LINKÖPING UNIVERSITY

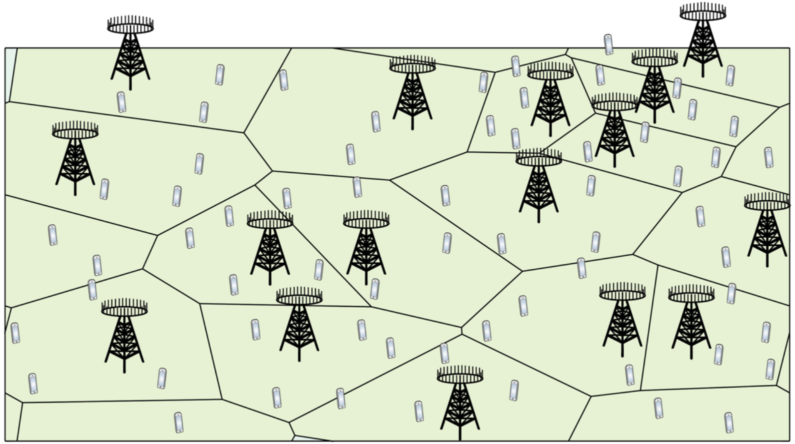
Three Practical Aspects of Massive MIMO

Emil Björnson and Erik G. Larsson

Department of Electrical Engineering (ISY), Linköping University, Linköping, Sweden

This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 619086.

Uplink Massive MIMO Network



- Many base stations (BSs)
  - M antennas per BS
  - K users per cell
- Channel coherence
  - S transmission symbols: B pilots, $S - B$ data symbols
- Properties of user i in cell l:
  - Channel to BS j: $\mathbf{h}_{jli} \sim CN\left(\mathbf{0}, \beta_{jli}\mathbf{I}_M\right)$
  - Transmit power: p_{li} Linear detection filter: $\mathbf{v}_{li} \in \mathbb{C}^M$

From Theory to Practice: Three Practical Aspects

- Theoretical analysis is mature
  - Concepts for estimation, uplink detection, downlink precoding
  - Many closed-form rate expressions (bounds, approximations, limits)
  - Promising performance results

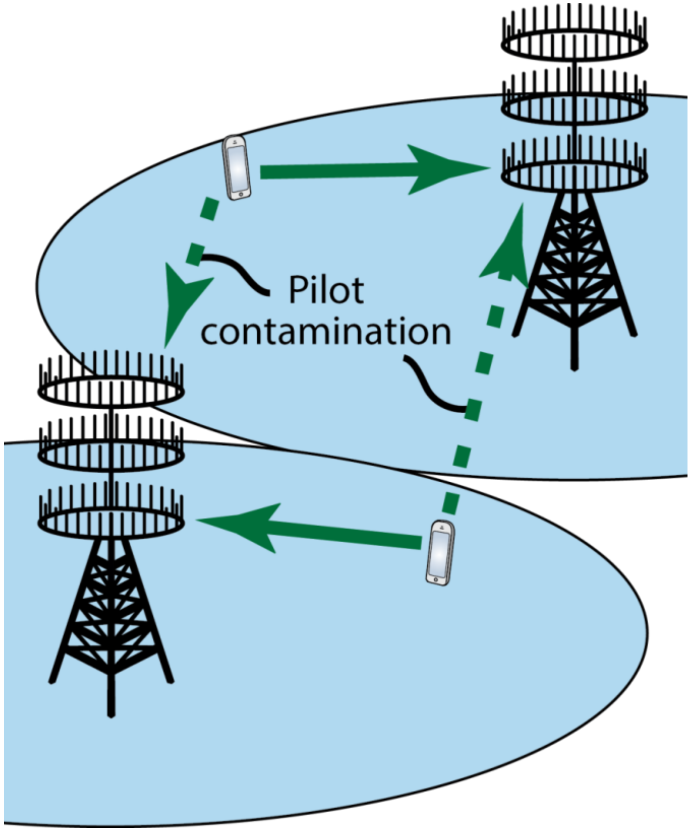
Is theoretical analysis becoming irrelevant?

- Revisit Simplifying Assumptions!
  - Pilot synchronism: How well do we need to synchronize cells?
  - Intermittent user activity: How do we handle non-full buffers?
  - Asymmetric deployment: What is a good cell geometry?

Pilot Synchronism

Pilot Synchronism

- Pilot Contamination
  - Two users send the same pilot
  - Base stations cannot separate them



- Assumption: Synchronous users
  - Time-synchronized users
  - Users send pilot simultaneously
  - Reasonable? Not over a large area
  - Necessary? [Ngo2013] shows that also data causes contamination

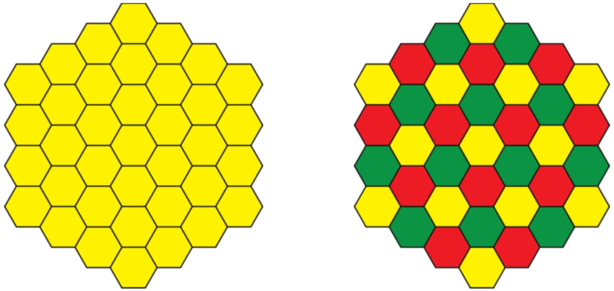
Pilot Synchronism (2)

- **Synchronous pilots**: Each cell picks K random pilots in each block
  - Risk of pilot collision between two users: $1/B$
  - Average pilot contamination in cell j: $\sum_{l\in\Phi\setminus\{j\}}\sum_{i=1}^{K}\frac{1}{B}\left(p_{li}\beta_{jli}\right)^2 M$
- **Asynchronous pilots:** Other cells send random interfering signals
  - All interfering users collide with a user sending a pilot
  - On average only $1/B$ of the power is along the pilot sequence
  - Average pilot contamination in cell j: $\sum_{l\in\Phi\setminus\{j\}}\sum_{i=1}^{K}\frac{1}{B}\left(p_{li}\beta_{jli}\right)^2 M$

Conclusion: No difference between these cases!

Pilot Synchronism (3)

- Any reason to have synchronous pilots?
  - Yes, if have a pilot reuse factor $f > 1$
  - Yes, if we optimize pilot allocation, instead of having random allocation



$f = 1$ $\quad$ $f = 3$

Intermittent User Activity

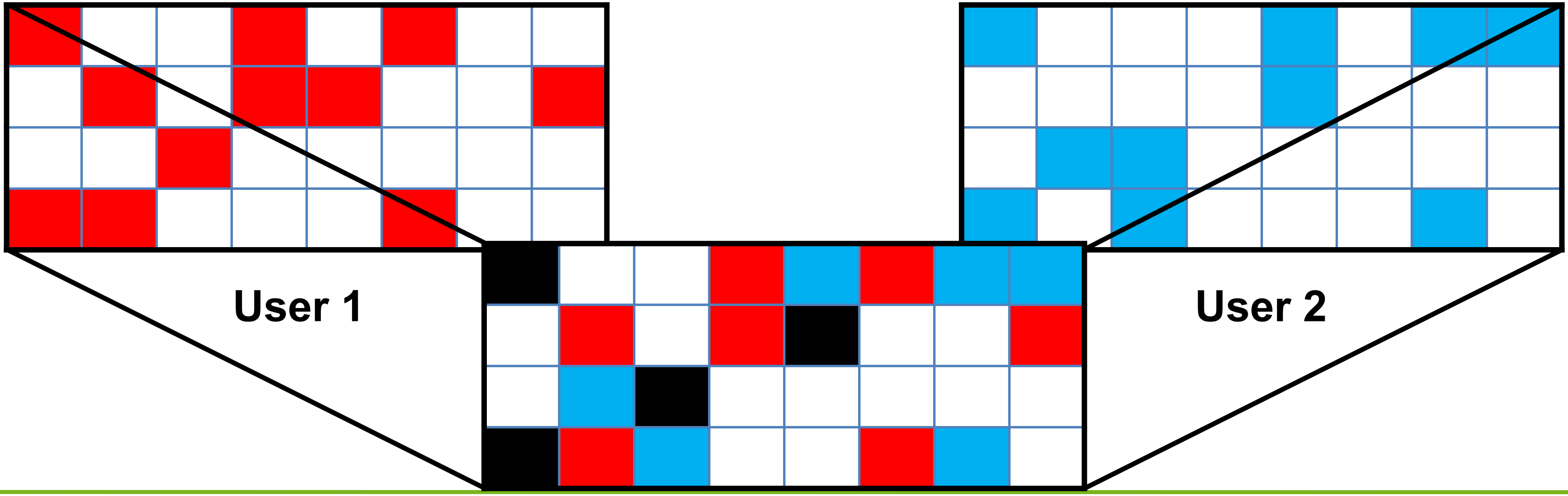
Intermittent User Activity

- Ergodic capacity as performance metric
  - Channel coding over long data sequences
    over many fading realizations
  - Implicit assumption: Continuous communication
    Full buffers: Active in each coherence block

- Are Real Applications Continuous?
  - Application layer: Yes! (e.g,. video)
  - Physical layer: No, TCP/IP is bursty!

Intermittent User Activity (2)

- Simple Model: Intermittent User Activity
  - Probability A of being active in a coherence block ($0 \leq A \leq 1$)
  - Independent between users and coherence blocks



Intermittent User Activity (3)

- Extending conventional capacity analysis
  - User k in cell j has a random variable $a_{jk} \in \{0,1\}$
  - Active if $a_{jk} = 1$ $\quad\quad \Pr\{a_{jk} = 0\} = 1 - A,\ \Pr\{a_{jk} = 1\} = A$

Theorem 1 (Lower Bound on Ergodic Capacity)

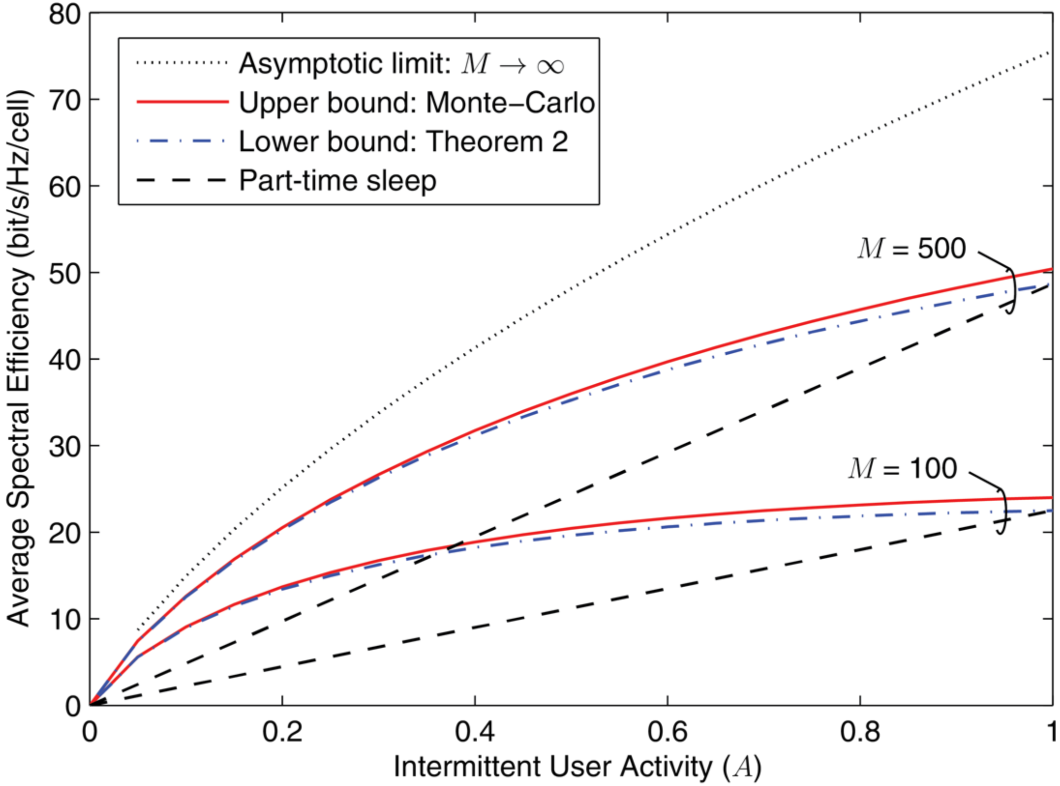
$$\mathrm{SE}_{jk} = A\left(1 - \frac{B}{S}\right)\log_2\left(1 + \mathrm{SINR}_{jk}\right)$$

$$\mathrm{SINR}_{jk} = \frac{p_{jk}\left|\mathbb{E}\{\mathbf{h}_{jjk}^H \mathbf{v}_{jk}\}\right|^2}{\sum_{l\in\Phi}\sum_{i=1}^{K}\mathbb{E}\left\{\left|a_{li}\mathbf{h}_{jli}^H\mathbf{v}_{jk}\right|^2\right\} - p_{jk}\left|\mathbb{E}\{\mathbf{h}_{jjk}^H\mathbf{v}_{jk}\}\right|^2 + \sigma^2\,\mathbb{E}\left\{\left\|\mathbf{v}_{jk}\right\|^2\right\}}$$

Closed form for MRC!

Interference power from user i in cell l $\quad$ Desired signal $\quad$ Noise

Simulation: Impact of User Activity



Parameters:

$\mathrm{SNR} = 5$ dB

$K = 30$

$S = 400$

B optimized

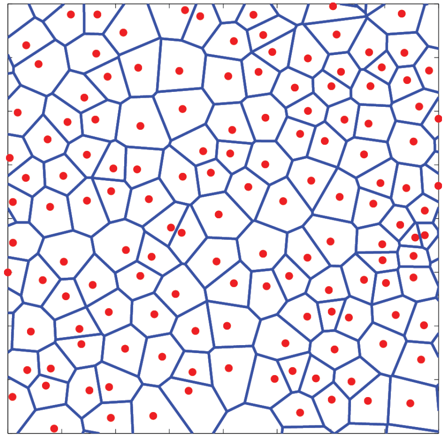
Random BSs

Asymmetric Deployment

Asymmetric Deployment

Andrews et al. "A Tractable Approach to Coverage and Rate in Cellular Networks"

- Shape of Cellular Networks
  - Classical: Symmetric hexagonal grid
  - Real networks are highly asymmetric
  - Asymmetry plays key role as cells shrink



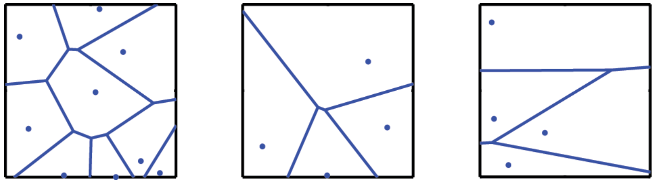
Homogeneous Poisson point process (PPP)

Independent and equally distributed BSs in $\mathbb{R}^2$

Density: λ BSs per km^2

Lower bound on practical performance

4 realizations in area $\mathcal{A}$ with $\lambda\mathcal{A} = 6$ BSs:



Asymmetric Deployment (2)

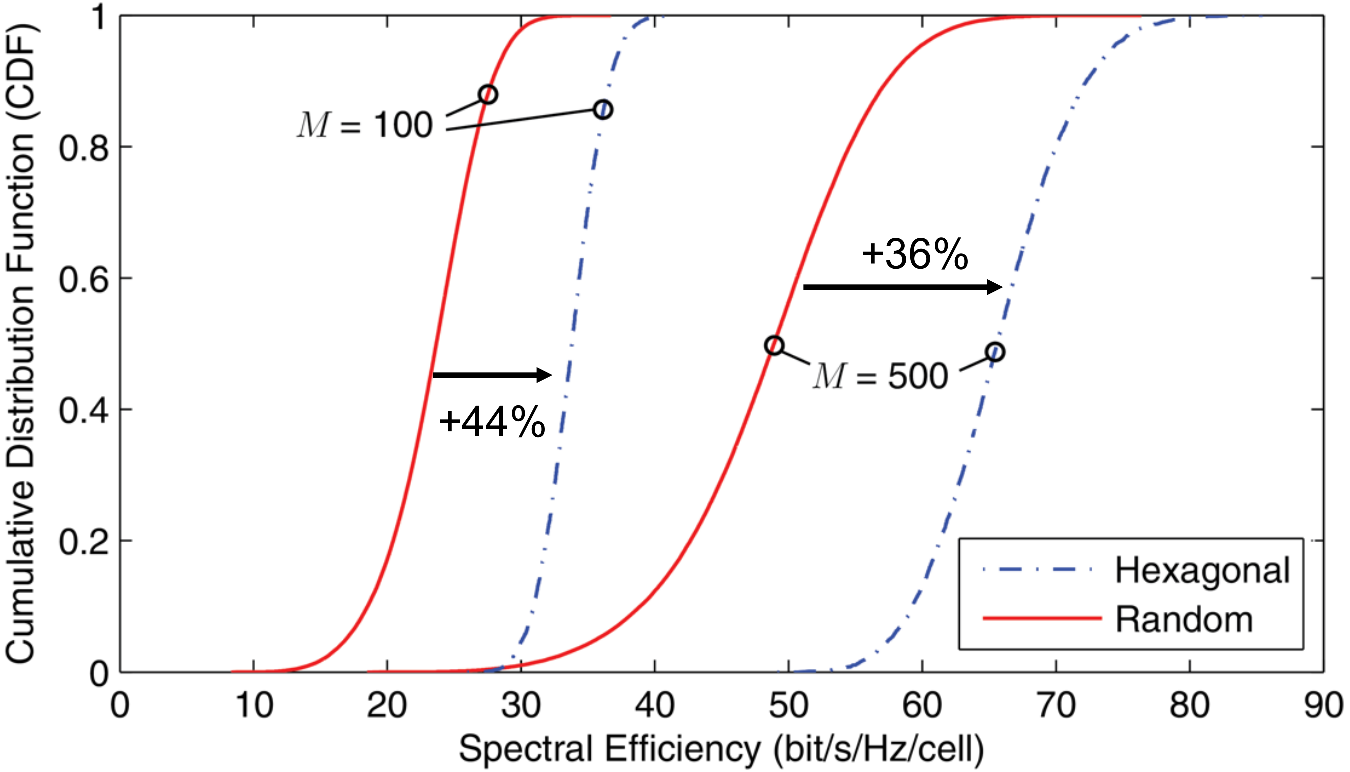
- Assumptions
  - Random pilot allocation
  - Pathloss: $\beta_{jjk} = \omega^{-1}(\text{distance [km]})^{-\alpha}$ $\quad(\alpha > 2)$
  - Loss at reference distance 1 km: ω
  - Statistical channel inversion: $p_{jk} = \rho/\beta_{jjk}$ $\quad(\text{SNR} = \rho/\sigma^2)$

Theorem 2 (Lower Bound on Average SE with MRC)

$$\underline{\text{SE}} = A\left(1 - \frac{B}{S}\right)\log_2(1 + \underline{\text{SINR}})$$

$$\underline{\text{SINR}} = \frac{M}{\left(1 + \frac{\sigma^2}{\rho B}\right)\left(1 + A(K-1) + \frac{\sigma^2}{\rho}\right) + \frac{2KA}{\alpha - 2}\left(1 + \frac{1 + A(K-1)}{B} + \frac{2\sigma^2}{\rho B}\right) + \frac{K^2}{B}\left(\frac{4A^2}{(\alpha-2)^2} + \frac{A^2}{\alpha - 1}\right) + \frac{AK(M+1-A)}{B(\alpha-1)}}$$

Simulation: Impact of Asymmetric Deployment



Parameters:

$\mathrm{SNR} = 5\ \mathrm{dB}$

$K = 30$

$S = 400$

$A = 1$

$B = 60$

Summary

Summary

- Theoretical limits of Massive MIMO are well studied
  - Important: Shift focus to practical aspects

- Three important aspects
  - Pilot synchronism: Only important when having pilot reuse factors
  - Intermittent user activity: Performance scales gracefully
  - Asymmetric deployment: Important with judicious deployment