A New Look at Cell-Free Massive MIMO:

Making It Practical with Dynamic Cooperation

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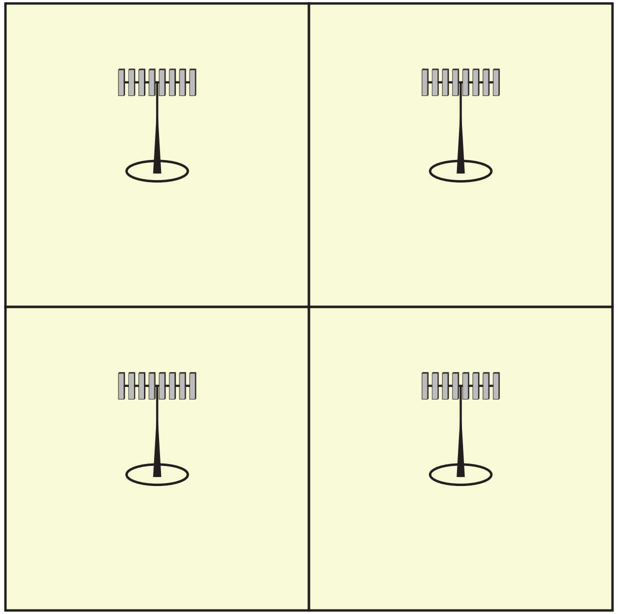
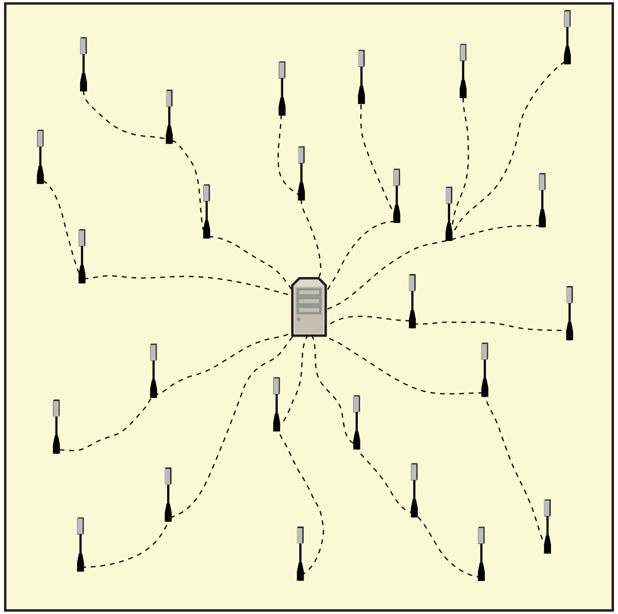
What is Cell-Free Massive MIMO?

Cellular network



Cell-free network



Massive number of distributed antennas

Connection to Massive MIMO:

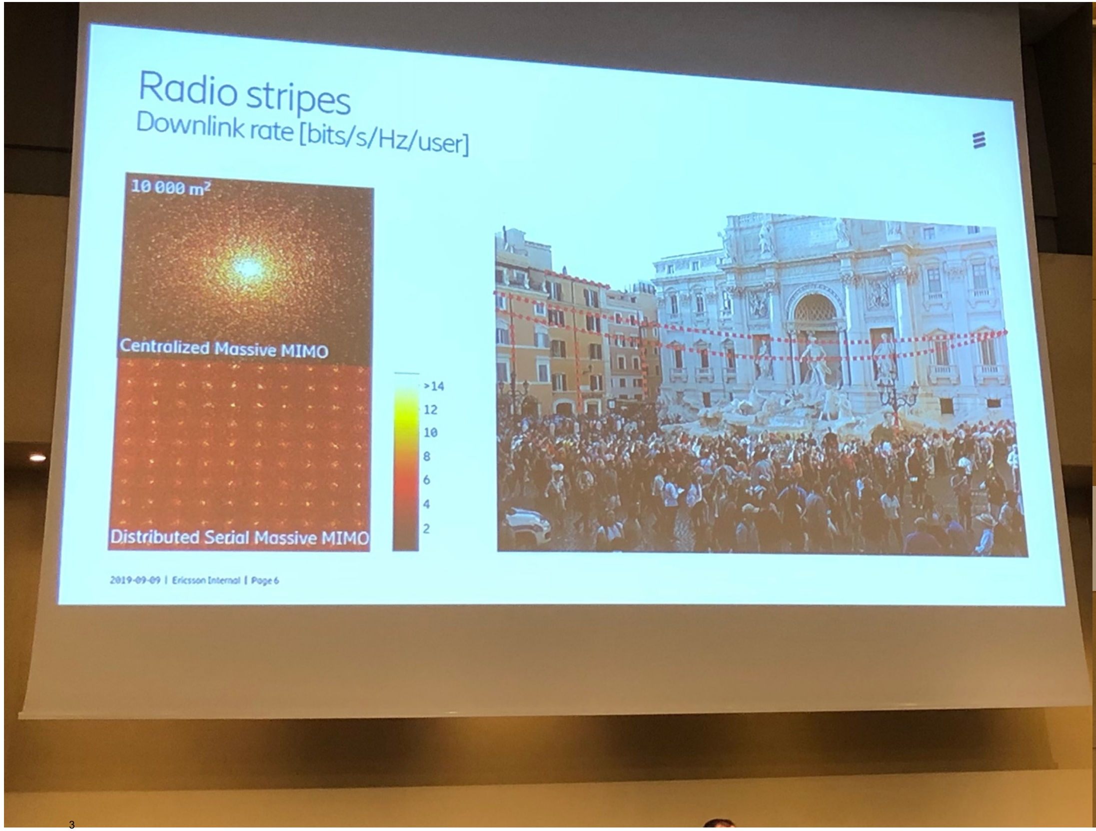
$M \gg K$

M antennas, K users

Connection to Cloud RAN:

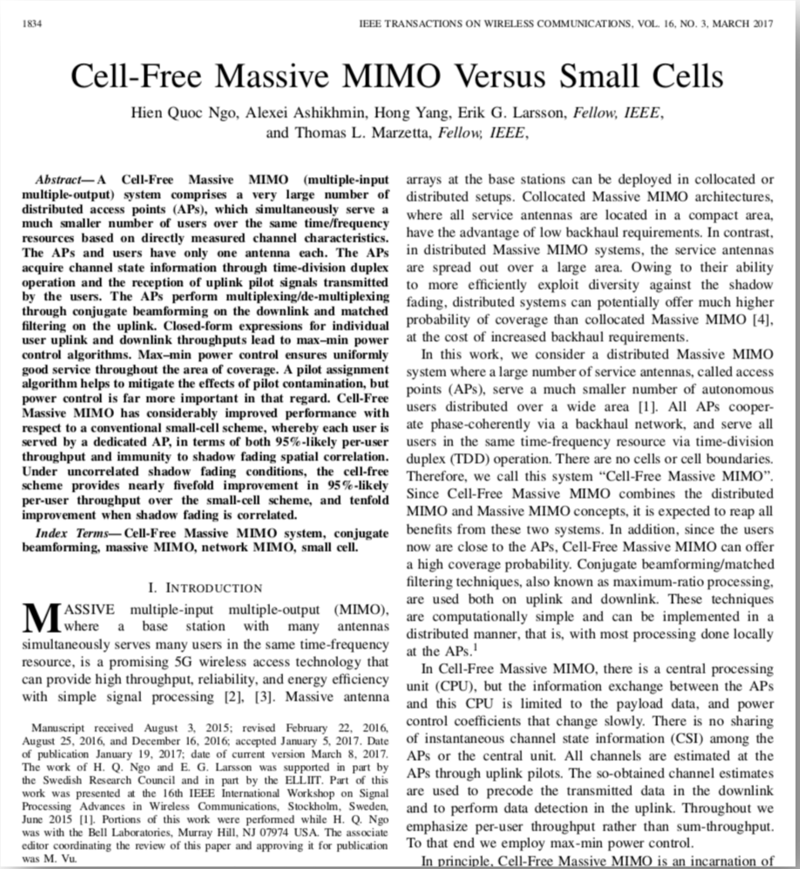
Possible architecture for implementation

Alternative names:
Radio stripes, Distributed Serial Massive MIMO



Talk by Magnus Frodigh
PIMRC 2019

Original Version of Cell-Free Massive MIMO



Cell-Free Massive MIMO Versus Small Cells

Hien Quoc Ngo, Alexei Ashikhmin, Hong Yang, Erik G. Larsson, *Fellow, IEEE*, and Thomas L. Marzetta, *Fellow, IEEE*,

***Abstract*—A Cell-Free Massive MIMO (multiple-input multiple-output) system comprises a very large number of distributed access points (APs), which simultaneously serve a much smaller number of users over the same time/frequency resources based on directly measured channel characteristics. The APs and users have only one antenna each. The APs acquire channel state information through time-division duplex operation and the reception of uplink pilot signals transmitted by the users. The APs perform multiplexing/de-multiplexing through conjugate beamforming on the downlink and matched filtering on the uplink. Closed-form expressions for individual user uplink and downlink throughputs lead to max–min power control algorithms. Max–min power control ensures uniformly good service throughout the area of coverage. A pilot assignment algorithm helps to mitigate the effects of pilot contamination, but power control is far more important in that regard. Cell-Free Massive MIMO has considerably improved performance with respect to a conventional small-cell scheme, whereby each user is served by a dedicated AP, in terms of both 95%-likely per-user throughput and immunity to shadow fading spatial correlation. Under uncorrelated shadow fading conditions, the cell-free scheme provides nearly fivefold improvement in 95%-likely per-user throughput over the small-cell scheme, and tenfold improvement when shadow fading is correlated.**

***Index Terms*—Cell-Free Massive MIMO system, conjugate beamforming, massive MIMO, network MIMO, small cell.**

I. INTRODUCTION

MASSIVE multiple-input multiple-output (MIMO), where a base station with many antennas simultaneously serves many users in the same time-frequency resource, is a promising 5G wireless access technology that can provide high throughput, reliability, and energy efficiency with simple signal processing [2], [3]. Massive antenna arrays at the base stations can be deployed in collocated or distributed setups. Collocated Massive MIMO architectures, where all service antennas are located in a compact area, have the advantage of low backhaul requirements. In contrast, in distributed Massive MIMO systems, the service antennas are spread out over a large area. Owing to their ability to more efficiently exploit diversity against the shadow fading, distributed systems can potentially offer much higher probability of coverage than collocated Massive MIMO [4], at the cost of increased backhaul requirements.

In this work, we consider a distributed Massive MIMO system where a large number of service antennas, called access points (APs), serve a much smaller number of autonomous users distributed over a wide area [1]. All APs cooperate phase-coherently via a backhaul network, and serve all users in the same time-frequency resource via time-division duplex (TDD) operation. There are no cells or cell boundaries. Therefore, we call this system "Cell-Free Massive MIMO". Since Cell-Free Massive MIMO combines the distributed MIMO and Massive MIMO concepts, it is expected to reap all benefits from these two systems. In addition, since the users now are close to the APs, Cell-Free Massive MIMO can offer a high coverage probability. Conjugate beamforming/matched filtering techniques, also known as maximum-ratio processing, are used both on uplink and downlink. These techniques are computationally simple and can be implemented in a distributed manner, that is, with most processing done locally at the APs.[1]

In Cell-Free Massive MIMO, there is a central processing unit (CPU), but the information exchange between the APs and this CPU is limited to the payload data, and power control coefficients that change slowly. There is no sharing of instantaneous channel state information (CSI) among the APs or the central unit. All channels are estimated at the APs through uplink pilots. The so-obtained channel estimates are used to precode the transmitted data in the downlink and to perform data detection in the uplink. Throughout we emphasize per-user throughput rather than sum-throughput. To that end we employ max-min power control.

In principle, Cell-Free Massive MIMO is an incarnation of

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- Assumptions: Each access point (AP)…

  …serves all K users

  …must estimate K channels

  …apply compute K ”beamformers”

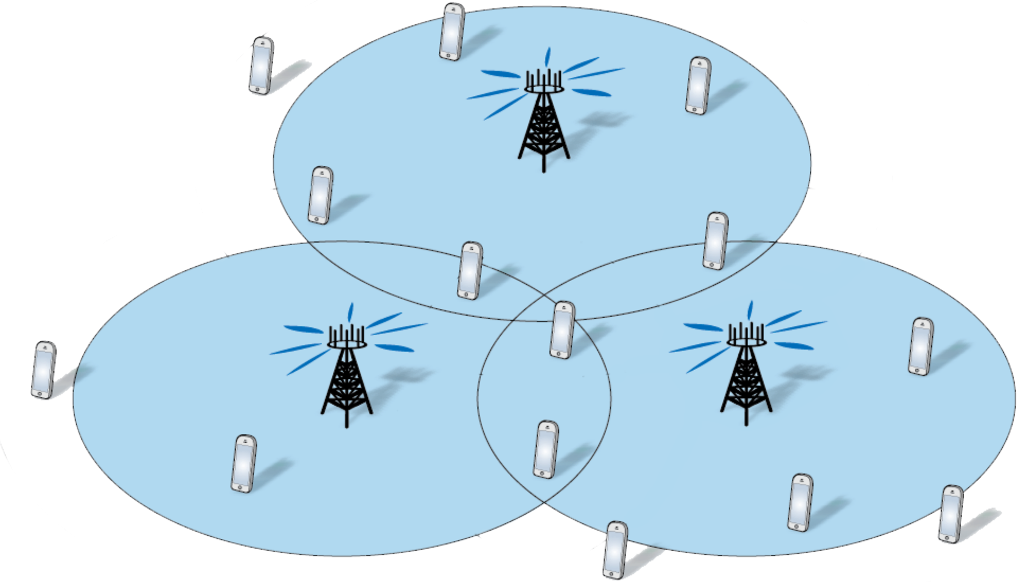
  …must send/receive data on fronthaul related to K users

  …gets power-control coefficients computed from system-wide problem

Not scalable!

We cannot let $K \to \infty$

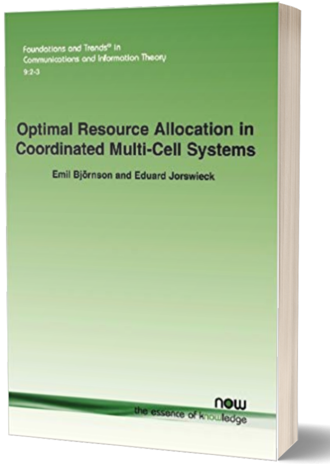
Solving the Scalability Issue



- **Dynamic cooperation clusters** enabling

  "*unified analysis of anything from interference channels to ideal network MIMO*" [R1]

  Originally proposed in [R2] to achieve a scalable base station cooperation framework without cell boundaries



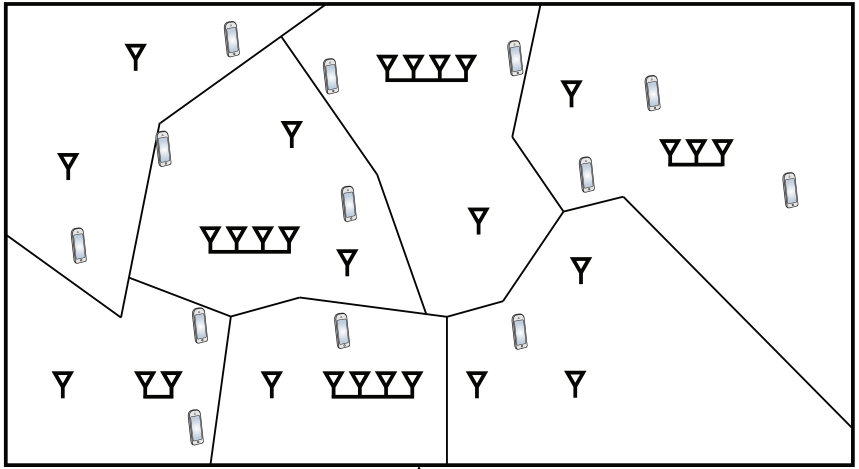
References

[R1] E. Björnson, E. Jorswieck, "*Optimal Resource Allocation in Coordinated Multi-Cell Systems*," Foundations and Trends in Communications and Information Theory, 2013.

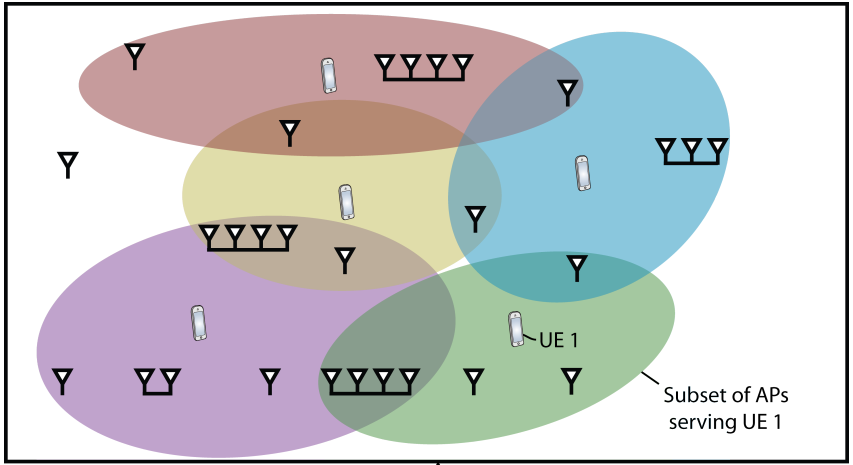
[R2] E. Björnson, N. Jaldén, M. Bengtsson, B. Ottersten, "*Optimality Properties, Distributed Strategies, and Measurement-Based Evaluation of Coordinated Multicell OFDMA Transmission*," IEEE Transactions on Signal Processing, 2011.

User-Centric vs. Network-Centric Cooperation Clustering

Network-centric clustering



User-centric clustering



Main approach in 4G
Not successful, not cell-free

Cell-free version
Used in Artemis pCell

Proposed: Scalable Cell-Free Massive MIMO

- Achieving *provable* scalability with dynamic cooperation clusters

> **Definition:** A cell-free network is *scalable* if the computational complexity and fronthaul signaling per AP remains finite as $K \to \infty$.

- TDD and block fading channels:

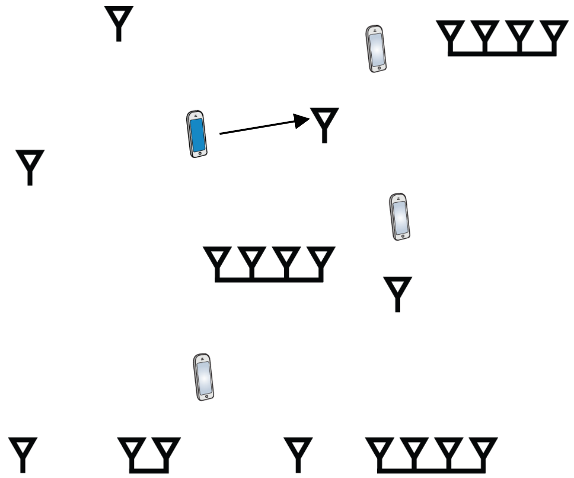
Pilots: τ_p	**Uplink and downlink data:** $\tau_c - \tau_p$

- **Proposed solution:** Each AP
  - Serves at most τ_p users (one per pilot)
  - Computes local channel estimates for only those τ_p users
  - Computes τ_p beamforming vectors only based on the τ_p estimates
  - Selects its power-control coefficients locally

Selecting Dynamic Cooperation Clusters

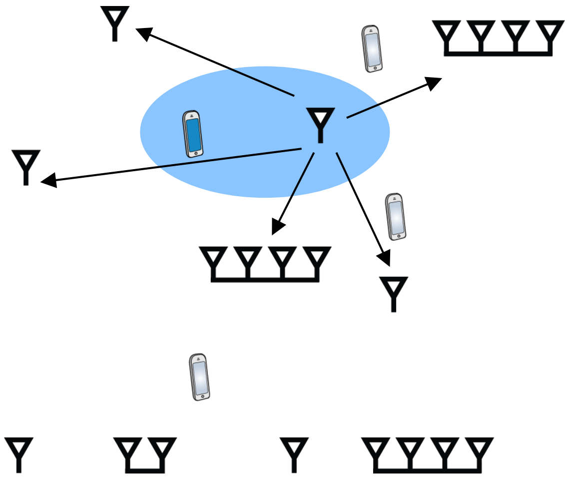
Step 1

User appoints: Master AP



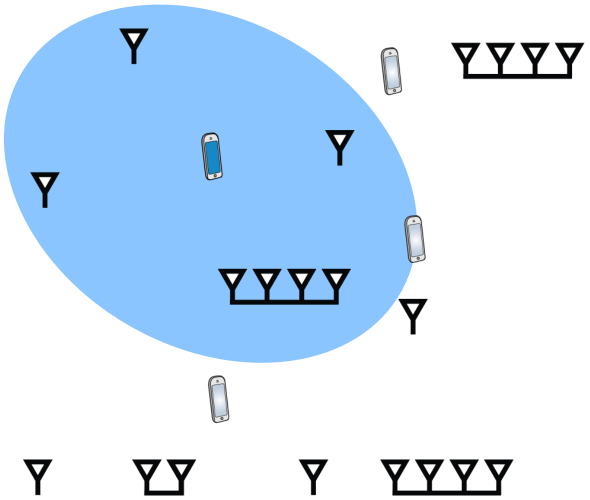
Step 2

Assign pilot, contact other APs



Step 3

Cluster has been formed



Which pilot?

One with least interference

Mobility:

Change Master AP and other APs

Analytical Results: Downlink

- Downlink spectral efficiency $$\frac{\tau_d}{\tau_c}\log_2\left(1+\frac{|\mathbb{E}\{\mathbf{h}_k^{\mathrm{T}}\mathbf{D}_k\mathbf{w}_k\}|^2}{\sum_{i=1}^{K}\mathbb{E}\{|\mathbf{h}_k^{\mathrm{T}}\mathbf{D}_i\mathbf{w}_i|^2\}-|\mathbb{E}\{\mathbf{h}_k^{\mathrm{T}}\mathbf{D}_k\mathbf{w}_k\}|^2+\sigma^2}\right)$$
    - L APs with N antennas
    - Channel from all APs to user k: $\mathbf{h}_k \in \mathbb{C}^{LN}$
    - Clusters represented by diagonal matrix $\mathbf{D}_k \in \mathbb{C}^{LN\times LN}$
- Precoding:

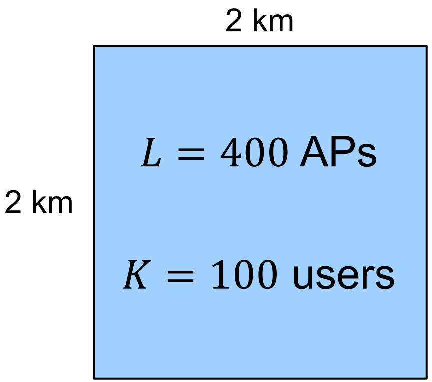
$$\mathbf{w}_{il}=\sqrt{\frac{\rho_{il}}{\mathbb{E}\{\|\bar{\mathbf{w}}_{il}\|^2\}}}\bar{\mathbf{w}}_{il}\quad \forall i\in\mathcal{D}_l$$

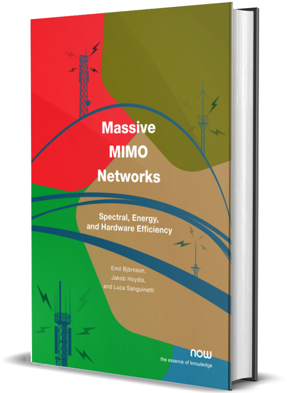
$$\bar{\mathbf{w}}_{kl}=\begin{cases}\hat{\mathbf{h}}_{kl}^{*} & \text{with MR,}\\ \left(\sum_{i\in\mathcal{D}_l}\rho_{il}\hat{\mathbf{h}}_{il}^{*}\hat{\mathbf{h}}_{il}^{\mathrm{T}}+\sigma^2\mathbf{I}_N\right)^{-1}\hat{\mathbf{h}}_{kl}^{*} & \text{with SLNR,}\end{cases}$$

Similar results in uplink!

Numerical Evaluation

- Simulation setup:
  - Random AP and user locations
  - Typical micro-cell channel model





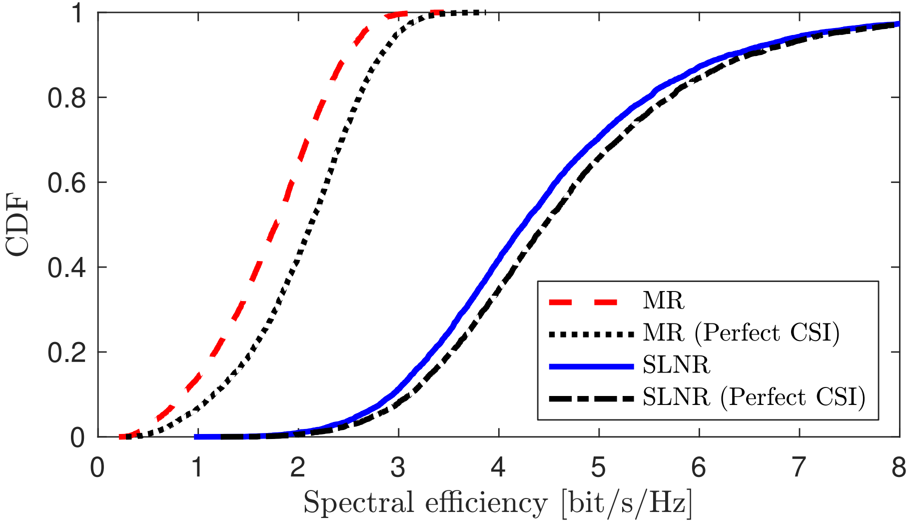
- Cooperation cluster formation
  - First $\tau_p = 10$ users get orthogonal pilots
  - The other access one after the other

- Equal downlink power allocation at each AP
  - Uplink: Heuristic scheme from

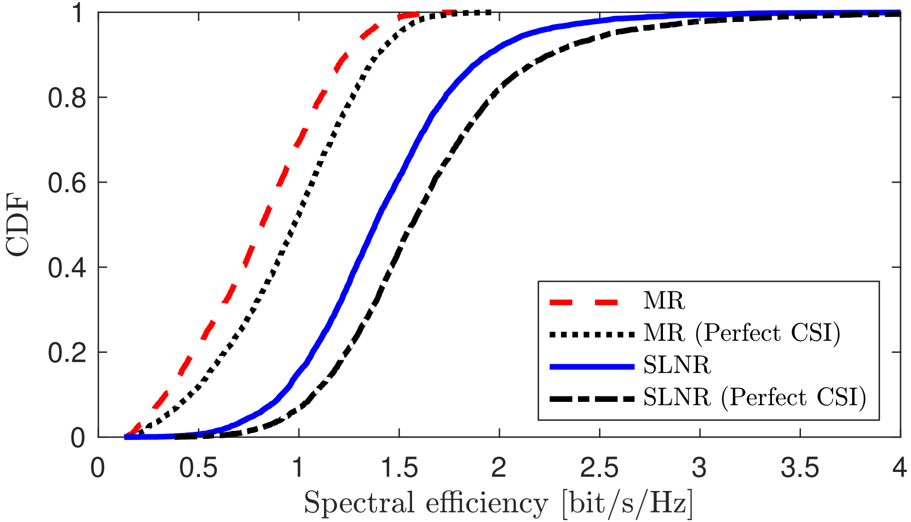
G. Interdonato, P. Frenger, and E. G. Larsson, "Scalability aspects of cell-free massive MIMO," in *IEEE ICC*, 2019.

Downlink Simulation Results

$N = 4$ antennas per AP



$N = 1$ antenna per AP

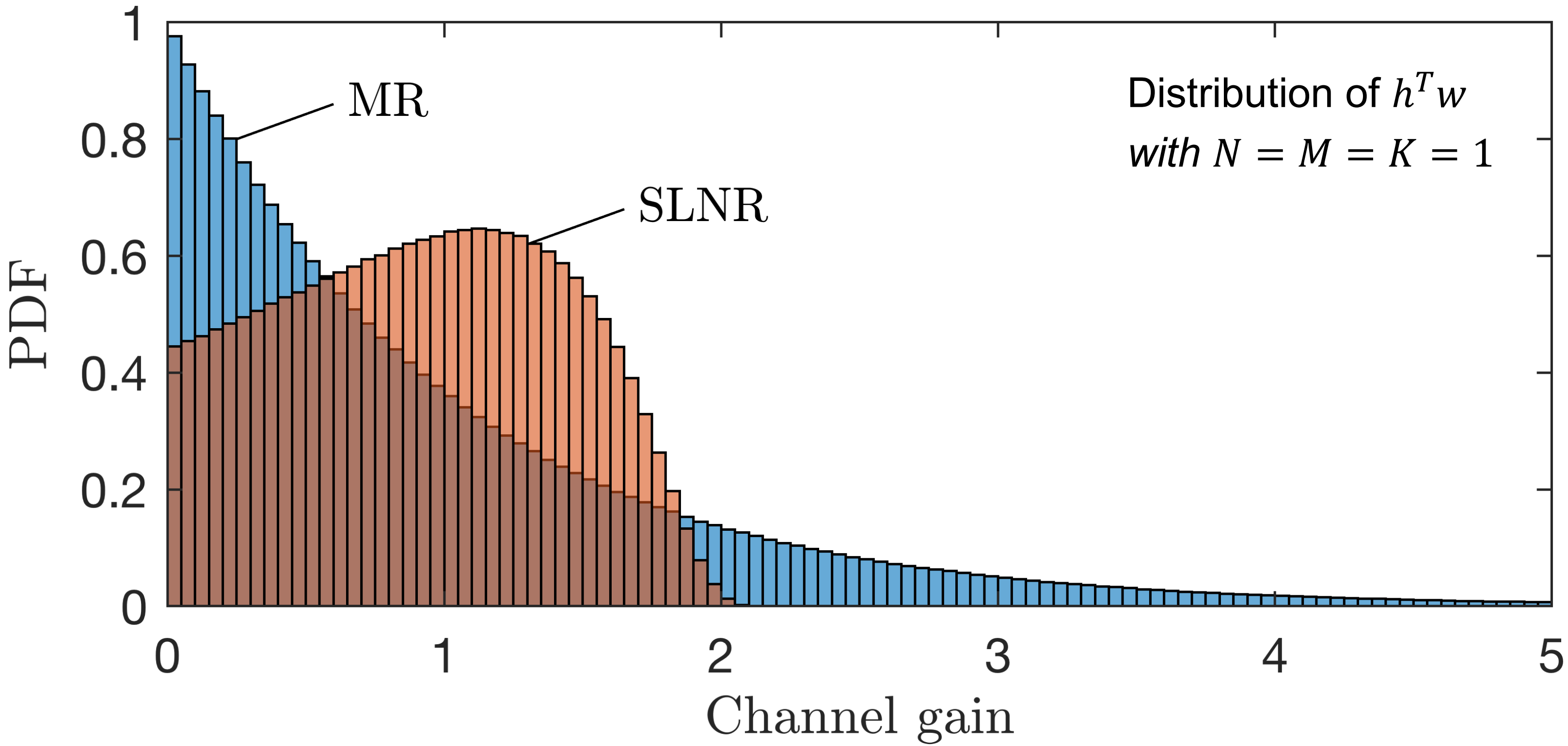


SLNR greatly outperforms MR

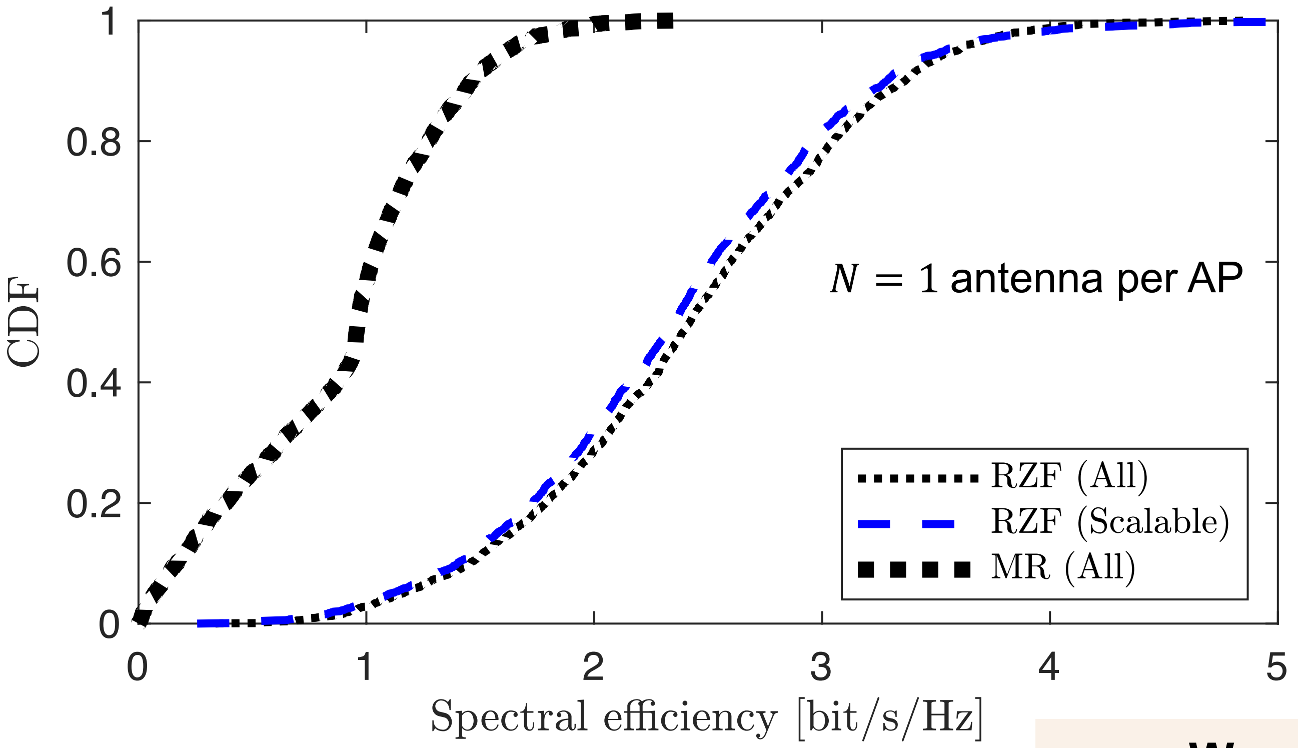
Both are scalable!

SLNR is better even with one antenna per AP

Why Isn't MR Optimal for $N = 1$?



Uplink Simulation Results



RZF:

Counterpart to SLNR

Price for scalability:

A few percent

We greatly outperform

Original Cell-Free Massive MIMO

Summary: A New Look at Cell-Free Massive MIMO

- Original Cell-free Massive MIMO is not scalable
  - But we can address that using the *dynamic cooperation clusters*

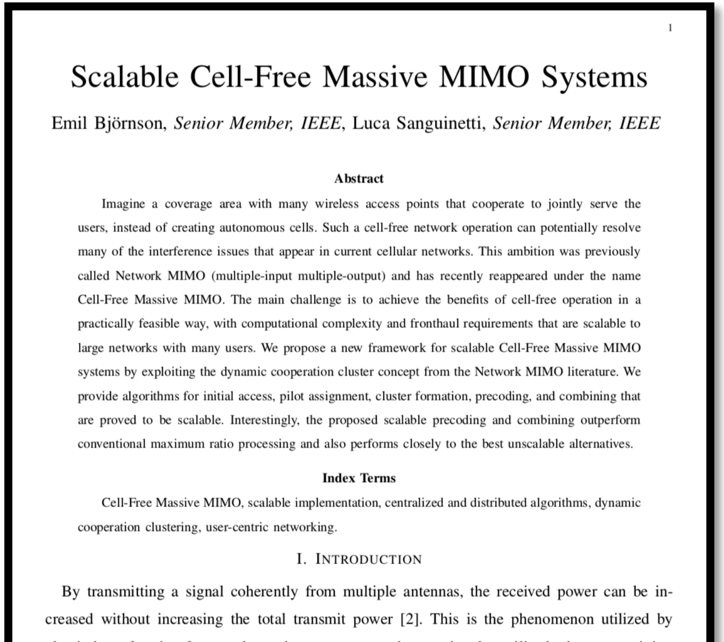
- New contributions
  - Access protocol for cluster formation
  - General spectral efficiency expressions
  - Discover that SLNR/RZF outperform MR

Open problems

Smart distributed power control

Utilize structure of fronthaul

Journal version on Arxiv:



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Scalable Cell-Free Massive MIMO Systems

Emil Björnson, *Senior Member, IEEE*, Luca Sanguinetti, *Senior Member, IEEE*

Abstract

Imagine a coverage area with many wireless access points that cooperate to jointly serve the users, instead of creating autonomous cells. Such a cell-free network operation can potentially resolve many of the interference issues that appear in current cellular networks. This ambition was previously called Network MIMO (multiple-input multiple-output) and has recently reappeared under the name Cell-Free Massive MIMO. The main challenge is to achieve the benefits of cell-free operation in a practically feasible way, with computational complexity and fronthaul requirements that are scalable to large networks with many users. We propose a new framework for scalable Cell-Free Massive MIMO systems by exploiting the dynamic cooperation cluster concept from the Network MIMO literature. We provide algorithms for initial access, pilot assignment, cluster formation, precoding, and combining that are proved to be scalable. Interestingly, the proposed scalable precoding and combining outperform conventional maximum ratio processing and also performs closely to the best unscalable alternatives.

Index Terms

Cell-Free Massive MIMO, scalable implementation, centralized and distributed algorithms, dynamic cooperation clustering, user-centric networking.

I. Introduction

By transmitting a signal coherently from multiple antennas, the received power can be increased without increasing the total transmit power [2]. This is the phenomenon utilized by

QUESTIONS?