On the Energy Efficiency, Spectral Efficiency and Coverage of Cell-Free Massive MIMO

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Outline

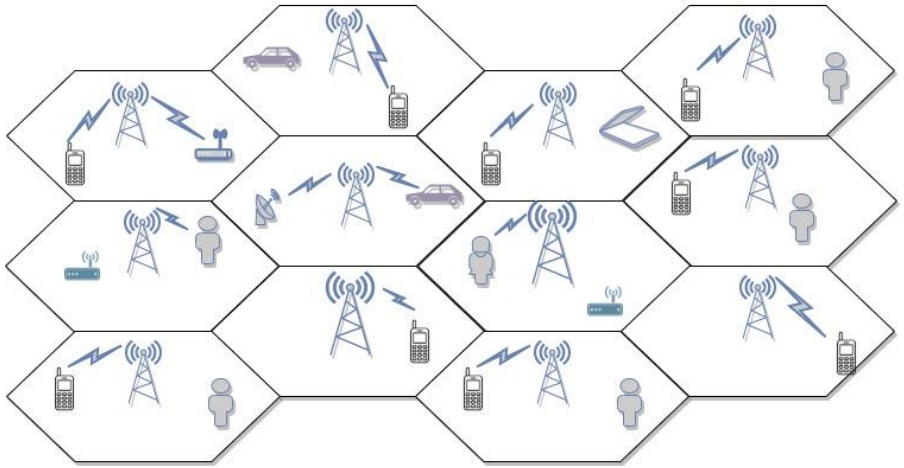
- **Why cell-free massive MIMO?**
- **What is cell-free massive MIMO?**
- **Main research results on cell-free massive MIMO**

The work mainly originates from:

"**Analysis and Design for Cell-Free Massive MIMO**", UKRI Future Leaders Fellowships grant, MR/S017666/1 (Duration 2019-2023, Value: £676K)

Why Cell-Free Massive MIMO?

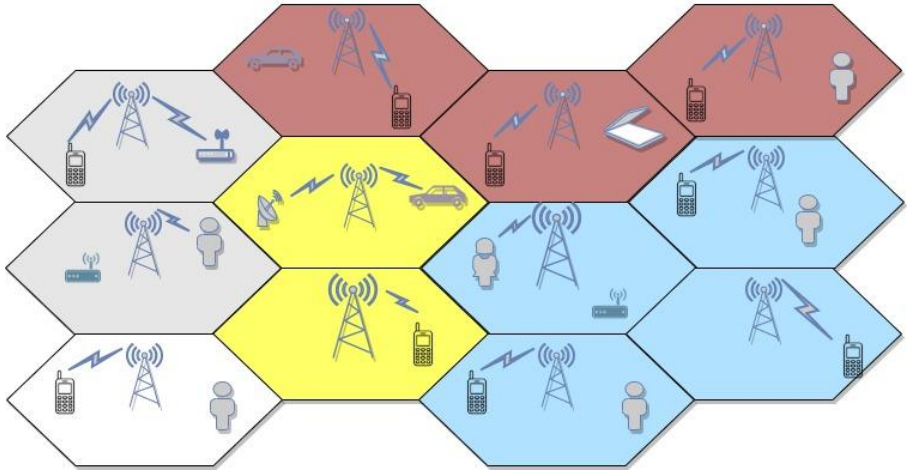
Conventional cellular networks



- First trial: 1970s
- Main drawbacks:
  - **Boundary effect**
  - Path loss

⇒ users at cell boundary perform poorly

Network MIMO, DAS, CoMP-JT



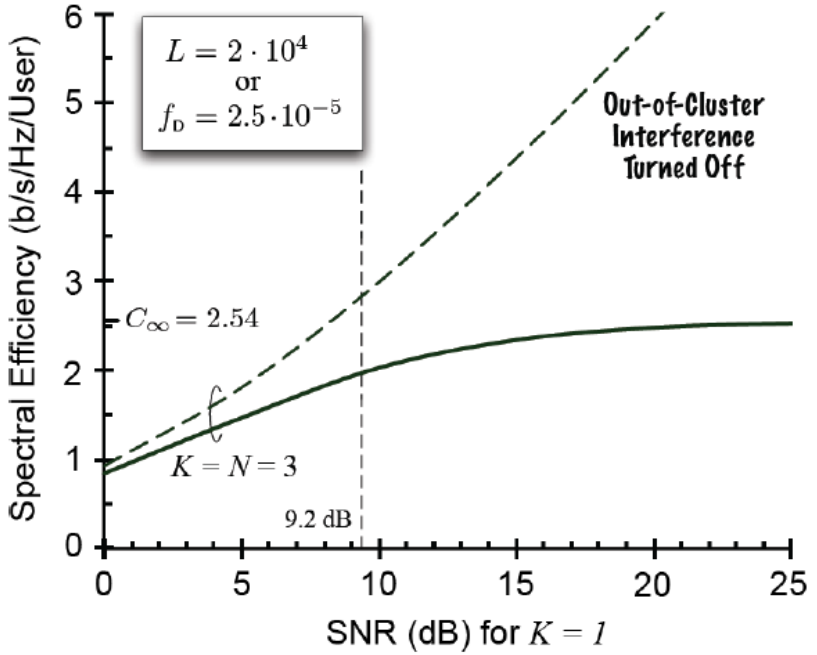
- First concept: 2000s
- Main drawbacks:
  - Huge backhaul signaling for CSI and data sharing
  - High computational complexity (non-linear processing, small-scale-based resource allocations)
  - **Simply shift from the cells to the clusters**

⇒ 3GPP LTE of CoMP-JT, but provides small practical gains

Why Cell-Free Massive MIMO?

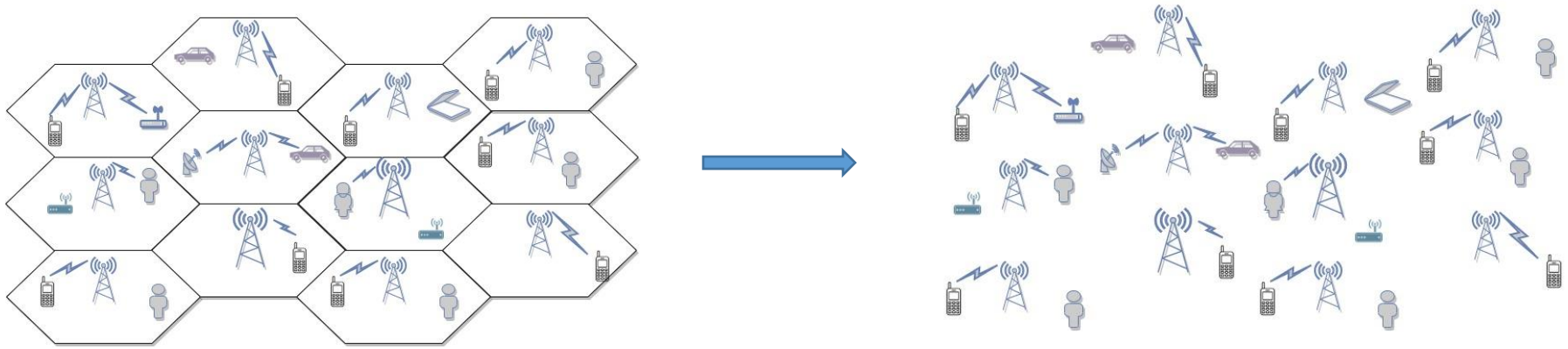
- A. Lozano, R. W. Heath, and J. G. Andrews, "*Fundamental limits of cooperation*," IEEE TIT, 2013.

Cellular networks: **"cooperation has fundamental limitations that cannot be overcome through faster backhaul, more sophisticated signal processing, or any other technological advance."**



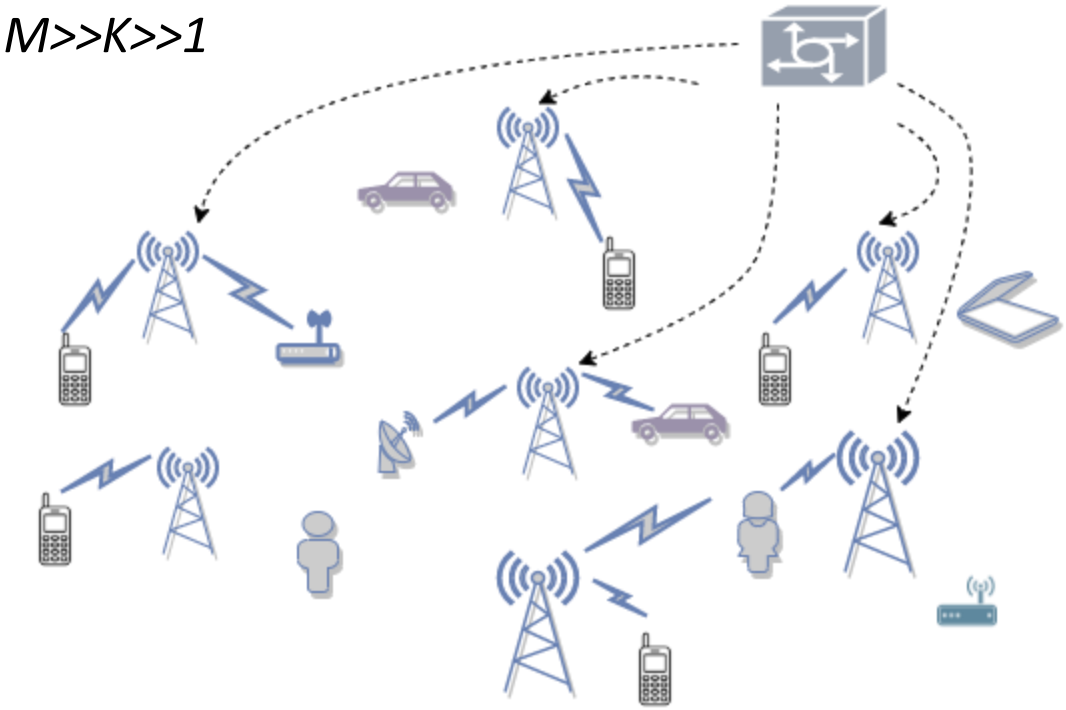
- **H. Q. Ngo**, A. Ashikhmin, H. Yang, E. G. Larsson, and T. L. Marzetta, "*Cell-free Massive MIMO versus small cells*," IEEE TCOM, 2017.

⇒ **Cell-free massive MIMO: everything and everywhere get connected**



What is Cell-Free Massive MIMO?

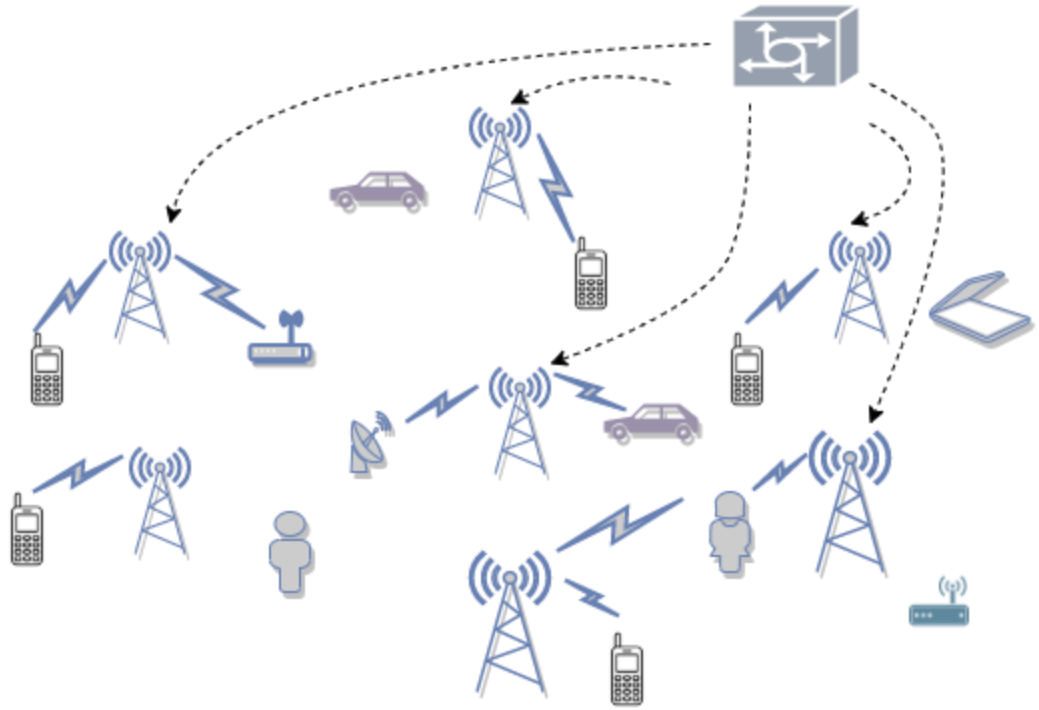
- **Network MIMO + massive MIMO**
  - *M* access points, *K* users randomly located in a wide area, *M>>K>>1*
  - Coherently send all signals to all users
  - **There are no cells or cell boundaries**



- **Benefits: network MIMO + massive MIMO**
  - Multiplexing gain & array gain

    ⇒ huge spectral efficiency & energy efficiency
  - Simplicity: linear processing
  - High coverage probability (macro diversity): **uniformly good quality-of-service**

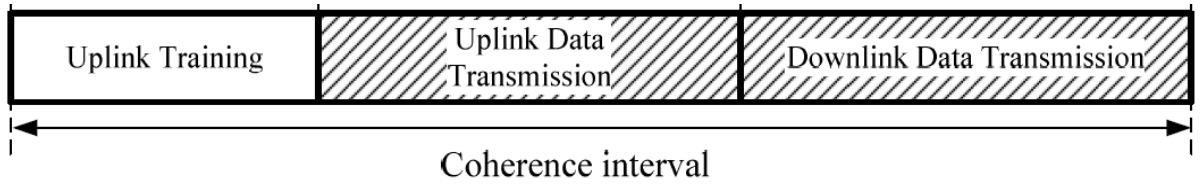
Research Aims



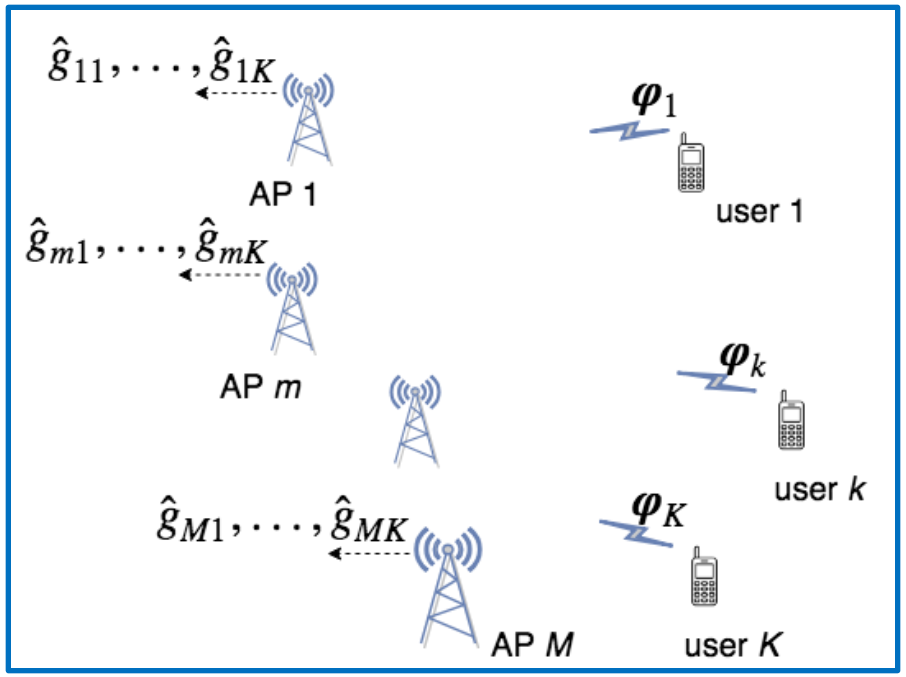
Propose and develop **a complete, useful, and practical cell-free massive MIMO system:** signal processing schemes, channel estimation, pilot assignment schemes, power controls, and AP selection schemes.

(1) TDD Cell-Free Massive MIMO with Distributed Processing

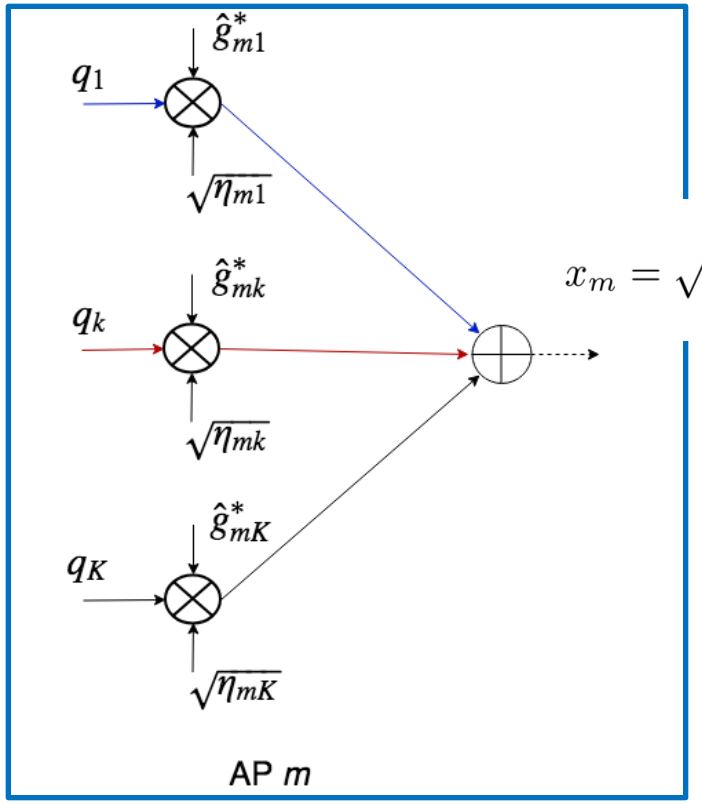
Propose a simple cell-free massive design: TDD operation, distributed conjugate beamforming, and max-min power control



Uplink training

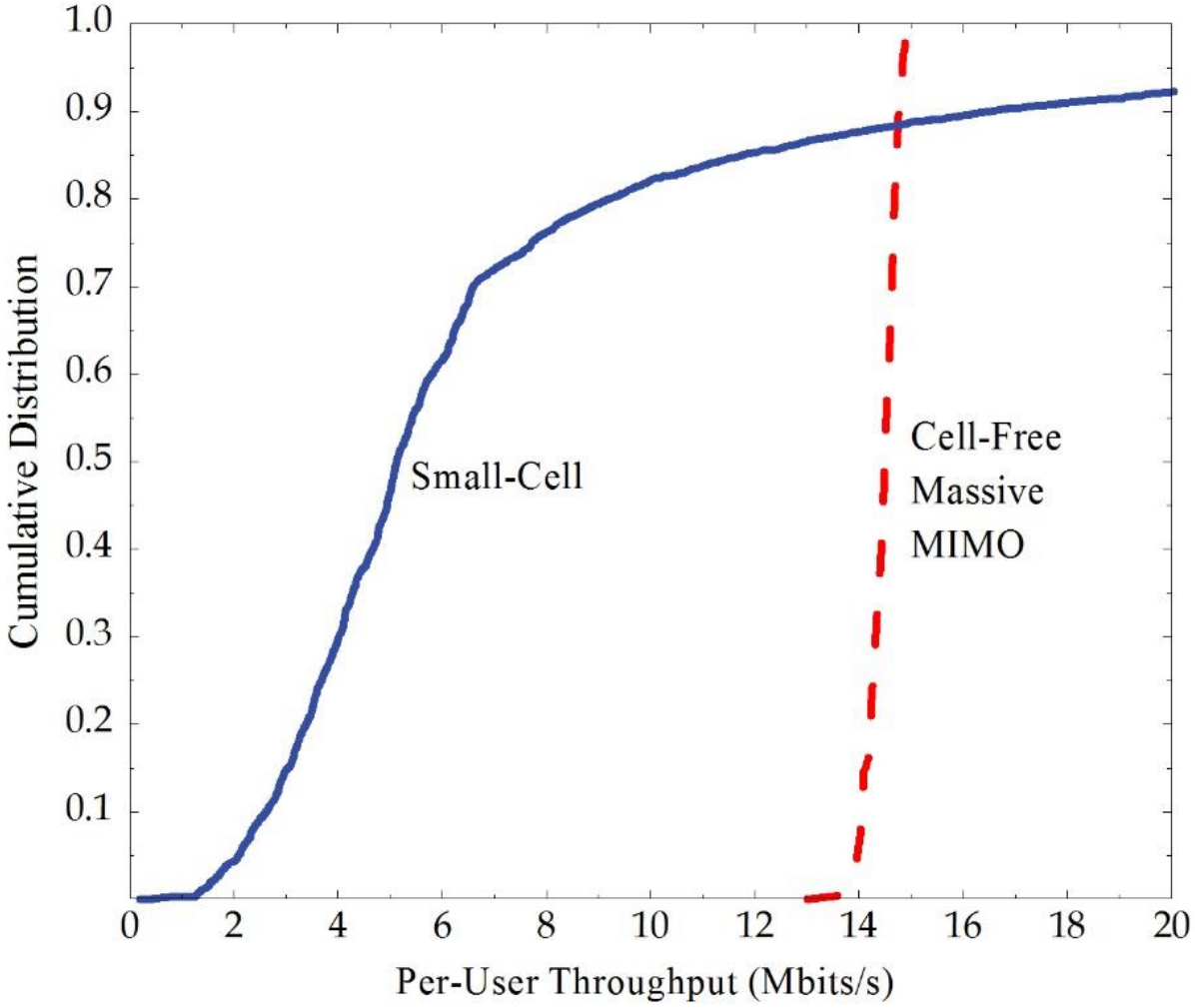


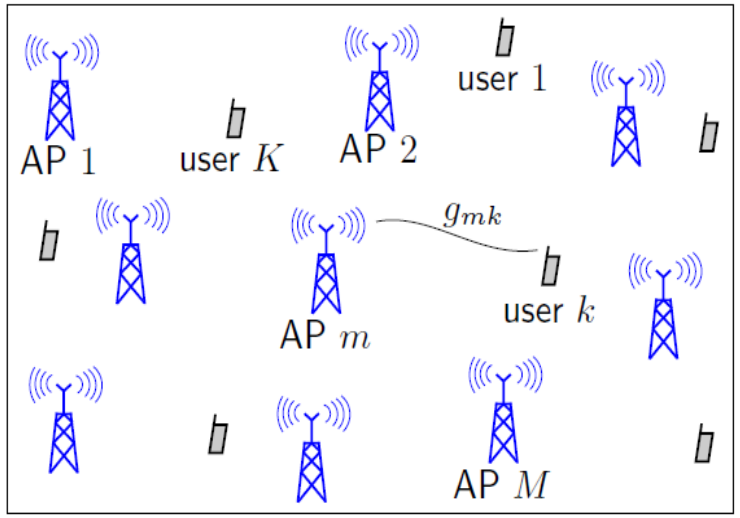
Downlink data with conjugate beamforming



$$x_m = \sqrt{\rho_{\mathrm{d}}} \sum_{k=1}^{K} \sqrt{\eta_{mk}} \hat{g}_{mk}^* q_k$$

Cell-Free Massive MIMO Vs. Small-Cell





Scenario	100 APs, 40 users, 1x1 km², max-min power control, random pilot assignment
Bandwidth, CF	20 MHz, 1.9 GHz
Radiated power	200 mW
Slot duration	1 ms (75 km/h mobility)
Shadowing, pathloss exponent	8 dB, 3.8

(2) Energy Efficiency Maximisation

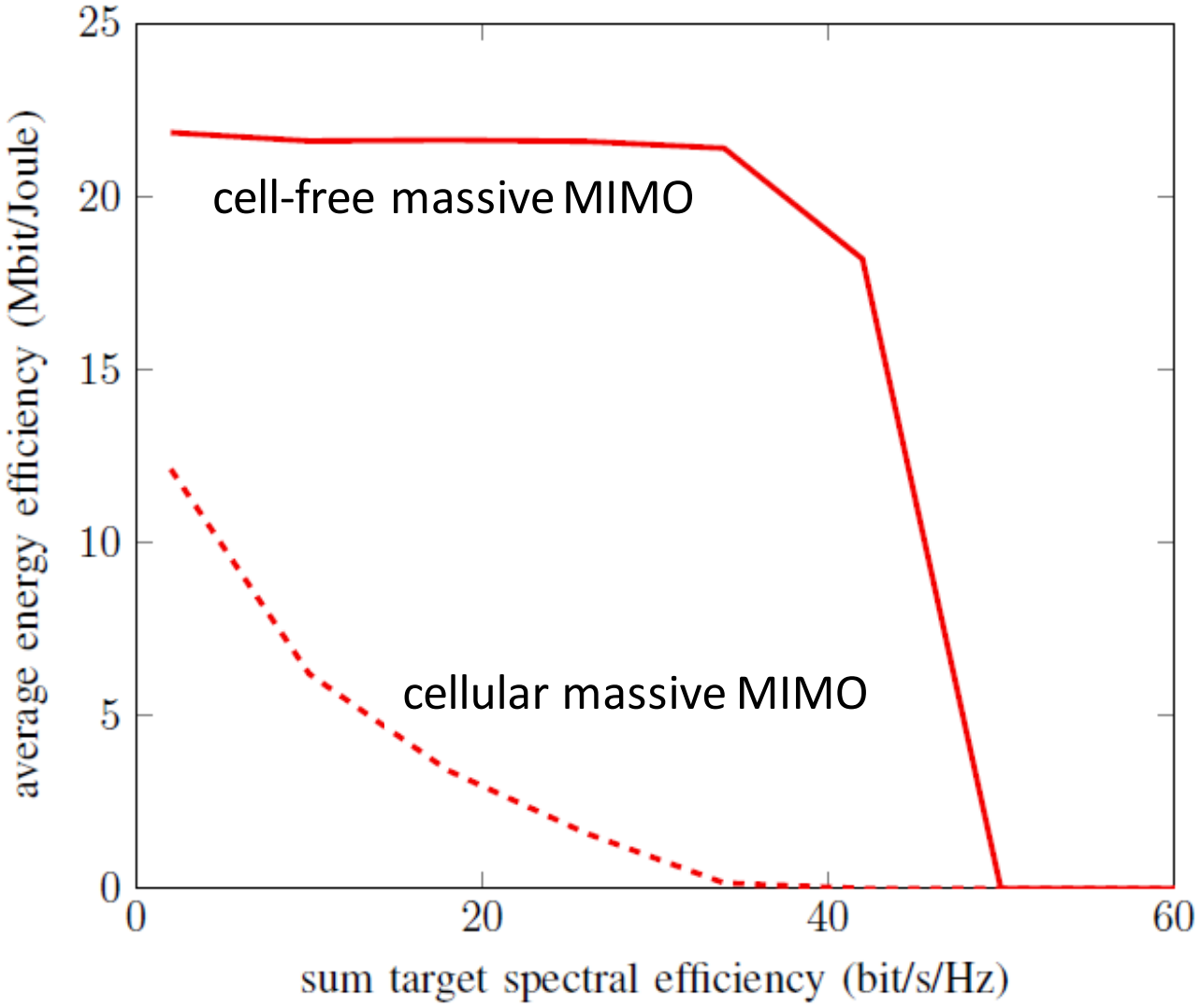
- **Propose an optimal power control algorithm which aims at maximizing the total energy efficiency**
- **New pilot assignment → improve the channel estimation quality**
- **Access point selection → reduce backhaul requirement**

$$\mathrm{E_e} = \frac{\sum_{k=1}^{K} \mathrm{S}_{\mathrm{e}k}}{\text{power (hardware power consumption + backhaul power consumption)}}$$

$$(\mathcal{P}): \begin{cases} \max\limits_{\{\eta_{mk}\}} & \mathrm{E_e}(\{\eta_{mk}\}) \\ \text{s.t.} & \mathrm{S}_{\mathrm{e}k}(\{\eta_{mk}\}) \geq \mathrm{S}_{\mathrm{o}k}, \ \forall k, \\ & \sum_{k=1}^{K} \eta_{mk}\gamma_{mk} \leq 1/N, \ \forall m, \\ & \eta_{mk} \geq 0, \ \forall k, \ \forall m, \end{cases}$$

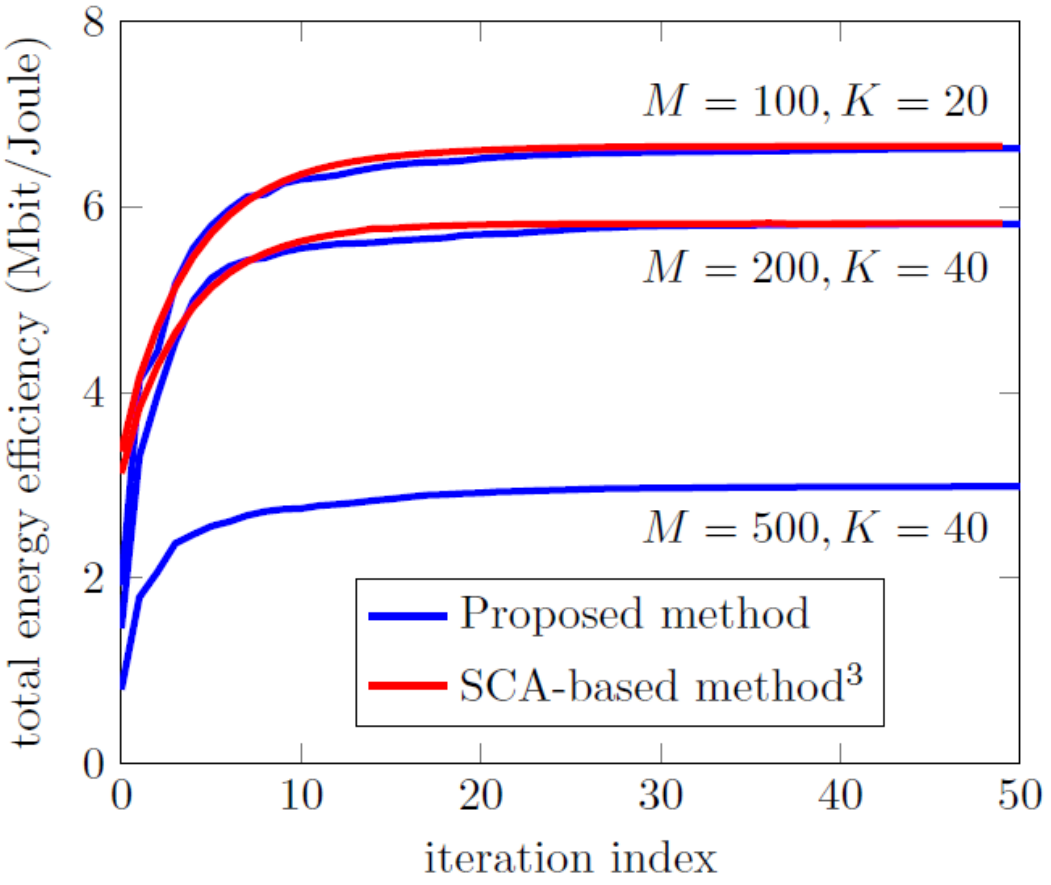
Solution: a sequence of second-order cone programs

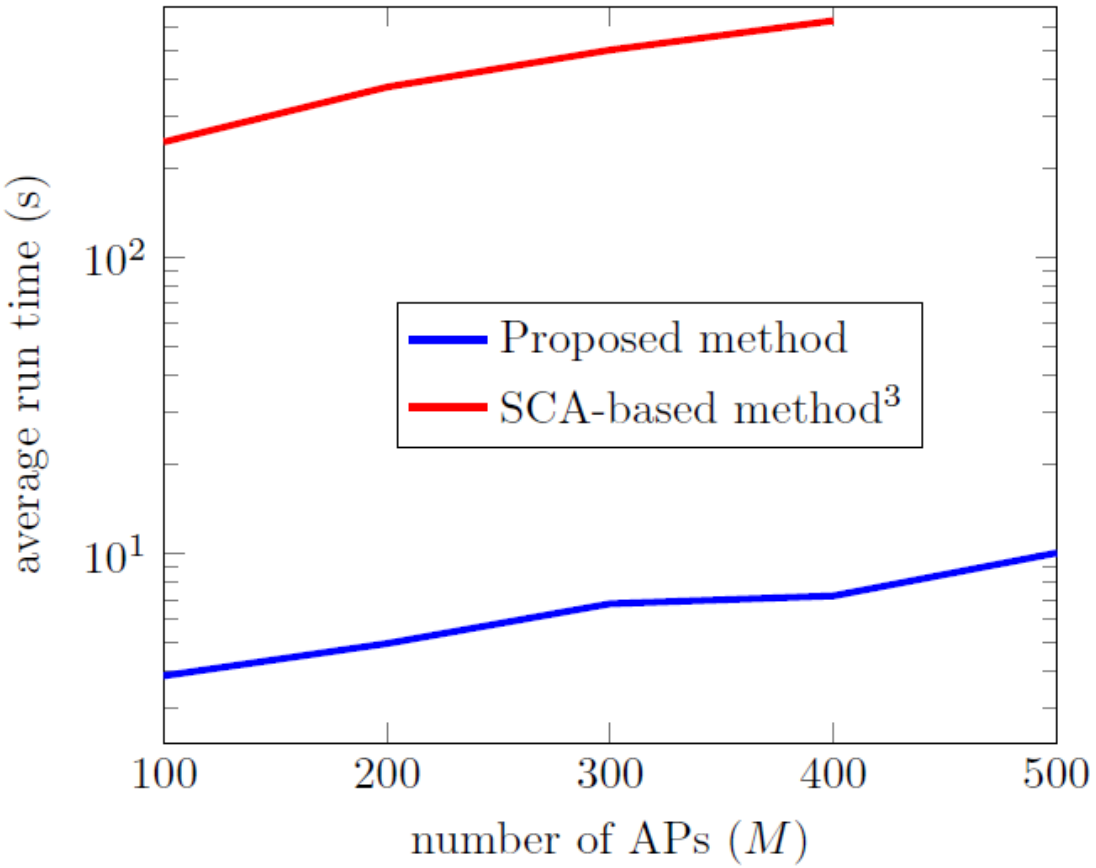
Cell-Free Massive MIMO Vs. Cellular Massive MIMO, 128 Antennas, 20 Users



(3) Low-Complexity Power Control

- **Propose to use a first-order method for nonconvex programming**





Compared to the second-order methods, the proposed method achieves the same performance, while its run time is much faster

Summary

- **Key points: novel cell-free massive MIMO designs**

- 10x spectral efficiency and 10x energy efficiency possible with M = 100 antennas/APs
- Very high coverage probability: offer uniformly good QoS for all users

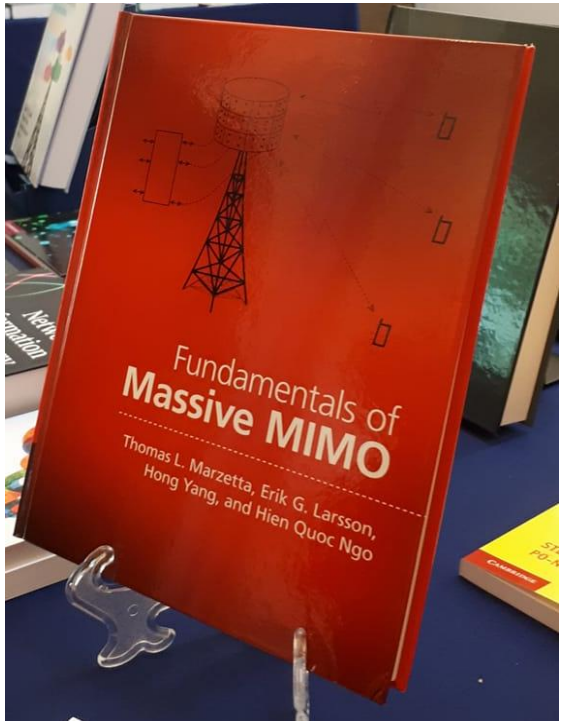
→ **Cell-free massive MIMO is a promising candidate which ensures connectivity for 6G**

- **Open/Ongoing research directions:**

- Scalable power control
- (Partially) distributed signal processing
- Backhaul requirements, channel state information acquisition
- Synchronization
- Cell-free massive MIMO and machine learning

Cell-Free Massive MIMO Blog (hosted by H. Q. Ngo, QUB):

https://cell-free.blogspot.com/



"Fundamentals of Massive MIMO"
- Cambridge University Press