Massive MIMO for 5G below 6 GHz

Achieving Spectral Efficiency, Link Reliability, and Low-Power Operation

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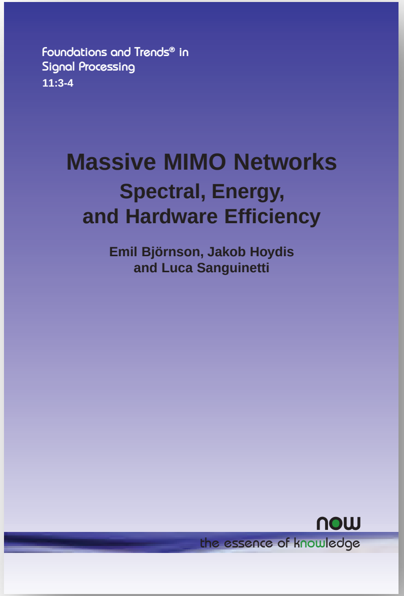
Dr. Emil Björnson

- *PhD from KTH, Sweden; Postdoc at SUPELEC, Paris, France*
- *Associate professor at Linköping University, Sweden*
- *10 year experience of MIMO research*
- *2 books and 7 best paper awards*
- *Some ten pending patent applications*
- *Writer at the Massive MIMO blog, http://massive-mimo.net*
- *First author of textbook "Massive MIMO Networks", Nov. 2017*



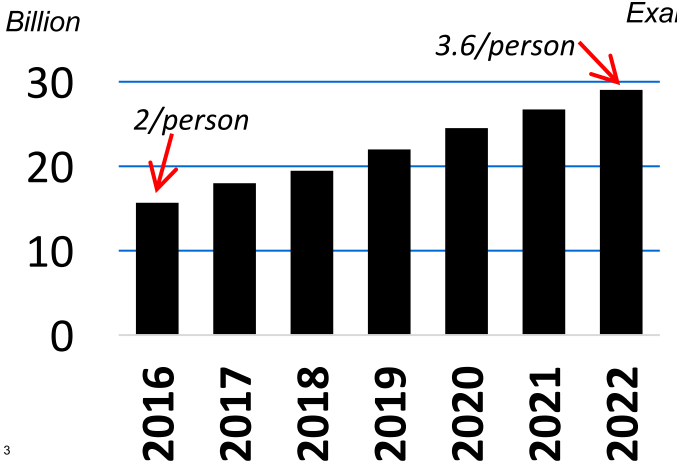
Outline

1. Why Cellular Networks Must Become More Efficient
2. How Massive MIMO Improves Spectral Efficiency
3. Beyond Mobile Broadband:
   Link Reliability, Low-Power Operation

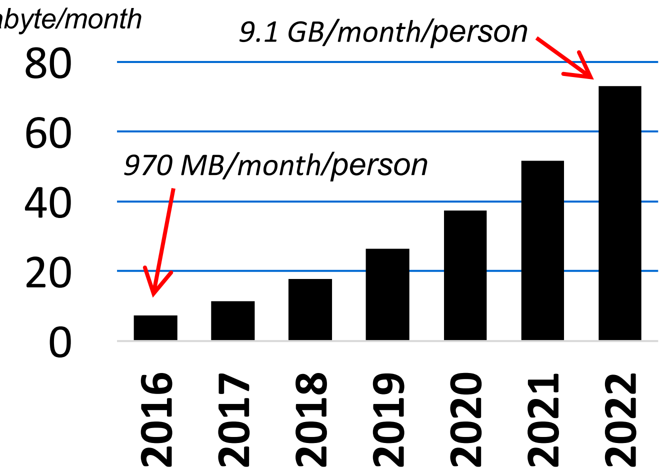
The Success of Wireless Communications

- More devices and data traffic every year
  - 10% more devices
  - 47% more traffic (33% more per device)

Connected devices



Data traffic



How to pay for this?

Higher network throughput in 5G

Revenue from new use cases:

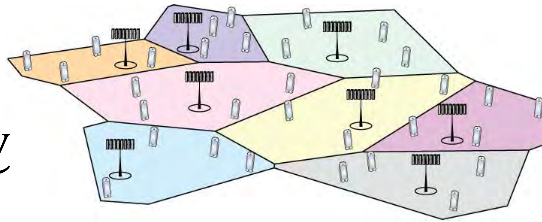
Internet-of-things

Ultra-reliable communication

etc.

Data source:
Ericsson Mobility Report (July, November 2017)

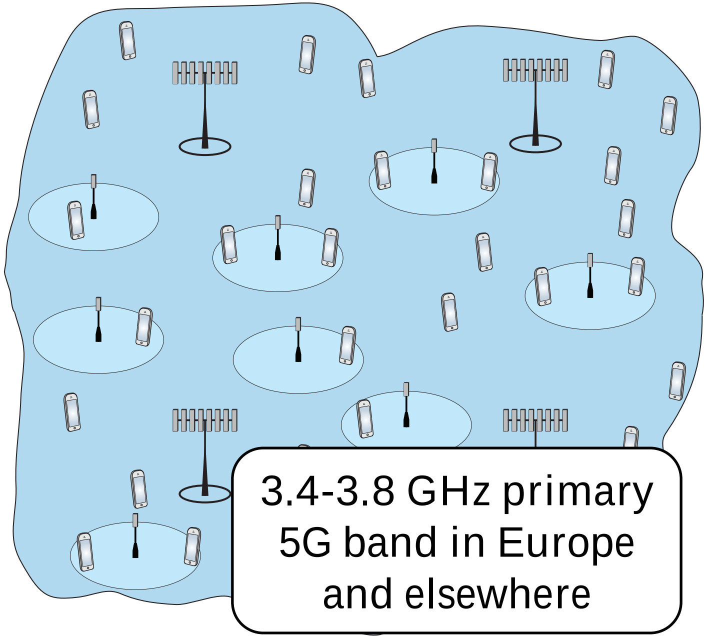
Improving Cellular Networks



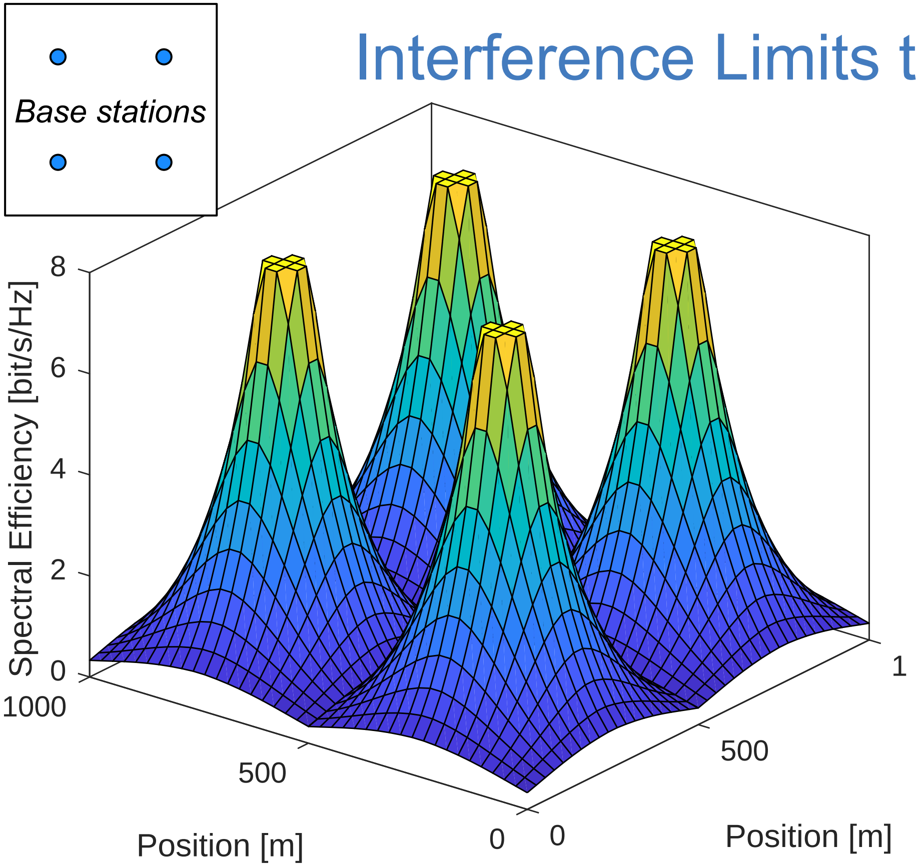
- Formula for Network Throughput [bit/s/km^2]:

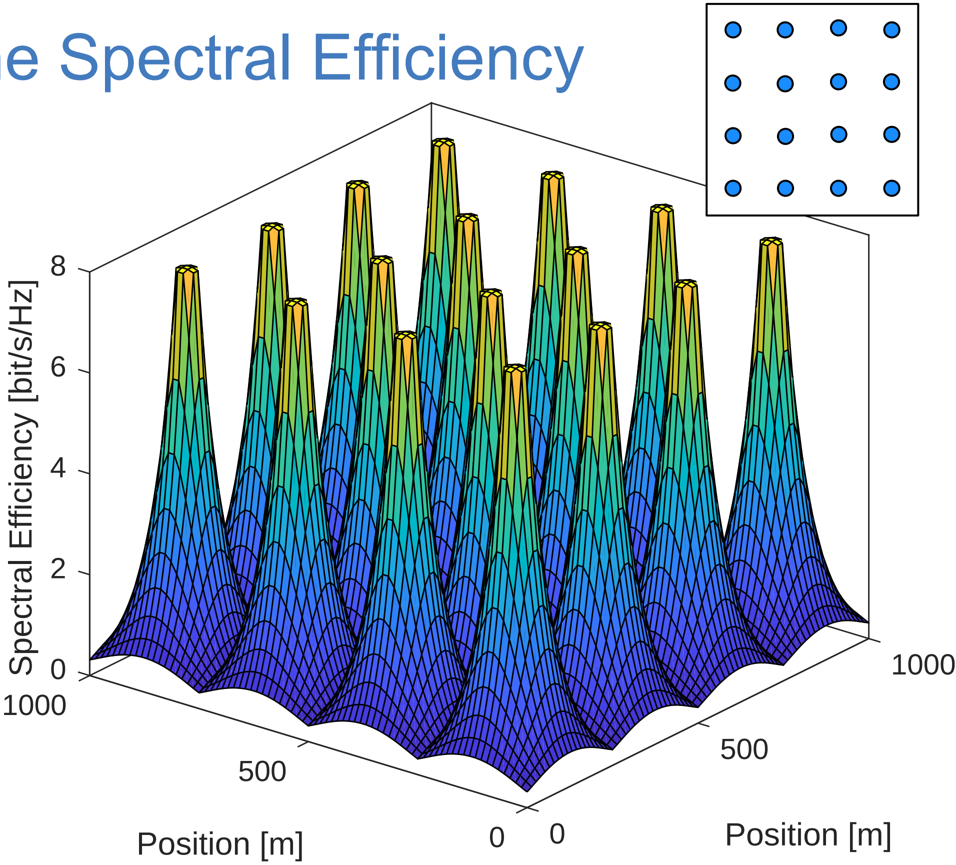
$$\underbrace{\text{Throughput}}_{\text{bit/s/km}^2} = \underbrace{\text{Cell density}}_{\text{Cell/km}^2} \cdot \underbrace{\text{Available spectrum}}_{\text{Hz}} \cdot \underbrace{\text{Spectral efficiency}}_{\text{bit/s/Hz/Cell}}$$

- Two-Tier Networks
  - Hotspot tier
    - High cell density, short range per cell
    - Wide bandwidths in mm-wave bands
    - Spectral efficiency less important
  - Coverage tier **(focus today)**
    - Provide coverage, elevated base stations
    - Outdoor-to-indoor coverage: Operate <6 GHz
    - High spectral efficiency is desired



Interference Limits the Spectral Efficiency





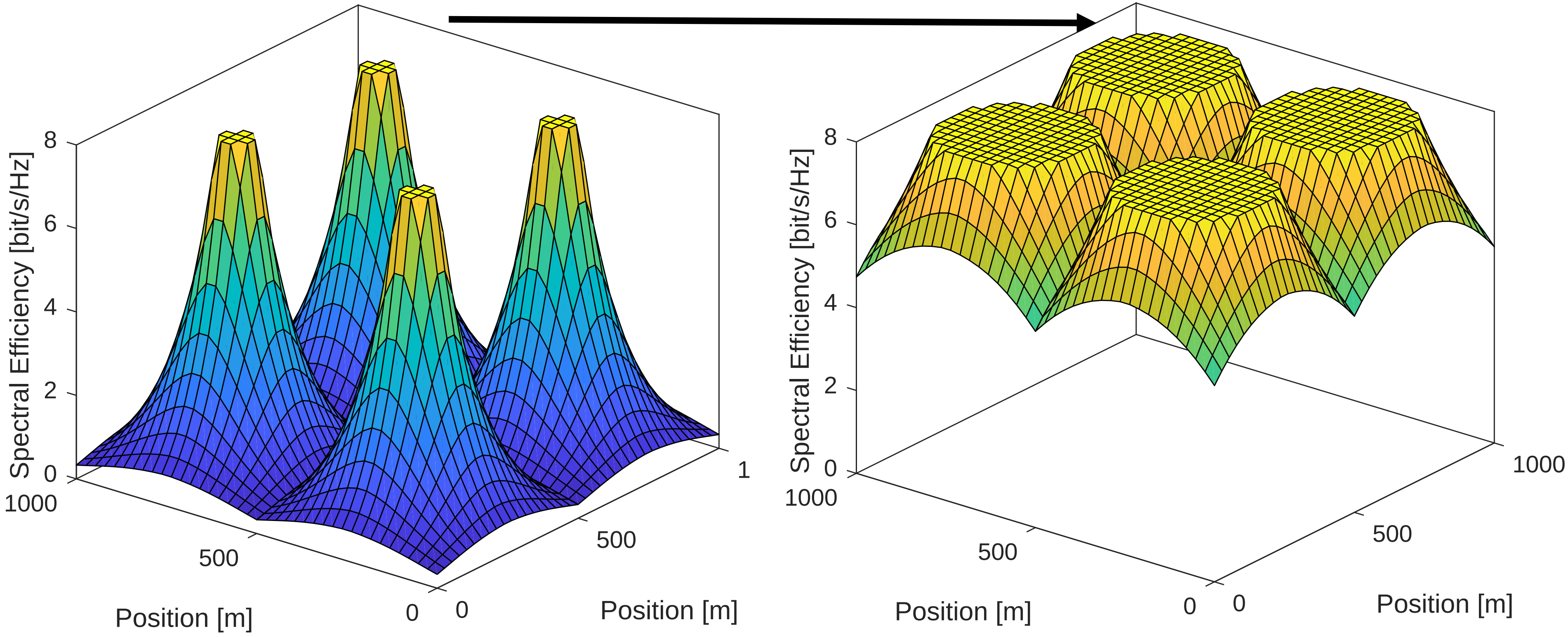
Mediocre performance at most places!

Cell densification is not a solution

Higher frequencies makes it worse

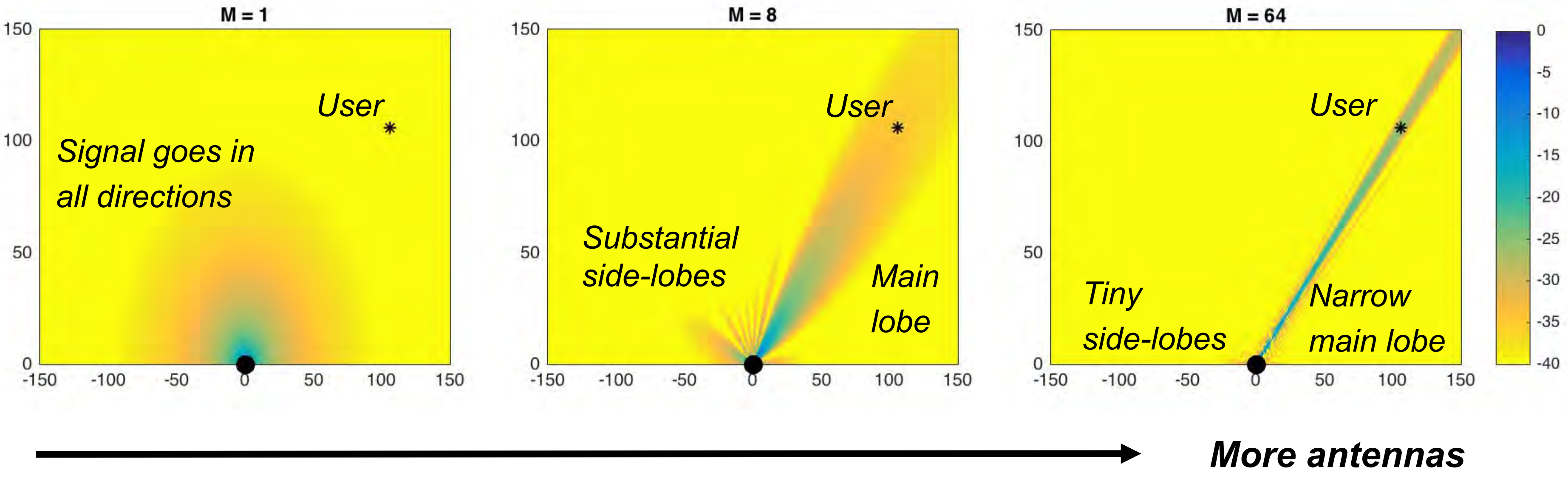
Pathloss exp: 3
Cell edge: 5-10 dB

How to Achieve More Uniform Coverage?



Desired: Stronger signal, same interference levels

Beamforming is the Solution!



Same transmit power

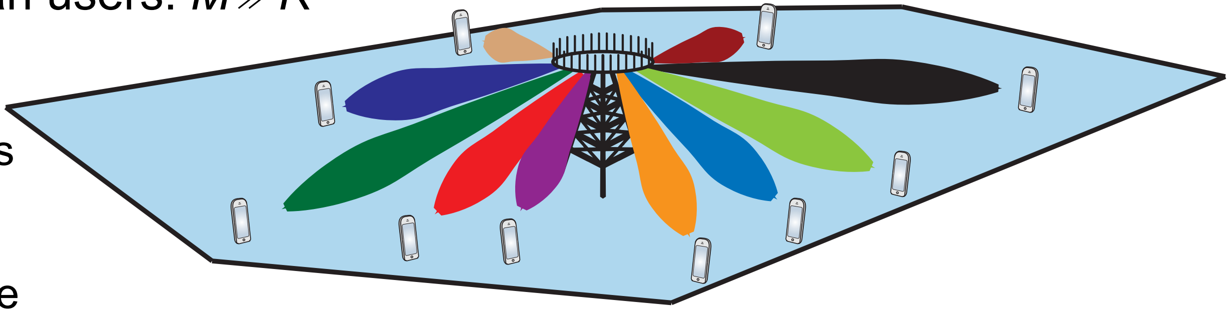
- Color indicates path loss in dB
- *M* base station (BS) antennas
- Main lobe focused at user

More antennas

- Narrower beams, laser-like
- Array gain: $10 \log_{10}(M)$ dB larger at user
- Less leakage in undesired directions

Massive MIMO (multiple input multiple output)

- Main Characteristics
  - Many BS antennas; e.g., M = 200 antennas, K = 40 single-antenna users
  - Many more antennas than users: $M \gg K$
  - High spectral efficiency
    - Many simultaneous users
    - Strong directive signals
    - Little interference leakage



Seminal work: Thomas L. Marzetta, “Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas,” IEEE Trans. Wireless Communications, 2010

- *Combines the best concepts from past decades of multi-user MIMO research*
- *2013 IEEE Marconi Prize Paper Award, 2015 IEEE W. R. G. Baker Award*

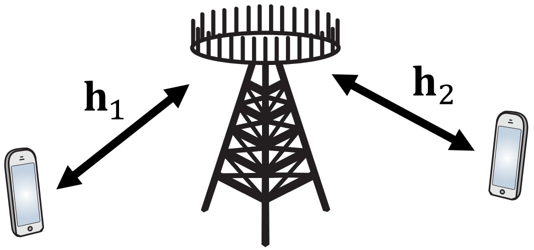
Massive MIMO Provides Favorable Propagation

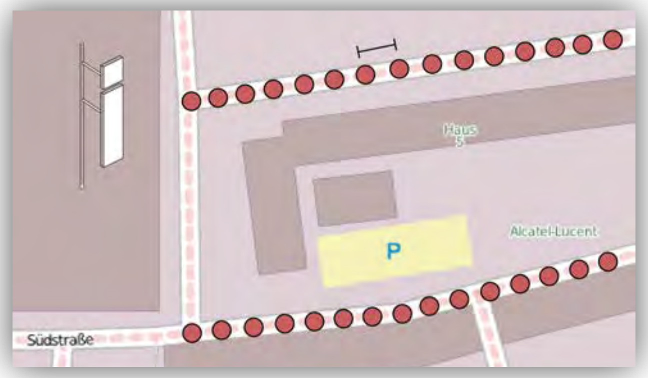
- **Consider two users**
  - *M*-dimensional channels: $\mathbf{h}_1, \mathbf{h}_2$

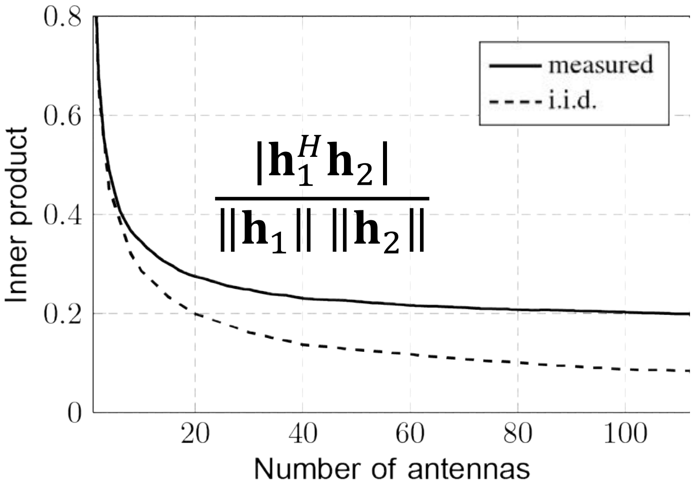
Favorable propagation

$\frac{\mathbf{h}_1}{\|\mathbf{h}_1\|}$ and $\frac{\mathbf{h}_2}{\|\mathbf{h}_2\|}$ are orthogonal

→ *Base station can fully separate the users*

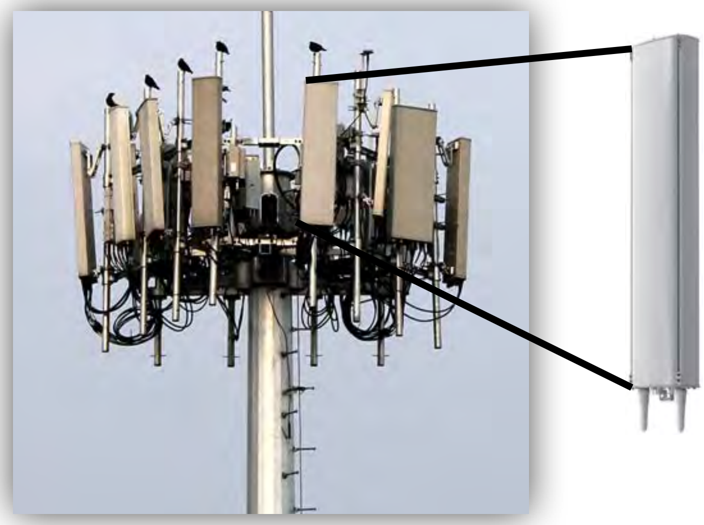




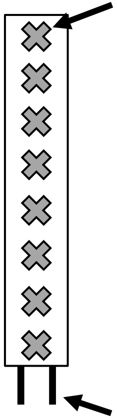


Source: J. Hoydis, C. Hoek, T. Wild, and S. ten Brink, "Channel Measurements for Large Antenna Arrays," ISWCS 2012

Deploying Many Antennas Below 6 GHz



Look inside



One dual-polarized antenna elements

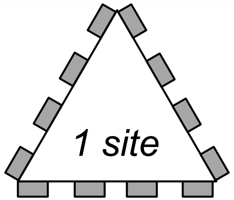
LTE: One input/output per polarization!

Massive MIMO: One per antenna element

Number of Antennas

- 8·8 = 64 per sector
- 192 antennas per site

3 sectors,
8-antenna LTE-A



One dual-polarized antenna panel

Upgrade Existing Sites to Massive MIMO

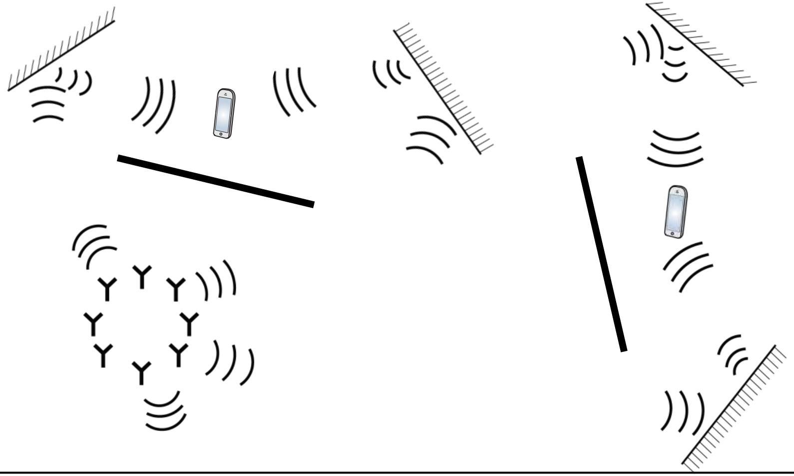
No sectorization (achieved by beamforming)

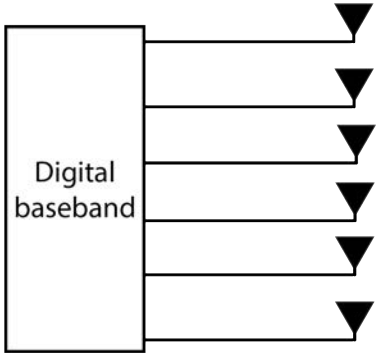
Equipment size similar to top-of-the-line LTE

Massive in numbers, not in size

Spatial Multiplexing Requires Digital Beamforming

- How to implement beamforming?
  - Send same signal from all antennas
    - Vary phase/amplitude per antenna
    - Vary phase/amplitude per subcarriers
- Spatial multiplexing: Superimpose beams





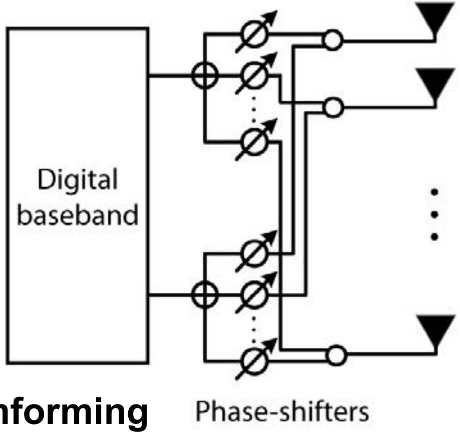
Digital beamforming

Flexible Implementation

Hybrid beamforming:
Cannot adapt amplitude or subcarriers

Digital beamforming: Full flexibility

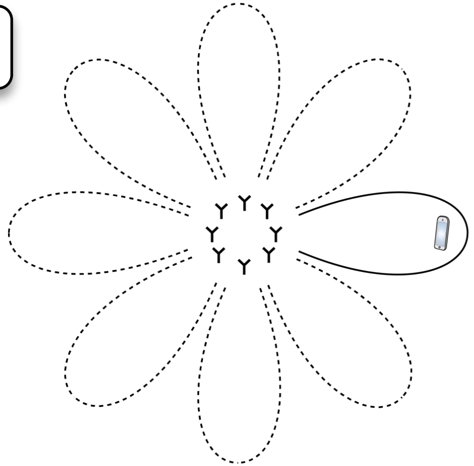
Digital is the future!



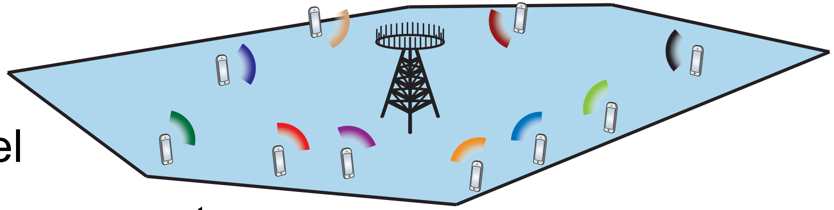
Hybrid beamforming

“Channel State Information isn’t Everything; it’s the Only Thing” – T. Marzetta

We need to know where the point the beam!



- **Conventional approach**: Grid-of-beams
  - Try 8 angular beams, user reports the best one
  - Good: Simple, works with both TDD and FDD
  - Bad: Never a perfect match; too much inter-user interference



- **Massive MIMO**: Uplink estimation
  - User sends pilot signal, BS estimates channel
  - Good: Well-matched estimates, scalable with many antennas
  - Bad: Only works in TDD, where uplink estimates useful for downlink

FDD = Frequency-division duplex, ***TDD = Time-division duplex***

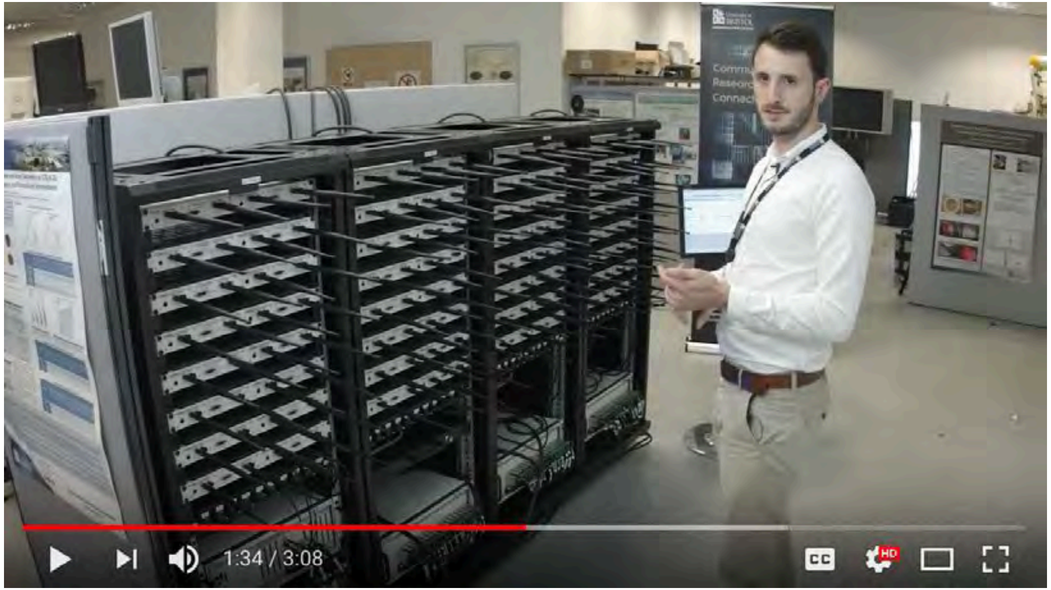
World Record in Spectral Efficiency

- 145.6 bit/s/Hz/cell
  - Set jointly by researchers in Bristol and Lund, 2016
  - 128 BS antennas
  - 22 single-antenna users
  - 256-QAM signals
  - 20 MHz band at 3.5 GHz

Is this practical?

Multiplexing tens of users is practical

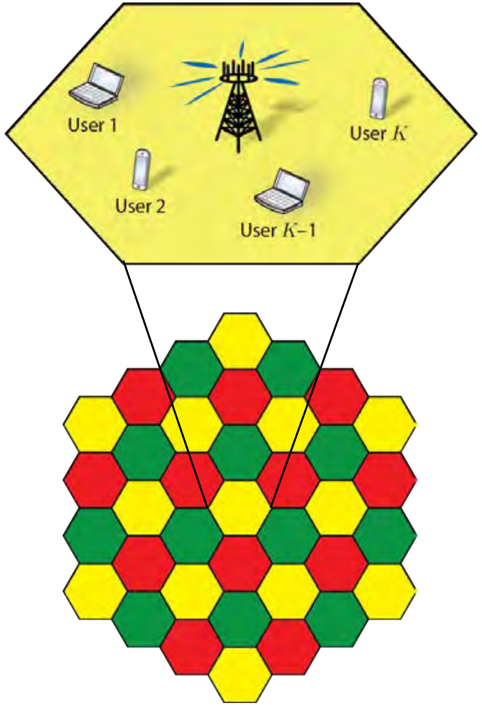
Low-order modulations will mainly be used in practice



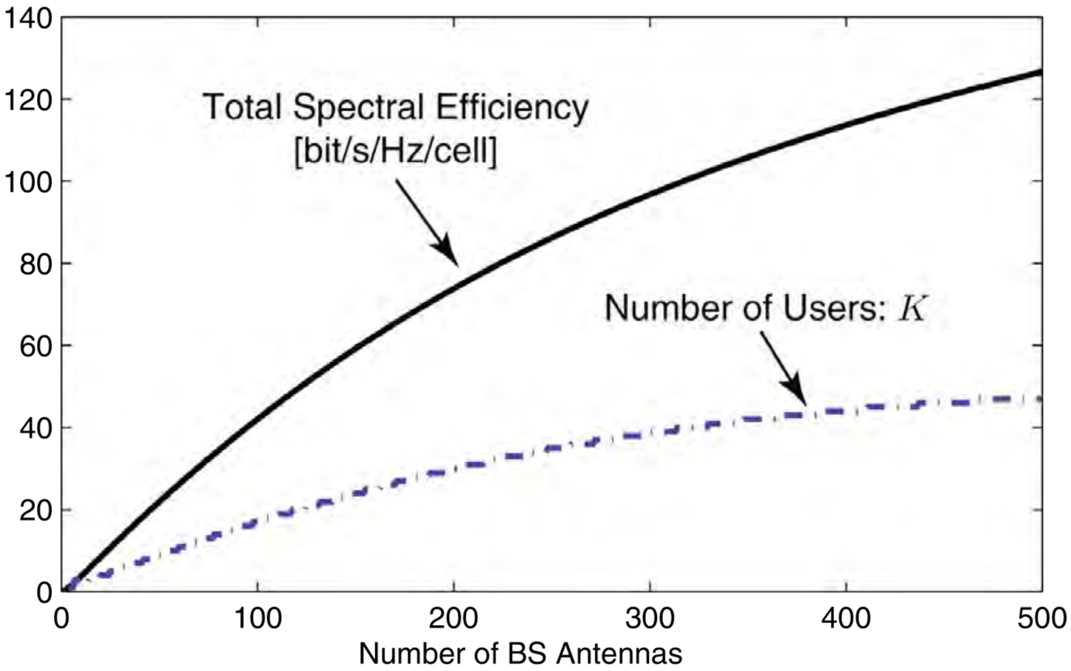
Screenshot from "Massive MIMO World Records"

Link: https://youtu.be/NoDP3g8XHVQ

High Spectral Efficiency in Cellular Networks



Pilots reused in every third cell



Uplink simulation: SNR 5 dB, i.i.d. Rayleigh fading, *zero-forcing combining, channels fixed for 500 channel uses*

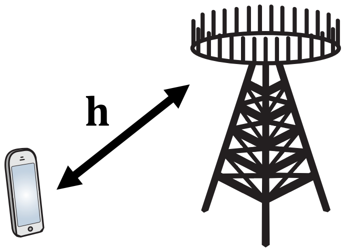
High spectral efficiency per cell, ~3 bit/s/Hz to every user

5G is More Than Broadband: Internet-of-things (IoT)

- Wirelessly connected society
  - Machines, vehicles – everything gets connected
  - Other use cases than mobile broadband
- Case 1: Link Reliability is Very Important
  - Connected factory robots, traffic safety applications, etc.
  - *Ultra-reliable low-latency communication (URLLC)*
- Case 2: Massive machine-type communication (mMTC)
  - Many low-cost sensors and actuators deployed everywhere (50 billion by 2020)
  - Sporadic transmission, battery should last for 5 years

Can Massive MIMO play a role here?

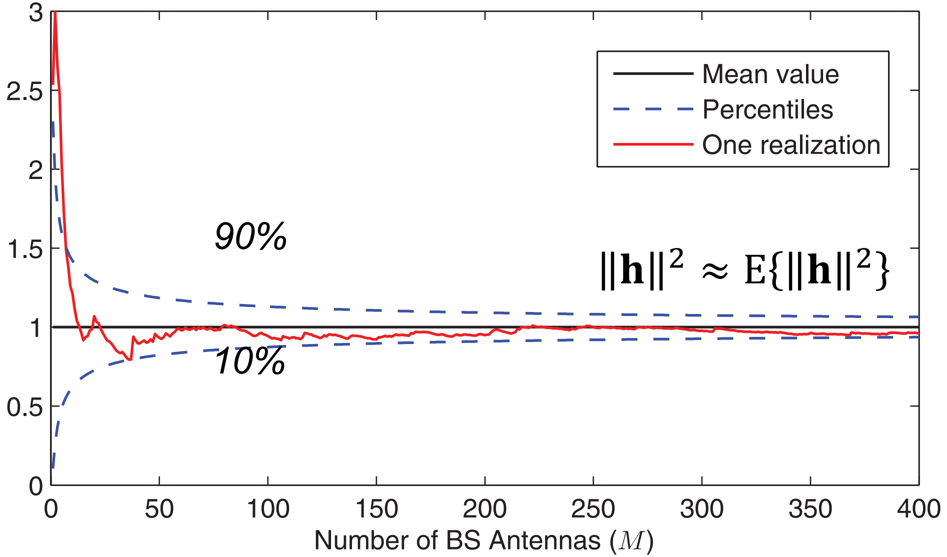
Channel Hardening



Consider a random channel, e.g., $\mathbf{h} \sim CN(\mathbf{0}, \mathbf{I}_M)$

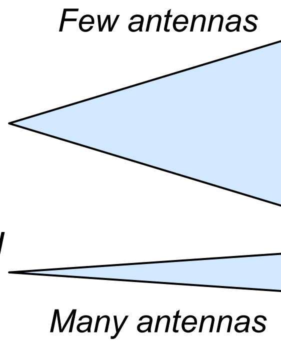
Variations of effective channel reduce with M:

$$\frac{1}{M}||\mathbf{h}||^2 \text{ has } \begin{cases} \text{Mean: } 1 \\ \text{Variance: } 1/M \end{cases}$$



Narrower beam:

Fewer multipath components involved



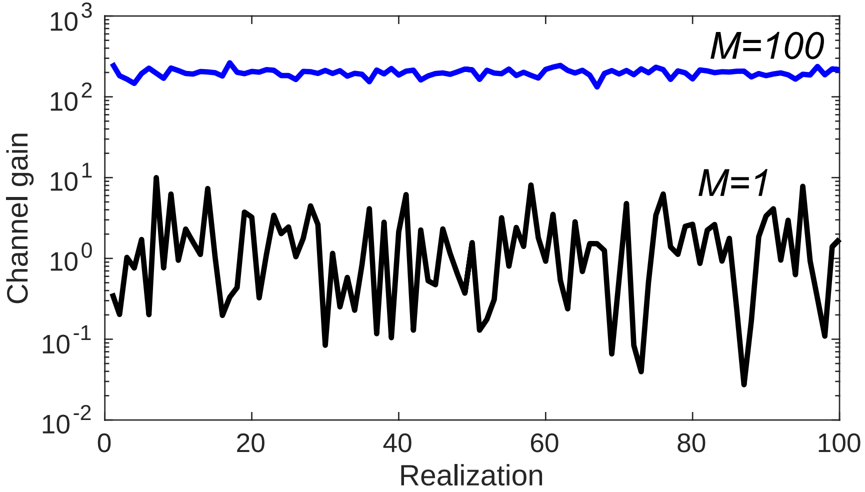
Double benefits:

$||\mathbf{h}||^2$ scales with M

Variations reduces

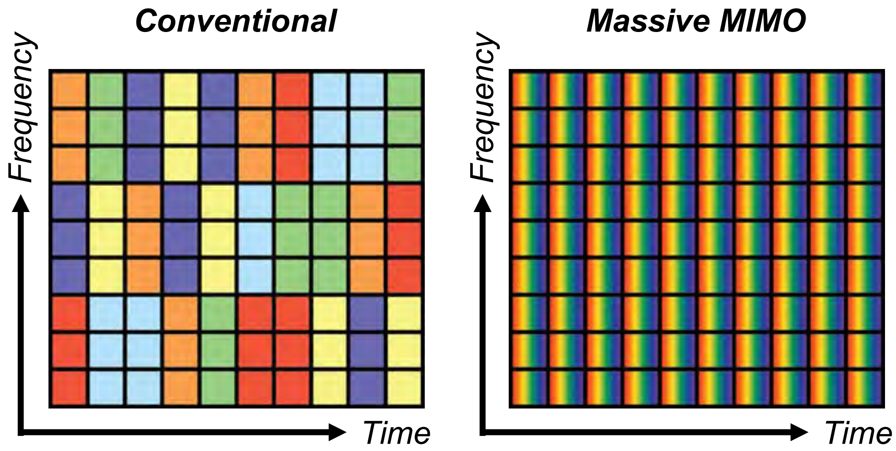
Great Link Reliability and Simplified Resource Allocation

Higher reliability, lower latency



- Lost package if $||\mathbf{h}||^2$ < threshold
  - Less likely with channel hardening
  - Fewer retransmissions

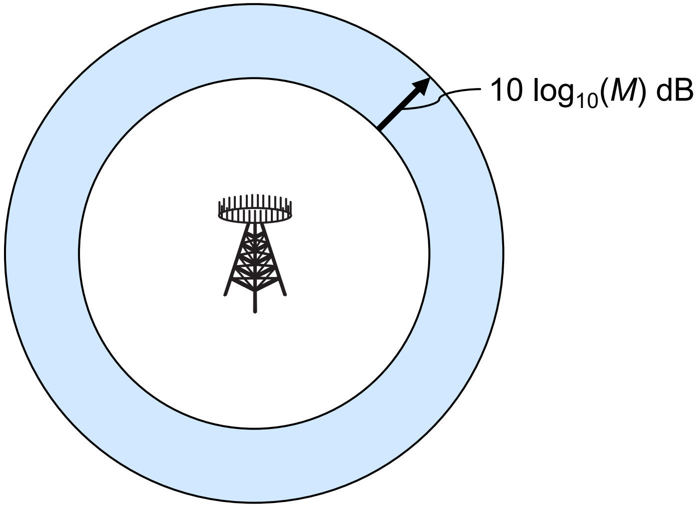
Resource allocation made simple



- All subcarriers good, all the time
  - No need to schedule based on fading
  - Each user gets the whole bandwidth, whenever needed

Two Ways to Exploit the Array Gain

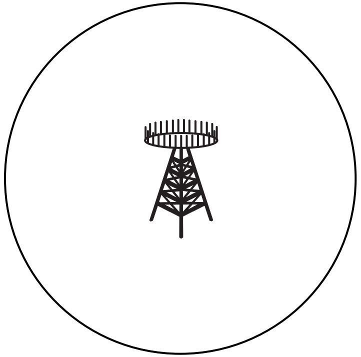
1) Range Extension



- Use same transmit power
  - Higher rates to already covered places
  - Reach new places (e.g., indoor)

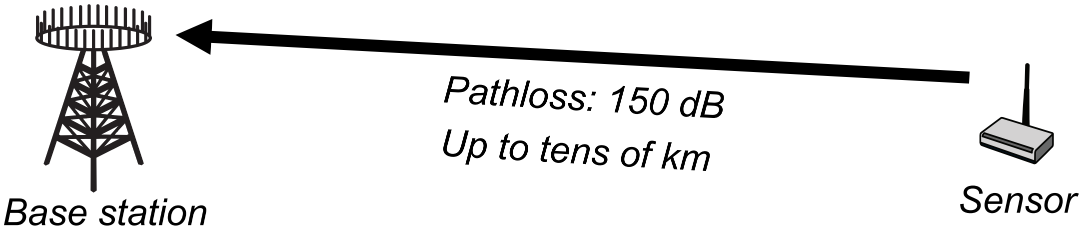
2) Low-Power Operation

Use 5 $\log_{10}(M)$ to 10 $\log_{10}(M)$ dB less power



- Same range with reduced power
  - Increase battery lifetime in uplink
  - Low power per antenna in downlink
    40 W → 4 W per BS, 40 mW/antenna

Supporting Internet-of-Things (IoT)



- SNR over 100 kHz channel:

$$\underbrace{20\ \text{dBm}}_{\text{Transmit power}} + \underbrace{2.15\ \text{dBi} + 2.15\ \text{dBi}}_{\text{Antenna gains}} - \underbrace{150\ \text{dB}}_{\text{Pathloss}} - \underbrace{-120\ \text{dBm}}_{\text{Noise power}} = -5.7\ \text{dB}$$

  - Sufficient for binary modulation with repetition coding
  - Transmit a few data packages per day (very low energy per package)

Massive MIMO with *M* = 100

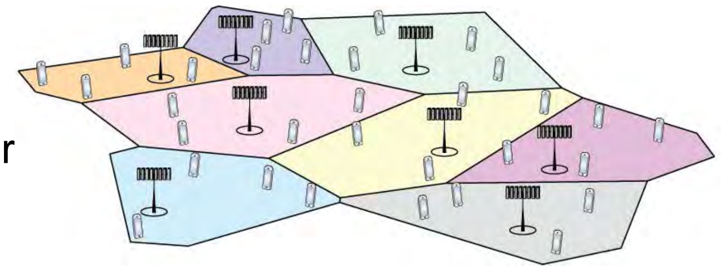
Increase SNR by 20 dB (range extension)

Improve link reliability

Reduce transmit power to 10 dB

Up to 10x longer battery life

Summary: Massive MIMO for 5G below 6 GHz

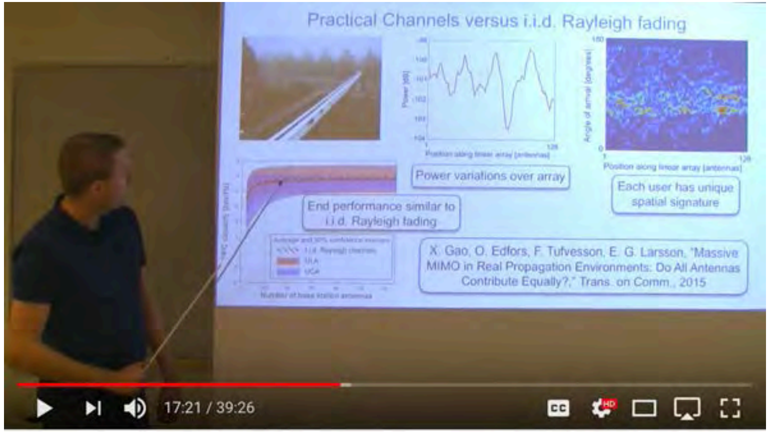


1. Mobile broadband applications
   - Very high spectral efficiency, multiplex many user
   - Great improvements at the cell edge
2. Ultra-reliable low-latency communication (URLLC)
   - Channel hardening alleviates small-scale fading
   - Fewer retransmissions, more predictable performance
3. Massive machine-type communication (mMTC)
   - Extend coverage, more cost-efficient deployment
   - Reduce transmit power for battery-power devices

Learn More: Blog and Book

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

Youtube channel:



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

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

$40 for paperback until Jan 31
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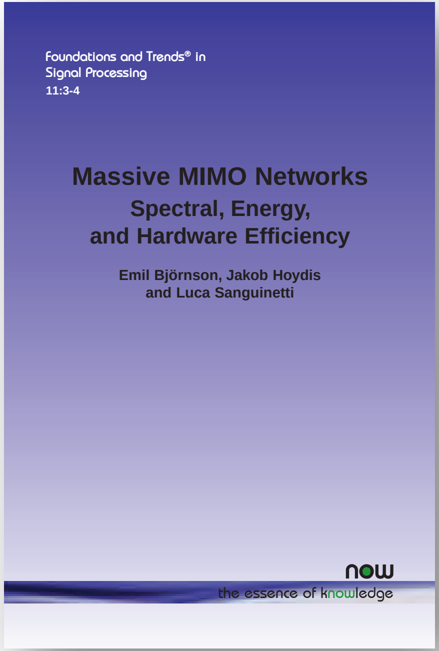


massivemimobook.com

Thank you!

Questions are most welcome!

Dr. Emil Björnson

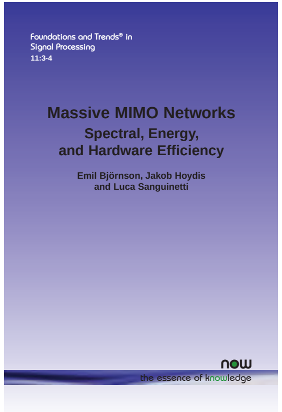
Slides, papers, and code available online:

http://www.ebjornson.com/research

http://www.massivemimobook.com

Special offer

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



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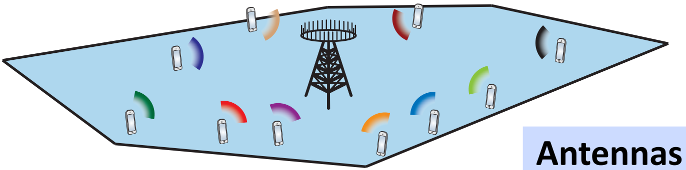
BACKUP SLIDES

Classical Multi-User MIMO vs. Massive MIMO



	Classic multi-user MIMO	Massive MIMO (Canonical)
Antennas M, users K	$M \approx K$	$M \gg K$
Signal processing	Non-linear is preferred	Linear is near optimal
Duplexing mode	Designed for TDD and FDD	Designed for TDD w. reciprocity
Instantaneous channel	Known at BS and user	Only needed at BS (hardening)
Channel quality	Affected by frequency-selective and fast fading	Almost no channel quality variations (hardening)
Variations in user load	Scheduling needed if $K > M$	Scheduling seldom needed
Resource allocation	Rapid due to fading	Only on a slow time scale
Cell-edge performance	Only good if BSs cooperate	Improved by array gain of M
BS cooperation	Highly beneficial if rapid	Only long-term coordination

MAMMOET (Massive MIMO for Efficient Transmission)
2014-2016

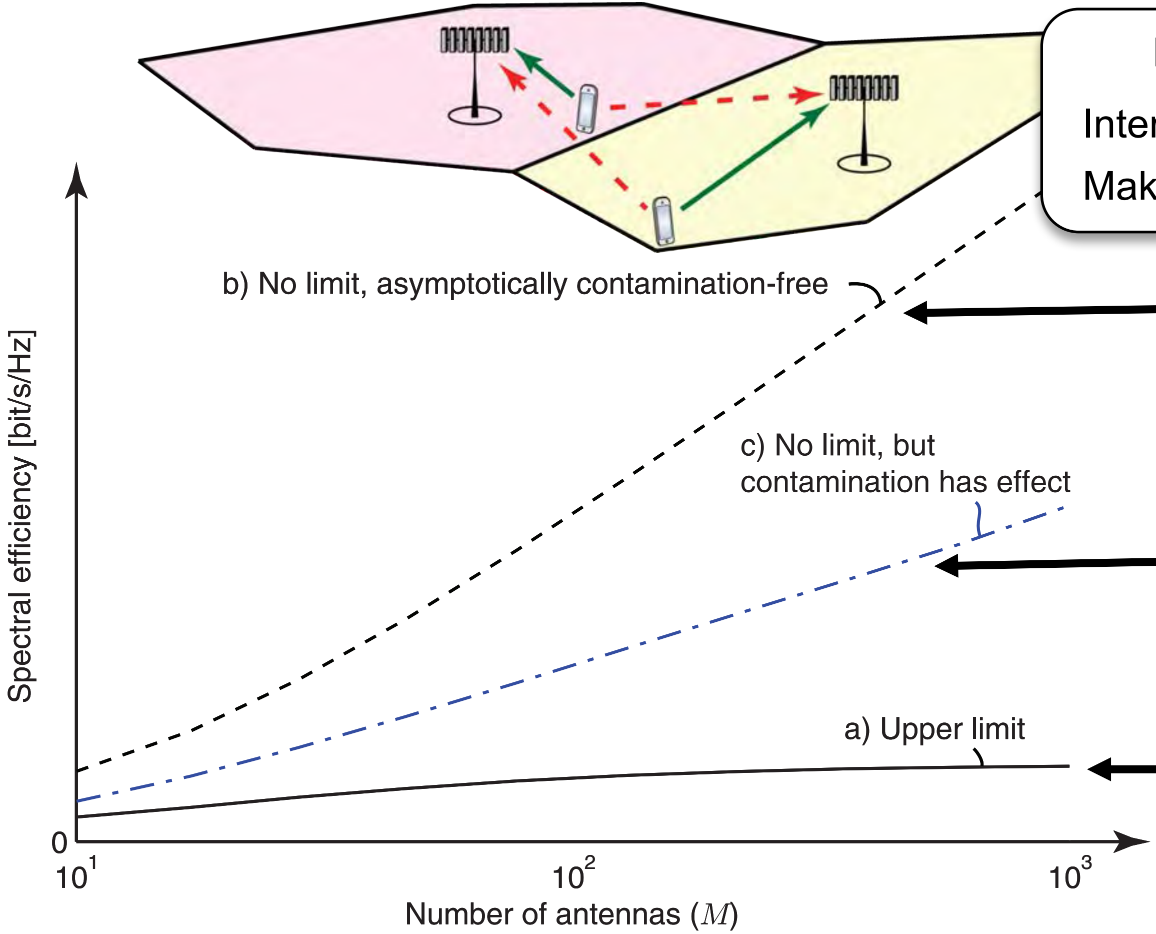
- Bridged many gaps between theoretical and practice
  - Testbed demonstrations (real-time operation, mobility)
  - New channel models
  - Concepts for efficient analog/digital hardware implementation
  - Deliverables available: https://mammoet-project.eu

MAMMOET Massive MIMO

Partners:

ERICSSON LINKÖPING UNIVERSITY imec Telefónica TECHNIKON infineon KU LEUVEN LUND UNIVERSITY

Pilot Contamination has Been Blown Out of Proportions



Pilots reused across cells

Interference contaminates estimates

Makes channels unfavorable

2012: Caire et al.

2013: Gesbert et al.

Special case:
One-ring model

2017: Björnson et al.

Any nontrivial channel
with spatial correlation

2010: Marzetta

Special case:
i.i.d. Rayleigh fading

Open Problems

More important things than "pilot contamination"!

- Make Massive MIMO work in FDD mode
  - Long-standing challenge. Is it practically feasible to exploit sparsity?
- Channel measurements, channel modeling, traffic modeling
  - Required for system level simulations
- Implementation-aware algorithmic design
  - Implement ZF with MR-like complexity. Utilize low-resolution hardware.
- Cross-layer design
  - Scalable protocols for random access, control signaling, scheduling
- New deployment characteristics
  - Multi-antenna users, distributed arrays, cell-free (network MIMO)