Which Variables Can be Optimized in Wireless Communications?

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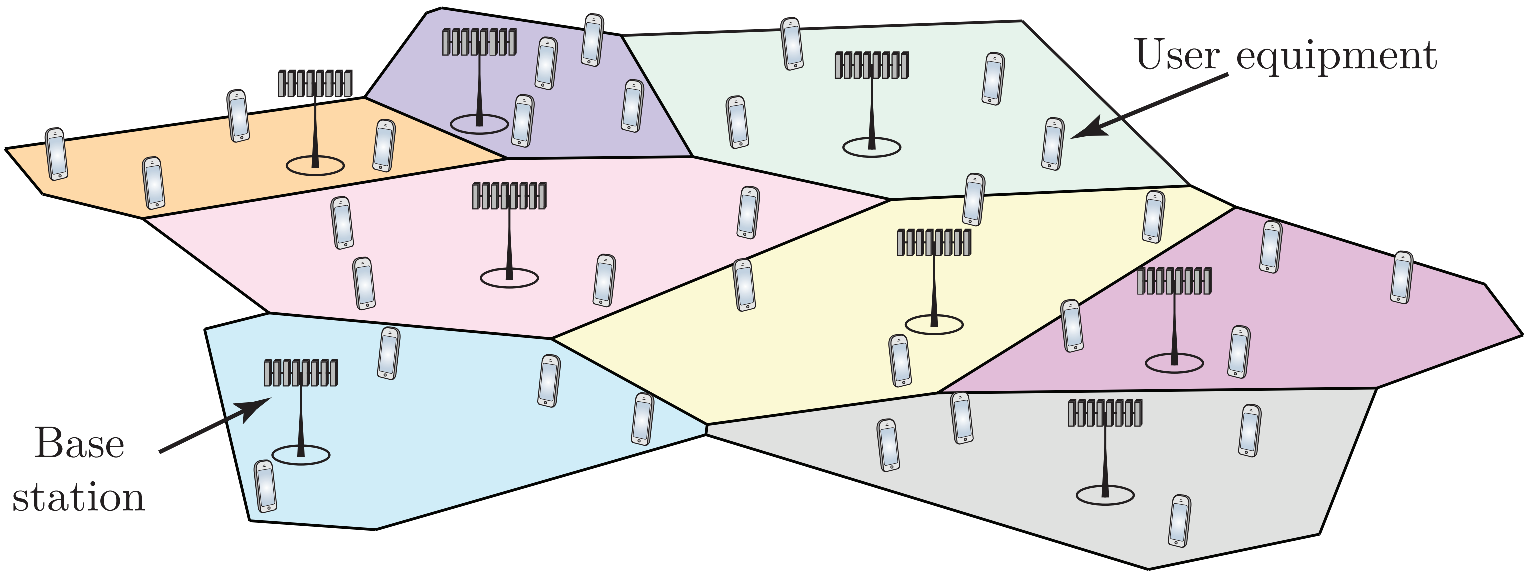
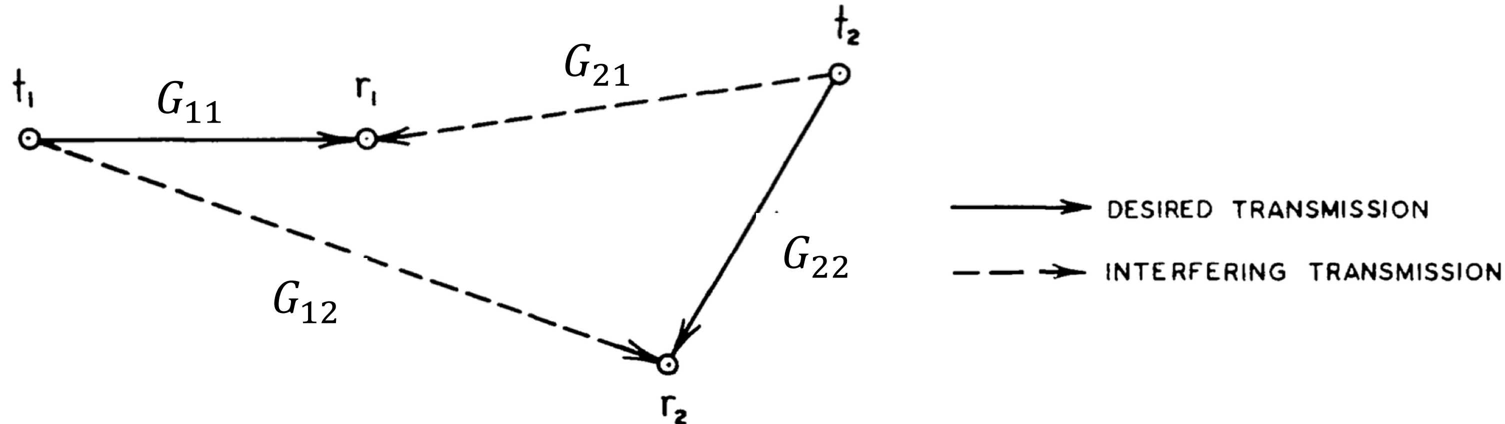
Cellular communications



- Reuse time/frequency resources across cells
  - Leads to co-user interference
  - Important to optimize transmit powers

Signal-to-interference-and-noise ratio (SINR)



K transmitters/receivers

P_i: Power of transmitter i

G_{ki}: Channel gain from transmitter k to receiver i

Desired signal

$$\mathrm{SINR}_i = \frac{G_{ii}P_i}{\sum_{k \neq i} G_{ki}P_k + \sigma^2}$$

Interference from transmitter k

Noise variance

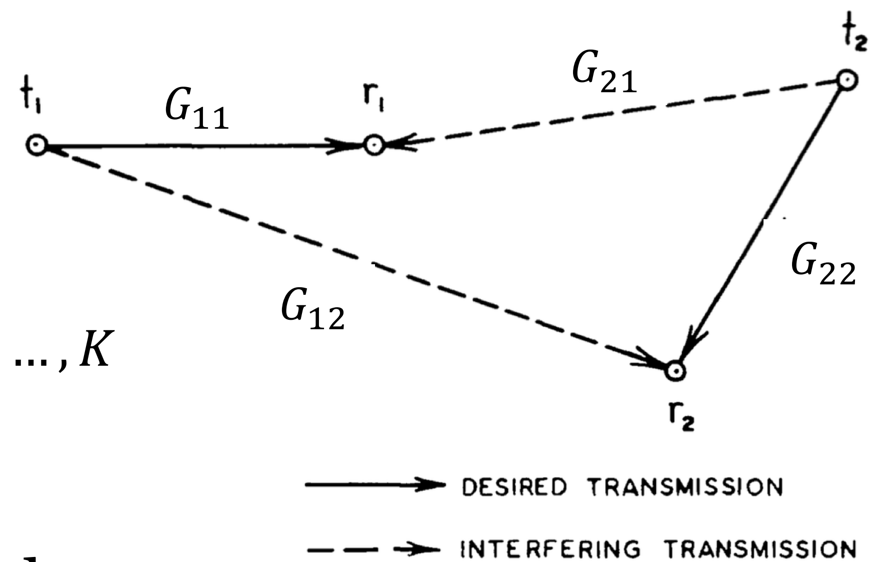
Minimize power under SINR constraints

- Optimization problem:

$$\underset{P_1,\dots,P_K \geq 0}{\text{minimize}} \quad \sum_{k=1}^{K} P_k$$

$$\text{s.t.} \ \frac{G_{ii}P_i}{\sum_{k\neq i} G_{ki}P_k + \sigma^2} \geq \gamma_i, \qquad i = 1,\dots,K$$

Required SINR level



<u>This is a linear program!</u>

Reference: F. Bock, B. Ebstein, *"Assignment of transmitter powers by linear programming,"* IEEE Trans. on Electromagnetic Compatibility, 1964

What has happened since 1964?

- Minimize power under SINR constraints
  - Beamforming: Multiple antennas at transmitter
  - Fading channels: Estimation errors, static effective SINRs
  - Other types of interference (e.g., distortion)

- Other objective functions

Sum rate:

– Maximize $\mathrm{SR}(P_1, \ldots, P_K) = \sum_{i=1}^{K} \log_2(1 + \mathrm{SINR}_i)$ s.t. $\sum_i P_i \leq P_{\max}$

Max-min fairness:

– Maximize $\mathrm{MMF}(P_1, \ldots, P_K) = \min_i \mathrm{SINR}_i$ s.t. $\sum_i P_i \leq P_{\max}$

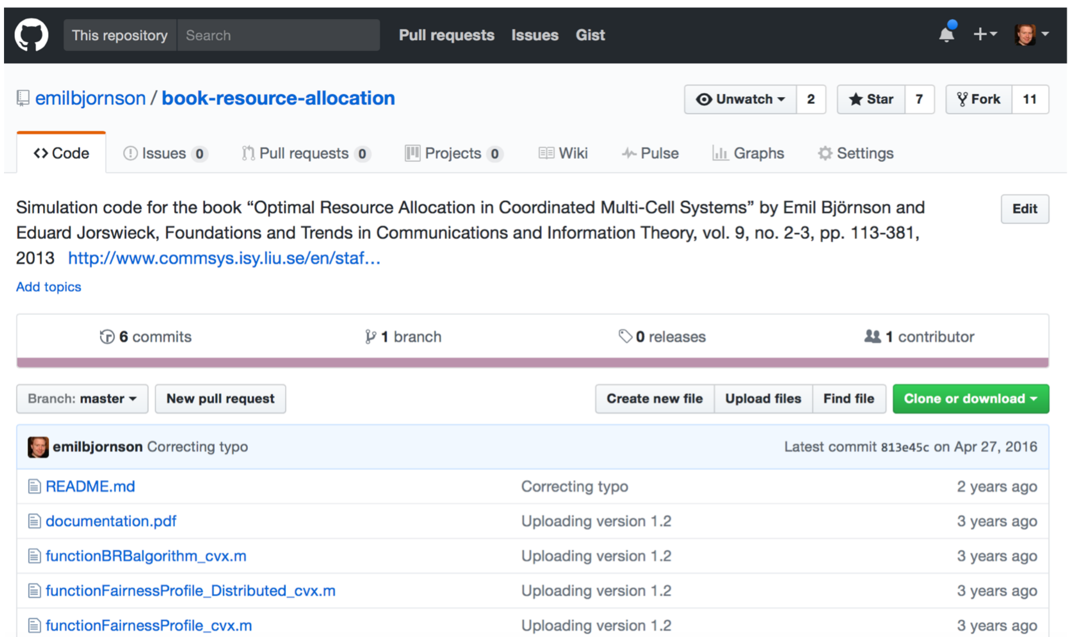
Energy efficiency:

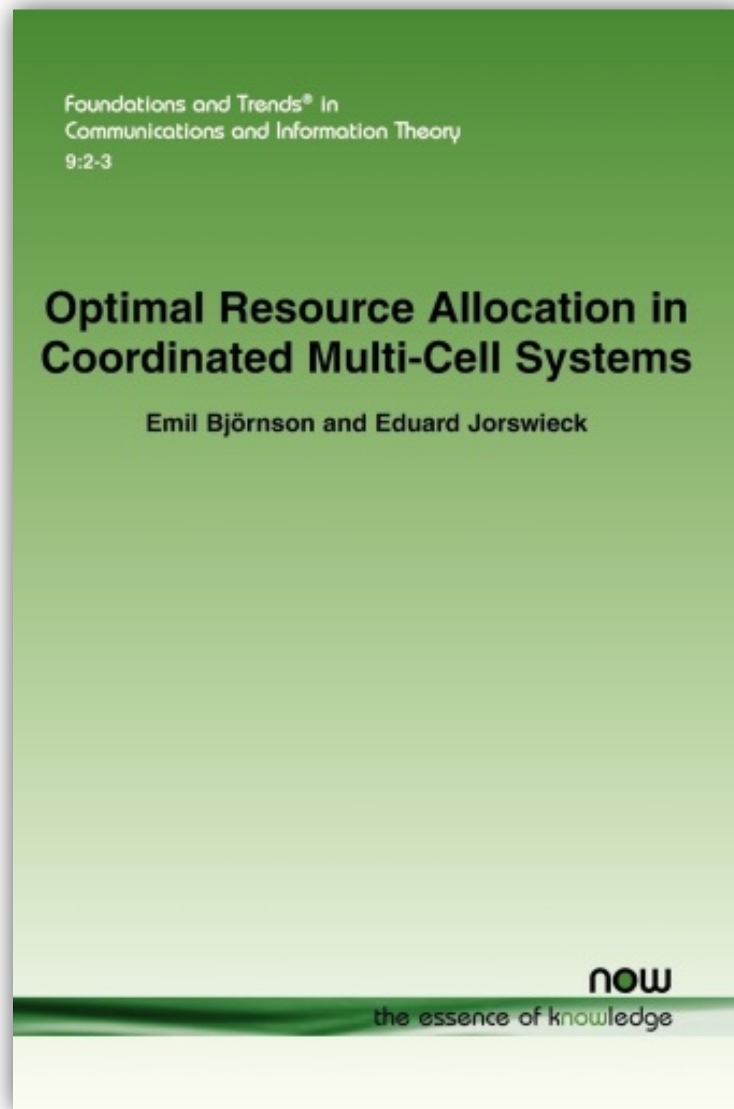
– Maximize $\mathrm{EE}(P_1, \ldots, P_K) = \frac{\mathrm{SR}(P_1,\ldots,P_N)}{\sum_i P_i + \text{circuit power}}$

Same optimization variables: Transmit powers!

This is textbook material

- One of several examples:





Can we optimize anything else?

- Potential optimization variables
  - M: Number of antennas per transmitter
  - K: Number of active users per cell
  - λ: Density of base stations
  - ϵ: Hardware quality indicator

- My objective: Maximize Energy efficiency

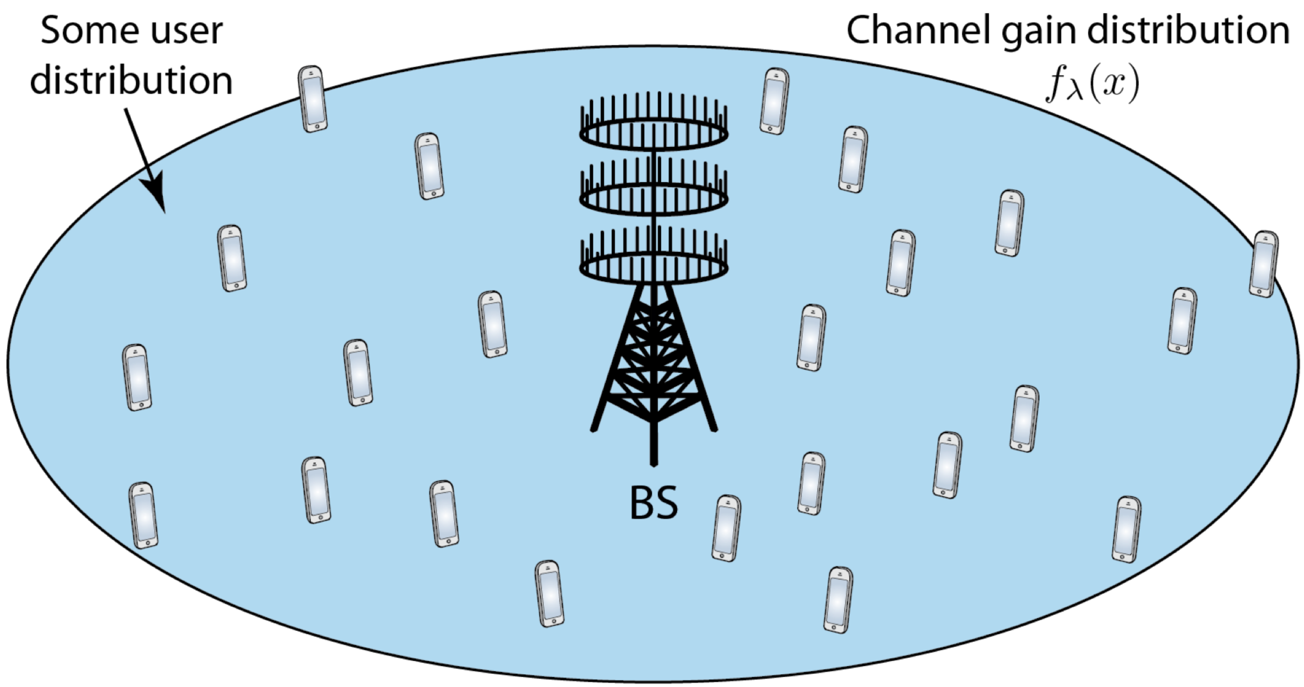
$$\text{EE [bit/Joule]} = \frac{\text{Average Sum Rate [bit/s/cell]}}{\text{Average Power Consumption [W/cell]}}$$

Energy-efficient multi-user system

- One cell with many users at random locations
  - Pick K users randomly and serve with rate R
  - Place M antennas at base station

Problem

Select (M, K, R) to maximize energy efficiency

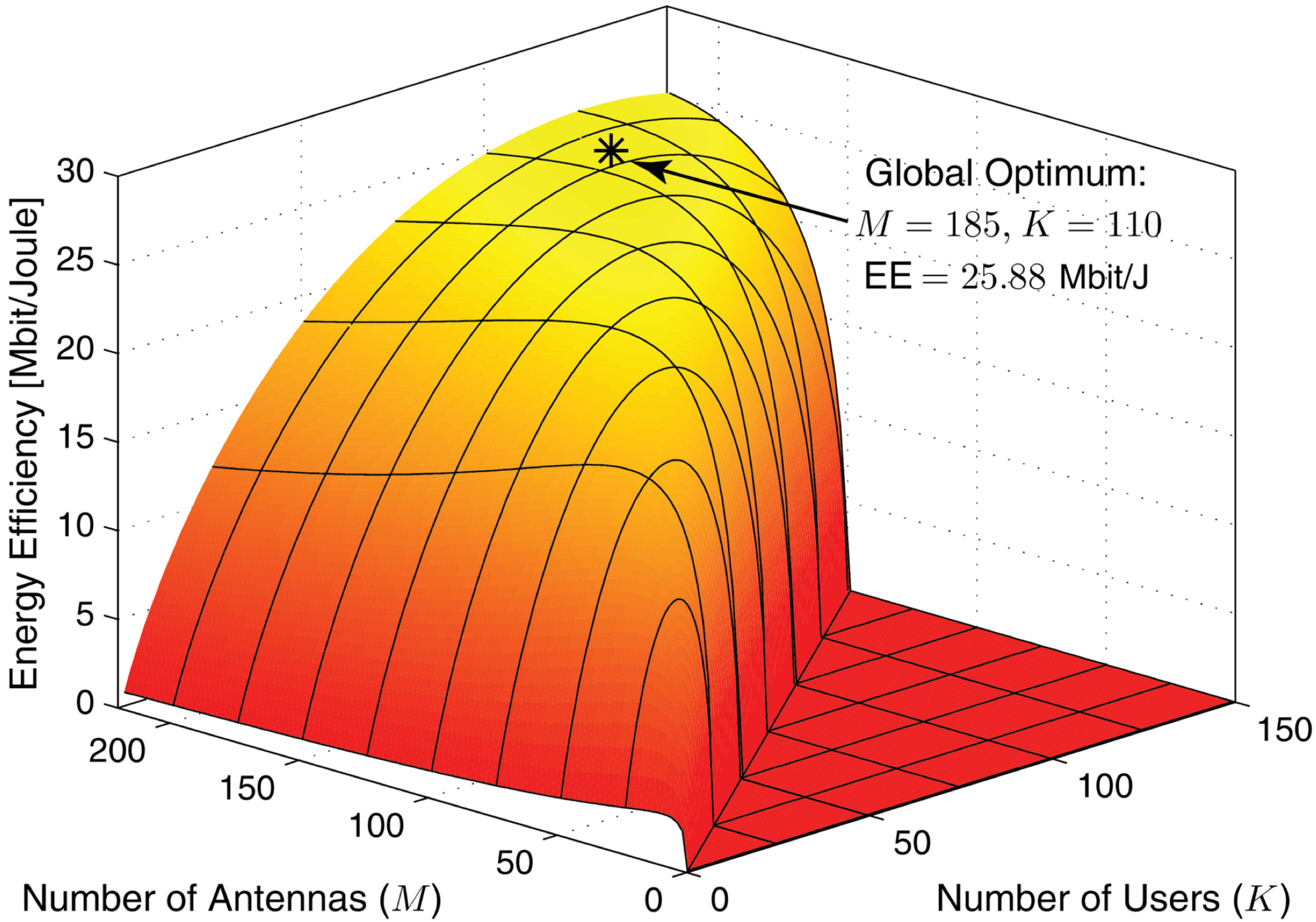


Modeling the optimization problem

- After some modeling effort ($\rho = (2^R - 1)/(M - K)$):

$$\underset{M,K,\rho}{\text{maximize}} \quad \frac{\overbrace{KB\log_2(1+\rho(M-K))}^{\text{Sum rate}}}{\underbrace{\rho B\sigma^2\mathcal{S}_\lambda K}_{\text{Transmit power}} + \underbrace{C_0 + D_1 M + C_1 K + D_2 MK + C_2 K^2 + C_3 K^3 + D_3 MK^2}_{\text{Circuit power}}}$$

  - Circuit power from transceivers and baseband computations
  - Assumptions: Same rate in uplink and downlink



Reference:

E. Björnson, L. Sanguinetti, J. Hoydis, M. Debbah, "*Optimal Design of Energy-Efficient Multi-User MIMO Systems: Is Massive MIMO the Answer*?," IEEE Trans. on Wireless Communications, 2015

2018 IEEE Marconi Prize Paper Award in Wireless Communications

Optimizing base station density: λ

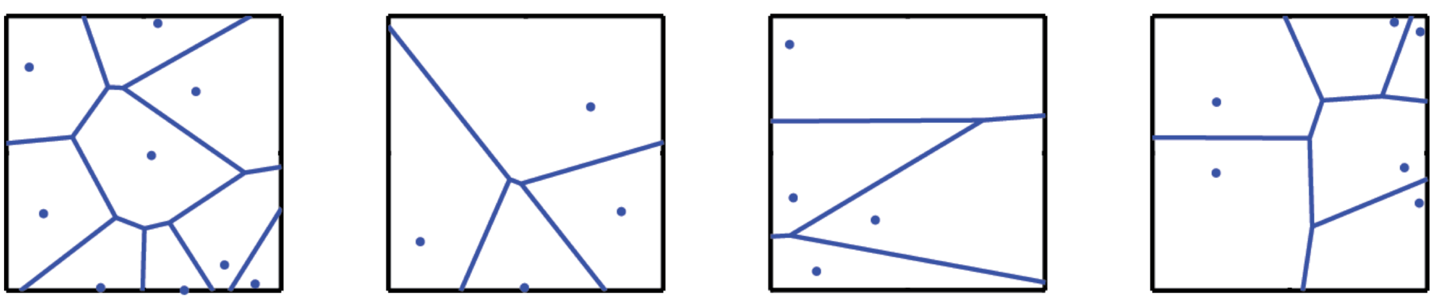
Homogeneous Poisson point process (PPP)

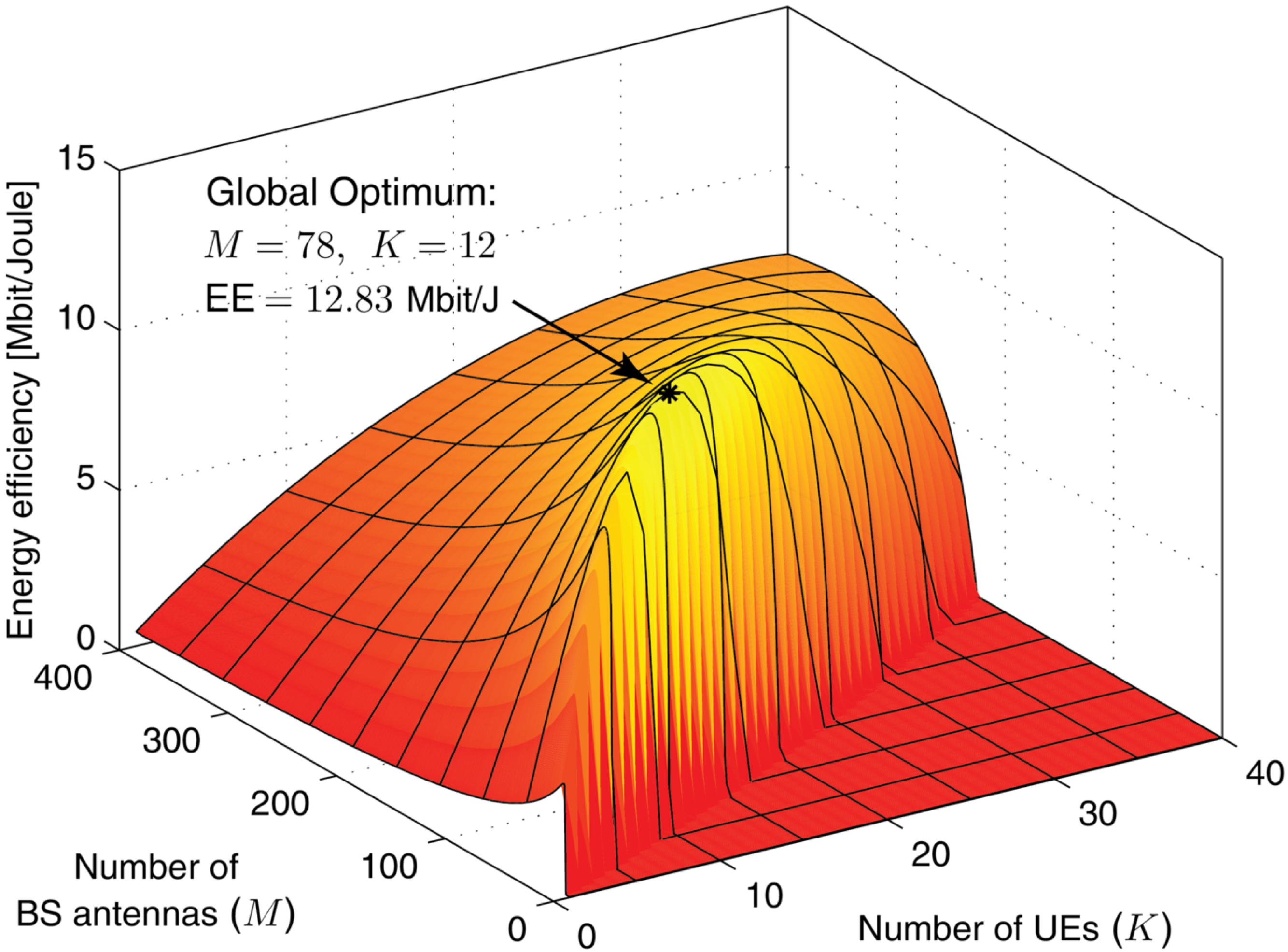
Independent and equally distributed points in $\mathbb{R}^2$

Density: λ BSs per km²

Po($\lambda\mathcal{A}$) BSs in any area of size $\mathcal{A}$ km²:
Uniformly distributed in the area

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





Insights

Make λ as large as possible

EE grows very slowly with λ for $\lambda > 10$ BS/km²

EE Maximization Problem

$$\begin{array}{ll} \underset{M,K,\rho,\lambda}{\text{maximize}} & \dfrac{K \cdot B \cdot \log_2\left(1+\underline{\mathrm{SINR}}(M,K,\rho)\right)}{\mathrm{P}_{\mathrm{total}}(M,K,\rho,\lambda)} \\ \text{subject to} & \underline{\mathrm{SINR}} = \gamma \end{array}$$

Reference:

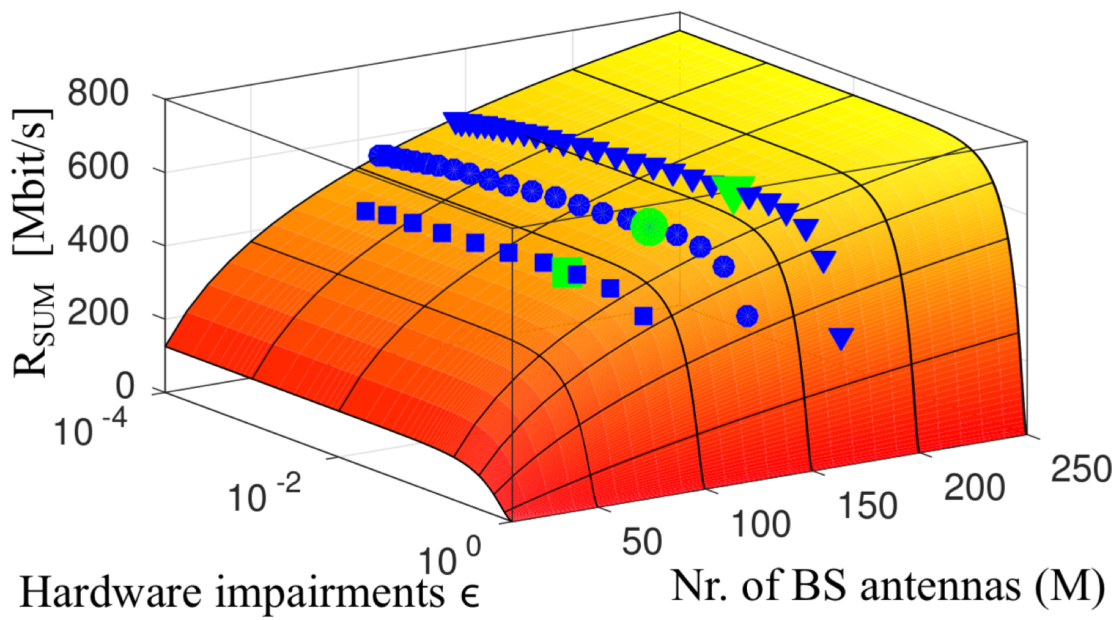
E. Björnson, et al., *"Deploying Dense Networks for Maximal Energy Efficiency: Small Cells Meet Massive MIMO,"* JSAC 2016

Hardware quality

- Design tradeoff
  - High-resolution hardware (little distortion, high power)
  - Low-resolution hardware (higher distortion, lower power)
  - Modeling: Fraction ϵ^2 of signal power replaced by distortion

Optimization Problem

$$\underset{M,\epsilon}{\text{maximize}} \quad \text{Sum rate}(M,\epsilon)$$
$$\text{subject to} \quad \text{Power}(M,\epsilon) \leq \gamma$$



Reference:
D. Verenzuela, et al., *"Hardware Design and Optimal ADC Resolution for Uplink Massive MIMO Systems,"* SAM 2016

Would you like to optimize wireless networks?

- Focus
  - Optimize design variables that previously been constant

- Possible research directions
  - Compare different network topologies
    - Massive MIMO (small λ, large M)
    - Small cells (large λ, small M)
  - Compare different hardware designs
    - Few transceivers with high quality
    - Many transceivers with low quality