Designing Wireless Broadband Access for Energy Efficiency

Are Small Cells the Only Answer?

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INTRODUCTION

Energy Efficiency

- Benefit-Cost Analysis of Networks

Cost:
Power Consumption
[Watt = Joule/s]

→ **_Network_** →

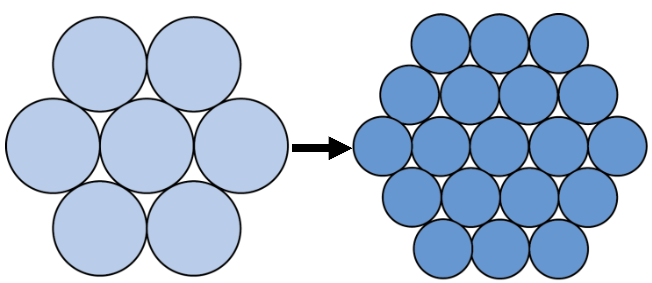
Benefit:
Sum Rate
[bit/s]

  - Definition: Energy Efficiency (EE):

$$\text{EE [bit/Joule]} = \frac{\text{Average Sum Rate } [\text{bit/s/km}^2]}{\text{Power Consumption } [\text{Joule/s/km}^2]}$$

  - Future networks: 1000x more data → 1000x higher EE

- How to Improve Energy Efficiency?
  - One approach: Reduce radiated power
    Achieved by smaller cells



Is Smaller Cells the Only Answer?

1. *Formulate EE maximization mathematically*
2. *Optimize cell density and other parameters – what do we get?*

PROBLEM FORMULATION

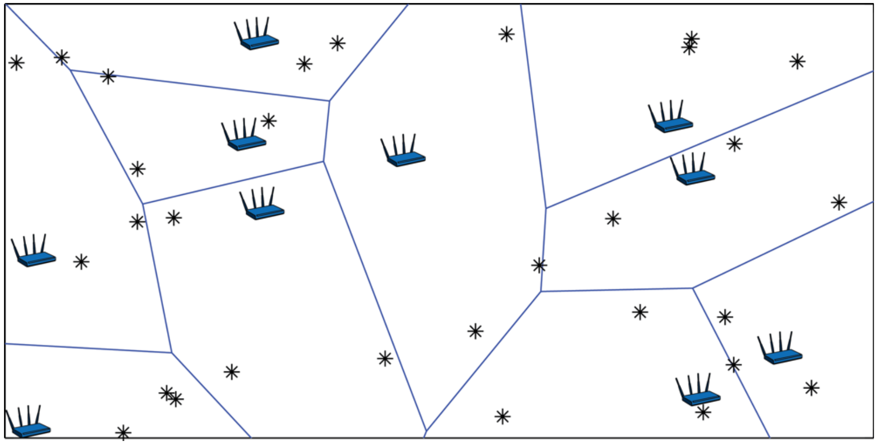
System Model and Average Rate

Random Network Deployment

Access points (AP) positions as Poisson point process (PPP) Ψ_λ

M *antennas per AP,* K *users per cell*

Pathloss: $\omega^{-1}(\text{distance [km]})^{-\alpha}$



Scenario: Downlink Broadband Access

Perfect channel knowledge

Zero-forcing precoding

Transmit power per user: ρ

Hardware distortion at users: ϵ^2

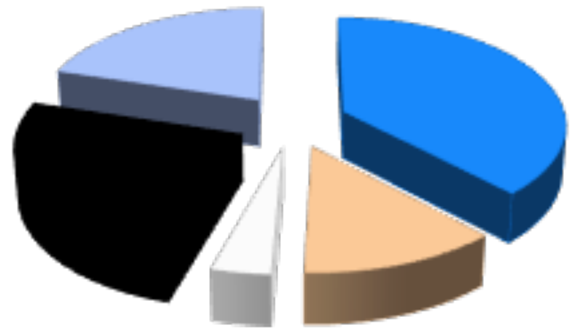
Proposition 1: Lower Bound on Average Rate

$$\underline{R} = B \cdot \log_2\left(1 + \frac{(1-\epsilon^2)(M-K)}{\frac{2K}{\alpha-2} + \epsilon^2(M-K) + \frac{M}{(\pi\lambda)^{\alpha/2}}\frac{\omega\sigma^2}{\rho}}\right)$$

Bandwidth

Generic Power Consumption Model

- Many Components Consume Power
  - Radiated transmit power
  - Baseband signal processing (e.g., precoding)
  - Active circuits (e.g., converters, mixers, filters)



- Area Energy Consumption $[\mathrm{Joule/s/km^2}]$:

$$\mathrm{AEC} = \lambda \left(\frac{K\rho}{\eta} + C_0 + D_0 M + C_1 K + D_1 M K \right)$$

Power amplifier
(η is efficiency)

Fixed power
(backhaul, load-ind. processing)

Circuit power per
transceiver chain

Cost of digital signal processing
(e.g., precoding)

***Nonlinear increasing function** of M and K*

***Many coefficients:** η, C_i, D_i for $i = 0,1$*

Problem Formulation

Energy Efficiency Optimization

$$\underset{\rho, \lambda, M, K}{\text{maximize}} \quad \frac{\lambda K \underline{R}}{\lambda\left(\frac{K\rho}{\eta} + C_0 + D_0 M + C_1 K + D_1 MK\right)}$$

$$\text{subject to} \quad \underline{R}/B = \gamma$$

Optimization variables:

ρ = *transmit power,* λ = *AP density,*

M = *antennas per AP,* K = *users per AP*

Spectral efficiency (SE) constraint γ needed to not get overly low rates

ANALYTICAL AND NUMERICAL RESULTS

Optimality of Small Cells

Theorem 1: Optimal AP Density

The EE increases with λ.

EE maximized as $\lambda \rightarrow \infty$ or at some upper value $\lambda_{\max}$

Saturation Property

Higher density λ → Less transmit power → Eventually negligible

Simulations show saturation at $\lambda \geq 10^2$
50 meters between APs: Saturation appears in practice!

Optimization of Remaining Variables

Theorem 2: Optimal Transmit Power

Constraint satisfied if $\rho^* = \dfrac{\frac{2^{\gamma}-1}{1-2^{\gamma}\epsilon^2}\frac{\omega\sigma^2\Gamma(\alpha/2+1)}{(\pi\lambda)^{\alpha/2}}}{M-K-\frac{2^{\gamma}-1}{1-2^{\gamma}\epsilon^2}\frac{2K}{\alpha-2}}$

Removes ρ *from*
EE optimization problem
(Only M ***and*** K ***remain)***

Theorem 3: Optimal Number of Antennas *(fixed* K*)*

EE maximized by $M^* = K + \dfrac{2K(2^{\gamma}-1)}{(\alpha-2)(1-2^{\gamma}\epsilon^2)} + \sqrt{\dfrac{2^{\gamma}-1}{1-2^{\gamma}\epsilon^2}\dfrac{K\omega\sigma^2\Gamma(\alpha/2+1)}{\eta(\pi\lambda)^{\alpha/2}(D_0+D_1K)}}$

Theorem 4: Optimal Number of Users *(fixed* $M/K=\beta$*)*

EE maximized by $K^* = \sqrt{\dfrac{\frac{2^{\gamma}-1}{1-2^{\gamma}\epsilon^2}\frac{\omega\sigma^2\Gamma(\alpha/2+1)}{\eta(\pi\lambda)^{\alpha/2}}}{\beta D_1(\beta-1-\frac{2^{\gamma}-1}{1-2^{\gamma}\epsilon^2}\frac{2}{\alpha-2})} + \dfrac{C_0}{\beta D_1}}$

Iterate between
these till convergence:
Find real-valued
global solution

Tradeoffs and connections established formulas!

Simulation Parameters

Simulation Parameter	Symbol	Value
Pathloss exponent	α	3.76
Pathloss over noise at 1 km	ω/σ^2	33 dBm
Amplifier efficiency	η	0.39
Level of hardware impairments	ϵ	0.05
Bandwidth	B	20 MHz
Static power	C_0	10 W
Circuit power per active user	C_1	0.1 W
Circuit power per AP antenna	D_0	1 W
Signal processing coefficient	D_1	3.12 mW

Impact of Number of Antennas and Users

Simulation

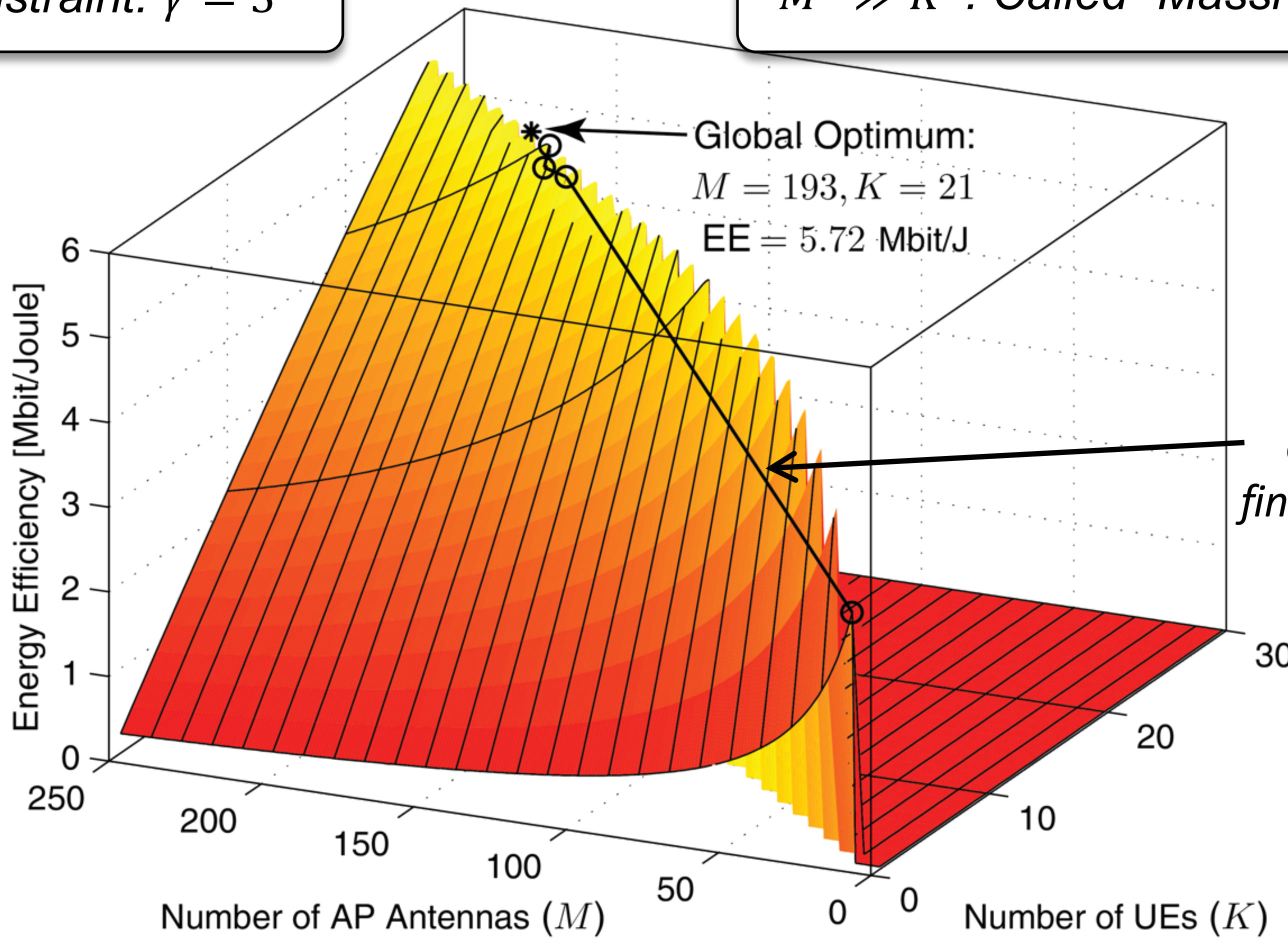
AP density $\lambda = 10^4$

SE constraint: $\gamma = 3$

Observations

Optimal: $M^* = 193,\ K^* = 21$

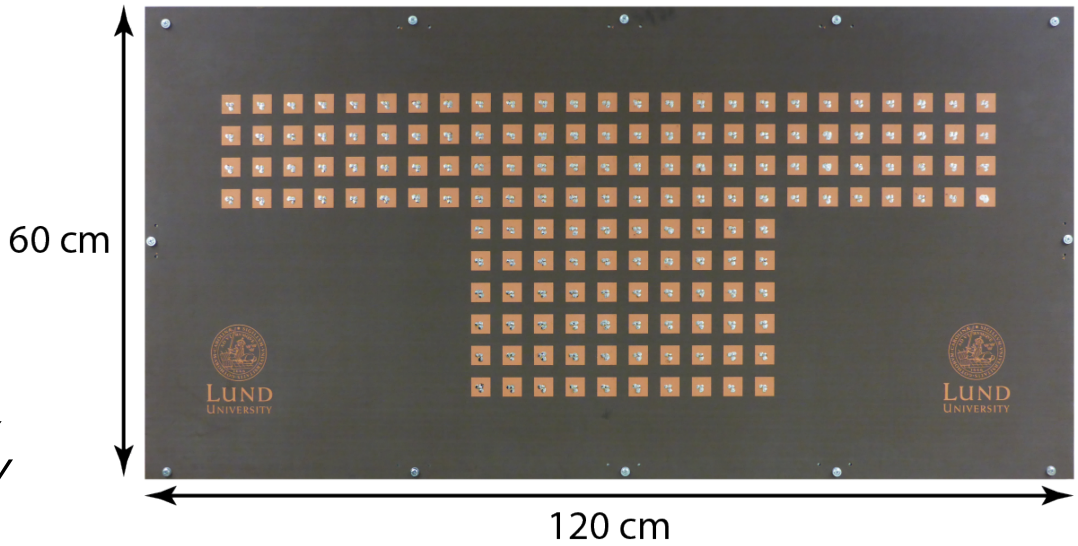
$M^* \gg K^*$*: Called "Massive MIMO"*



Alternating optimization finds real-valued solution

Is it Ridiculous with 200 Antennas?

- Dimensionality: Half-wavelength Antenna Spacing
  - Example: 3.7 GHz
    Spacing: 4 cm
  - Array = Flat-screen TV



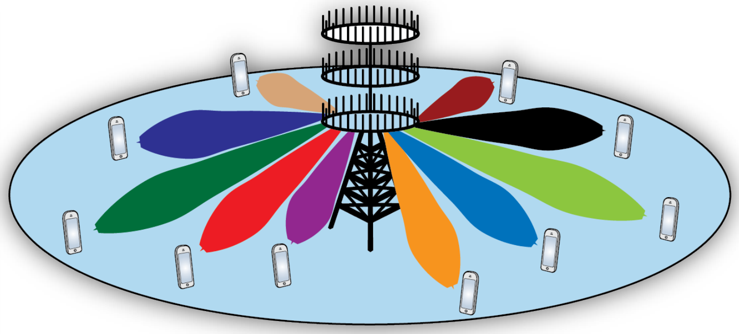
160 dual-polarized antennas,
LuMaMi testbed, Lund University

Why Massive MIMO, Not Only Small Cells?

Small cells improve SNR, but not SINR

Massive MIMO improves SINRs by precoding

Circuit power costs are shared between users



Impact of User Density

Simulation

Fixed user density μ users/km²

EE maximization with: $K\lambda = \mu$

Range: $\mu = 10^2$ (rural) to $\mu = 10^5$ (mall)

Low User Density

Add more cells with $K \approx 1$

Most important to reduce pathloss

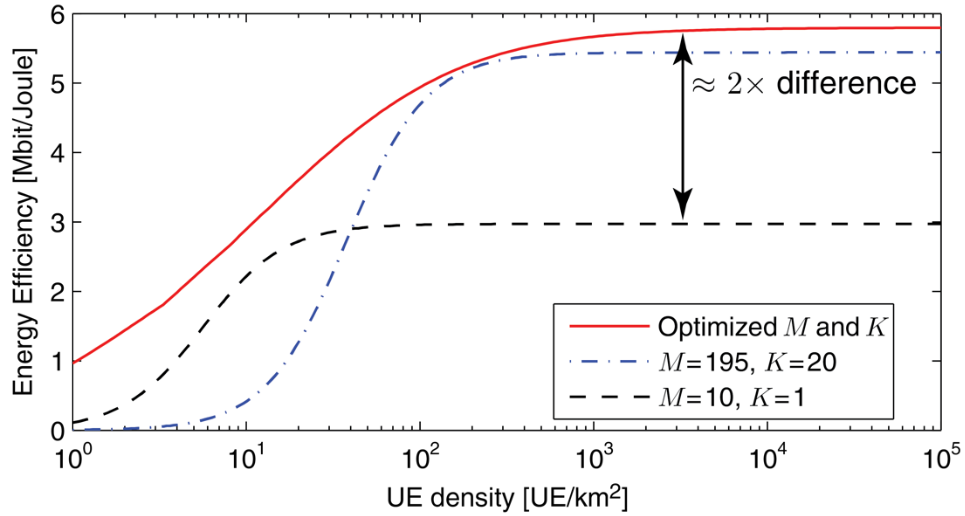
High User Density

Small cells with Massive MIMO

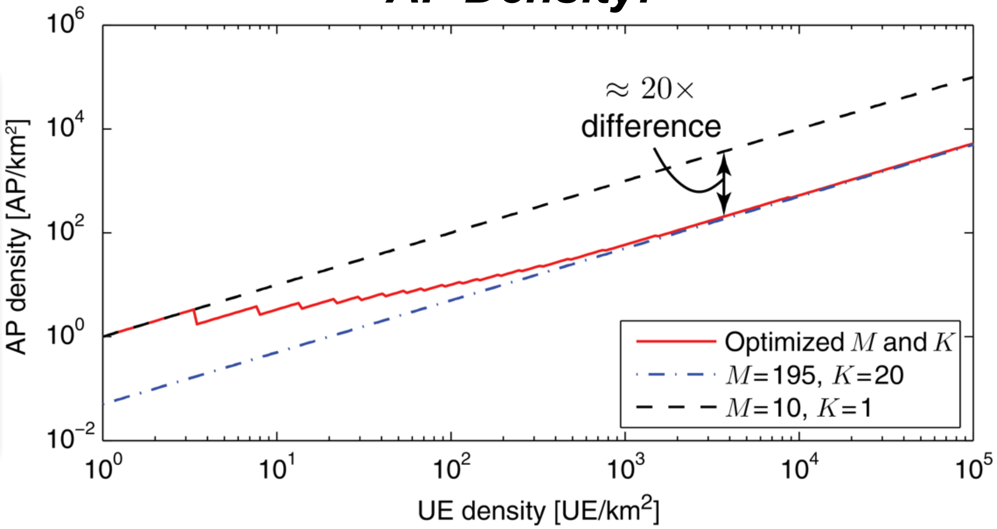
Saturation for $\mu \geq 100$

Covers most practical scenarios:
EE independent of user load!

Energy Efficiency:



AP Density:



SUMMARY

Summary

- Designing Networks for Energy Efficiency
  - Optimize: AP density, transmit power, and antennas/users per cell
  - Analytical optimization: EE maximizing network deployment was found!
  - Solution: Small cells with Massive MIMO capability
  - Intuition: Small cells → Negligible transmit power
    Massive MIMO → Less interference, share costs over users

- Further Results:
  - Take channel estimation and imperfect channel knowledge into account

1. E. Björnson, L. Sanguinetti, M. Kountouris, "*Deploying Dense Networks for Maximal Energy Efficiency: Small Cells Meet Massive MIMO*," Submitted to IEEE JSAC. (http://arxiv.org/pdf/1505.01181)
2. E. Björnson, L. Sanguinetti, M. Kountouris, "*Energy-Efficient Future Wireless Networks: A Marriage between Massive MIMO and Small Cells*," Proceedings of IEEE SPAWC, July 2015. (http://arxiv.org/pdf/1506.01051)

QUESTIONS?

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