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

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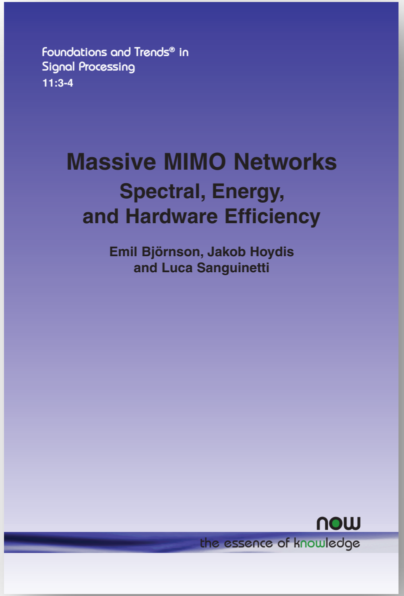
- *Postdoc at SUPELEC, Paris, France*
- *Associate professor at Linköping University*
- *10 year experience of MIMO research*
- *2 books and 7 best paper awards*
- *Several pending patent applications*
- *Writer at the Massive MIMO blog, http://massive-mimo.net*



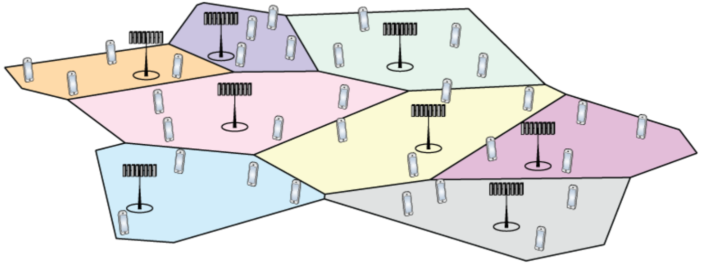
Outline

1. What is the Point of Massive MIMO?
2. How Big is Massive MIMO?
3. How Big Can it Get?

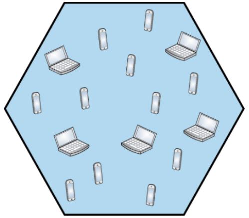
Improving Cellular Communications

Cellular networks

Coverage area divided into cells
Users served by a base station



- Increase Network Throughput [bit/s/km²]
  - Consider a given area



- Simple Formula for Network Throughput:

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

***Conventional approach**:*
Expensive to deploy more base stations

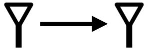
***Spectrum is scarce**:*
Plenty of mm-wave spectrum, but only for short-range scenarios

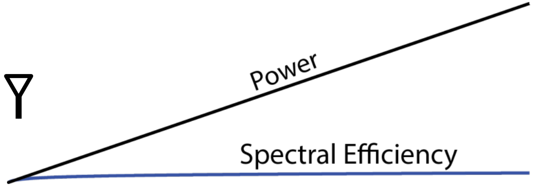
Can we improve it?
Improve technology, upgrade base stations

My focus:
Spectrum <5 GHz

How to Increase Spectral Efficiency?

- Point-to-Point Spectral Efficiency:





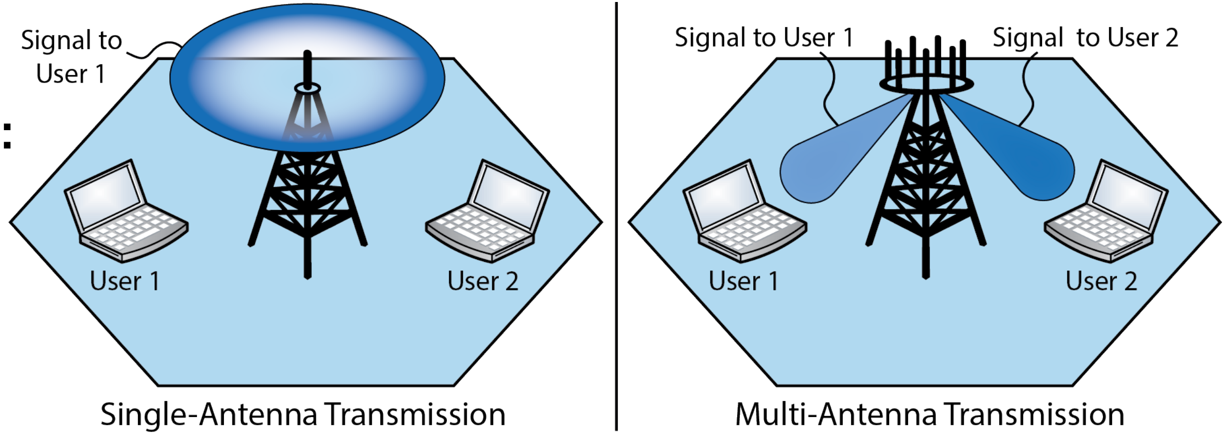
  - Shannon's capacity limit:

$$\log_2\left(1 + \frac{\text{Received Signal Power}}{\text{Interference Power} + \text{ Noise Power}}\right) \quad [\text{bit/s/Hz/user}]$$

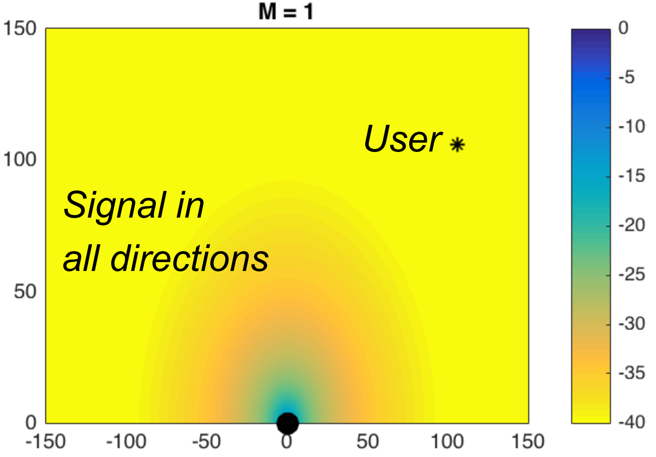
  - Issue: 4 bit/s/Hz → 8 bit/s/Hz requires $17\times$ more power!

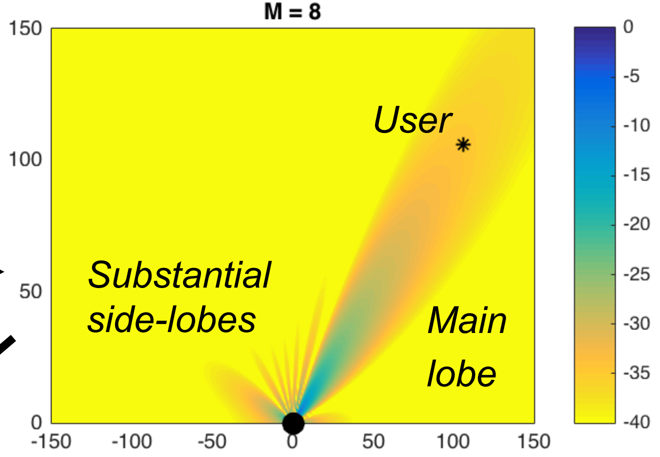
Many Parallel Transmissions:

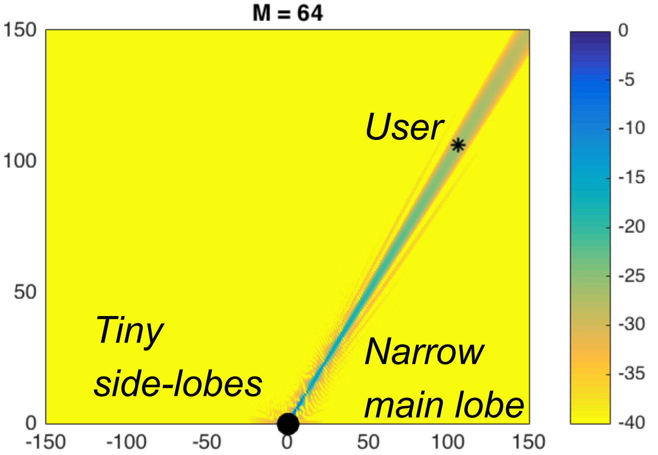
Spatially focused to respective user



More Antennas → More Directivity







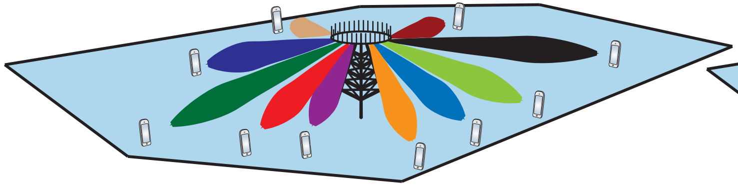
Same transmit power

- M base station antennas
- Color indicates pathloss in dB
- Main lobe focused at user

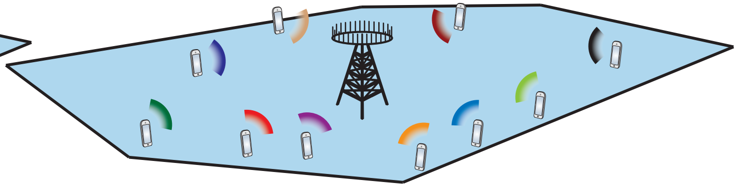
More antennas

- Array gain: $10 \log_{10}(M)$ larger at user
- Less leakage in other directions

Multi-User MIMO (Multiple-input Multiple-output)



Downlink: Multi-user beamforming



Uplink: Multi-user detection

Early Works

1987: J. Winters, "*Optimum combining for indoor radio systems with multiple users*," IEEE Trans. Commun.

1990: S. Swales, M. Beach, D. Edwards, J. McGeehan, "*The performance enhancement of multibeam adaptive base-station antennas for cellular land mobile radio systems,*" IEEE Trans. Veh. Technol.

1991: S. Anderson, M. Millnert, M. Viberg, B. Wahlberg, "*An adaptive array for mobile communication systems*," IEEE Trans. Veh. Technol.

Standards

2005: HC-SDMA

2008: LTE

2013: 802.11ac (WiFi)

Disappointing Results

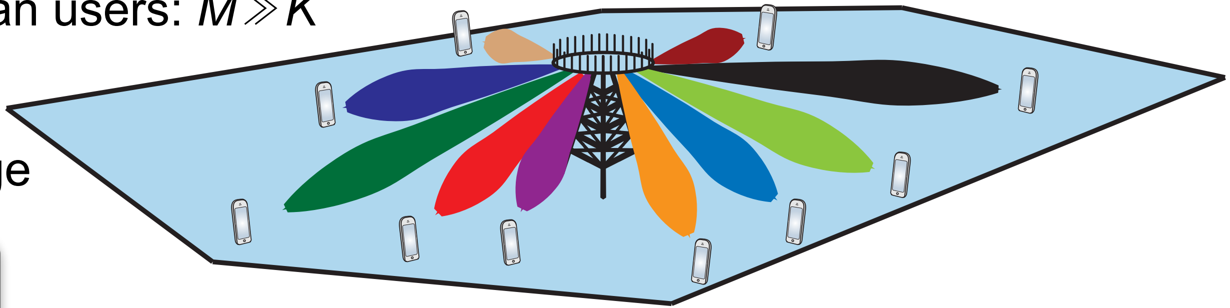
Few antennas: Small theoretical gains

Insufficient channel knowledge:
A lot of interference

Cell densification: Few users to multiplex

Massive MIMO: Taking Multi-User MIMO to the Next Level

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



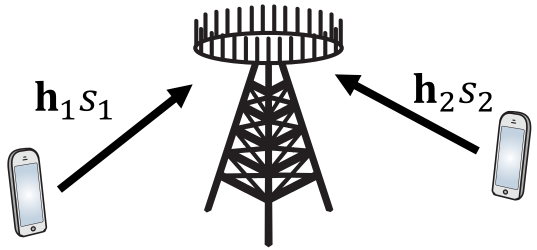
Spectral efficiency grows with number of users!

Seminal work: T. Marzetta, "Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas," IEEE Trans. Wireless Communications, 2010.

- *2013 IEEE Guglielmo Marconi Prize Paper Award*
- *2015 IEEE W. R. G. Baker Award*

Motivated by Asymptotic Results

- **Example: Uplink with i.i.d. Rayleigh Fading**
  - Two users, send signals s_k for $k = 1,2$
  - Channels: $\mathbf{h}_k = [h_{k1} \dots h_{kM}]^T \sim CN(\mathbf{0}, \mathbf{I}_M)$
  - Noise: $\mathbf{n} \sim CN(\mathbf{0}, \mathbf{I}_M)$
  - Received: $\mathbf{y} = \mathbf{h}_1 s_1 + \mathbf{h}_2 s_2 + \mathbf{n}$



Linear Detector $\mathbf{v}_1$ for User 1: $\tilde{y}_1 = \mathbf{v}_1^{\mathrm{H}} \mathbf{y} = \boxed{\mathbf{v}_1^{\mathrm{H}} \mathbf{h}_1} s_1 + \boxed{\mathbf{v}_1^{\mathrm{H}} \mathbf{h}_2} s_2 + \boxed{\mathbf{v}_1^{\mathrm{H}} \mathbf{n}}$

Maximum ratio filter: $\mathbf{v}_1 = \frac{1}{M} \mathbf{h}_1$

Signal remains: $\boxed{\mathbf{v}_1^{\mathrm{H}} \mathbf{h}_1} = \frac{1}{M} \|\mathbf{h}_1\|^2 \xrightarrow{M \to \infty} \mathrm{E}[|\mathrm{h}_{11}|^2] = 1$

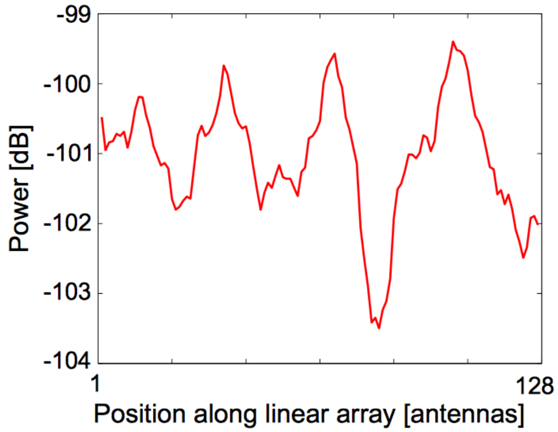
Interference vanishes: $\boxed{\mathbf{v}_1^{\mathrm{H}} \mathbf{h}_2} = \frac{1}{M} \mathbf{h}_1^{\mathrm{H}} \mathbf{h}_2 \xrightarrow{M \to \infty} \mathrm{E}[\mathrm{h}_{11}^{\mathrm{H}} \mathrm{h}_{21}] = 0$

Noise vanishes: $\boxed{\mathbf{v}_1^{\mathrm{H}} \mathbf{n}} = \frac{1}{M} \mathbf{h}_1^{\mathrm{H}} \mathbf{n} \xrightarrow{M \to \infty} \mathrm{E}[\mathrm{h}_{11}^{\mathrm{H}} \mathrm{n}_1] = 0$

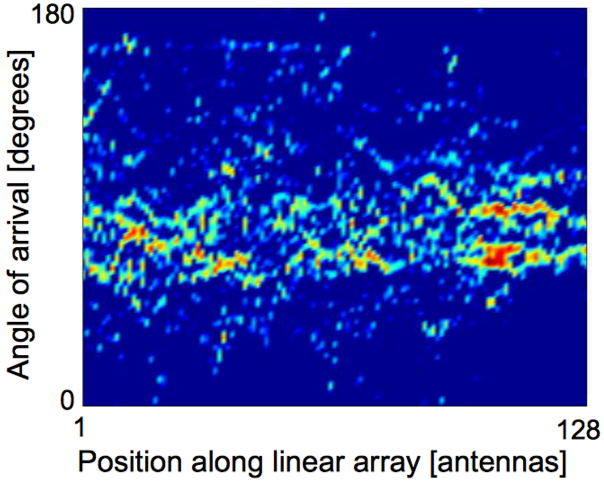
Asymptotically noise and interference free communication:

$\tilde{y}_1 \xrightarrow{M \to \infty} s_1$

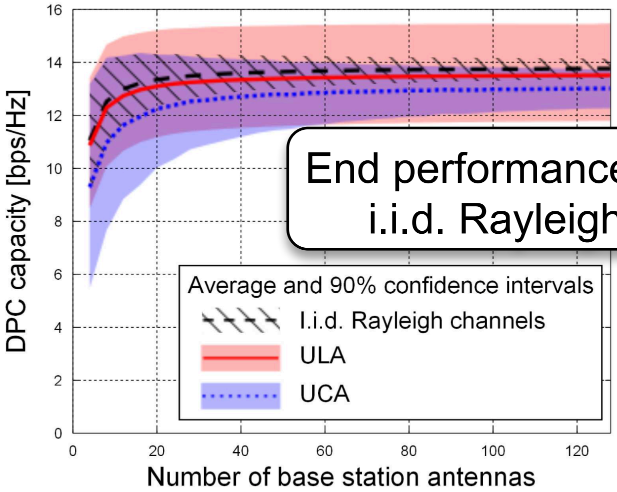
Practical Channels versus i.i.d. Rayleigh fading



Power variations over array



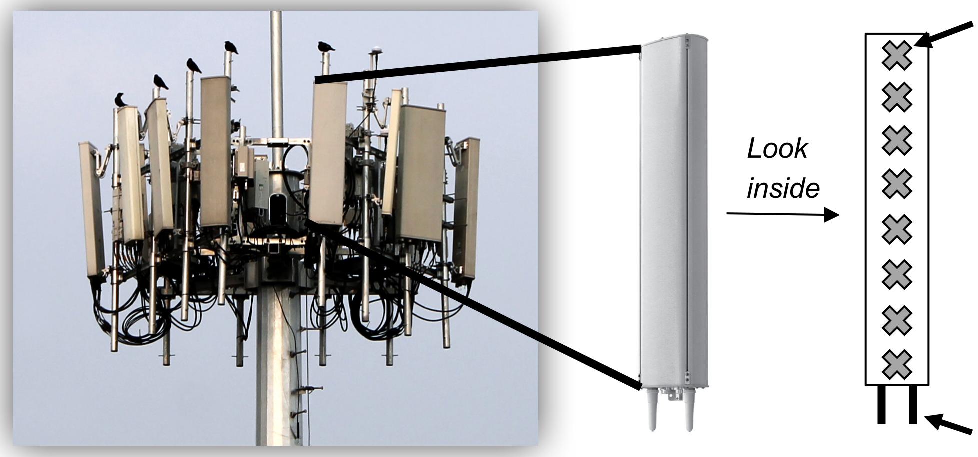
Each user has unique spatial signature



End performance similar to i.i.d. Rayleigh fading

X. Gao, O. Edfors, F. Tufvesson, E. G. Larsson, “Massive MIMO in Real Propagation Environments: Do All Antennas Contribute Equally?,” Trans. on Comm., 2015

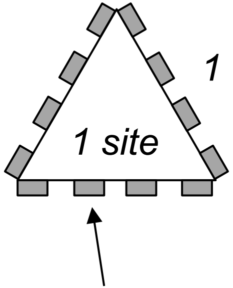
How Large is “Massive”?



3 sectors, 8-antenna LTE-A

Number of Antennas?

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



First Generation of Massive MIMO

Each antenna element becomes digitally steerable

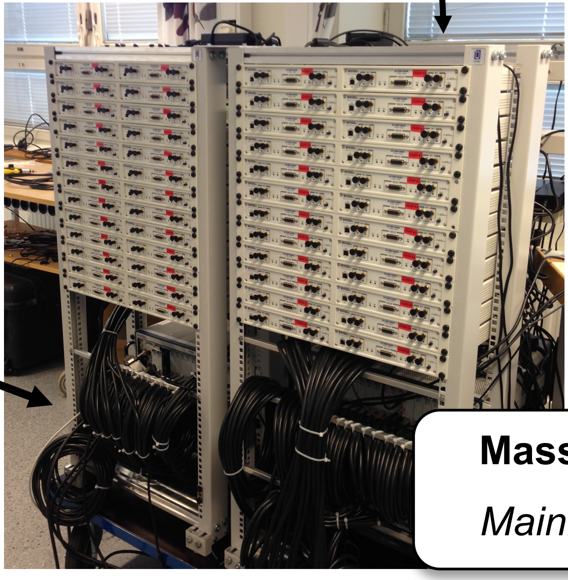
Massive in numbers: 64 inputs/outputs instead of 8

Not massive in size: Same size 8-antenna LTE-A

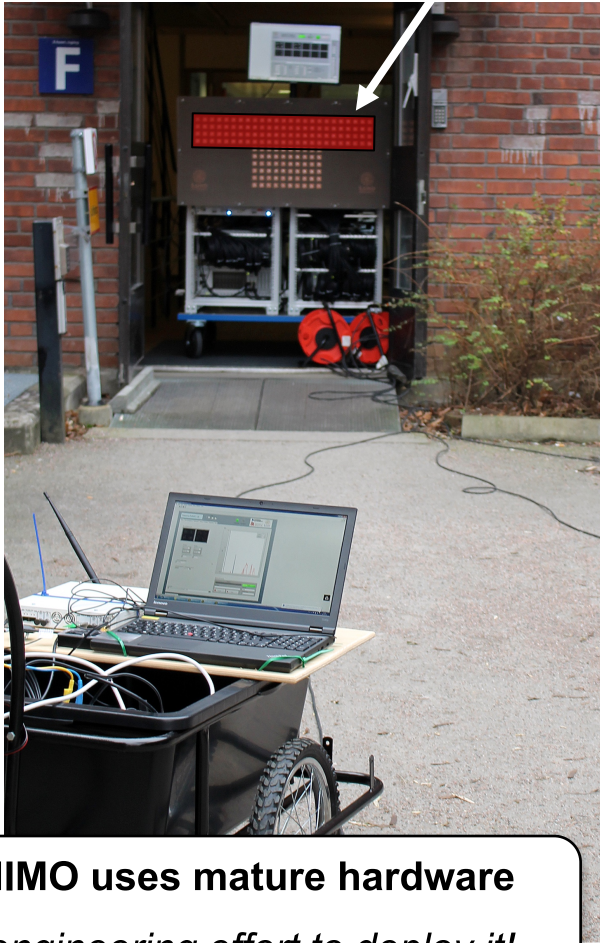
Building Massive MIMO

- Example: Lund University
  - Off-the-shelf hardware
  - 50 software-defined radios (SDRs) for 100 base station antennas
  - 6 SDRs for 12 users
  - 4 FPGAs for processing

A lot of cables…



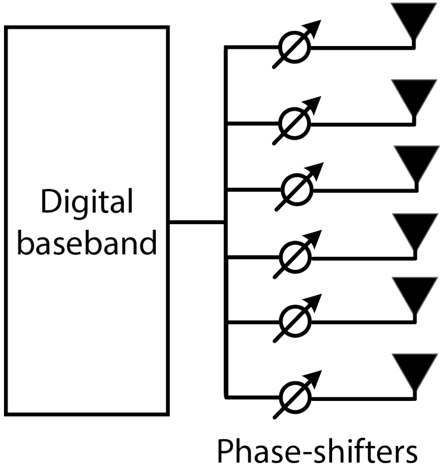
Antenna array



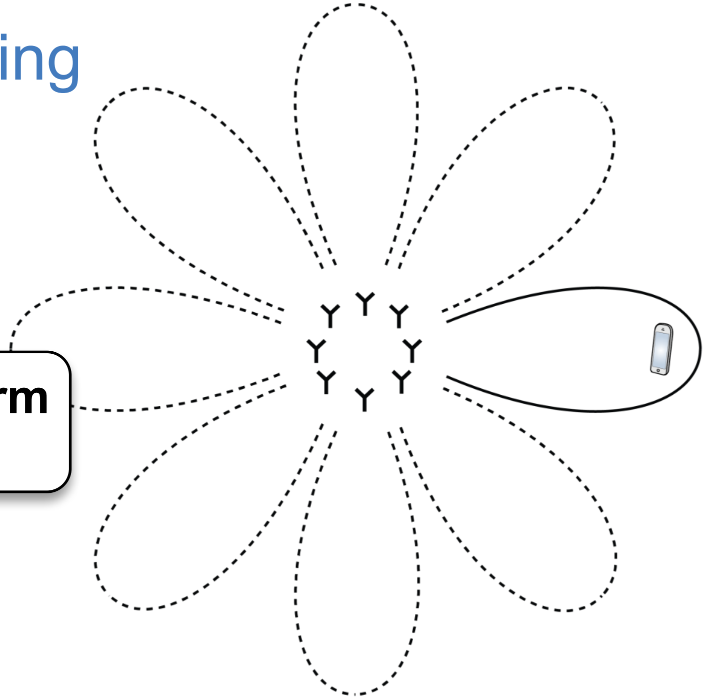
Massive MIMO uses mature hardware

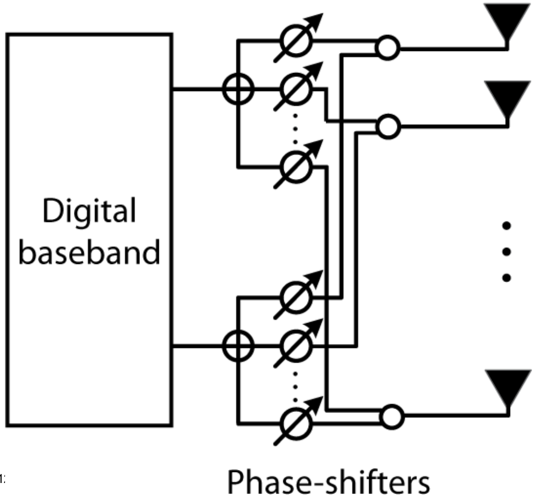
Mainly an engineering effort to deploy it!

Analog Beamforming



Adjust phase-shifts to form one angular beam

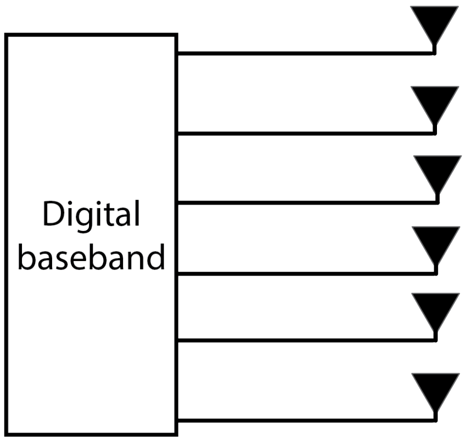




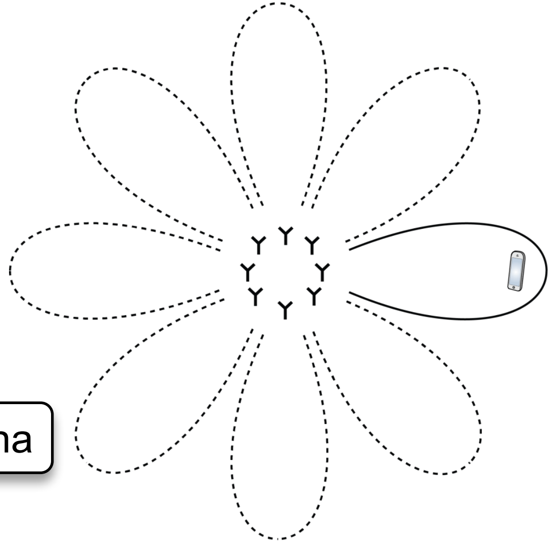
Hybrid analog-digital beamforming

- Create multiple angular beams
- Only one phase per signal and same power on all antennas

Digital Beamforming

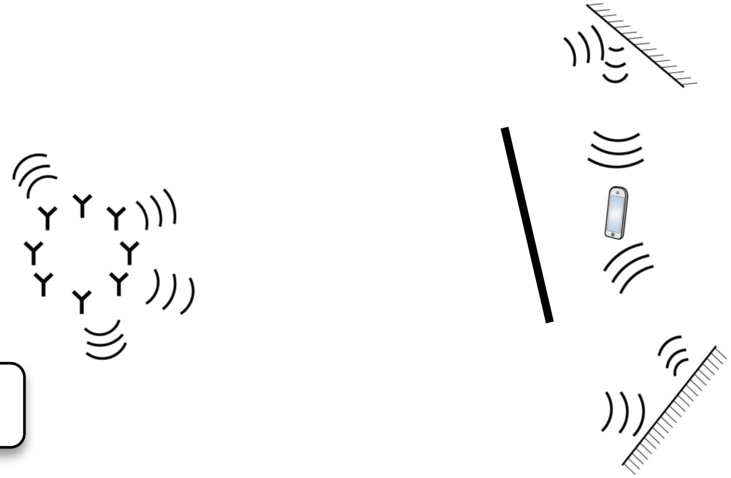


Full flexibility: Any signal on any antenna



Mandatory for non-line-of-sight scenarios

- Multipath propagation is complicated
- Require different phase and power per antenna and user

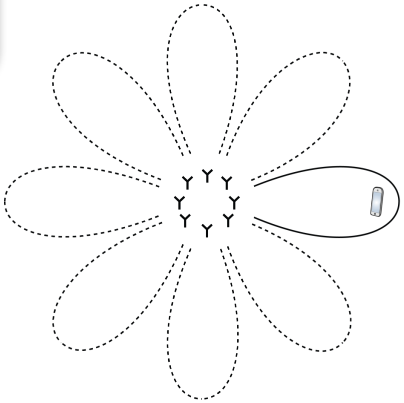


5G must have this flexibility! (<5 GHz)

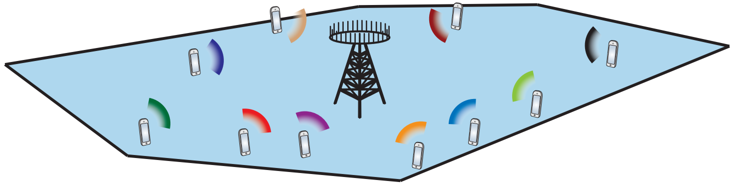
“Channel State Information isn’t Everything; it’s the Only Thing” – T. Marzetta

We need to know where the point the beam!

- Give strong received signal
- Limit interference between users



- **Conventional approach**: Grid-of-beams
  - Try 8 angular beams, user reports the best one
  - Good: Simple, works with both TDD and FDD
  - Bad: Only works in line-of-sight and single-user transmission

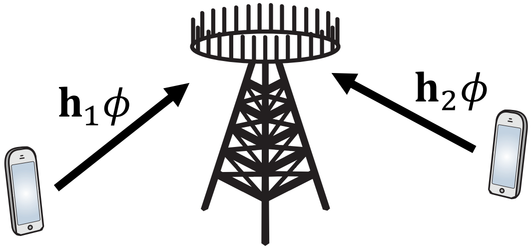


- **Massive MIMO**: Uplink estimation
  - User sends pilot signal, BS estimates channel
  - Good: Works in any propagation scenario, scalable for large arrays
  - Bad: Only works in TDD, where uplink estimates useful for downlink

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

Pilot Contamination

- Pilot Length τ_p Limited by Channel Coherence
  - Only τ_p orthogonal pilots
  - Some users reuse pilot ϕ



- Received pilot: $\mathbf{y} = \mathbf{h}_1\phi + \mathbf{h}_2\phi + \mathbf{w}$
  - Estimate: $\hat{\mathbf{h}}_1 = \mathbf{y}/\phi = \mathbf{h}_1 + \mathbf{h}_2 + \mathbf{w}/\phi$

Channels: $\mathbf{h}_k \sim CN(\mathbf{0}, \mathbf{I}_M)$

Noise: $\boldsymbol{w} \sim CN(\mathbf{0}, \mathbf{I}_M)$

Received signal with maximum ratio filter: $\mathbf{v}_1 = \frac{1}{M}\hat{\mathbf{h}}_1$

Signal remains: $\mathbf{v}_1^H\mathbf{h}_1 = \frac{1}{M}\left(\|\mathbf{h}_1\|^2 + \cancel{\mathbf{h}_2^H\mathbf{h}_1} + \cancel{\boldsymbol{w}^H\mathbf{h}_1/\phi}\right) \xrightarrow{M\to\infty} 1$

Interference remains: $\mathbf{v}_1^H\mathbf{h}_2 = \frac{1}{M}\left(\cancel{\mathbf{h}_1^H\mathbf{h}_2} + \|\mathbf{h}_2\|^2 + \cancel{\boldsymbol{w}^H\mathbf{h}_2/\phi}\right) \xrightarrow{M\to\infty} 1$

Asymptotically:
Signal and interference from pilot-sharing users remain!

Will Pilot Contamination Limit Performance?

With i.i.d. Rayleigh fading

- Yes! Marzetta showed it in 2010
- Has encouraged a lot of research

In general: No!

Natural power variations change everything!

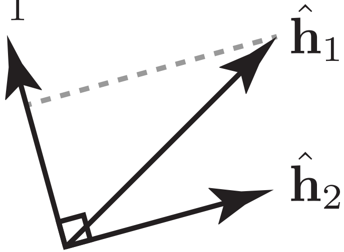
Utilize user's spatial characteristics:

Receive $\mathbf{y} = \mathbf{h}_1\phi + \mathbf{h}_2\phi + \mathbf{w}$

Obtain linearly independent $\hat{\mathbf{h}}_1$ and $\hat{\mathbf{h}}_2$

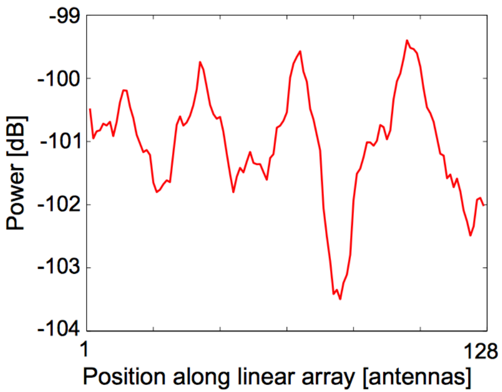
Select $\mathbf{v}_1$

Orthogonal only to $\hat{\mathbf{h}}_2$



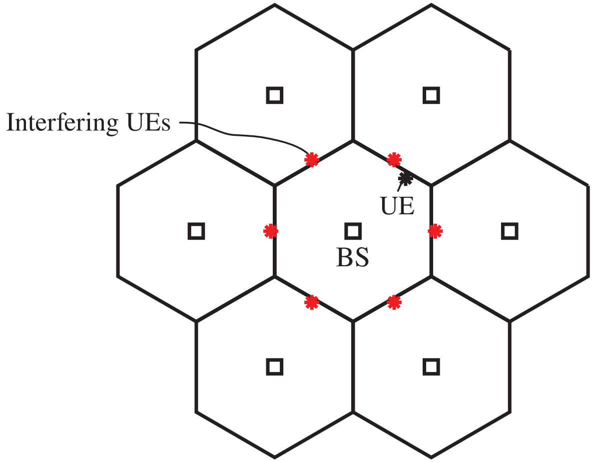
$\boxed{\mathbf{v}_1^H \hat{\mathbf{h}}_2 = 0}$

Recall:
Power variations over an array

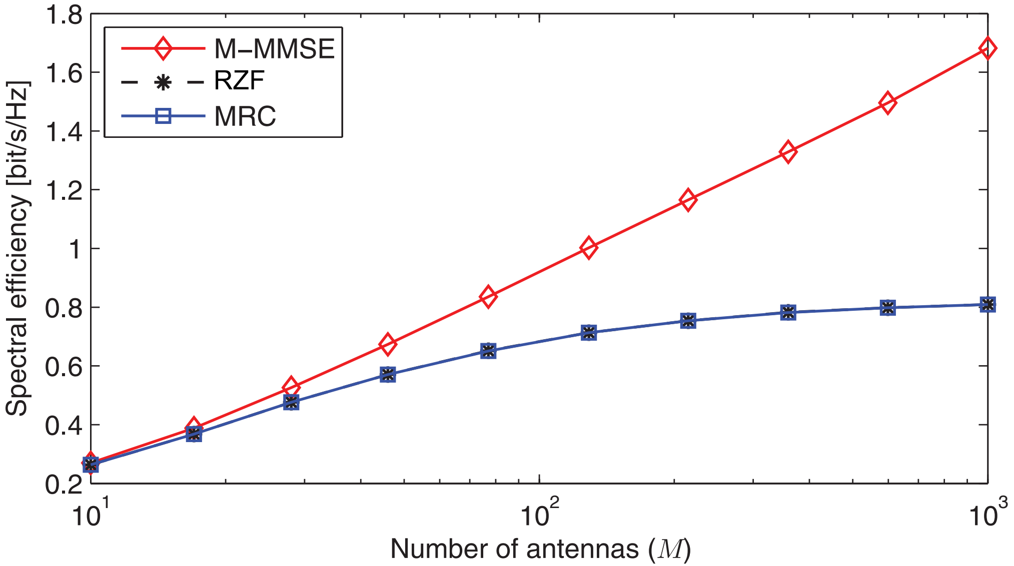


E. Björnson, J. Hoydis, L. Sanguinetti, "Massive MIMO has Unlimited Capacity," IEEE Transactions on Wireless Communications, to appear

How Big Can We Make Massive MIMO?



Everyone uses the same pilot!



Spectral efficiency grows logarithmically with *M*

If utilizing spatial characteristics using M-MMSE filter

Implications:

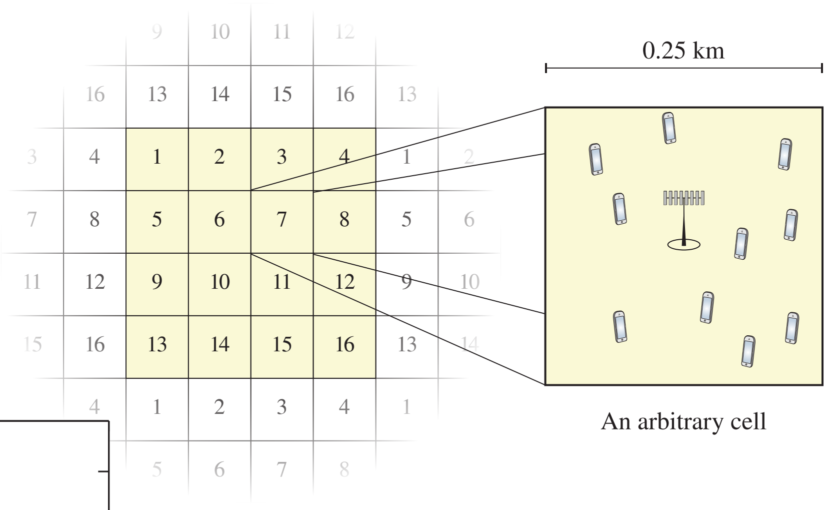
- Can always handle more traffic by adding more antennas
- But diminishing returns when increasing *M*

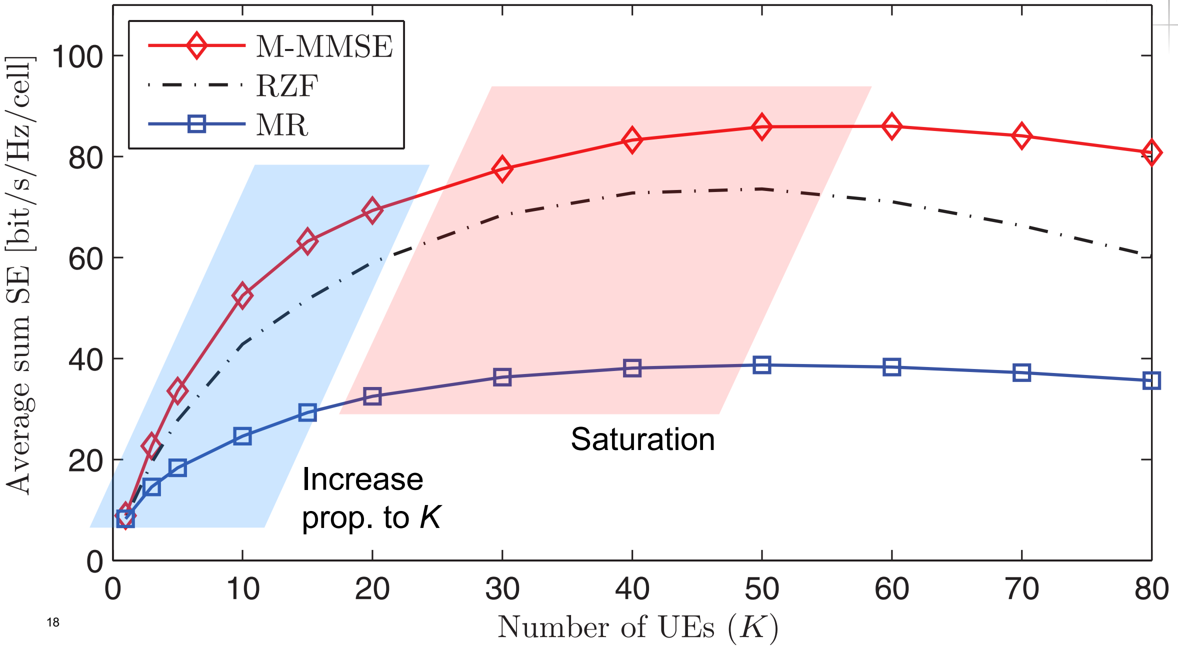
Practical Implications

Simulation

100 antennas per base station

Channel is fixed for 200 symbols



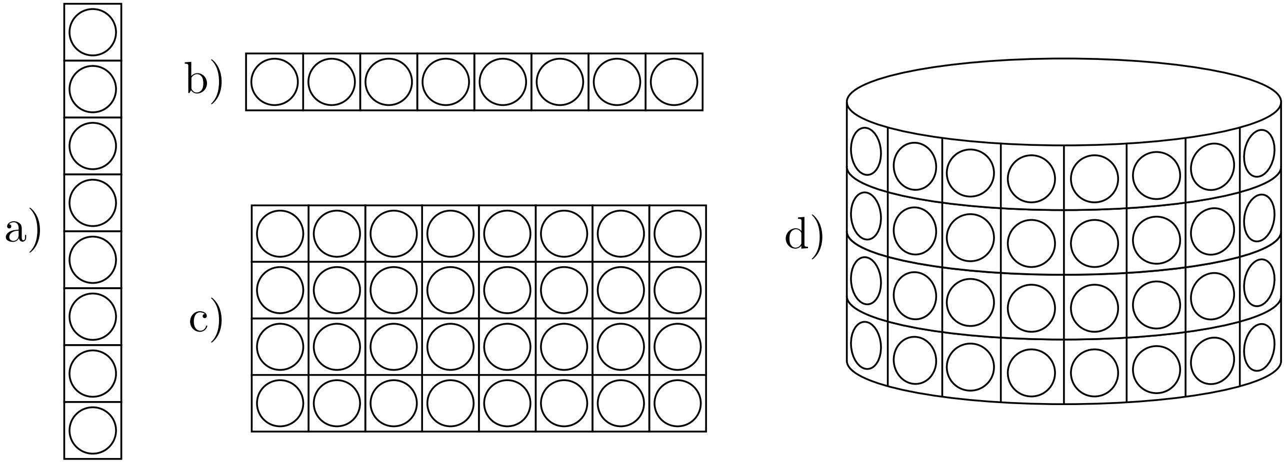


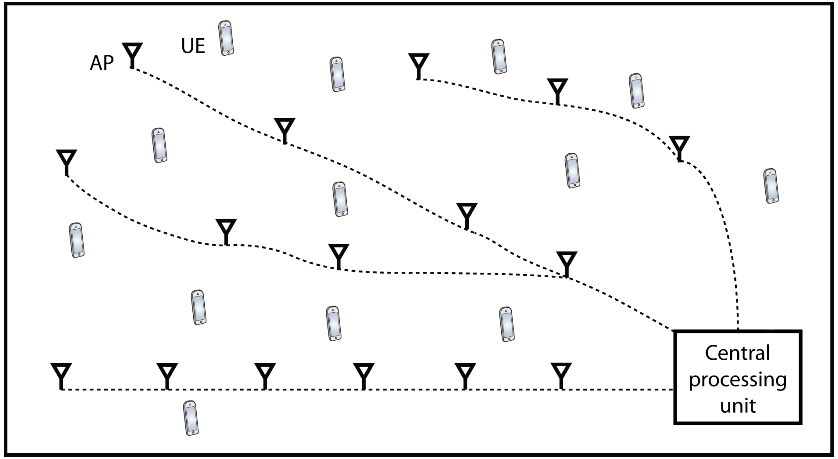
Identify maximum K in your application

Select M to make the sum spectral efficiency right for this K

How to Deploy Many Antennas?

Array geometries:
1D, 2D with sectors
3D without sectors



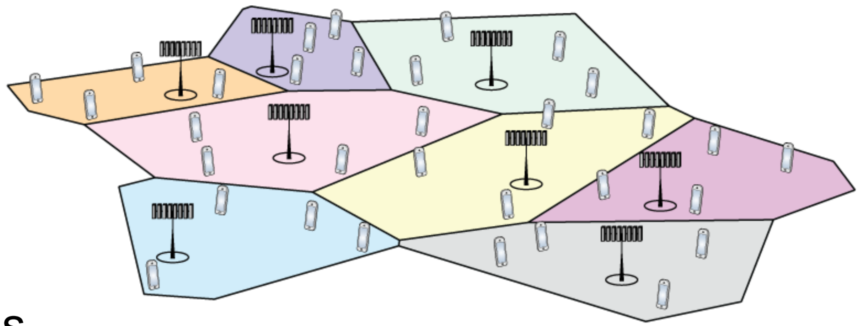


Distributed deployment

1. Multiple arrays per cell

2. Cell-free approach

Summary: How Big Can Massive MIMO Get?



- Massive MIMO
  - Delivers extreme spectral efficiency
- No Theoretical Capacity Limit
  - Grows towards infinity as M increases
  - Increase M when higher spectral efficiency is needed
  - Pilot contamination can be dealt with
- Practical Limits
  - 100-antenna arrays not larger than in 4G
  - Increasing cost of deploying base stations
  - Distributed deployment in the future

Learn More: Blog and Book

- Many Online Resources
  - Info Point (https://massivemimo.eu): Library with research papers
  - LinkedIn Group: “Massive MIMO for 5G”

MASSIVE MIMO

News — commentary — mythbusting

MACROCELL MASSIVE MIMO AT 4.5 GHZ: FIELD TRIALS IN JAPAN

NOVEMBER 18, 2016 ERIK G. LARSSON 1 COMMENT EDIT

This impressive experiment serves 23 terminals with 64 base station antennas, at 4.5 GHz carrier, with a reported total spectral efficiency in the cell of nearly 80 bps/Hz. Several of the terminals are mobile, though it is not clear how fast.

Merouane Debbah, Vice-President of the Huawei France R&D center, confirms to the Massive MIMO blog that this spectral efficiency was achieved in the downlink, using TDD and exploiting channel reciprocity. This comes as no surprise, as it is not plausible that this performance could be sustained with FDD-style CSI feedback.

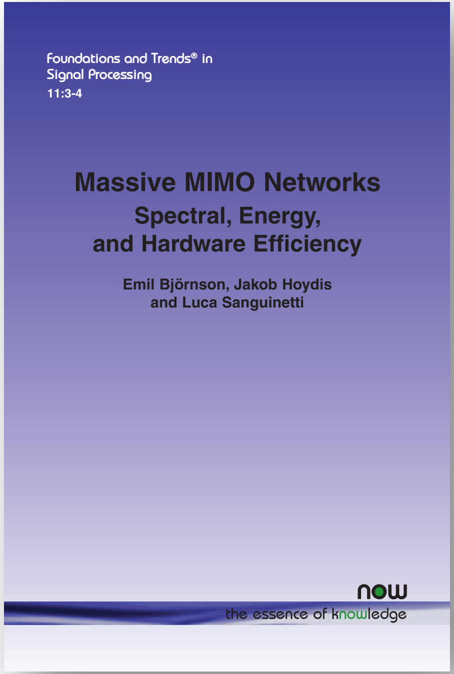
www.massive-mimo.net

Upcoming book:

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

500 pages, Matlab code

www.massivemimobook.com



Thank you!

Dr. Emil Björnson

Slides, papers, and code available online:

http://www.ebjornson.com/research

http://www.massivemimobook.com