Beyond the Cellular Paradigm

Cell-Free Architectures with Radio Stripes

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Outline

1. Cellular communications
   - Properties and weaknesses

2. Beyond the cellular paradigm
   - Basics of cell-free networks
   - Ways to deal with interference
   - Implementation aspects: Radio stripes
   - Deployment examples

The Cellular Architecture was Proposed in the 1950s

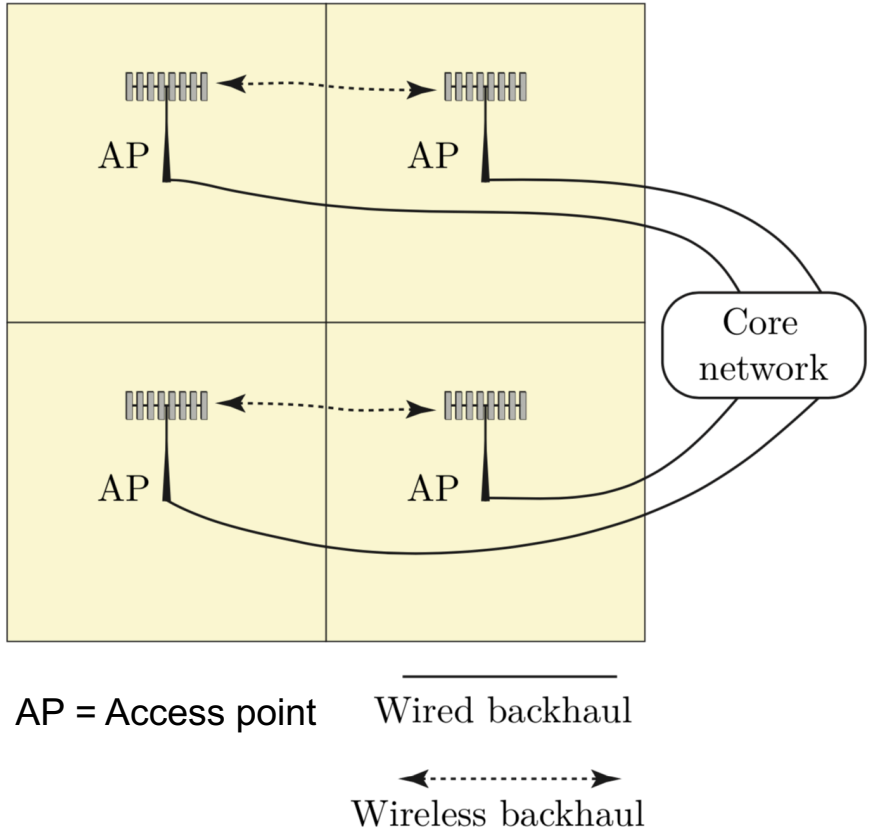
Designed for mobile telephone systems

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.

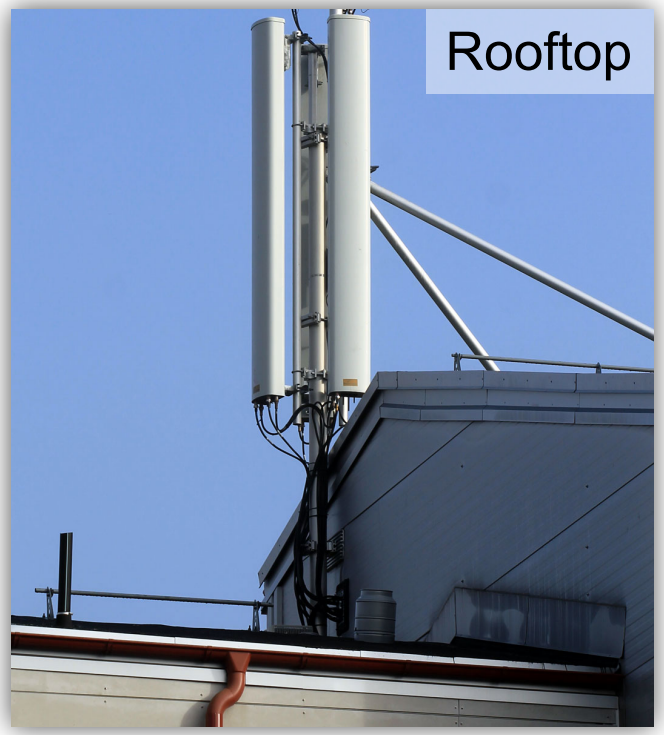
Reuse of spectrum in space: Densify as usage increases

Control interference by fractional spectrum reuse, reduce power



Sparse Deployment of Access Points

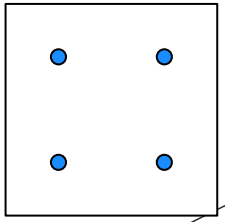
Visible installation

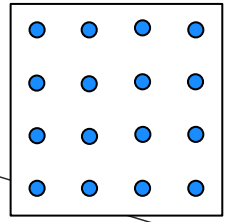


Sensitive to blocking

Large variation in distance to users → Large signal strength variations

Large Performance Variations Unavoidable





Most users get mediocre performance

Enough for voice calls, not for data!

Pathloss exponent: 3

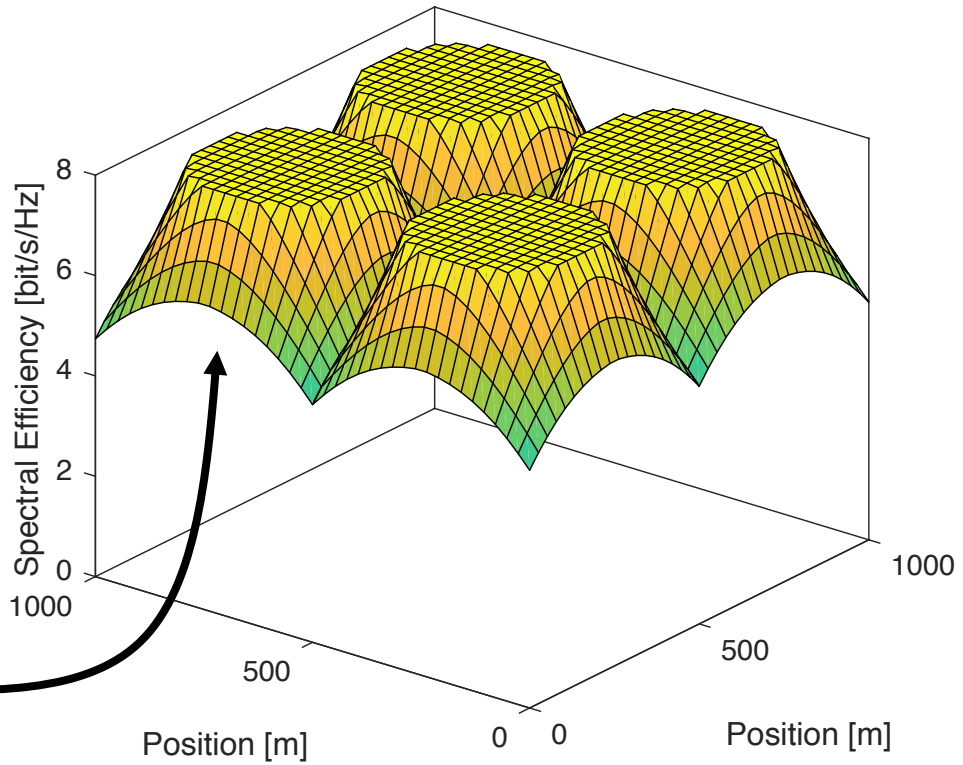
5-10 dB at cell edge

Wireless Dream: (Almost) Uniformly Good Service Quality

Users request same service everywhere

Easy to serve users in cell center

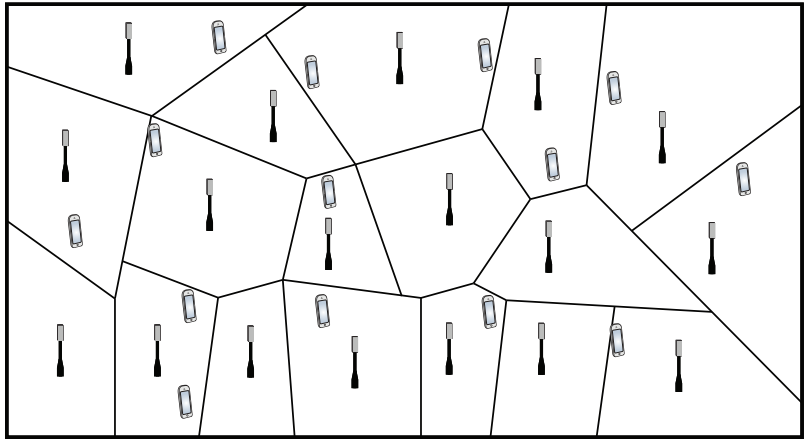
Most *active users* are at cell edge!



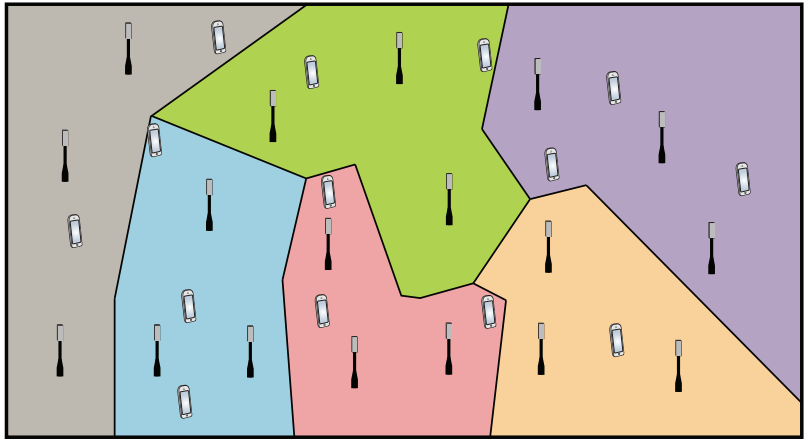
Can we deliver this somehow?

Coordinated Multipoint Transmission

A 4G attempt to solve the issue within the cellular paradigm



Conventional cellular network



Cellular with cooperation clusters

Not a successful solution

A lot of backhaul signaling

Hard to standardize

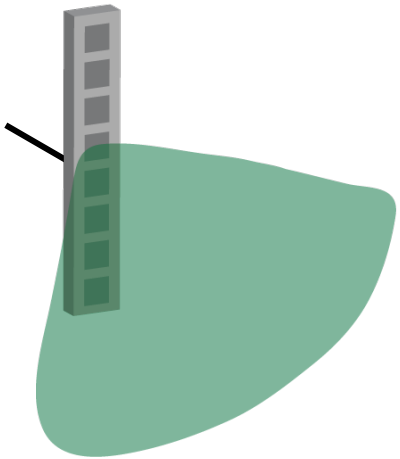
Coordinated scheduling

Coordinated spatial beamforming

Joint transmission

Massive MIMO: 5G Attempt to Improve Spectral Efficiency

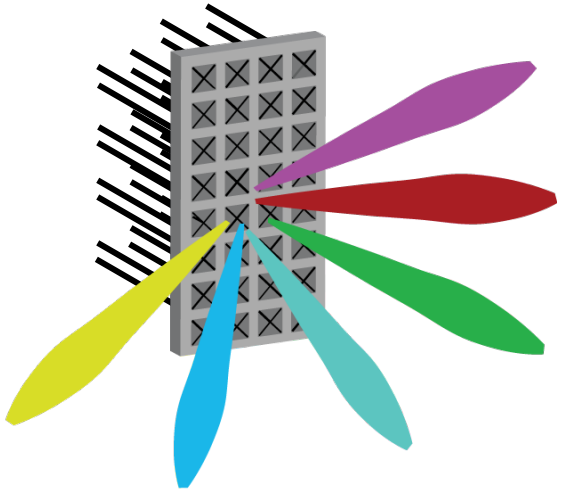
1 high-gain antenna



Classical antenna

Always the same directivity

64 low-gain antennas



“Massive MIMO”

Strong, adaptive directivity

Separate users in space

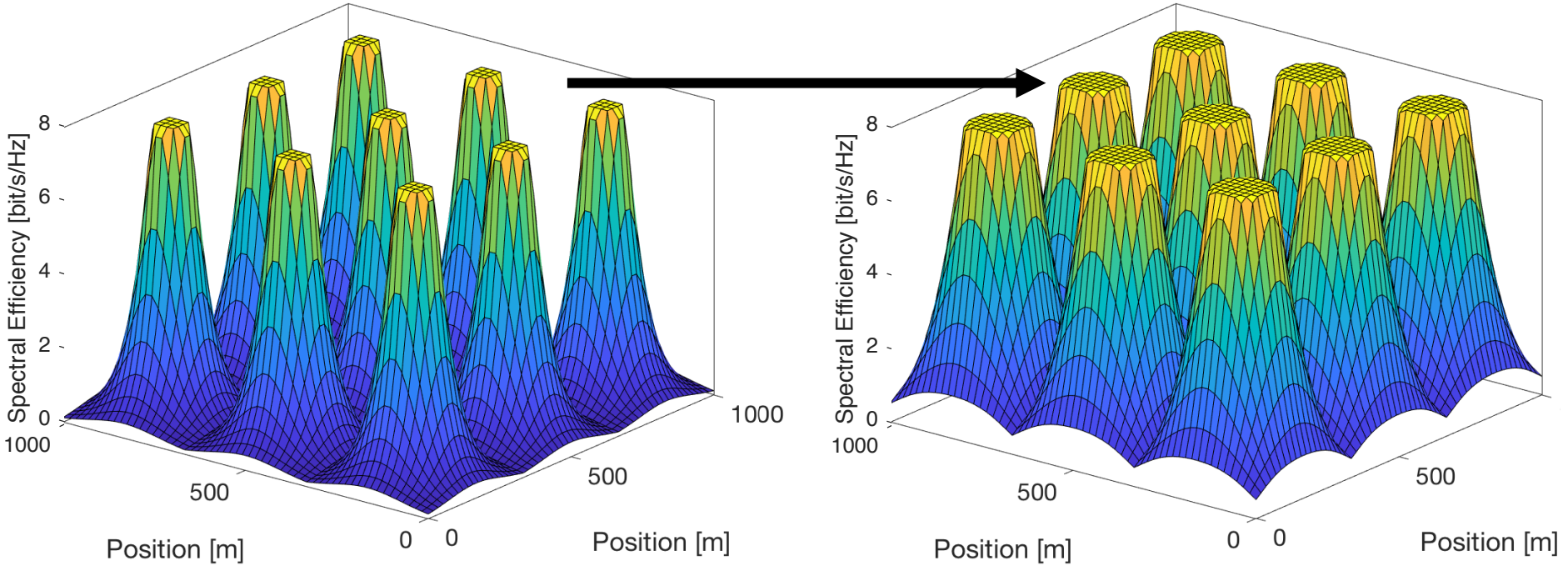
Reduce interference

Massive MIMO
(multiple-input multiple-output):

M antennas $\gg K$ users

Can 5G Deliver Uniformly Good Service Everywhere?

Handles more users and give stronger signals, but problems remain!

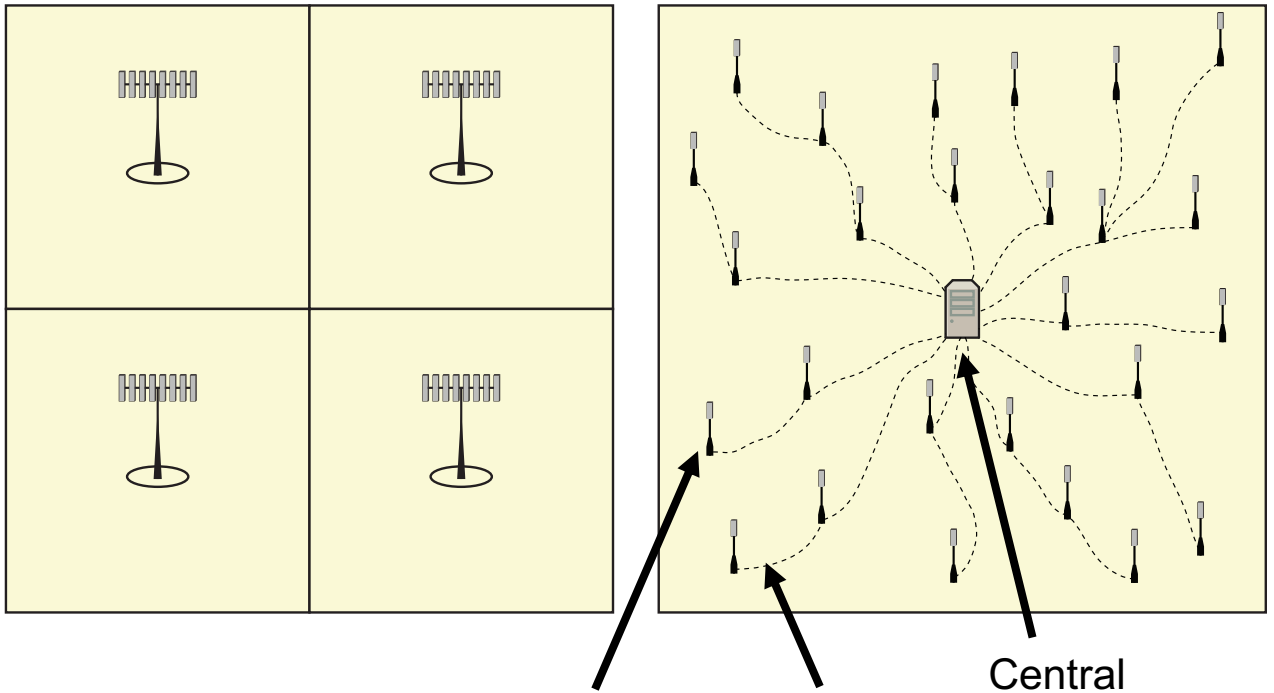


mmWave bands: Worse signal variations!

Moving Beyond the Cellular Paradigm

Cellular network

Cell-free network



Massive number of distributed antennas:

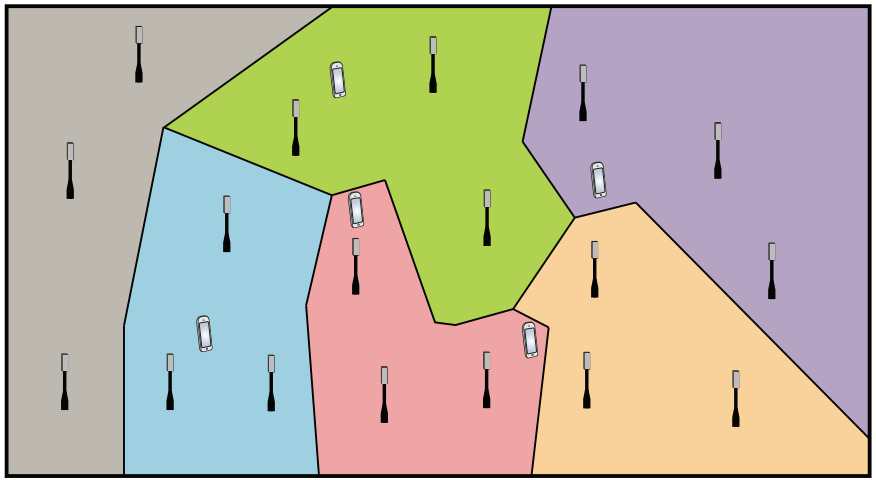
Short distance from user to some antennas

Connection to Massive MIMO:

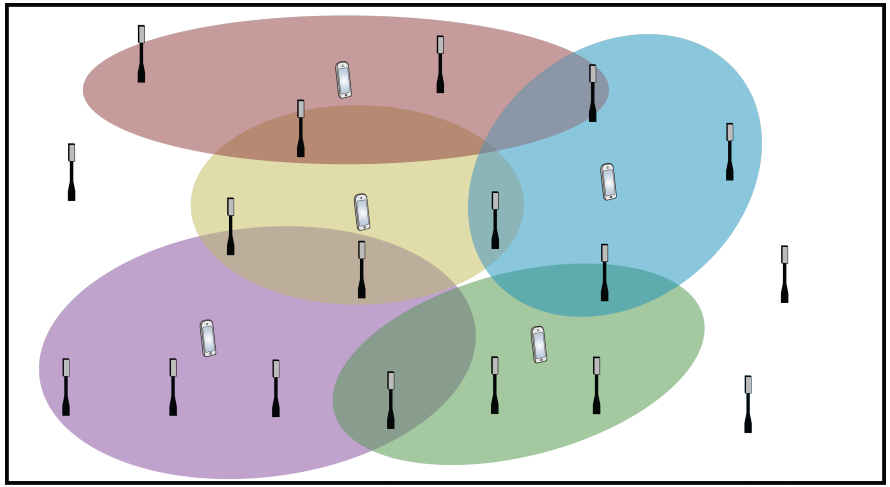
$M \gg K$

M antennas, K users

Difference from 4G Coordinated Multipoint



Cellular: Coordinated multipoint



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

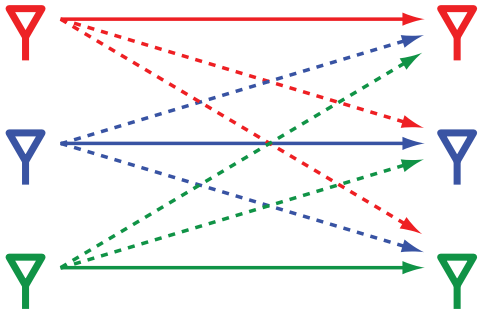
Network-centric design

User-centric design

Uplink: Philosophy of Interference Rejection

Cellular network:

3 desired signals:
One per transmitter

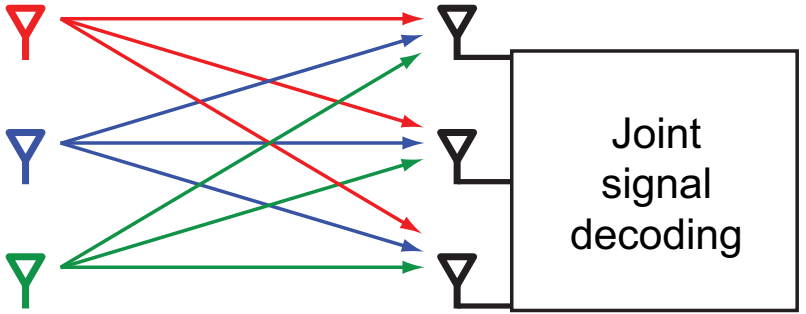


Each receiver:
1 observation
1 desired signal
2 interfering ones

Too few observations to reject interference

Cell-free network:

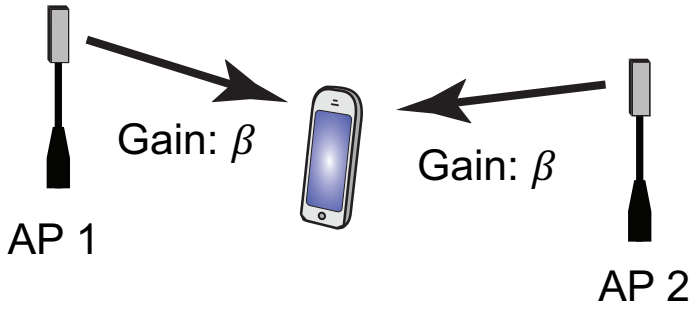
3 desired signals:
One per transmitter



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: $P\beta$

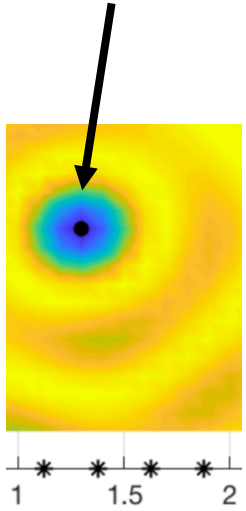
2. **Transmit from both APs:** $P/2$ from each AP
   - Received power: $\left(\sqrt{\frac{P}{2}} \cdot \sqrt{\beta} + \sqrt{\frac{P}{2}} \cdot \sqrt{\beta}\right)^2 = 2 \cdot P\beta$

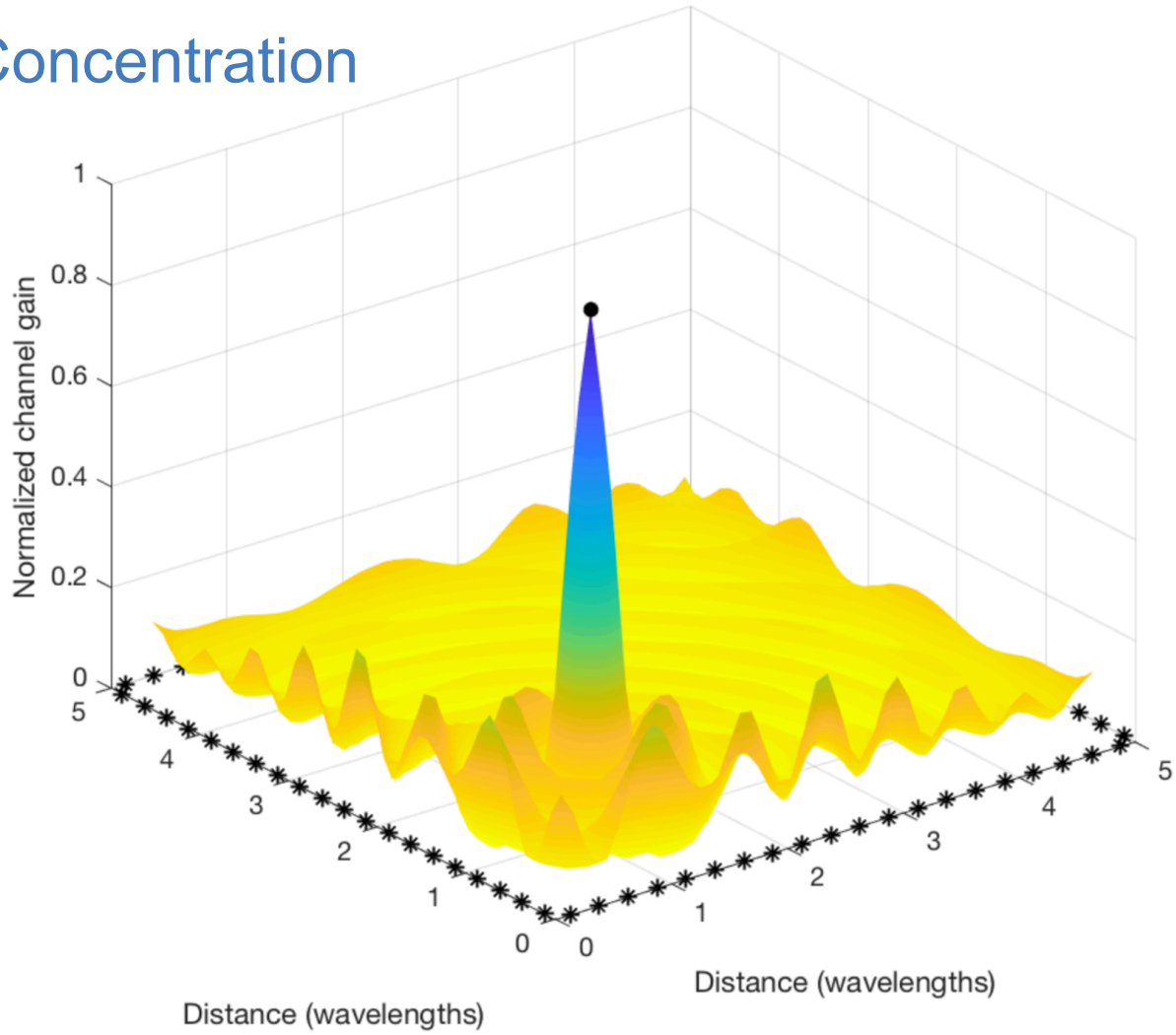
Coherent combination!

Downlink Power Concentration

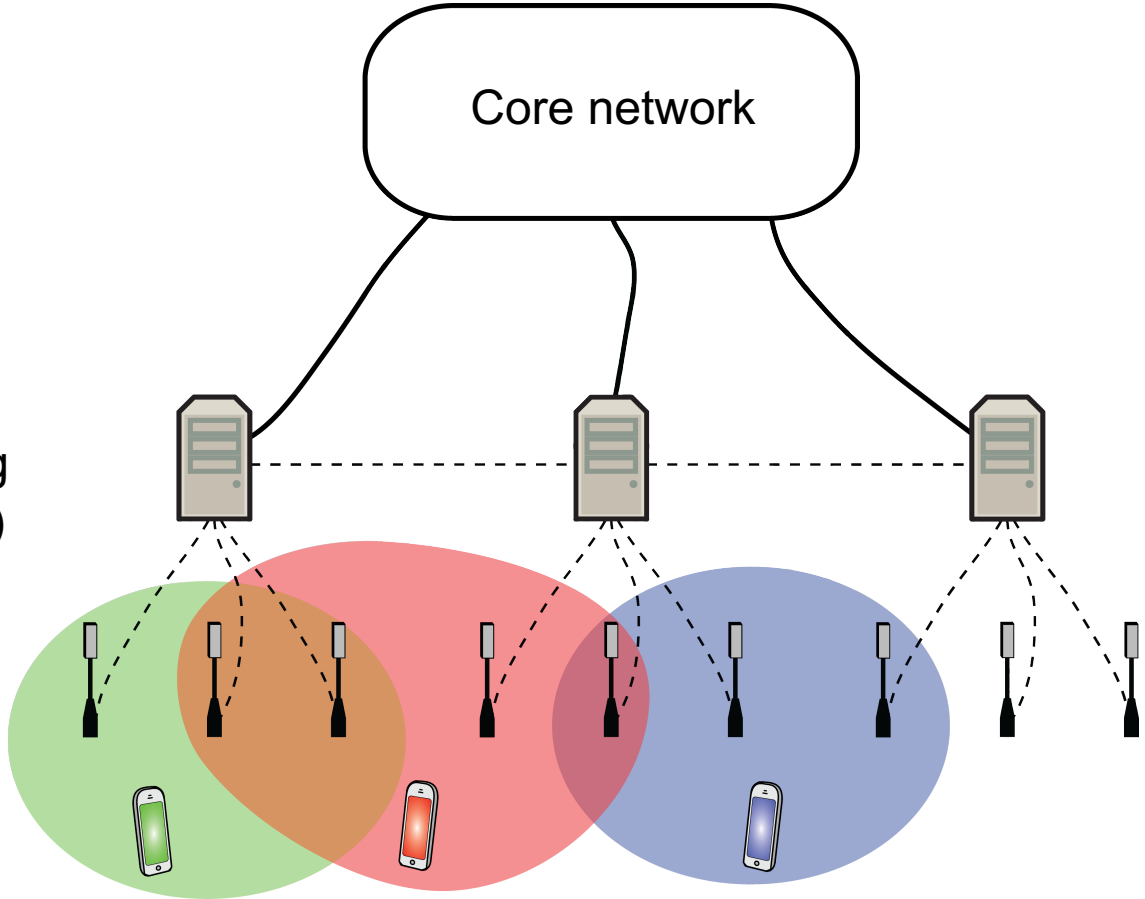
Strong signal:

Ball with diameter $\lambda/2$





Signal Processing: Centralized versus Distributed



Processing tasks

Channel estimation

Precoding/combining

Data en-/de-coding

Centralized version

Every done at a CPU

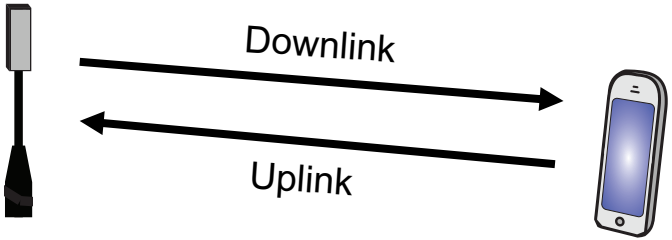
Distributed version

Most processing at AP, fusing of signals at a CPU

Efficient Channel Estimation – No Feedback is Needed!

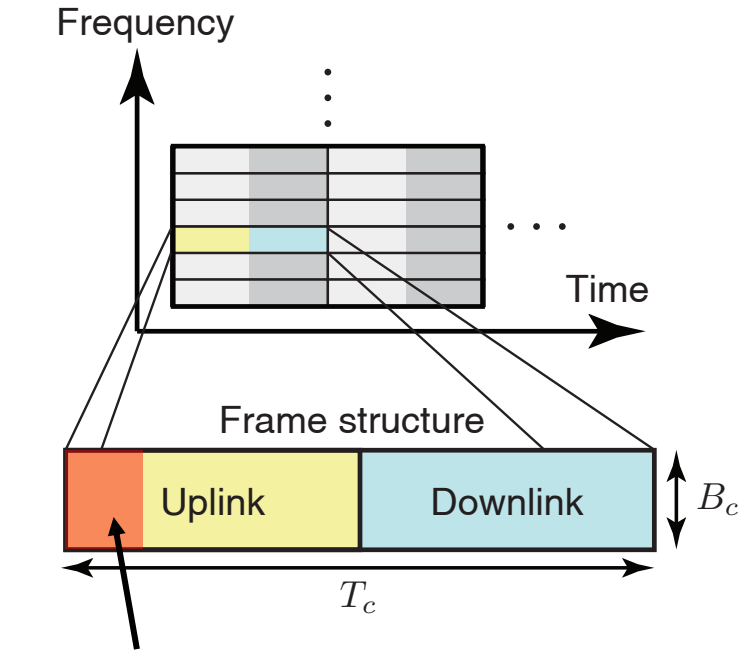
Time-division duplex

Downlink and uplink on same frequency



Estimate channels at AP from uplink pilots

No need to share between APs

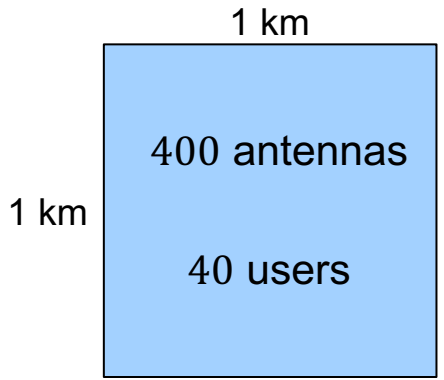


Pilots signals

The rest is used for data

Simulation Setup

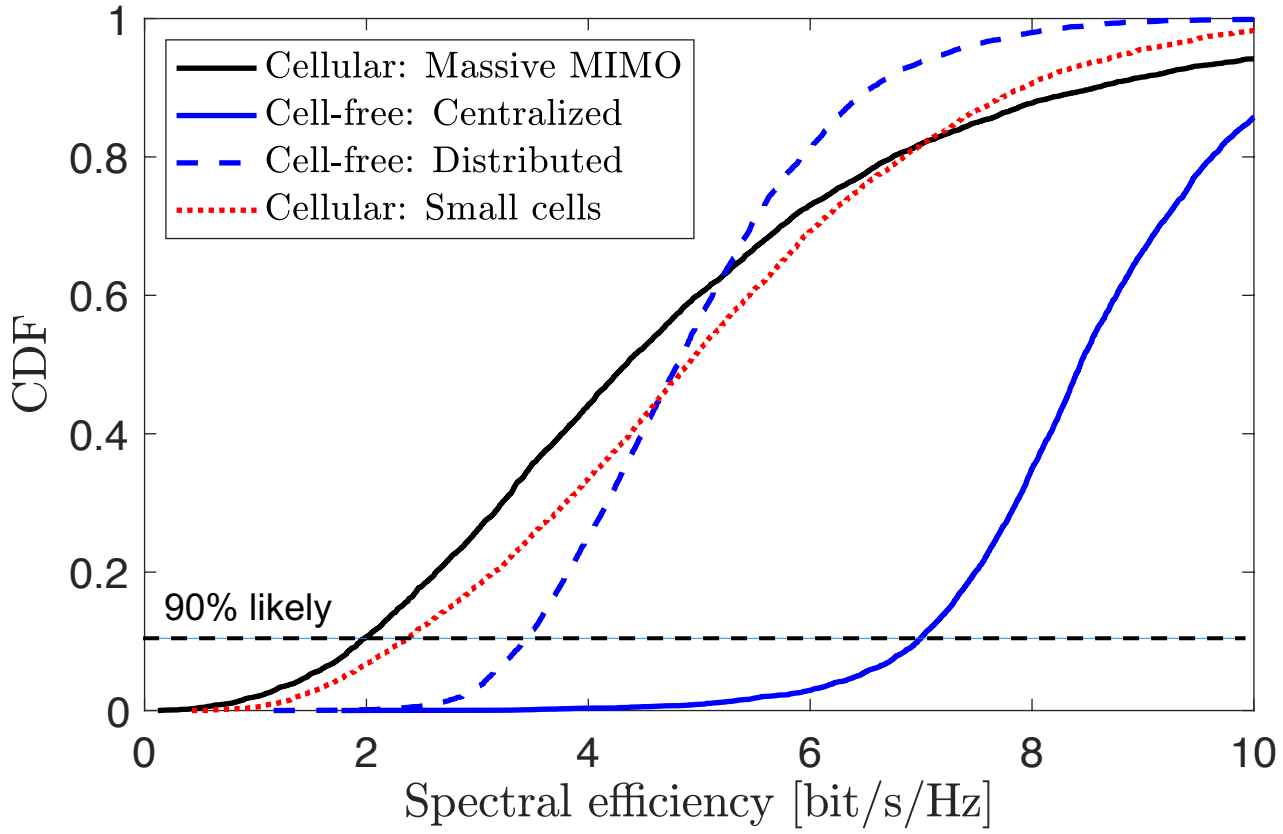
- **Cell-free setups**
  - 400 APs on a square grid
  - Centralized or distributed processing
- **Cellular setups**
  - Massive MIMO: 4 APs, 100 antennas each
  - Small cells: Same AP locations in cell-free case



3GPP Urban Microcell model
Uplink, 20 MHz, 100 mW power

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

Uplink Simulation Results

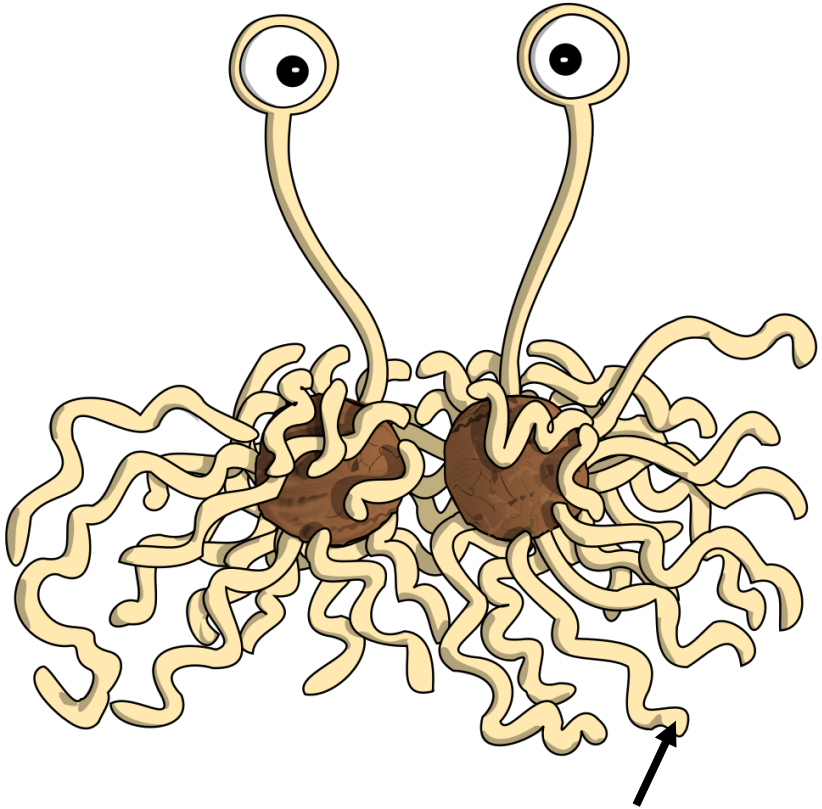


Cell-free
Improves 90% likely performance

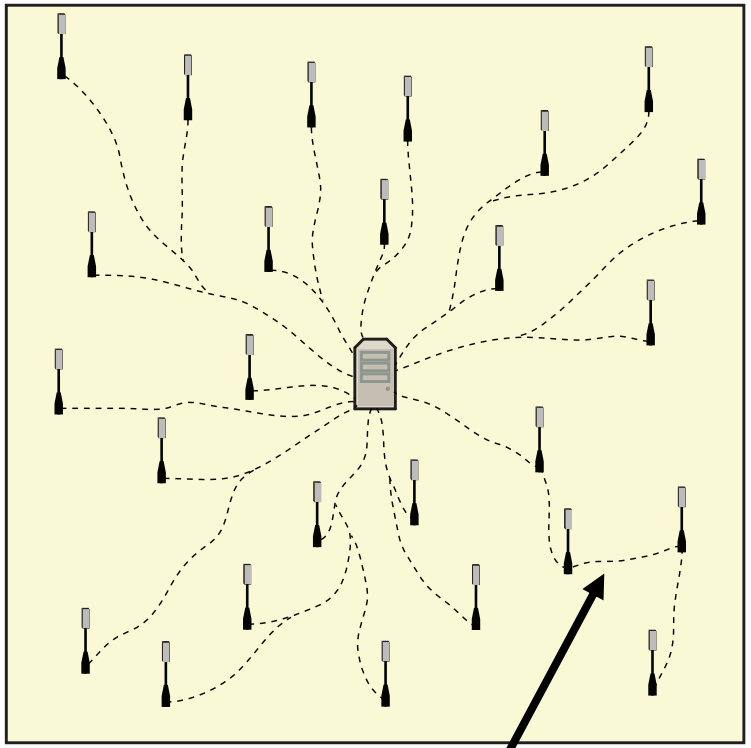
Centralized version
Best performance

Distributed version
Increases worst-case performance

Practical Convenience: Avoid Creating a Spaghetti Monster

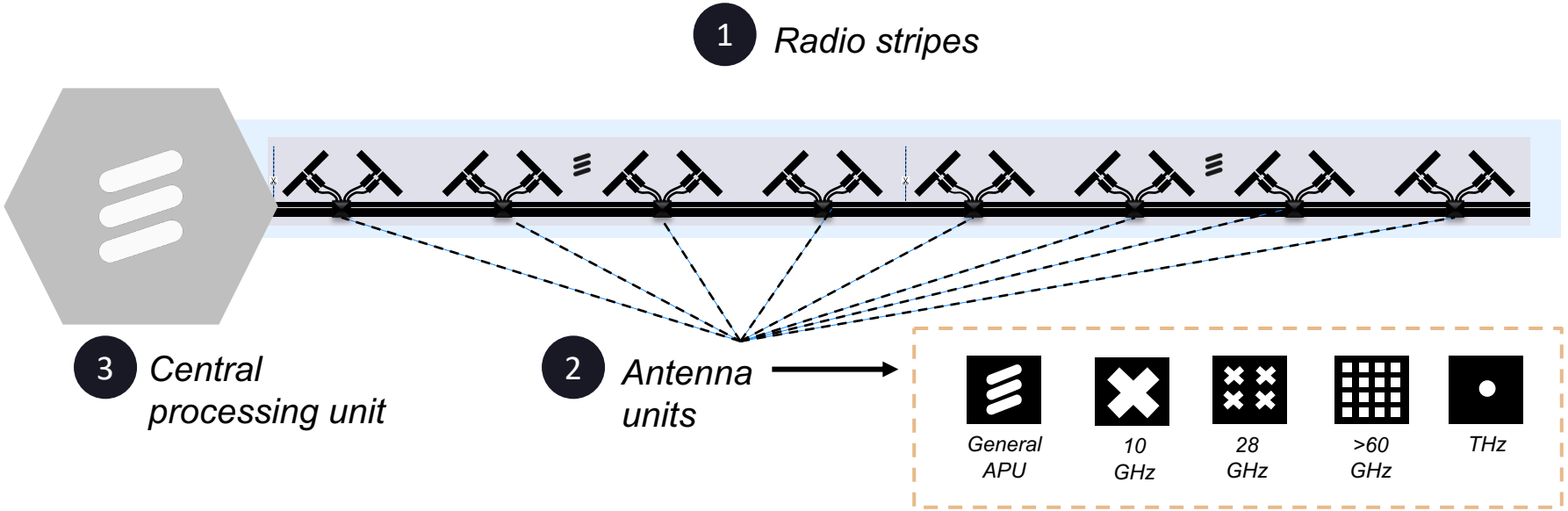


Dedicated fronthaul



Alternative: Serial fronthaul

Implementation Architecture: Radio Stripes



Can create as long stripes as we need

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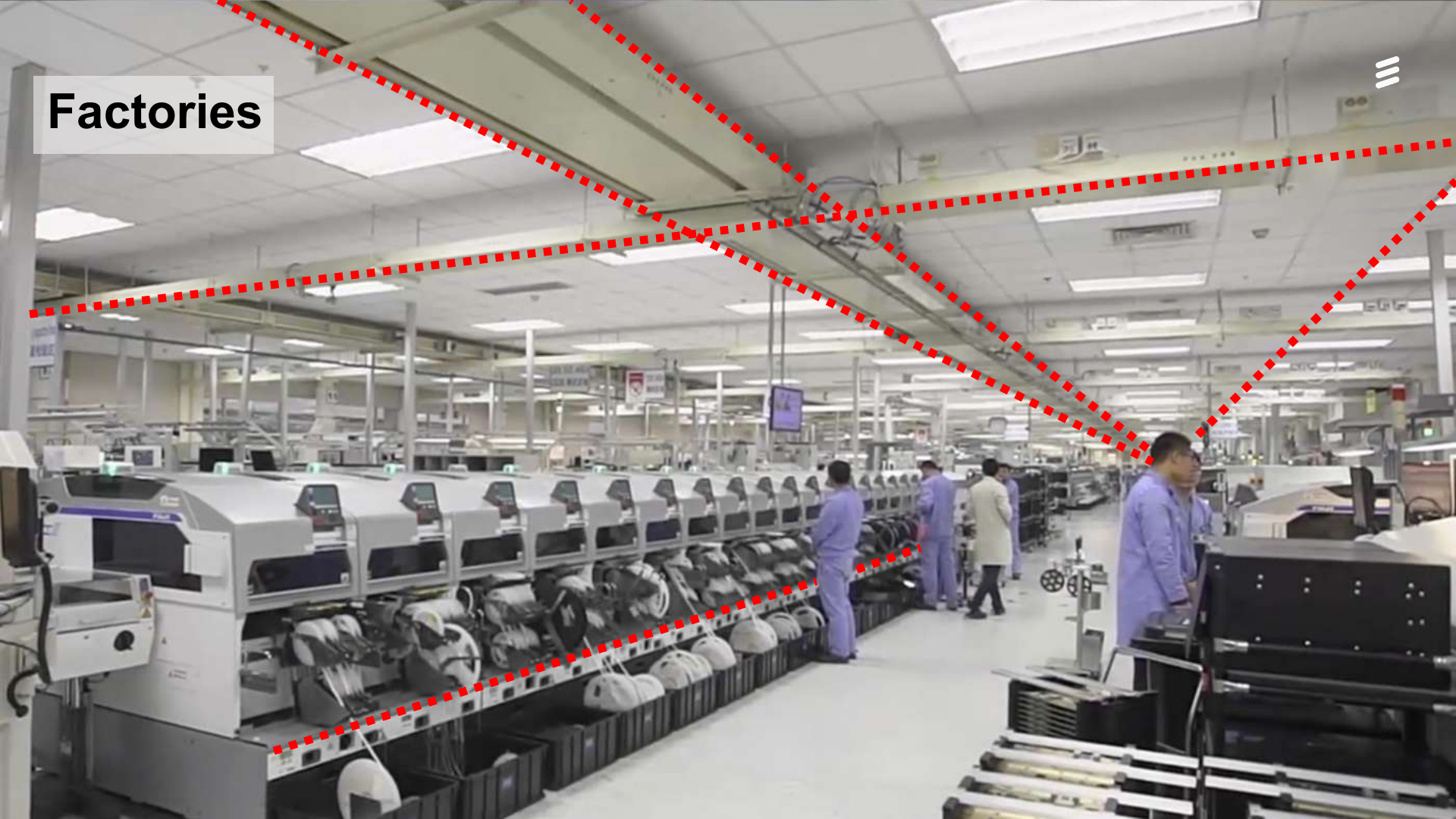
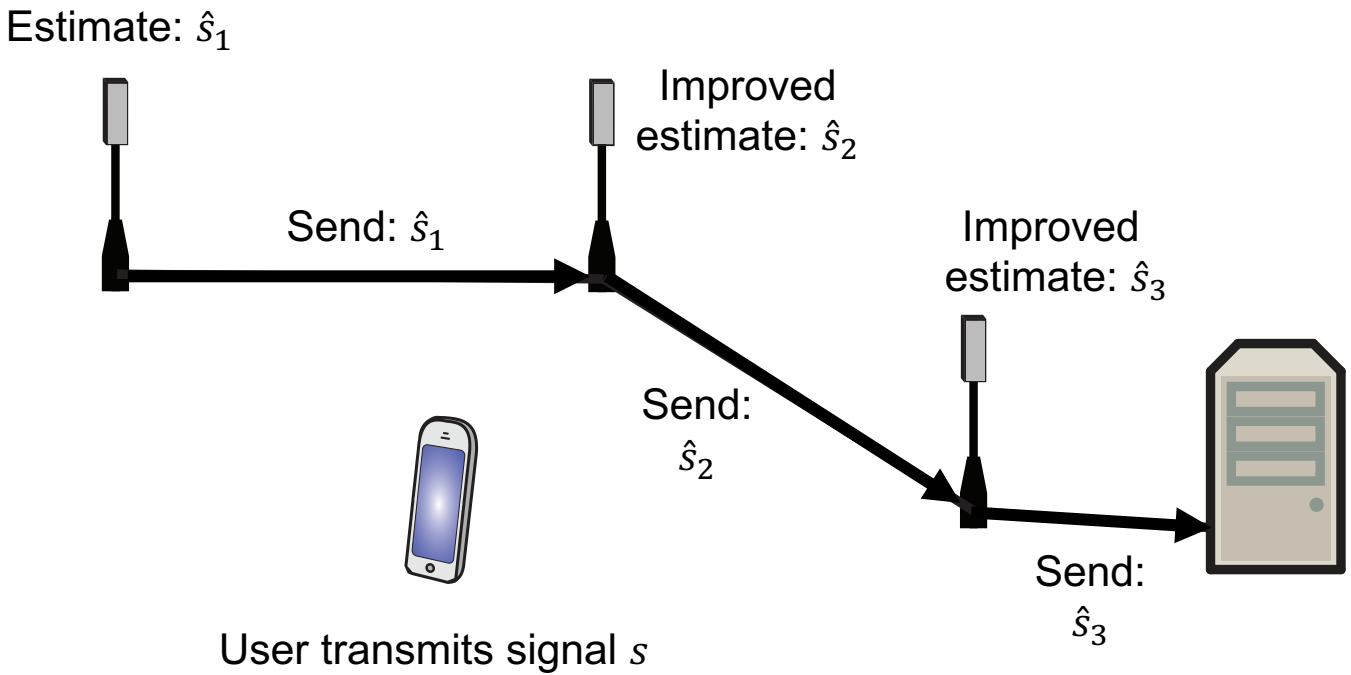
Cultural places

Factories




Stadium

Making Use of Serial Fronthaul: Sequential Processing



Fewer cables

Fronthaul capacity per cable does not grow with number of APs

Reference: Z. H. Shaik, E. Björnson, E. G. Larsson, "Cell-Free Massive MIMO With Radio Stripes and Sequential Uplink Processing," IEEE ICC 2020.

Radio Stripe: Implementation Details

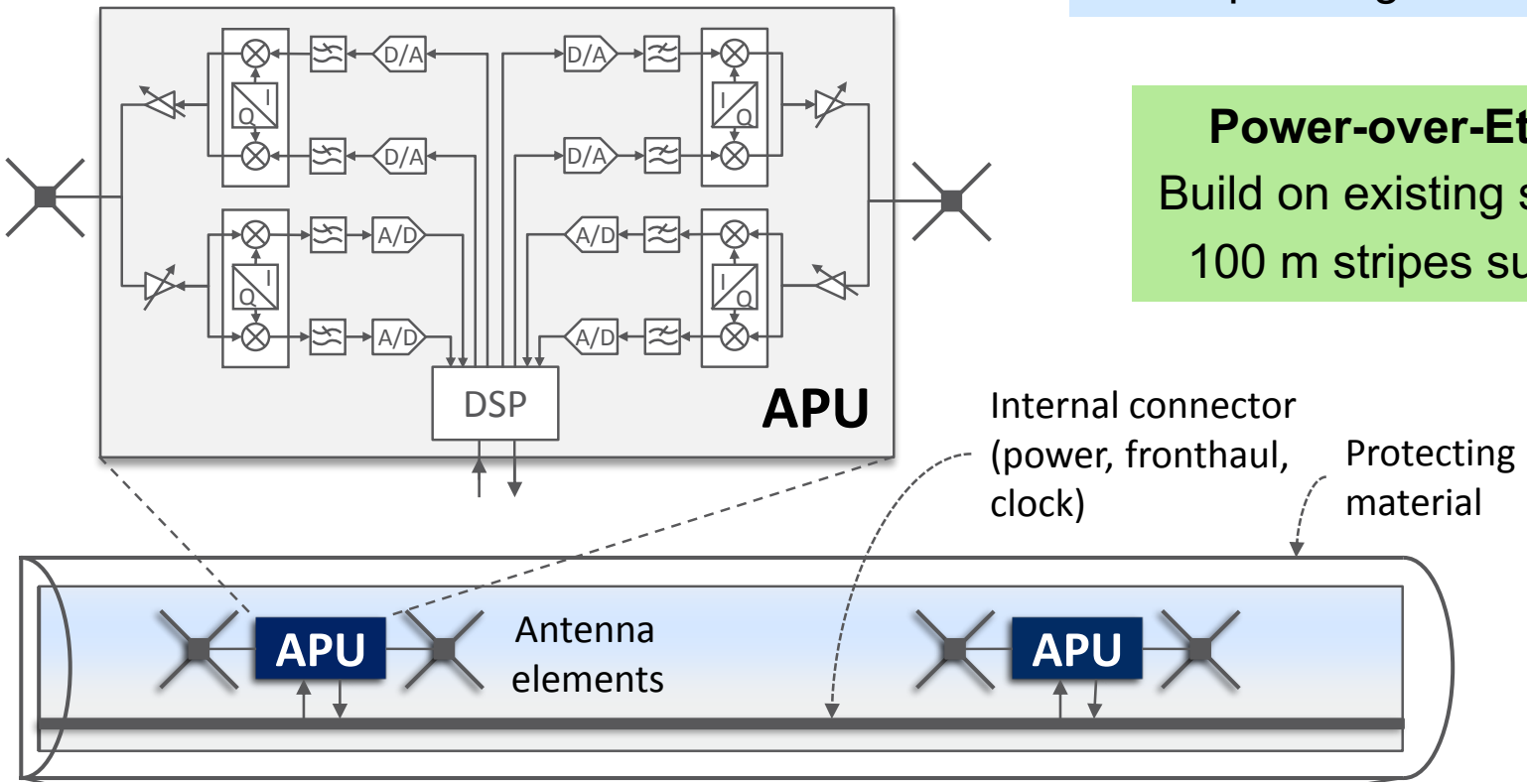
Low power

Cell-phone grade components

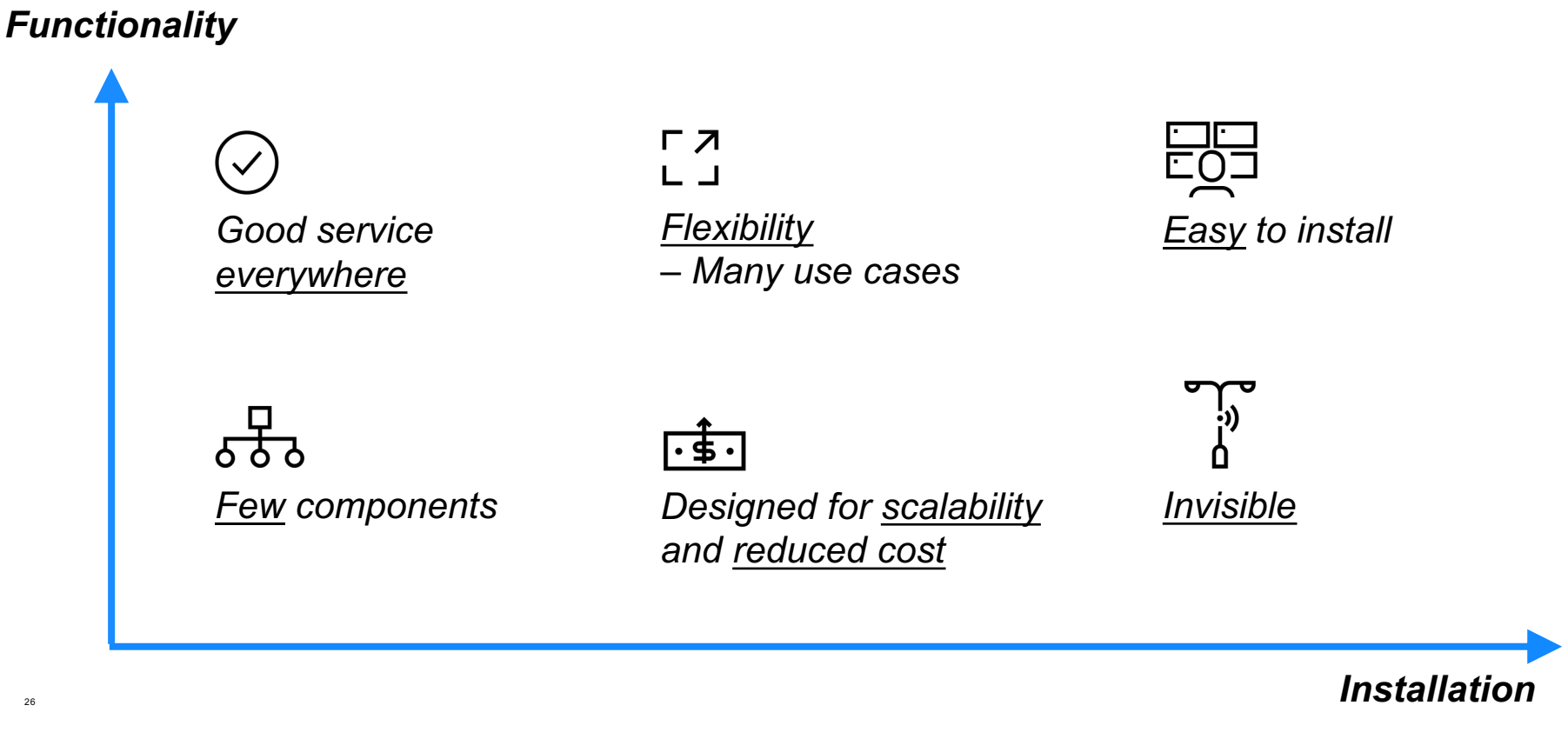
Power-over-Ethernet

Build on existing standards

100 m stripes supported



Summary:
Many Benefits of Cell-free Architecture and Radio Stripes



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 Journal on Wireless Communications and Networking, 2019.
3. E. Björnson, L. Sanguinetti, “Making Cell-Free Massive MIMO Competitive With MMSE Processing and Centralized Implementation,” IEEE Trans. Wireless Commun., 2020.
4. Z. H. Shaik, E. Björnson, E. G. Larsson, “Cell-Free Massive MIMO With Radio Stripes and Sequential Uplink Processing,” IEEE ICC 2020.

Acknowledgements

I would like to thank my collaborators listed above, many working at:

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