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Cell-free Massive MIMO:

Fundamentals and Energy-Aware C-RAN Implementation

A tutorial by

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Wireless Communications for Growing Opportunities

Cell-free Massive MIMO: Fundamentals and Energy-Aware C-RAN Implementation

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Program at a Glance

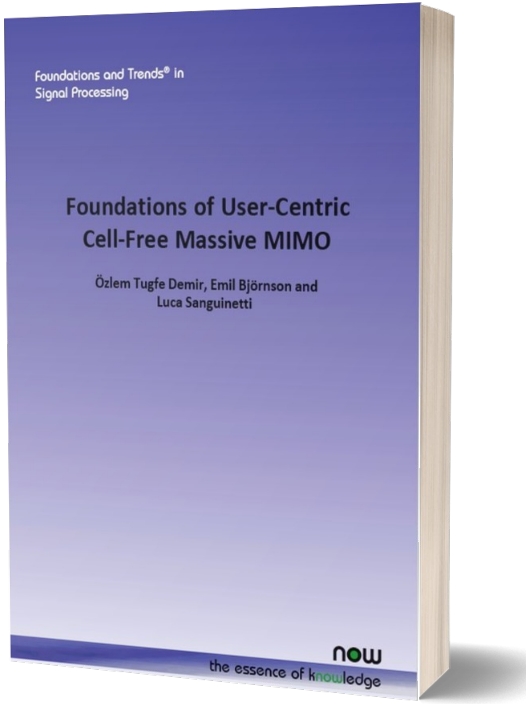
Part 1

- From cellular to cell-free massive MIMO (30 min) – Emil
- Fundamental theory (60 min) – Emil
    - Based on the book and its assumptions

Coffee Break (30 min)

Part 2

- Energy-aware C-RAN implementation (75 min) – Özlem
    - Radio, fronthaul, and cloud power consumption modeling
    - Energy-saving mechanisms
- Emerging research challenges (15 min) – Emil



https://github.com/emilbjornson/cell-free-book

PART 1

FUNDAMENTALS OF CELL-FREE MASSIVE MIMO

Outline of Part 1

1. Motivation: Importance of spectral efficiency
2. Cell-free Massive MIMO:
   Fundamental models and algorithms
3. Reasons for a sequential fronthaul design
   and optimized algorithms
4. Summary

Thanks to my collaborators

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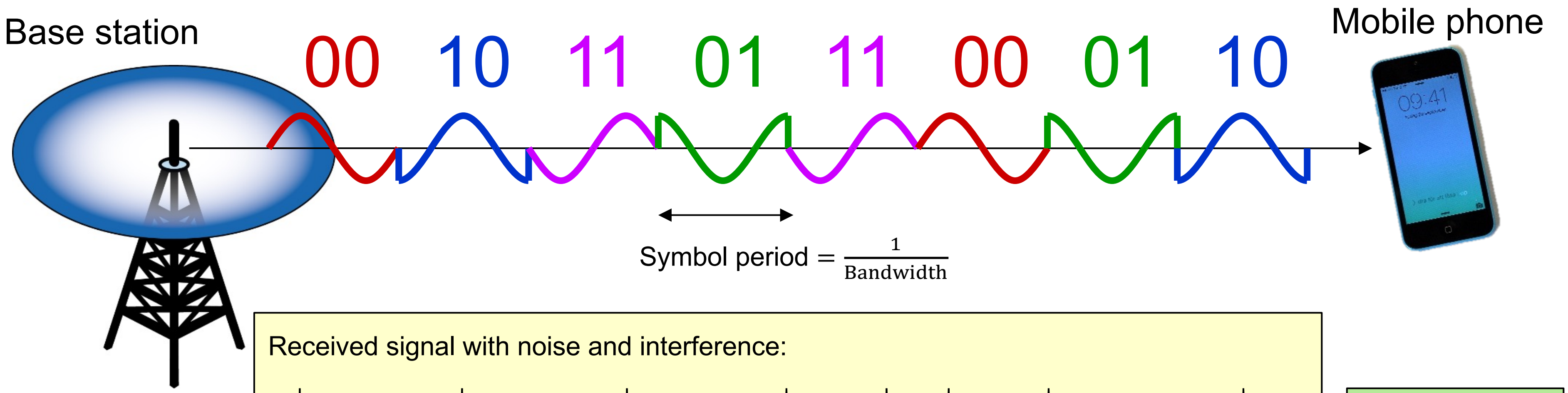
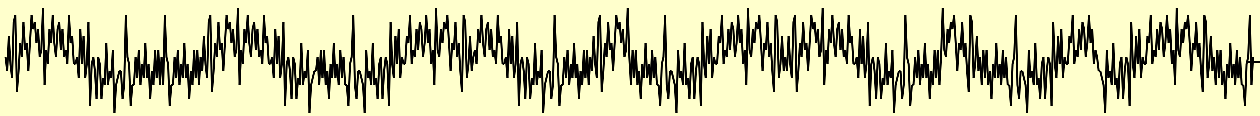
MOTIVATION

Wireless Communications in a Nutshell



Symbol period $= \frac{1}{\text{Bandwidth}}$

Received signal with noise and interference:



Communication algorithm

0010110111000110

How many bits can we transmit *reliably*?

Shannon capacity: $\text{Bandwidth} \cdot \log_2\left(1 + \frac{\text{Signal power}}{\text{Interference+noise power}}\right)$ bit/s

Spectral efficiency [bit/s/Hz]

The Cellular Architecture was Proposed in the 1950s

Designed for mobile telephone systems

Bullington, K. (1953). "Frequency economy in mobile radio bands". The Bell System Technical Journal.

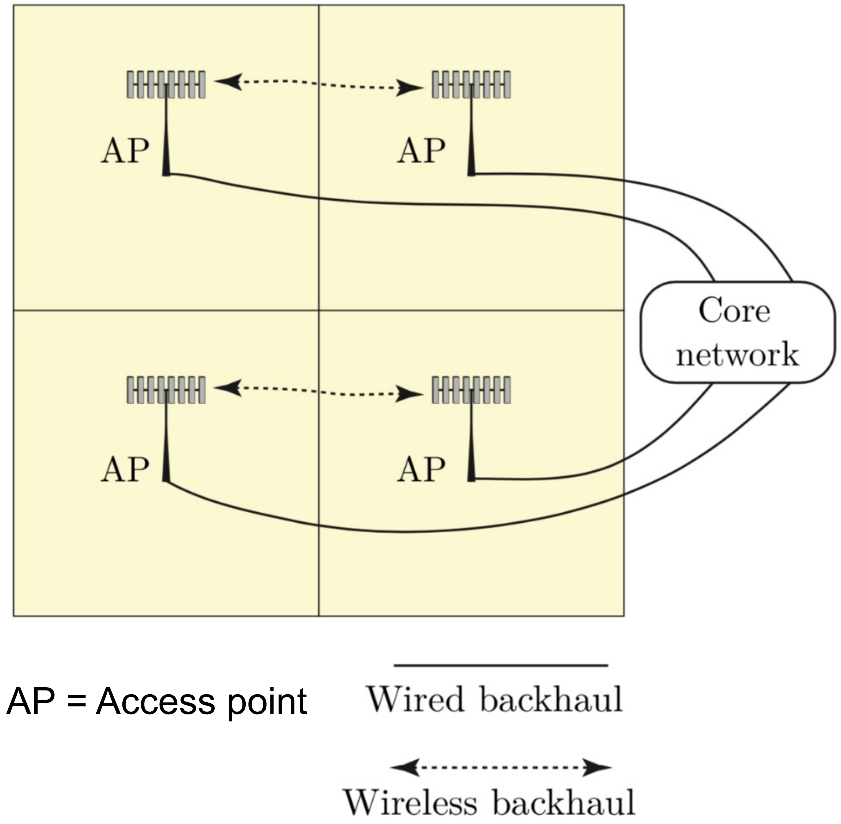
Schulte, H. J. and W. A. Cornell (1960). "Multi-area mobile telephone system". IEEE Trans. Veh. Technol.

Reuse of spectrum in space:

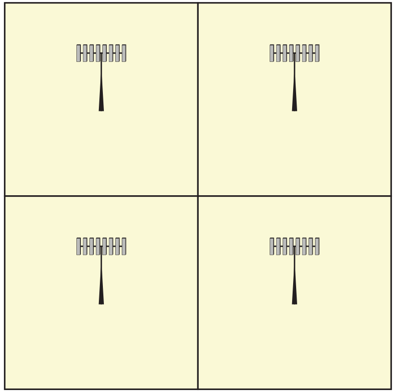
Densify as usage increases

Control interference

5G networks are still *cellular*

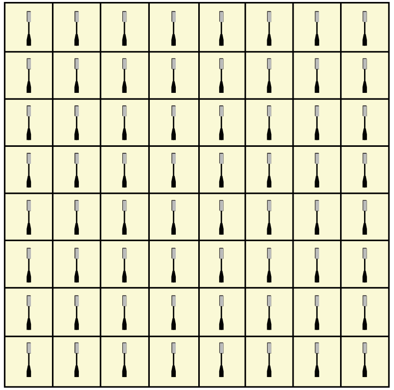


Spectral Efficiency in Cellular Networks

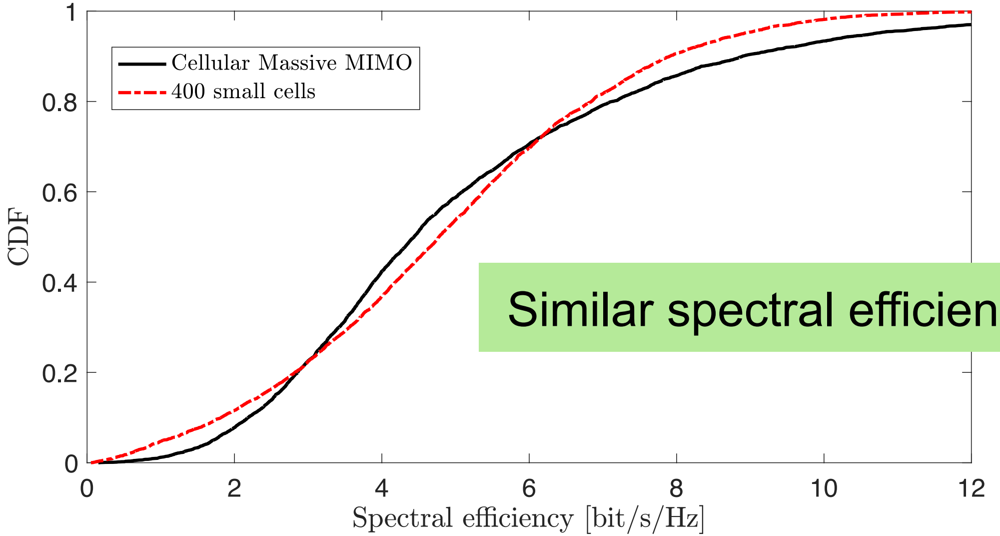


4 cells, 100 antennas
"Massive MIMO"

Large variations!



400 cells, 1 antenna
"Small cells"



Similar spectral efficiency statistics

MIMO = Multiple input multiple output

What Data Rates Do We Need?

Application	Required data rate
HD 1080p streaming	5-10 Mbit/s
4k streaming	20-25 Mbit/s
Online gaming	1-10 Mbit/s
Immersive 360° 8k VR	50-200 Mbit/s

Per device

4G Peak Rates

Low-mobility: 1 Gbit/s

High-mobility: 100 Mbit/s

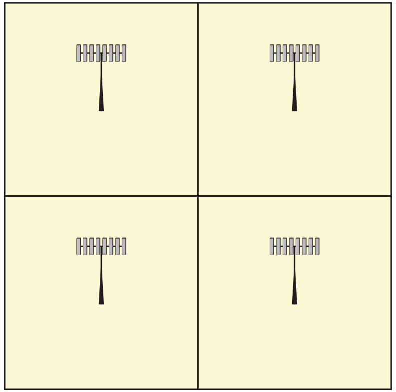
5G Peak Rates: 20×

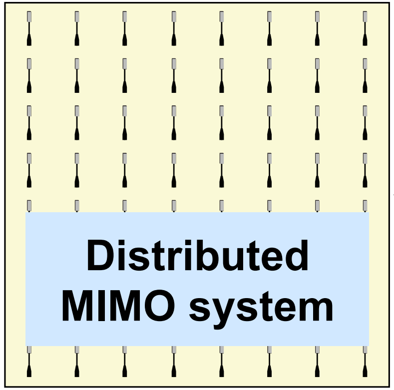
The *real* challenge:

Consistent performance!

A Potential Solution

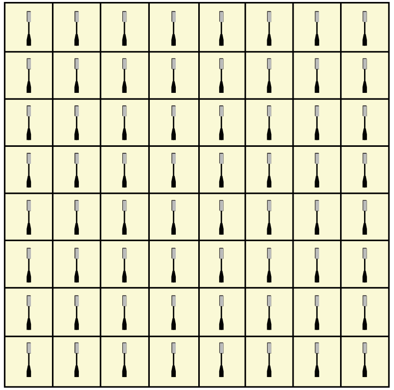
4 cells, 100 antennas

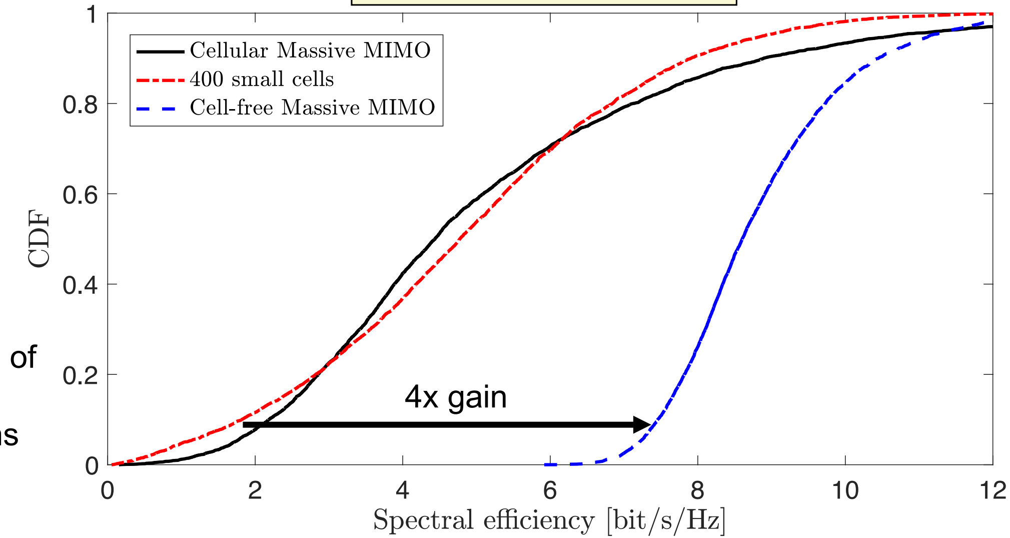


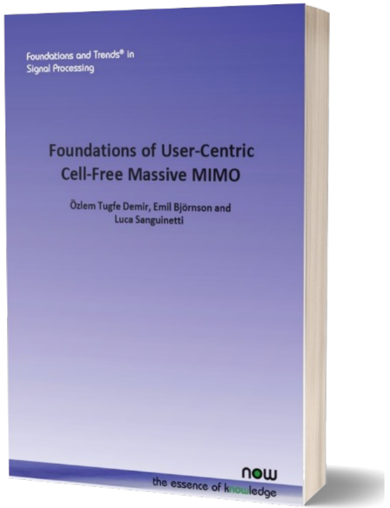


All antennas cooperate

400 cells, 1 antenna

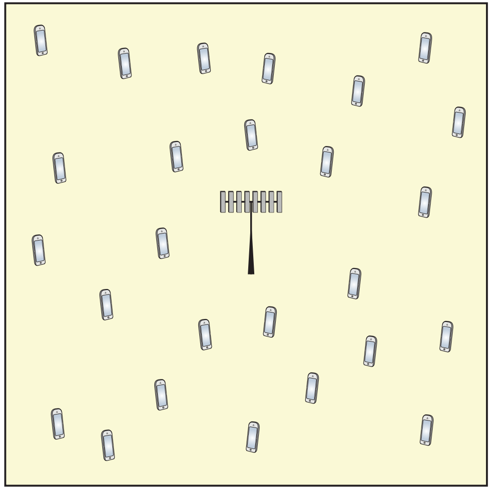




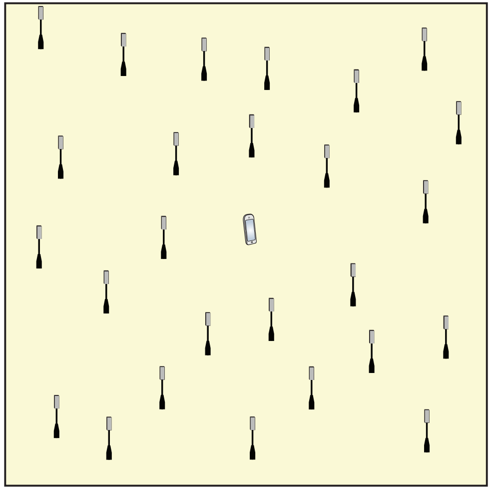


Ö. T. Demir, E. Björnson, L. Sanguinetti, “Foundations of User-Centric Cell-Free Massive MIMO,” Foundations and Trends in Signal Processing, 2021.

A Paradigm Shift: *User-Centric Cell-Free* Networks



AP surrounded by users



User surrounded by APs

Connection to Massive MIMO:

$L \gg K$

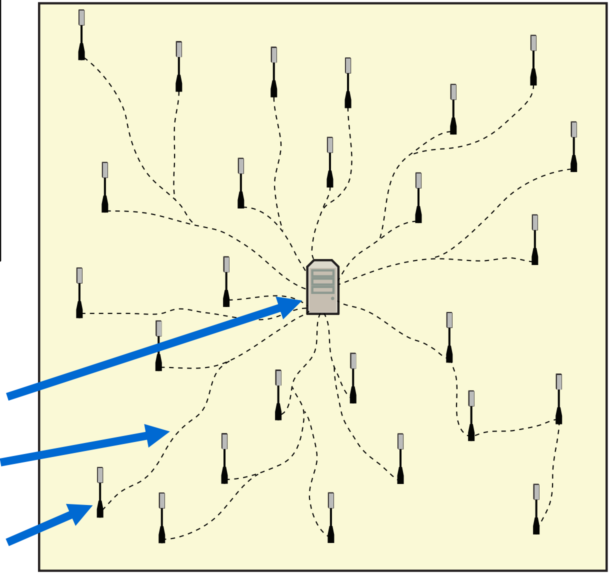
L APs, K users

Cloud RAN infrastructure:

Central processing unit

Fronthaul

Access point



Unique operation regime

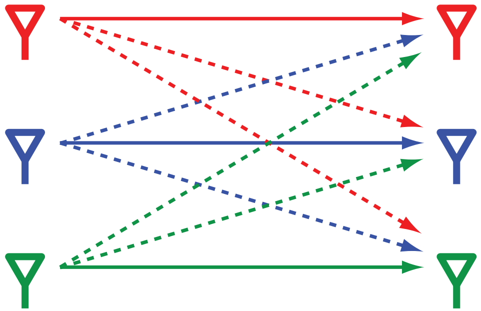
Each AP serves more users than it has antennas

Uplink: Philosophy of Interference Rejection

Cellular network:

3 desired signals:

One per transmitter



Each receiver:

1 observation

1 desired signal

2 interfering ones

Too few observations to remove interference

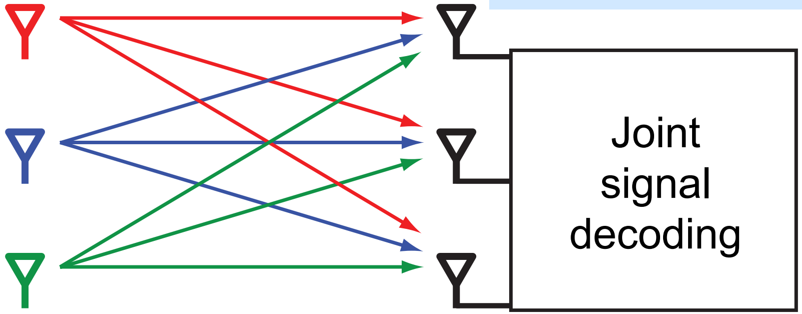
Cell-free network:

Noisy signal decoding

Minimize MSE $\mathbb{E}\{|\text{signal} - \text{estimate}|^2\}$

3 desired signals:

One per transmitter

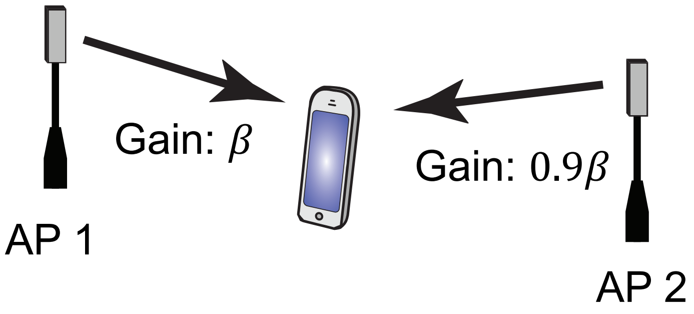


Enough observations:

3 observation

3 desired signal

Downlink: Why Transmit From More Than One AP?



- **Example:** Two APs
  - Total transmit power P

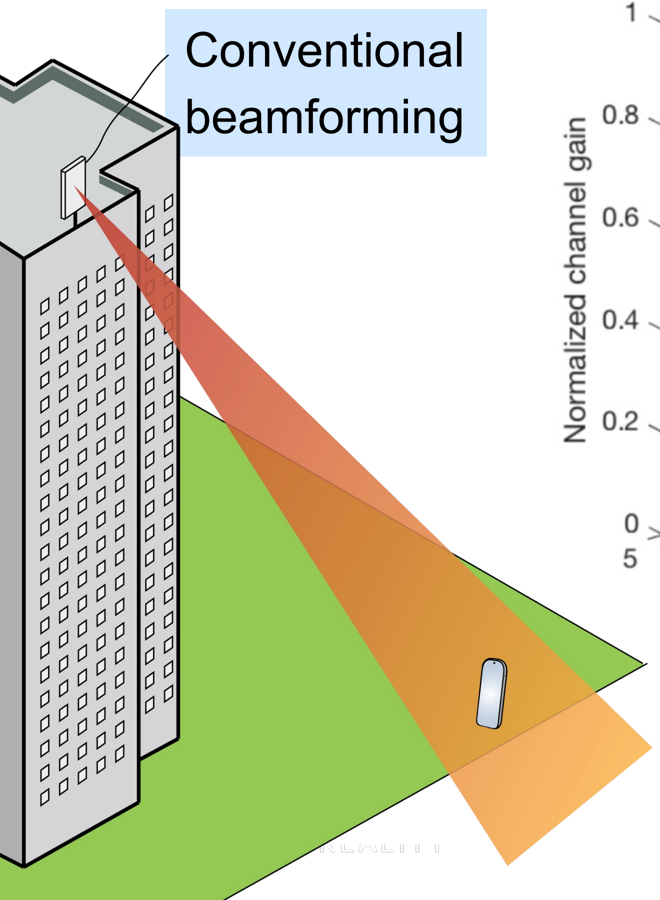
1. **Transmit from AP 1:**
   - Received power: $P\beta$

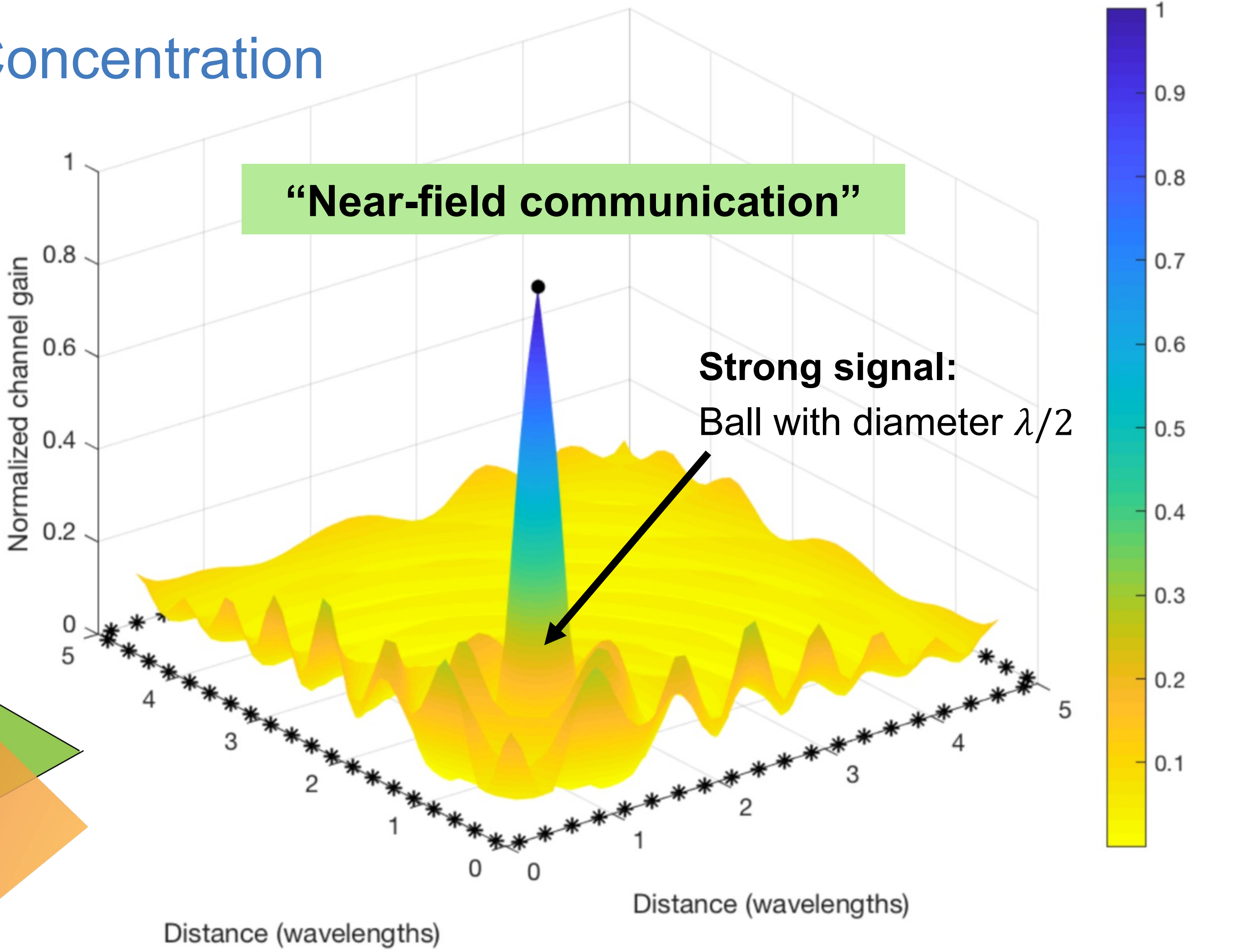
2. **Transmit from both APs:** $P/2$ from each AP
   - Received power: $\left(\sqrt{\frac{P}{2}}\cdot\sqrt{\beta}+\sqrt{\frac{P}{2}}\cdot\sqrt{0.9\beta}\right)^2 \approx 1.9\cdot P\beta$

Optimized power allocation:
Minimize MSE $\mathbb{E}\{|\mathrm{signal}-\mathrm{estimate}|^2\}$

Coherent combination!

Downlink Power Concentration



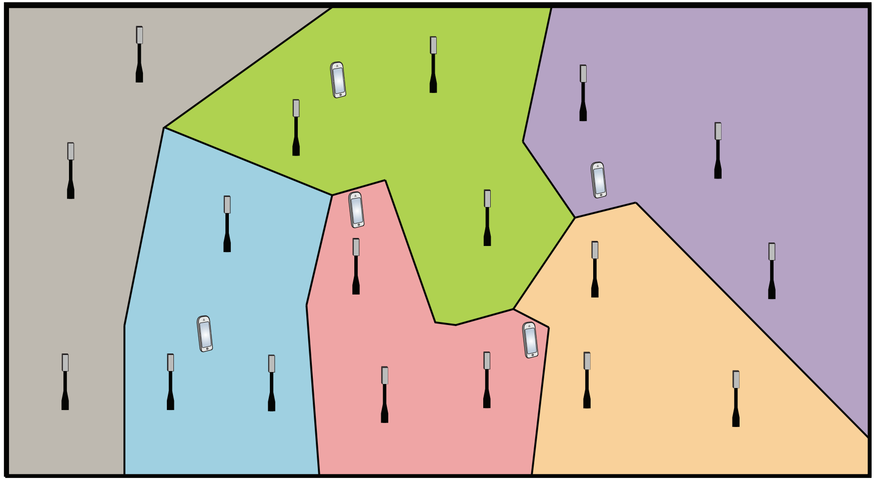


Brief Historical Background

1. Interference avoidance and decoding, 1950–2005
   - Frequency reuse patterns, sectorization, etc.
   - Successive interference cancelation (e.g., NOMA)
2. Spatial interference rejection: 2000–2010
   - Turn interference channels into MAC/broadcast channels: Underpins Cell-free Massive MIMO
   - Many names: Network MIMO, Group cells, multicell cooperative network, ...
3. Coordinated multipoint: 2005–2015
   - An attempt to implement these concepts in 4G
   - Add-on to cellular networks, not particularly successful
4. Cell-free Massive MIMO networks: 2015–
   - Restart of the topic in [NAY+15], using methodology from Cellular Massive MIMO
   - Focused on scalability, many more APs than UEs, distributed architecture...

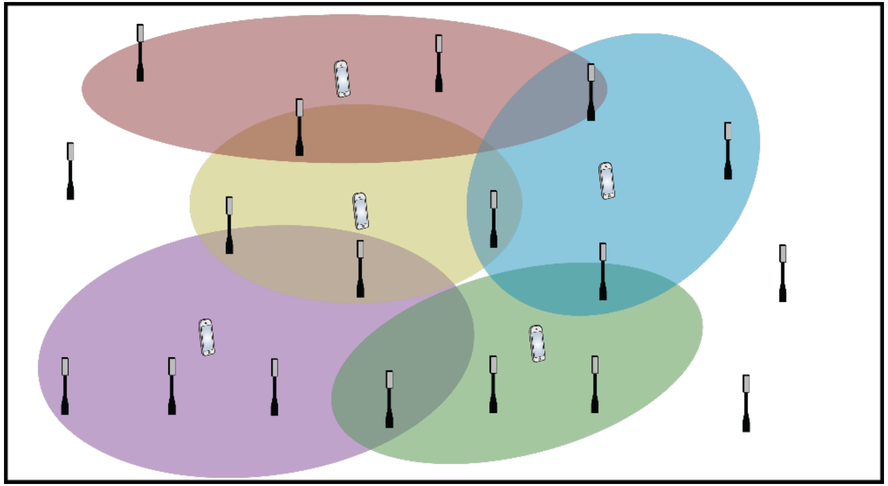
[NAY+15] H. Q. Ngo and A. E. Ashikhmin and H. Yang and E. G. Larsson and T. L. Marzetta, "Cell-free Massive MIMO: Uniformly great service for everyone," IEEE SPAWC 2015.

Key Difference from 4G Coordinated Multipoint



Cellular: Coordinated multipoint

Network-centric design



Cell-free: Each user served by all AP in its area of influence

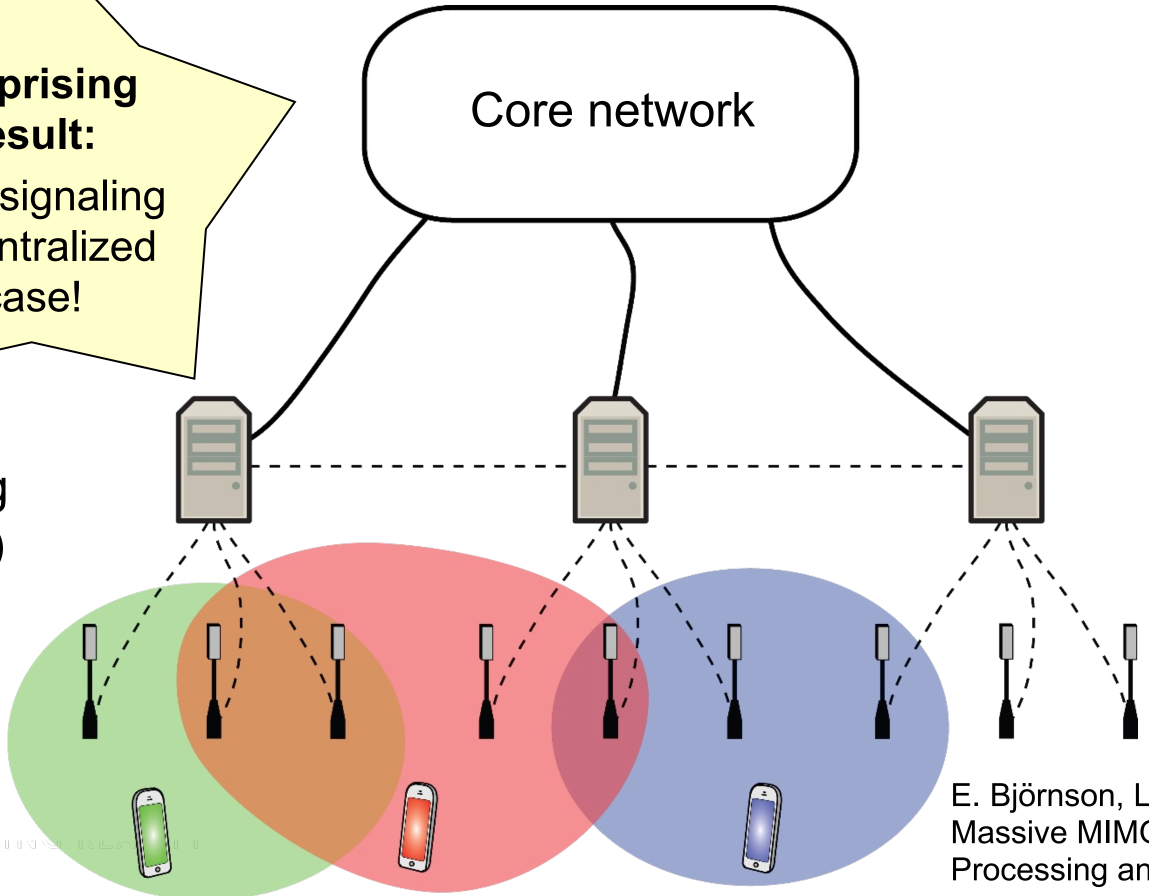
User-centric design

Signal Processing: Centralized versus Distributed

Surprising result:
Less signaling in centralized case!

Central processing unit (CPU)

Access point (AP)



Processing tasks
Channel estimation
Precoding/combining
Data en-/de-coding

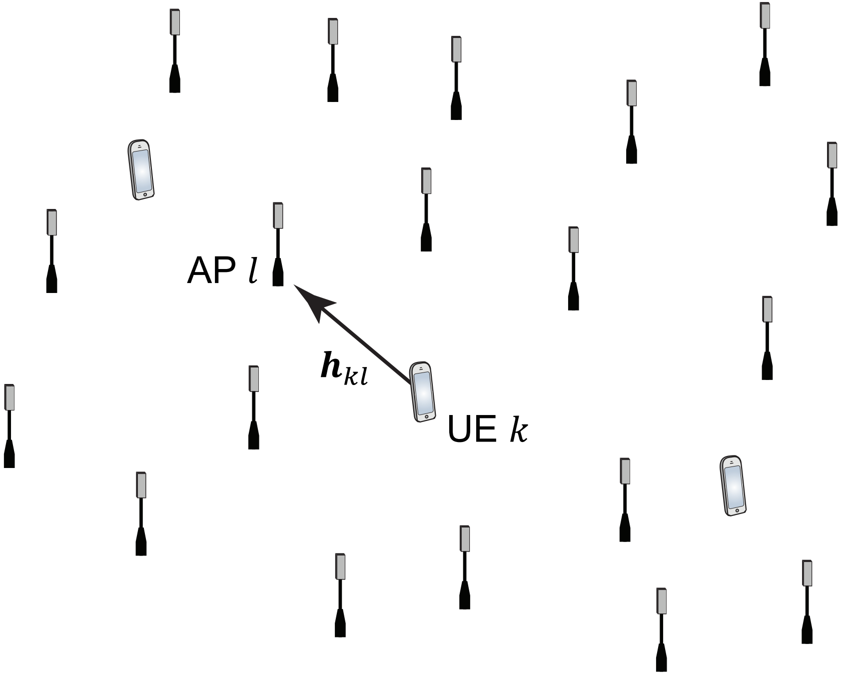
Centralized version
Everything done at CPU, maximum rate

Distributed version
Most processing at AP, fusing at a CPU

E. Björnson, L. Sanguinetti, “Making Cell-Free Massive MIMO Competitive With MMSE Processing and Centralized Implementation,” 2020.

FUNDAMENTAL MODELS AND ALGORITHMS

Basic Notation



Cell-free Network

L access points (APs), N antennas per AP

K single-antenna user equipments (UEs)

Channel notation

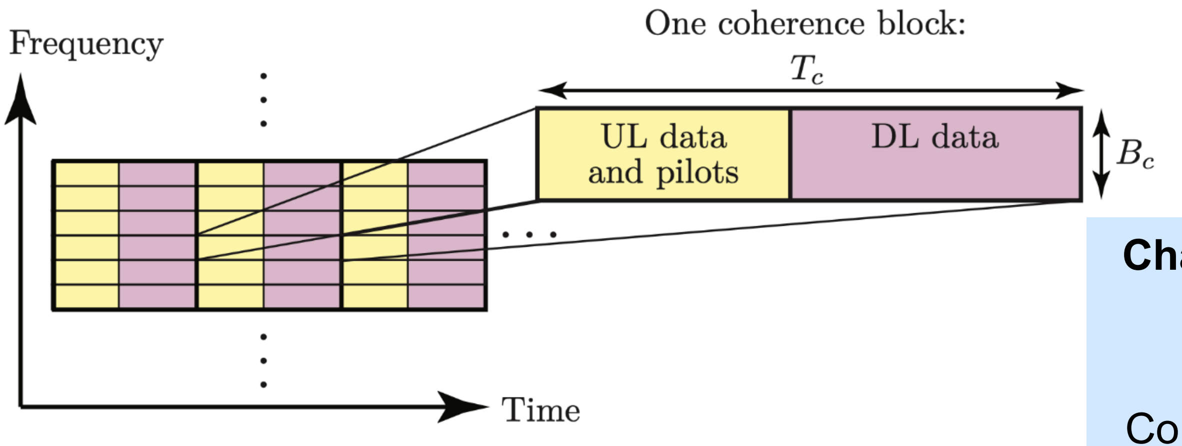
$\boldsymbol{h}_{\text{UE's index AP's index}}$

Correlated Rayleigh fading

$$\boldsymbol{h}_{kl} \sim CN(\boldsymbol{0}, \boldsymbol{R}_{kl})$$

Spatial correlation matrix and pathloss: $\boldsymbol{R}_{kl} \in \mathbb{C}^{N \times N}$

Coherence Block Modeling



Channel change in time/frequency

≈ Constant for T_c s

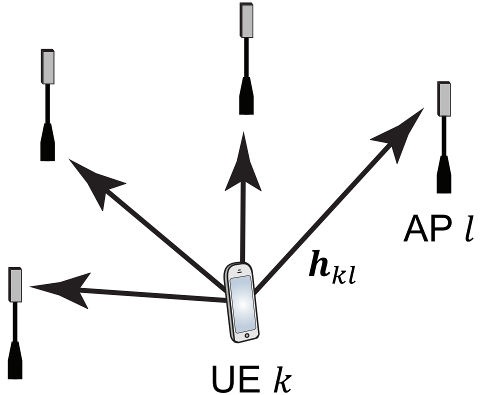
≈ Constant for B_c Hz

Coherence block: $\tau_c = T_c B_c$ samples

Time-division duplex operation

1. One channel realization per block
2. Uplink pilots: Each UE transmit a "pilot" to enable channel estimation
3. Uplink data: Each UE transmits data; AP decodes based on channel estimates
4. Downlink data: AP beamforms data to UEs based on channel estimates

Principle of Uplink Channel Estimation



UE k sends a predefined pilot signal $\phi \in \mathbb{C}$

Received signal at AP l:

$$\boldsymbol{y}_l^{\text{pilot}} = \boldsymbol{h}_{kl}\phi + \boldsymbol{n}_l$$

Noise: variance σ^2

Simple channel estimate:

$$\widehat{\boldsymbol{h}}_{kl} = \frac{\phi^*}{|\phi|^2}\boldsymbol{y}_l^{\text{pilot}} = \boldsymbol{h}_{kl} + \frac{\phi^*}{|\phi|^2}\boldsymbol{n}_l$$

MMSE estimate:

$$\widehat{\boldsymbol{h}}_{kl} = \phi^* \boldsymbol{R}_{kl}(|\phi|^2 \boldsymbol{R}_{kl} + \sigma^2 \boldsymbol{I}_N)^{-1} \boldsymbol{y}_l^{\text{pilot}}$$

Any number of APs can estimate the channel from a single pilot transmission!

Reuse pilots: Pilot contamination exists but is not a big deal

MMSE = Minimum mean-squared error

Uplink Data Transmission

- Received signal at AP l:

$$\boldsymbol{y}_l = \sum_{i=1}^{K} \boldsymbol{h}_{il} s_i + \boldsymbol{n}_l$$

Noise: variance σ^2

Data signal: power p_i

Centralized implementation

Collect received signals:

$$\begin{bmatrix} \boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_L \end{bmatrix} = \sum_{i=1}^{K} \begin{bmatrix} \boldsymbol{h}_{i1} \\ \vdots \\ \boldsymbol{h}_{iL} \end{bmatrix} s_i + \begin{bmatrix} \boldsymbol{n}_1 \\ \vdots \\ \boldsymbol{n}_L \end{bmatrix}$$

Simple notation: $\boldsymbol{y} = \sum_{i=1}^{K} \boldsymbol{h}_i s_i + \boldsymbol{n}$

Receive combining

Estimate s_k using $\boldsymbol{v}_k \in \mathbb{C}^{LN}$:

$$\boldsymbol{v}_k^H \boldsymbol{y} = \boldsymbol{v}_k^H \boldsymbol{h}_k s_k + \sum_{i=1, i \neq k}^{K} \boldsymbol{v}_k^H \boldsymbol{h}_i s_i + \boldsymbol{v}_k^H \boldsymbol{n}$$

Desired signal

Interference

Noise

How should we select $\boldsymbol{v}_k$?

MMSE Receive Combining and Uplink Spectral Efficiency

Design goal: Minimize MSE $\mathbb{E}\left\{\left|s_k - \boldsymbol{v}_k^H \boldsymbol{y}\right|^2 \middle| \text{channel estimates}\right\}$

Solution: $\boldsymbol{v}_k^{\mathrm{MMSE}} = p_k \left(\sum_{i=1}^{K} p_i \left(\widehat{\boldsymbol{h}}_i \widehat{\boldsymbol{h}}_i^H + \boldsymbol{C}_i \right) + \sigma^2 \boldsymbol{I}_{LN} \right)^{-1} \widehat{\boldsymbol{h}}_k$

MMSE estimate: $\widehat{\boldsymbol{h}}_i = \begin{bmatrix} \widehat{\boldsymbol{h}}_{i1} \\ \vdots \\ \widehat{\boldsymbol{h}}_{il} \end{bmatrix}$

Error covariance:

$$\boldsymbol{C}_i = \mathbb{E}\left\{ \left(\boldsymbol{h}_i - \widehat{\boldsymbol{h}}_i\right)\left(\boldsymbol{h}_i - \widehat{\boldsymbol{h}}_i\right)^H \right\}$$

An uplink spectral efficiency of UE k is

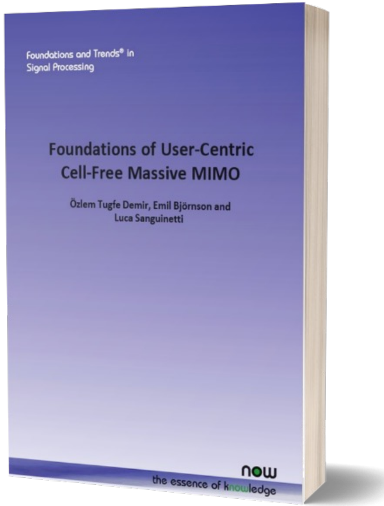
$$\mathrm{SE}_k^{\mathrm{ul}} = \frac{\tau_u}{\tau_c} \mathbb{E}\left\{ \log_2\left(1 + \mathrm{SINR}_k^{\mathrm{ul}}\right) \right\}$$

$$\mathrm{SINR}_k^{\mathrm{ul}} = \frac{p_k \left| \boldsymbol{v}_k^H \widehat{\boldsymbol{h}}_k \right|^2}{\sum_{i=1, i\neq k}^{K} p_i \left| \boldsymbol{v}_k^H \widehat{\boldsymbol{h}}_i \right|^2 + \sum_{i=1}^{K} p_i \boldsymbol{v}_k^H \boldsymbol{C}_i \boldsymbol{v}_k + \sigma^2 \|\boldsymbol{v}_k\|^2}$$

$$\underset{\boldsymbol{v}_k^{\mathrm{MMSE}}}{\leq} p_k \widehat{\boldsymbol{h}}_k^H \left(\sum_{i=1, i\neq k}^{K} p_i \widehat{\boldsymbol{h}}_i \widehat{\boldsymbol{h}}_i^H + \sum_{i=1}^{K} p_i \boldsymbol{C}_i + \sigma^2 \boldsymbol{I}_{LN} \right)^{-1} \widehat{\boldsymbol{h}}_k$$

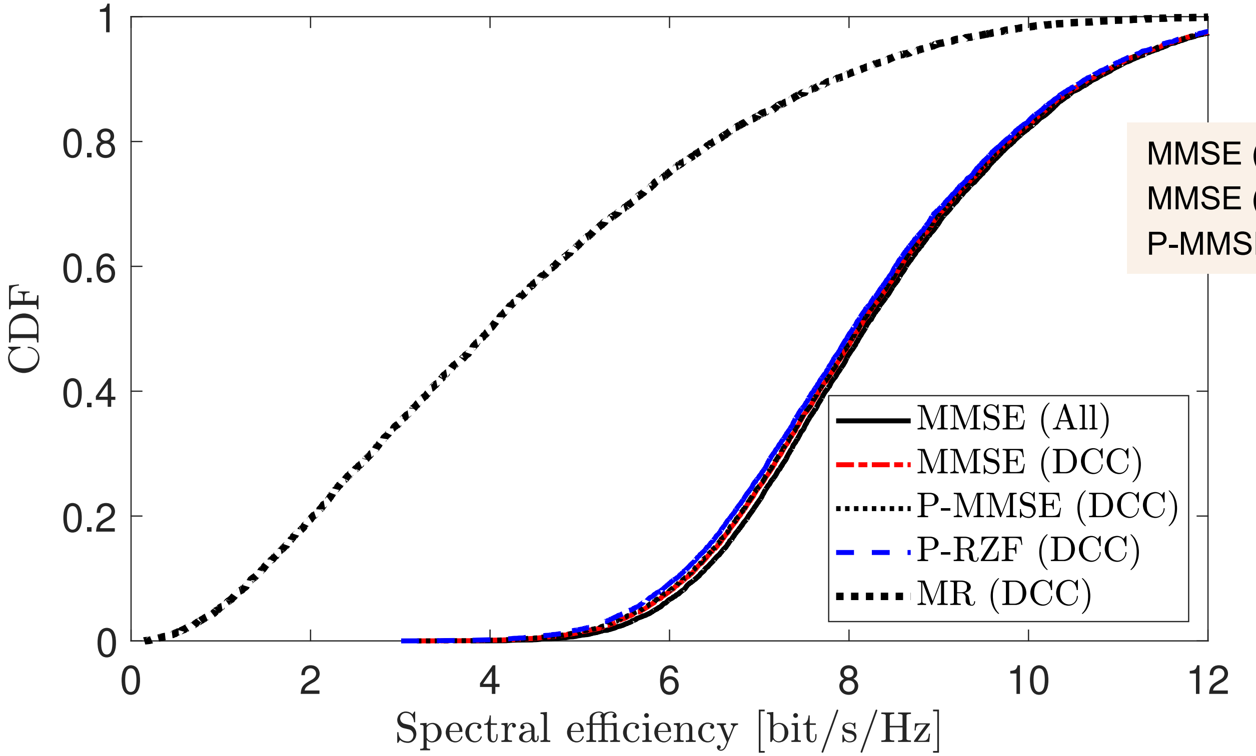
Simulation Parameters

Parameter	Value
Network area	1 km $\times$ 1 km
Network layout	Random deployment
Number of APs	400 or 100
Number of antennas per AP	1 or 4
Number of total antennas	$M = LN = 400$
Bandwidth	$B = 20\,\text{MHz}$
Receiver noise power	$\sigma^2_{\text{UL}} = -94\,\text{dBm}$
Maximum uplink transmit power	100 mW
Maximum downlink transmit power	200 mW
Samples per coherence block	$\tau_c = 200$
Channel gain at 1 km	$\Upsilon = -140.6\,\text{dB}$
Pathloss exponent	$\alpha = 3.67$
Height difference between AP and UE	10 m
Standard deviation of shadow fading	$\sigma_{\text{sf}} = 4$



https://arxiv.org/abs/2108.02541

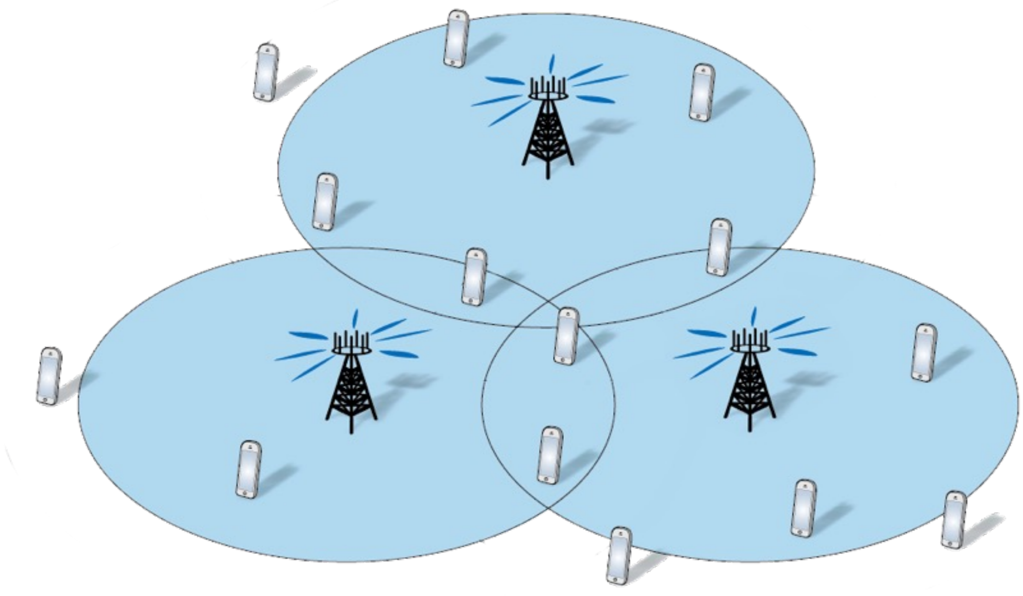
Simplified “Scalable” Combining Schemes



MMSE (All): What has been described
MMSE (DCC): Limit the number of UEs per AP
P-MMSE, P-RZF, MR (DCC): Simplified schemes

Figure 5.4: $L = 400$ APs, $N = 1$ antennas per AP, $K = 40$ UEs

Dynamic Cooperation Clusters (DCC)

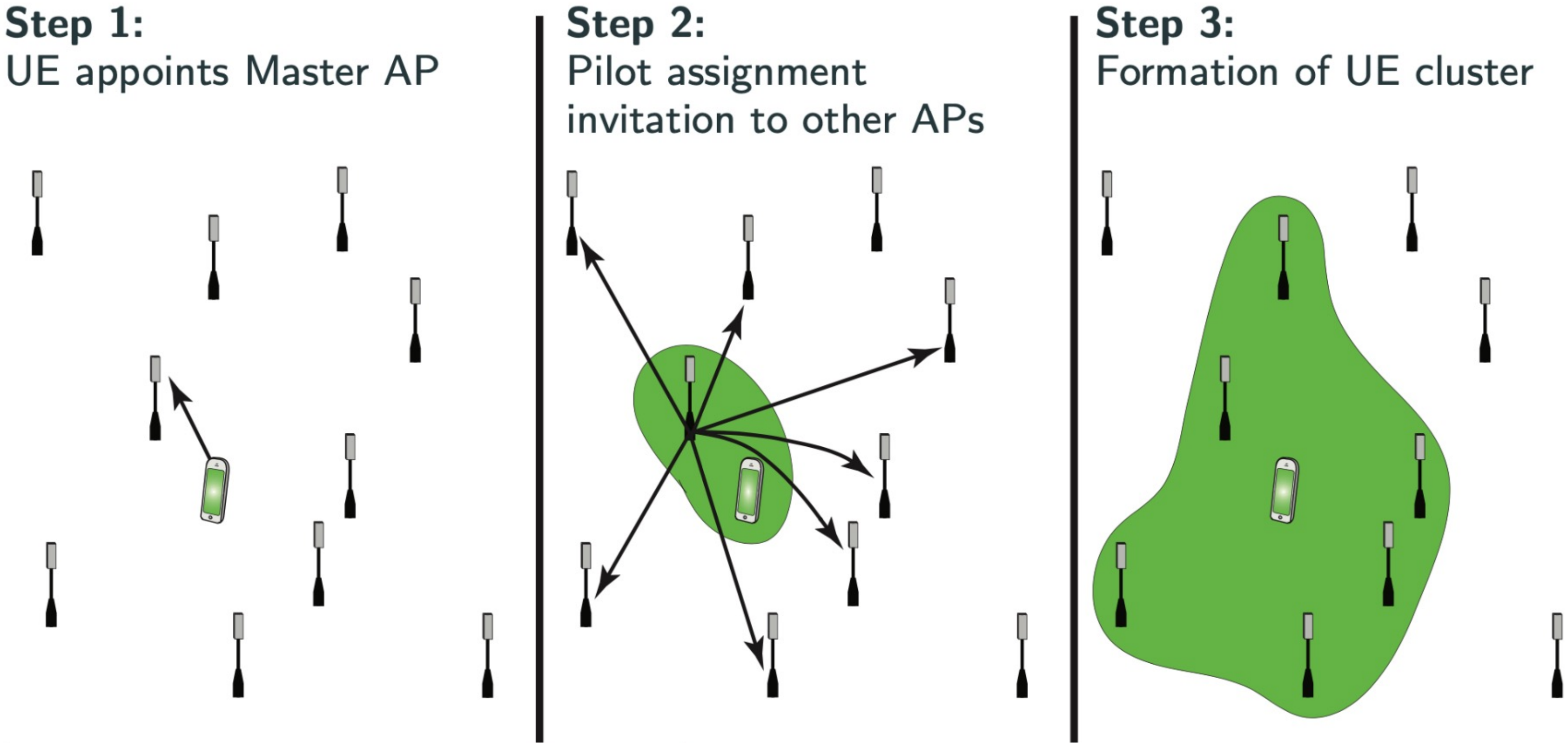


Originally proposed to enable scalable implementation of *Network MIMO*

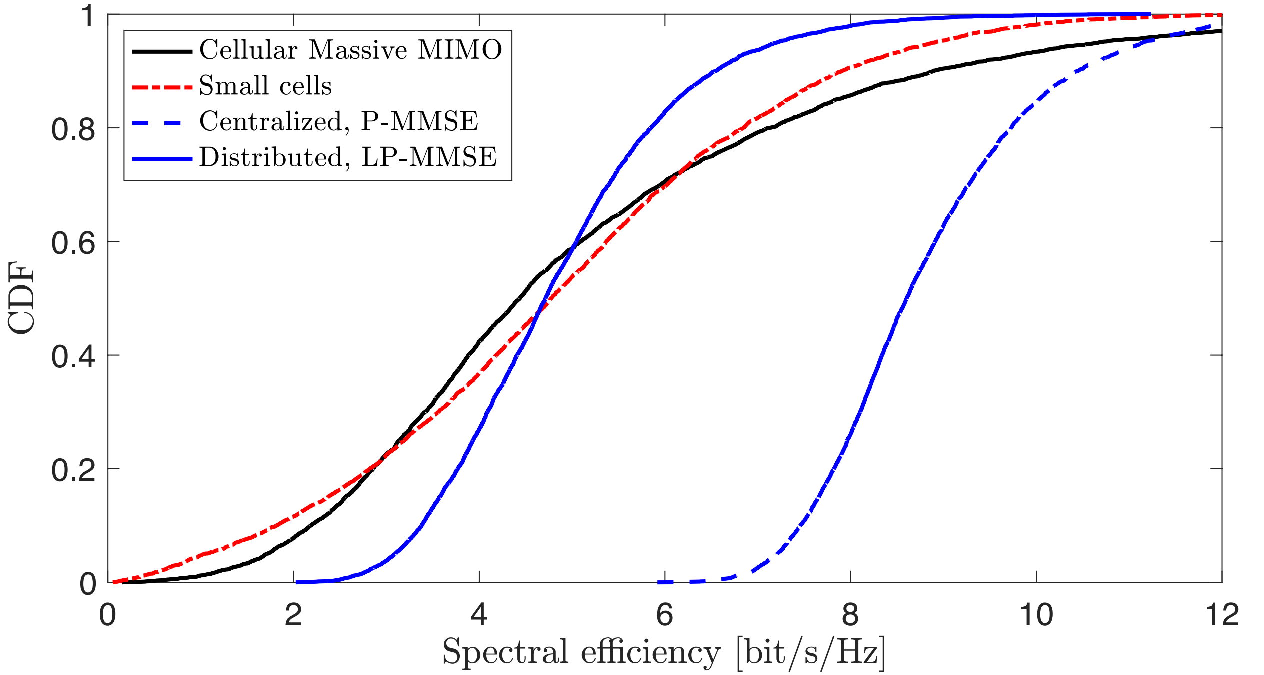
E. Björnson, E. Jorswieck, "Optimal Resource Allocation in Coordinated Multi-Cell Systems," Foundations and Trends in Communications and Information Theory, 2013.

Creating User-Centric Cooperation Clusters

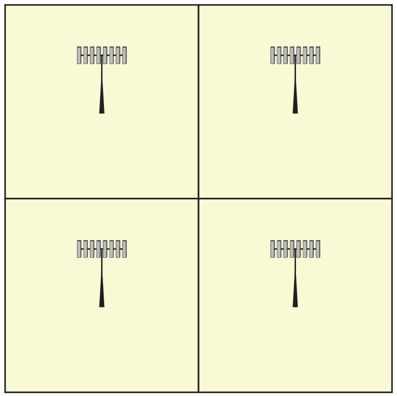
Access based method:



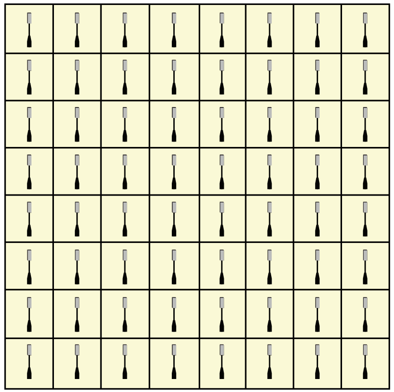
What about Distributed Combining Schemes?



4 cells, 100 antennas



400 cells, 1 antenna



Use centralized schemes if it should be worth it!

Figure 5.9: $L = 400$ APs, $N = 1$ antennas per AP, $K = 40$ UEs

Downlink Data Transmission

- Received signal at UE k:

$$y_k = \sum_{l=1}^{L} \boldsymbol{h}_{kl}^{H} \left(\sum_{i=1}^{K} \boldsymbol{w}_{il} \, \varsigma_i \right) + n_k$$

Noise: variance σ^2

Precoding vector

Data signal: unit power

Centralized implementation

Use "long" vectors:

$$y_k = \sum_{i=1}^{K} \begin{bmatrix} \boldsymbol{h}_{k1} \\ \vdots \\ \boldsymbol{h}_{kL} \end{bmatrix}^{H} \begin{bmatrix} \boldsymbol{w}_{i1} \\ \vdots \\ \boldsymbol{w}_{iL} \end{bmatrix} \varsigma_i + n_k$$

$$\text{Simple notation: } y_k = \sum_{i=1}^{K} \boldsymbol{h}_k^H \boldsymbol{w}_i \varsigma_i + n_k$$

Uplink-downlink duality

If $\boldsymbol{v}_k \in \mathbb{C}^{LN}$ is a good uplink combining, then $\boldsymbol{w}_k = \text{constant} \cdot \boldsymbol{v}_k \in \mathbb{C}^{LN}$ is a good downlink precoding.

Practical issues: Power allocation

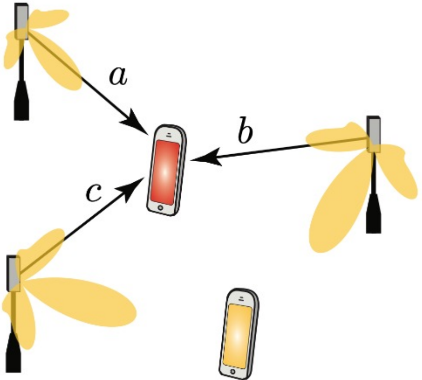
Downlink Spectral Efficiency

A downlink spectral efficiency of UE k is

$$\mathrm{SE}_k^{\mathrm{dl}} = \frac{\tau_d}{\tau_c} \log_2\left(1 + \mathrm{SINR}_k^{\mathrm{dl}}\right)$$

$$\mathrm{SINR}_k^{\mathrm{dl}} = \frac{\left|\mathbb{E}\{\boldsymbol{h}_k^H \boldsymbol{w}_k\}\right|^2}{\sum_{i=1}^{K} \mathbb{E}\left\{\left|\boldsymbol{h}_k^H \boldsymbol{w}_i\right|^2\right\} - \left|\mathbb{E}\{\boldsymbol{h}_k^H \boldsymbol{w}_k\}\right|^2 + \sigma^2}$$

Note: No channel estimates available at receiver



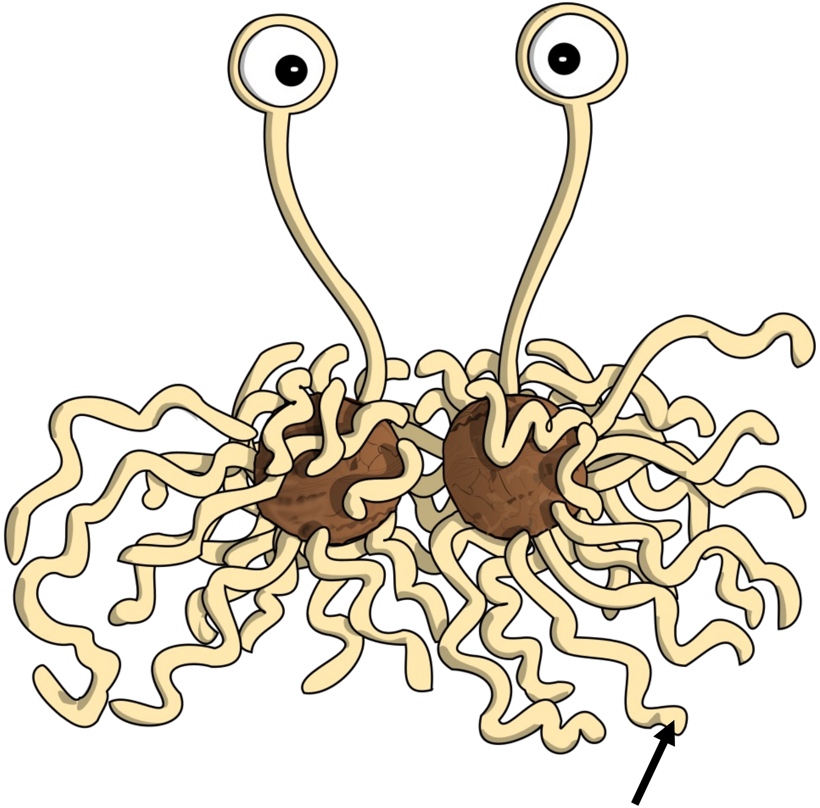
Interference suppression

Centralized precoding: $a + b + c \approx 0$

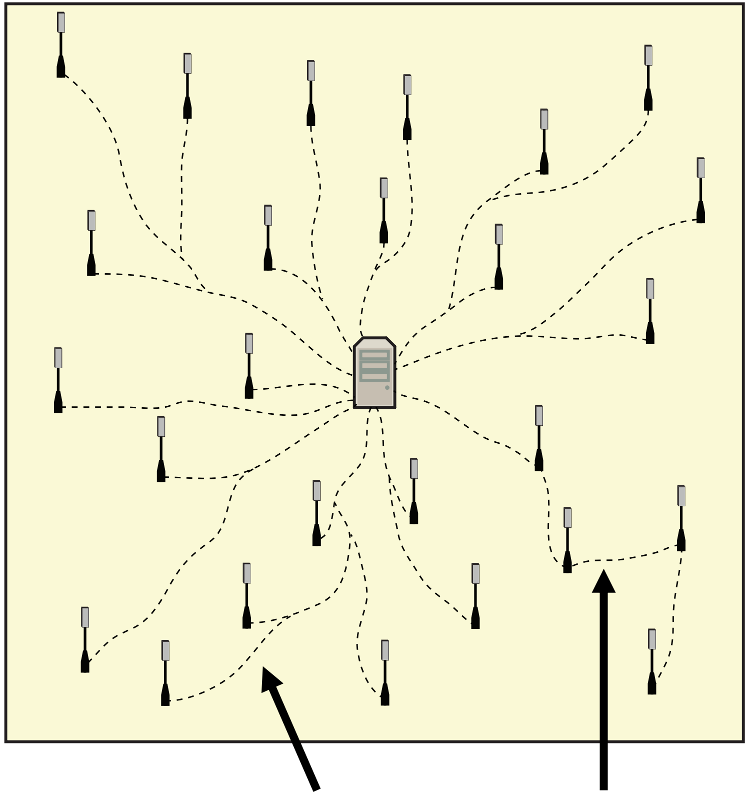
Distributed precoding: $a \approx 0, b \approx 0, c \approx 0$

SEQUENTIAL FRONTHAUL AND PROCESSING

Practical Issue: Avoid Creating a Spaghetti Monster



Dedicated fronthaul

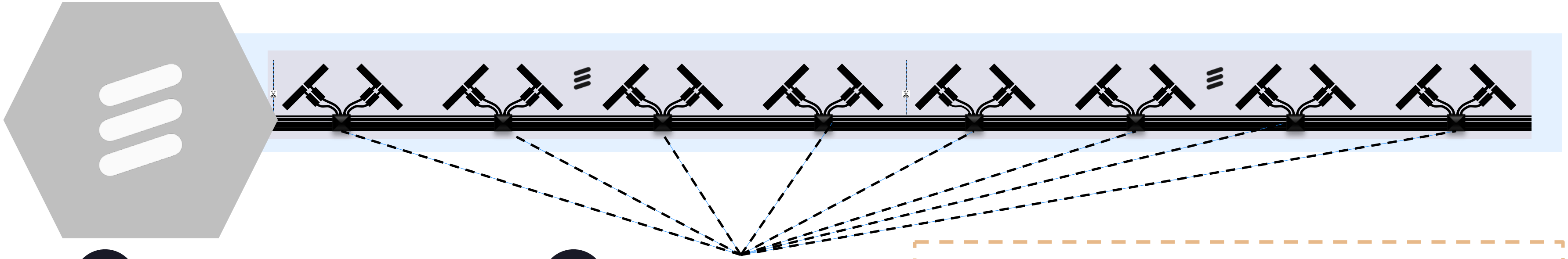


Fronthaul

Potential solution:
Sequential fronthaul

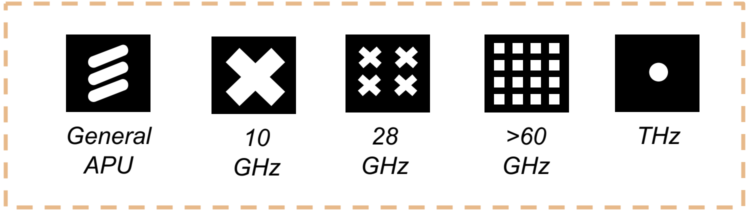
Sequential Implementation Concept: Radio Stripes

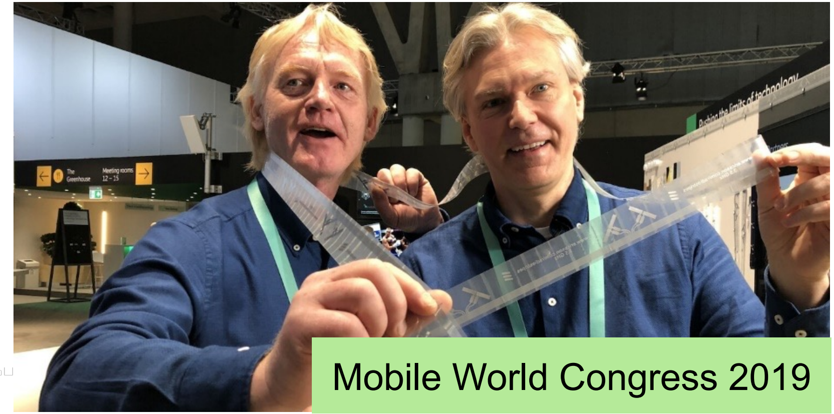
1 *Radio stripes*



3 *Central processing unit*

2 *Antenna units*





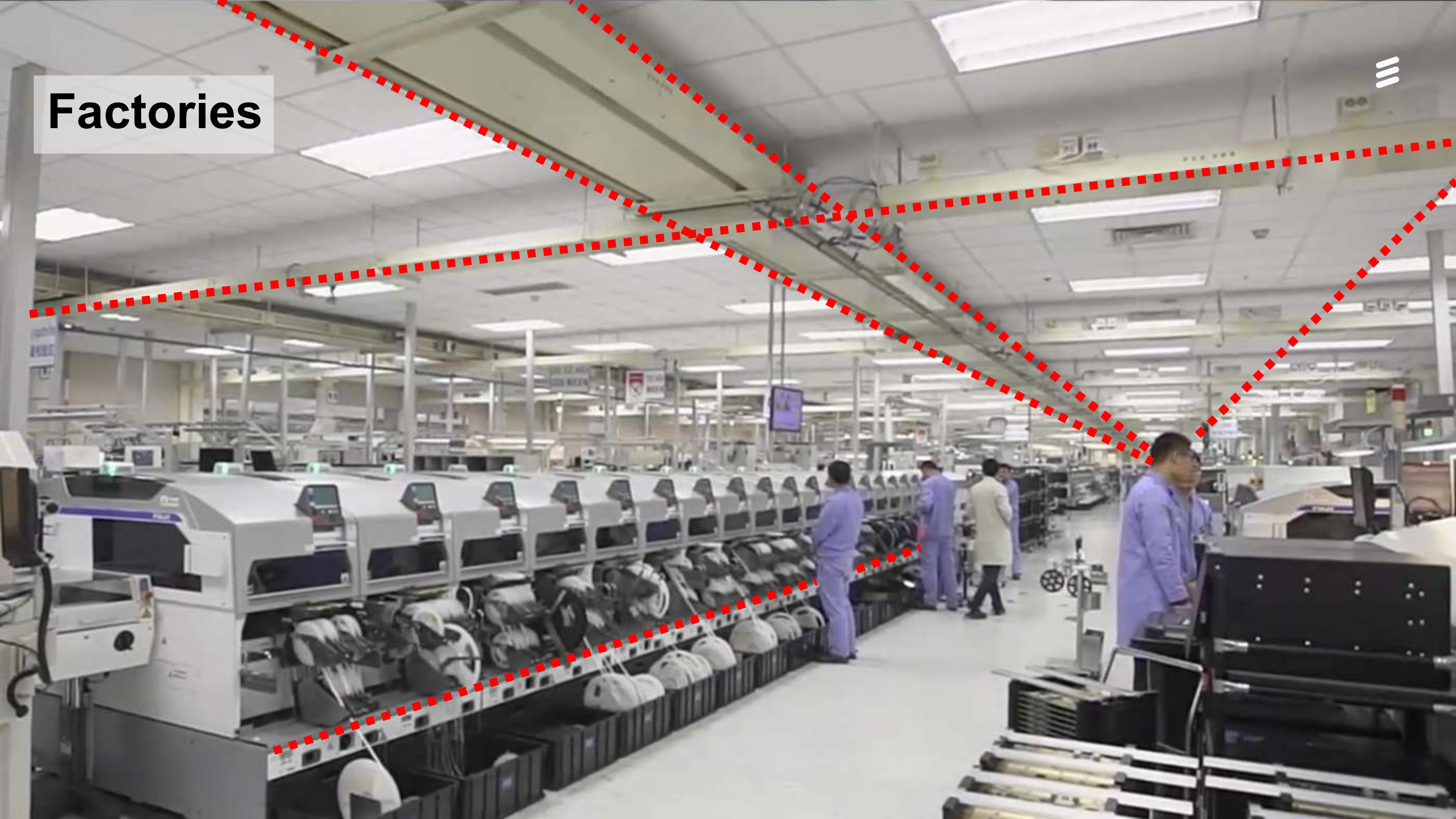
P. Frenger, J. Hederen, M. Hessler, G. Interdonato, Improved antenna arrangement for distributed massive MIMO, WO2018103897A1

LINKÖPING UNIVERSITY

ERICSSON

Cultural places

Factories



Stadium

Radio Stripe: Implementation Details

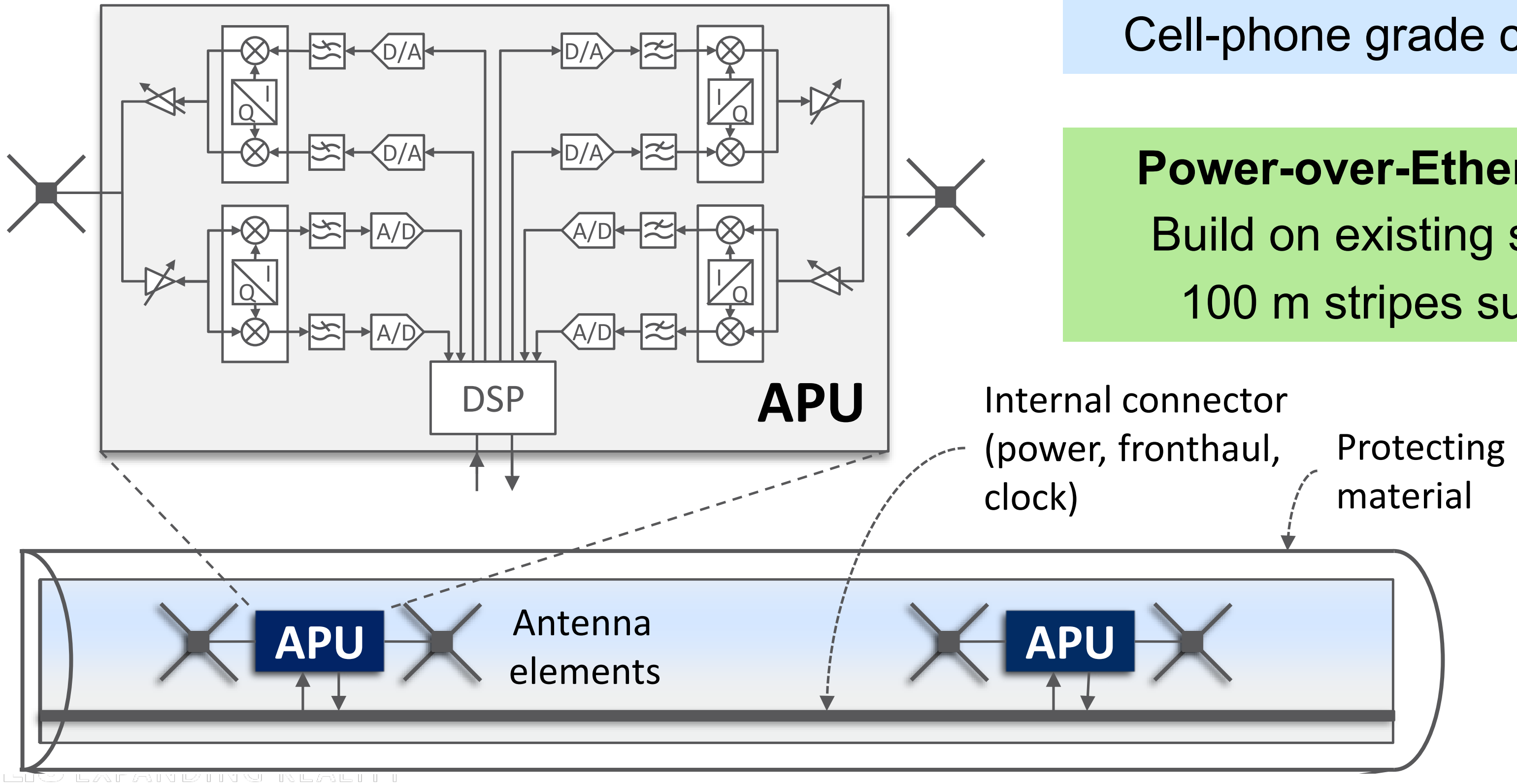
Low power and cost?

Cell-phone grade components

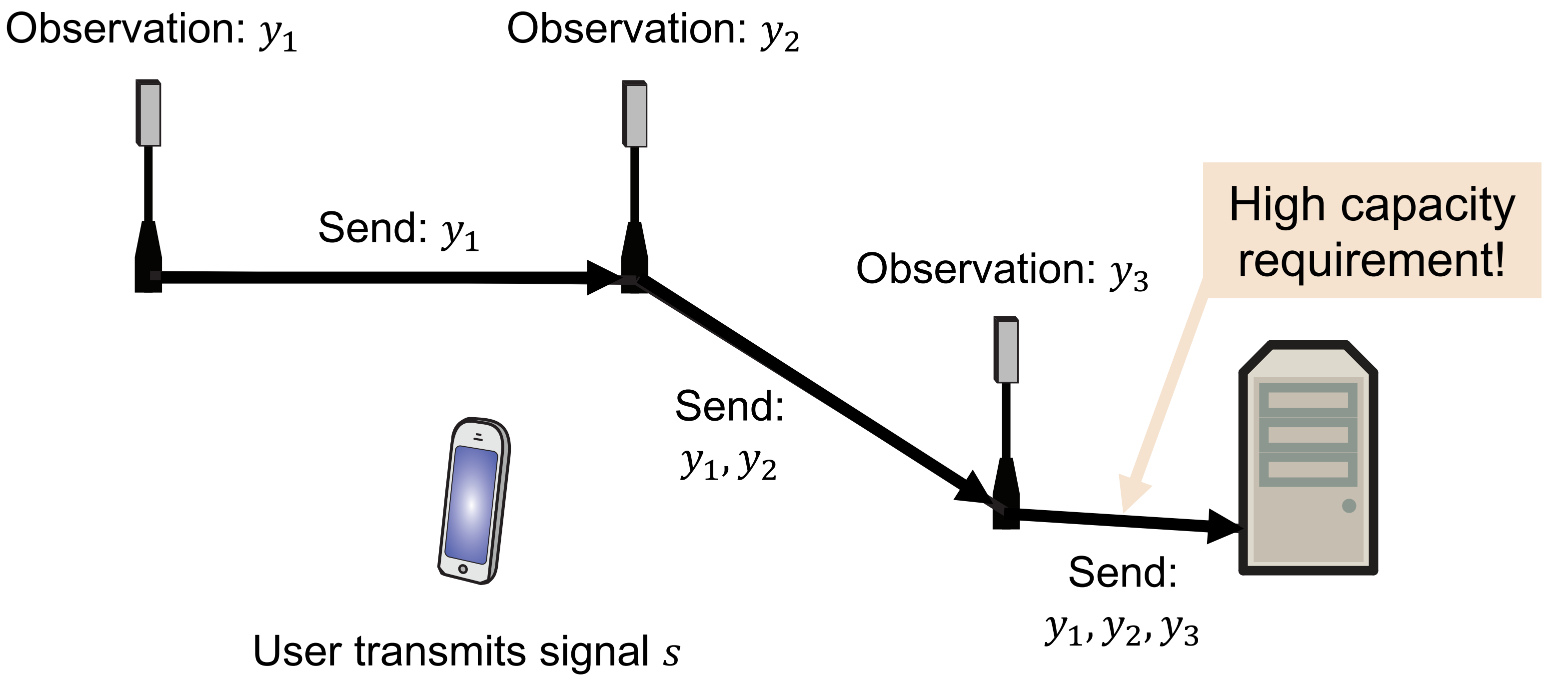
Power-over-Ethernet/Fiber

Build on existing standards

100 m stripes supported



Issue with Serial Fronthaul: Capacity Requirement Accumulates



Can we design the processing to circumvent this issue?

Sequential Uplink Processing: Kalman Approach

A priori: $\hat{s}_0$
Covariance: C_0

Estimate at ~~time 1~~ AP 1 — Observation: y_1

Estimate: $\hat{s}_1$
Covariance: C_1

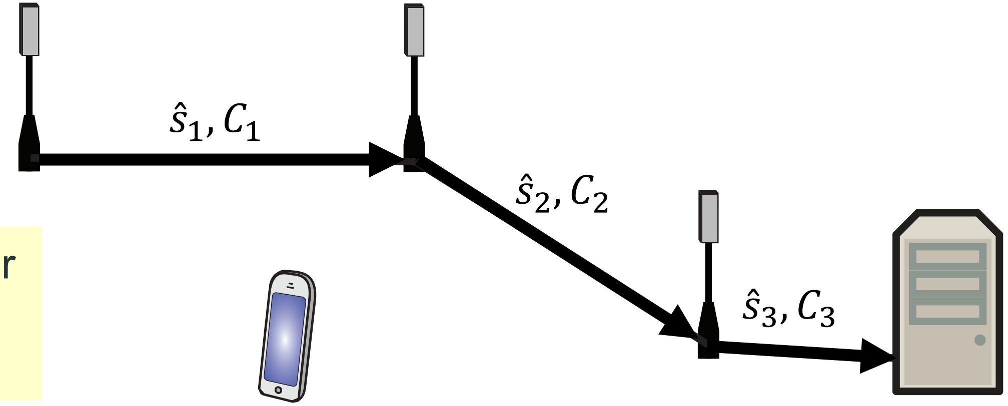
Estimate at ~~time 2~~ AP 2 — Observation: y_2

Estimate: $\hat{s}_2$
Covariance: C_2

Estimate at ~~time 3~~ AP 3 — Observation: y_3

Estimate: $\hat{s}_3$
Covariance: C_3

Sequential linear MMSE: Same as centralized MMSE implementation

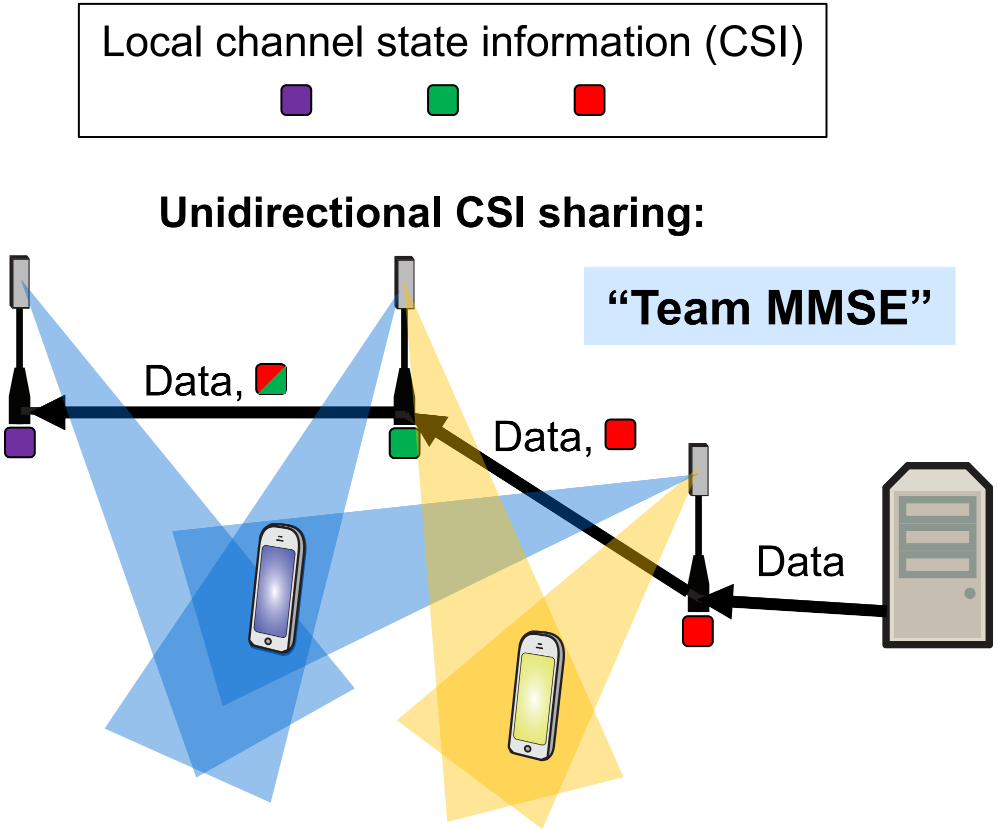


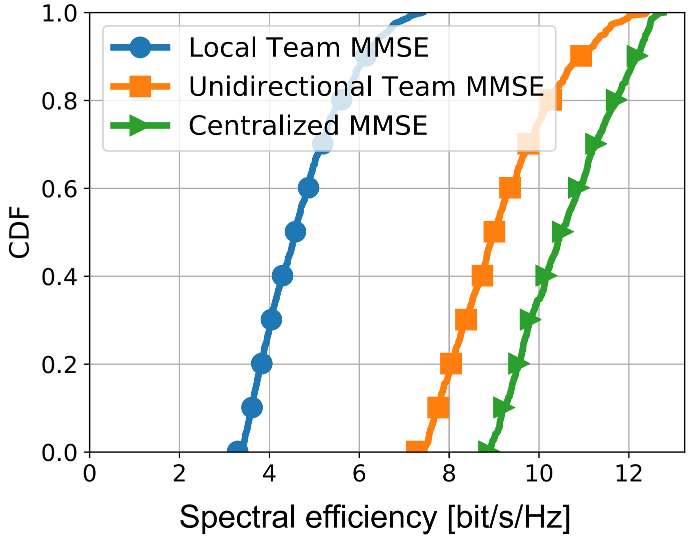
Fronthaul capacity per cable does not grow with number of APs

Delays?
Small for large data blocks

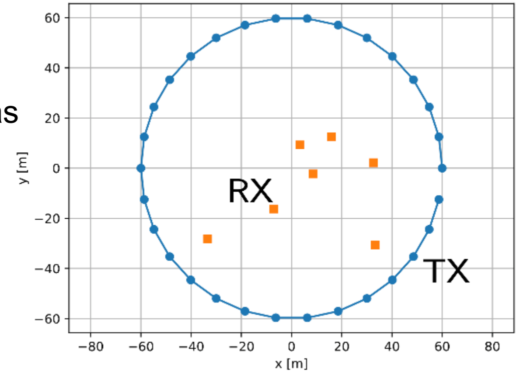
Z. H. Shaik, E. Björnson, E. G. Larsson, "MMSE-Optimal Sequential Processing for Cell-Free Massive MIMO With Radio Stripes," IEEE TCOM, 2021.

Sequential Downlink Processing: Team-Decision Approach



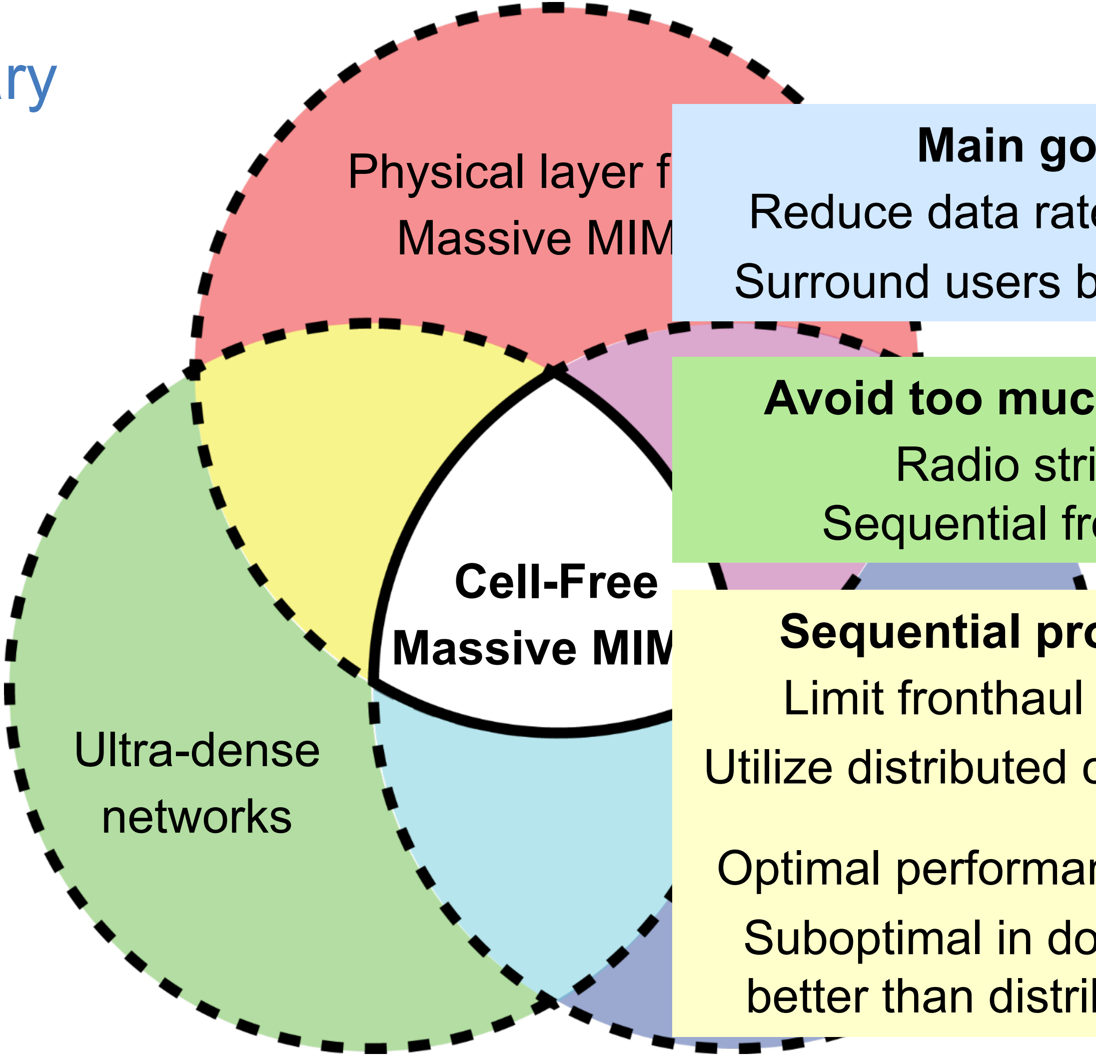


Example:
L = 30 APs
N = 2 antennas
K = 7 users



L. Miretti, E. Björnson, D. Gesbert, “Team MMSE Precoding with Applications to Cell-free Massive MIMO,” IEEE TWC, 2022.

Summary



Main goal:

Reduce data rate variations

Surround users by antennas

Avoid too much cabling

Radio stripes:

Sequential fronthaul

Sequential processing

Limit fronthaul signaling

Utilize distributed computations

Optimal performance in uplink

Suboptimal in downlink, but better than distributed case

Key References from Part 1

1. H. Q. Ngo, A. Ashikhmin, H. Yang, E. G. Larsson, T. L. Marzetta, “Cell-free Massive MIMO versus small cells,” IEEE Trans. Wireless Commun., 2017.
2. G. Interdonato, E. Björnson, H. Q. Ngo, P. Frenger, E. G. Larsson, “Ubiquitous Cell-Free Massive MIMO Communications,” EURASIP J. Wireless Commun. Net., 2019.
3. Ö. T. Demir, E. Björnson, L. Sanguinetti, “Foundations of User-Centric Cell-Free Massive MIMO,” Foundations and Trends in Signal Processing, 2021. **Code on GitHub**
4. E. Björnson, L. Sanguinetti, “Making Cell-Free Massive MIMO Competitive With MMSE Processing and Centralized Implementation,” IEEE TWC, 2020. **Code on GitHub**
5. E. Björnson, L. Sanguinetti, “Scalable Cell-Free Massive MIMO Systems,” IEEE TCOM, 2020. **Code on GitHub**
6. Z. H. Shaik, E. Björnson, E. G. Larsson, “MMSE-Optimal Sequential Processing for Cell-Free Massive MIMO With Radio Stripes,” IEEE TCOM, 2021. **Code on GitHub**
7. L. Miretti, E. Björnson, D. Gesbert, “Team MMSE Precoding with Applications to Cell-free Massive MIMO,” IEEE TWC, 2022. **Code on GitHub**

QUESTIONS?

YouTube
Bilibili
Podcast
Blog

WIRELESS FUTURE

PART 2

ENERGY-AWARE C-RAN IMPLEMENTATION OF CELL-FREE MASSIVE MIMO

Outline of Part 2

1. From Distributed RAN to Open RAN
2. Fronthaul transport technologies
3. End-to-end power consumption modeling
4. Joint resource allocation for end-to-end power minimization
5. How to save energy in a cell-free network?

My research is sponsored by

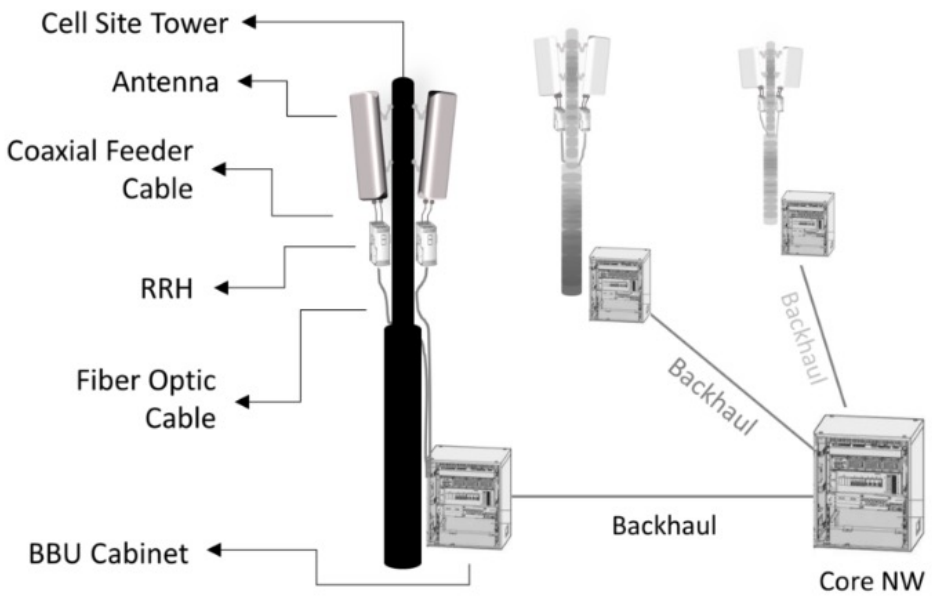
TÜBİTAK

International Fellowship for Early Stage Researchers

Scientific and Technological Research Council of Türkiye

FROM DISTRIBUTED RAN TO OPEN RAN

Traditional D-RAN Architecture



3G/4G RAN (UTRAN, E-UTRAN)

D-RAN

Radio and signal processing units are separated.

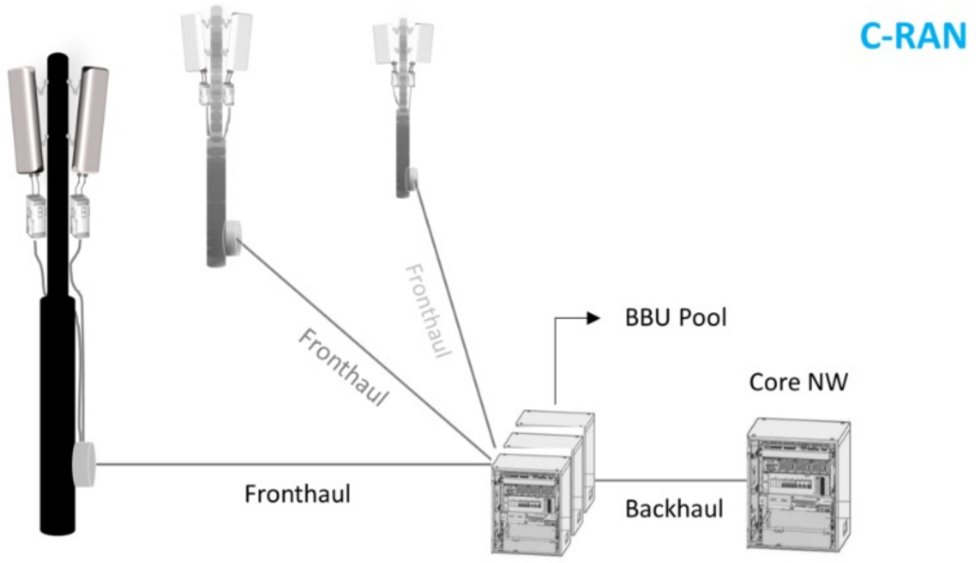
Co-located RRH and BBU

- High operational cost
- Insufficient resource sharing
- Vendor lock-in

D-RAN: Distributed Radio Access Network
RRH: Remote radio head
BBU: Baseband unit

https://telecompedia.net/ran/

C-RAN Architecture



BBUs of multiple cells in the BBU Pool (Hotel)

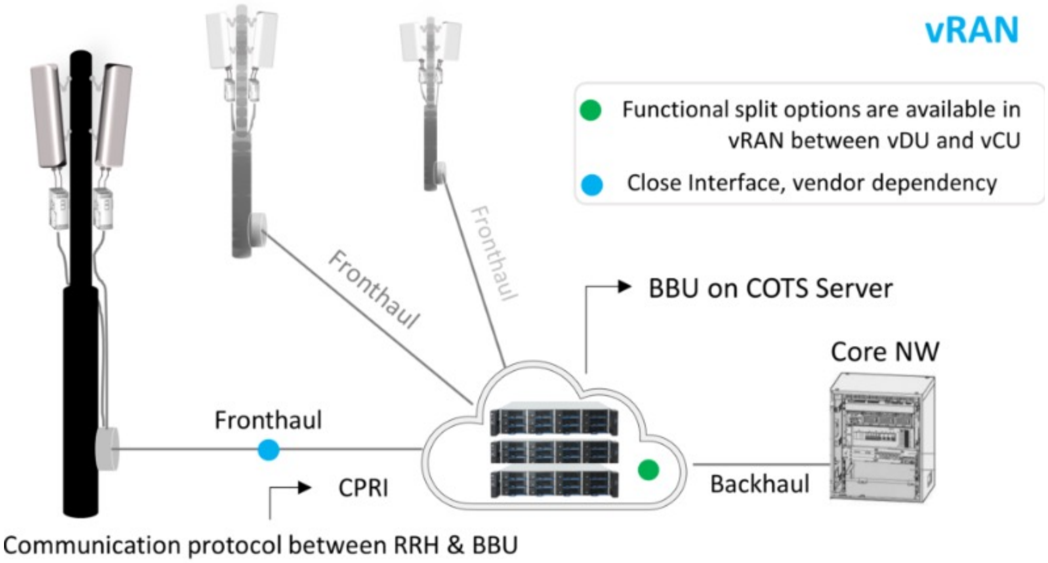
- Dynamically shared resources (CPU,RAM) in the BBU pool
- Reduced operational cost
- Improved inter-cell coordination

- High data burden on fronthaul
- Still vendor lock-in

C-RAN: Centralized-RAN, Cloud-RAN

https://telecompedia.net/ran/

Virtualized C-RAN Architecture



No hardware dependency

BBU as a software package on COTS server

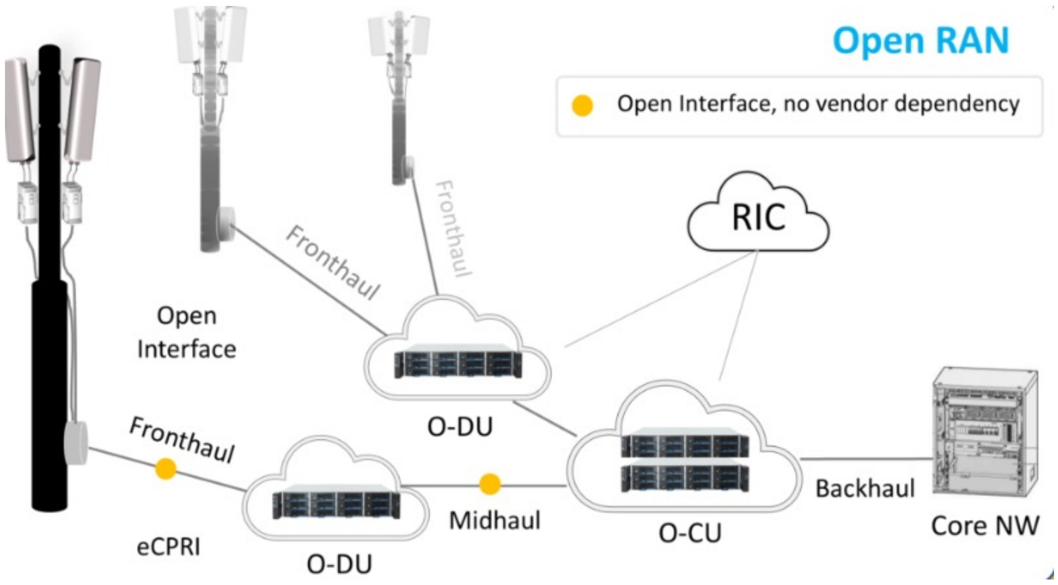
- Software-hardware decoupling
- Virtualization of all resources and functions
- Via network function virtualization (NFV) increased efficiency, flexible scheduling

COTS: Commercial-of-the-shelf

- Not open interfaces
- RRH and BBU should be from the same vendor

https://telecompedia.net/ran/

O-RAN Architecture



Latest enhanced version of RAN

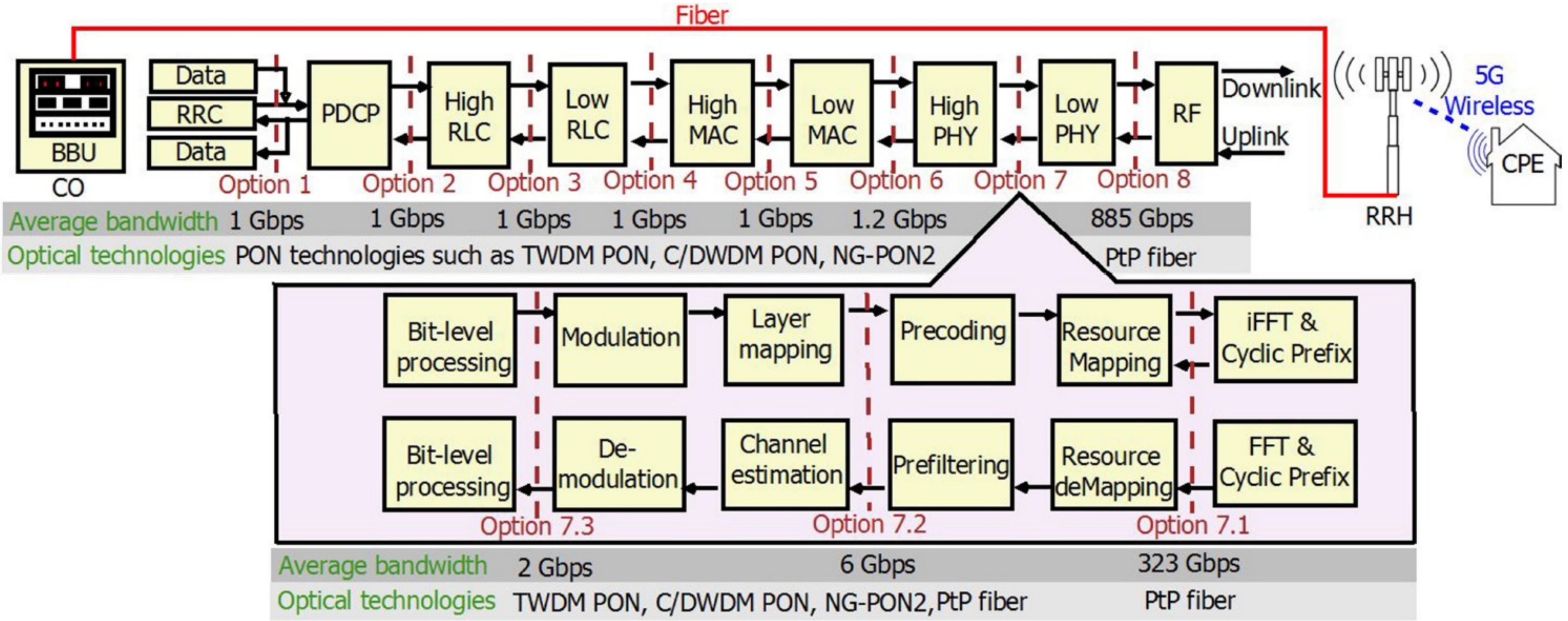
- All benefits of C-RAN and vRAN
- Open interfaces between RRH, O-DU, and O-CU
- No vendor lock-in

RIC: RAN intelligent controller
O-CU: O-RAN central unit
O-DU: O-RAN distributed unit

https://telecompedia.net/ran/

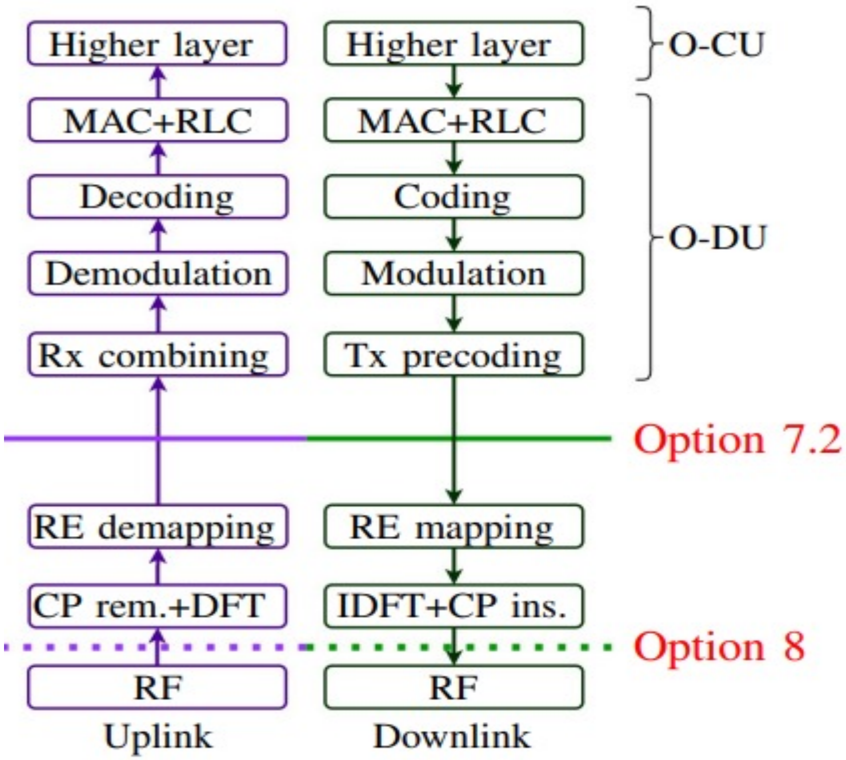
Functional Splits

Fronthaul data requirement becomes smaller!



Ranaweera, Chathurika, et al. "Optical transport network design for 5G fixed wireless access." *Journal of Lightwave Technology* 37.16 (2019): 3893-3901.

Functional Splits From Cell-free Massive MIMO Perspective



- ✓ APs exchange the physical-layer (layer 1) signals through fronthaul links with the O-Cloud.
- ✓ Intra-PHY functional split is possible since the symbols are processed jointly after some independent PHY processing operations (Option 7.1 or Option 7.2).

Fronthaul Requirements for Cell-free Massive MIMO

- ✓ *Intra-physical-layer functional split is possible with* ***eCPRI****-based fronthaul transmission, BUT still there is a* ***huge fronthaul capacity requirement****:*

Approximately 1 Gb/s per AP

- ✓ *Time and wavelength division multiplexed passive optical network (****TWDM-PON****)*

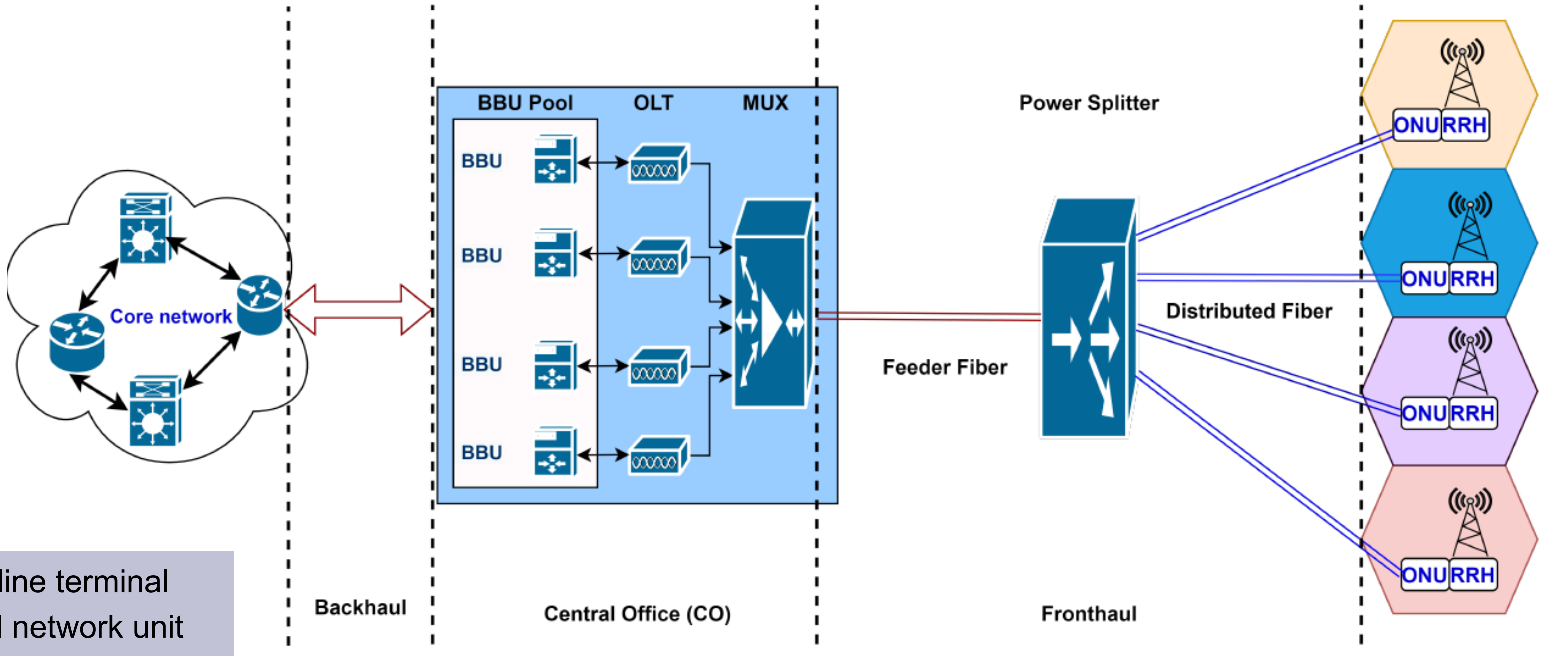
Ex: 4 wavelengths, each with 10 Gb/s capacity

- ✓ *Ethernet-based passive optical network (****EPON****):*

Ex: 4 lanes of 25 Gb/s capacity each

FRONTHAUL TRANSPORT TECHNOLOGIES

Passive Optical Networks (PON) for 5G and Beyond



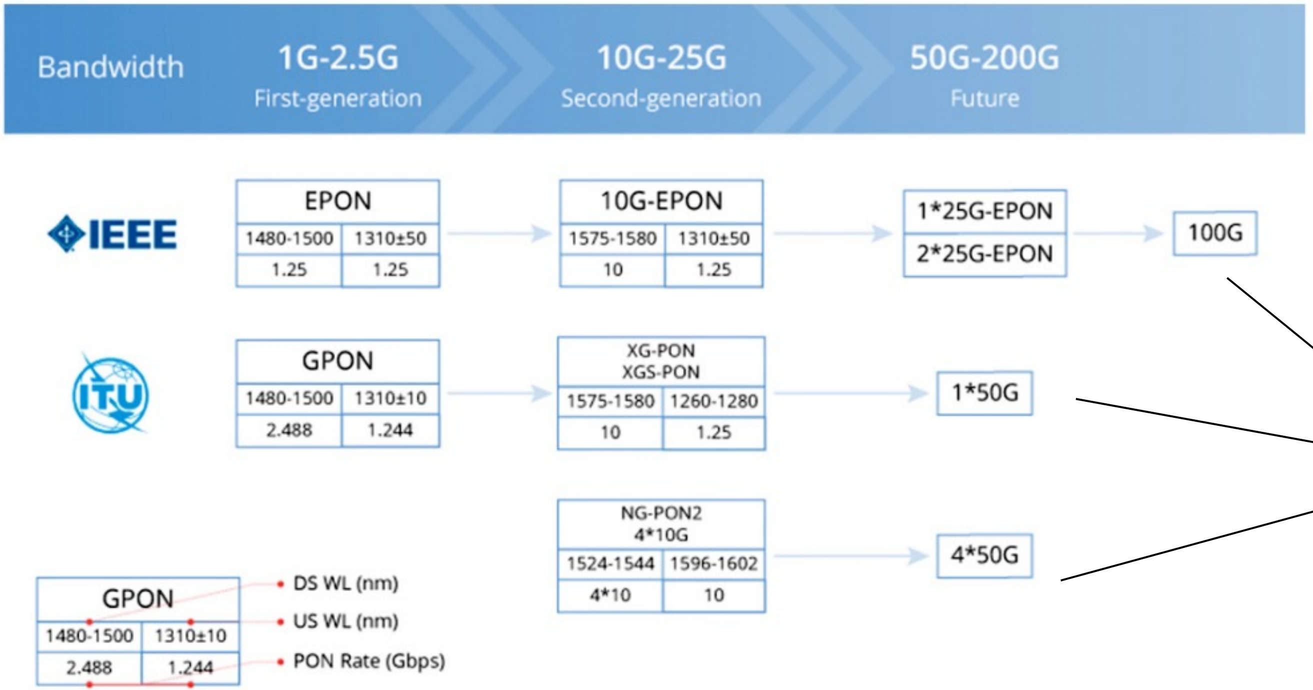
OLT: Optical line terminal
ONU: Optical network unit

Point-to-multipoint via passive splitter

- Low latency connections
- Large volume of data traffic

Fayad, Abdulhalim, et al. "Design of cost-efficient optical fronthaul for 5G/6G networks: An optimization perspective." *Sensors* 22.23 (2022): 9394.

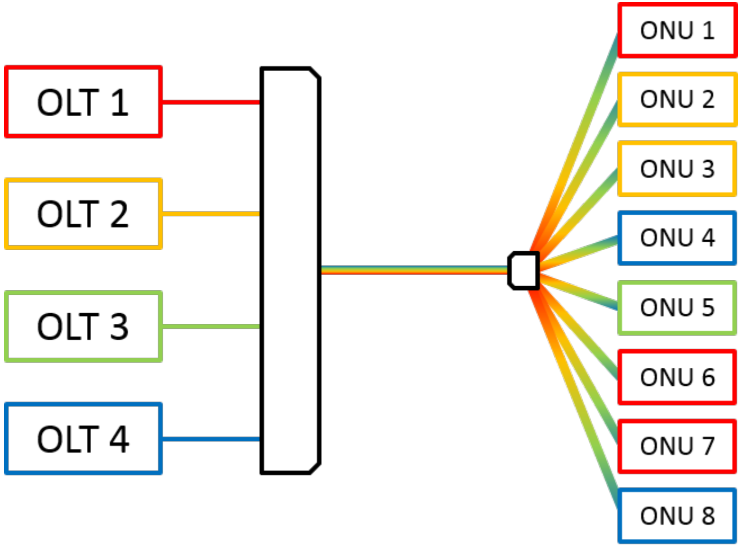
Evolution of PON Technology



50-100 APs can be served!

https://community.fs.com/article/8-revolutionary-steps-the-evolutionary-path-of-pon-technology.html

NG-PON2 (Next-Generation PON 2)



2015 ITU Standard

Time- and wavelength-division multiplexing **(TWDM-PON)**

Four wavelengths (4x10 Gbps)

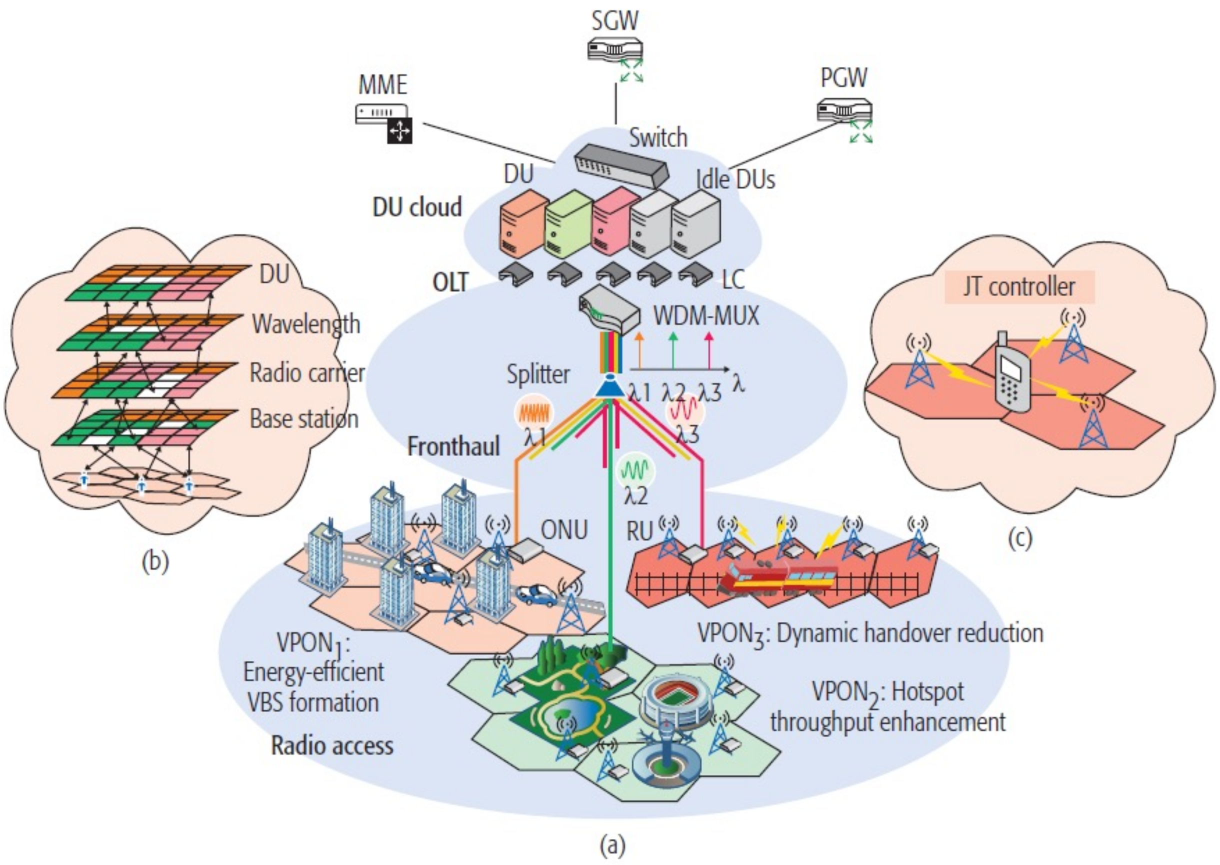
OLT: Optical line terminal
ONU: Optical network unit

Virtualization at Radio, Fronthaul, and Cloud Level

Virtualized channels with dynamically assigned radio, fronthaul, and processing resources

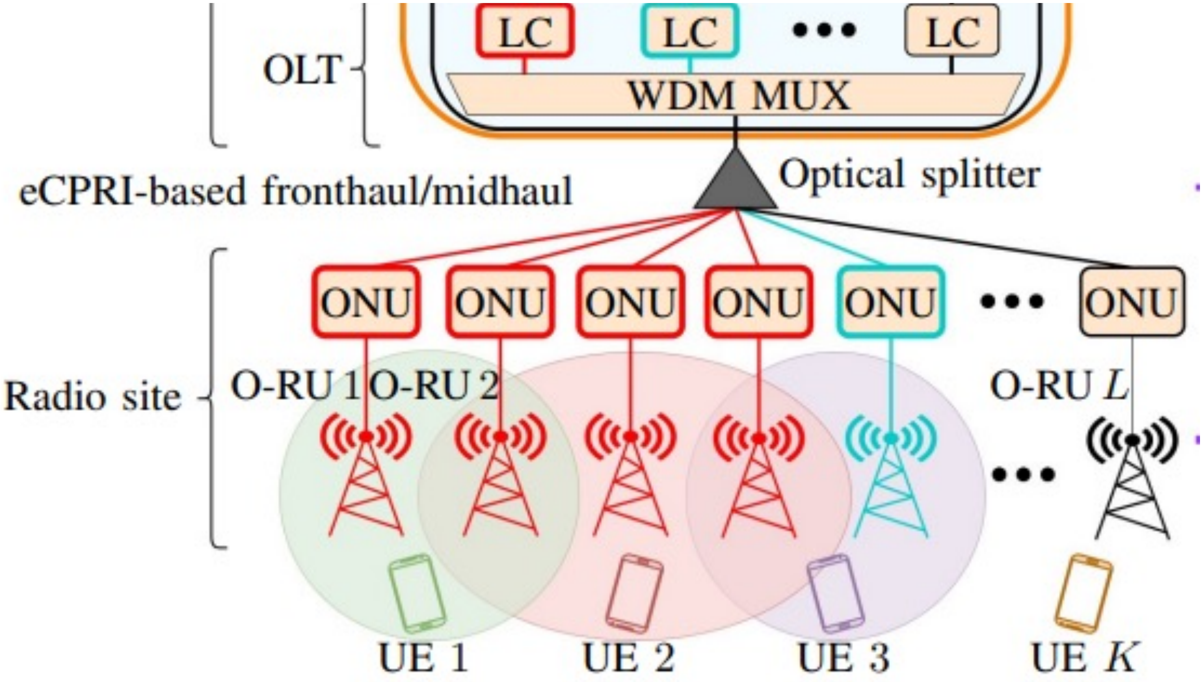
according to

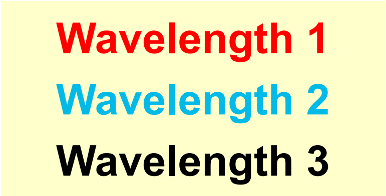
dynamically varying traffic and user needs



X. Wang, C. Cavdar, L. Wang, M. Tornatore, H. S. Chung, H. H. Lee, S. M. Park, and B. Mukherjee, ``Virtualized cloud radio access network for 5G transport,'' *IEEE Commun. Mag.*, vol. 55, no. 9, pp. 202209, Sep. 2017.

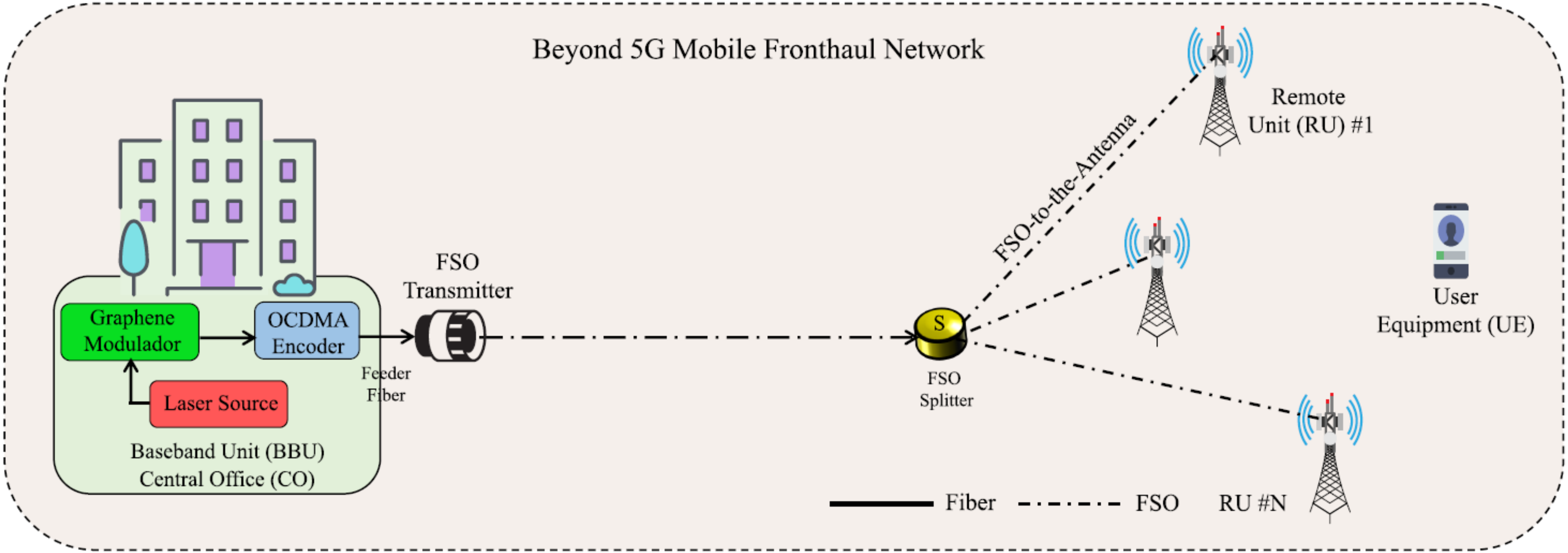
Cell-free Massive MIMO with TWDM-PON





Ö. T. Demir, M. Masoudi, E. Björnson, and C. Cavdar, “Cell-Free Massive MIMO in O-RAN: Energy-Aware Joint Orchestration of Cloud, Fronthaul, and Radio Resources,” *IEEE Journal on Selected Areas in Communications, 2024.*

Wireless fronthaul: FSO (Free-space Optics)



Cost-effective alternative

Adversely affected by visibility and weather conditions

* Fayad, Abdulhalim, et al. "Design of cost-efficient optical fronthaul for 5G/6G networks: An optimization perspective." *Sensors* 22.23 (2022): 9394.

* Neves, Daniel, et al. "Beyond 5G fronthaul based on FSO using spread spectrum codes and graphene modulators." *Sensors* 23.8 (2023): 3791.

Wireless Fronthaul: Microwaves & Millimeter-wave & THz

Microwaves:

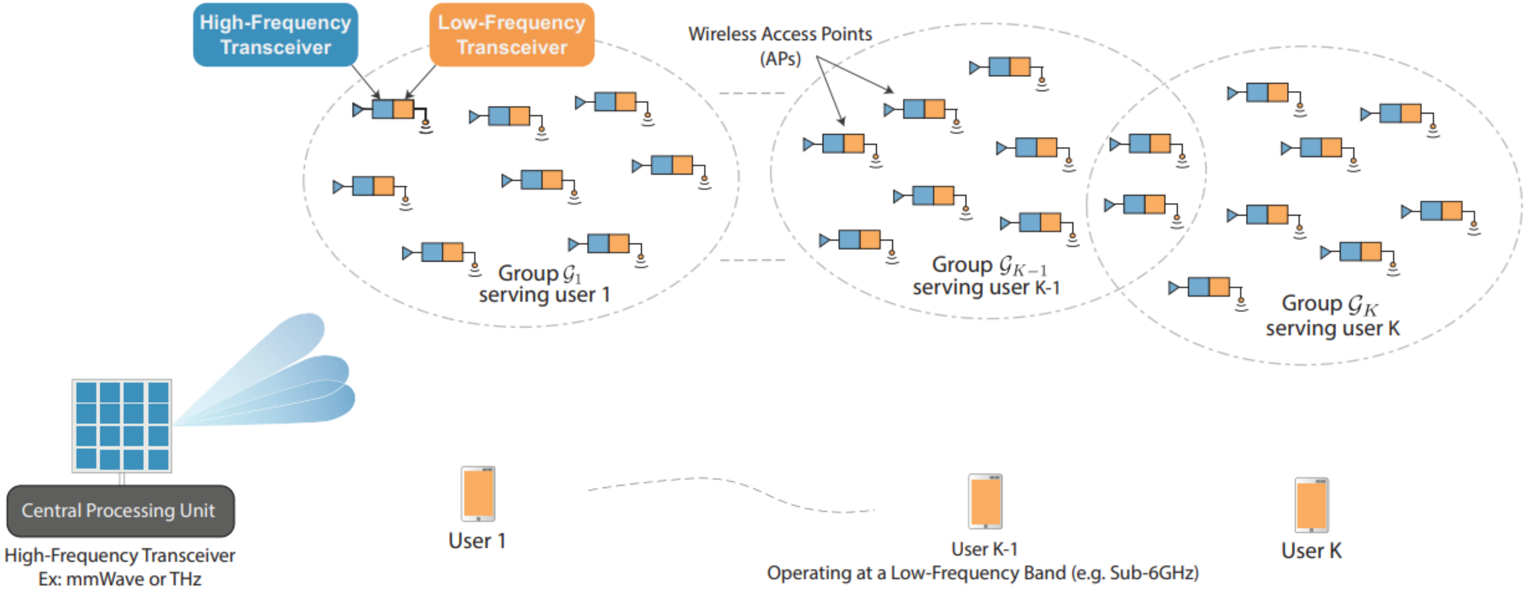
- Less affected by bad weather conditions as FSO
- Serve larger transmission distances
- Expensive (depends on licensed frequencies)

Millimeter-wave & THz:

- Provides low-latency and high-capacity connection
- Sensitive to weather conditions

* Fayad, Abdulhalim, et al. "Design of cost-efficient optical fronthaul for 5G/6G networks: An optimization perspective." *Sensors* 22.23 (2022): 9394.

Cell-free Massive MIMO with Wireless Fronthaul

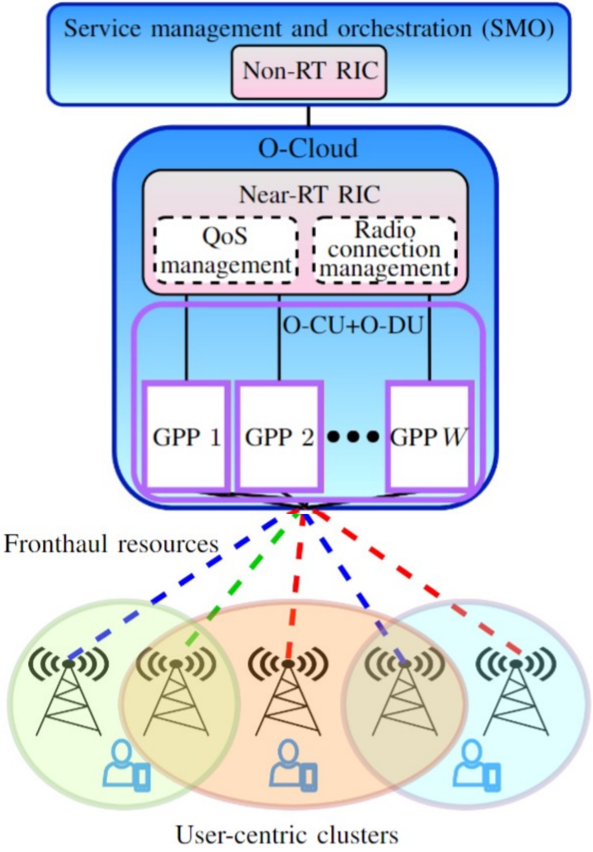


Data rates approach the optimal rates obtained with optical fiber-based fronthaul

Demirhan, Umut, and Ahmed Alkhateeb. "Enabling cell-free massive MIMO systems with wireless millimeter wave fronthaul." *IEEE Transactions on Wireless Communications* 21.11 (2022): 9482-9496.

END-TO-END POWER CONSUMPTION MODELING

Cell-free Massive MIMO on Top of O-RAN

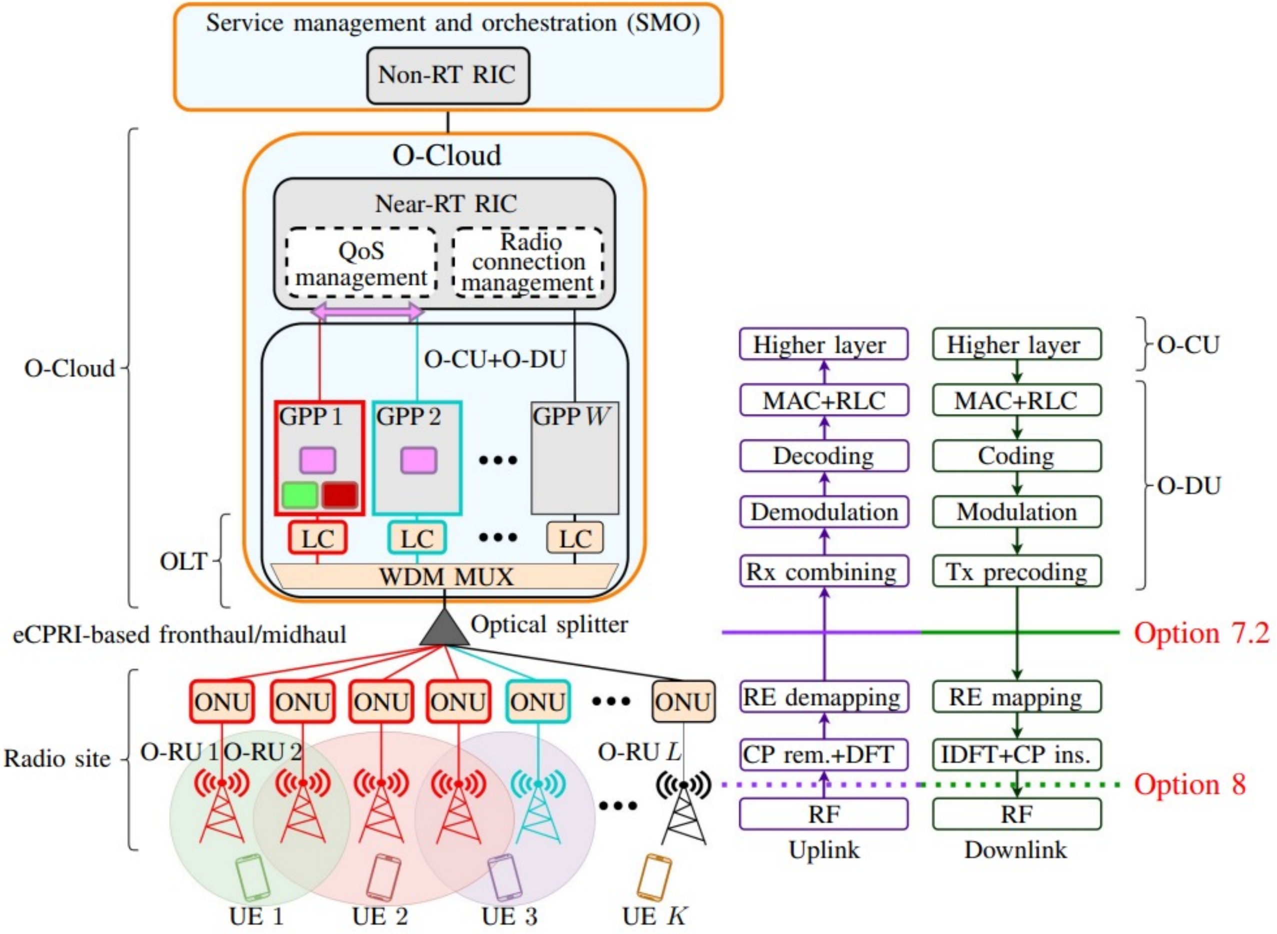


- Joint orchestration of
  - radio,
  - fronthaul, and
  - cloud resources.

RIC (RAN intelligent controller)
GPP (general purpose processor)
CU (central unit)
DU (distributed unit)

- Ö. T. Demir, M. Masoudi, E. Björnson, and C. Cavdar, "Cell-Free Massive MIMO in O-RAN: Energy-Aware Joint Orchestration of Cloud, Fronthaul, and Radio Resources," *IEEE Journal on Selected Areas in Communications, 2024.*

Cell-free Massive MIMO on Top of O-RAN



Downlink Spectral Efficiency

L ← *Number of APs* K ← *Number of UEs*

N ← *Number of antennas per AP*

Uplink pilot transmission: *Channels* $\mathbf{h}_{kl} \in \mathbb{C}^N$ *are estimated in the DU cloud.*

Downlink data transmission: *The transmitted signal from AP l:*

$$\mathbf{x}_l = \sum_{i=1}^{K} \underbrace{\sqrt{p_{il}}}_{\text{Power coefficients}} \overbrace{x_{i,l}}^{\text{Binary variables to denote whether UE } i \text{ is served by AP } l} \underbrace{\mathbf{w}_{il}\varsigma_i}_{\text{Precoded downlink signal of UE } i} \in \mathbb{C}^N$$

$$\boxed{\mathrm{SINR}_k = \frac{\left|\mathbf{b}_k^{\mathrm{T}}\boldsymbol{\rho}_k\right|^2}{\sum_{i=1}^{K} \boldsymbol{\rho}_i^{\mathrm{T}}\mathbf{C}_{ki}\boldsymbol{\rho}_i + \sigma^2}}$$

$$\boxed{\boldsymbol{\rho}_k = \left[\sqrt{p_{k1}}x_{k,1} \;\ldots\; \sqrt{p_{kL}}x_{k,L}\right]^{\mathrm{T}}}$$

Power Consumption Modeling

Total Power Consumption

$$P_{\text{tot}} = \sum_{l=1}^{L} P_{\text{AP},l} + \sum_{l=1}^{L} z_l P_{\text{ONU}} + P_{\text{DU-C}}$$

Binary variables to denote whether AP l is active

AP power consumption

$$P_{\text{AP},l} = z_l P_{\text{AP},0} + \Delta^{\text{tr}} \sum_{k=1}^{K} x_{k,l} p_{kl}$$

Idle power + load-dependent power

DU cloud power consumption

Binary variables to denote how many LCs/DUs are active

$$P_{\text{DU-C}} = \frac{1}{\sigma_{\text{cool}}} \Bigg(\underbrace{P_{\text{disp}}}_{\text{GPP dispatcher power}} + \underbrace{P_{\text{OLT}} \sum_{w=1}^{W} w\ell_w}_{\text{OLT power}} + \underbrace{\sum_{w=1}^{W} wd_w P^{\text{proc}}_{\text{DU-C},0} + \Delta^{\text{proc}}_{\text{DU-C}} \frac{C_{\text{DU-C}}}{C_{\max}} \Bigg)}_{\text{GPP processing power (idle + load-dependent)}}$$

Total GOPS for Cell-free Operation in O-Cloud

GOPS for LP-MMSE transmit precoding

$$C_{\mathrm{prec},l} = \underbrace{\frac{N_{\mathrm{used}}}{T_s \tau_c 10^9}\left(8N\tau_p^2 + 8N^2\left(\tau_p + \sum_{i=1}^{K} x_{i,l}\right)\right)}_{\text{Channel estimation}}$$

$$+ \underbrace{\frac{N_{\mathrm{used}}\tau_d}{T_s \tau_c 10^9} 8N \sum_{i=1}^{K} x_{i,l}}_{\text{Precoding}} + \underbrace{\frac{N_{\mathrm{used}}}{T_s \tau_c 10^9} 8N \sum_{i=1}^{K} x_{i,l}}_{\text{Reciprocity calibration}}$$

$$+ \underbrace{\frac{N_{\mathrm{used}}}{T_s \tau_c 10^9}\left(\left(4N^2 + 4N\right)\tau_p + 8N^2 \sum_{i=1}^{K} x_{i,l} + \frac{8\left(N^3 - N\right)}{3}\right)}_{\text{Precoding computation}}$$

Total GOPS

$$\mathcal{Z}\sum_{l=1}^{L} z_l + \mathcal{X}\sum_{l=1}^{L}\sum_{k=1}^{K} x_{k,l} + \mathcal{F}$$

Malkowsky *et al.*, "The world's first real-time testbed for massive MIMO: Design, implementation, and validation," *IEEE Access*, vol. 5, pp. 9073–9088, 2017.

Desset *et al.*, "Massive MIMO for energy-efficient communications," in *2016 46th European Microwave Conference (EuMC)*. IEEE, 2016, pp. 138–141.

Debaillie *et al.*, "A flexible and future-proof power model for cellular base stations," in *VTC Spring*, 2015.

JOINT RESOURCE ALLOCATION FOR END-TO-END POWER MINIMIZATION

Power-efficient AP Selection, DU (GPP) and Power Allocation

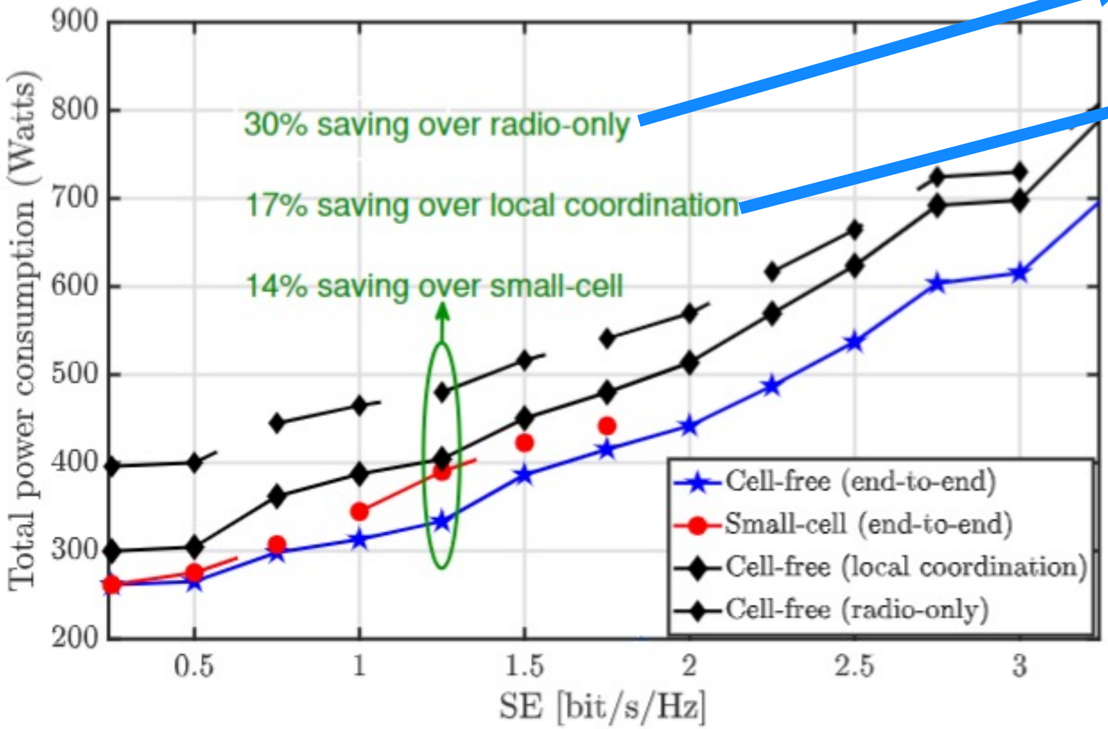
- Optimally minimize the total end-to-end network power by joint allocation of
  - transmit powers, $\boldsymbol{\rho}_k = \left[\sqrt{p_{k1}}x_{k,1} \; \cdots \; \sqrt{p_{kL}}x_{k,L}\right]^{\mathrm{T}}$
  - optical fronthaul resources, $\ell_w \in \{0,1\}$
  - processing resources of the DU cloud, $d_w \in \{0,1\}$
  - the set of active APs, $z_l \in \{0,1\}$
  - UE-AP association $x_{k,l} \in \{0,1\}$
- to meet the spectral efficiency (SE) requirements

$$\frac{\left|\mathbf{b}_k^{\mathrm{T}}\boldsymbol{\rho}_k\right|^2}{\sum_{i=1}^{K}\boldsymbol{\rho}_i^{\mathrm{T}}\mathbf{C}_{ki}\boldsymbol{\rho}_i + \sigma^2} \geq \gamma_k, \quad \forall k$$

- under fronthaul, cloud processing, and per-AP transmit power constraints
- The optimal solution is obtained by solving a mixed-binary second-order cone programming problem.

Reduced Power Consumption with Cell-free Operation

16 APs, 8 UEs, 1 km x 1 km area



Fixedly assigned fronthaul and cloud resources

Fixedly assigned fronthaul resources and the partial intra-LC cloud resource sharing mechanism

Less number of active APs and DUs with cell-free network

Increased Maximum Rate with Greater Energy Efficiency

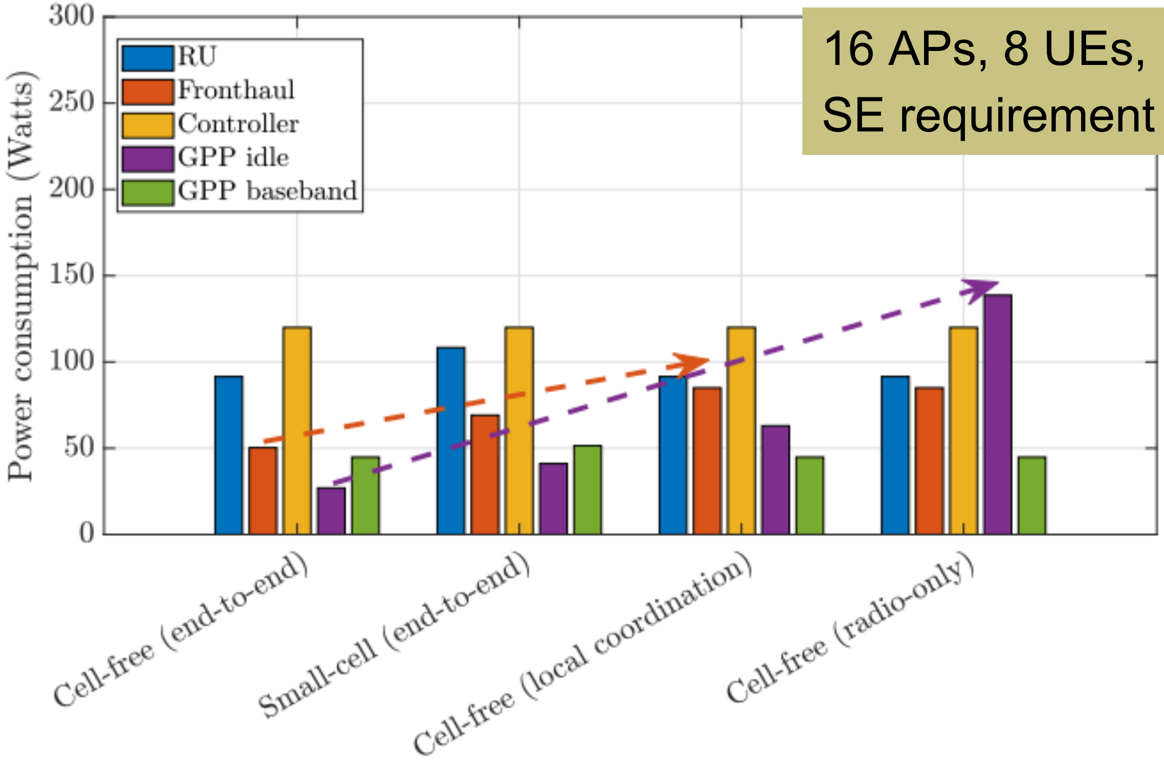
16 APs, 8 UEs, 1 km x 1 km area

MAXIMUM PROVIDED RATE AND ENERGY PER BIT.

	Maximum Rate (Mbps)	Energy Per Bit (Joule/bit)
Cell-free	440	$1.9 \cdot 10^{-6}$
Small-cell	260	$2 \cdot 10^{-6}$

Cell-free massive MIMO increases the maximum rate with slightly less energy per bit compared to small-cell!

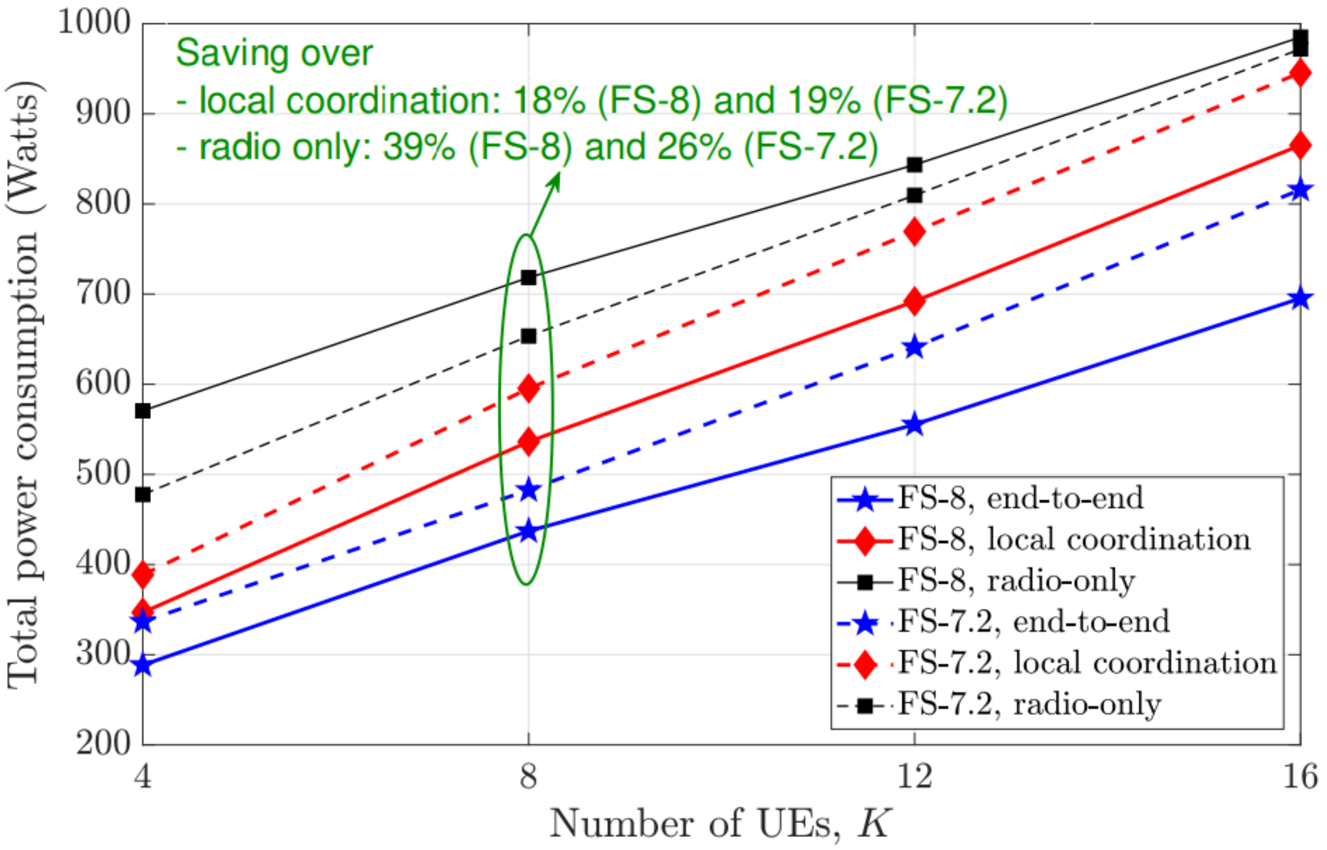
Shutting Down Unused Network Components: Key to Energy Saving



16 APs, 8 UEs, 1 km x 1 km area

SE requirement is 1.25 bit/s/Hz

Impact of Functional Splitting



HOW TO SAVE ENERGY IN A CELL-FREE NETWORK?

Optimizing Energy Efficiency

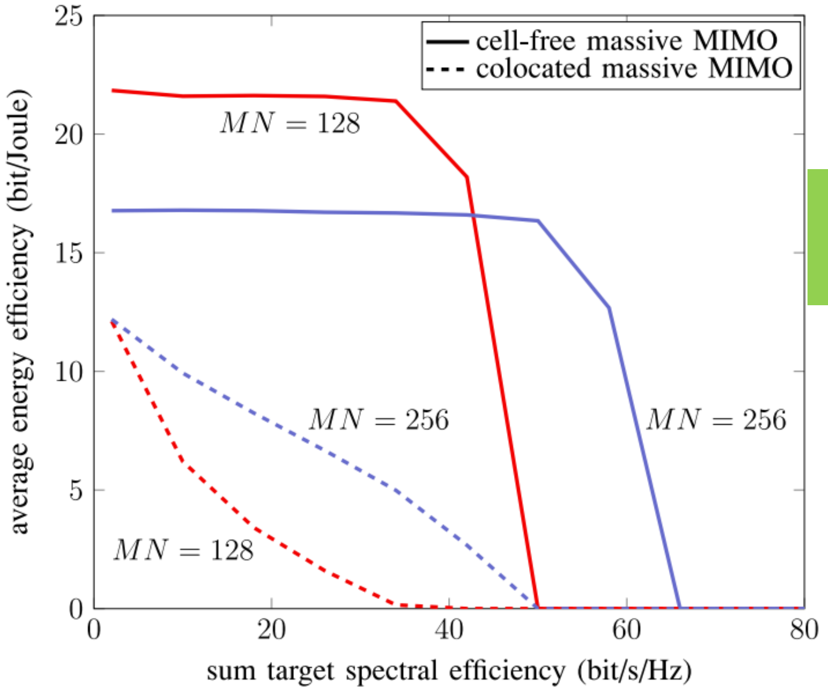


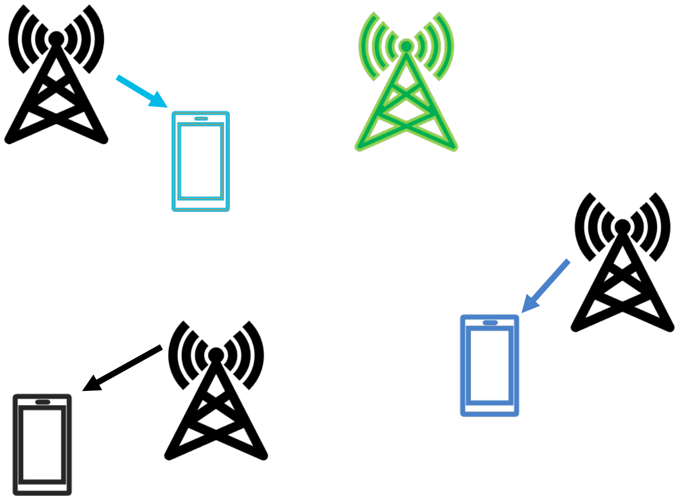
Fig. 8. Average total energy efficiency versus sum spectral efficiency target. Here, $K = 20$, and $\tau_p = 40$, $D = 1$ km.

Cell-free massive MIMO is more energy efficient by a factor of at least two!

Ngo, Hien Quoc, et al. "On the total energy efficiency of cell-free massive MIMO." *IEEE Transactions on Green Communications and Networking* 2.1 (2017): 25-39.

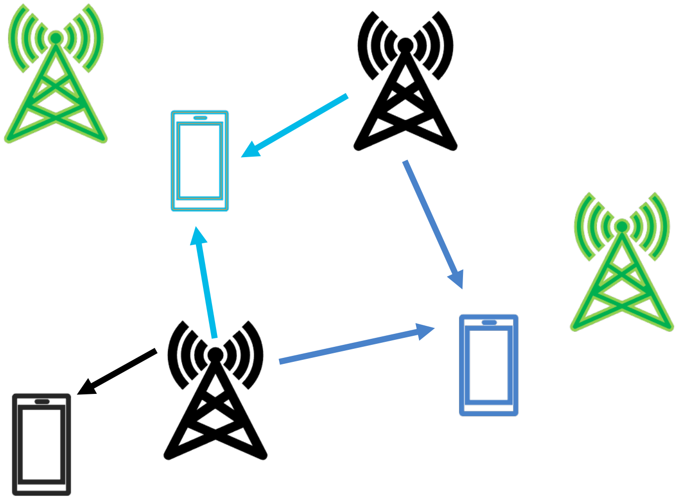
Energy Saving: Impact of Cell-free Operation

Traditional Small-Cell



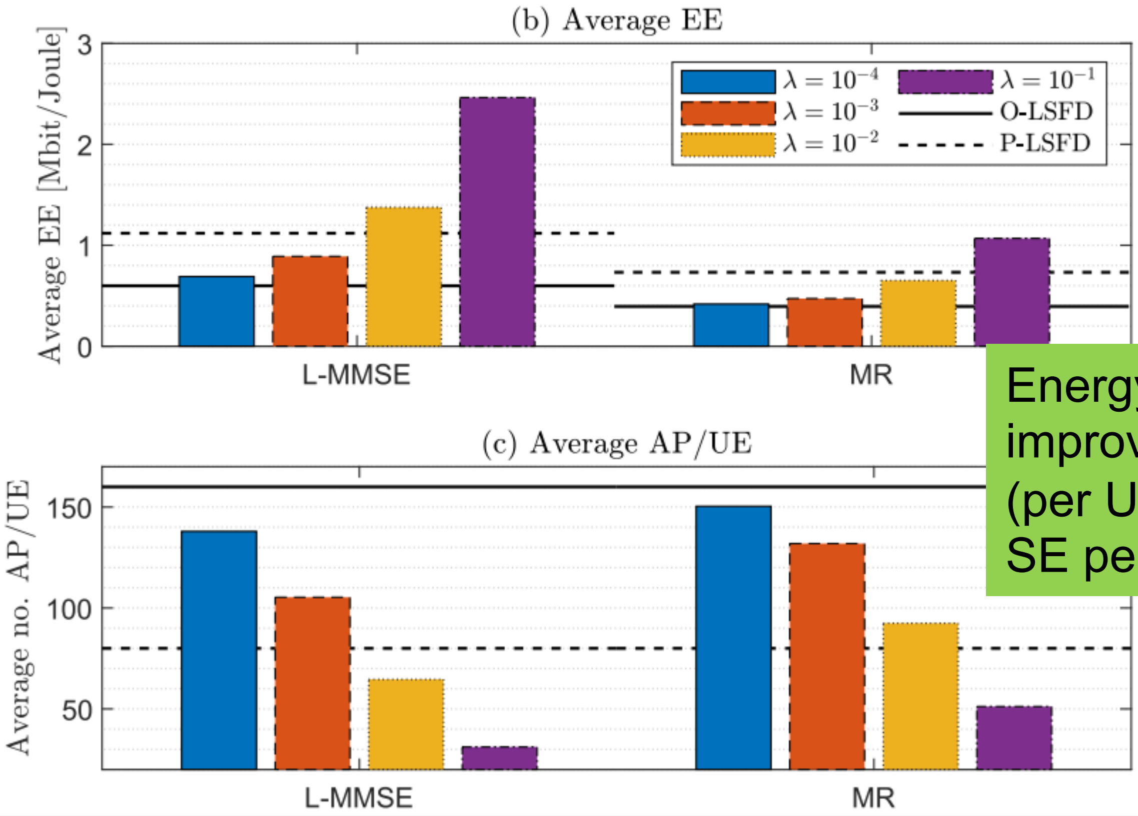
1 inactive AP

Cell-Free Massive MIMO



2 inactive APs

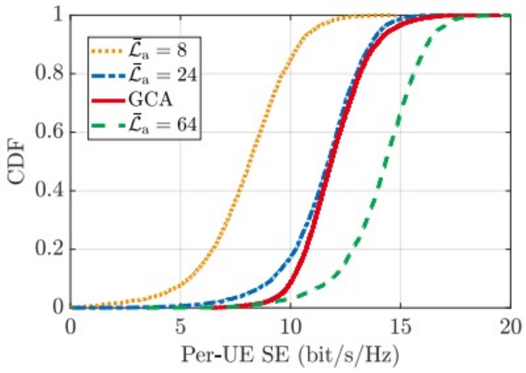
Energy Saving: Impact of Sparse Association



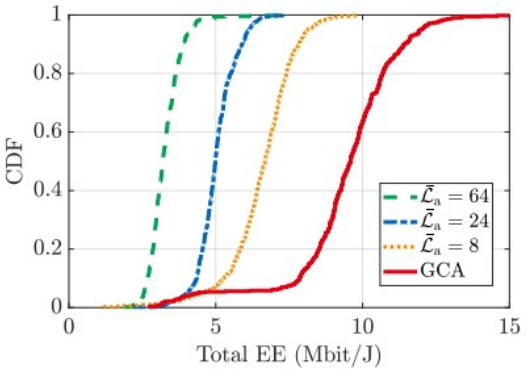
Energy efficiency can be improved by activating less APs (per UE) without compromising SE performance.

Chen, Shuaifei, et al. "Energy-efficient cell-free massive MIMO through sparse large-scale fading processing." *IEEE Transactions on Wireless Communications* (2023).

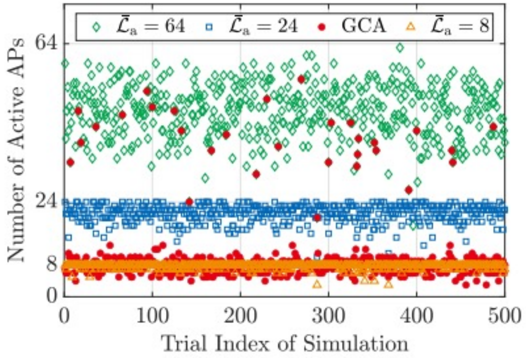
Energy Saving: Impact of Joint AP On/Off and User-centric Clustering



(a) Per-UE SE



(b) Total EE

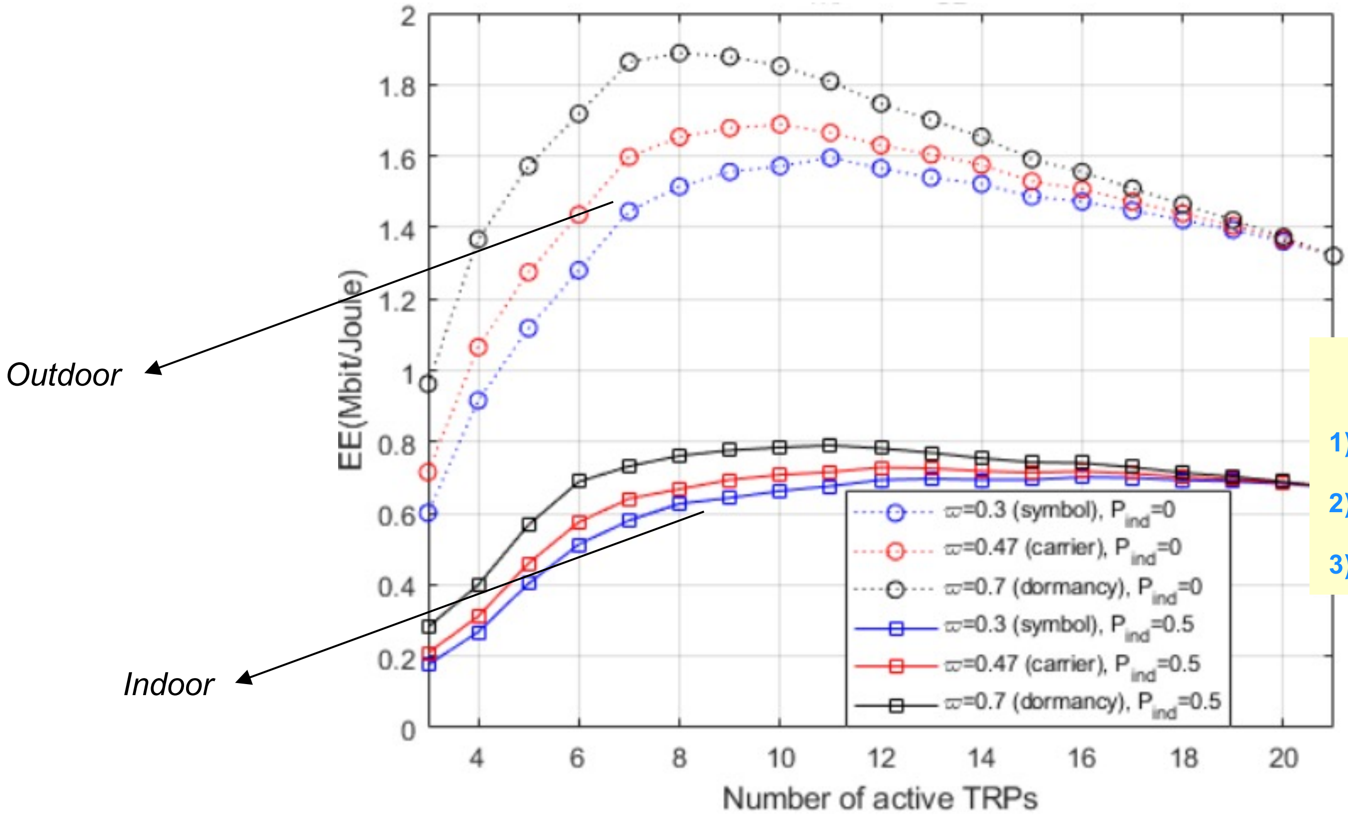


(c) Number of Active APs

Via joint optimization, both SE and EE can be improved.

Ito, Masaaki, et al. "Joint AP on/off and user-centric clustering for energy-efficient cell-free massive MIMO systems." *2022 IEEE 96th Vehicular Technology Conference (VTC2022-Fall)*. IEEE, 2022.

Energy Saving: Impact of Sleep Strategies

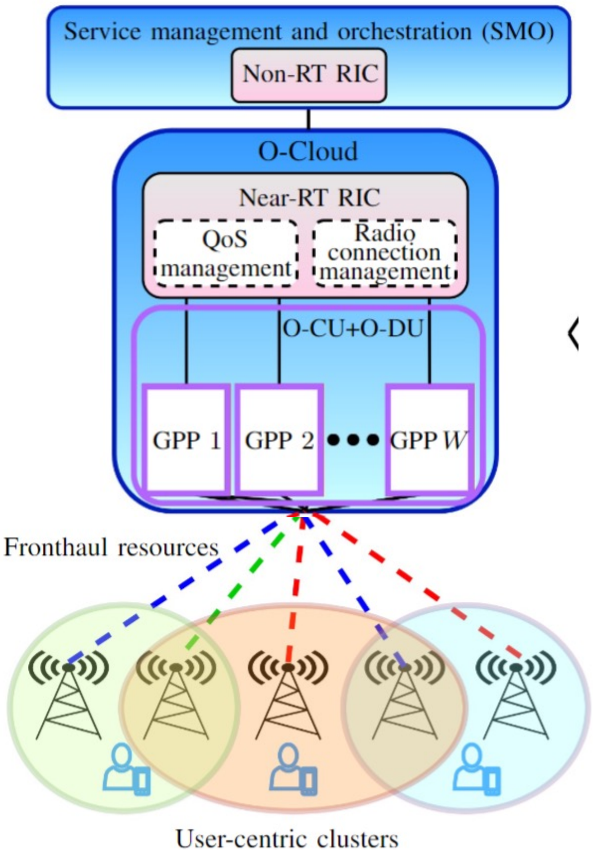


Adaptive switch-off

1) **symbol shutdown**
2) **carrier shutdown**
3) **deep dormancy**

Riera-Palou, Felip, et al. "Energy efficient cell-free massive MIMO on 5G deployments: sleep modes strategies and user stream management." *arXiv preprint arXiv:2306.06404* (2023).

Summary



Main goal:

Energy-efficient cell-free implementation on C-RAN

Handle practical fronthaul challenges

End-to-end energy awareness

O-RAN architecture

Promising wired & wireless fronthaul technologies

Energy saving in a cell-free network

Benefit from cell-free operation

Limit the AP-UE association and active APs

Benefit from deactivating unused network components

Benefit from energy-aware resource allocation

PART 2B

EMERGING RESEARCH CHALLENGES

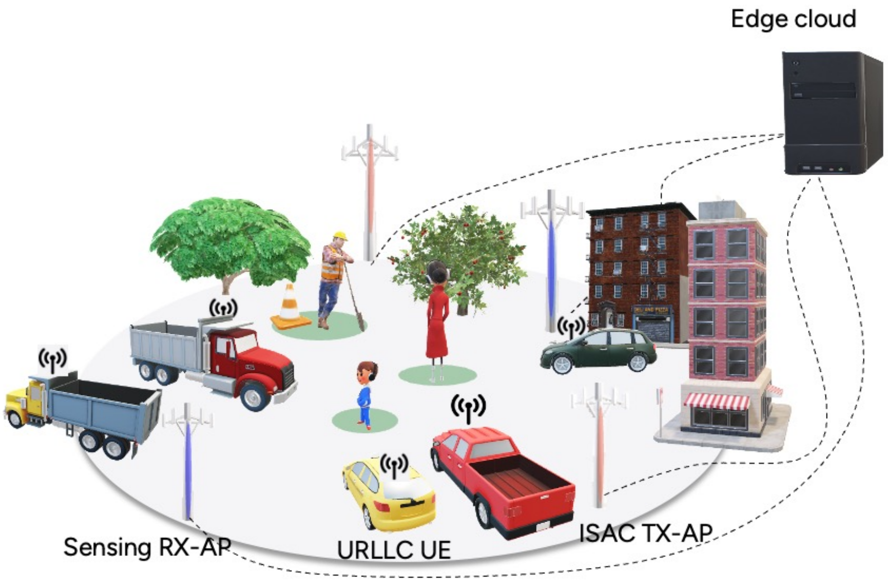
Integrated Sensing and Communication (ISAC)

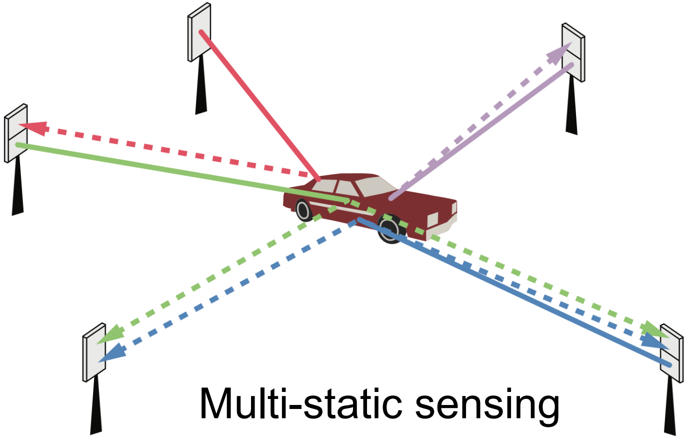
Localization

Use UE signal to estimate UE location

Sensing

Reflect AP signals on objects to
a) detect target; b) estimate velocity





Multi-static sensing

Turn some APs into sensing receivers
AP synchronization is unique feature

Z. Behdad, Ö. T. Demir, K. W. Sung, E. Björnson, C. Cavdar, "Multi-Static Target Detection and Power Allocation for Integrated Sensing and Communication in Cell-Free Massive MIMO," TWC, 2024

Massive Synchronization

Types of synchronization

1) Frequency; 2) Time;

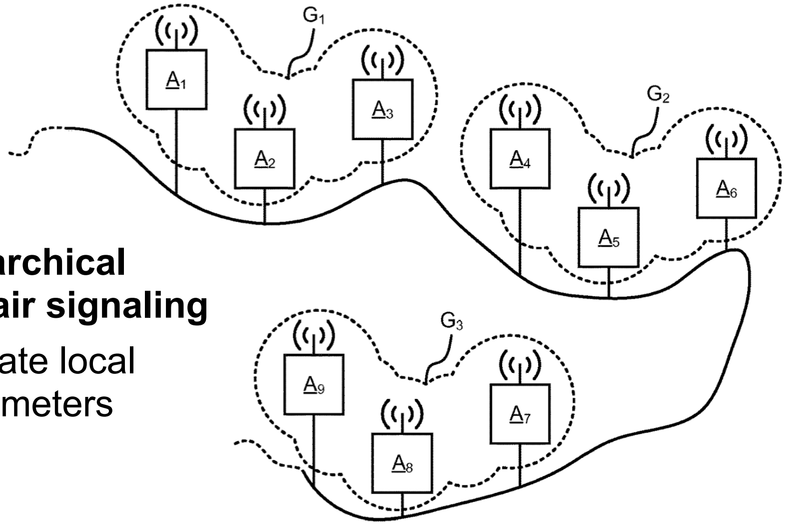
3) Phase; 4) Reciprocity

Underlying issues

- Different local oscillators
- Different TX/RX components
- Delay spread

Hierarchical over-the-air signaling

Estimate local parameters



E. G. Larsson, “Massive Synchrony in Distributed Antenna Systems,” TSP, 2024.

P Frenger, E Björnson, E Larsson, “Distributed MIMO synchronization,” US Patent 11,564,188

Cell-Free Massive MIMO in 6G Bands

7-15 GHz band vs. 3.5 GHz

2^2 to 4^2 times more antennas

Advanced MIMO inside each AP

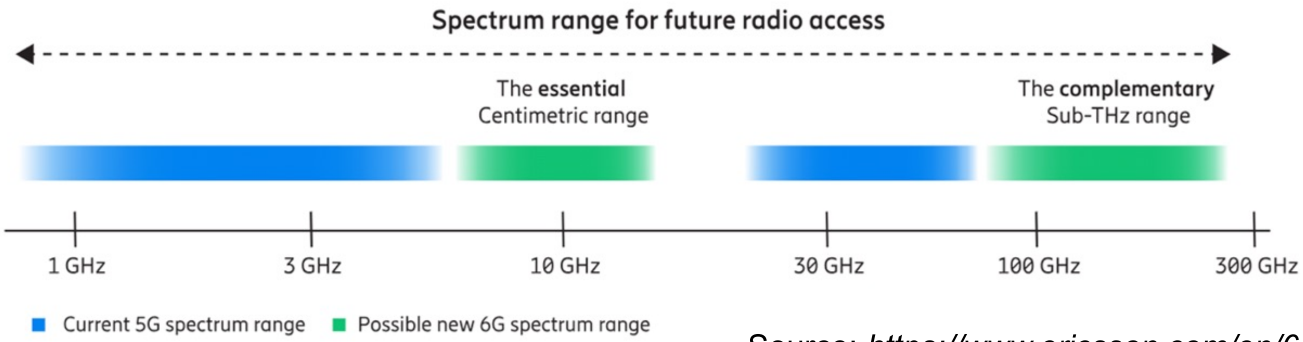
Distributed processing more useful?

Multi-antenna user devices

Mostly missing in academic literature

Shorter coherence time

Will pilot contamination be an issue?



Source: *https://www.ericsson.com/en/6g/spectrum*

Distributed Resource and Mobility Management

Some resources to manage

Time-frequency scheduling

User-centric AP clusters

Pilot assignment

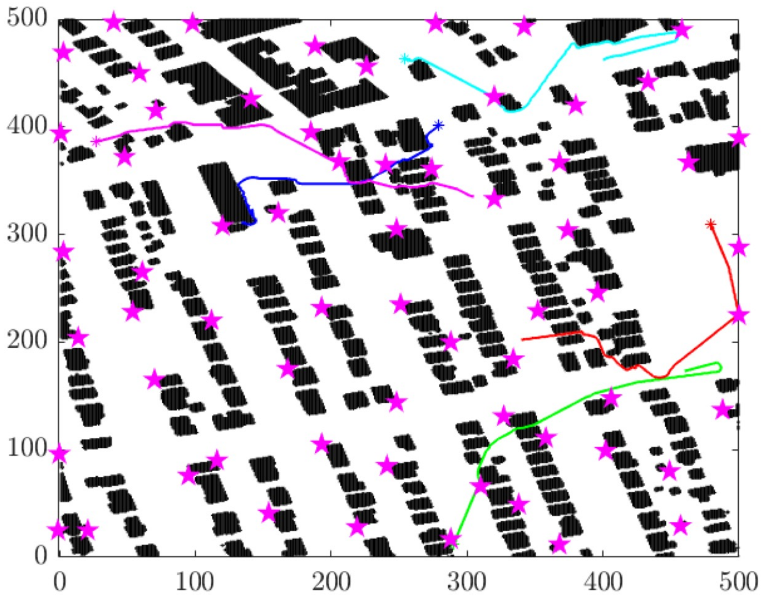
Must be redone under mobility

Cellular networks

Divide-and-conquer: solve per cells

Cell-free networks

Nontrivial to make it scalable



Potential solution

Local adjustment, might propagate

M. Zaher, E. Björnson, M. Petrova, “Soft Handover Procedures in mmWave Cell-Free Massive MIMO Networks,” TWC, 2024