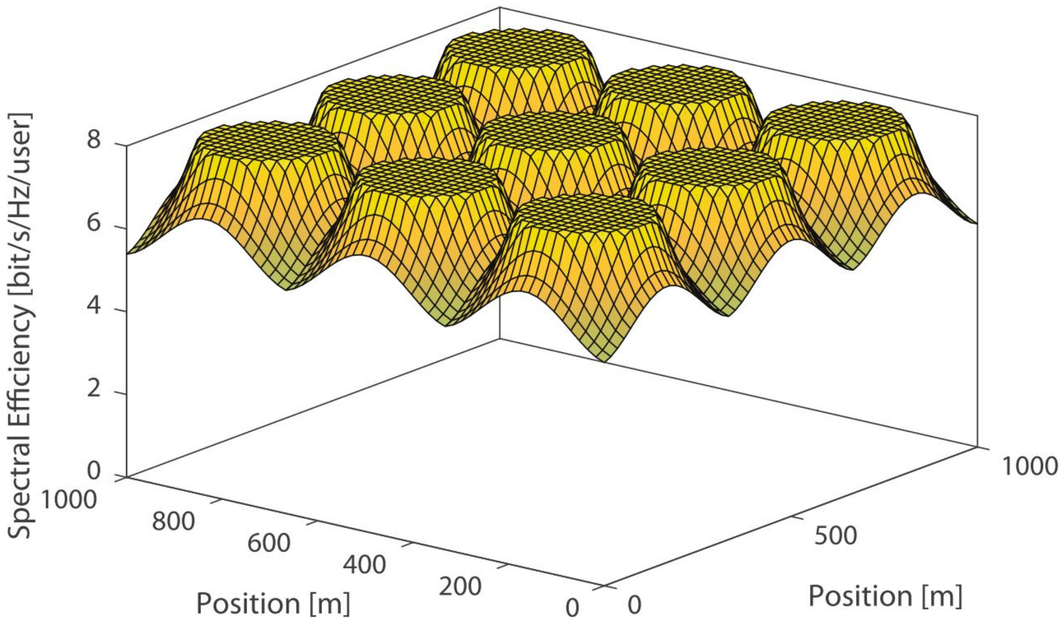
More uniform coverage than cell-based systems

- The SE of the 95% likely UEs is increased in user-centric cell-free massive MIMO systems
- Parameters setting: nine APs are deployed on a regular grid; UEs at different locations

Cellular network



User-centric cell-free massive MIMO



Evolution of Cell-Free Massive MIMO Networks

Timeline

- Distributed MIMO
- Canonical cell-free massive MIMO
- User-centric cell-free massive MIMO
  - Also known as **User-centric distributed massive MIMO**
- Scalable user-centric cell free massive MIMO ⟵

Scalable user-centric cell free massive MIMO

Scalability

- User-centric cell-free massive MIMO systems are not scalable

- To determine whether a system is scalable or not, let $K \to \infty$ and check which of the following points are implementable:

  1) Signal processing for channel estimation
  2) Signal processing for data reception and transmission
  3) Fronthaul signaling for data and CSI sharing
  4) Power control optimization

Definition

- A cell-free massive MIMO systems is scalable if the four above-listed points have finite complexity and resource requirements for each AP as $K \to \infty$

- Necessary condition: limit the number of UEs that each AP can serve

Modelling a cell-free massive MIMO network

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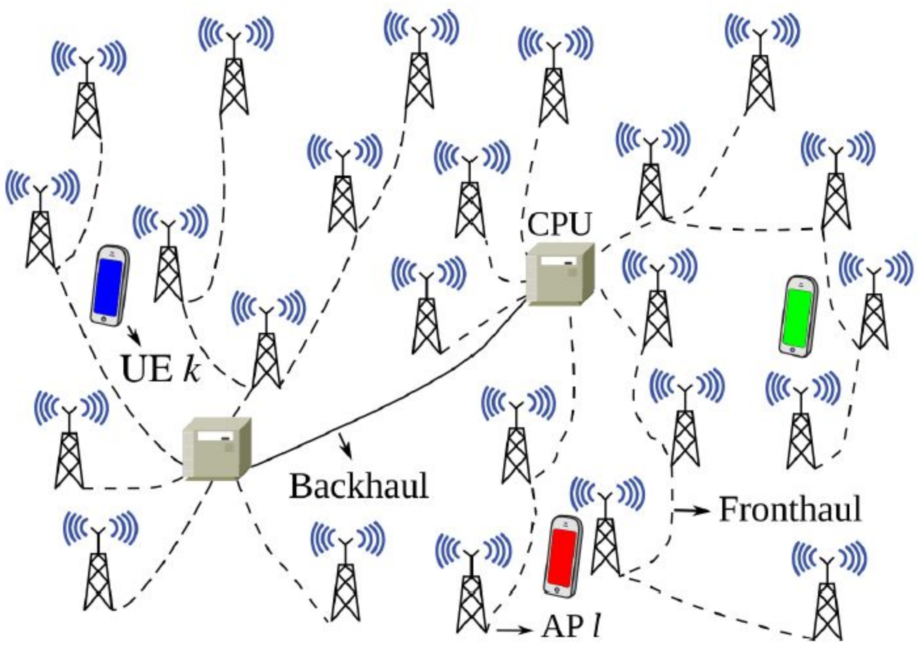
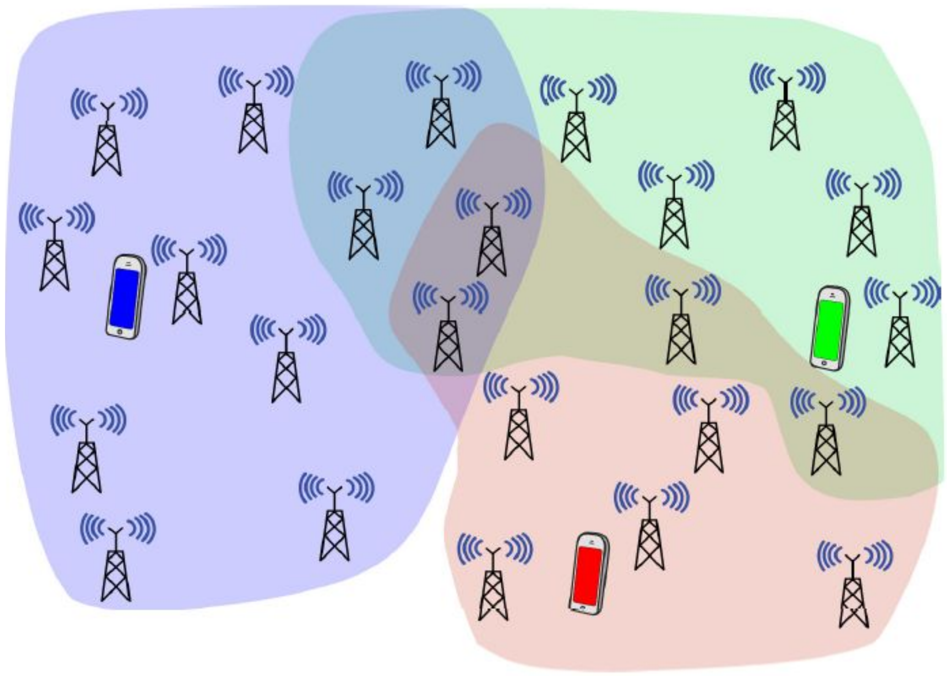
User-centric cell-free massive MIMO networks

System model

- It is considered a cell-free massive MIMO network composed of L APs and K UEs
- Each AP is equipped with N antennas
- The total number of antennas in the network is $M = NL$

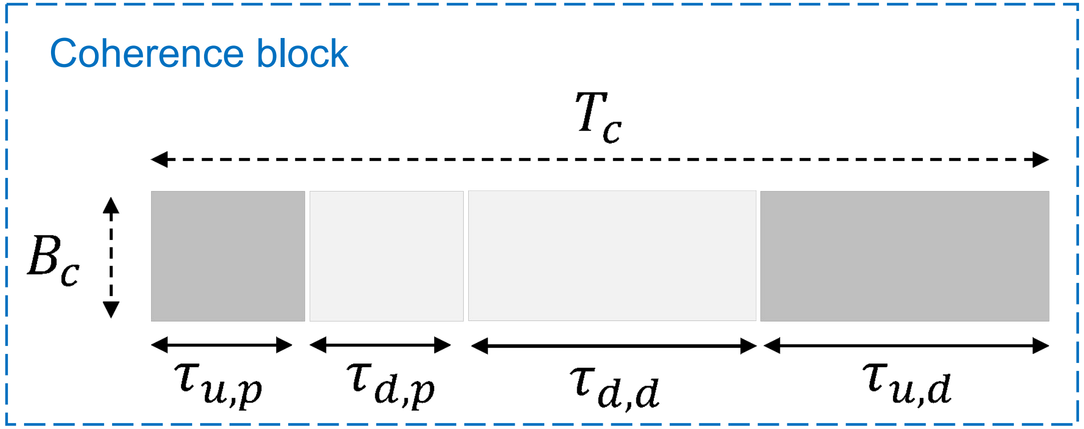




Time Division Duplexing (TDD) Protocol

Simplified frame structure and important concepts

- Coherence time (T_c) : the frequency response of a fading channel becomes flat (constant)
- Coherence bandwidth (B_c) : the bandwidth associated with the coherence time
- Coherence block (τ_c): number of complex samples available for signal transmission



Number of samples per coherence block:

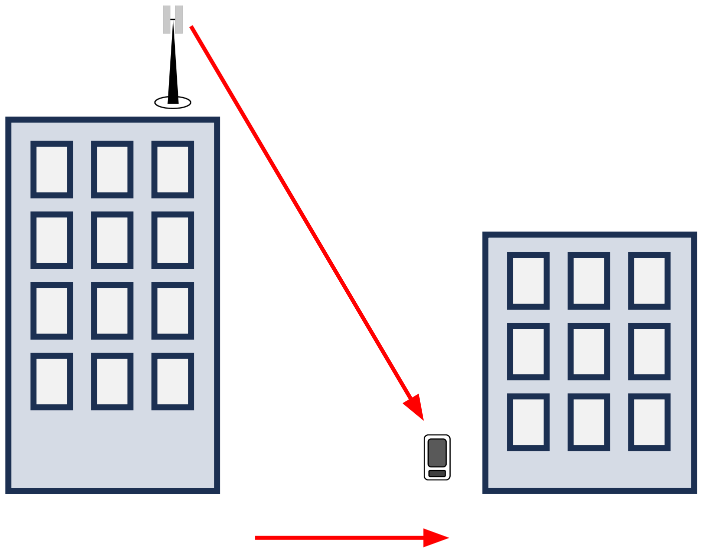
$$\tau = B_c T_c \rightarrow T_c = \frac{\lambda}{4v} \quad B_C = \frac{1}{2T_D}$$

$$\tau = \tau_{u,p} + \tau_{d,p} + \tau_{d,d} + \tau_{u,d}$$

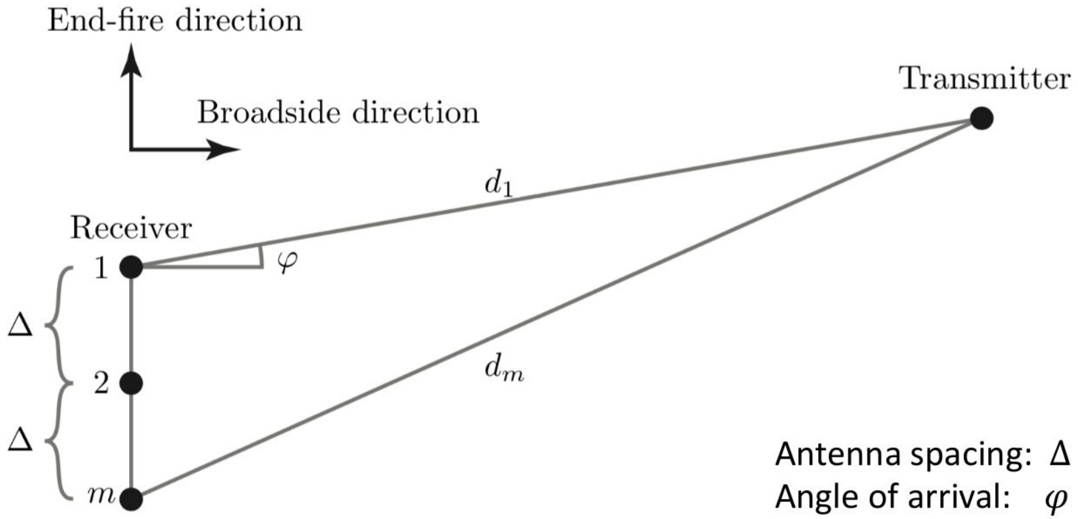
TDD can exploit reciprocity

System model: LoS component

- The channel vector between the AP *l* and UE *k* is denoted as $\mathbf{h}_{kl} \in \mathbb{C}^{N \times 1}$ and it can be calculated as



Uniform linear array



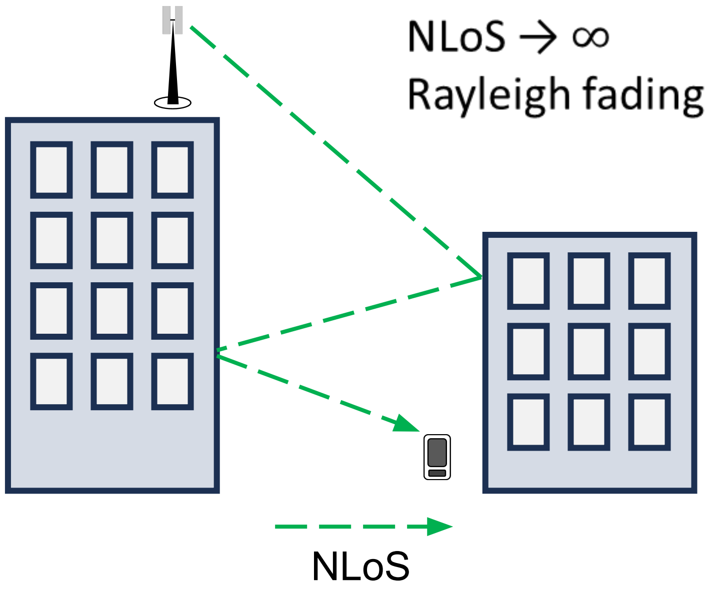
Antenna spacing: Δ
Angle of arrival: φ

$$\mathbf{h}_{kl}^{\text{LoS}} = \sqrt{\beta_{kl}} \left[1, e^{-\text{j}\pi \sin(\varphi_{kl}) \cos(\theta_{kl})}, \cdots, e^{-\text{j}(N-1)\pi \sin(\varphi_{kl}) \cos(\theta_{kl})}\right]^{\text{T}}$$

Large-scale gain (β_{kl}) · Azimuth angle (φ_{kl}) · Elevation angle (θ_{kl})

System model: NLoS component

- The channel vector between the AP *l* and UE *k* is denoted as $\mathbf{h}_{kl} \in \mathbb{C}^{N\times 1}$ and it can be calculated as



Statistical covariance matrix

$$\mathbf{R}_{kl} \in \mathbb{C}^{N\times N}$$

$$\mathbf{h}_{kl} = \sqrt{\mathbf{R}_{kl}}\,\mathbf{g}_{kl}$$

$$\mathbf{g}_{kl} \in \mathbb{C}^{N\times 1}$$

Composed of elements that are i.i.d complex Gaussian RVs, i.e., $\mathcal{N}_{\mathbb{C}}(0,1)$

- For all APs in the network, we have

$$\mathbf{h}_k = \left[\mathbf{h}_{k1}^{\mathrm{T}}, \ldots, \mathbf{h}_{kL}^{\mathrm{T}}\right]^{\mathrm{T}} \in \mathbb{C}^{M\times 1} \qquad \mathbf{R}_k = \mathrm{diag}\left(\mathbf{R}_{k1}, \ldots, \mathbf{R}_{kL}\right) \in \mathbb{C}^{M\times M}$$

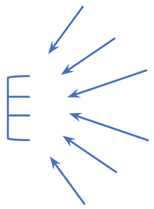
Collective vector

System model: Correlation matrix

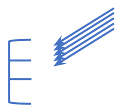
- Matrix describing the macroscopic effects of propagation, including antenna gains and radiation patterns at the transmitter and receiver.

$$\mathbf{R}_{kl} = \begin{bmatrix} \text{Large-scale gain ant. 1} & \text{Corr. ant. 1 }\backslash\text{\& 2} & \text{Corr. ant. 1 }\backslash\text{\& 3} \\ \text{Corr. ant. 2 }\backslash\text{\& 1} & \text{Large-scale gain ant. 2} & \text{Corr. ant. 2 }\backslash\text{\& 3} \\ \text{Corr. ant. 3 }\backslash\text{\& 1} & \text{Corr. ant. 3 }\backslash\text{\& 2} & \text{Large-scale gain ant. 3} \end{bmatrix} \qquad \mathbf{R}_k = \mathrm{diag}\left(\mathbf{R}_{k1}, \ldots, \mathbf{R}_{kL}\right) \in \mathbb{C}^{M \times M}$$

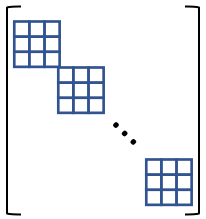
For N=3



Uncorrelated channel

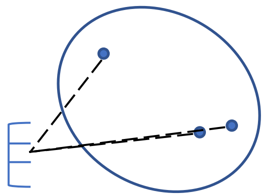


Correlated channel



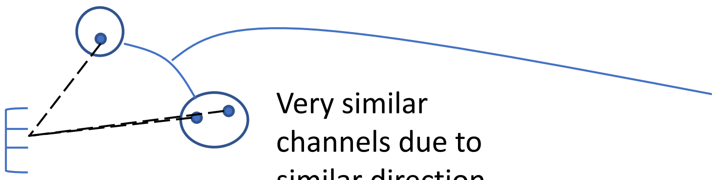
- The presence of correlation in the channel can favor or hinder interference cancellation

Absence of correlation



All users have uniformly different channels

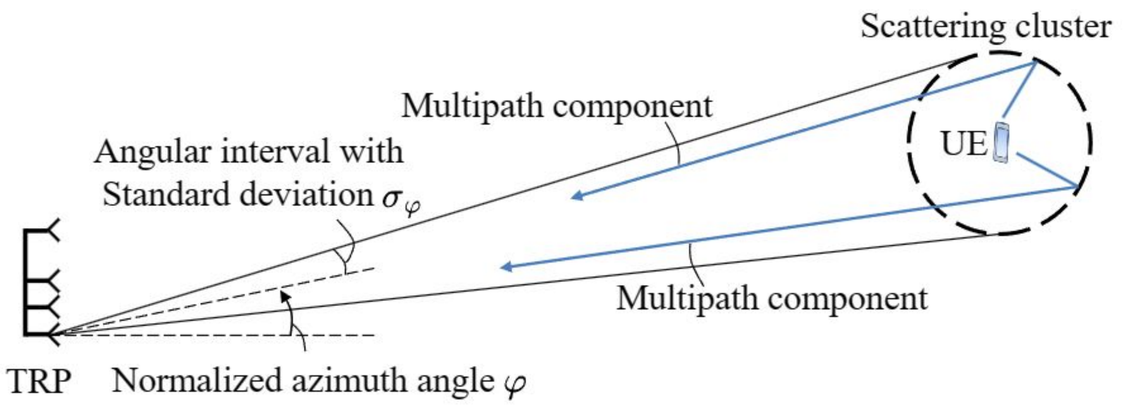
Existence of correlation



Very similar channels due to similar direction, strong interference

Very different channels due to very different directions, weak interference

System model: Correlation matrix



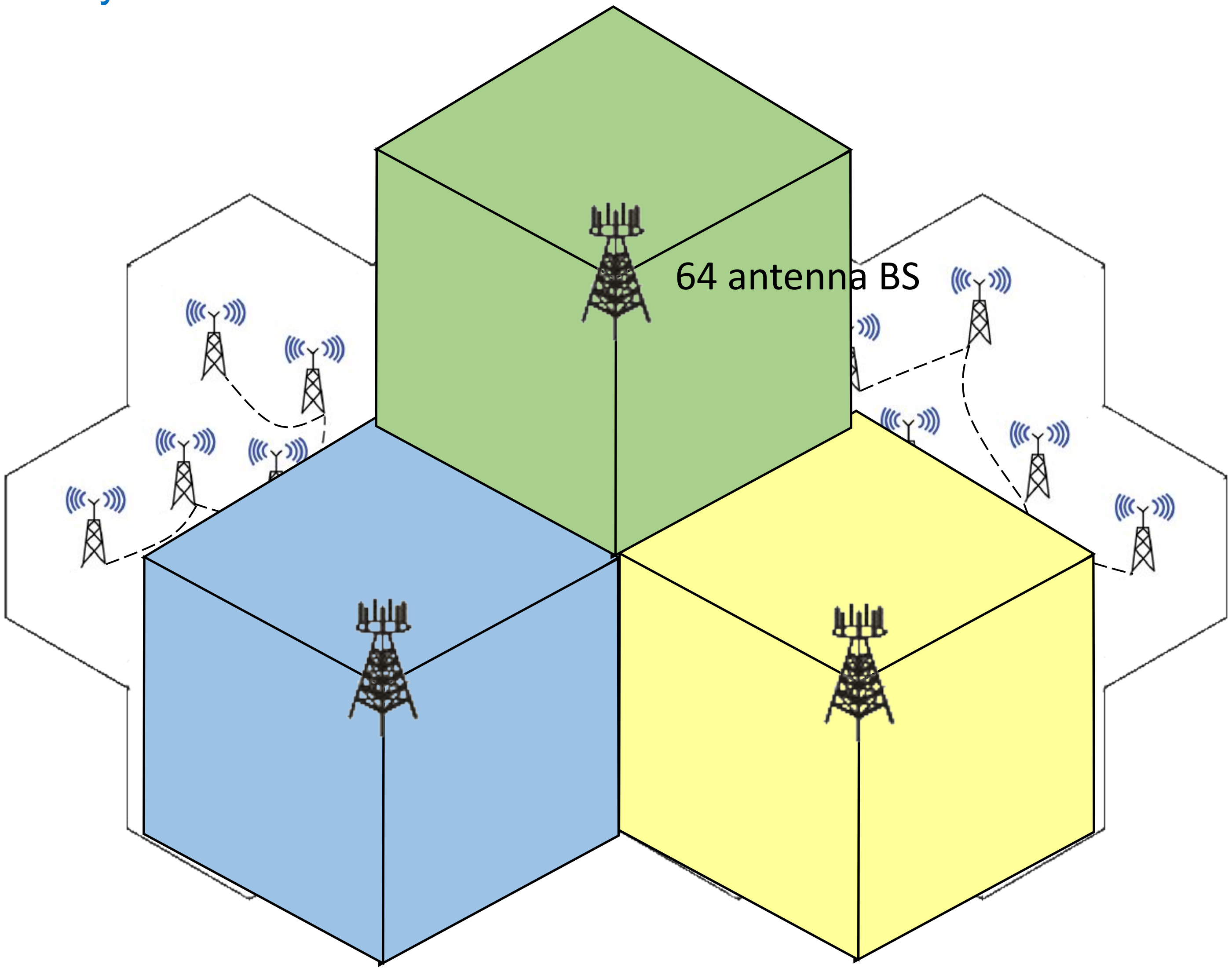
$$[\mathbf{R}]_{l,m} = \beta \int e^{2\pi \mathrm{j} d_{\mathrm{H}}(l-m)\sin(\bar{\varphi})} f(\bar{\varphi}) d\bar{\varphi} \qquad \bar{\varphi} = \varphi + \delta$$

$$[\mathbf{R}]_{m\ell} = \beta \int \int e^{\cdots} f(\bar{\varphi},\bar{\theta}) d\bar{\varphi} d\bar{\theta} \qquad f(\bar{\varphi},\bar{\theta}) = \frac{1}{\cdots} e^{-\frac{(\bar{\varphi}-\varphi)^2}{2\sigma_\varphi^2}} e^{-\frac{(\bar{\theta}-\theta)^2}{2\sigma_\theta^2}}$$

$$\delta \sim \mathcal{N}(0, \sigma_\varphi^2) \qquad \delta \sim U[-\sqrt{3}\sigma_\varphi, \sqrt{3}\sigma_\varphi] \qquad \delta \sim \mathrm{Lap}(0, \sigma_\varphi/\sqrt{2})$$

User-centric cell-free massive MIMO network

System model: Channel Model

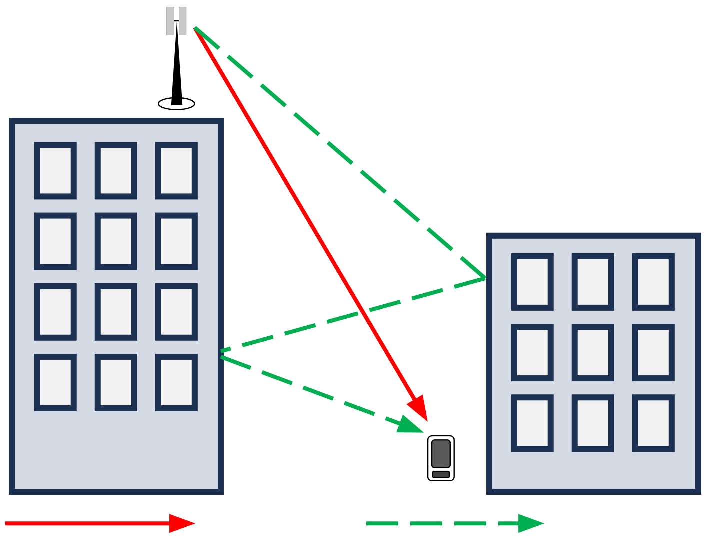


Low LOS probability

High LOS probability

System model: Channel Model

- The channel vector between the AP *l* and UE *k* is denoted as $\mathbf{h}_{kl} \in \mathbb{C}^{N\times 1}$ and it can be calculated as



$$\mathbf{h}_{kl} = \underbrace{\sqrt{\frac{\kappa_{kl}}{1+\kappa_{kl}}}\mathbf{h}_{kl}^{\mathrm{LOS}}\, e^{j\theta_{kl}}}_{\bar{\mathbf{h}}_{kl}\, e^{j\theta_{kl}}} + \underbrace{\sqrt{\frac{1}{1+\kappa_{kl}}}\mathbf{h}_{kl}^{\mathrm{NLOS}}}_{\tilde{\mathbf{h}}_{kl}},$$

Rician factor

Random phase shifts: $\theta_{kl} \sim \mathcal{U}[0, 2\pi)$

LoS component

NLoS component

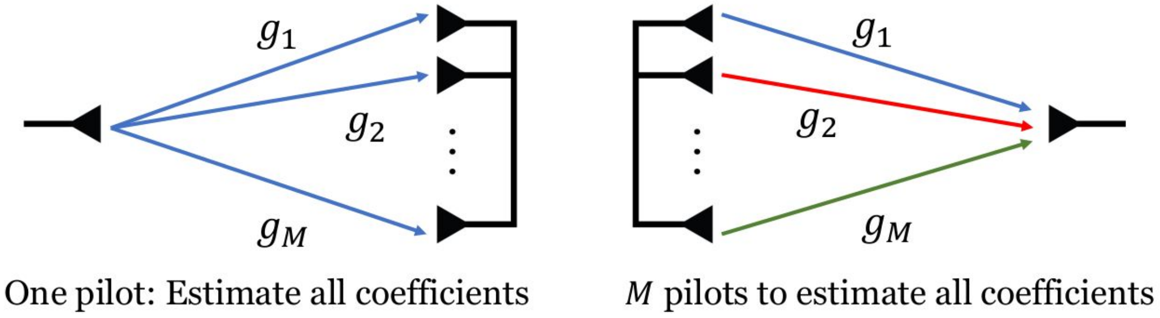
- Rician factor is the power ratio between LoS and NLoS component

$$\kappa_{kl} = 10^{13-0.03 d_{lk}}$$ → Distance

$$\kappa_{kl} = \frac{p_{\mathrm{LoS}}(d_{lk})}{1 - p_{\mathrm{LoS}}(d_{lk})}$$ → LoS probability

System model: channel estimation

- The channel vector is estimated by transmitting pilots



Scales with the number of transmitters

- Pilots are known signals designed to be mutually orthogonal

$$\phi_{t_1}^{\mathrm{H}} \phi_{t_2} = \begin{cases} \sqrt{\tau_p}, & \text{if } t_1 = t_2 \\ 0, & \text{if } t_1 \neq t_2. \end{cases}$$

- Example: [0 0 0 1], [0 0 1 0], [0 1 0 0], [1 0 0 0]

n samples = *n* orthogonal pilots!

User-centric cell-free massive MIMO network

System model: channel estimation

- AP *l* receives the signal of all users

Power, Noise

$$\mathbf{y}_l^{\text{pilot}} = \sum_{k=1}^{K} \sqrt{\eta_k}\,\mathbf{h}_{kl}\phi_{t_k} + \mathbf{n}_l$$

- To estimate the channel of UE *k,* AP *l* correlates with its pilot

$$\mathbf{y}_{t_k l}^{\text{pilot}} = \phi_{t_k}^{\text{H}}\mathbf{y}_l^{\text{pilot}} = \sum_{i\in\mathcal{P}_k}\sqrt{\tau_p\eta_i}\,\mathbf{h}_{il} + \mathbf{n}_{t_k l},$$

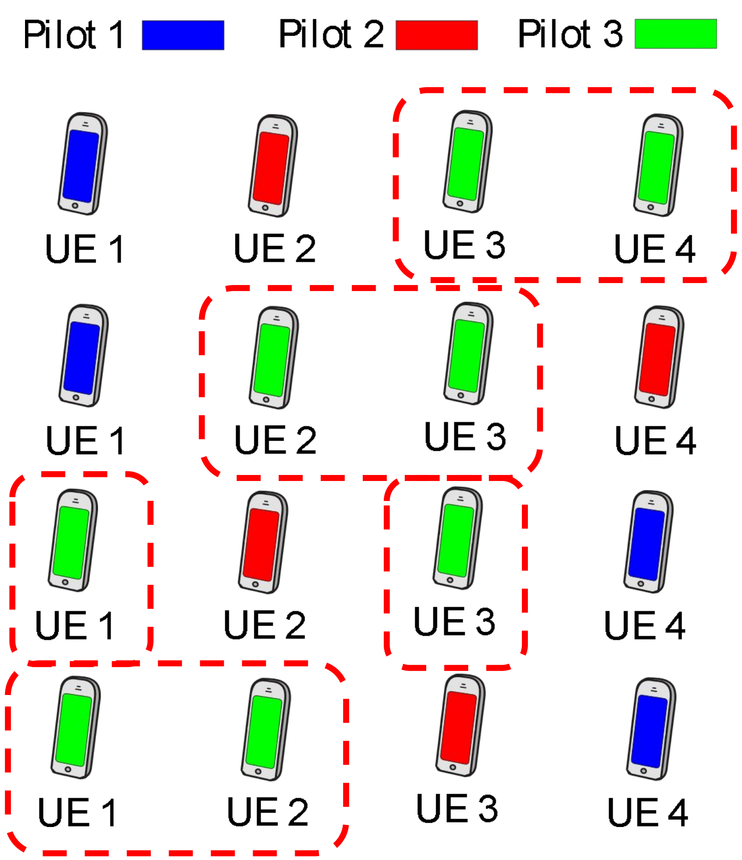
All UEs with pilot index t_k

- Pilot interference happens among users with the same pilot

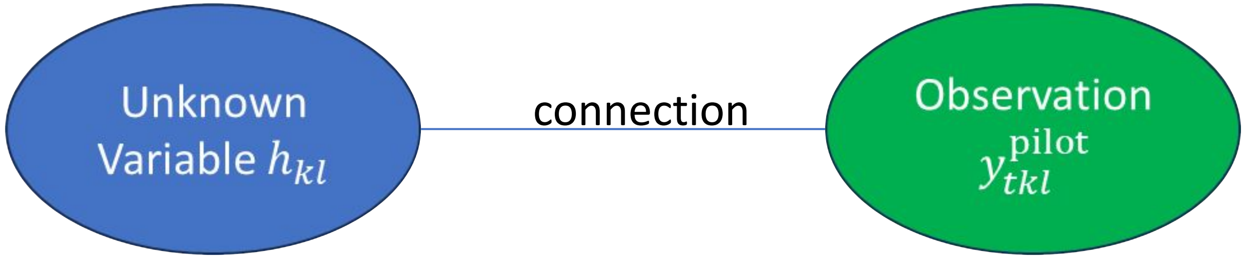
$$\mathbb{E}\left\{\widehat{\mathbf{h}}_{kl}\widehat{\mathbf{h}}_{il}^{\text{H}}\right\} = \sqrt{\eta_k\eta_i}\,\tau_p\mathbf{R}_{kl}\boldsymbol{\Psi}_{t_k l}^{-1}\mathbf{R}_{il}, \quad i \in \mathcal{P}_k.$$

$$\mathbf{R}_{kl} = \mathbb{E}\{\mathbf{h}_{kl}\mathbf{h}_{kl}^{\text{H}}\} = (\overline{\mathbf{h}}_{kl}\overline{\mathbf{h}}_{kl}^{\text{H}} + \widetilde{\mathbf{R}}_{kl})$$

$$\boldsymbol{\Psi}_{t_k l} = \mathbb{E}\{(\mathbf{y}_{t_k l}^{\text{pilot}})(\mathbf{y}_{t_k l}^{\text{pilot}})^{\text{H}}\} = \textstyle\sum_{i\in\mathcal{P}_k}\eta_i\tau_{up}\mathbf{R}_{il} + \sigma_{\text{ul}}^2\mathbf{I}_N$$



System model: channel estimation



- Least-square (LS) estimation

$$\hat{\mathbf{h}}_{kl} = \frac{1}{\sqrt{\eta_k \tau_p}} \mathbf{y}_{t_k l}^{\text{pilot}}$$

Minimizes $\left\|\mathbf{y}_{t_k l}^{\text{pilot}} - \sqrt{p_k \tau_p}\mathbf{h}_{kl}\right\|^2$

No need for channel statistics

- Minimum mean square estimation (MMSE)

$$\hat{\mathbf{h}}_{kl} = \sqrt{\tau_p \eta_k}\mathbf{R}_{kl}\boldsymbol{\Psi}_{tl}^{-1}\mathbf{y}_{tl}^{\text{pilot}}$$

Minimizes $\mathbb{E}\{\|\mathbf{h}_{kl} - \hat{\mathbf{h}}_{kl}\|^2\}$

Needs channel statistics

Known channel and noise distribution

AP cluster matrix

Binary matrix indicating the APs serving the UE

- Dimension: *L x K.*
- In this example, L = 6 and K =5

The matrix **D** also indicates the subset of UEs that each AP serves

- The number of UEs that each AP serves is limited in a scalable system

$$) = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{pmatrix} \begin{matrix} 5 \\ 0 \\ 2 \\ 3 \\ 2 \\ 1 \end{matrix}$$

1 5 2 3 2

APs per UE

UEs per AP

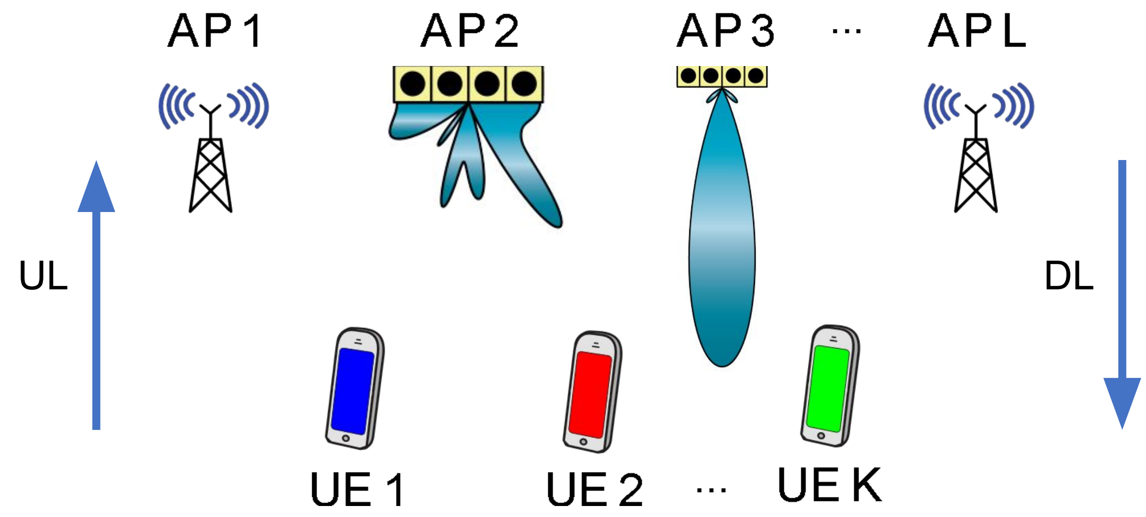
User-centric cell-free massive MIMO network

System model: data transmission

- UL phase:
  - UEs send data to the APs
  - Combining vectors are computed based on channel estimates
- DL phase:
  - APs send data to the UEs
  - Precoding vectors are computed based on combining vectors
- Combining and precoding are signal-processing techniques used to improve the desired signal and mitigate interference

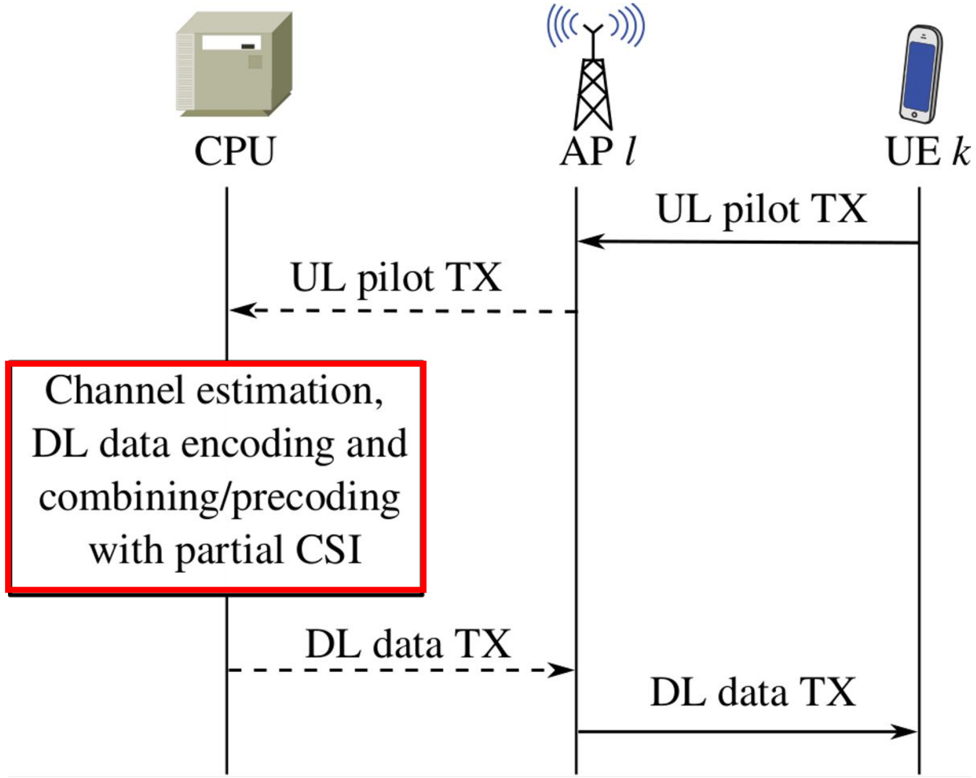
$$\mathbf{w}_k = \sqrt{\rho_k}\,\frac{\mathbf{v}_k}{\sqrt{\mathbb{E}\left\{\mathbf{v}_k^{\mathrm{H}}\mathbf{D}_k\mathbf{v}_k\right\}}}$$

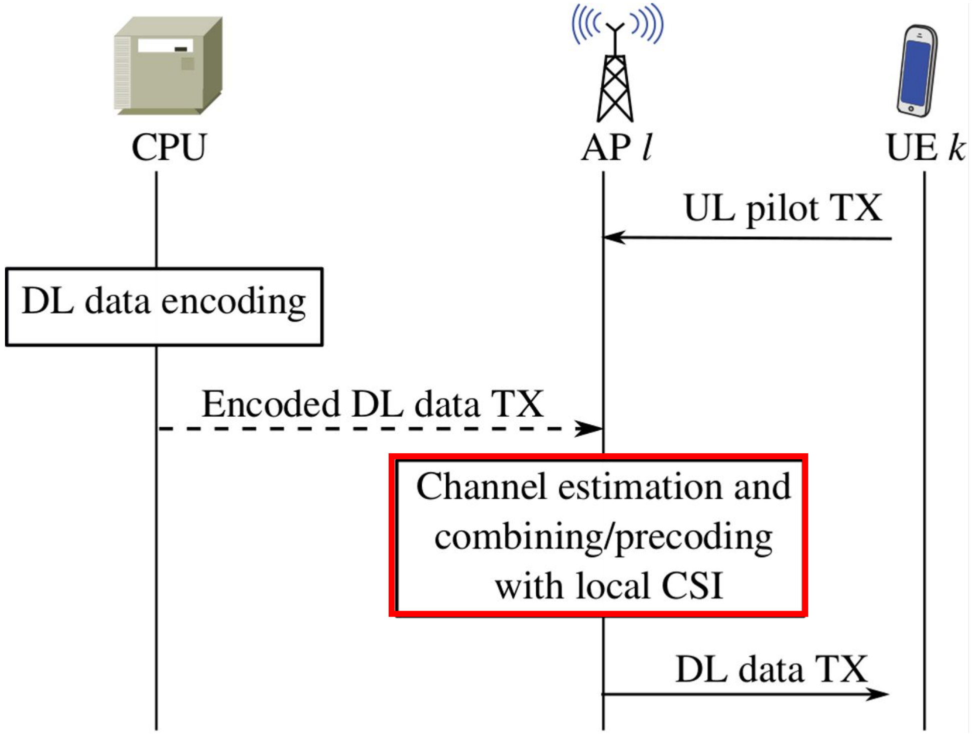
Combing vector; Power; Precoding vector; APs that serve UE k



System model: data transmission

- Combining and precoding can be performed at CPUs or APs

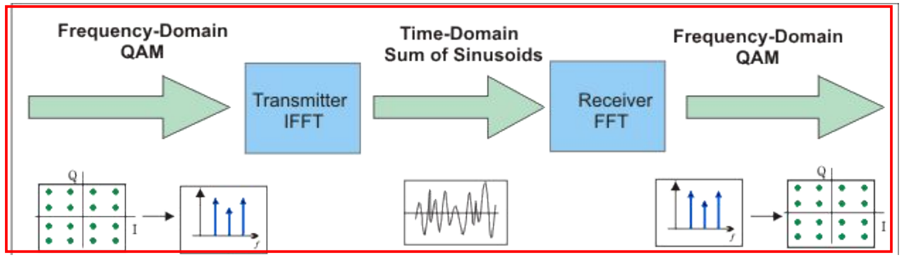


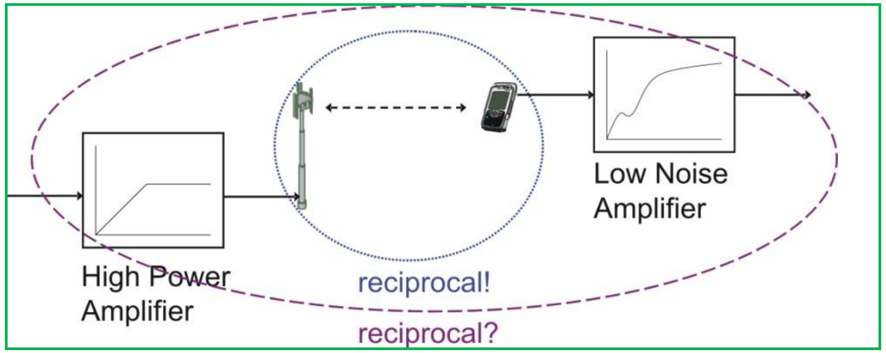


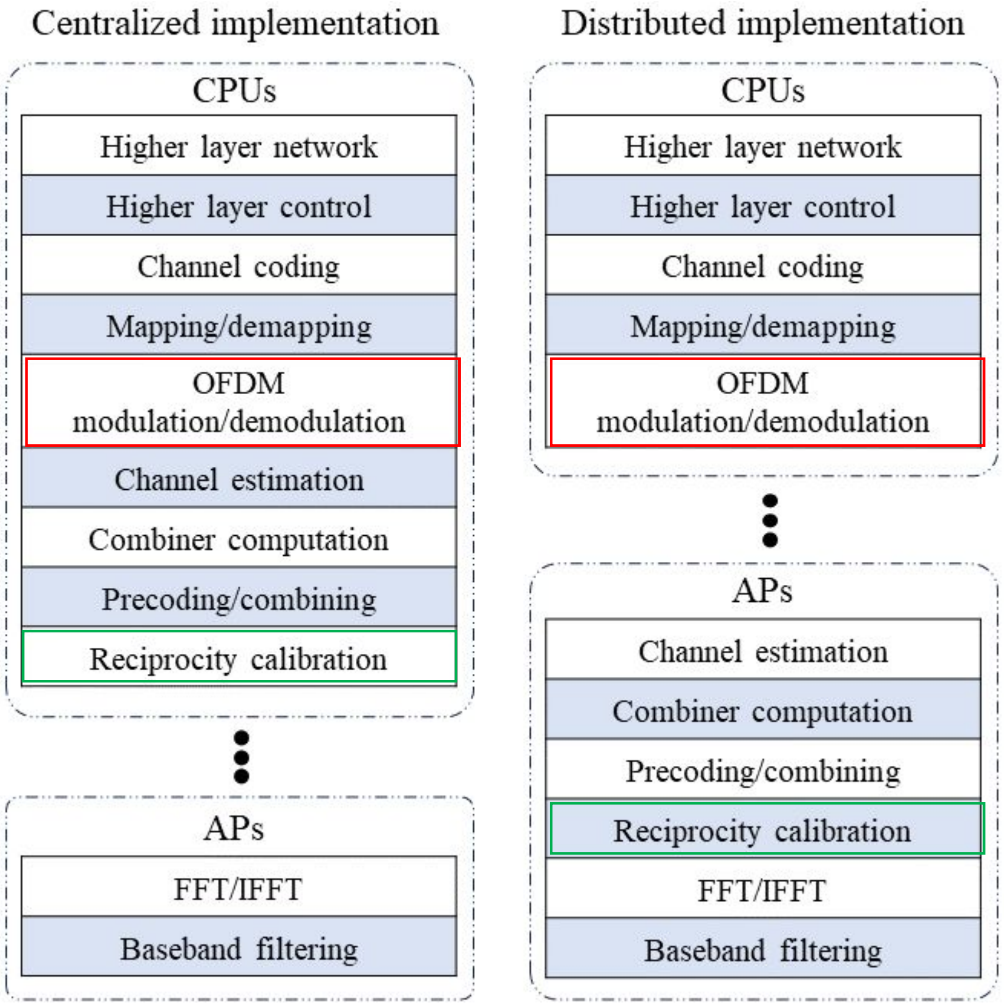
User-centric cell-free massive MIMO network

System model: network implementation

- Distribution of the processing functions in CPUs and RUs for centralized and distributed implementations
- Each task has an associated processing computational complexity and power consumption







User-centric cell-free massive MIMO network

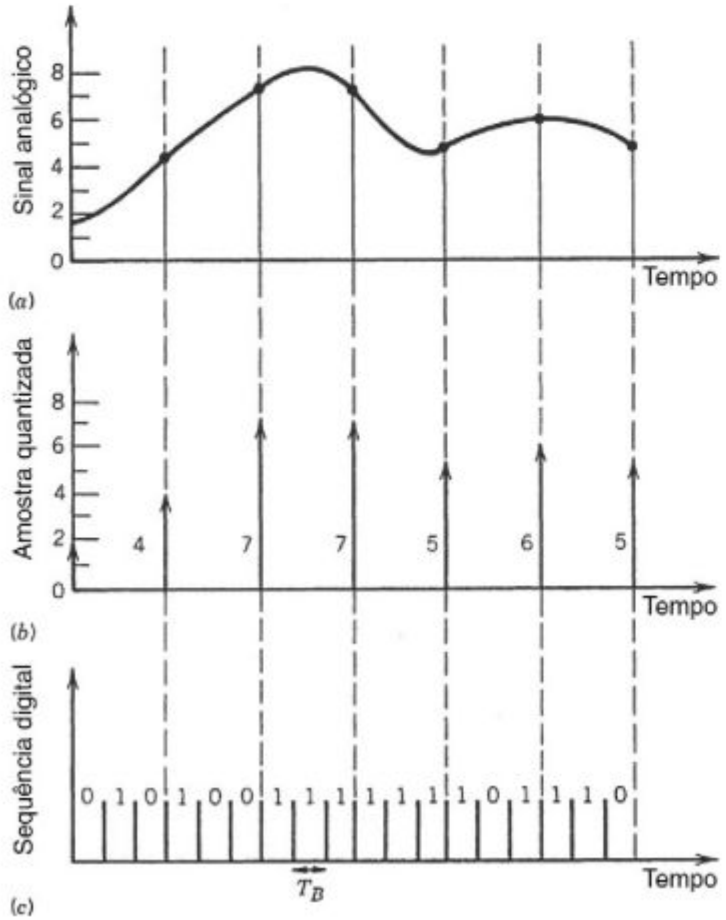
System model: distortions due to fronthaul limitations

Bussgang Decomposition

$$\hat{\mathbf{y}} = \mathcal{Q}_\theta(\mathbf{y}) \approx \alpha_\theta \mathbf{y} + \tilde{\mathbf{q}}_\theta,$$

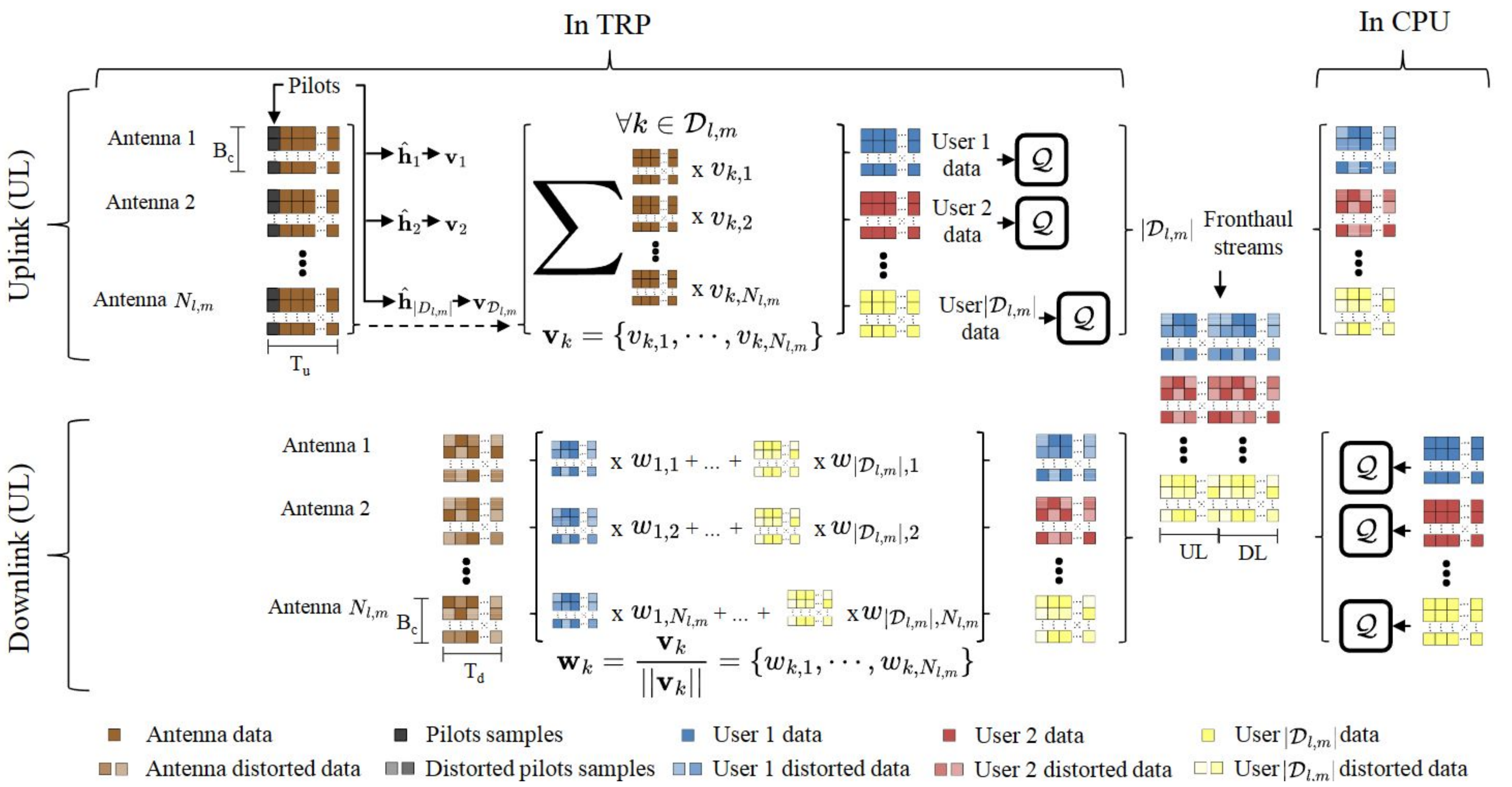
Gaussian

Bits per sample	Distortion rate	Correlation coefficient (α_θ)
1	0.3634	0.6366
2	0.1175	0.8825
3	0.03454	0.96546
4	0.009497	0.990503
5	0.002499	0.997501
> 5	$1 - \alpha_\theta$	$1 - \frac{\pi\sqrt{3}}{2} 2^{-2(\text{bits})}$



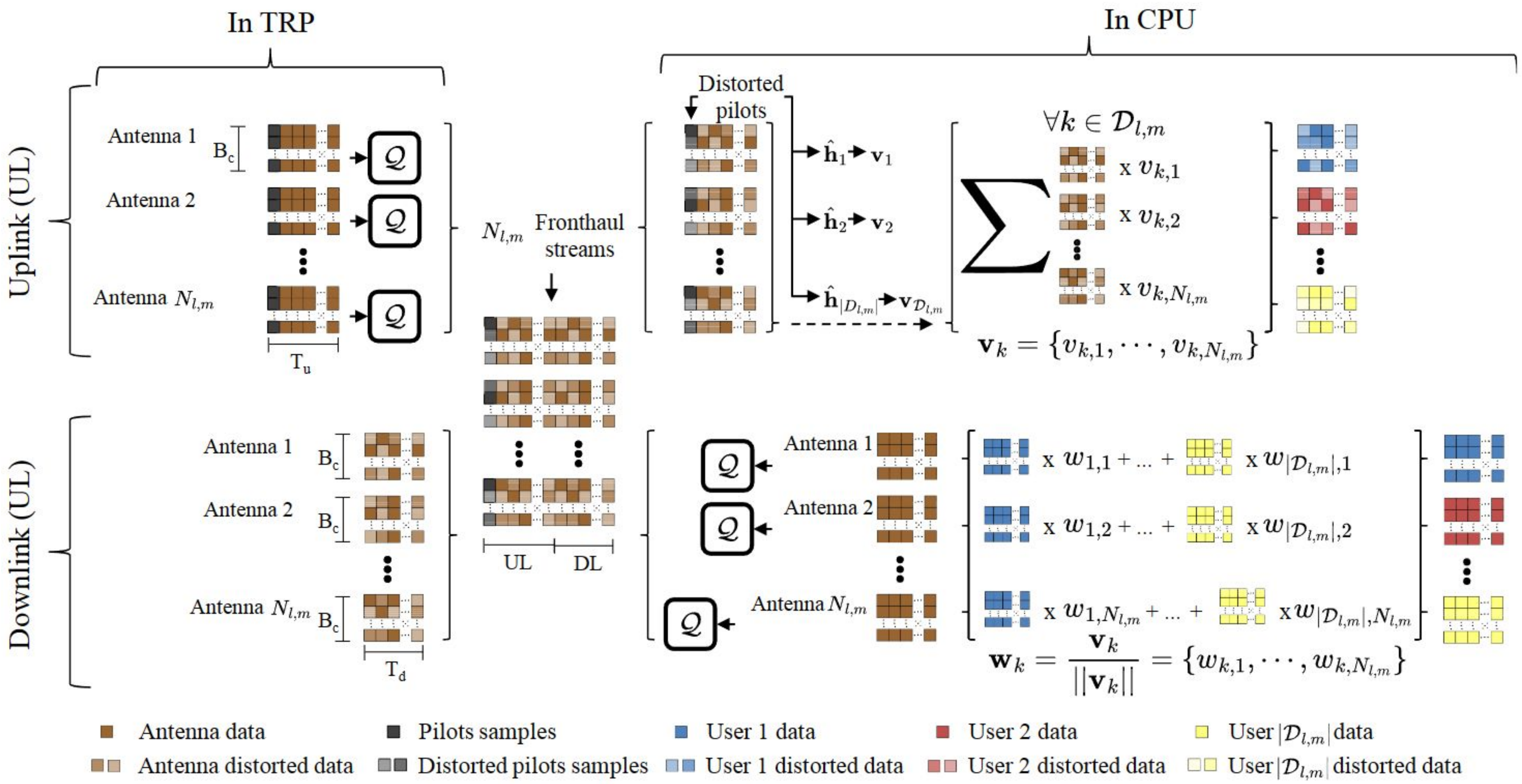
Modelando redes cell-free massive MIMO

System model: distortions due to fronthaul limitations (distributed processing)



Modelando redes cell-free massive MIMO

System model: distortions due to fronthaul limitations (centralized processing)



Modelando redes cell-free massive MIMO

System model: fronthaul bitrate

$$F_{l,m,t} = \begin{cases} 2B\left(1-\frac{\tau_p}{\tau_c}\right)\sum_k b_{l,k}^{\text{data}}, & \text{for BTRP} \\ 2N\,B\left[\left(1-\frac{\tau_p}{\tau_c}\right)b_l^{\text{data}} + \frac{\tau_p}{\tau_c} b_l^{\text{pil}}\right], & \text{for BCPU} \end{cases},$$

Example for a maximum of 10 GB of capacity, 10 TRPs (4 antennas), 8 users and 20 pilots, B=100 MHz, and a coherence block with 200 samples:

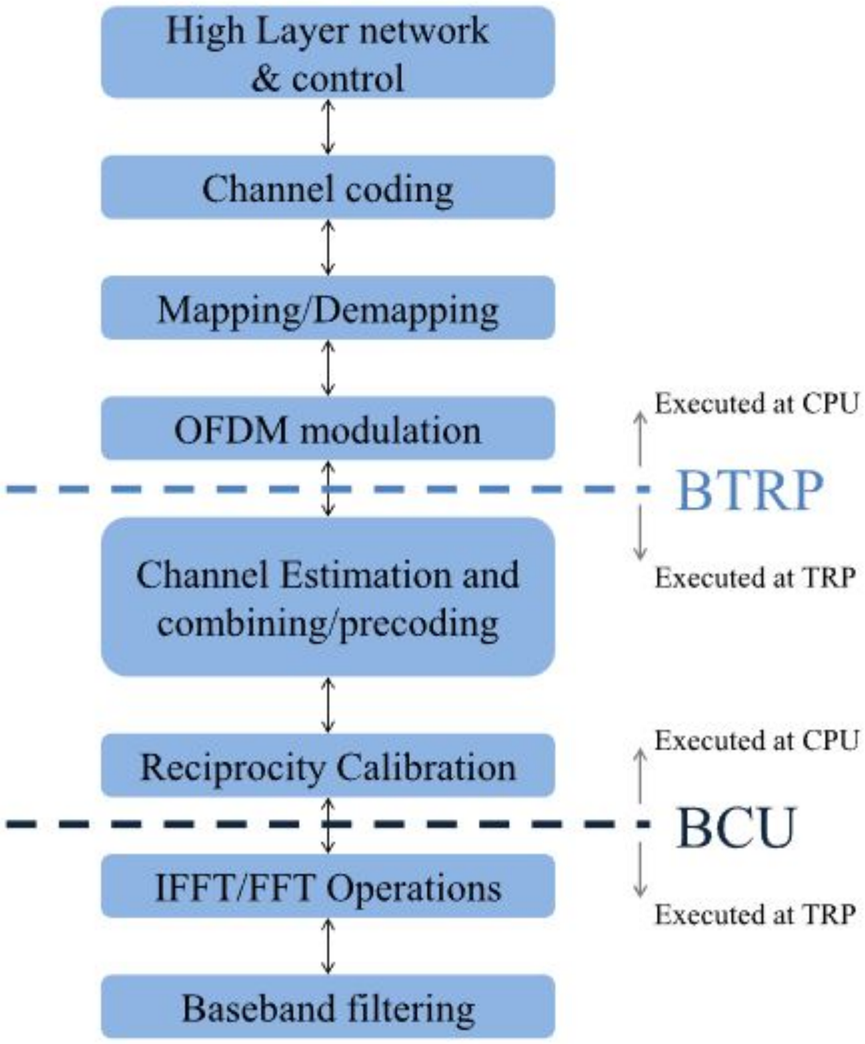
10*10^9/(2*100*10^6*(1-20/200)*8)= $b_{l,k}^{\text{data}}$

6,94= $b_{l,k}^{\text{data}}$

7 users will have 7 bits ← → 1 user will have 6 bits

10*10^9/(2*4*100*10^6)=12.5

b_l^{pil} =17bits b_l^{data} =12 bits ← 12.5 = $\left(1-\frac{\tau_p}{\tau_c}\right)b_l^{\text{data}} + \frac{\tau_p}{\tau_c} b_l^{\text{pil}}$



System model: centralized combiners

- P-MMSE: finds the trade-off of maximizing the desired signal and mitigating interference

$$\mathbf{v}_k^{\mathrm{P-MMSE}} = p_k \left(\sum_{i \in \mathcal{S}_k} p_i \mathbf{D}_k \widehat{\mathbf{h}}_i \widehat{\mathbf{h}}_i^{\mathrm{H}} \mathbf{D}_k + \mathbf{Z}_{\mathcal{S}_k} + \sigma_{\mathrm{ul}}^2 \mathbf{I}_{LN} \right)^{-1} \mathbf{D}_k \widehat{\mathbf{h}}_k$$

UEs that most interfere with UE *k*

$$\mathbf{Z}_{\mathcal{S}_k} = \sum_{i \in \mathcal{S}_k} p_i \mathbf{D}_k \mathbf{C}_i \mathbf{D}_k$$

Correlation matrix of the estimation error

- P-RZF: interference between the UEs tends to zero

$$\mathbf{v}_k^{\mathrm{P-RZF}} = \left[\mathbf{D}_k \widehat{\mathbf{H}}_{\mathcal{S}_k} \left(\widehat{\mathbf{H}}_{\mathcal{S}_k}^{\mathrm{H}} \mathbf{D}_k \widehat{\mathbf{H}}_{\mathcal{S}_k} + \sigma_{\mathrm{ul}}^2 \mathbf{P}_{\mathcal{S}_k}^{-1} \right)^{-1} \right]_{:,1}$$

Neglects Z_{Sk}

Regularized pseud-inverse

User-centric cell-free massive MIMO network

System model: distributed combiners

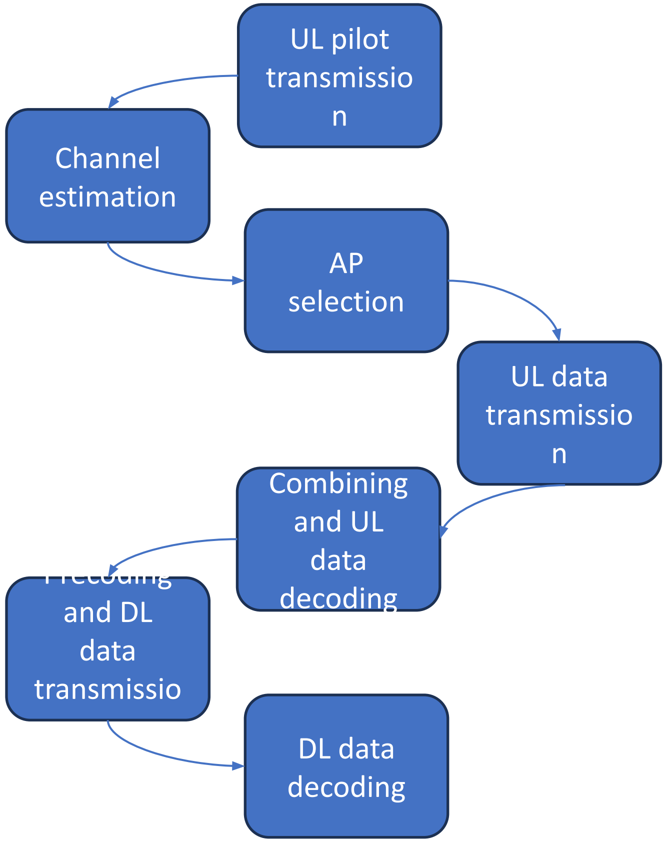
- LP-MMSE: same as P-MMSE, but uses only local channel estimates

$$\mathbf{v}_{kl}^{\mathrm{LP-MMSE}} = p_k \left(\sum_{i \in \mathcal{D}_l} p_i \left(\widehat{\mathbf{h}}_{il} \widehat{\mathbf{h}}_{il}^{\mathrm{H}} + \mathbf{C}_{il} \right) + \sigma_{\mathrm{ul}}^2 \mathbf{I}_N \right)^{-1} \mathbf{D}_{kl} \widehat{\mathbf{h}}_{kl}.$$

UEs served by AP *l*

- MR: maximizes the desired signal

$$\mathbf{v}_{kl}^{\mathrm{MR}} = \widehat{\mathbf{h}}_{kl}.$$



User-centric cell-free massive MIMO network

System model: DL data transmission

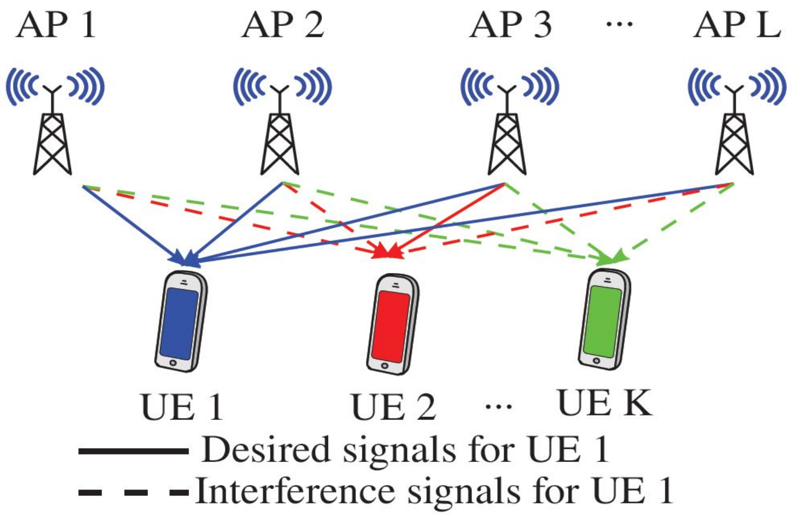
- Transmitted signals

Data symbol of UE k

$$\mathbf{x}_l = \sum_{i=k}^{K} \alpha_{l,k}^{\mathrm{dl}} \mathbf{D}_{l,k} \mathbf{w}_{l,k} \varsigma_k^{\mathrm{dl}} + \mathbf{q}_l^{\mathrm{dl}},$$

$$\mathbf{q}_l^{\mathrm{dl}} \sim \begin{cases} \mathcal{CN}\left(0, \alpha_l^{\mathrm{dl}}\left(\alpha_l^{\mathrm{dl}} - 1\right) \sum_{k=1}^{K} \mathbb{E}\left\{\mathbf{w}_{l,k}\mathbf{w}_{l,k}^{\mathrm{H}}\right\}\right), \text{ for BCPU} \\ \sum_{i=k}^{K} \mathbf{D}_{l,k}\mathbf{w}_{l,k} q_{l,k}^{\mathrm{dl}}, \text{ for BTRP} \end{cases}$$

$$q_{l,k}^{\mathrm{ul}} \sim \mathcal{CN}\left(0, \alpha_{l,k}\left(\alpha_{l,k} - 1\right)\right)$$



- Received signals

$$y_k^{\mathrm{dl}} = \sum_{l=1}^{L} \sum_{m=1}^{M_l} \left(\mathbf{h}_{l,k}\right)^H \mathbf{x}_l + n_k^{\mathrm{dl}},$$

$$y_k^{\mathrm{dl}} = \underbrace{\sum_{l=1}^{L} \alpha_{l,k}^{\mathrm{dl}} \mathbf{h}_{l,k}^H \mathbf{D}_{l,k} \mathbf{w}_{l,k}^{\mathrm{dl}} s_k^{\mathrm{dl}}}_{\text{Desired Signal}} + \underbrace{\sum_{\substack{i=1 \\ i \neq k}}^{K} \sum_{l=1}^{L} \sum_{m=1}^{M_l} \alpha_{l,i}^{\mathrm{ul}} \mathbf{h}_{l,k}^H \mathbf{D}_{l,i} \mathbf{w}_{l,i}^{\mathrm{dl}} s_i^{\mathrm{dl}}}_{\text{Inter-User Interference}} + \underbrace{n_k^{\mathrm{dl}}}_{\text{Receiver Noise}} + \underbrace{\sum_{l=1}^{L} \mathbf{h}_{l,k}^H \mathbf{q}_l}_{\text{Quantization Noise}}.$$

$$y_k^{\text{dl}} = \underbrace{\sum_{l=1}^{L} \alpha_{l,k}^{\text{dl}} \mathbf{h}_{l,k}^H \mathbf{D}_{l,k} \mathbf{w}_{l,k} \varsigma_k^{\text{dl}}}_{\text{Desired Signal}} + \underbrace{\sum_{\substack{i=1 \\ i \neq k}}^{K} \sum_{l=1}^{L} \sum_{m=1}^{M_l} \alpha_{l,i}^{\text{ul}} \mathbf{h}_{l,k}^H \mathbf{D}_{l,i} \mathbf{w}_{l,i} \varsigma_i^{\text{dl}}}_{\text{Inter-User Interference}} + \underbrace{n_k^{\text{dl}}}_{\text{Receiver Noise}} + \underbrace{\sum_{l=1}^{L} mathbfh_{l,k}^H \mathbf{q}_l}_{\text{Quantization Noise}},$$

System model: DL spectral efficiency

- If UEs have only statistical CSI knowledge, i.e., E {αkk}

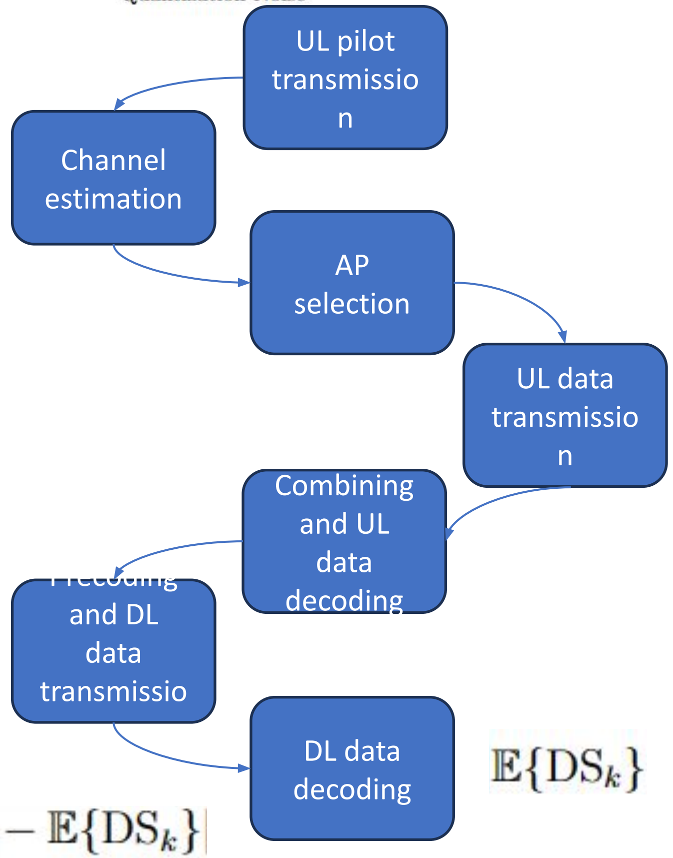
Pre-log factor

$$R_k^{\text{UatF}} = \phi B \log_2(1 + \underline{\text{SINR}}_k), \quad \text{SE}_k = \phi \log_2(1 + \underline{\text{SINR}}_k),$$

$$\underline{\text{SINR}}_k = \frac{|\mathbb{E}\{\text{DS}_k\}|^2}{\mathbb{E}\{|\text{DS}_k - \mathbb{E}\{\text{DS}_k\}|^2\} + \mathbb{E}\{|\text{IS}_k|^2\} + \mathbb{E}\{|\text{QN}_k|^2\} + \sigma^2_{\text{ul|dl}}},$$

Noise power

Known as hardening bound



$$\mathbb{E}\{\text{DS}_k\}$$

$$\text{DS}_k - \mathbb{E}\{\text{DS}_k\}$$

New interference

System model: Energy efficiency

Bandwidth

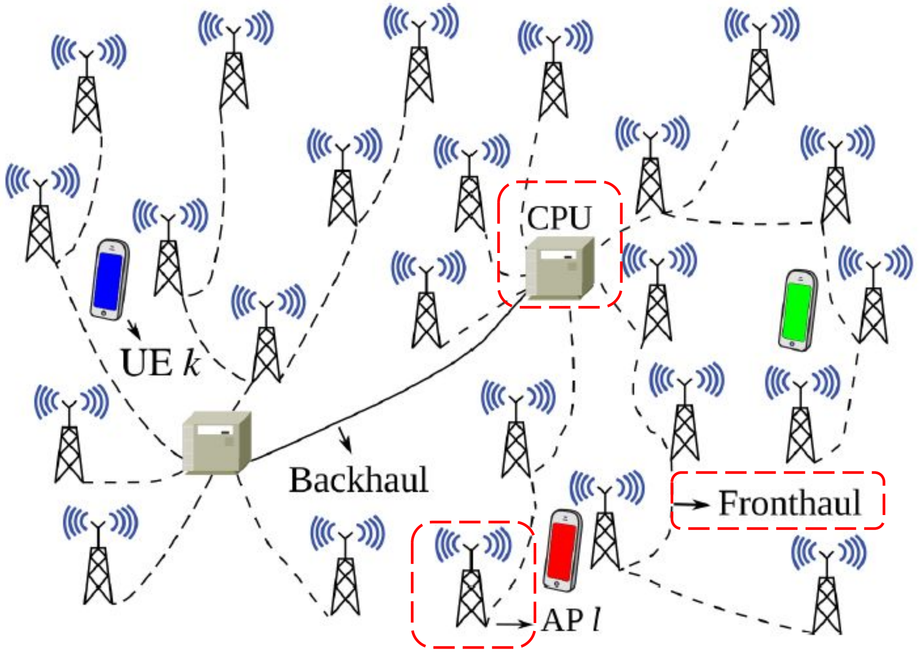
$$\mathrm{EE}_{\mathrm{tot}} = \frac{B \sum_{k=1}^{K} \mathrm{SE}_k}{P_{\mathrm{tot}}}$$

Power consumption of AP *l*

Power of CPU signal processing tasks

$$P_{\mathrm{tot}} = \sum_{l=1}^{L} P_l + \sum_{l=1}^{L} P_{\mathrm{fh},l} + P_{\mathrm{CPU}}$$

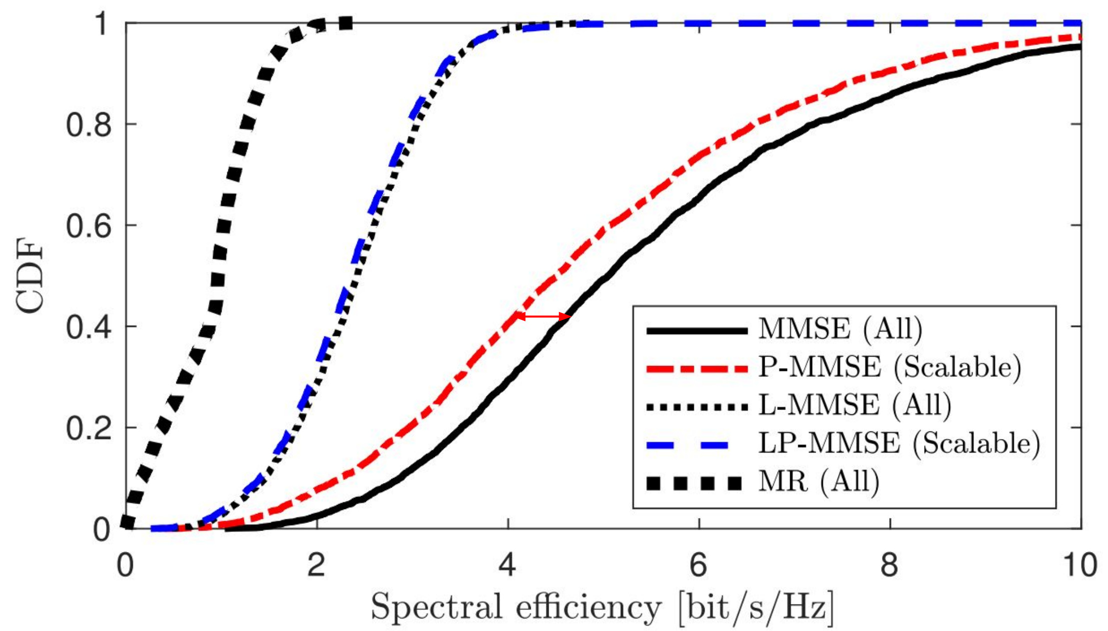
Power of fronthaul links between AP *l* and CPU



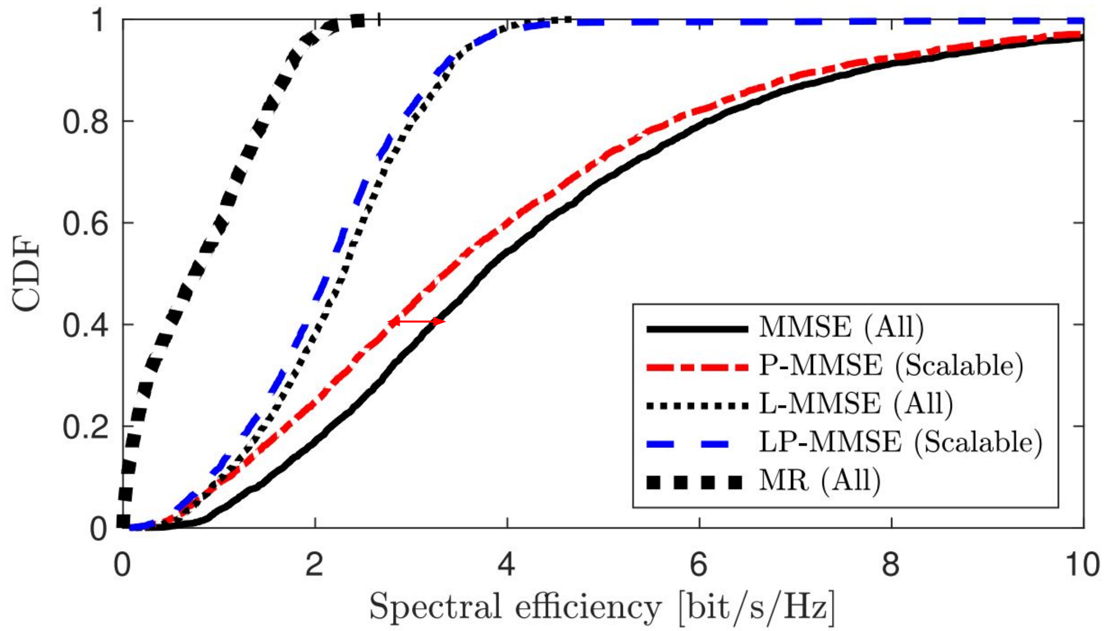
Simulation results

Scalable cell-free system vs canonical cell-free

- Negligible losses in SE
- The distributed implementation (LP-MMSE) is almost not affected



Parameters setting: L = 400 APs, K = 100 UEs, N = 1



Parameters setting: L = 100 APs, K = 100 UEs, N = 4

User-centric cell-free massive MIMO network

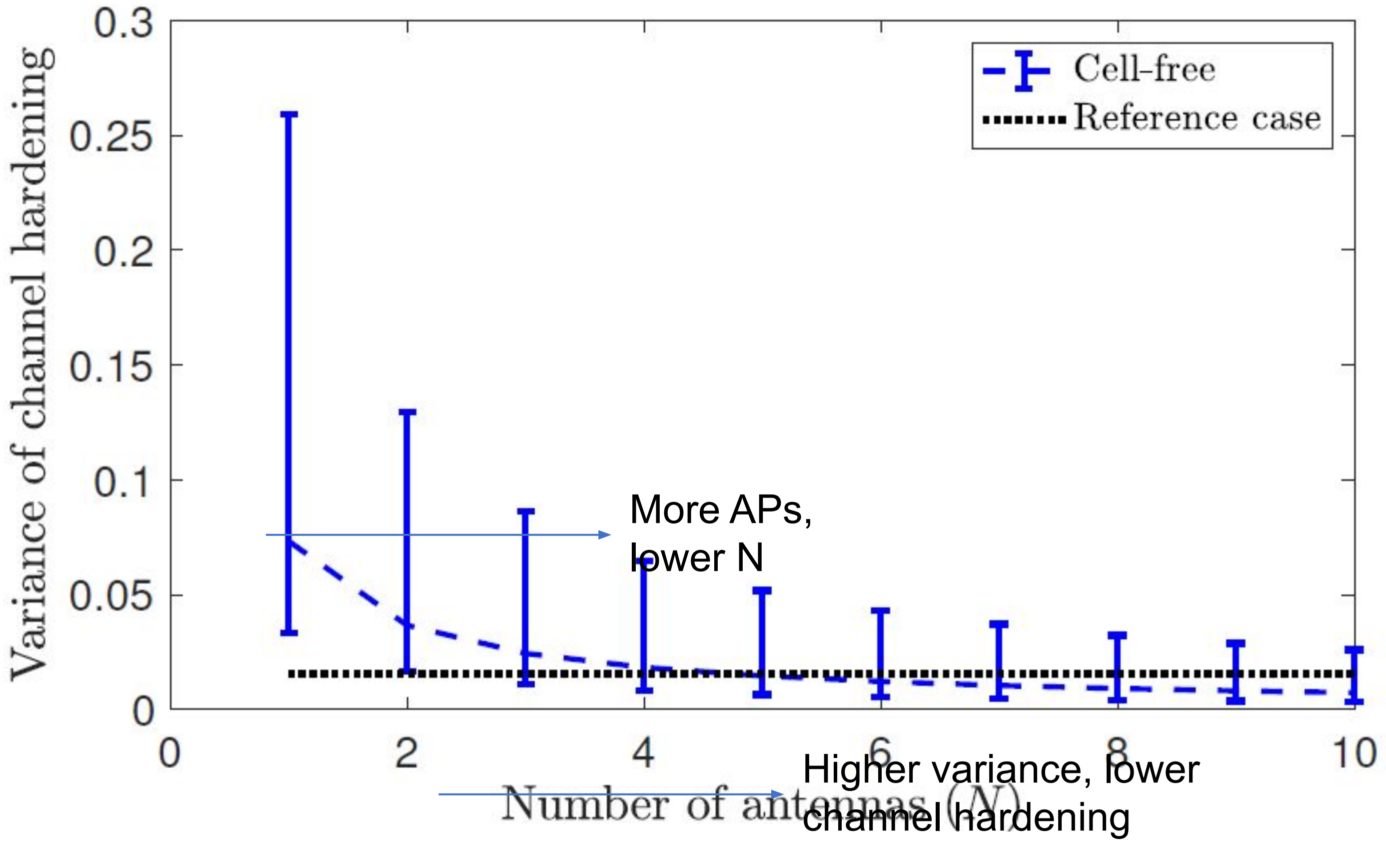
System model: channel hardening

UE effective channel

$$CH_k = \frac{\mathrm{VAR}\left(\eta_{k,k}\right)}{\left(\mathbb{E}\left[\eta_{k,k}\right]\right)^2}$$

$$\eta_{k,k'} = \sum_{l=1}^{L} \alpha_{l,k}^{DL} \boldsymbol{h}_{l,k}^{H} \boldsymbol{D}_{l,k'} \mathbf{w}_{l,k'}\,, \quad k \epsilon \{1,2,\cdots,K\}$$

Reference case: cellular system, i.i.d. Rayleigh fading → 1/L



User-centric cell-free massive MIMO network

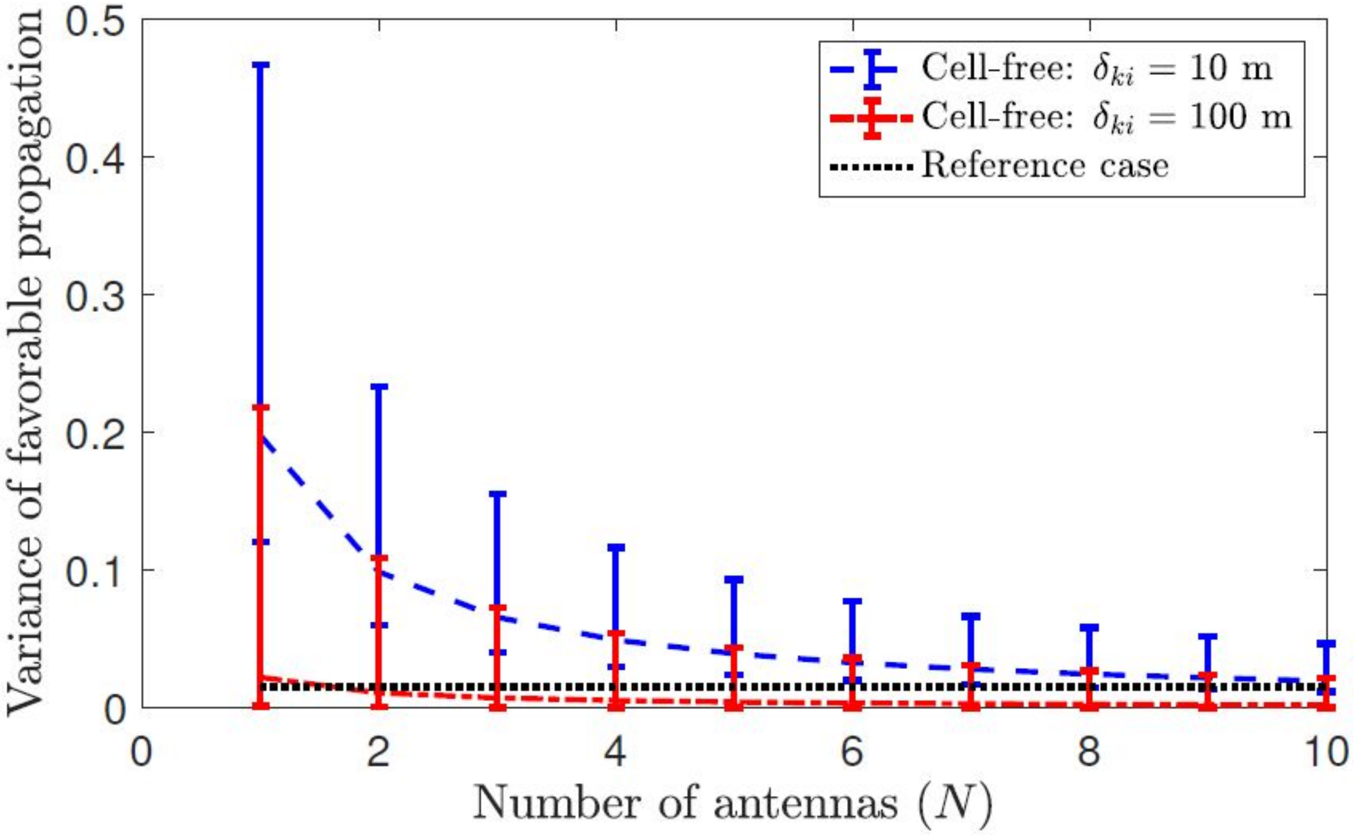
System model: favorable propagation

Interfering effective channel

$$FP_k = \frac{\mathrm{VAR}(\eta_{k,k'})}{\left(\mathbb{E}[\eta_{k,k}]\right)^2}, \forall k' \neq k$$

$$\eta_{k,k'} = \sum_{l=1}^{L} \alpha_{l,k}^{DL} \boldsymbol{h}_{l,k}^{H} \boldsymbol{D}_{l,k'} \boldsymbol{w}_{l,k'}, \quad k \epsilon \{1,2,\cdots,K\}$$

Reference case: cellular system, i.i.d. Rayleigh fading → 1/L



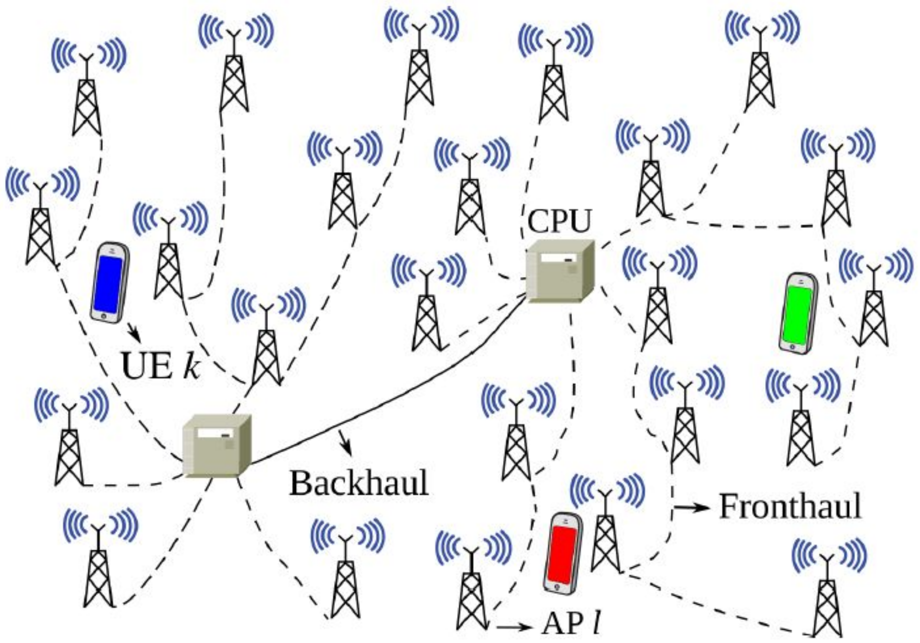
A comparison among AP selection strategies

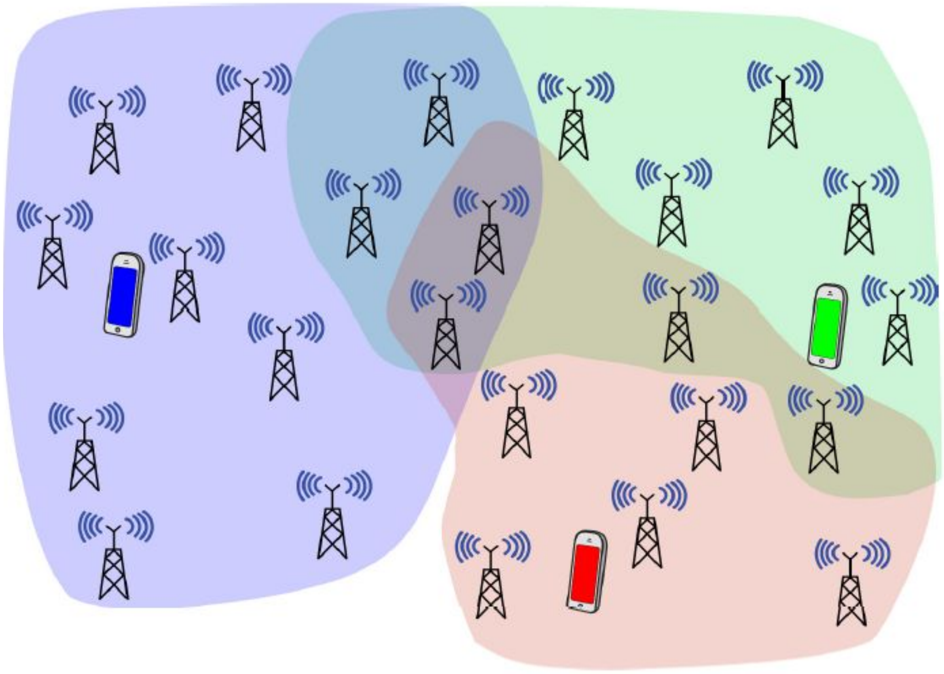
XLIII Simpósio Brasileiro de Telecomunicações e
Processamento de Sinais

AP selection (AP clustering)

AP selection schemes (common approaches)

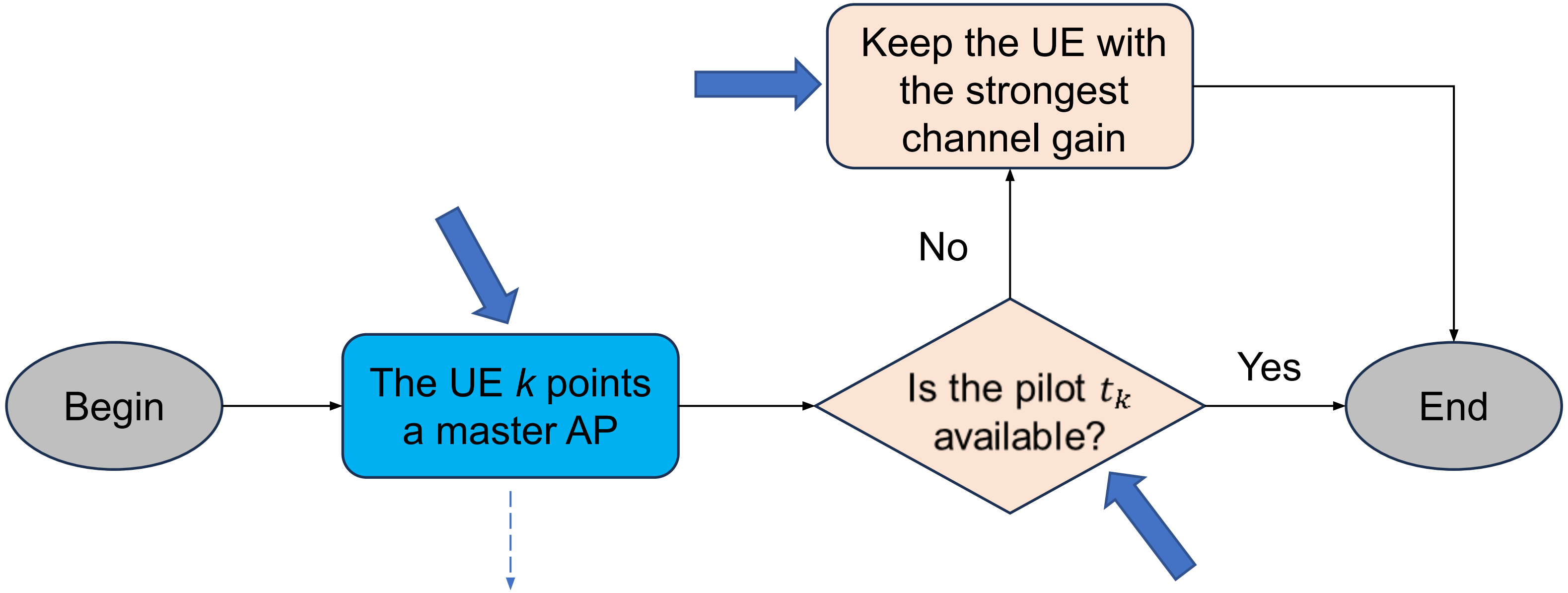
- Canonical cell-free (CF) massive MIMO
- User-centric clustering (UCC)
- Largest-large-scale-fading-based (LSFB)





Relates AP selection process to pilot assignment

- In this scheme each AP can serve up to $\tau_{u,p}$ UEs

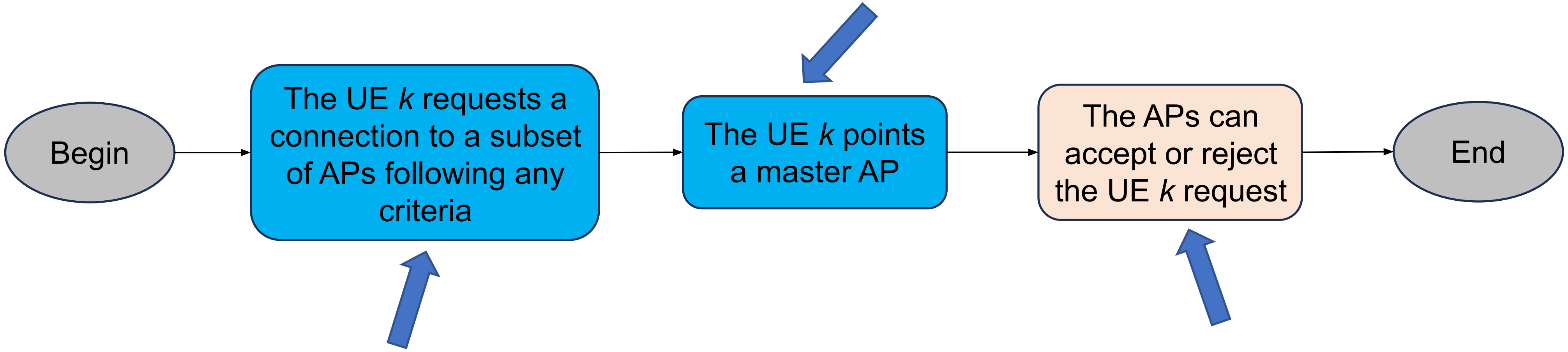


- Assigns a pilot t_k
- Informs the other APs that the UE k has entered the network

Matched Decision

A general framework

- The AP selection considers the most suitable connections for both UEs and APs
- It can be adjusted according to different criteria

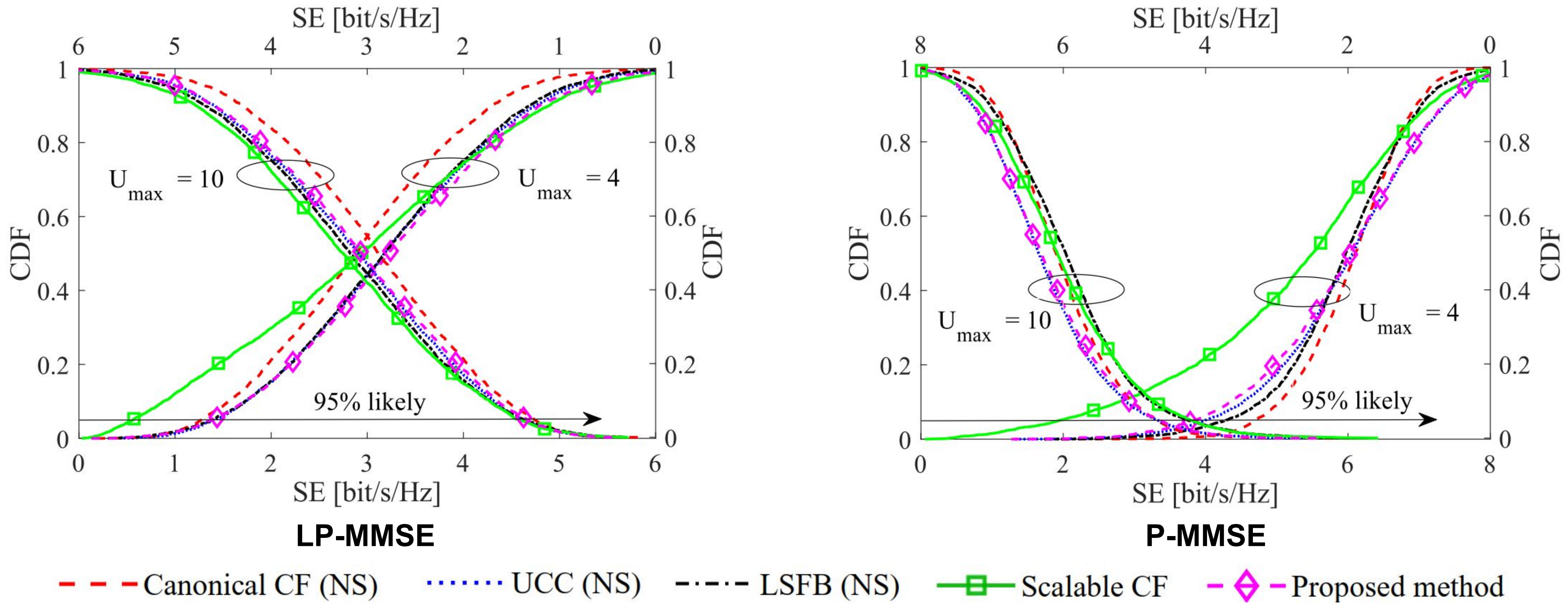


- It can behave like the previous AP selection schemes, but providing scalability and guaranteeing connection

AP selection (AP clustering)

A comparison, downlink (DL) spectral efficiency (SE)

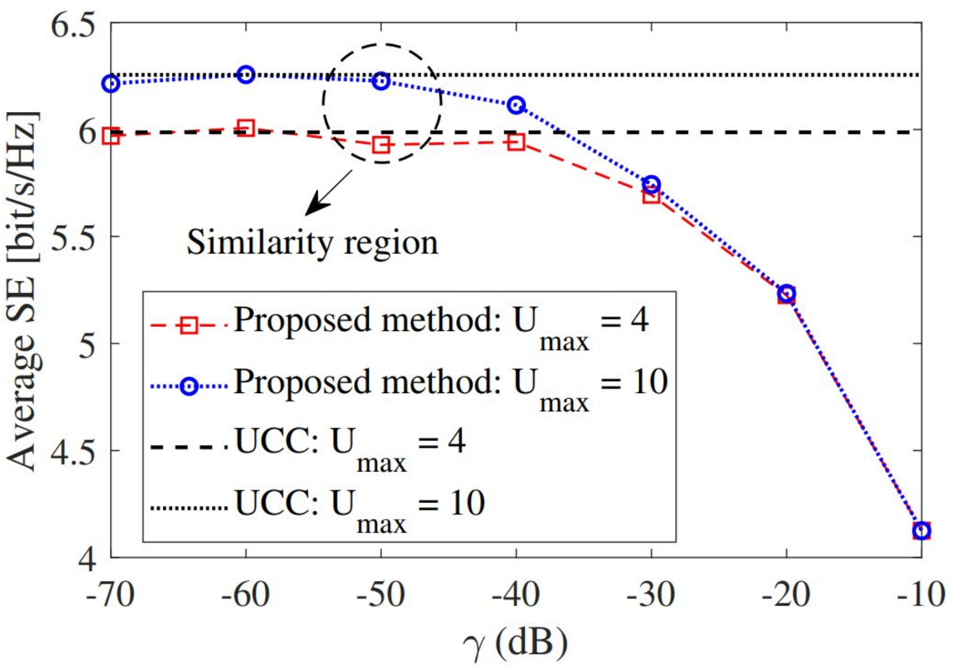
- Parameters setting: L = 100 APs, K = 25 UEs, N = 1
- U_{max} denotes the maximum number of UEs that each AP can serve



AP selection (AP clustering)

A comparison, downlink (DL) spectral efficiency (SE)

- The matched decision can behave like other AP selection strategies while affording scalability and ensuring connection of the UE with the network



Time complexity

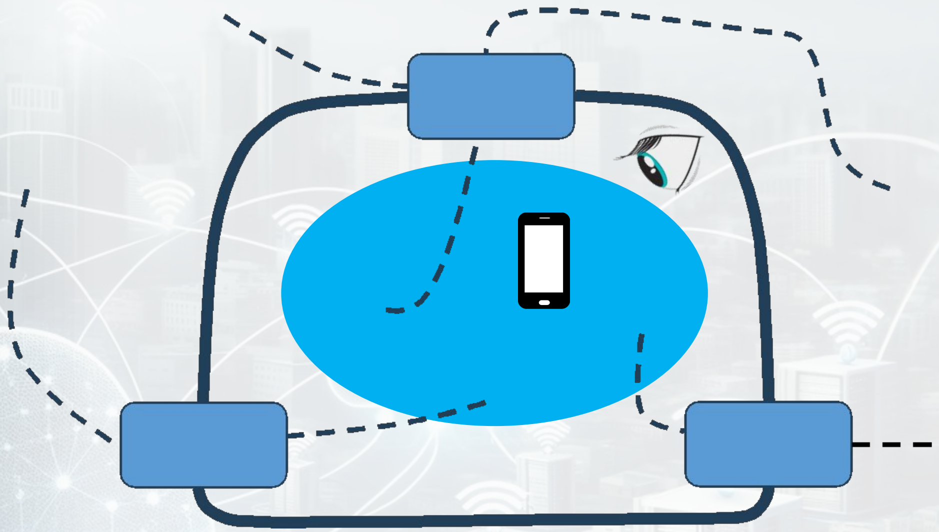
AP selection method	Complexity
UCC	$\mathcal{O}(LK \log K)$
LSFB	$\mathcal{O}(L \log L)$
Scalable CF	$\mathcal{O}(L\tau_p)$
Matched Decision	$\mathcal{O}(LU_{\max})$

Some researches regarding user-centric cell-free massive MIMO systems

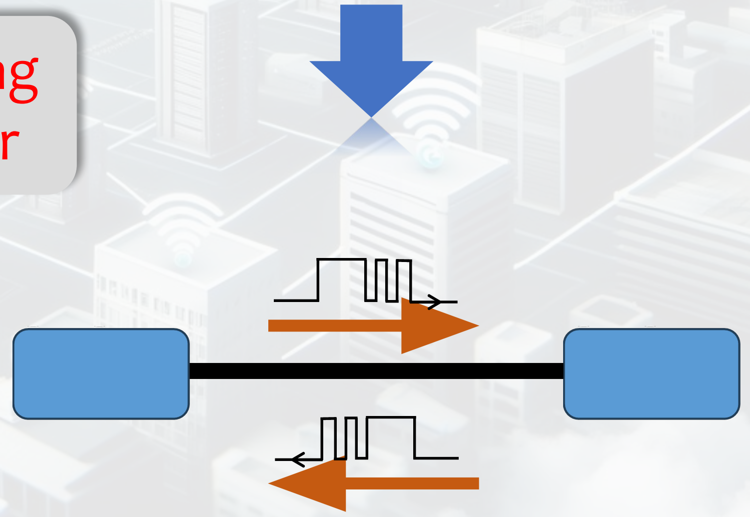
XLIII Simpósio Brasileiro de Telecomunicações e Processamento de Sinais

Reducing Inter-CPU Coordination in User-centric D-mMIMO

Problem

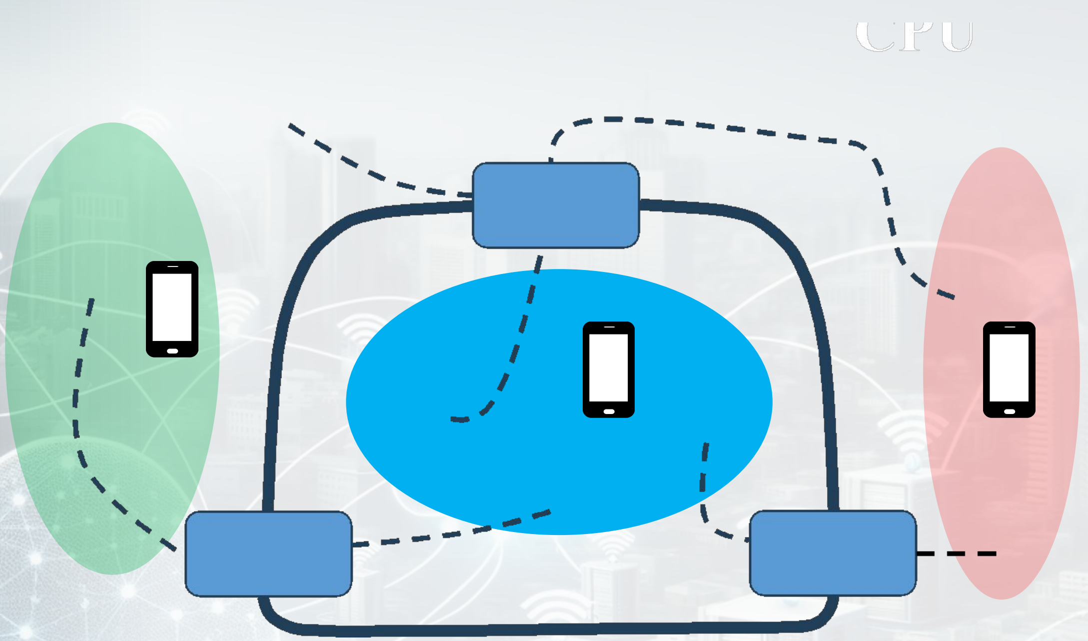


RUs connected to different CPUs

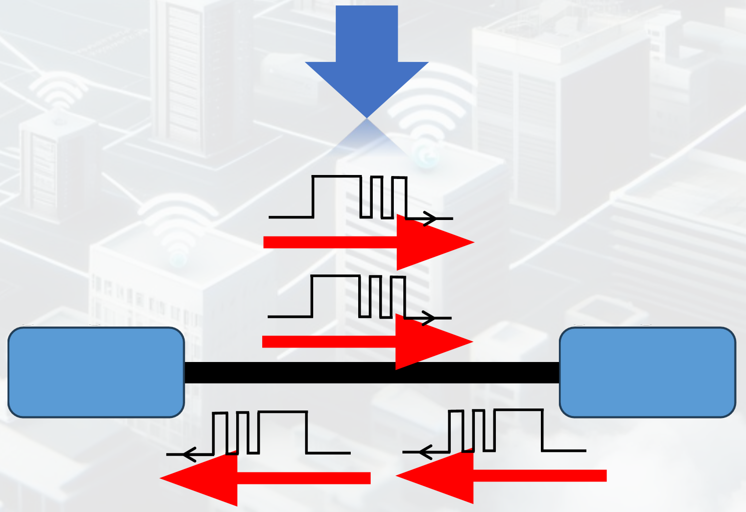


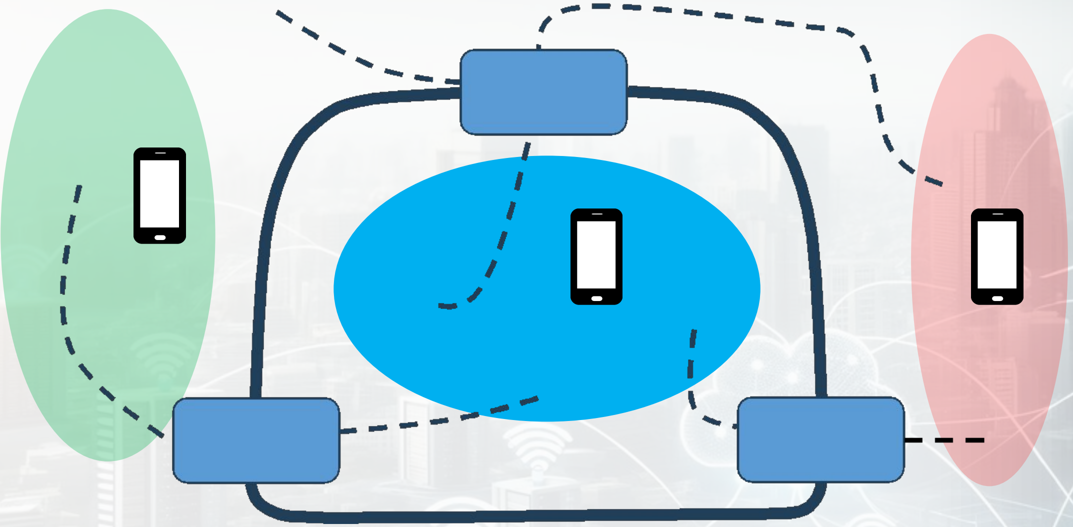
Backhaul signaling to serve the user

Problem



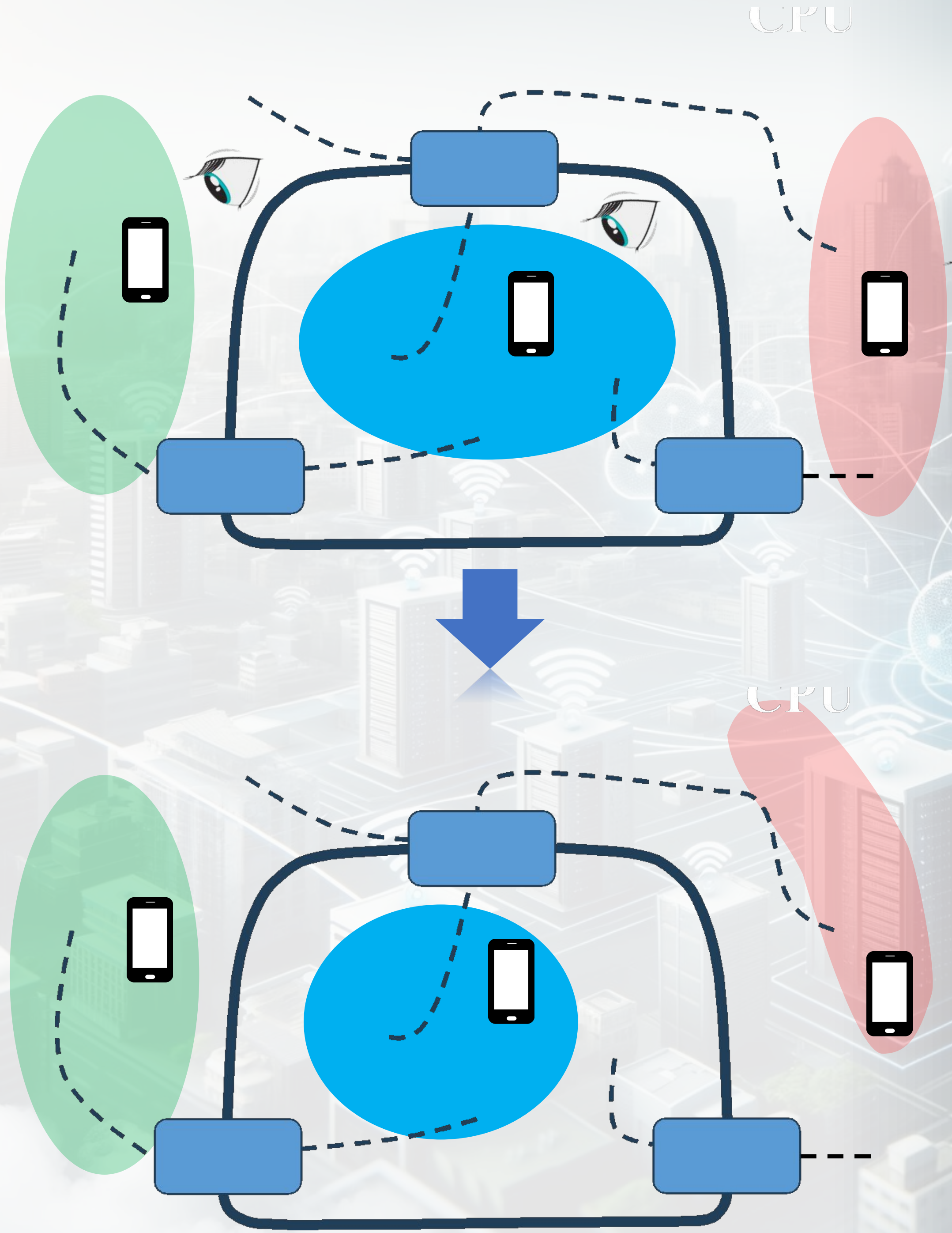
more users; more signaling





Decrease the number of CPUs in RU clusters

Proposed Solution



Proposed Solution

Performance Gain

Benefits

Low complexity

80% of signaling reduction

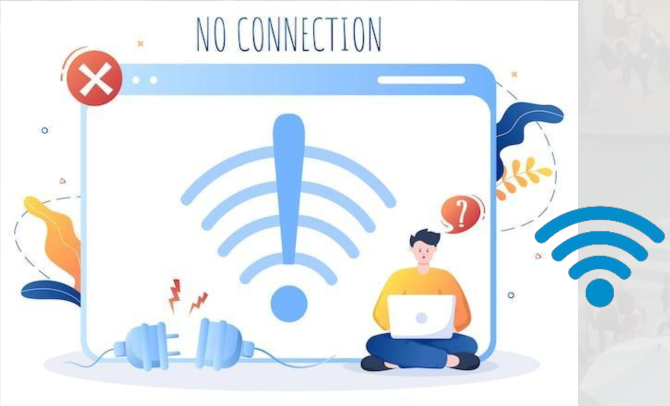
2.5% of losses in spectral efficiency

Backhaul Traffic (Gbps)

Spectral Efficiency (bit/s/Hz)

User-centric D-mMIMO System Assisted by UAV Swarm

Natural disasters disrupt power



Terrestrial network malfunction

Problem

Problem

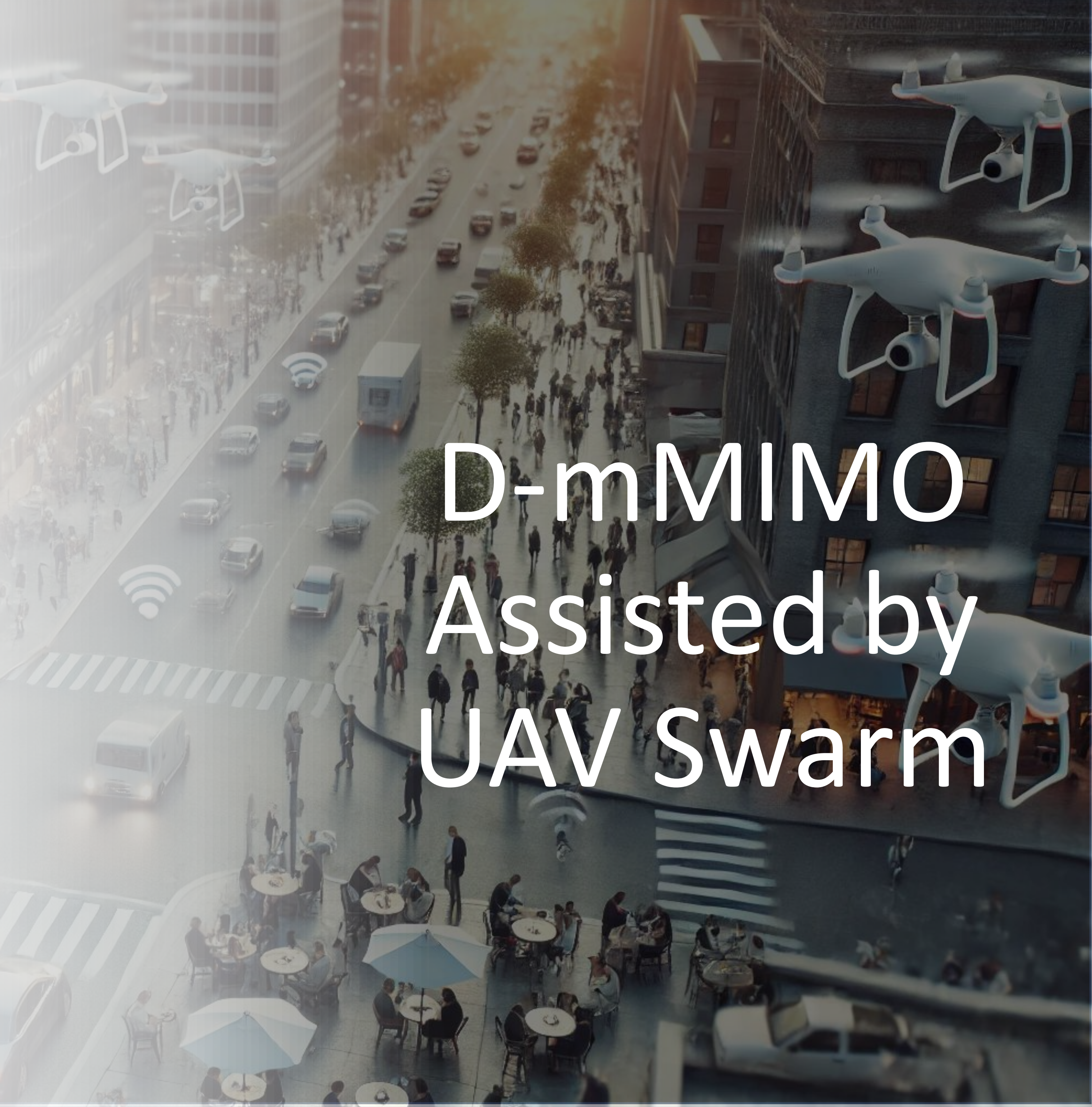
Surge in user density

Terrestrial network congestion

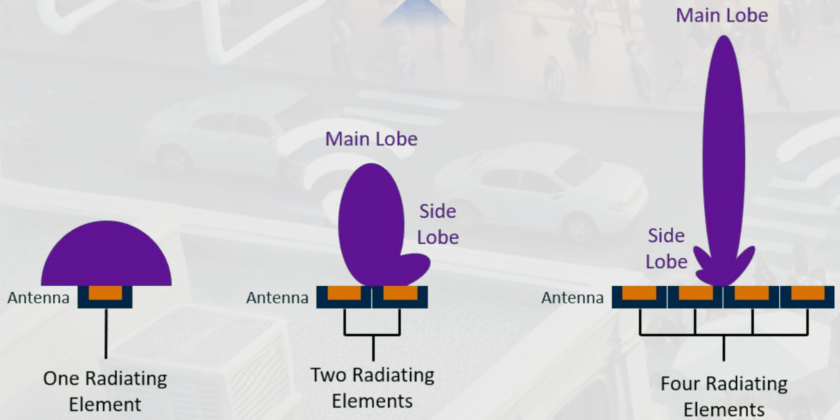
Research

Use of UAVs as TRPs

D-mMIMO Assisted by UAV Swarm

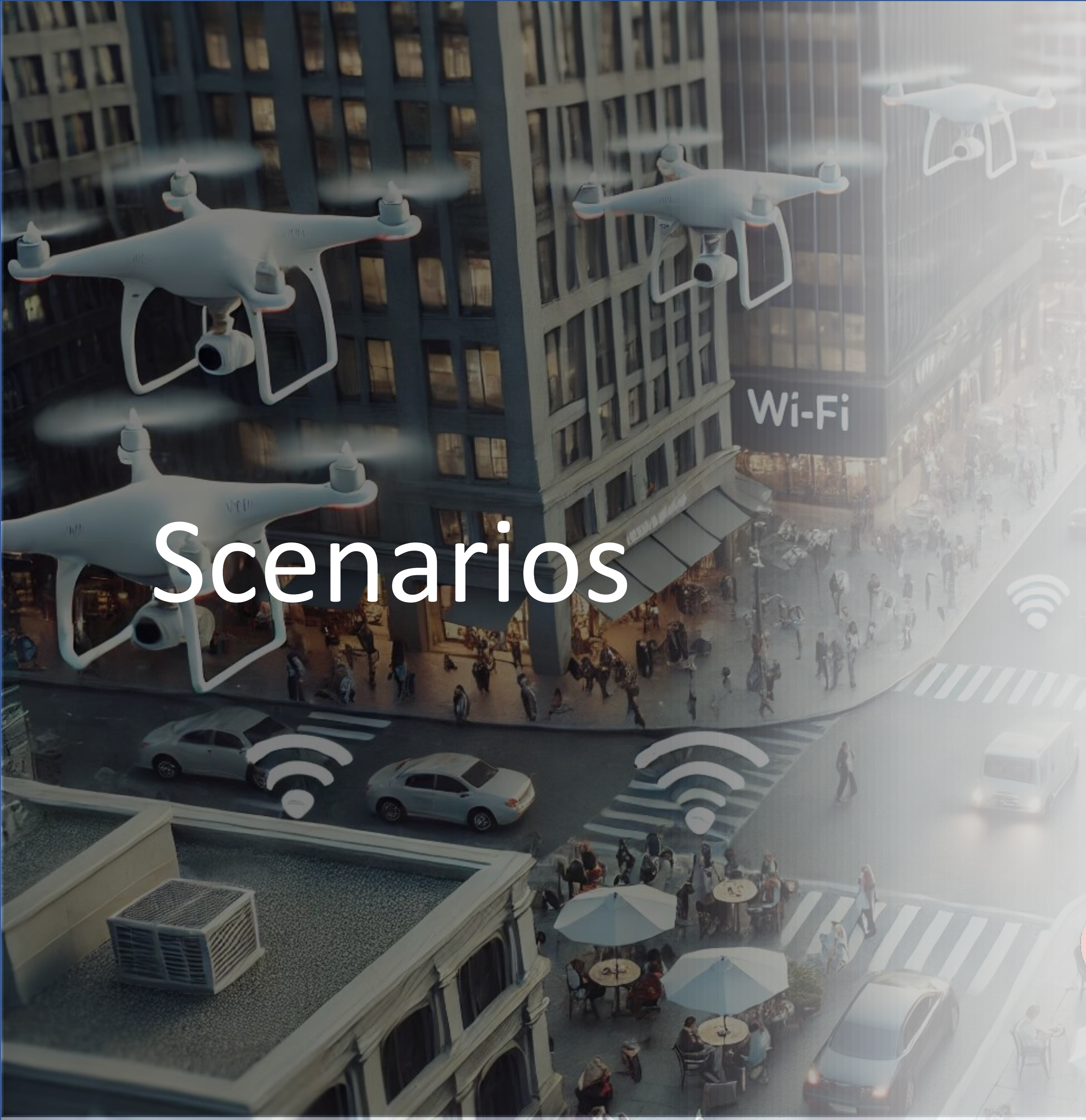


Cooperative UAV swarm



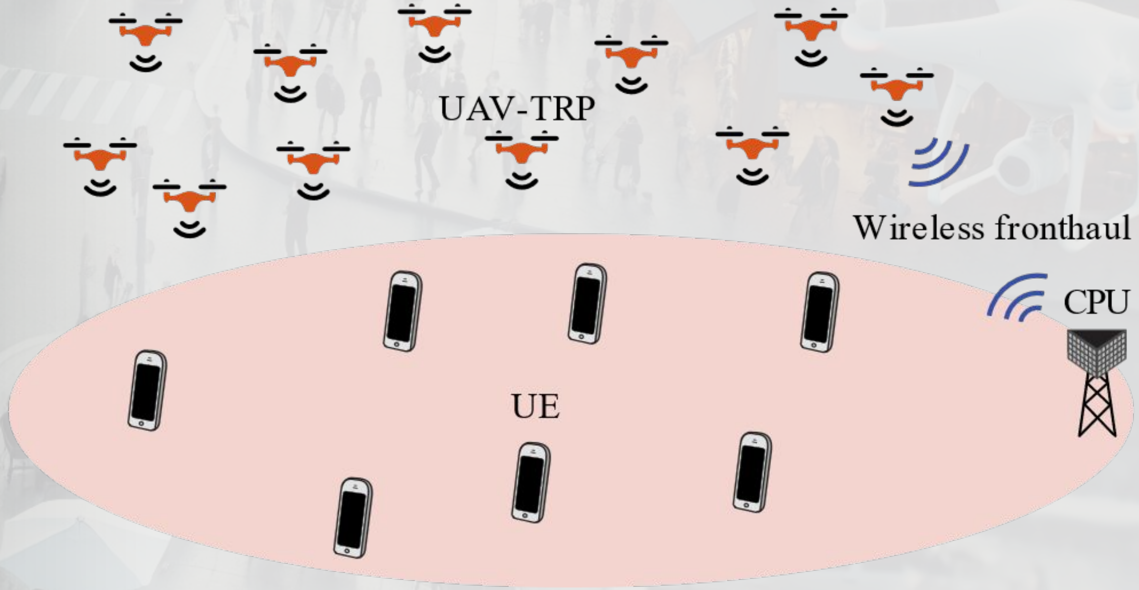
Leads to array gain in D-mMIMO

Scenarios



1 Malfunction

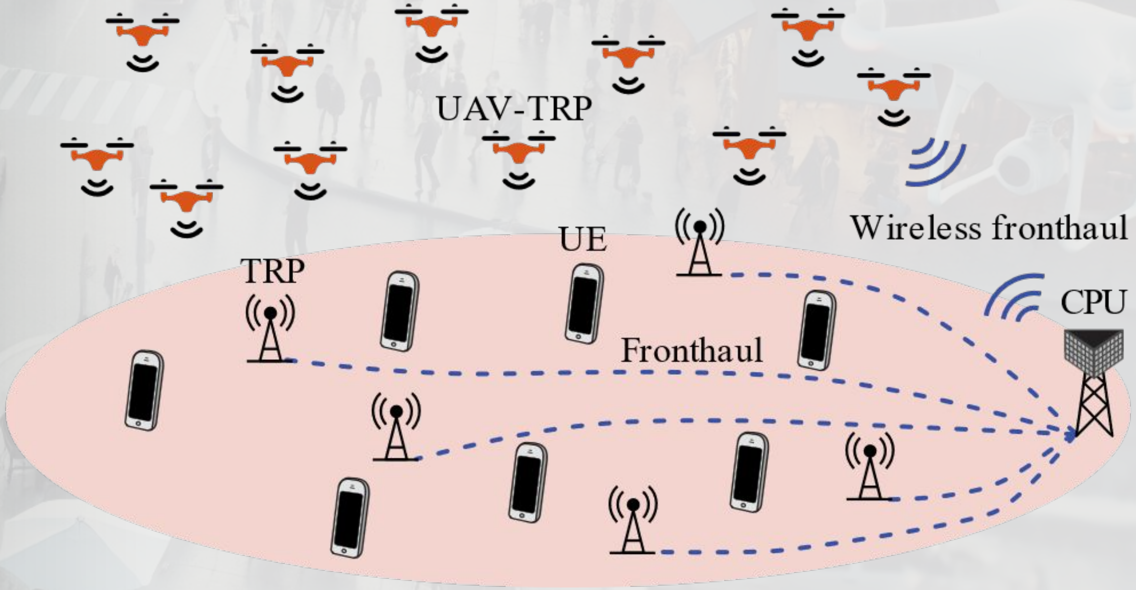
✓Aerial network



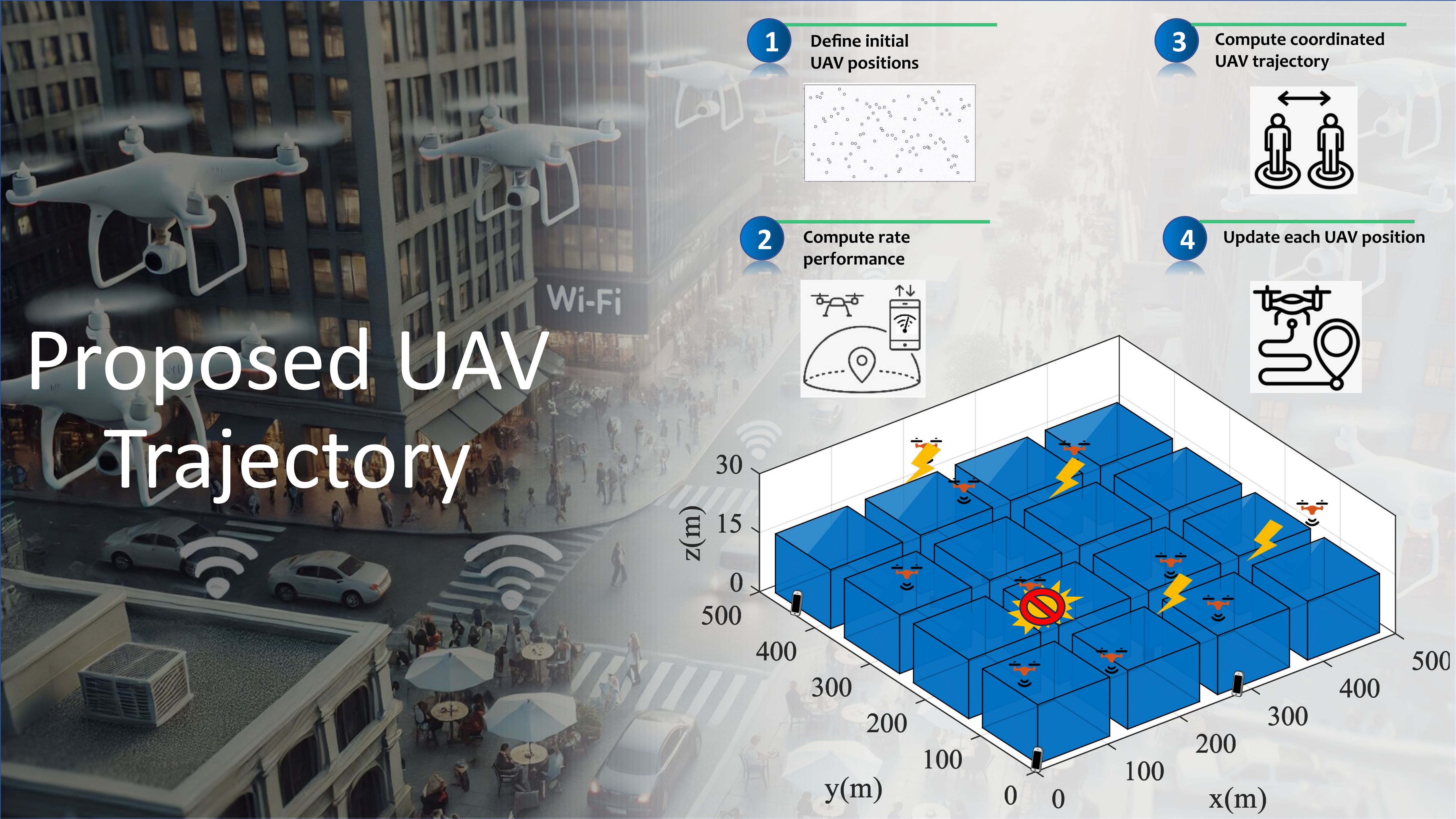
Scenarios

2 Congestion

✓Aerial and terrestrial network



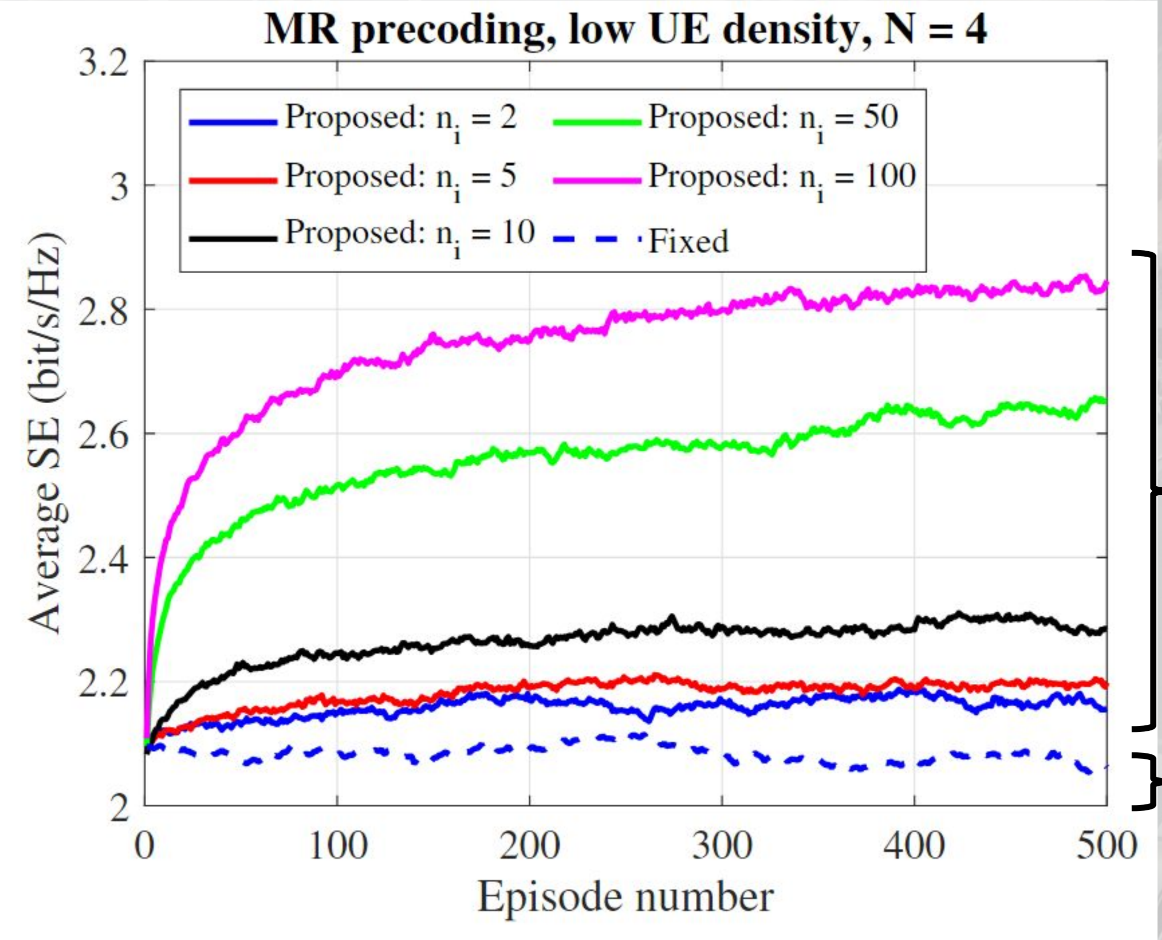

How to optimize UAV positions?
Wi-Fi
User Mobility


Proposed UAV Trajectory
1
Define initial UAV positions
2
Compute rate performance
3
Compute coordinated UAV trajectory
4
Update each UAV position
Wi-Fi
z(m)
30
15
0
500
400
300
200
100
0
y(m)
0
100
200
300
400
500
x(m)

Benefits

Low complexity

Performance improvement



Up to 38% data rate increase

Proposed

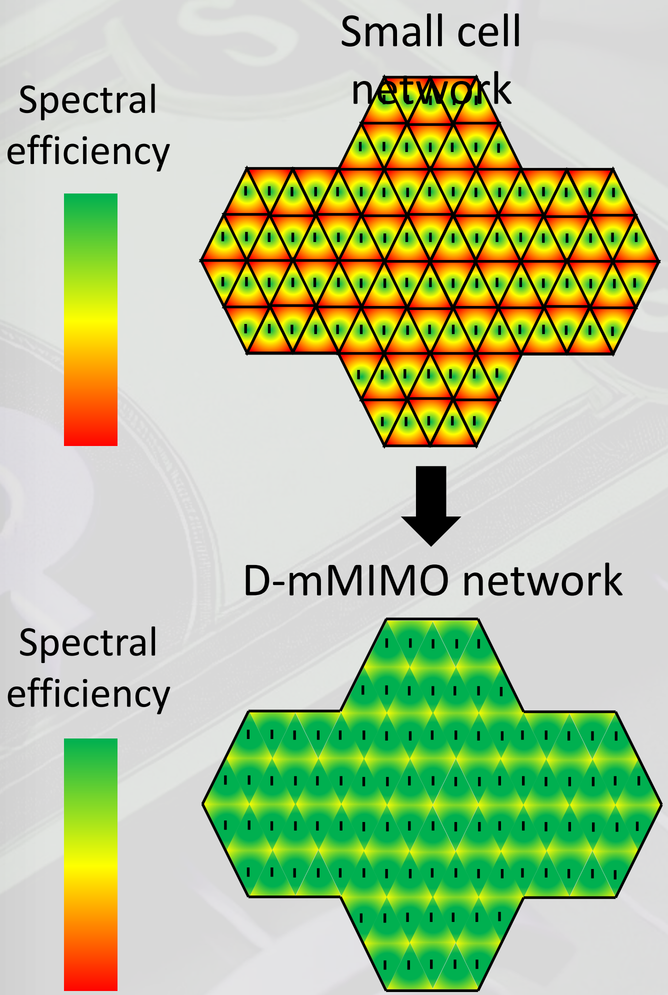
Baseline

Performance Gain

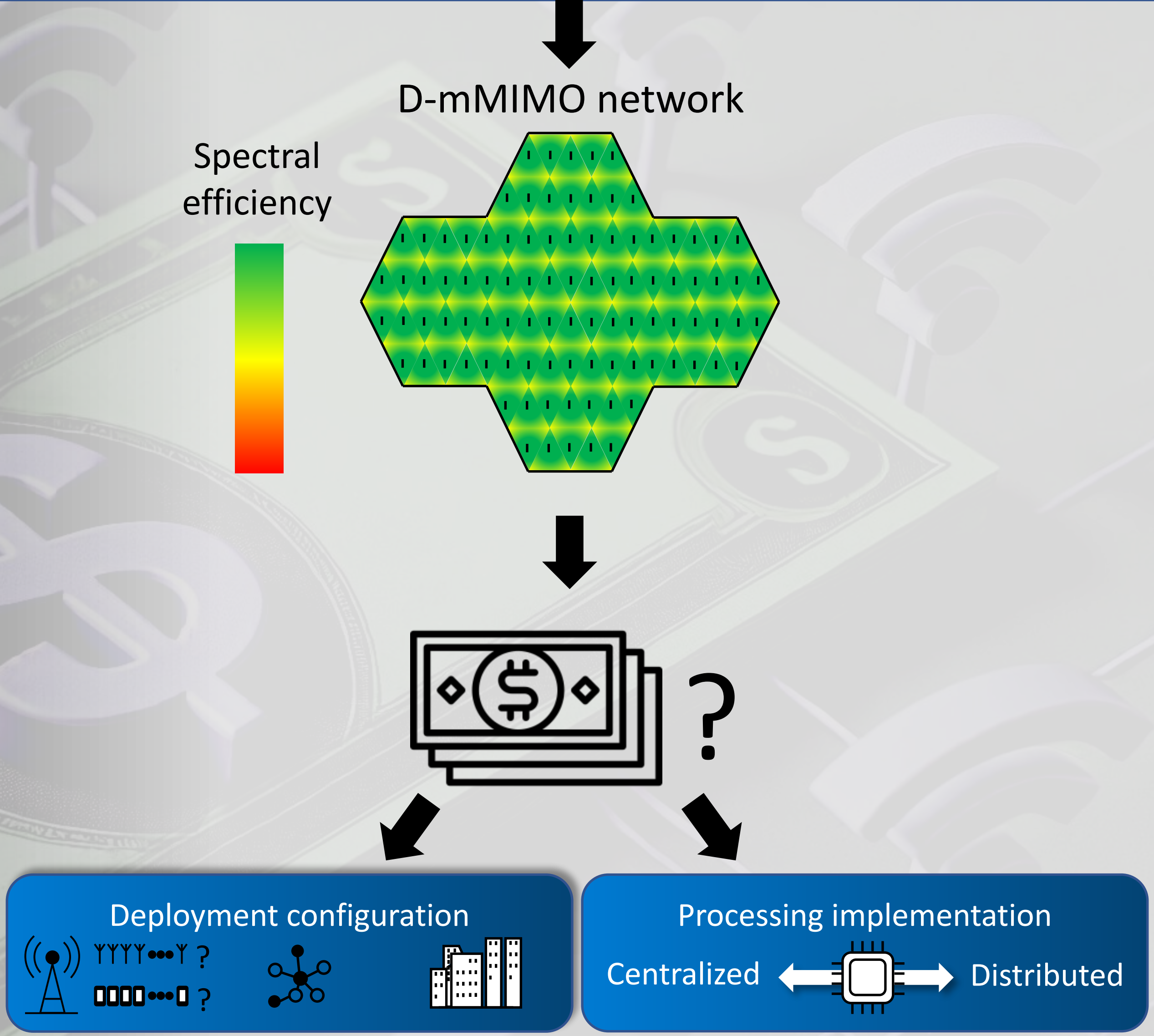
Feasibility Analysis for User-centric D-mMIMO

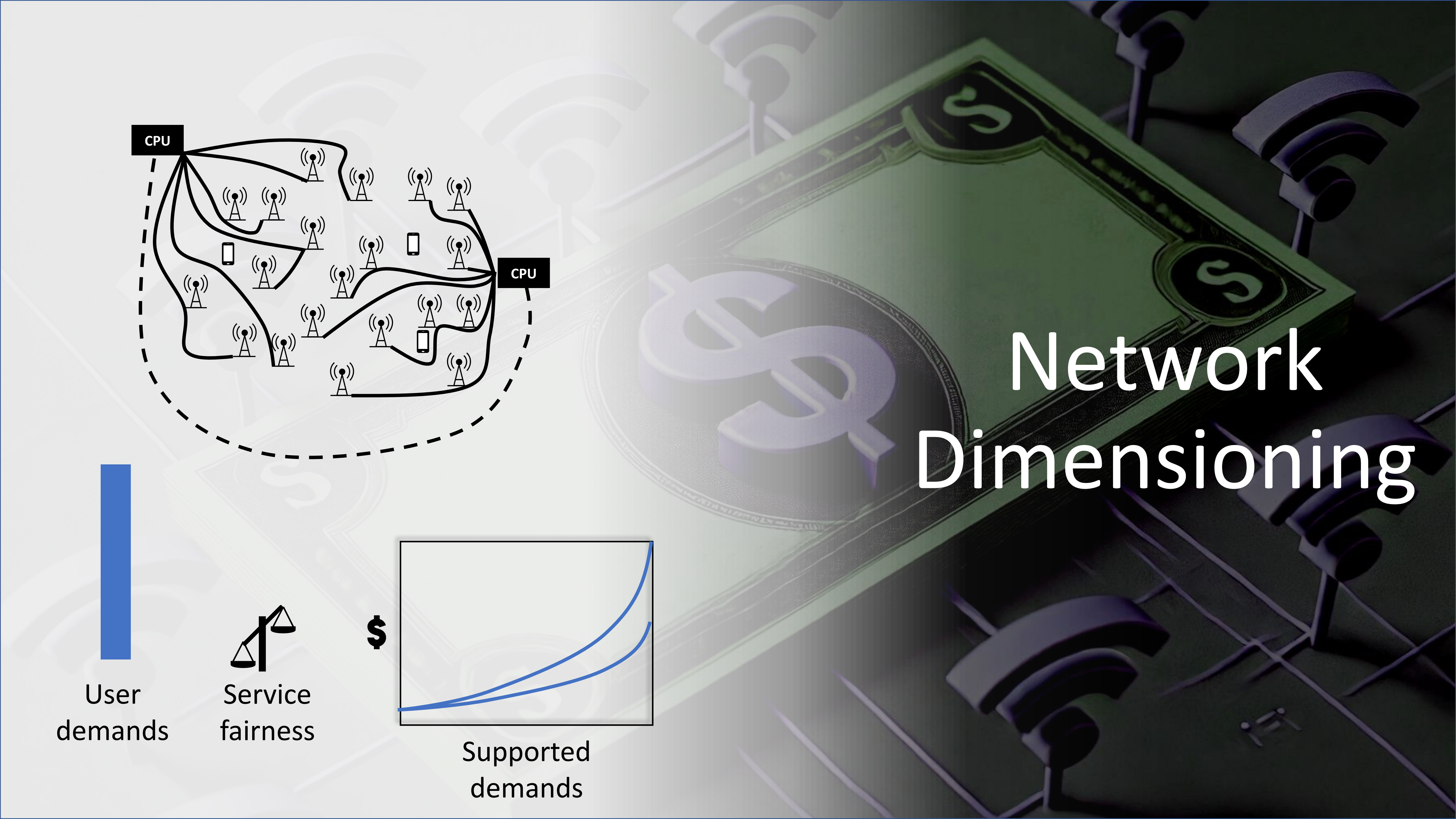
UNIVERSIDADE FEDERAL DO PARÁ

Problem

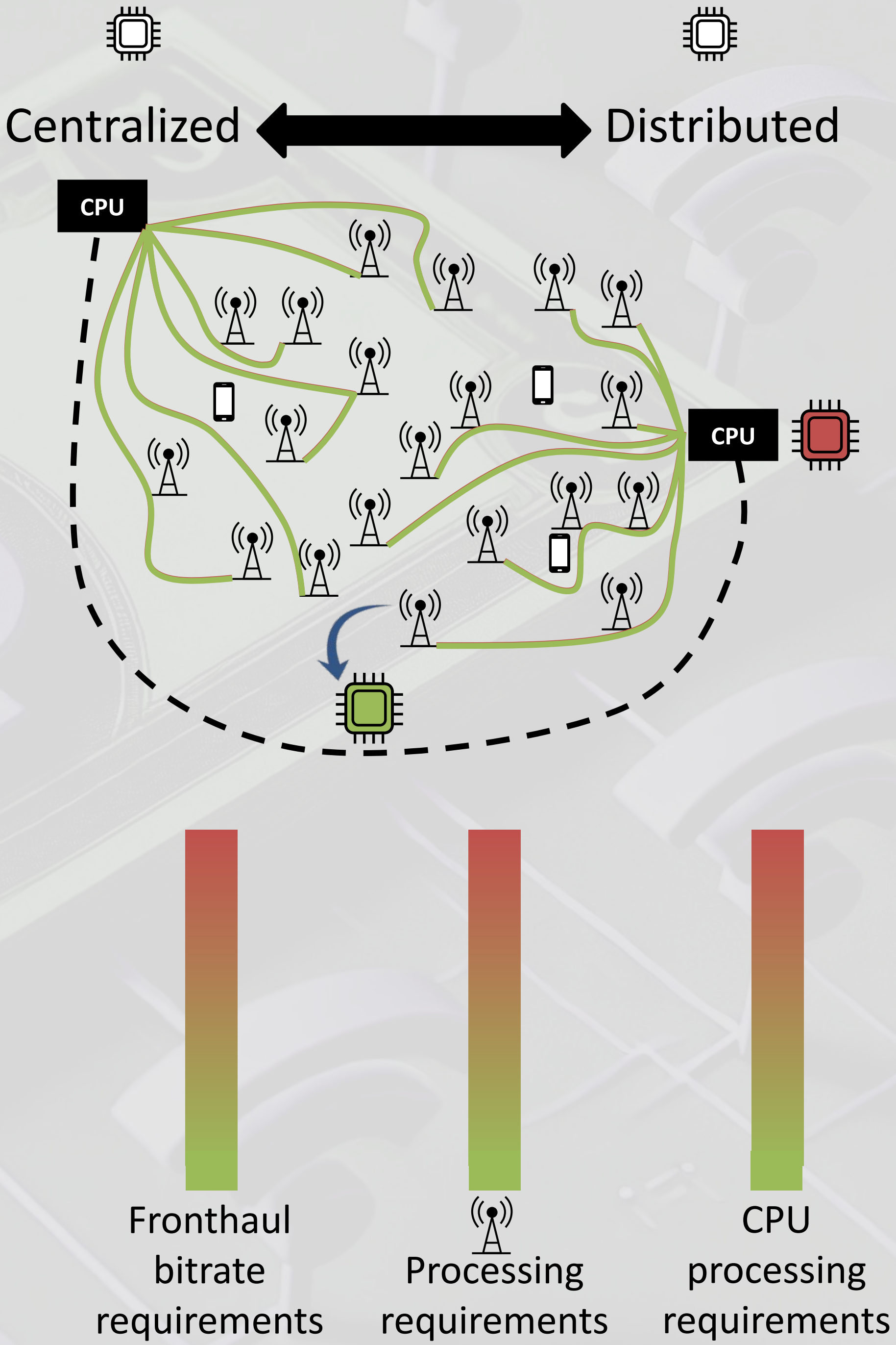

Small cell network
Spectral efficiency
D-mMIMO network
Spectral efficiency

Problem

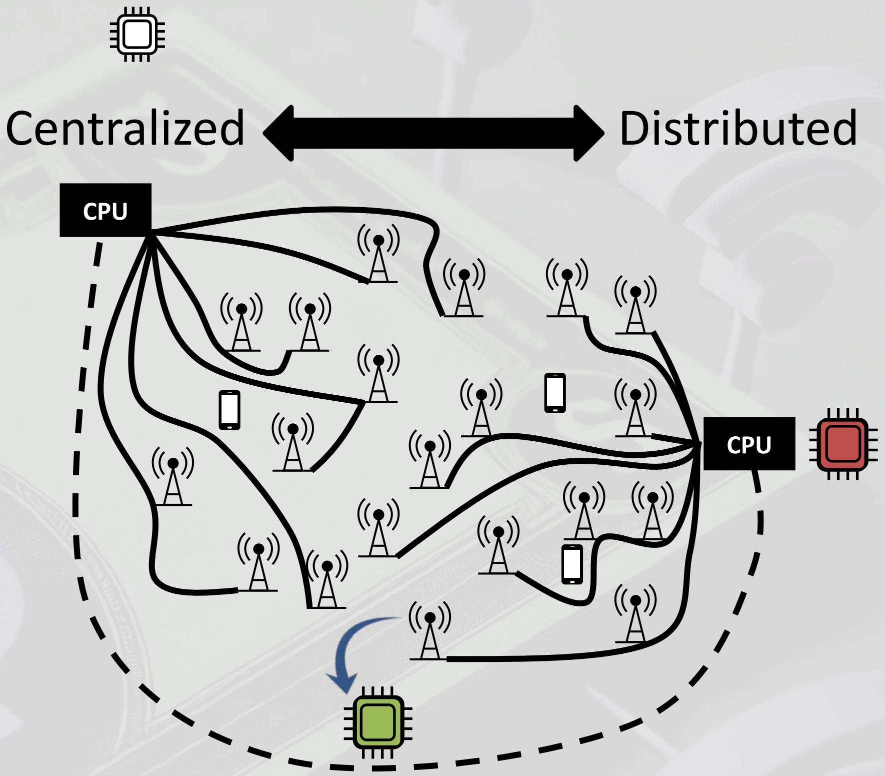

D-mMIMO network
Spectral efficiency
?
Deployment configuration
Processing implementation
Centralized
Distributed

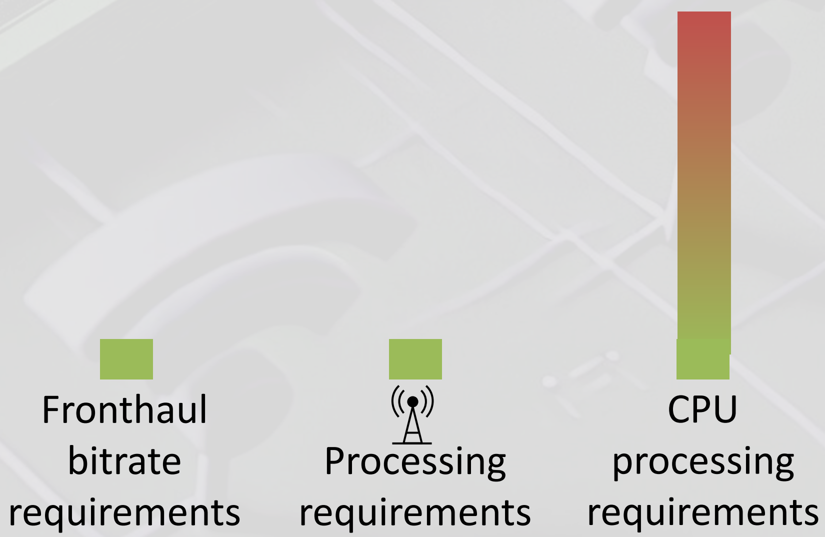

CPU
CPU
User demands
Service fairness
$
Supported demands
Network Dimensioning

Fronthaul and Processing Requirements

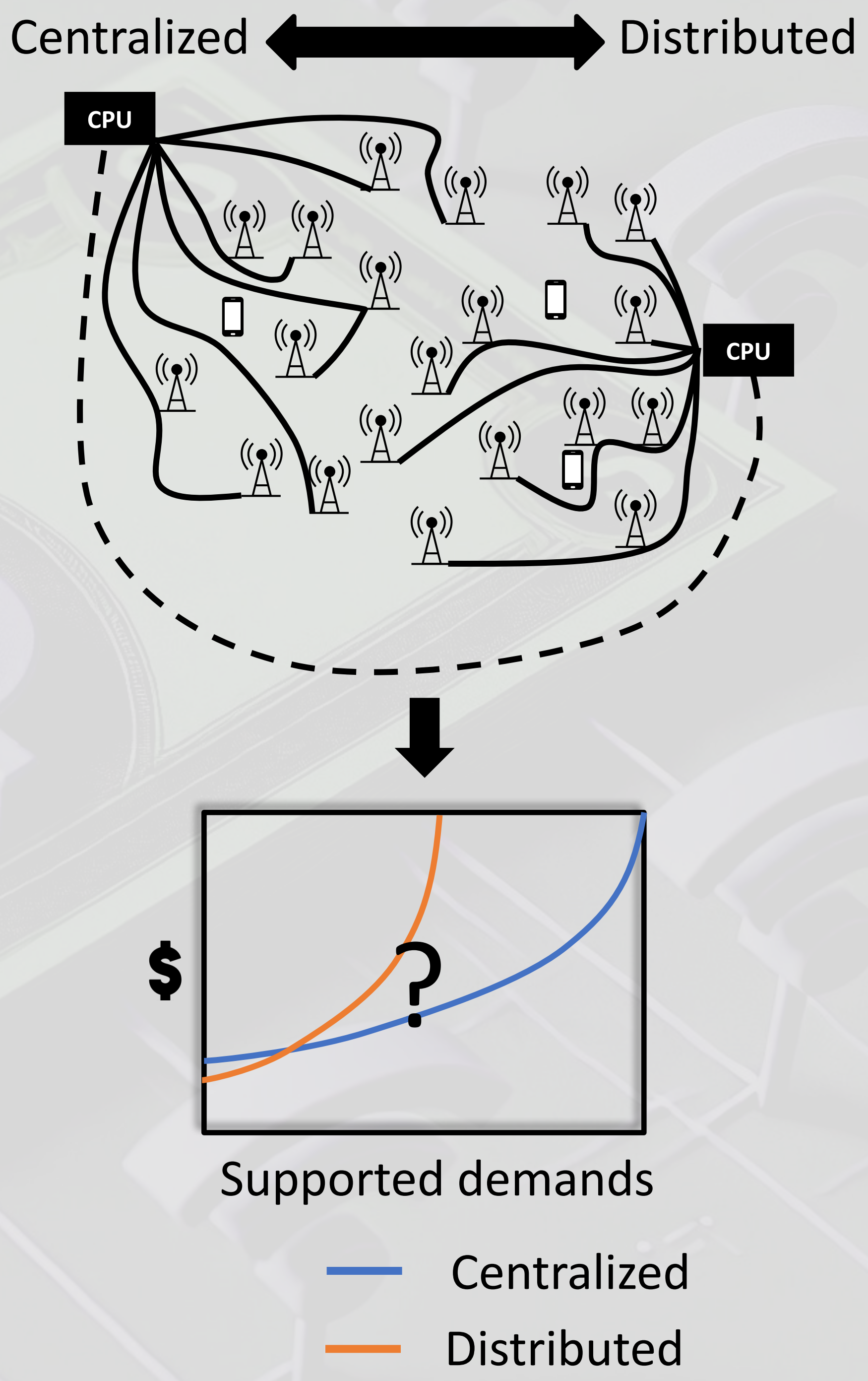


Fronthaul and Processing Requirements

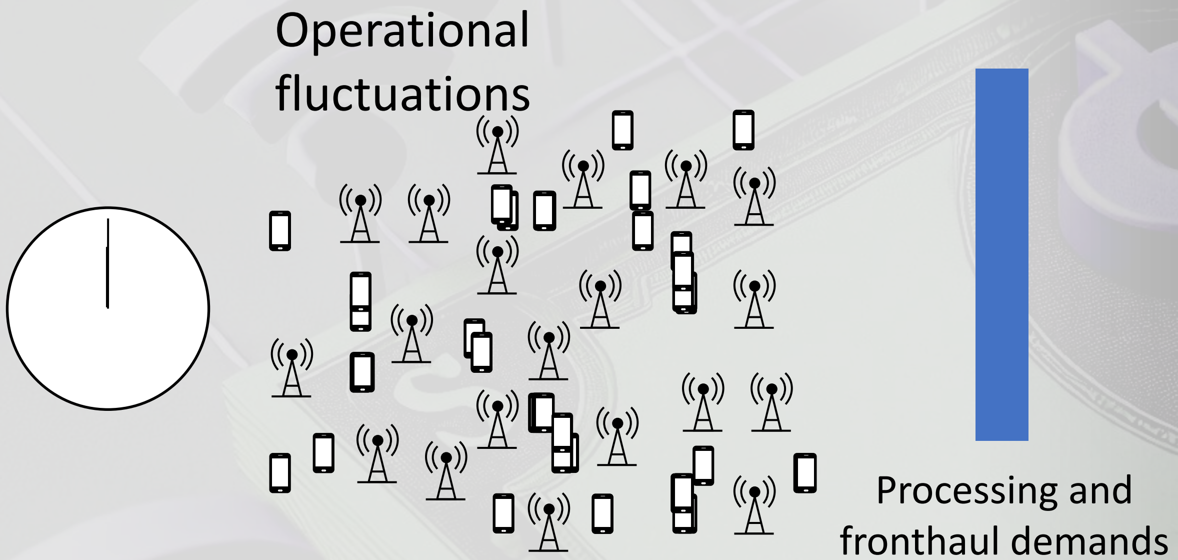




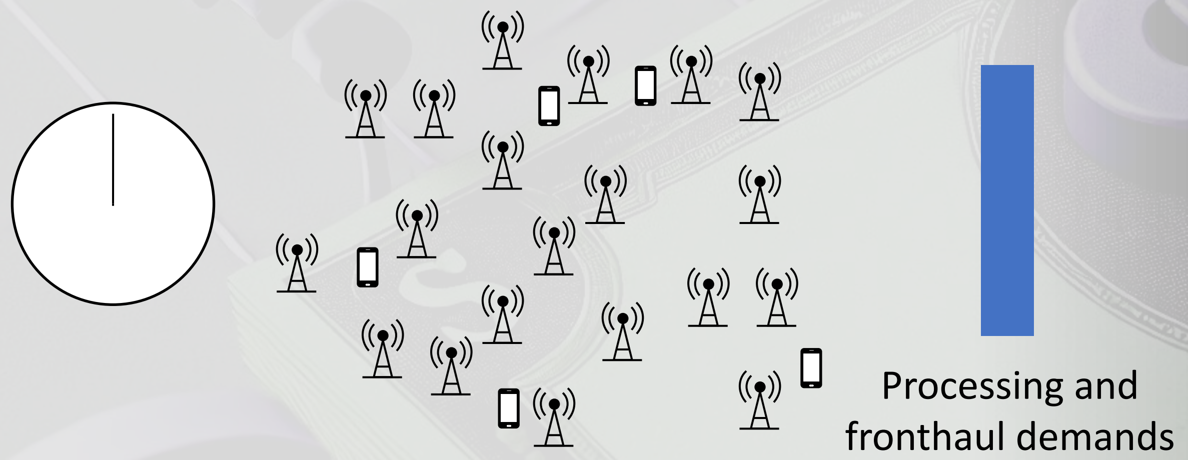
Fronthaul and Processing Requirements



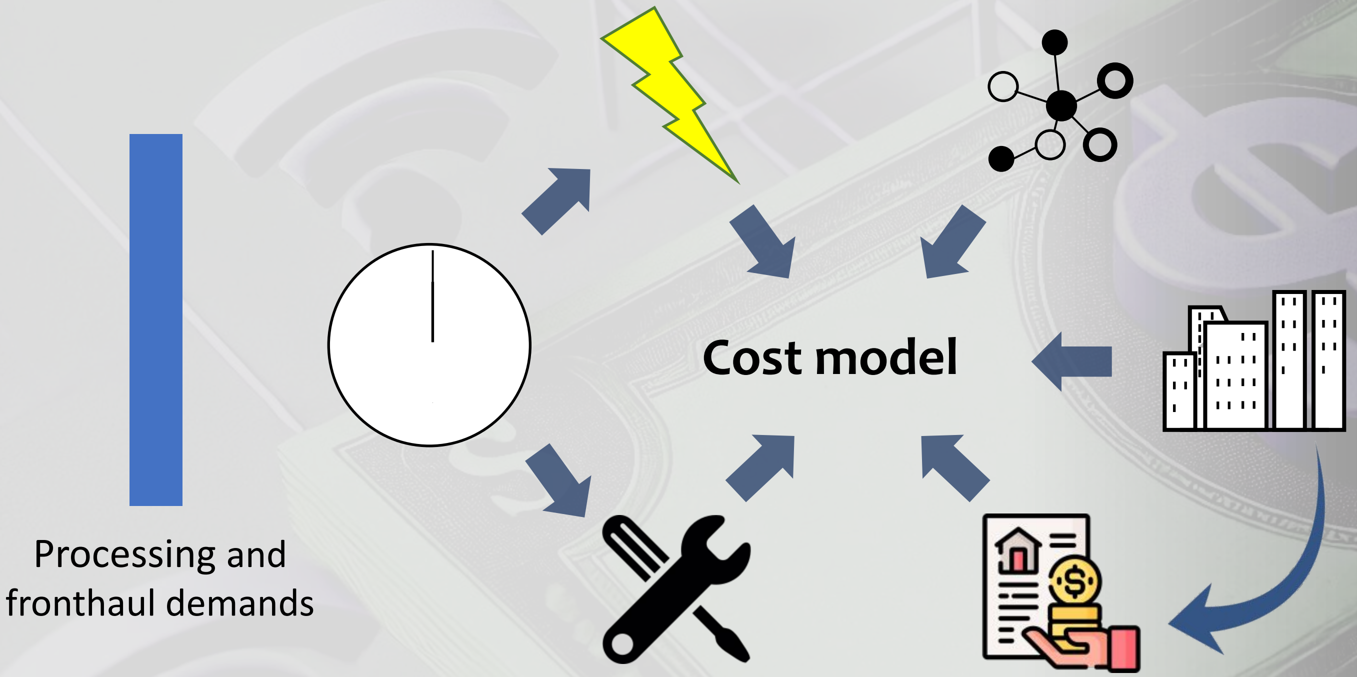
Cost Assessment



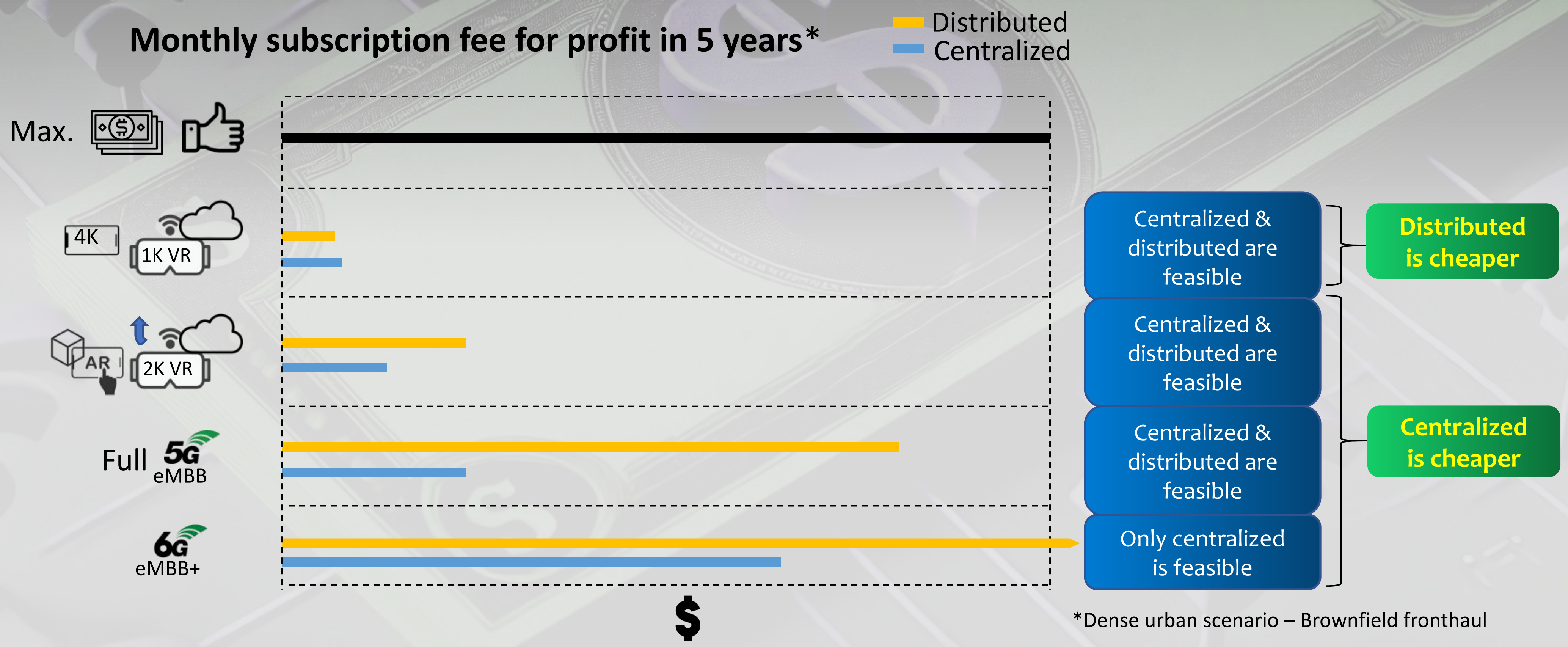
Cost Assessment



Cost Assessment

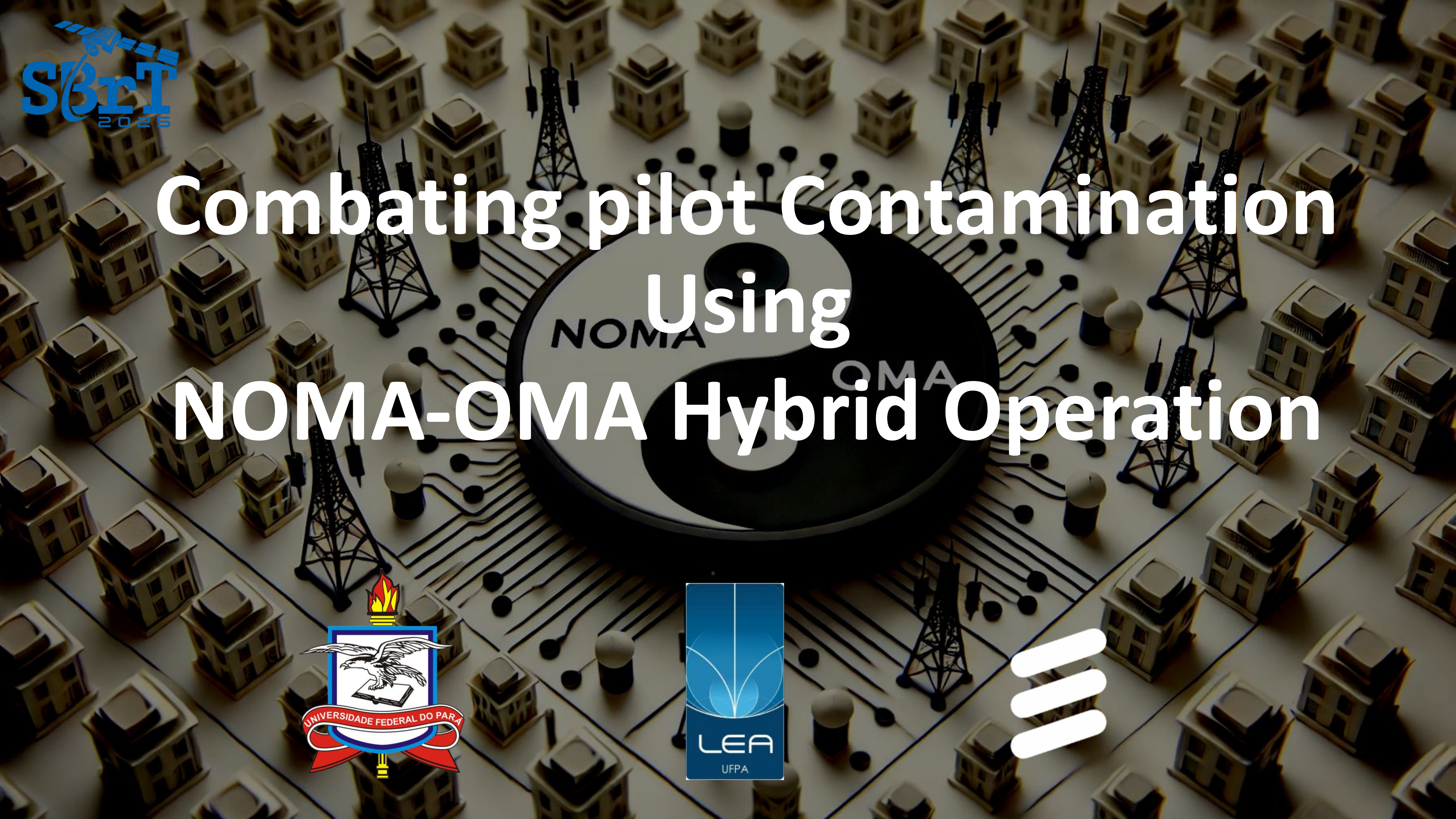


Profitability
Distributed vs. Centralized

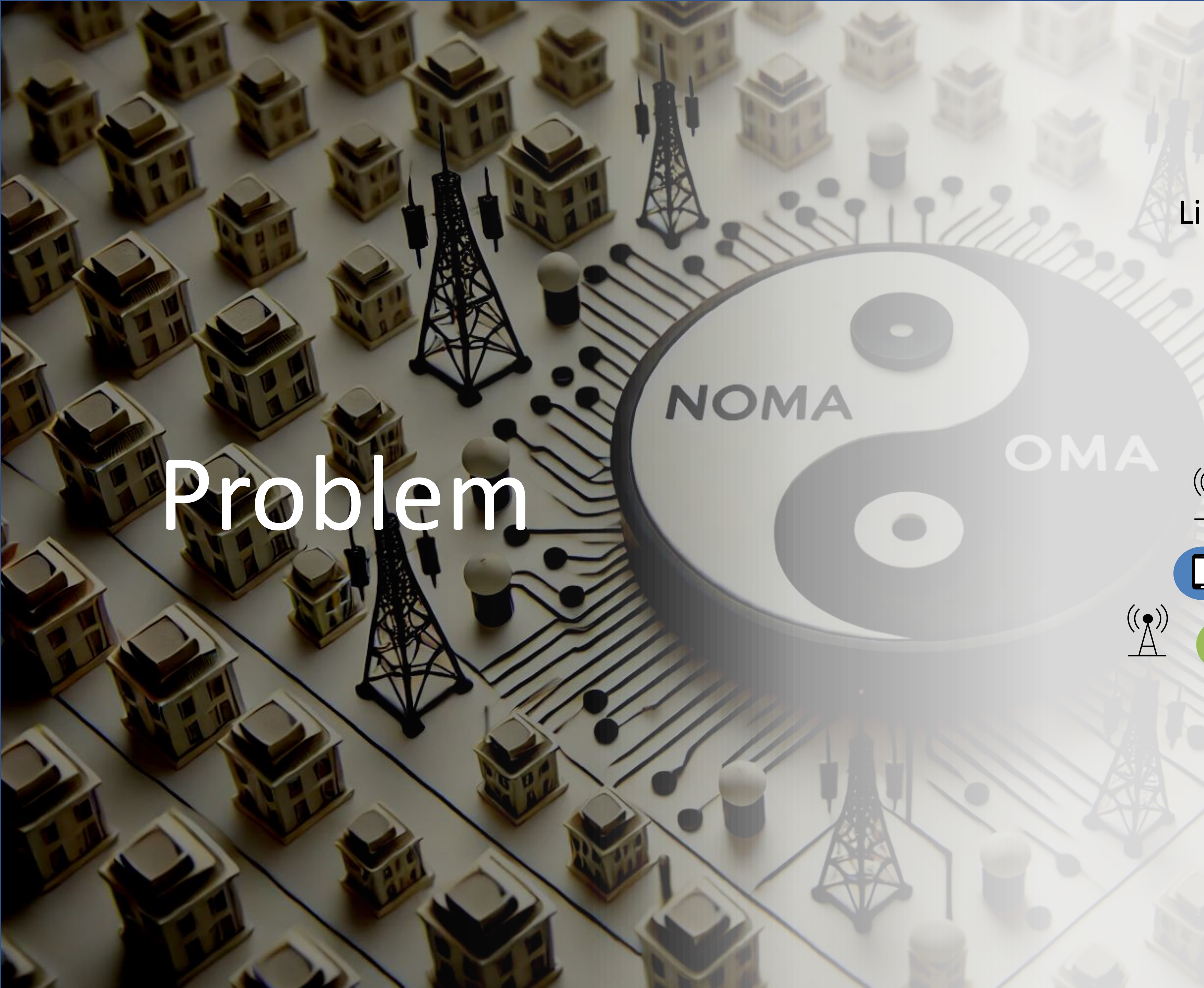


*Dense urban scenario – Brownfield fronthaul

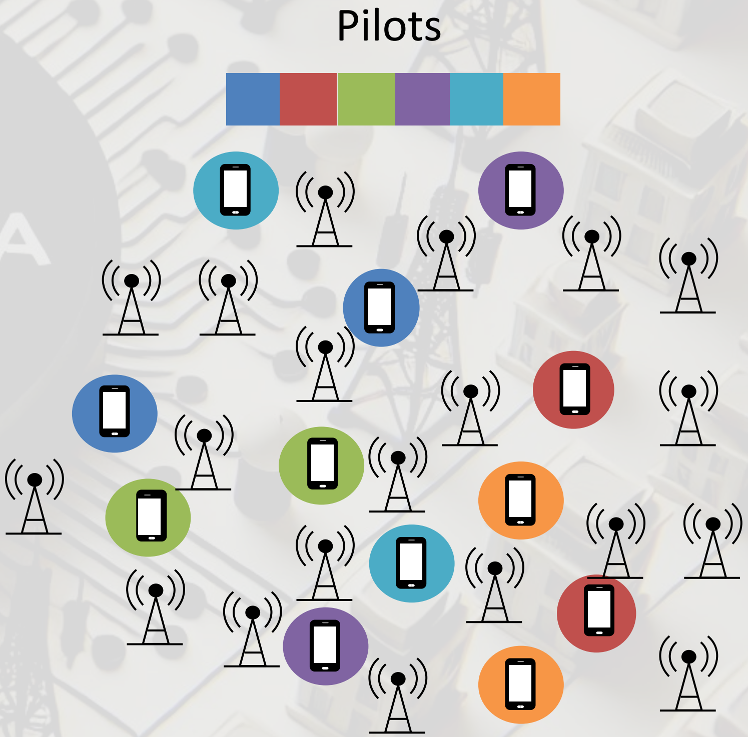
Combating pilot Contamination Using NOMA-OMA Hybrid Operation

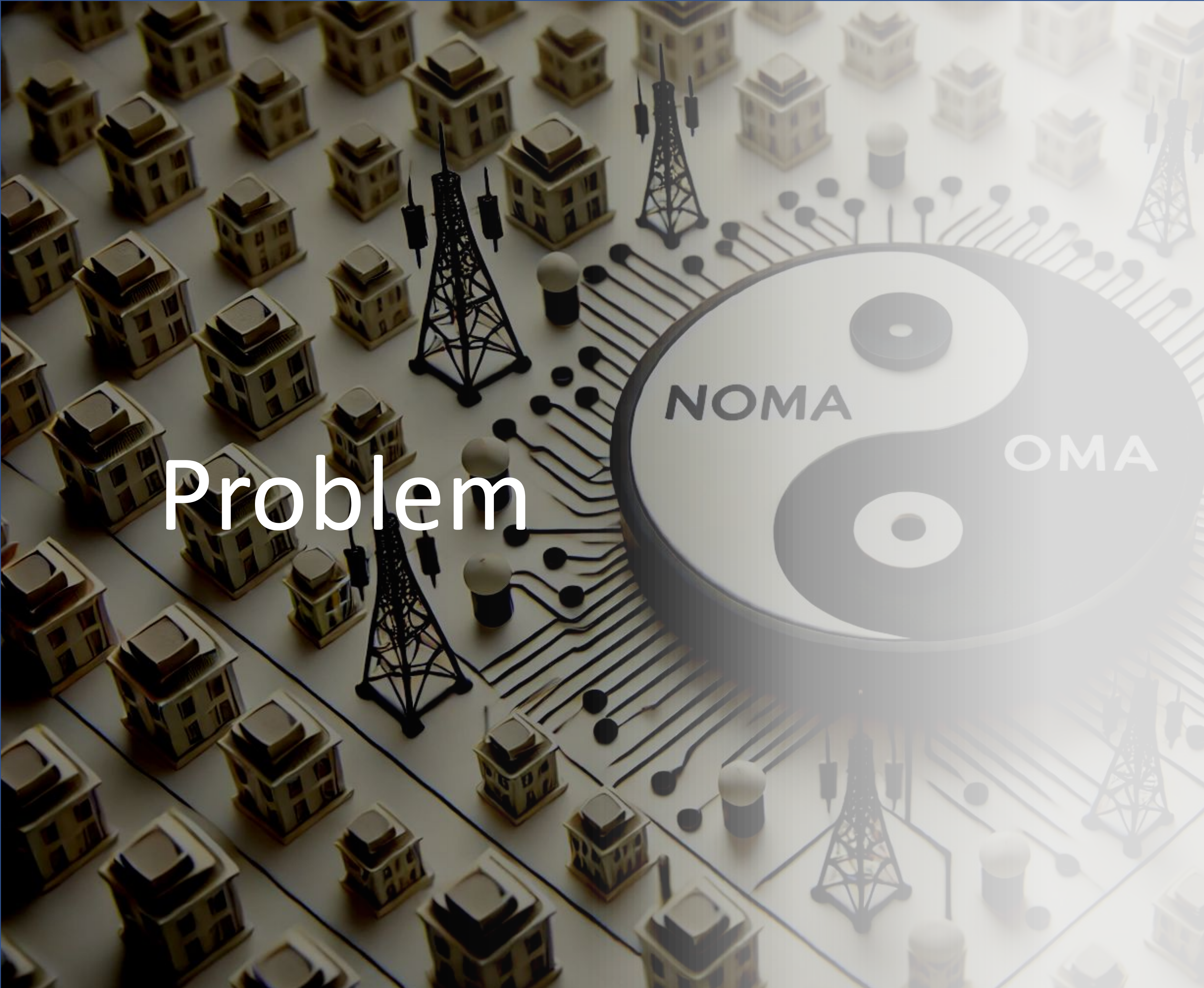


Problem



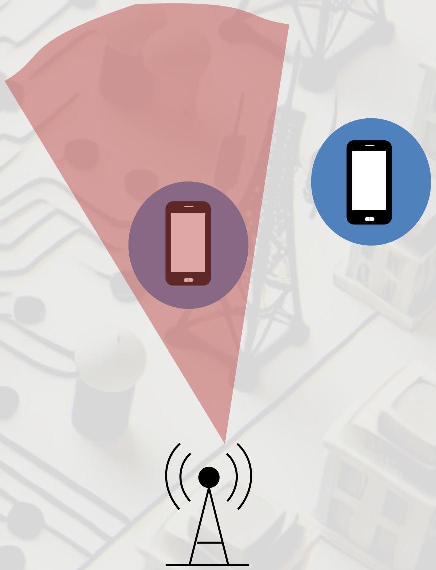
Limited estimation resources





Problem

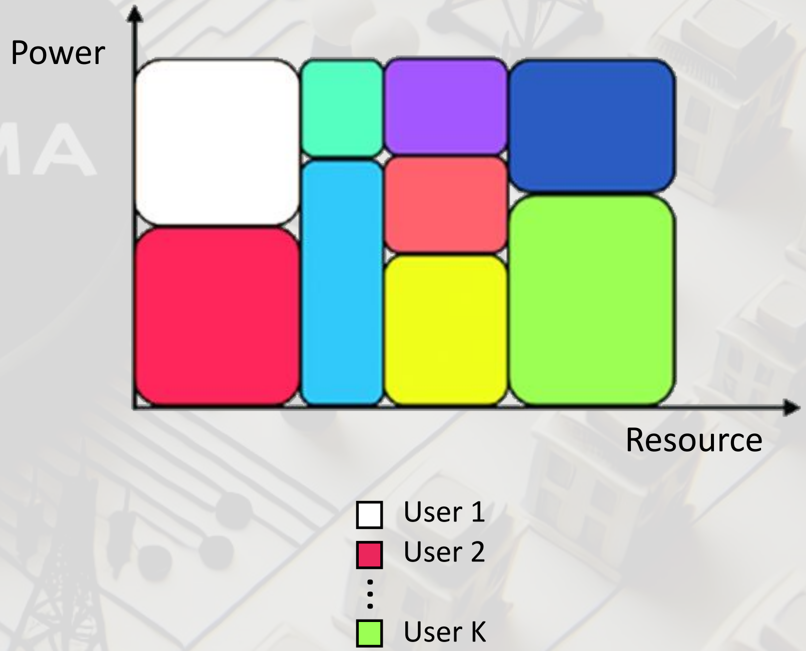
Pilot reuse consequence:



Coherent interference generation

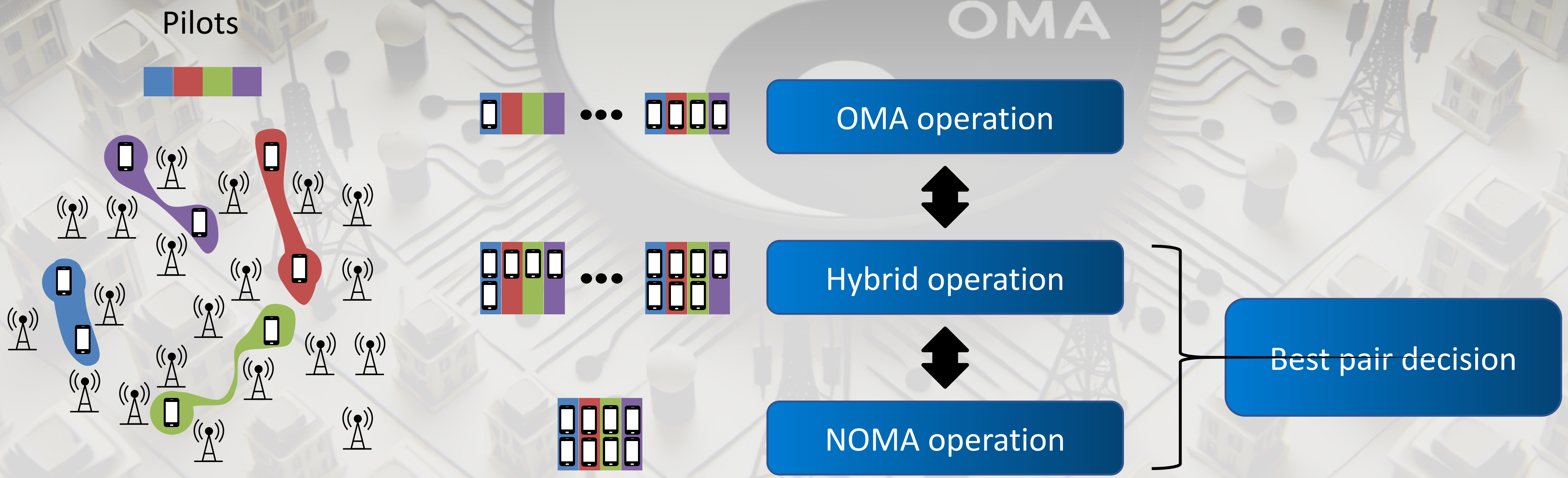
Problem

NOMA ⚔ Coherent interference

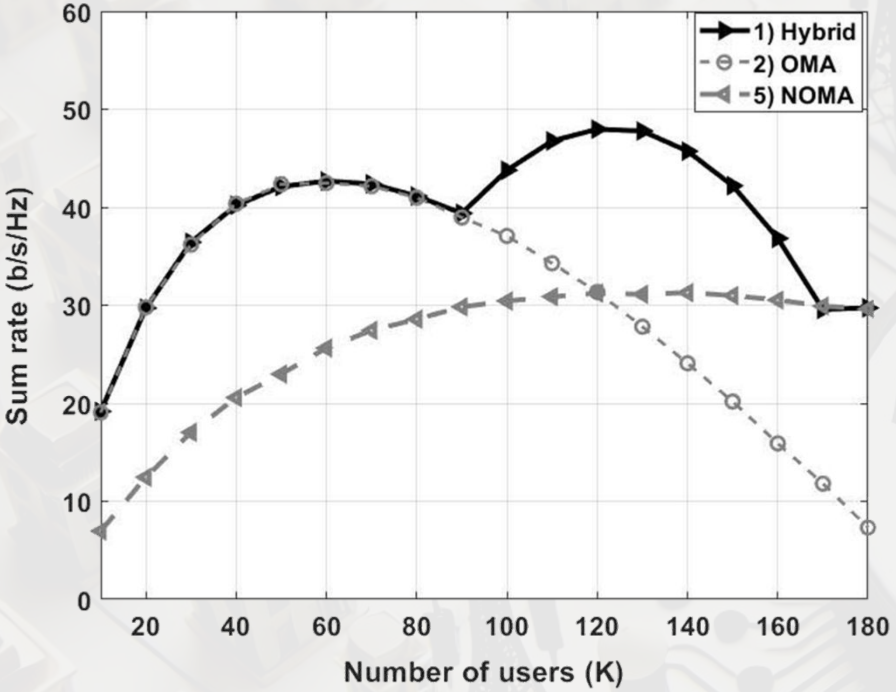



NOMA
OMA
Dynamic
decision policy
NOMA
OMA
Research

Decision Policy



Perfomance Gains



Proposed

Up to 53% improvement for NOMA

Up to 71% improvement for OMA