Downlink Spectral Efficiency of Cell-Free Massive MIMO with Full-Pilot Zero-Forcing

GlobalSIP, November 26-29, 2018

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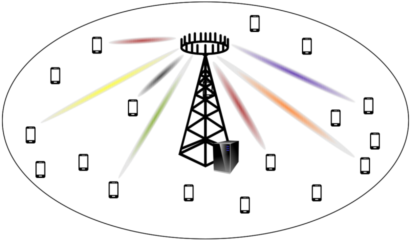
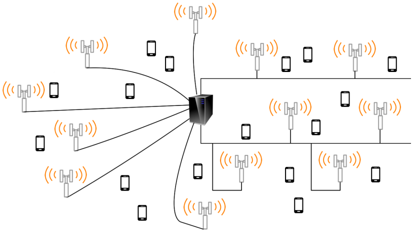
Massive MIMO is a key enabler of 5G



- Higher spectral and energy efficiency
- Close-to-optimal linear signal processing
- Scalability relying on TDD system *channel reciprocity*
- *Favorable propagation* and *channel hardening*

Cell-Free Massive MIMO focuses on the user



- baseline Massive MIMO operation
- distributed architecture ensures ubiquitous connectivity
- coherent transmission increases macro-diversity
- user-centric data transmission eliminates cell boundaries

G. Interdonato, E. Björnson, H. Q. Ngo, P. Frenger, and E. G. Larsson, "Ubiquitous Cell-Free Massive MIMO Communications," *Submitted to IEEE Comm. Mag.*

Motivations

- maximum-ratio transmission (MRT): fully distributed and scalable
- zero-forcing (ZF): unscalable in cell-free massive MIMO
  - instantaneous CSI from each AP to the CPU
  - centralized precoder computation
  - deal with huge pseudo-inverse matrices
  - precoders from the CPU to the APs

Interference suppression while preserving system scalability?

Full-pilot ZF (fpZF)

Uplink pilots from **all** the UEs and precoder based on **local** CSI

$$\mathbf{w}_{l,i_k} = \frac{\bar{\mathbf{H}}_l \left(\bar{\mathbf{H}}_l^{\mathsf{H}} \bar{\mathbf{H}}_l\right)^{-1} \mathbf{e}_{i_k}}{\sqrt{\mathsf{E}\left\{\left\|\bar{\mathbf{H}}_l \left(\bar{\mathbf{H}}_l^{\mathsf{H}} \bar{\mathbf{H}}_l\right)^{-1} \mathbf{e}_{i_k}\right\|^2\right\}}} \in \mathbb{C}^{M \times 1}.$$

- L APs M antennas per AP
- K UEs i_k: index of the pilot used by UE k
- $\forall$ AP: number of precoders $=$ number of orthogonal pilots

$$\mathbf{x}_l = \sum_{k=1}^{K} \sqrt{\rho_{l,k}} \mathbf{w}_{l,i_k} q_k,$$

E. Björnson, E. G. Larsson, and M. Debbah "Massive MIMO for Maximal Spectral Efficiency: How Many Users and Pilots Should Be Allocated?," *IEEE Trans. on Wireless Comm., Feb 2016*

Downlink Spectral Efficiency

$$\mathrm{SE}_k^{\mathrm{fpZF}} = \xi^{\mathrm{DL}} \left(1 - \frac{\tau_{\mathrm{P}}}{\tau_{\mathrm{C}}}\right) \log_2 \left(1 + \mathrm{SINR}_k^{\mathrm{fpZF}}\right) \quad [\mathrm{bit/s/Hz}],$$

$$\mathrm{SINR}_k^{\mathrm{fpZF}} = \frac{(M - \tau_{\mathrm{P}}) \left(\sum\limits_{l=1}^{L} \sqrt{\rho_{l,k}\gamma_{l,k}}\right)^2}{(M - \tau_{\mathrm{P}}) \sum\limits_{t \in \mathcal{P}_k \setminus \{k\}} \left(\sum\limits_{l=1}^{L} \sqrt{\rho_{l,t}\gamma_{l,k}}\right)^2 + \sum\limits_{l=1}^{L}\sum\limits_{t=1}^{K} \rho_{l,t}\left(\beta_{l,k} - \gamma_{l,k}\right) + 1}$$

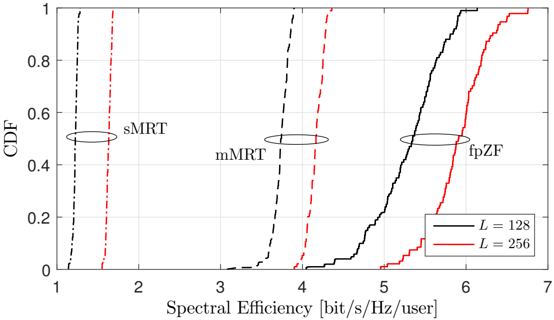
- τ_{P} orthogonal pilots
- $\mathcal{P}_k$: set of indices of UEs that transmit the same pilot as UE k
- $\beta_{l,k}$ mean-square of the **real** channel
- $\gamma_{l,k}$ mean-square of the channel **estimate**, $\beta_{l,k} \geq \gamma_{l,k}$
- Necessary condition: $M > \tau_{\mathrm{P}}$

Max-min Fairness Power Control

$$\begin{aligned} \underset{\{\rho_{l,k} \geq 0\}}{\text{maximize}} \quad & \min_{k} \mathrm{SE}_k^{\mathrm{fpZF}} \\ \text{subject to} \quad & \sum_{k=1}^{K} \rho_{l,k} \leq P_{\max,l}, \ \forall l, \end{aligned}$$

- Uniformly good service to all the UEs
- Second-order cone program (SOCP)
- Global optimal solution by using interior-point methods

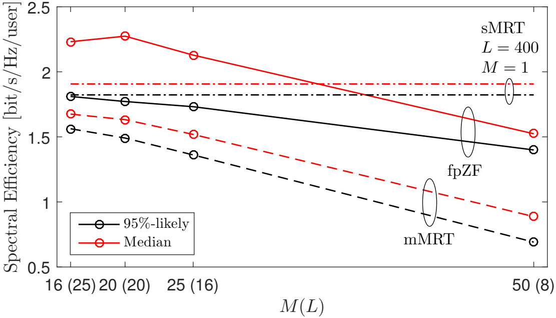
fpZF outperforms MRT, power being equal



$$M^{\text{mMRT}} = M^{\text{fpZF}} = 64,\ M^{\text{sMRT}} = 1,\ K = 20,\ \tau_{\text{P}} = 10.$$

- sMRT (mMRT): single(multi)-antenna APs implementing MRT
- M: number of antennas per AP
- L: number of APs

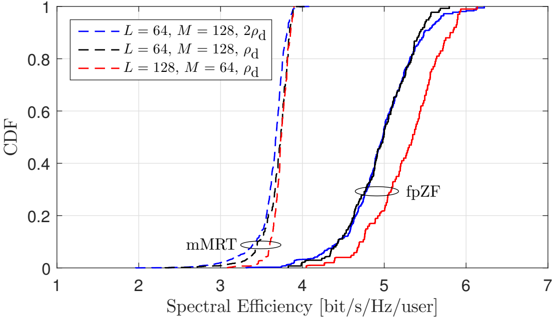
fpZF outperforms MRT, LM being equal



$$LM = 400,\ K = 20,\ \tau_{\mathrm{P}} = 10.$$

- for system adequately distributed (L moderately large), fpZF performs better
- the macro-diversity gain is dominant over the array gain
- with respect to sMRT, fpZF is M^{fpZF} times more power efficient.

fpZF gains more from the distributed topology



$$LM = 8192,\ K = 20,\ \tau_\mathrm{P} = 10.$$

- fpZF benefits more from accurate channel estimates than mMRT
- doubling the per-AP radiated power does not help
- distributing the power over more APs rather than more antennas

Take-home messages

- fpZF improves SE by suppressing multi-user interference
- fpZF is a fully distributed and scalable scheme in that:
    - precoders are designed at each AP
    - no additional fronthauling overhead, local CSI is utilized.

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Table: Simulation settings

Description	Value	Description	Value
Simulation area	500×500 m^2	τ_{C} (symbols)	200
AP/UE distribution	unif. rand.	ξ^{DL}	0.5
AP/UE antenna height	15/1.65 m	σ_{sh}	8 dB
Carrier frequency	2 GHz	Bandwidth	20 MHz
Noise figure	9 dB	K	20
max AP radiated power	200 mW	max UE radiated power	100 mW