Wireless Networks With Uniform Performance: Distributed MIMO and Sequential Fronthaul

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Outline

1. Importance of spectral efficiency
2. Distributed (cell-free) MIMO (multiple input multiple output)
3. Reasons for a sequential fronthaul design (radio stripes)
4. Algorithms designed for sequential fronthauls
5. Summary

My research is sponsored by

Future Research Leader Grant

Wallenberg Academy Fellow Grant

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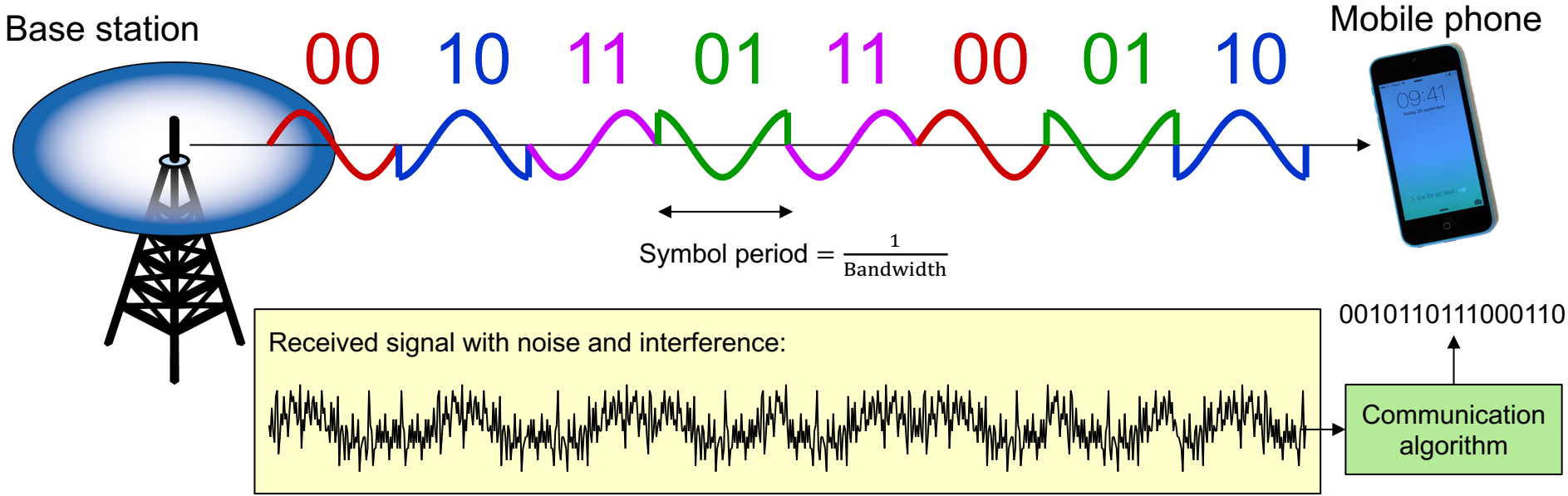
Wireless Communications in a Nutshell



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.

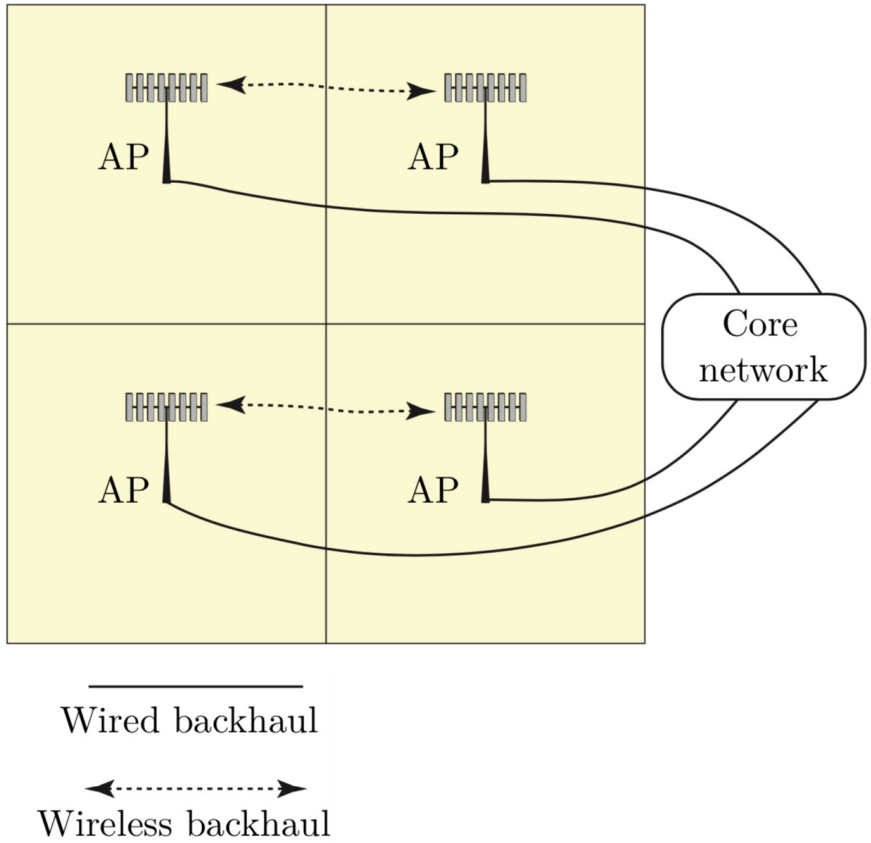
Schulte, H. J. and W. A. Cornell (1960). "Multi-area mobile telephone system". IEEE Trans. Veh. Technol.

Reuse of spectrum in space:

Densify as usage increases

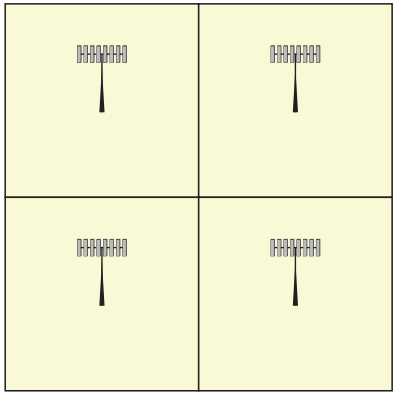
Control interference

5G networks are still *cellular*



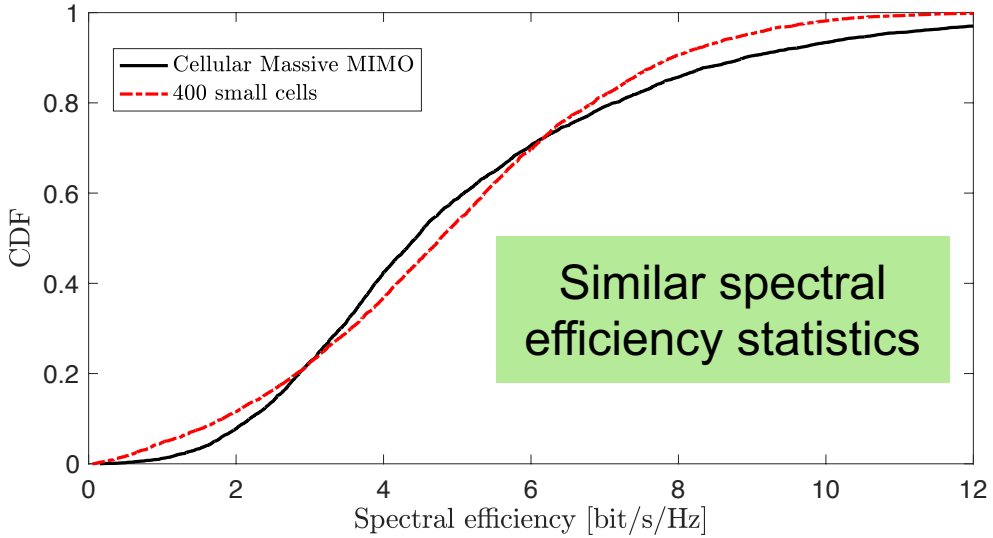
AP = Access point

Spectral Efficiency in Cellular Networks

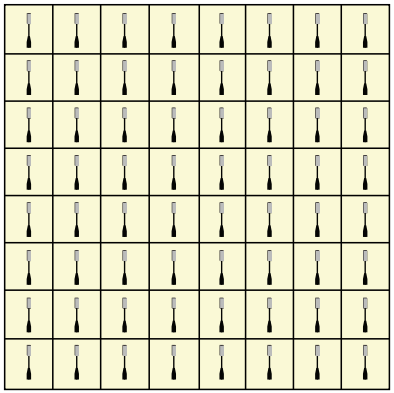


4 cells, 100 antennas
"Massive MIMO"

Large variations!



Similar spectral efficiency statistics



400 cells, 1 antenna
"Small cells"

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

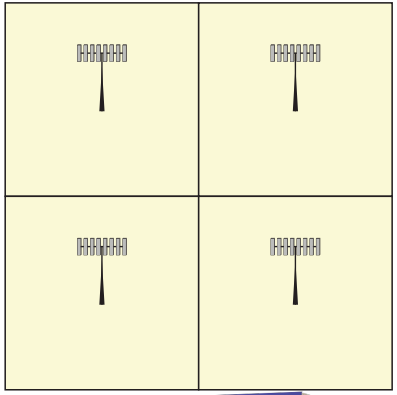
5G Peak Rates: 20×

The *real* challenge

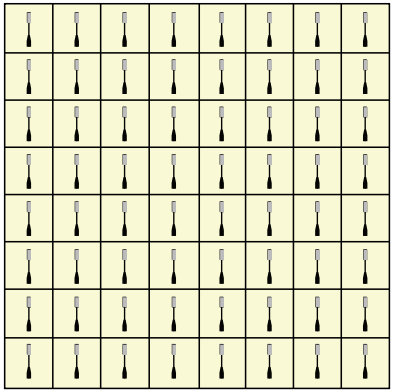
Consistent performance!

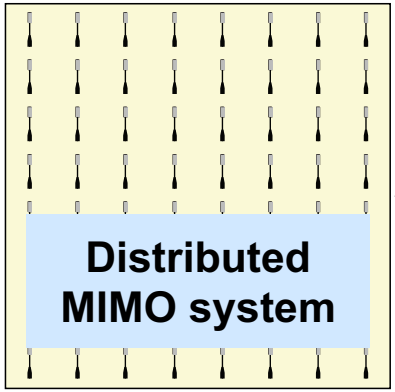
A Potential Solution

4 cells, 100 antennas

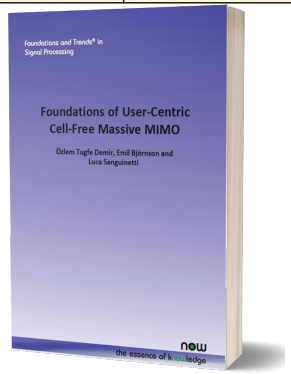


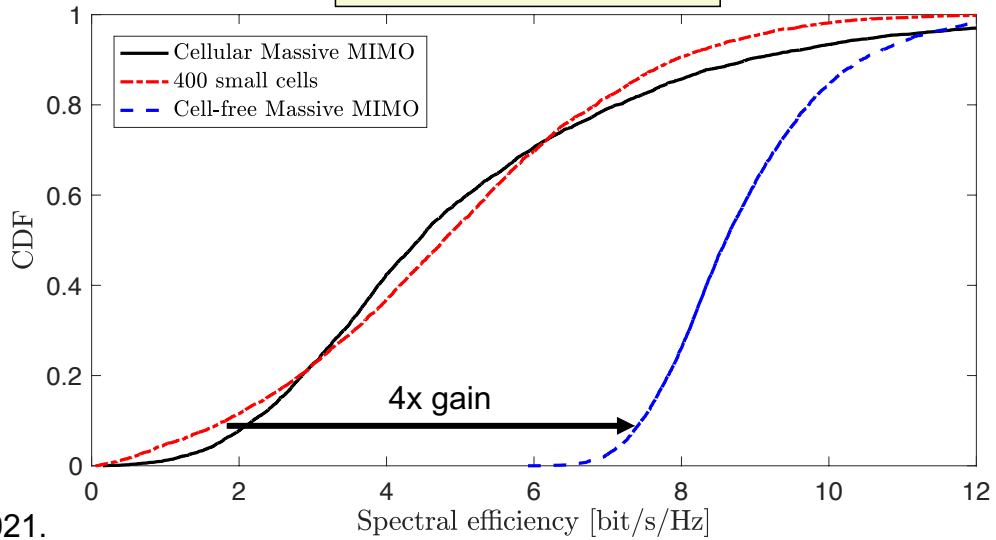
400 cells, 1 antenna





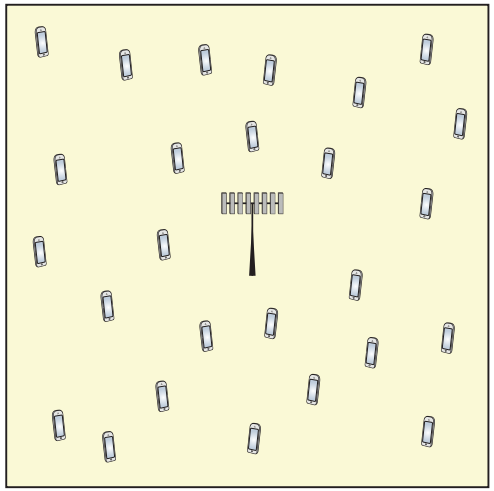
All antennas cooperate



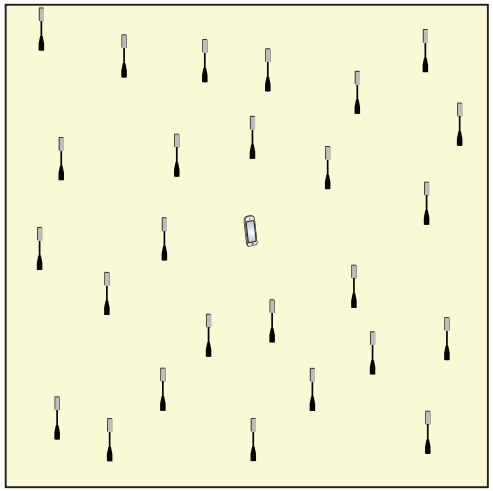


Reference: Ö. T. Demir, E. Björnson, L. Sanguinetti, "Foundations of User-Centric Cell-Free Massive MIMO," 2021.

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



AP surrounded by users



User surrounded by APs

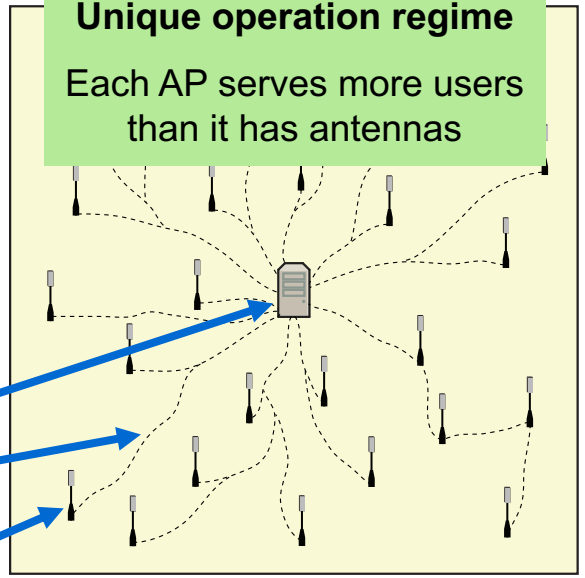
Connection to Massive MIMO:

$L \gg K$

L APs, K users

Unique operation regime

Each AP serves more users than it has antennas



Cloud RAN infrastructure:

Central processing unit

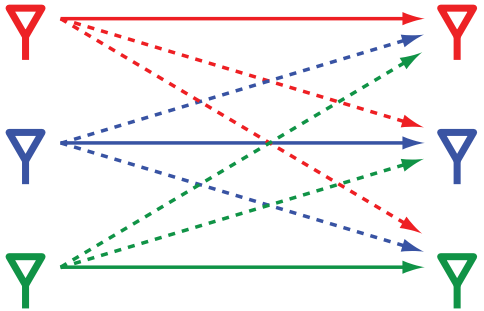
Fronthaul

Access point

Uplink: Philosophy of Interference Rejection

Cellular network:

3 desired signals:
One per transmitter



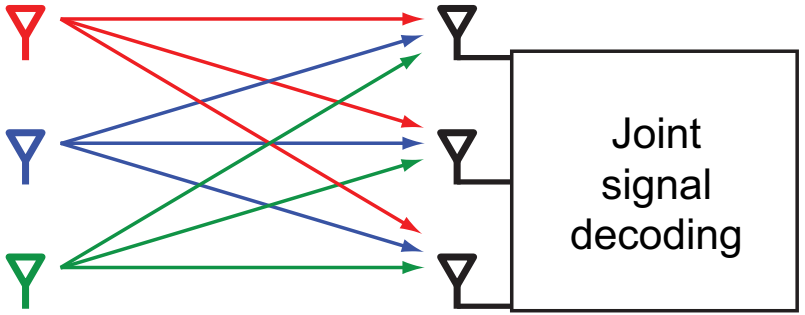
Each receiver:
1 observation
1 desired signal
2 interfering ones

Too few observations to remove interference

Cell-free network:

3 desired signals:
One per transmitter

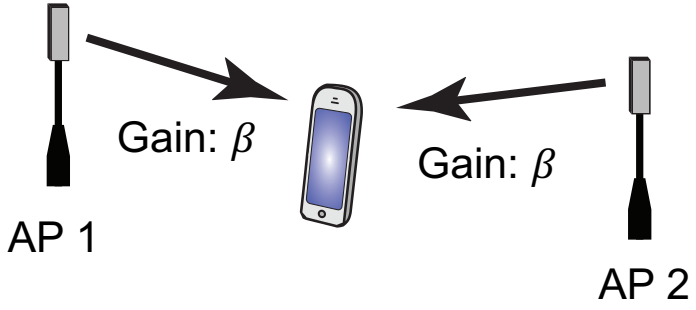
Noisy signal decoding
Minimize MSE $\mathbb{E}\{|\text{signal} - \text{estimate}|^2\}$



Enough observations:
3 observation
3 desired signal

Downlink: Why Transmit From More Than One AP?

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



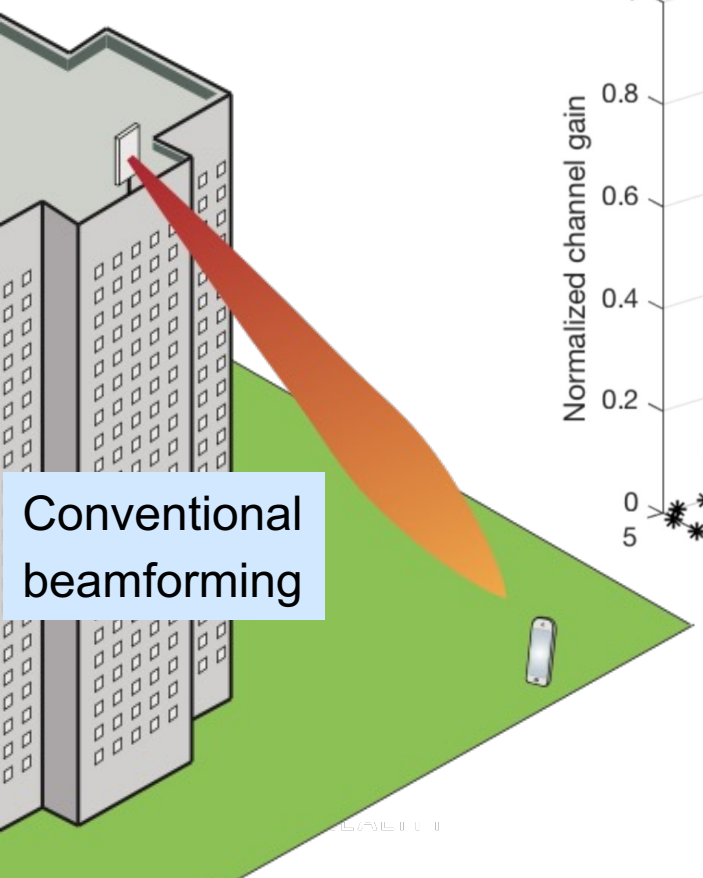
1. **Transmit from AP 1:**
   - Received power: $P\beta$

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

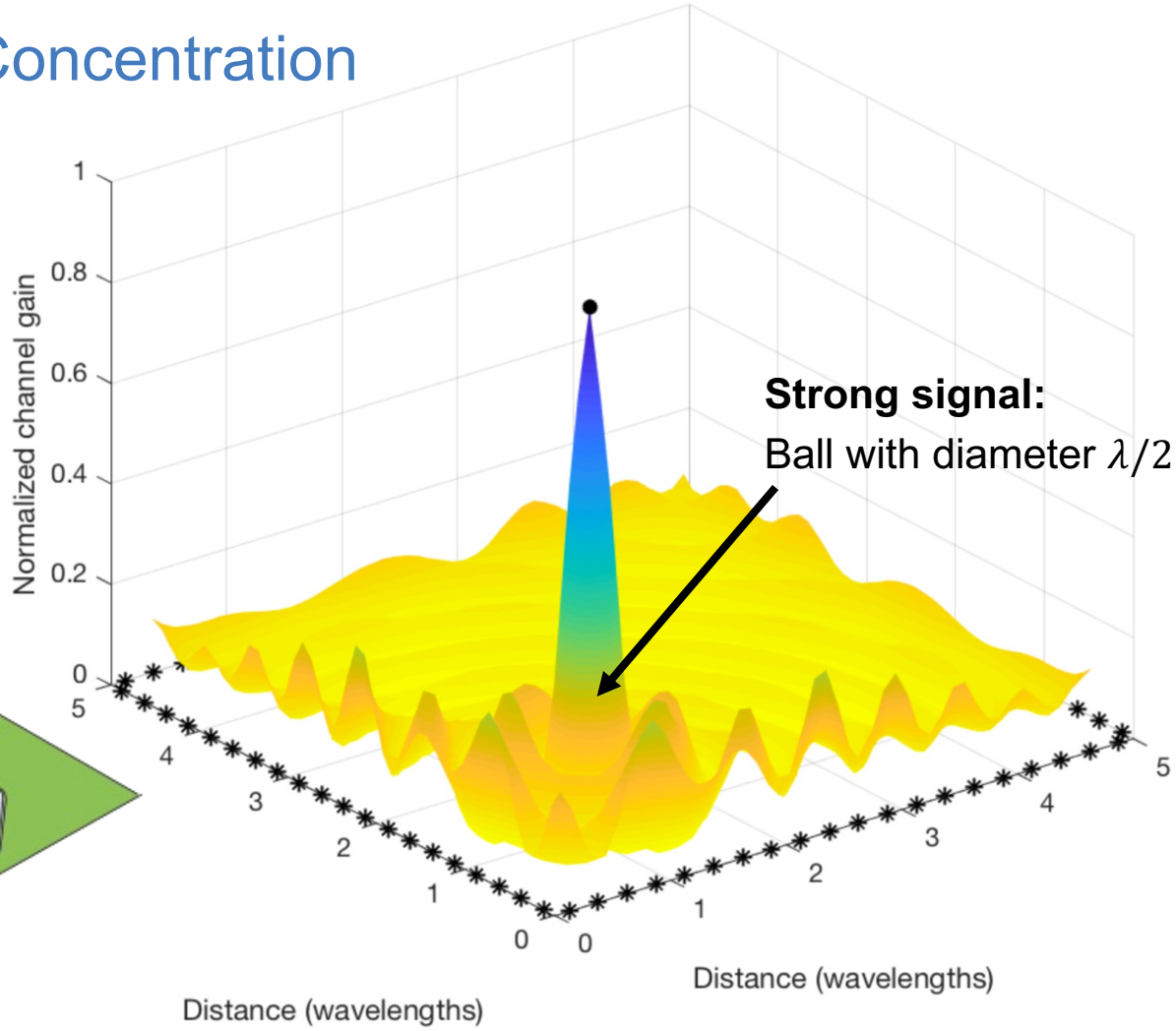
Optimized power allocation:
Minimize MSE $\mathbb{E}\{|\text{signal} - \text{estimate}|^2\}$

Coherent combination!

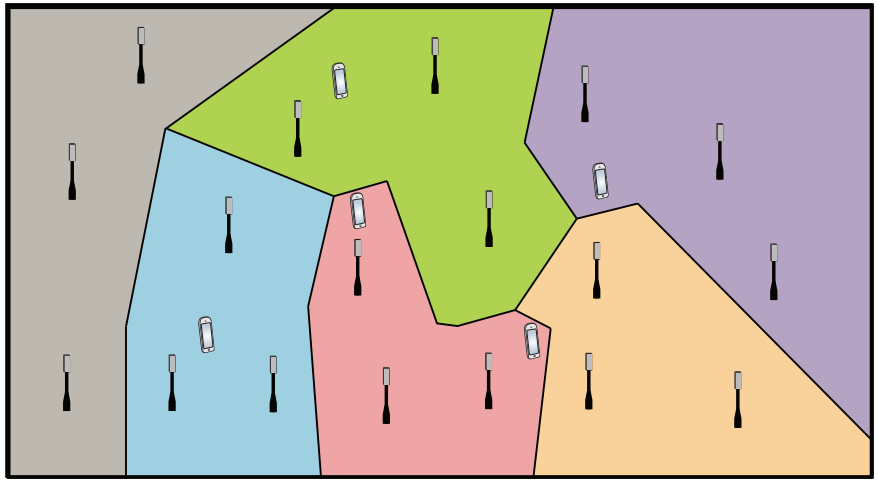
Downlink Power Concentration



Conventional beamforming

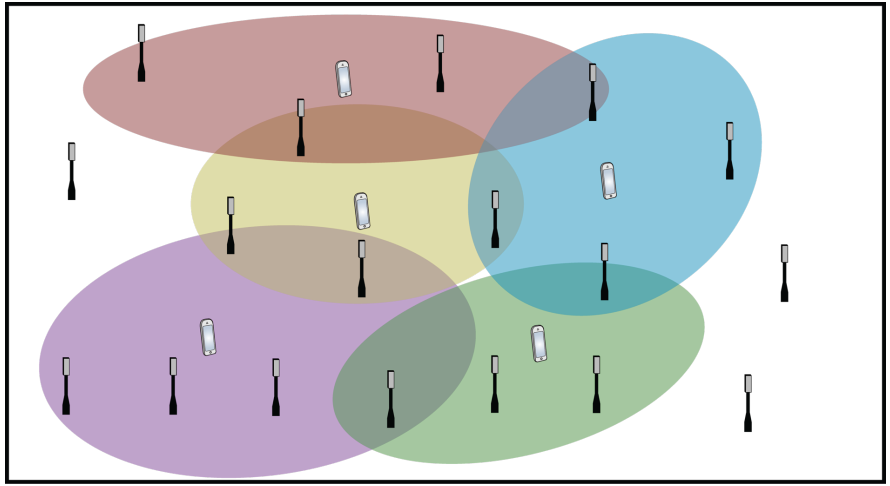


Difference from 4G Coordinated Multipoint



Cellular: Coordinated multipoint

Network-centric design

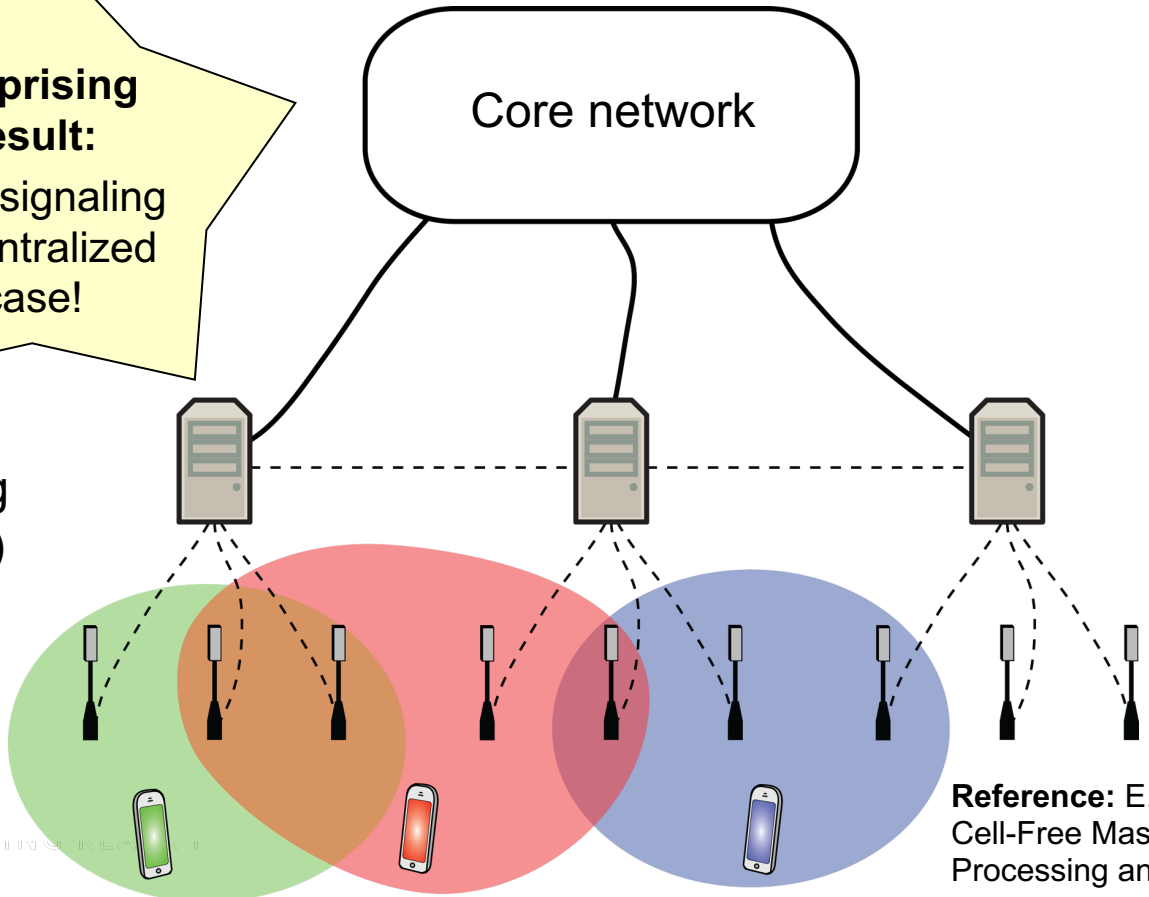


Cell-free: Each user served by all AP in its area of influence

User-centric design

Signal Processing: Centralized versus Distributed

Surprising result:
Less signaling in centralized case!



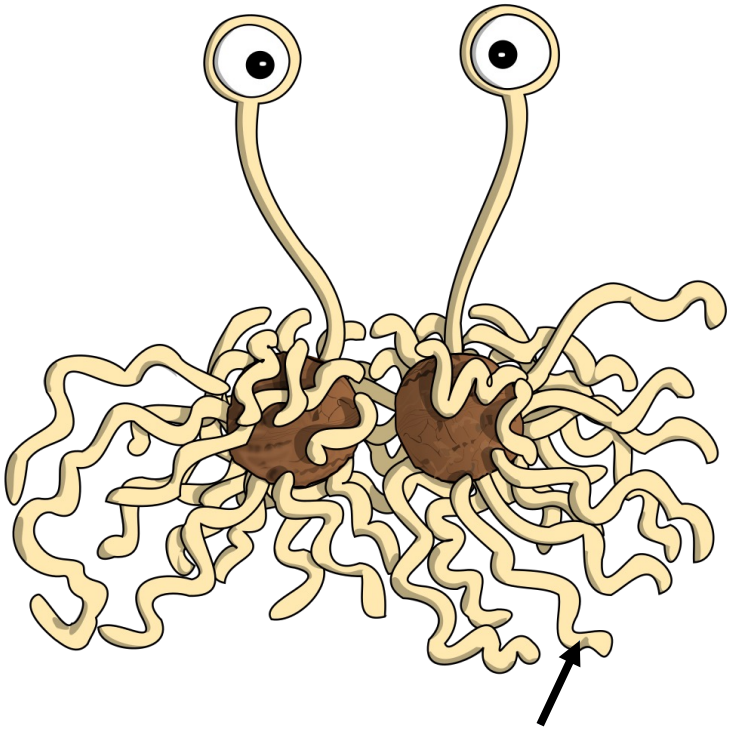
Processing tasks
Channel estimation
Precoding/combining
Data en-/de-coding

Centralized version
Everything done at CPU, maximum rate

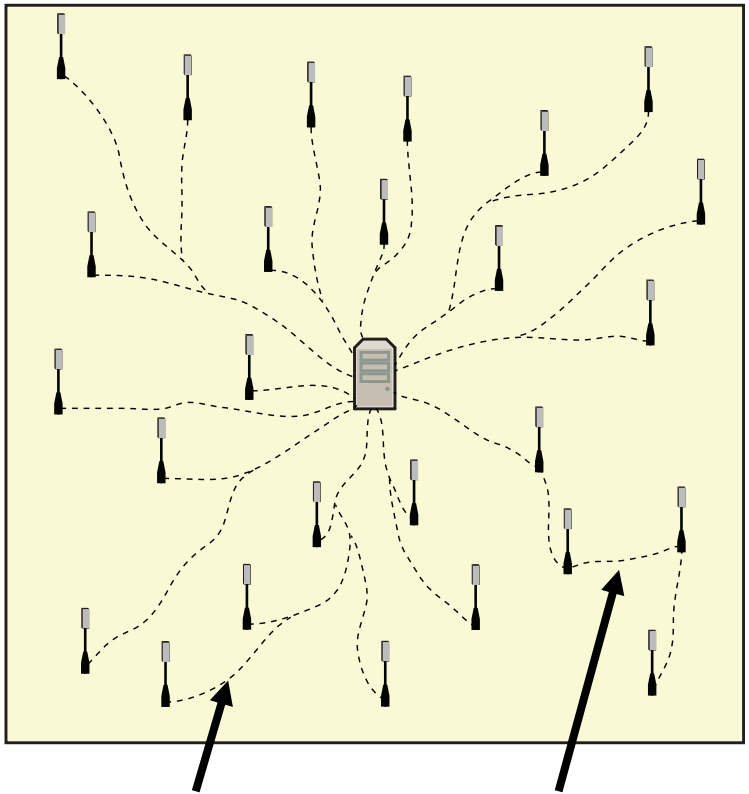
Distributed version
Most processing at AP, fusing at a CPU

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

Practical Issue: Avoid Creating a Spaghetti Monster



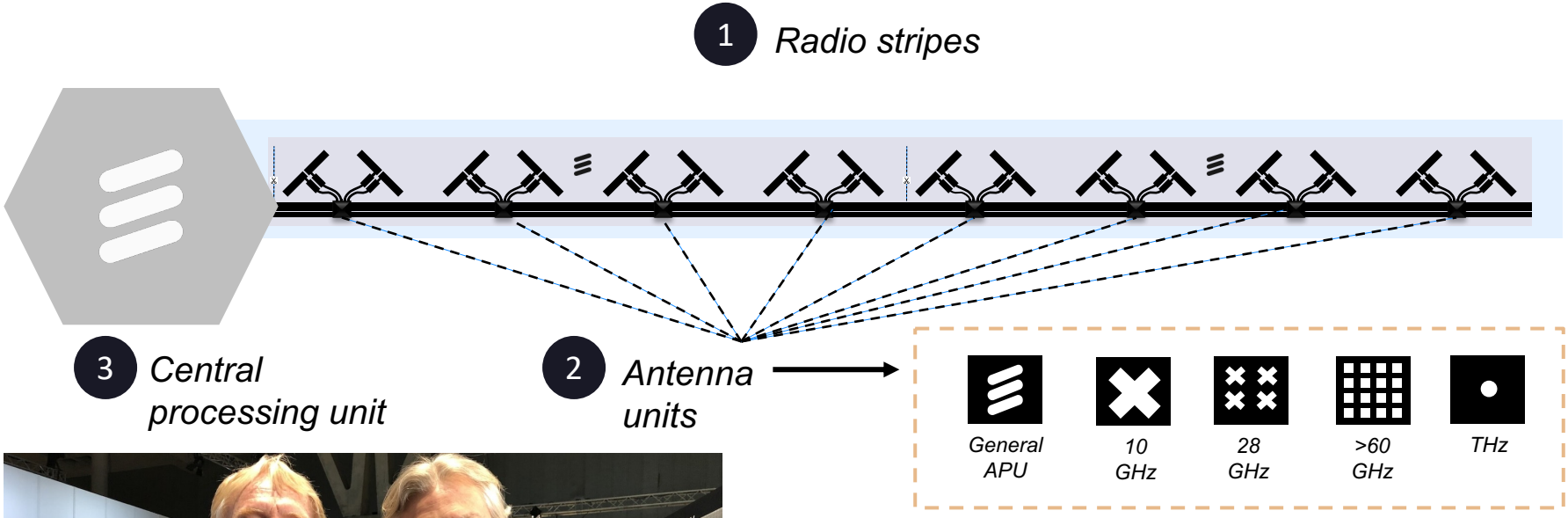
Dedicated fronthaul

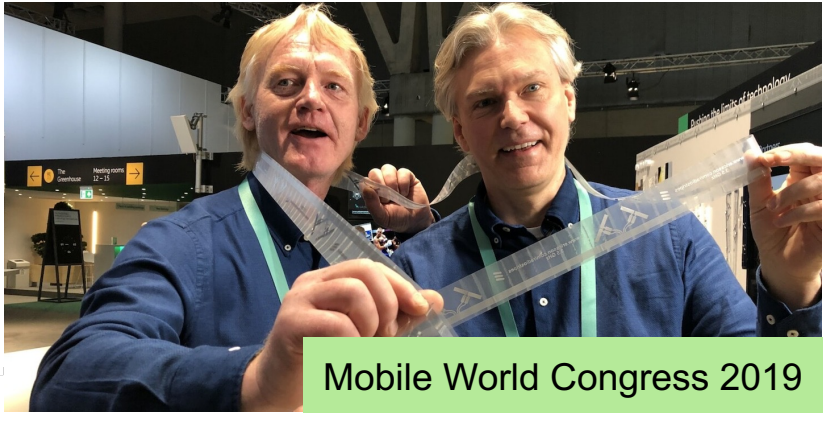


Fronthaul

Potential solution:
Sequential fronthaul

Sequential Implementation Concept: Radio Stripes





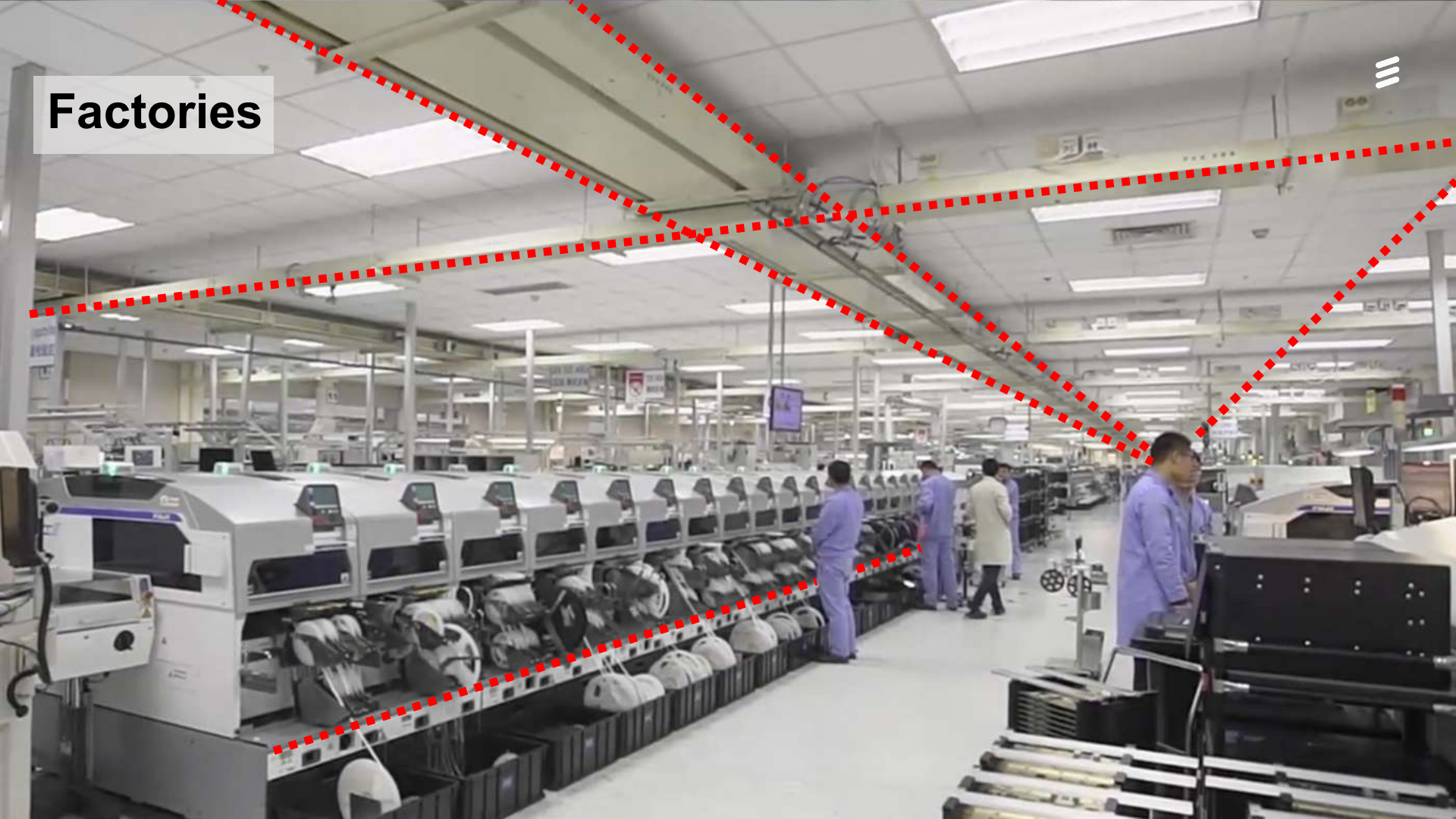
Mobile World Congress 2019

LINKÖPING UNIVERSITY

ERICSSON

Cultural places

Factories

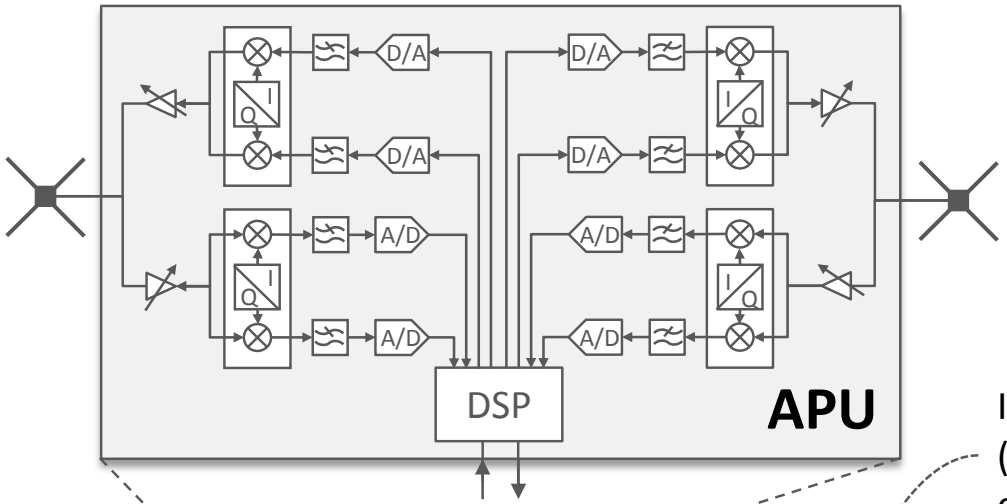


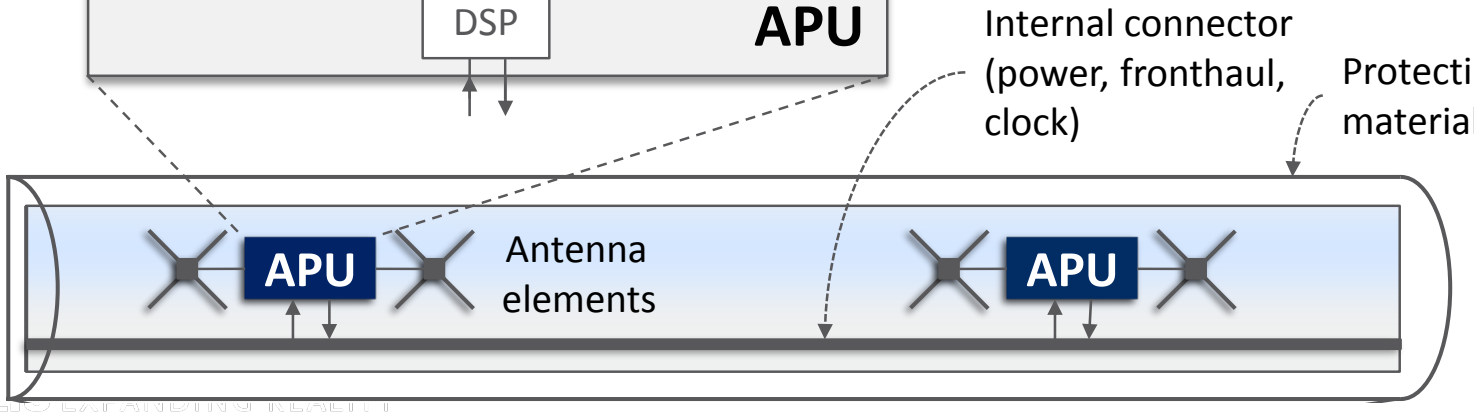

Stadium
FIFA
Brasil
SONY

Radio Stripe: Implementation Details

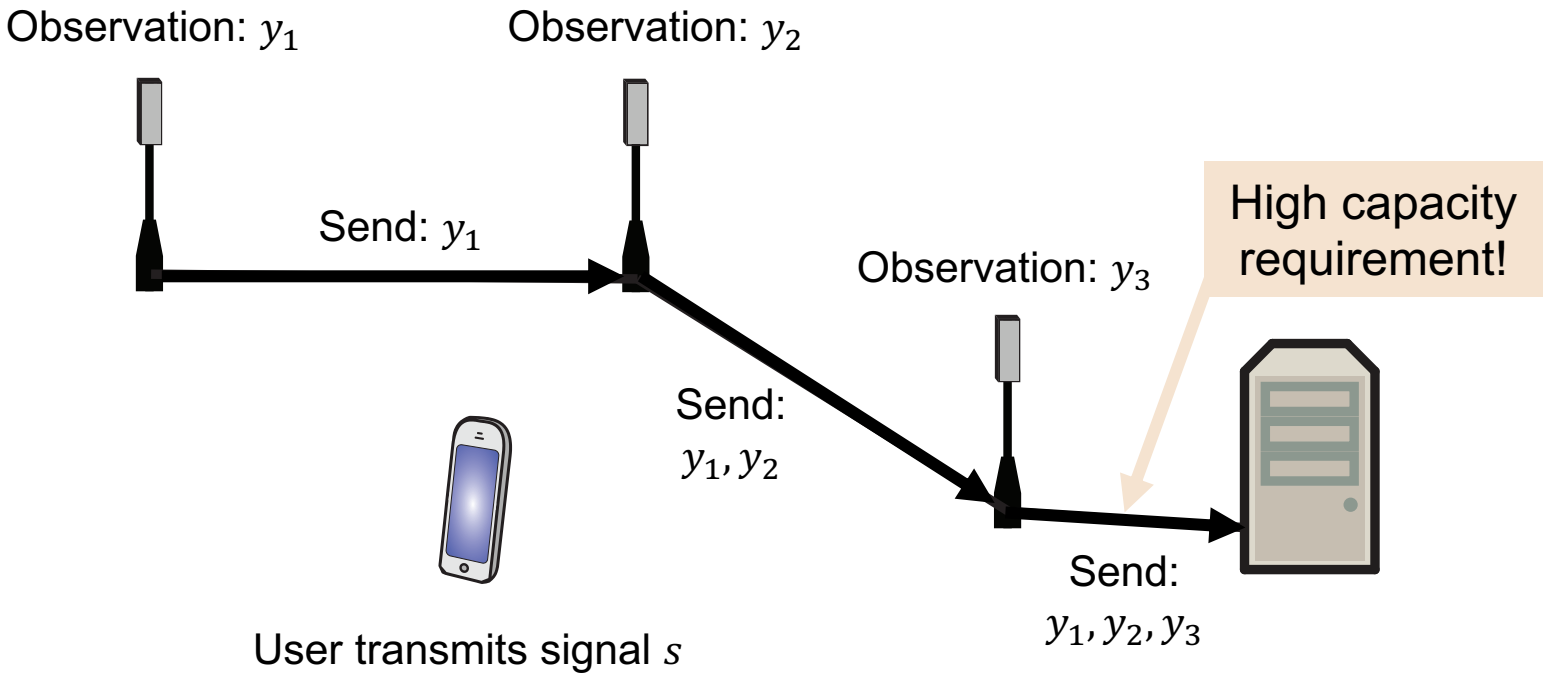
Low power and cost?
Cell-phone grade components

Power-over-Ethernet/Fiber
Build on existing standards
100 m stripes supported



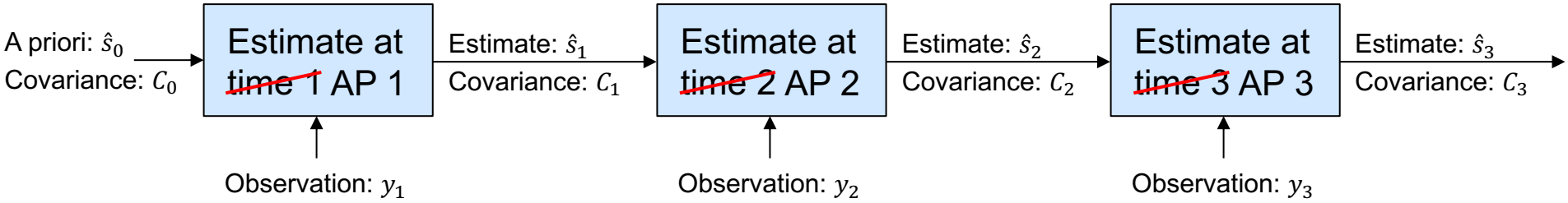


Issue with Serial Fronthaul: Capacity Requirement Accumulates

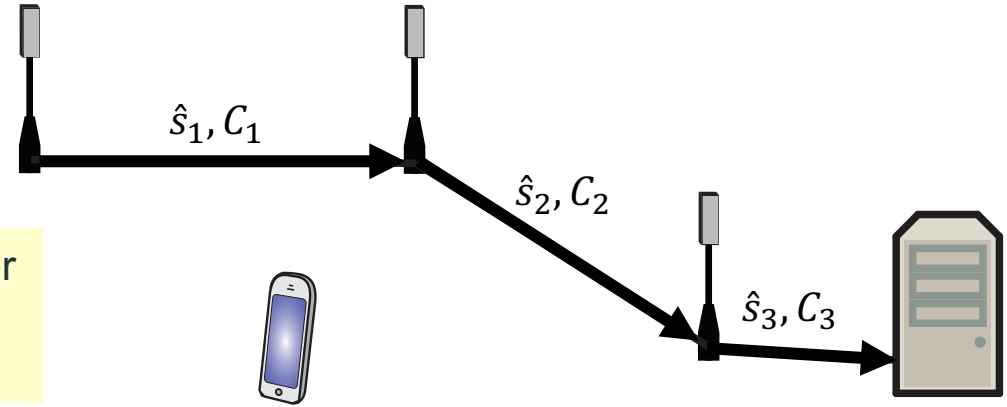


Can we design the processing to circumvent this issue?

Sequential Uplink Processing: Kalman Approach



Sequential linear MMSE: Same as centralized MMSE implementation



Delays?

Small for large data blocks

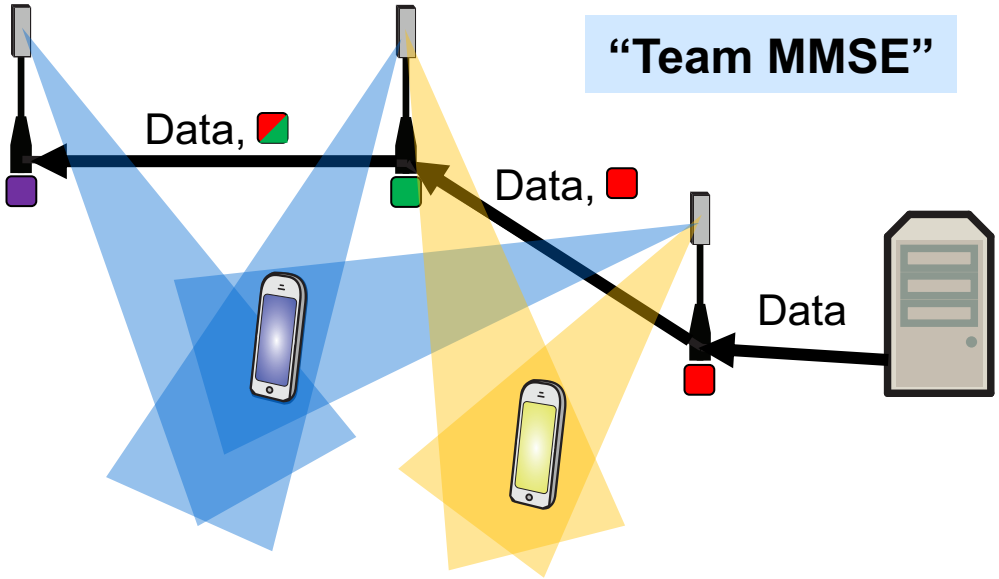
Fronthaul capacity per cable does not grow with number of APs

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

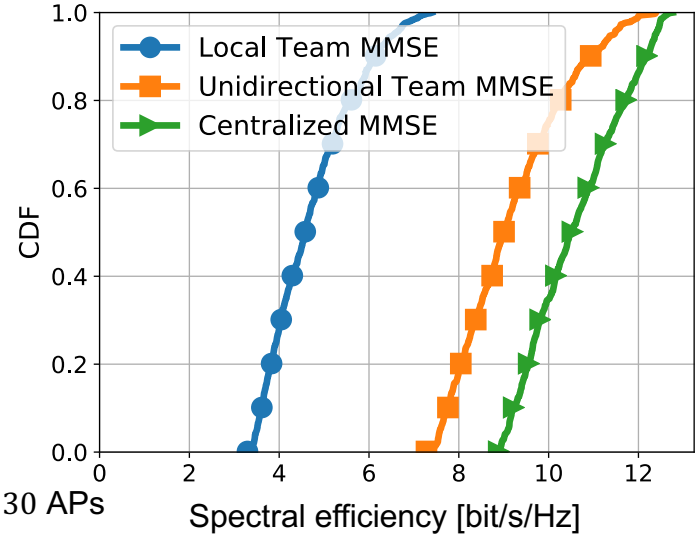
Sequential Downlink Processing: Team-Decision Approach

Local channel state information (CSI)

Unidirectional CSI sharing:



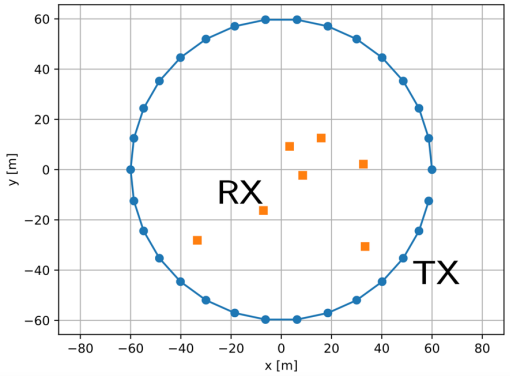
"Team MMSE"



$L = 30$ APs

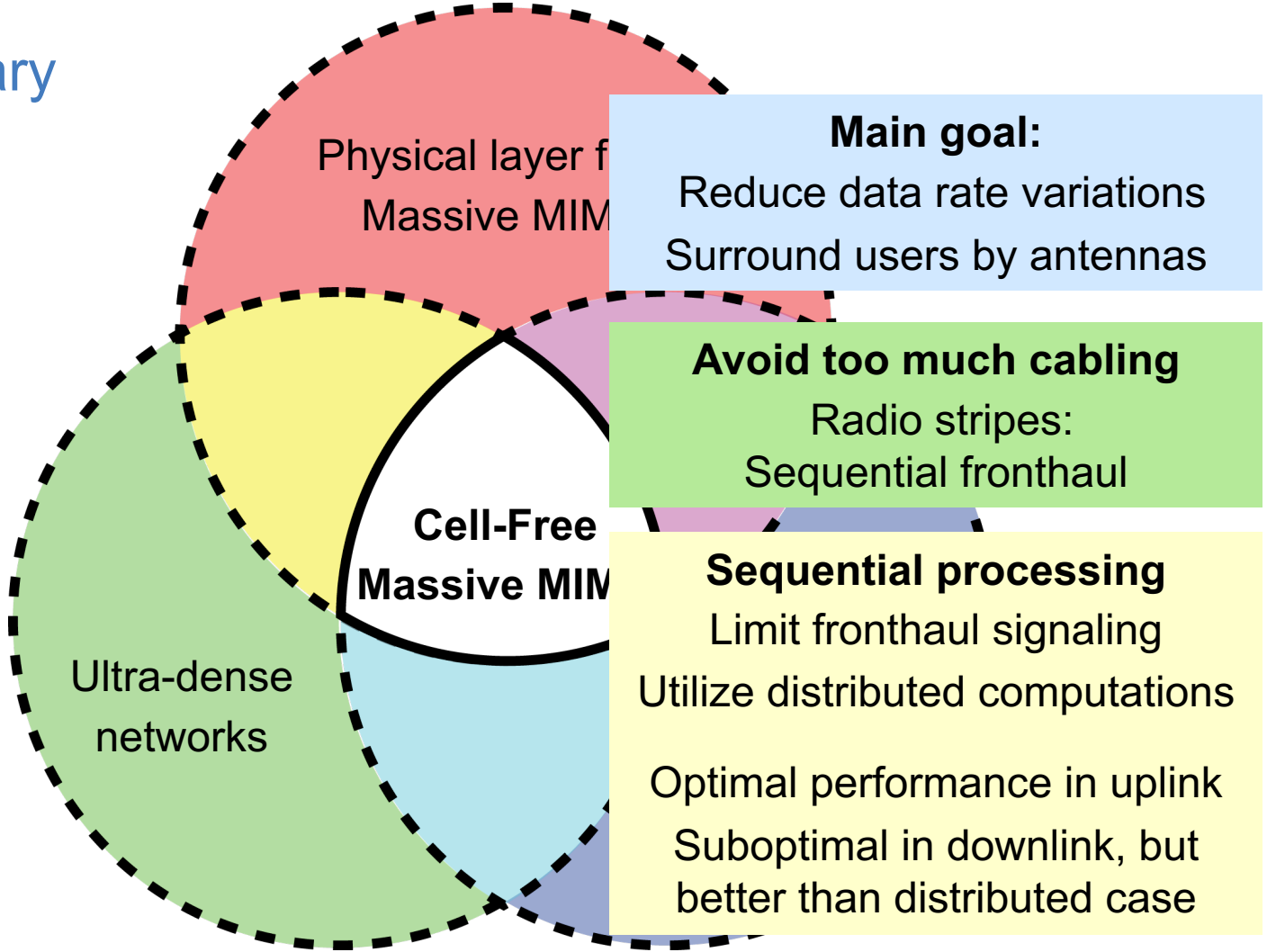
$N = 2$ antennas

$K = 7$ users



Reference: 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

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

I would like to thank my collaborators, many of them mentioned above

QUESTIONS?

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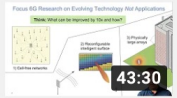
2. 

Evolving Mobile Broadband Connectivity Towards 6G
Wireless Future

3. 

Towards 6G: Massive MIMO is a Reality—What is Next?
Wireless Future

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Reinventing the Wireless Network Architecture Towards 6G: Cell-free Massive MIMO and Radio Stripes
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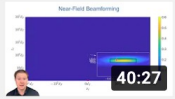
5. 

Physically Large Antenna Arrays: When the Near-Field Becomes Far-Reaching
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