Designing Energy Efficient 5G Networks: When Massive Meets Small

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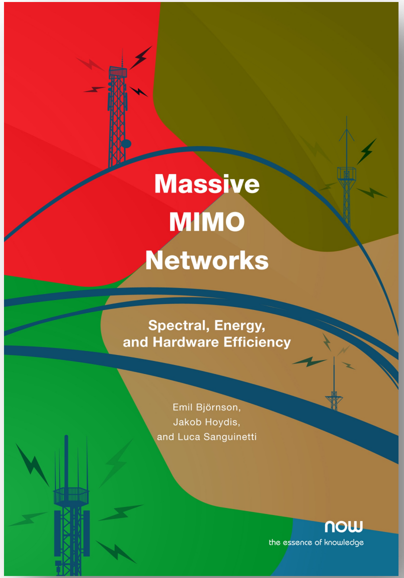
Dr. Emil Björnson

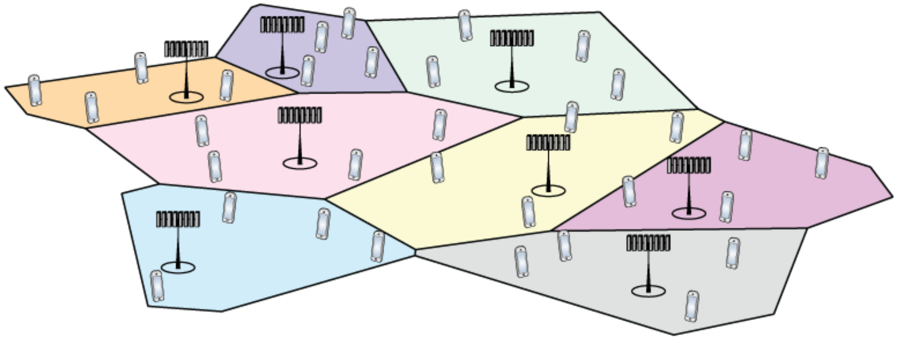
- *Associate professor at Linköping University*
- *10 year experience of MIMO research*
- *2 books and 8 best paper awards*
- *Tens of pending patent applications*
- *Writer at the Massive MIMO blog, http://massive-mimo.net*



Outline

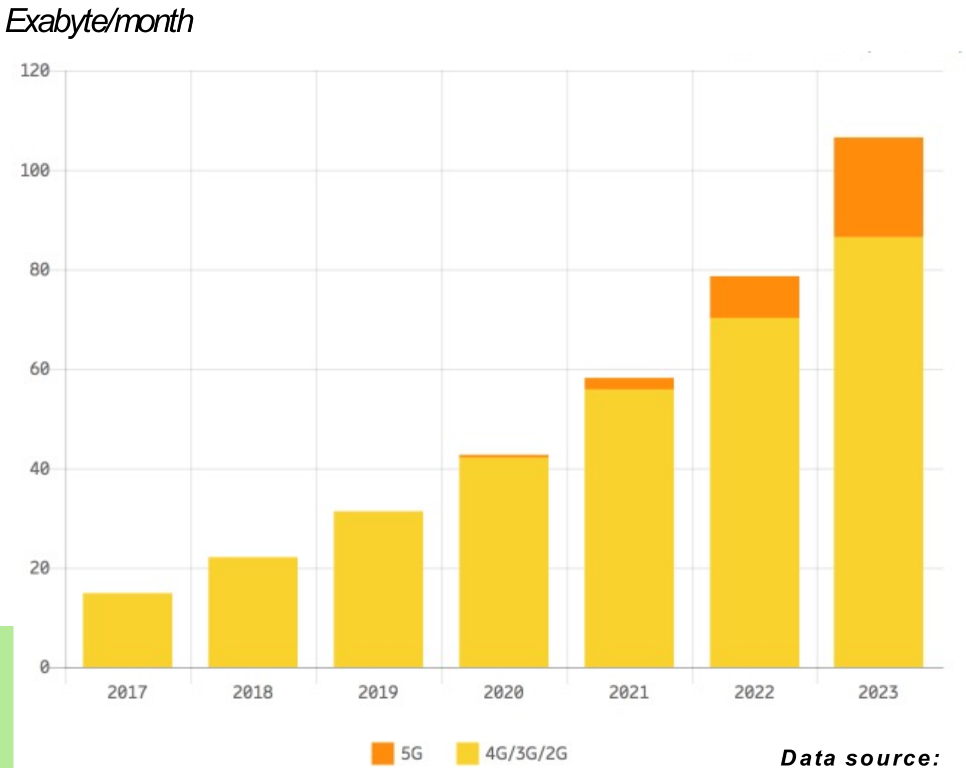
1. What is Energy Efficiency?
2. Potential Solutions for Higher Energy Efficiency
3. Case study: When Massive MIMO meets Small Cells

Exponential Traffic Growth in Cellular Networks



- 39% More Data Every Year
  - 7x from 2017 to 2023
  - Video dominant application

Same trend for energy consumption?
Can we make 5G more energy efficient?



Data source:

Ericsson Mobility Report (June 2018)

What is Energy Efficiency?

- Benefit-Cost Analysis:

Cost:
Energy consumption
(Watt=Joule/s)

→ **Cellular network** →

Benefit:
Data throughput
(bit/s)

- Benefit-Cost Ratio:

$$\text{Energy efficiency [bit/Joule]} = \frac{\text{Data throughput[bit/s/km}^2\text{]}}{\text{Energy consumption [Joule/s/km}^2\text{]}}$$

Environmental concerns

Energy production is mainly non-renewable

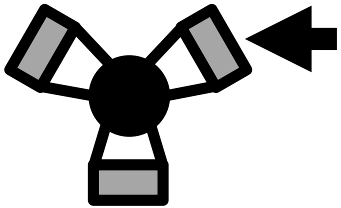
Economical concerns

Energy price: Joule/€

Other costs can also be included

Energy Consumption of a 4G/LTE Base Station

One site, three base stations



Dual-polarized antenna panel

Power amplifiers

Data throughput
Up to 28 Mbit/s

Energy consumption
1.35 kW

Energy efficiency
28 Mbit/s / 1.35 kW = 20 kbit/Joule

Reference:

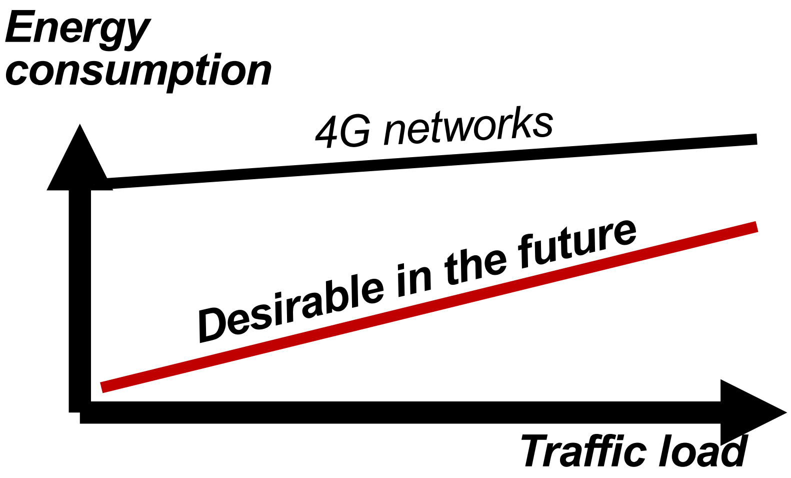
Auer et al., "How much energy is needed to run a wireless network?," IEEE Wireless Communication, 2011

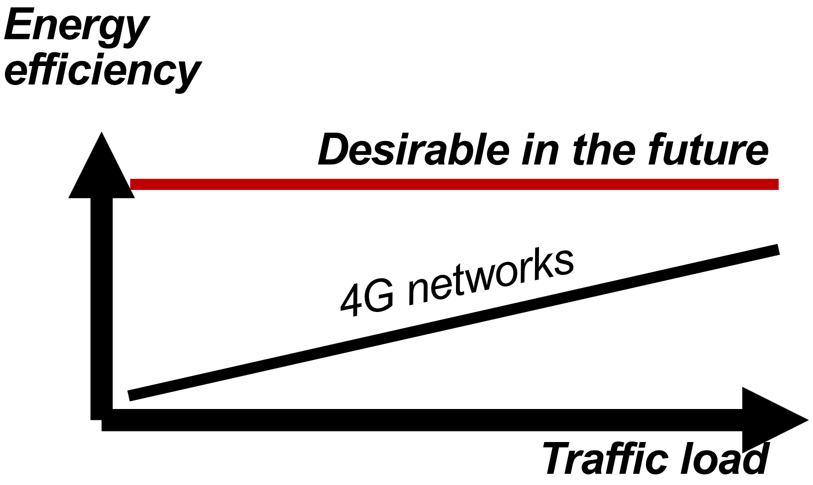
Is 4G Becoming More Energy Efficient?

“While traffic in mobile networks has grown tremendously over the last few years, networks have become increasingly energy efficient.”

- *Ericsson Mobility Report, Nov. 2015*

- *13 times more traffic, 40% higher energy consumption*



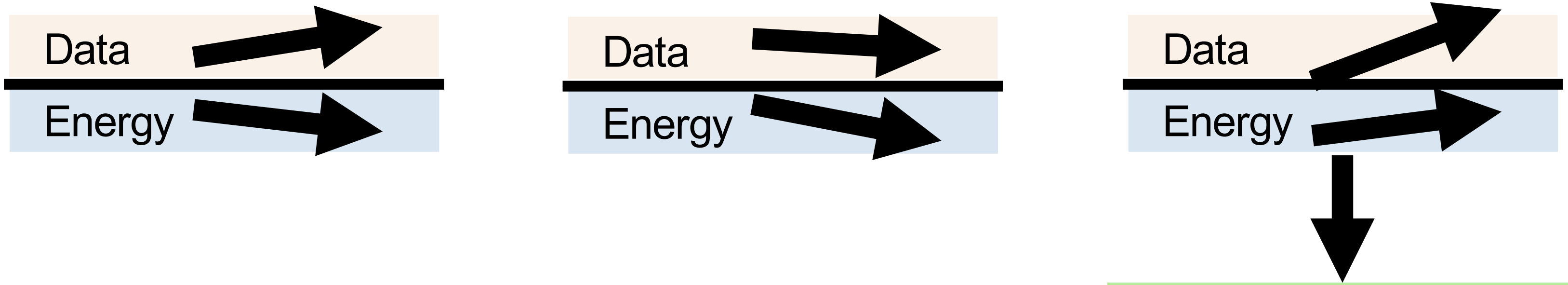


Yes, but not in the right way

How to Design Energy Efficient Networks?

$$\text{Energy efficiency [bit/Joule]} = \frac{\text{Data throughput[bit/s/km}^2]}{\text{Energy consumption [Joule/s/km}^2]}$$

- Many possible solutions:



Non-trivial tradeoffs!

Complex networks

Most likely solution

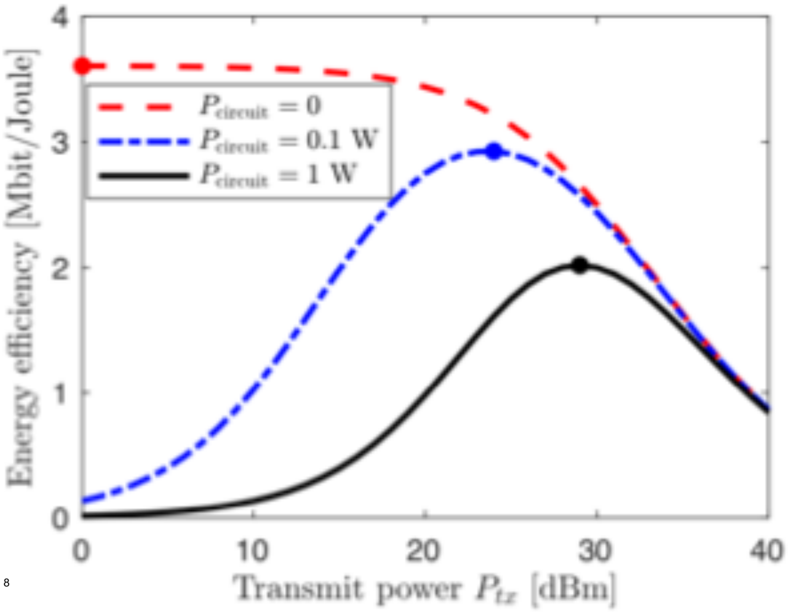
Higher energy consumption, but more energy efficient

Potential Solution: Power Control

- Consider point-to-point transmission:

$$\frac{\text{Data throughput}}{\text{Energy consumption}} = \frac{B \log_2\left(1 + \frac{P_{tx}\beta}{BN_0}\right)}{\frac{P_{tx}}{\mu} + P_{\text{circuit}}}$$

Bandwidth · *Transmit power* · *Pathloss* · *Noise power spectral density* · *Amplifier efficiency* · *Circuit power*



Unimodal functions

Control transmit power to find optimum

Circuit power

Must be accurately modeled

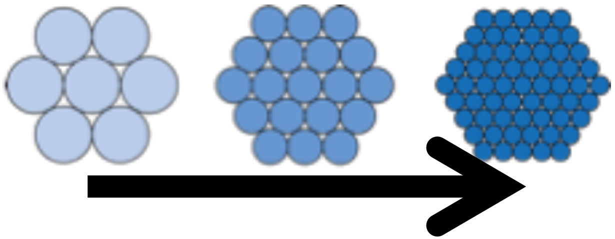
$B = 10$ MHz, $\mu = 0.25$, $BN_0/\beta = 0$ dBm

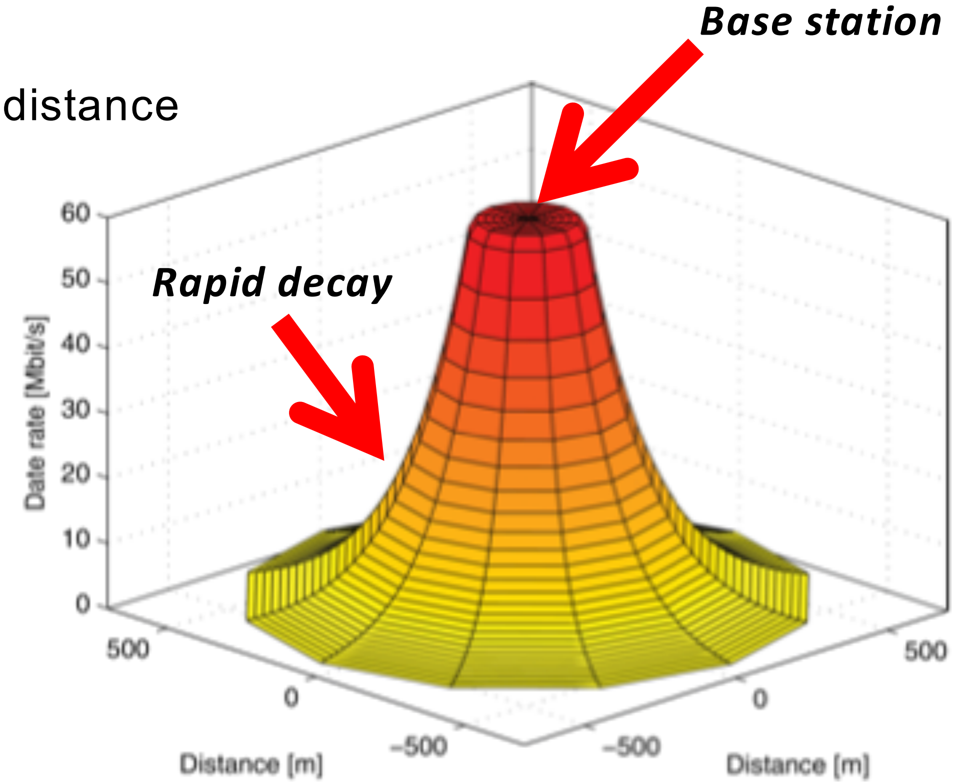
Potential Solution: Smaller Cells

- Signal power decays rapidly with distance
  - 0.001% received at 1 m
  - 0.00001% received at 10 m
  - Faster decay in non-line-of-sight

Smaller cells → Lower loss → Reduce power

1 km^2





Tradeoff: Energy consumption [Joule/s/km^2] = Transmit power + Circuit power

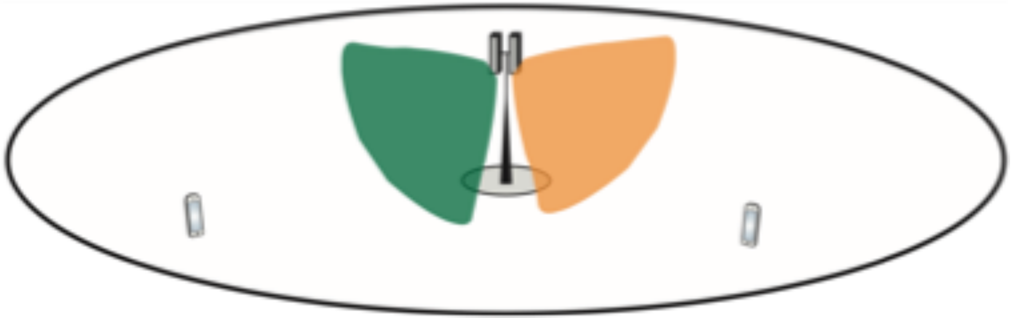
Potential Solution: Massive MIMO (multiple-input, multiple-output)

- Direct signals by beamforming
  - Use antenna array
  - Higher received power
  - Spatial multiplexing

More antennas → Reduce power, multiplex users

Throughput

Tradeoff: Transmit power + Circuit power



Few antennas: Broad beams

Massive number of antennas: Narrow beams

Energy Efficiency Optimization

- How to Find Energy Efficient Network Design?
  1. Select network design variables: $M, K, \rho, \lambda, \tau$
  2. Model throughput and energy consumption as functions of these variables
  3. Solve:

$$\underset{M, K, \rho, \lambda, \tau}{\text{maximize}} \quad \frac{\text{Data throughput}\,(M, K, \rho, \lambda, \tau)}{\text{Energy consumption}\,(M, K, \rho, \lambda, \tau)}$$

References

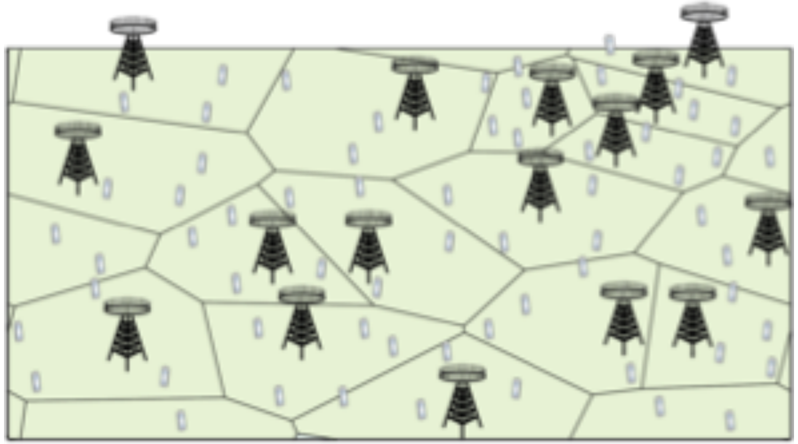
[1] E. Björnson, L. Sanguinetti, J. Hoydis, M. Debbah, "Optimal Design of Energy-Efficient Multi-User MIMO Systems: Is Massive MIMO the Answer?," IEEE Transactions on Wireless Communications, 2015. **2018 Marconi Prize Paper Award in Wireless Communications**

[2] E. Björnson, L. Sanguinetti, M. Kountouris, "Deploying Dense Networks for Maximal Energy Efficiency: Small Cells Meet Massive MIMO," IEEE Journal on Selected Areas in Communications, 2016.

[3] A. Pizzo, D. Verenzuela, L. Sanguinetti, E. Björnson, "Network Deployment for Maximal Energy Efficiency in Uplink with Multislope Path Loss," IEEE Transactions on Green Communications and Networking, 2018.

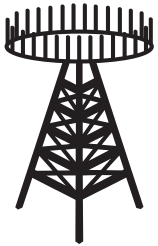
Case Study: Network and Optimization Variables

- Practical Random-like Deployment
  - Approximated by Poisson point process
  - Density: λ base stations per km^2
  - Po($\lambda\mathcal{A}$) random locations in area of $\mathcal{A}$ km^2



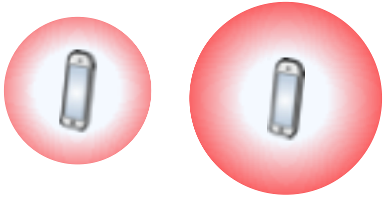
- Optimization variables:

M antennas

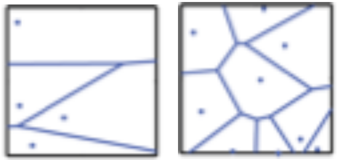


K users per cell

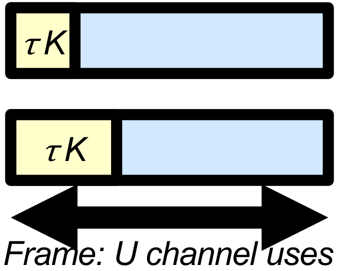
Transmit power ρ



Base station density λ



Pilot reuse factor τ



Modeling Data Throughput

- Average uplink sum rate per cell:

$$\text{Data throughput} = \overset{\text{Multiplexed users}}{K} \cdot \overbrace{\left(1 - \frac{\tau K}{U}\right)}^{\text{Data fraction per frame}} \overbrace{B \log_2(1 + \text{SINR})}^{\text{Data rate per user}}$$

$$\text{SINR} = \frac{M}{\left(K + \frac{BN_0}{\rho}\right)\left(1 + \frac{2}{\tau(\alpha-2)} + \frac{BN_0}{\rho}\right) + \frac{2K}{\alpha-2}\left(1 + \frac{BN_0}{\rho}\right) + \frac{K}{\tau}\left(\frac{4}{(\alpha-2)^2} + \frac{1}{\alpha-1}\right) + \frac{M}{\tau(\alpha-1)}}$$

- Some assumptions:

Pathloss exponent: α

Power decays as $\omega \cdot$ *kilometers*$^{-\alpha}$

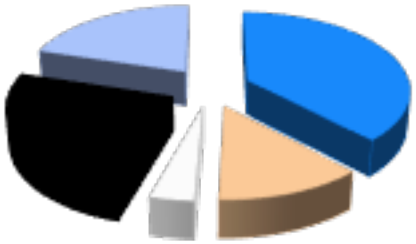
Maximum-ratio processing

using MMSE estimation

Power control for uniform service

Same SNR $\rho/(BN_0)$ for everyone

Modeling Energy Consumption



- Depends strongly on hardware
  - Characterized by parameters: μ, $C_{0,0}$, $C_{0,1}$, $C_{1,0}$, $C_{1,1}$, A

Energy consumption =

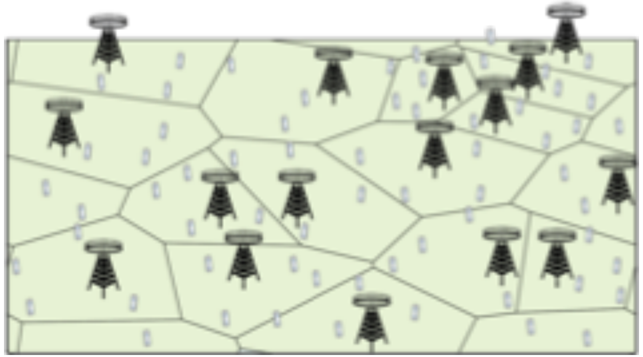
$$\underbrace{K\frac{\rho\omega}{\mu}\frac{\Gamma(\alpha/2-1)}{(\pi\lambda)^{\alpha/2}}\left(1-\frac{\tau K-1}{U}\right)}_{\textit{Transmit power with amplifier inefficiency}} + \overset{\textit{Fixed circuit power}}{C_{0,0}} + \underbrace{C_{0,1}M + C_{1,0}K}_{\textit{Power per transceiver chain}} + \overbrace{C_{1,1}MK}^{\textit{Signal processing}} + \underbrace{A\cdot \text{Data throughput}}_{\textit{Coding/decoding/backhaul}}$$

Parameter values change over time

Model remains fixed – rerun simulations

Simulation Parameters

Parameter	Symbol	Value
Frame length	U	400
Bandwidth	B	20 MHz
Pathloss exponent	α	3.76
Noise over pathloss at 1 km	$(B N_0)/\omega$	33 dBm
Amplifier efficiency	η	0.39
Static power	$C_{0,0}$	10 W
Circuit power per active user	$C_{1,0}$	0.1 W
Circuit power per BS antenna	$C_{0,1}$	0.2 W
Signal processing coefficient	$C_{1,1}$	3.12 mW
Coding/decoding/backhaul	A	$1.15 \cdot 10^{-9}$ J/bit



Test other values?

Download code from Github

Impact of Cell Densification

Different base station densities

All other variables optimized

Constraint: SINR is given

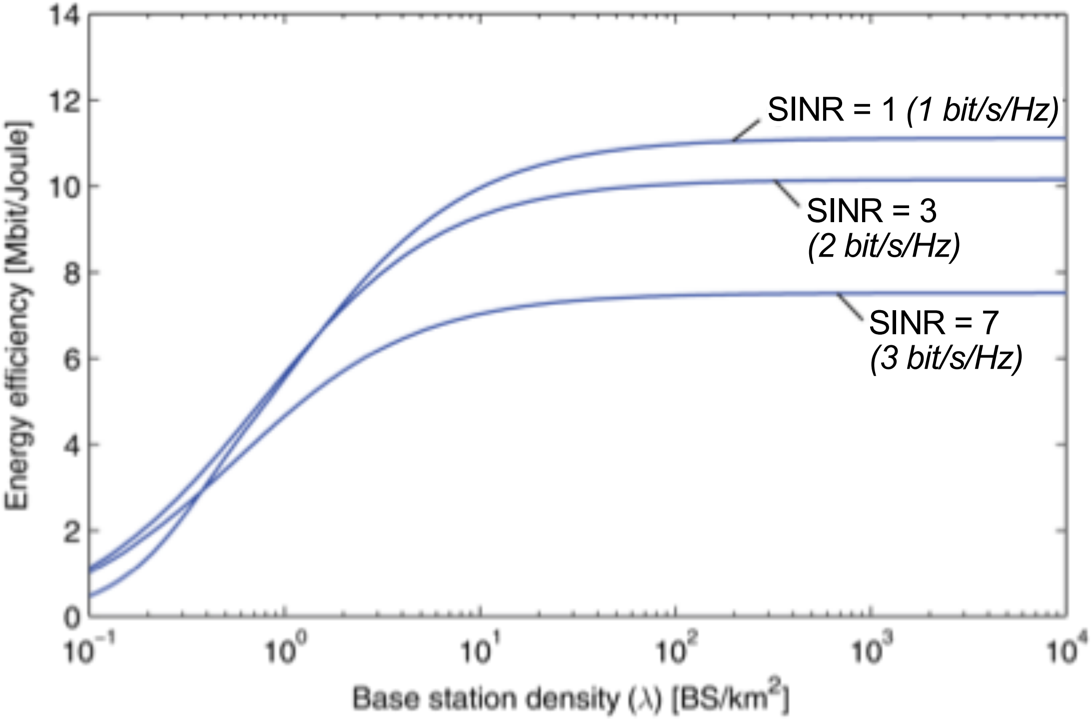
Smaller SINR:
More energy efficient

Energy efficiency grows with λ

Saturates at $\lambda = 10$

150-300 m between base stations

Satisfied in urban areas – today!



Impact of Number of Antennas and Users

Optimized τ, λ, ρ

Constraint: SINR = 3

Optimal: Massive MIMO

$M = 89, K = 10, \tau \approx 7$

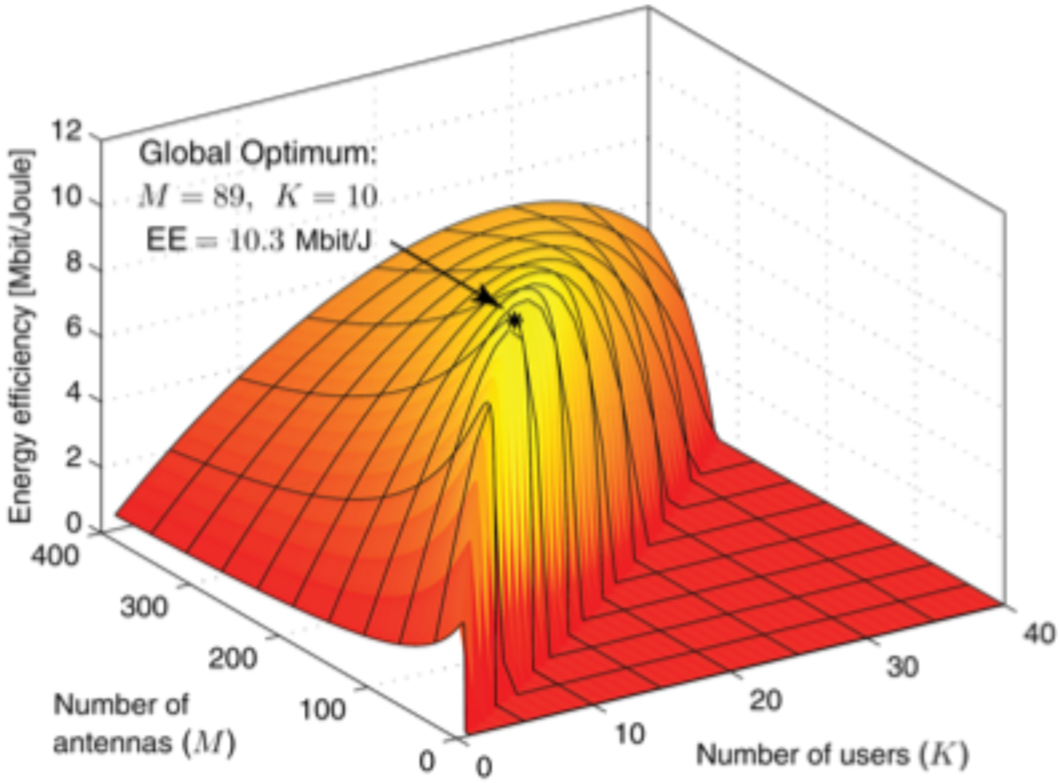
500 times higher efficiency than today

Why not only small cells?

Small cells improve SNR, not SINR

Massive MIMO:

- Improves cell-edge SINR
- Circuit power shared



Energy Consumption at Optimal Solution

- What Consumes Energy?
  - Recall model:

$$C_{0,0} + C_{0,1}M + C_{1,0}K + C_{1,1}MK + A \cdot \text{Data throughput}$$

Dominating Parts

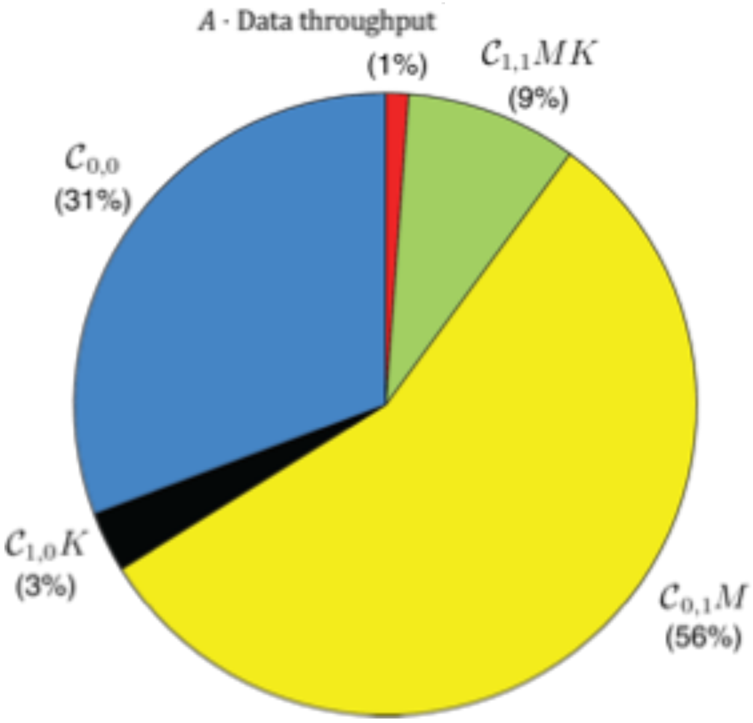
Power of BS transceivers: $C_{0,1}M$

Fixed power consumption: $C_{0,0}$

How to Improve Future Hardware?

Improve the dominating parts

Good design: No part is dominating

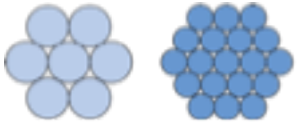


Four Common Misconceptions

Misconception	***Reality***
"We can turn off inactive base stations to save energy"	*Degrades network coverage – **no operator wants that**! (Discontinuous transmission is ok)*
"We normalize the bandwidth to B = 1 Hz and the noise power to 1 without loss of generality"	***No**, the noise power is BN_0. We cannot normalize anything – actual transmit power matters!*
"The energy efficiency is measured in bit/Joule/Hz"	*It **makes no sense** to divide with B to get bit/Joule/Hz since the noise depends on B*
"The radiated energy efficiency of Massive MIMO goes to infinity as $M \rightarrow \infty$"	*Yes, but the **actual** energy efficiency goes to zero since circuit power grows with M*

Conclusions

- Designing Energy Efficient 5G Networks
  - First step: Densify to a few hundred meters between base stations
    - Transmit power becomes negligible
  - Then: Use Massive MIMO
    - Suppress interference spatially
    - Share circuit power between users



Optimal solution: Combination of small cells and Massive MIMO

Methodology for energy efficiency maximization useful in many setups

Other variables: Bandwidth, frequency band, hardware components

Learn More: Blog and Book

- Massive MIMO blog: **www.massive-mimo.net**

Youtube channel:

Massive MIMO for 5G: How Big Can it Get?

https://www.comsoc.org/webinars/

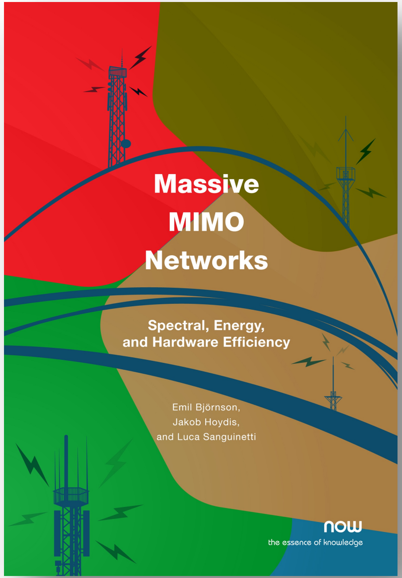
https://youtu.be/m9wEAucKoWo

New book:

Emil Björnson, Jakob Hoydis and Luca Sanguinetti (2017), "**Massive MIMO Networks: Spectral, Energy, and Hardware Efficiency**"

517 pages, Matlab code, Teaching material available

Contact me for a free PDF!



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Thank you!

Questions are most welcome!

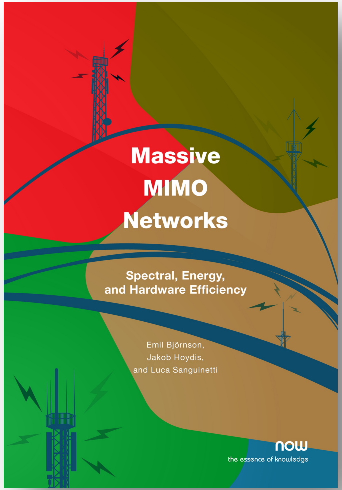
Dr. Emil Björnson

Slides, papers, and code available online:

http://www.ebjornson.com/research

http://www.massivemimobook.com

Emil Björnson, Jakob Hoydis and Luca Sanguinetti (2017),
"Massive MIMO Networks: Spectral, Energy, and Hardware Efficiency"



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