Smart Signal Processing for Massive MIMO in 5G and Beyond

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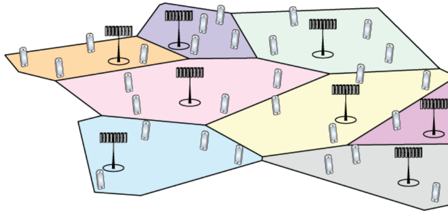
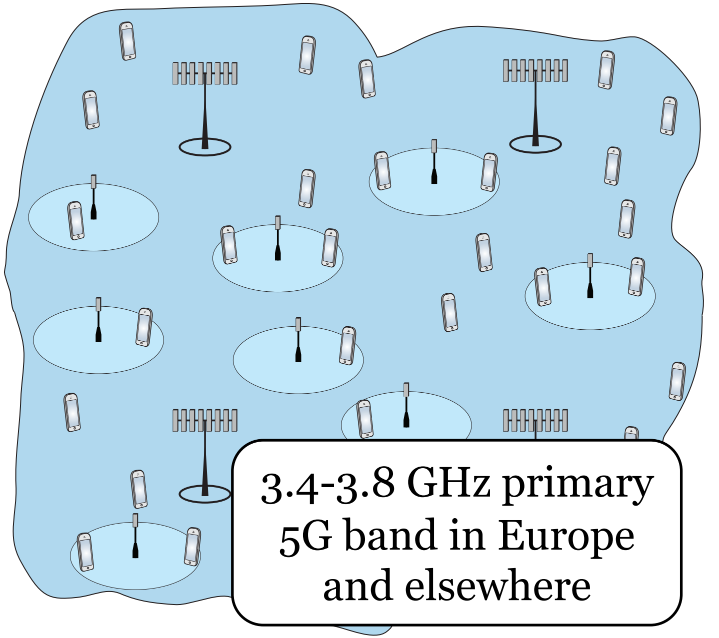
Raising the Efficiency of Cellular Communications



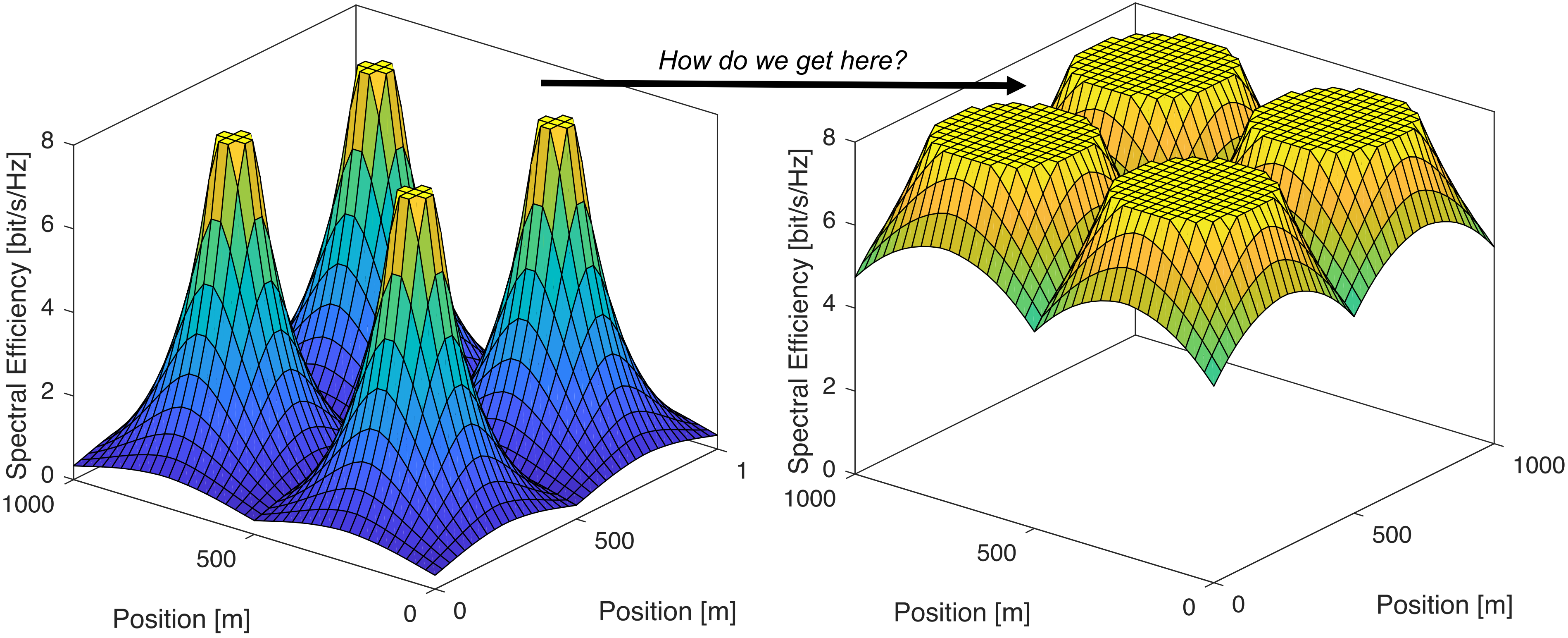
Formula for data throughput [bit/s/km²]:

$$\text{Area Throughput [bit/s/km}^2\text{]} = \frac{\text{Spectrum [Hz]} \times \text{Spectral efficiency [bit/s/Hz/cell]}}{\text{Cell size [km}^2\text{/cell]}}$$

- **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

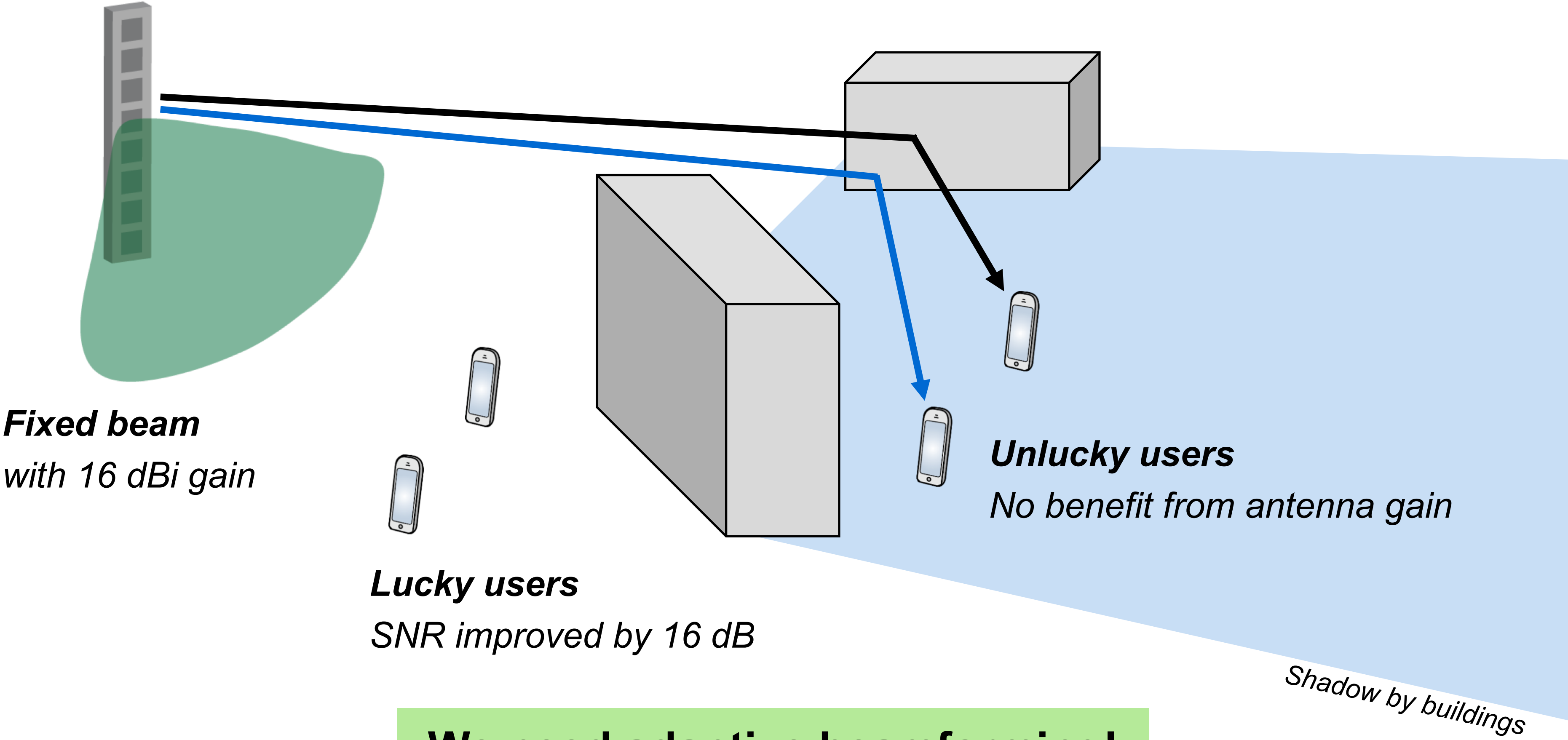


Non-uniform Spectral Efficiency is the Issue!



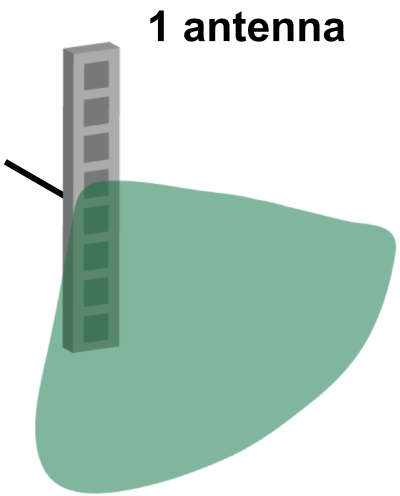
Desired: Stronger signal, same interference levels

Stronger Signals for Unlucky Users

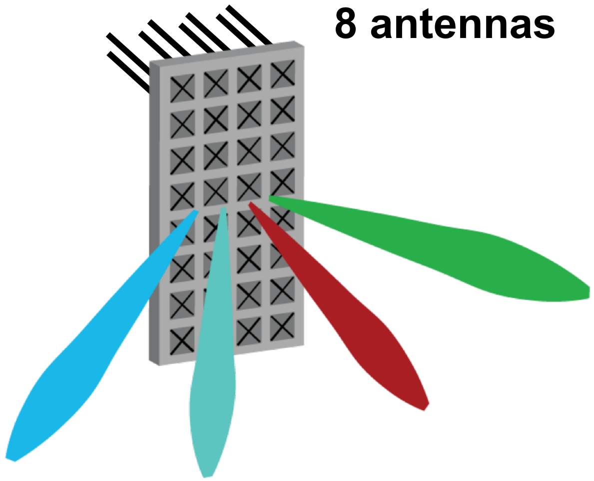


We need adaptive beamforming!

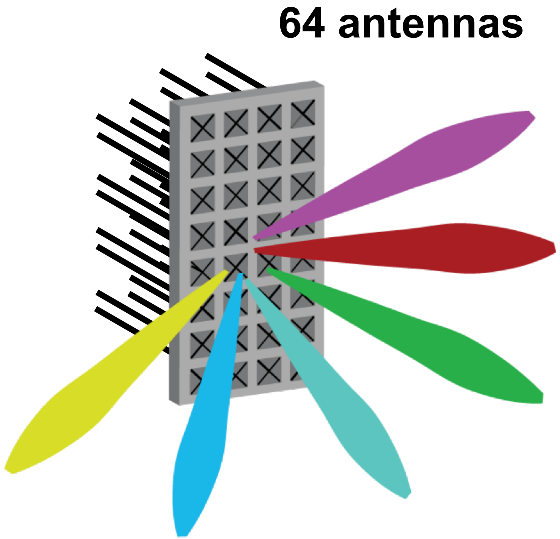
Evolution of Adaptive Beamforming in LTE



Sector antenna
8 elements (7 dBi each)
1 transceiver chain
Fixed beam 16 dBi



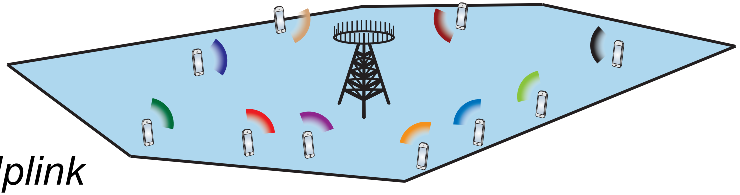
Classical antenna array
64 elements (32 per polarization)
8 transceiver chains (2 per column)
Up to 8 horizontal beams



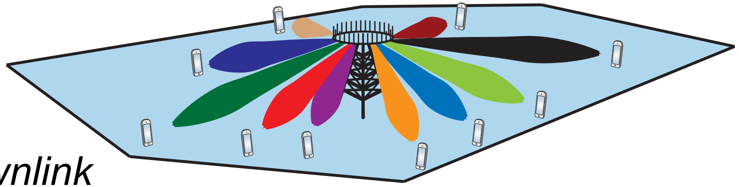
Massive antenna array
64 elements
64 transceiver chains
Up to 64 3D beams

Number of antennas equals number of transceiver chains!

Using Multiple Beams for Spatial Multiplexing



Uplink



Downlink

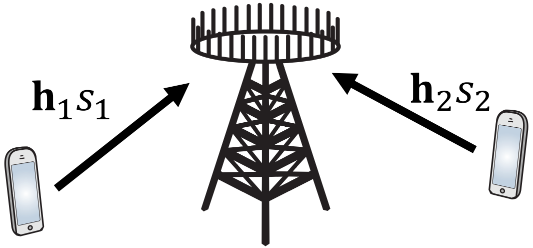
- Space-division multiple access (SDMA)
  - Uplink in 1980s: Use M antennas to resolve K signals
  - Downlink in 1990s: Transmit beamformed signals to multiple users
  - Typical: $M \approx K$

Massive MIMO approach: Massive number of antennas, $M \to \infty$

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

Interference-Free Communication with Many Antennas

- **Example: Uplink**
  - Two users, send signals s_k for $k = 1,2$
  - Channels: $\mathbf{h}_k \in \mathbb{C}^M$, random, zero mean, unit variance
  - Noise: $\mathbf{n} \sim CN(\mathbf{0}, \mathbf{I}_M)$
  - Received: $\mathbf{y} = \mathbf{h}_1 s_1 + \mathbf{h}_2 s_2 + \mathbf{n}$



Detection of s_1 using matched filter $\mathbf{v}_1 = \frac{1}{M}\mathbf{h}_1$:

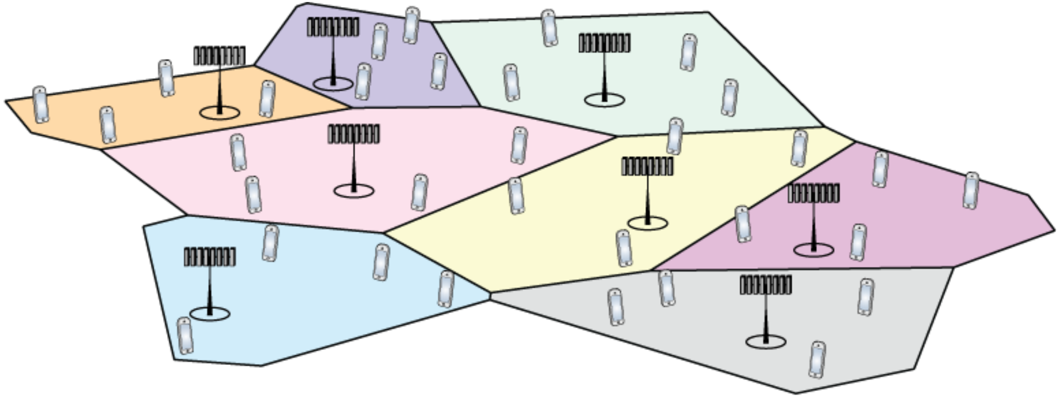
$$\mathbf{v}_1^{\mathrm{H}}\mathbf{y} = \frac{1}{M}\mathbf{h}_1^{\mathrm{H}}\mathbf{h}_1 s_1 + \frac{1}{M}\mathbf{h}_1^{\mathrm{H}}\mathbf{h}_2 s_2 + \frac{1}{M}\mathbf{h}_1^{\mathrm{H}}\mathbf{n}$$

$$\xrightarrow{M\to\infty} \quad s_1 \quad + \quad 0 \quad + \quad 0$$

"Law of large numbers"

Conclusion: Noise and interference free communication

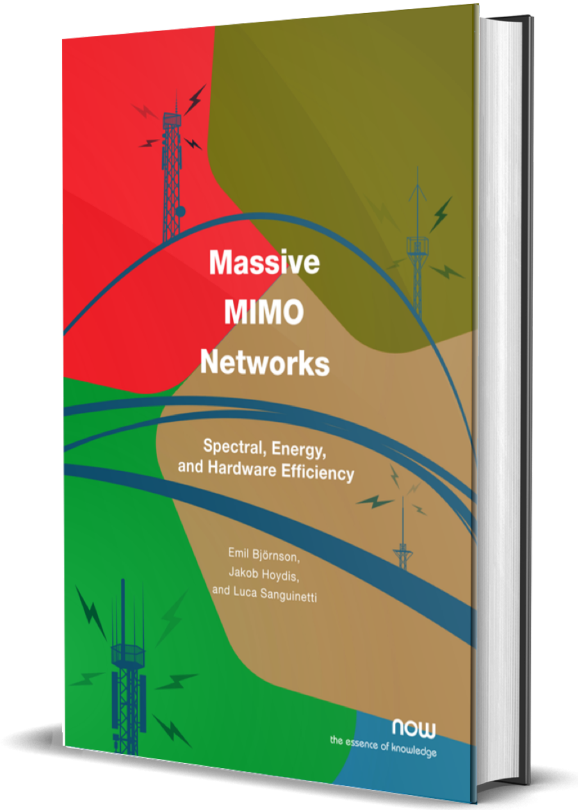
Canonical Form of Massive MIMO



- Cellular network
  - Many antennas M per base station
  - Spatial multiplexing of many users K
  - Antenna-user ratio: $M/K > 1$
  - Linear transmit precoding and receive combining

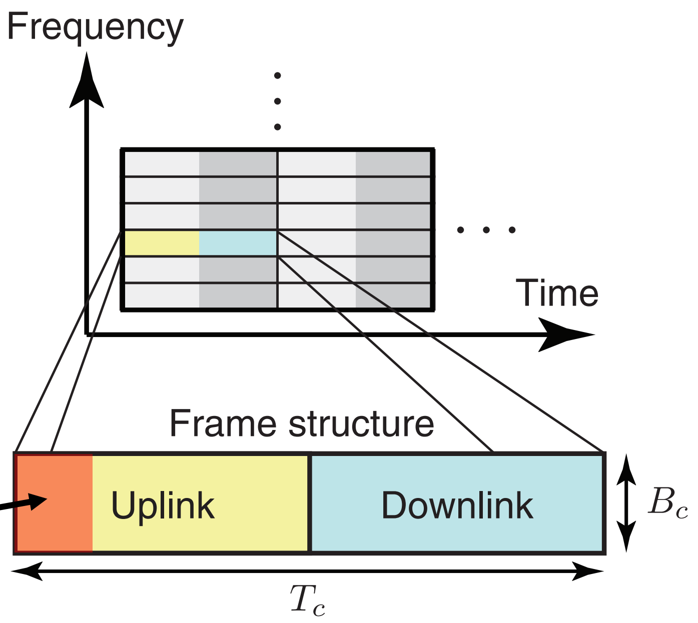
$M \geq 64$

$K \geq 8$



Massive MIMO in TDD Operation

- Frame structure = *Coherence block*
  - Coherence time: T_c s
  - Coherence bandwidth: B_c Hz
  - Block length: $\tau_c = T_c B_c$ symbols
  - Typically: $\tau_c \in [100{,}10000]$



Pilots to estimate channels:
K symbols

Uplink and downlink payload data
$\tau_c - K$ symbols

Many Signal Processing Schemes to Choose Between

Channel estimation

LS (least squares)

MMSE (minimum-mean squared error)

Element-wise MMSE

…

Precoding and combining

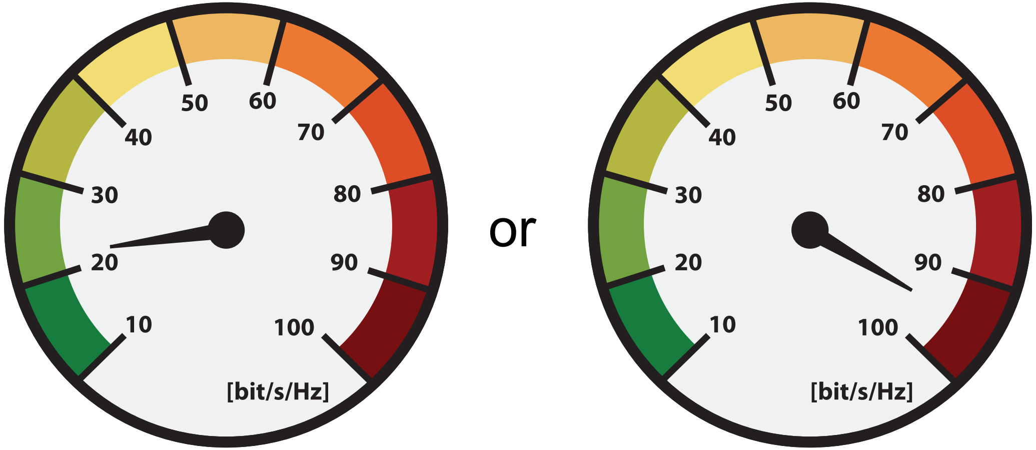
Matched filtering

Zero-forcing (ZF)

Regularized ZF

MMSE processing

…



Some choices are smart, some are just bad…

Matched Filtering is *Not* Optimal

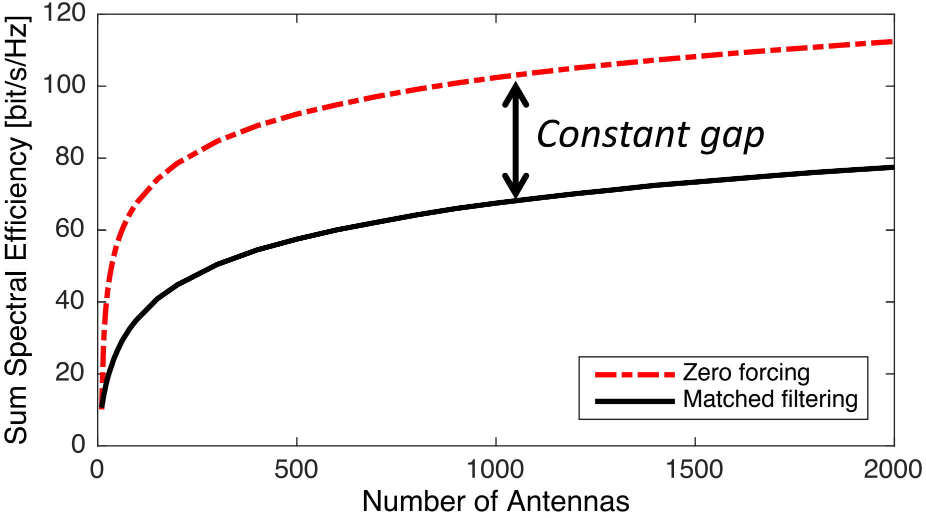
Uplink example

- 10 users, SNR = 15 dB, i.i.d. Rayleigh fading
- Inter-cell interference is 30 dB weaker

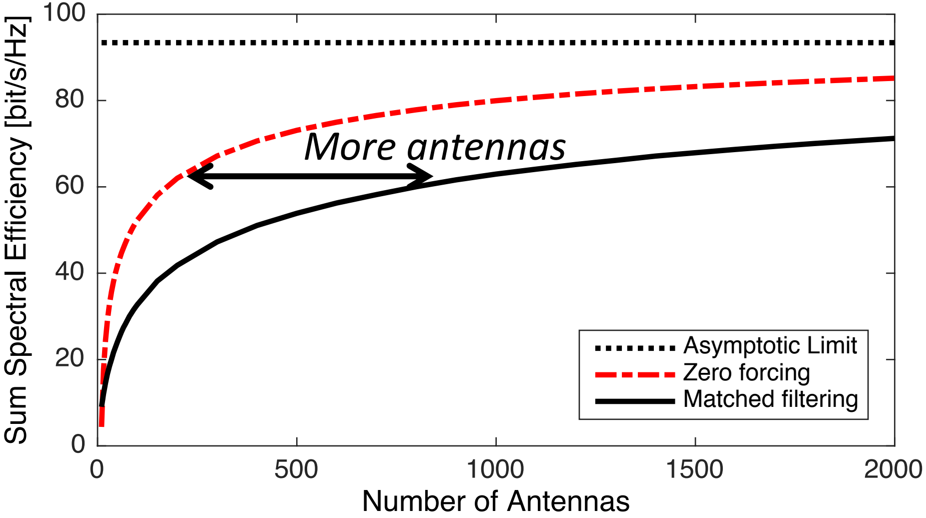
Bad processing:

Matched filtering

Single-cell setup



Multi-cell setup



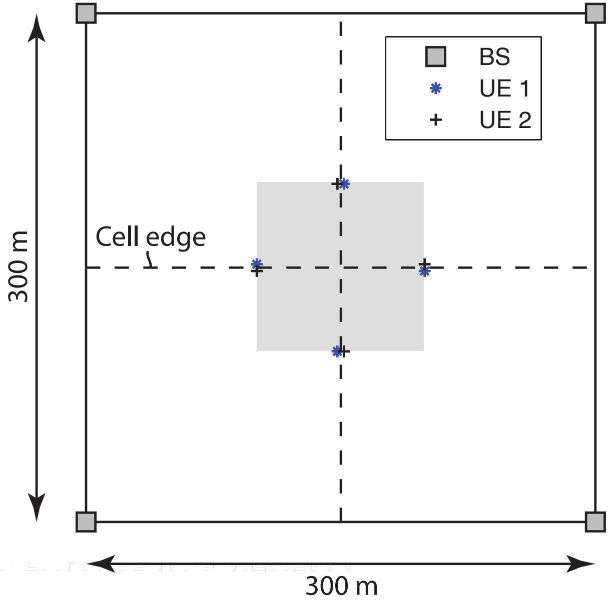
Zero-Forcing is *Not* Optimal Either

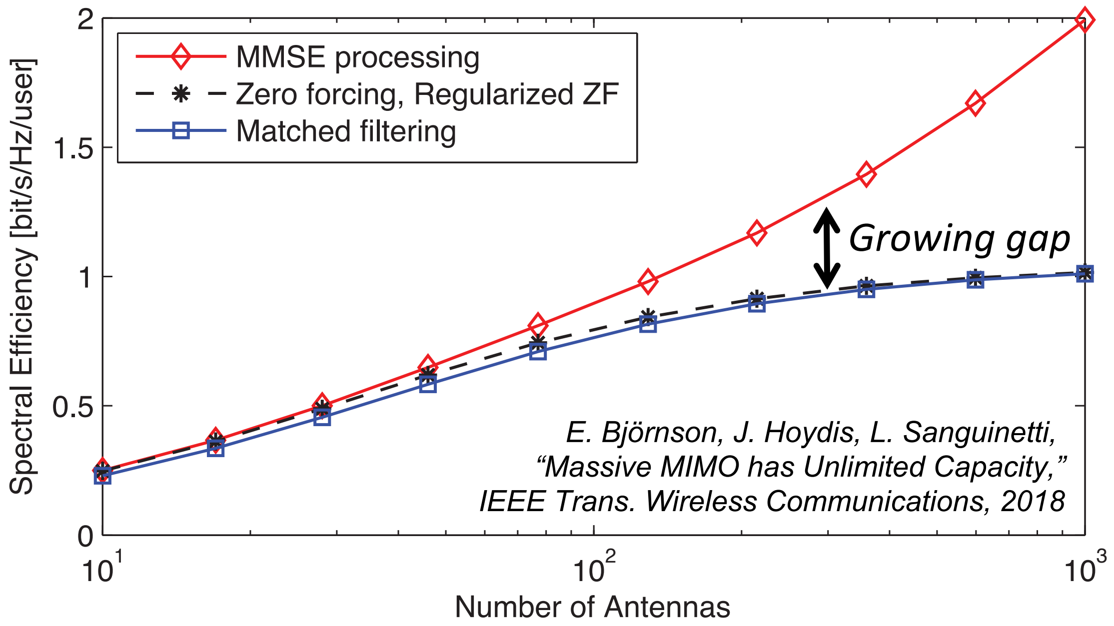
- **Uplink example**
  - Rayleigh fading with *a little* spatial correlation
  - SNR -6 dB in the cell, similar to other cells

Bad processing:

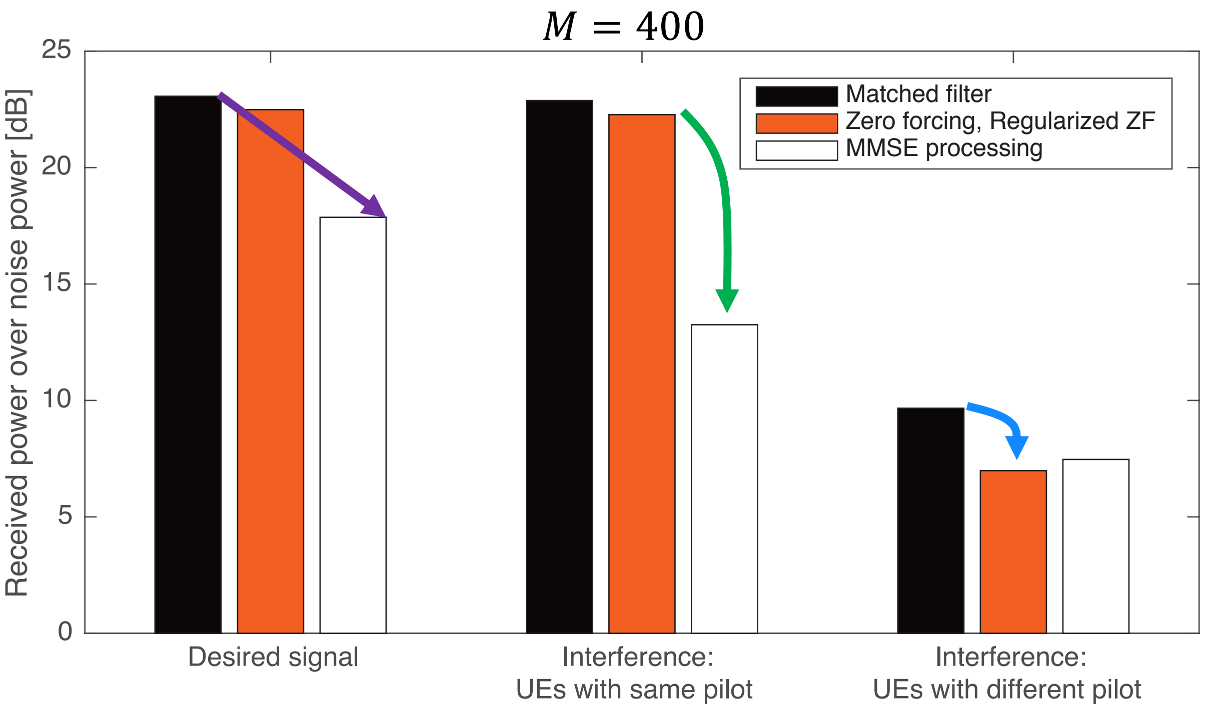
Matched filtering

Zero forcing





Interference from Other Cells is the Bottleneck



Matched filtering:

Ignores interference

Zero forcing:

Suppress interference from own cell

MMSE processing:

Suppress interference from anywhere

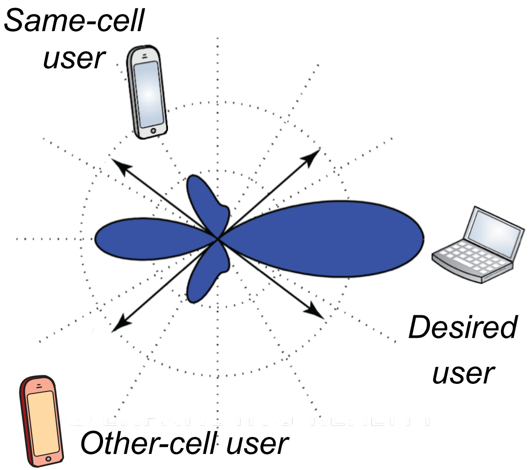
Price to pay: Loss in desired signal power

What Makes MMSE Processing Smart?

- **Example: Uplink with L cells**
  - $\mathbf{H}_l^j = \left[\mathbf{h}_{l1}^j \ \ \dots \ \ \mathbf{h}_{lK}^j\right] \in \mathbb{C}^{M \times K}$ Channels to BS j from UEs in cell l

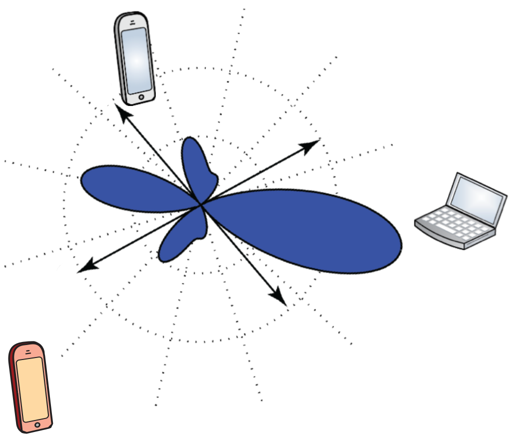
Matched filter:

$$\mathbf{V}_j = \frac{1}{M}\mathbf{H}_j^j$$



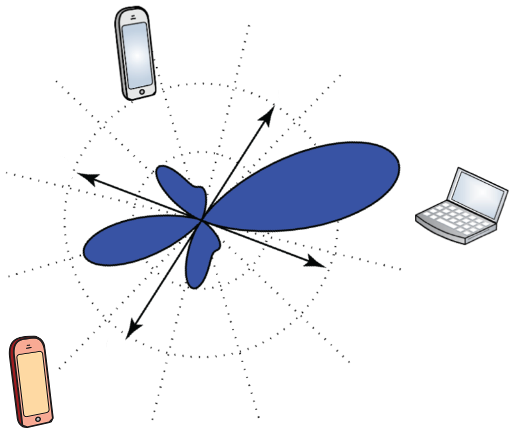
Regularized zero forcing:

$$\mathbf{V}_j = \left(\mathbf{H}_j^j\left(\mathbf{H}_j^j\right)^H + \mathbf{I}\right)^{-1}\mathbf{H}_j^j$$



MMSE processing: $\mathbf{V}_j =$

$$\left(\left[\mathbf{H}_1^j \ \dots \ \mathbf{H}_L^j\right]\left[\mathbf{H}_1^j \ \dots \ \mathbf{H}_L^j\right]^H + \mathbf{I}\right)^{-1}\mathbf{H}_j^j$$



"…all known capacity lower bounds approach a finite limit when $M \to \infty$" Marzetta et al., Fundamentals of Massive MIMO (p. 158)

- We only know an estimate $\widehat{\mathbf{H}}_l^j$ of $\mathbf{H}_l^j$
  - Same K pilots used in every cell – *pilot contamination*
  - With i.i.d. Rayleigh fading

$$\widehat{\mathbf{H}}_l^j \propto \widehat{\mathbf{H}}_j^j, \qquad l = 1, \dots, L$$

Hence: $$[\widehat{\mathbf{H}}_1^j \; \dots \; \widehat{\mathbf{H}}_L^j][\widehat{\mathbf{H}}_1^j \; \dots \; \widehat{\mathbf{H}}_L^j]^H \propto \widehat{\mathbf{H}}_j^j \left(\widehat{\mathbf{H}}_j^j\right)^H$$

Destroys the gain of MMSE processing!

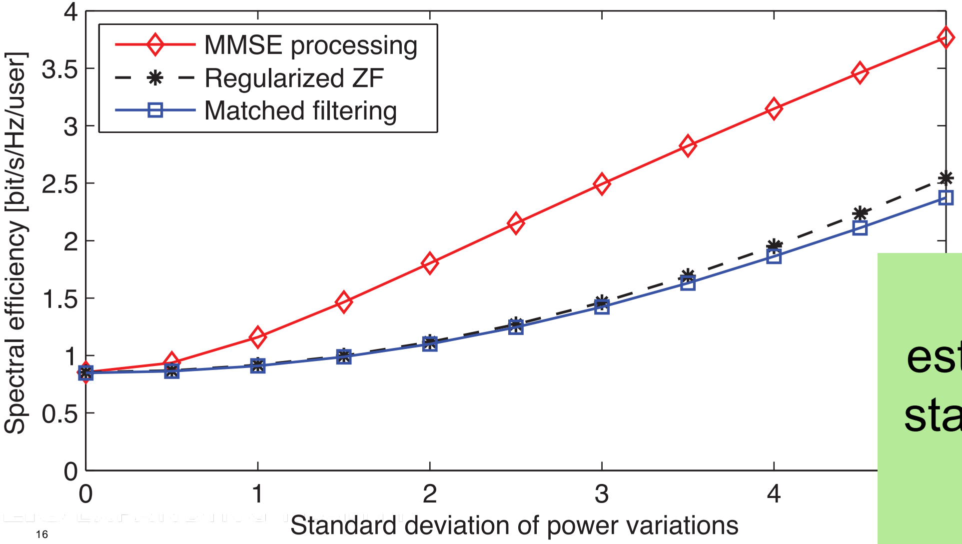
Causes the upper limit

This is an artifact of using a simplistic channel model!

A Little Spatial Channel Correlation Changes Everything

- Natural power variations – easy to estimate
  - 4-7 dB in ULA measurements (Lund University)

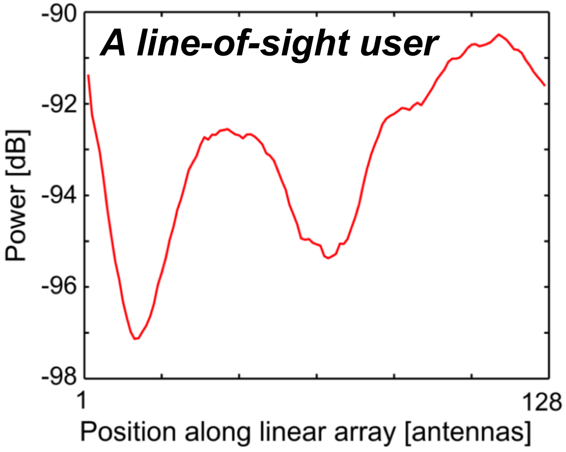
X. Gao, O. Edfors, F. Tufvesson, E. G. Larsson, “*Massive MIMO in Real Propagation Environments: Do All Antennas Contribute Equally?*,” IEEE Trans. Comm., 2015

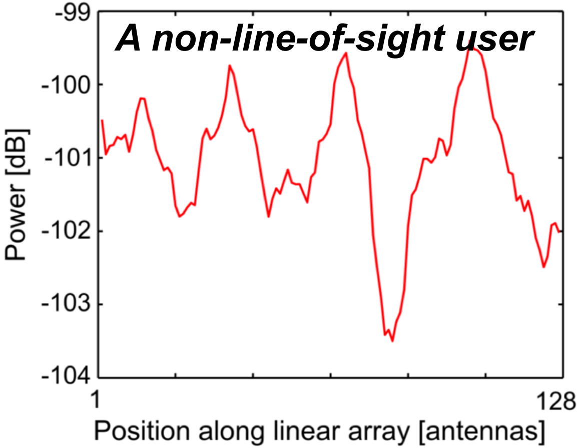


Random power variations

Channel estimator uses statistics to get

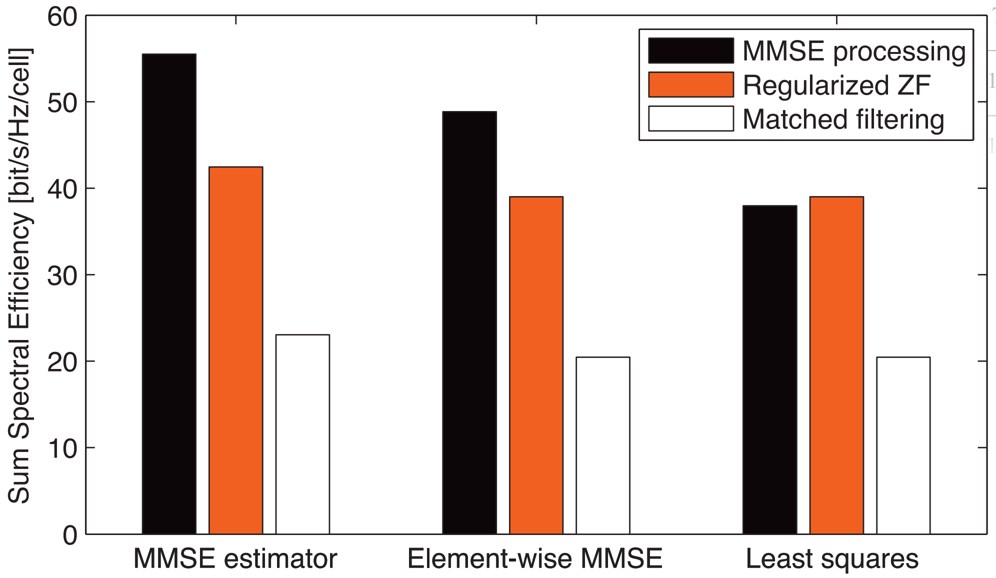
$$\widehat{\mathbf{H}}_l^j \not\propto \widehat{\mathbf{H}}_j^j$$



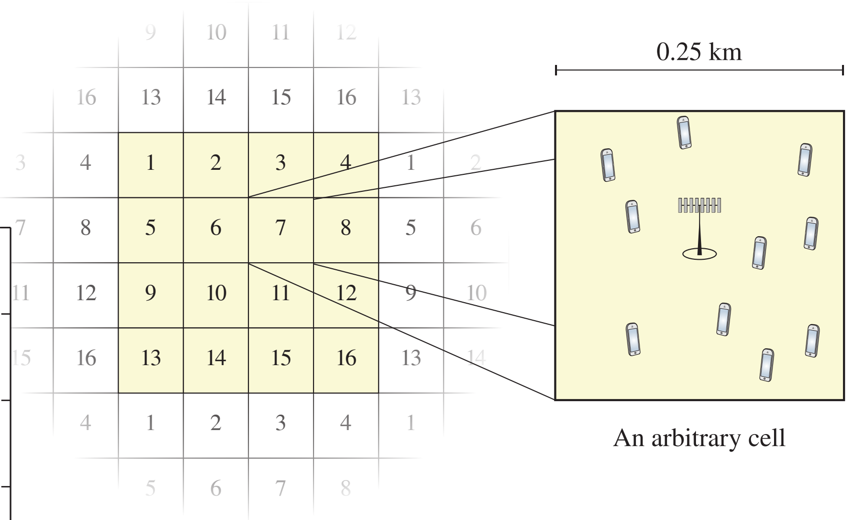


Which Channel Estimation Scheme to Use?

- Compare different channel estimators
  - 16 cells, $M = 100$, $K = 10$



Full channel statistics | *Known average power per element* | *No statistical knowledge*



Smart estimation:

MMSE or Element-wise MMSE

Least squares

OK if “bad” processing is used

Conclusion: Dangerous to Extrapolate Results

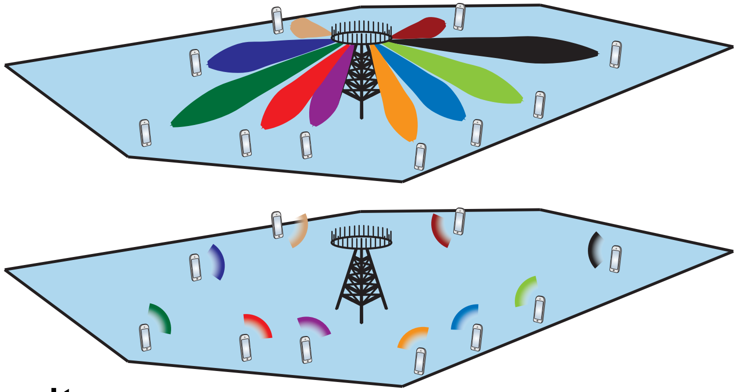
- From single-cell to multi-cell
  - Zero-forcing only good in single-cell scenarios
  - **Smart signal processing: MMSE processing for precoding/combining**
- Observations based on simplistic channel models
  - Tractable with i.i.d. fading – lead to overemphasize on pilot contamination
  - Matched filtering is not asymptotically optimal
  - **Smart signal processing: Uses spatial correlation**

Is any of this new insights?

Interference rejection combining known for decades

Yet, bad signal processing schemes dominates the Massive MIMO literature!

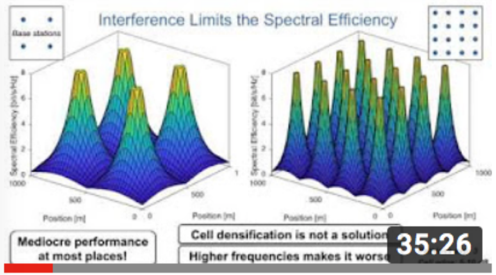
Definition: Massive MIMO 2.0



- **Massive MIMO system**
  - At least 64 antennas, at least 8 users
- **Smart channel estimation**
  - TDD operation, utilizing channel reciprocity
  - Exploit spatial correlation for better channel estimation
- **Smart precoding and combining**
  - MMSE processing to suppress all kinds of interference

Massive MIMO blog

Youtube channel:



Massive MIMO for 5G below 6 GHz

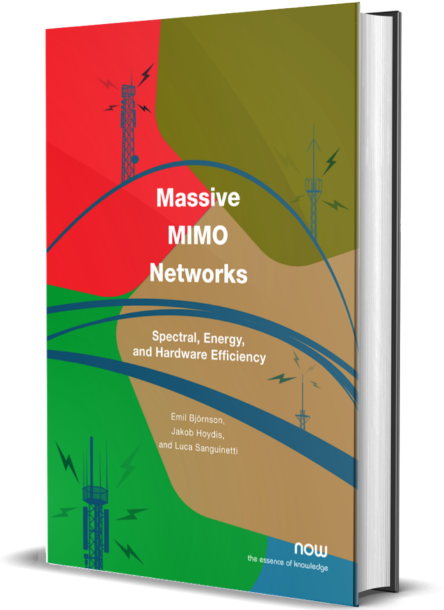
Communication Systems, Link...
12K views • 6 months ago

Papers: *ebjornson.com/research*

Code: *github.com/emilbjornson*

Questions?

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



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