Massive MIMO:
Ten Myths and One Critical Question

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Biography

- 2007: Master of Science in Engineering Mathematics, Lund, Sweden
- 2011: PhD in Telecommunications, KTH, Stockholm, Sweden
  (Advisors: *Björn Ottersten, Mats Bengtsson*)
- 2012-2014: Post-Doc at Supélec, Gif-sur-Yvette, France
  (Host: *Mérouane Debbah)*
- 2014-: Assistant Professor and Docent Linköping University, Sweden
  (Current team: Advisor of 2 PhD students, Co-advisor of 3 PhD students)

Current research topics

Massive MIMO, energy-efficient communication, radio resource optimization

Incredible Success of Wireless Communications

Martin Cooper's law

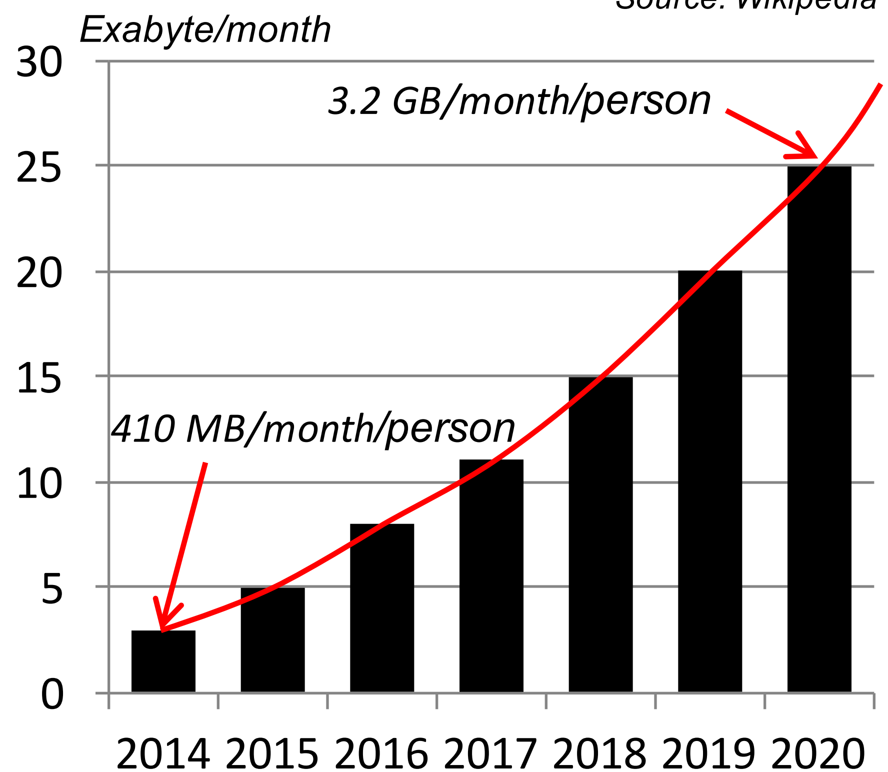
The number of voice/data connections has doubled every 2.5 years (+32% per year) since the beginning of wireless

Last 45 years: 1 Million Increase in Wireless Traffic

Two-way radio, FM/AM radio, satellites, cellular, WiFi, etc.

Source: Wikipedia

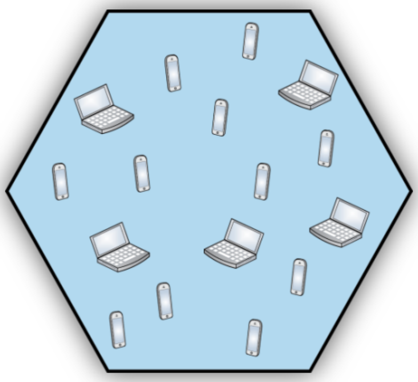
- Future Network Traffic Growth
  - 38% annual data traffic growth
  - Slightly faster than in the past!
  - Exponential increase



Source: Ericsson (November 2014)

Evolving Wireless Networks for Higher Traffic

- Network Throughput [bit/s/km^2]
  - Consider a given area
  - Demand increases by 30-40% per year!



- Simple Formula for Network Throughput:

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

  - Ways to Achieve 1000x Improvement in 5G:

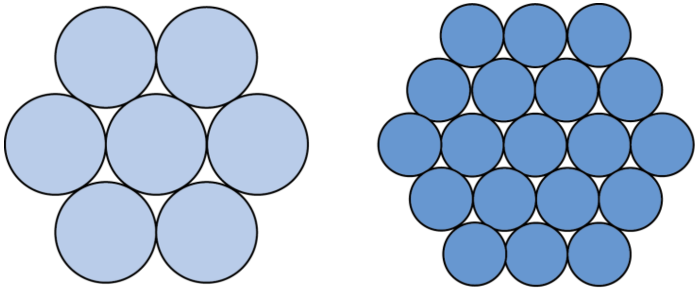
	More spectrum	Higher cell density	Higher spectral efficiency
Nokia (2011)	10x	10x	10x
SK Telecom (2012)	3x	56x	6x

How can Academia Help?

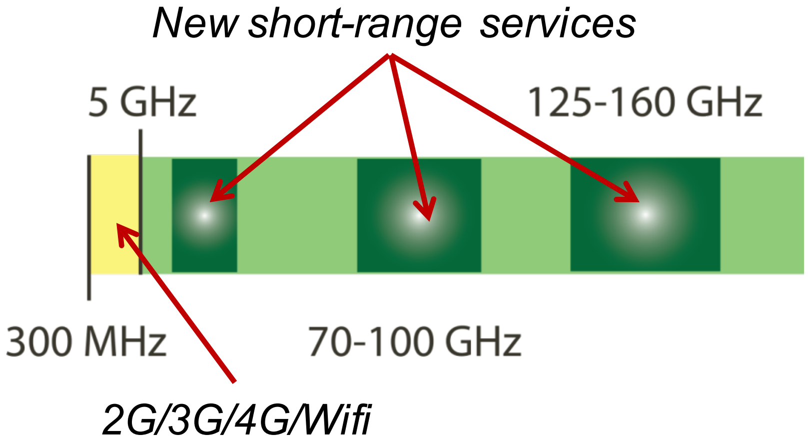
Identify new radical solutions! Achieve 20x not +20%

Conventional Solutions

- Higher Cell Density
  - Traditional way to improve throughput
  - Cut cell radius by z → z^2 times more cells
  - Issues: High rent and deployment costs
    Interference is not getting better
    WiFi + Cellular is already very dense: *Coverage is the issue*!



- More Spectrum
  - Suitable for coverage: Below 5 GHz
  - Already allocated for services! (cellular: 550 MHz, WiFi: 540 MHz)
  - Above 5 GHz: High propagation losses → Mainly short-range hotspots



Higher Spectral Efficiency

*"What if we issued a challenge in Washington?
Think of it as Race to the Top, the Spectrum Edition.
Imagine that we decided to reward the first person who finds a way to make spectrum use below 5 GHz 50 or 100 times more efficient over the next decade. The reward could be something simple—say 10 megahertz of spectrum suitable for mobile broadband."*

FCC Commissioner Jessica Rosenworcel
Marconi Society Anniversary Symposium, Oct. 2, 2014.

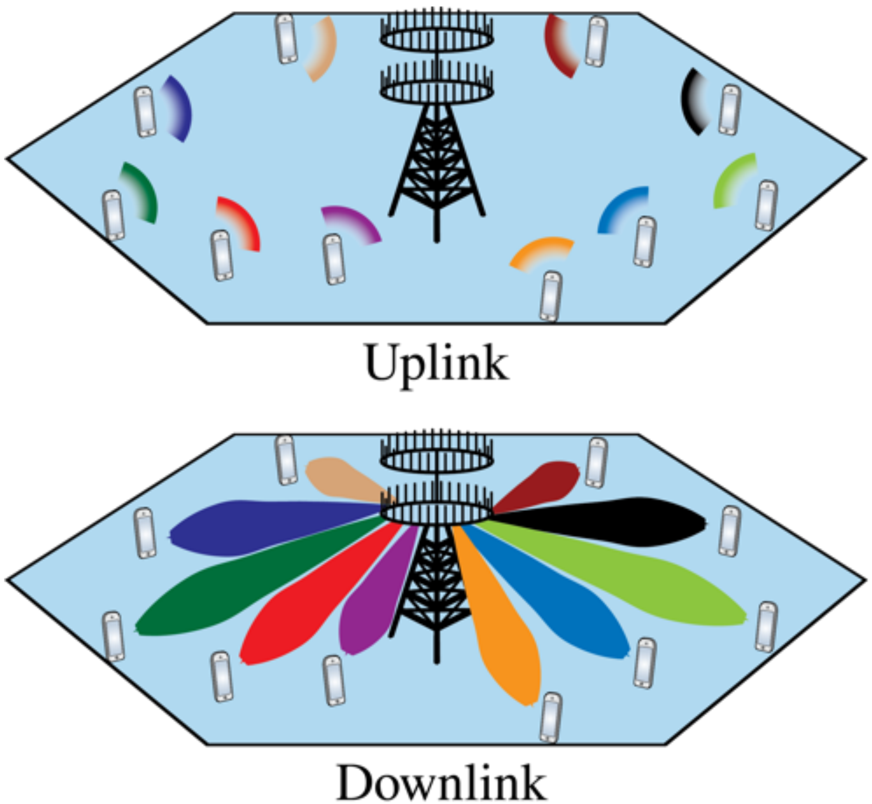
Price of sub-5 GHz Spectrum

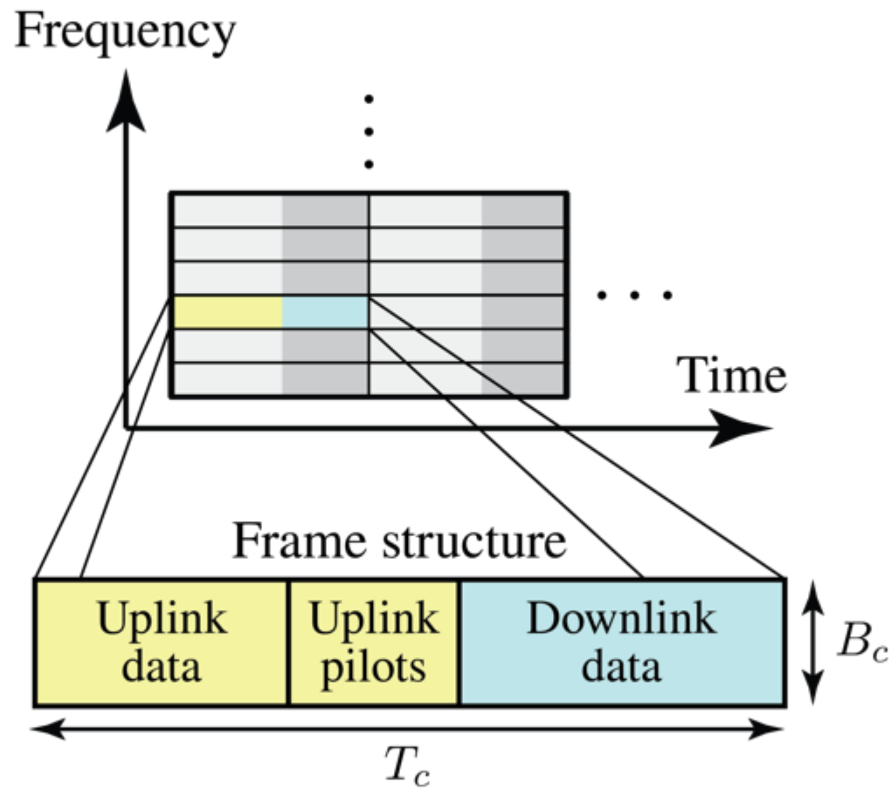
January 2015: FCC sold 65 MHz at 1.7-2.1 GHz for $45 billion

Can FCC's vision be achieved?

WHAT IS MASSIVE MIMO?

Massive MIMO Protocol





- Massive MIMO
  - Many antennas (M) at BSs
  - More antennas than users (K)
  - Very directive signals
  - Little interference leakage

- Time-Division Duplex (TDD)
  - Matched to channel coherence
  - Each frame: $S = T_c B_c$ symbols
  - Typically: $S \in [100, 10000]$
  - Linear signal processing using CSI

What is the Key Difference from Today?

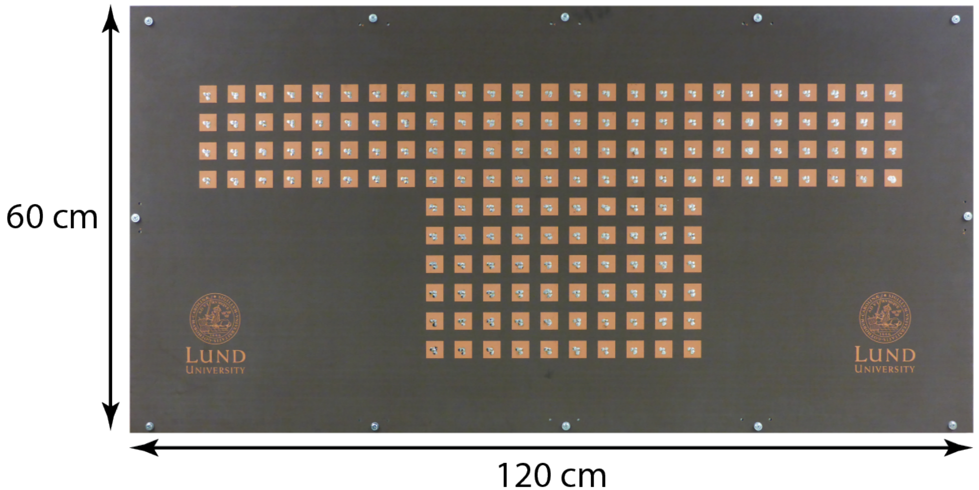
- Number of Antennas? **No, we already have many antennas!**
  - 3G/UMTS: 3 sectors x 20 element-arrays = 60 antennas
  - 4G/LTE-A: 4-MIMO x 60 = 240 antennas

Typical vertical array:
10 antennas x 2 polarizations
Only 1-2 transceiver chains

Massive MIMO Characteristics

Many dipoles with transceiver chains

Spatial multiplexing of tens of users



***160 antenna elements,** LuMaMi testbed, Lund University*

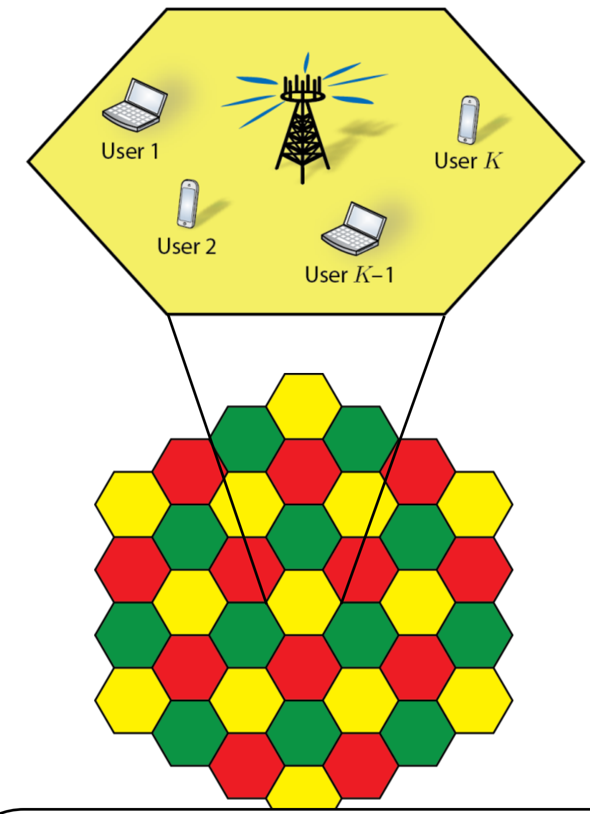
3 sectors, 4 vertical arrays per sector
Image source: gigaom.com

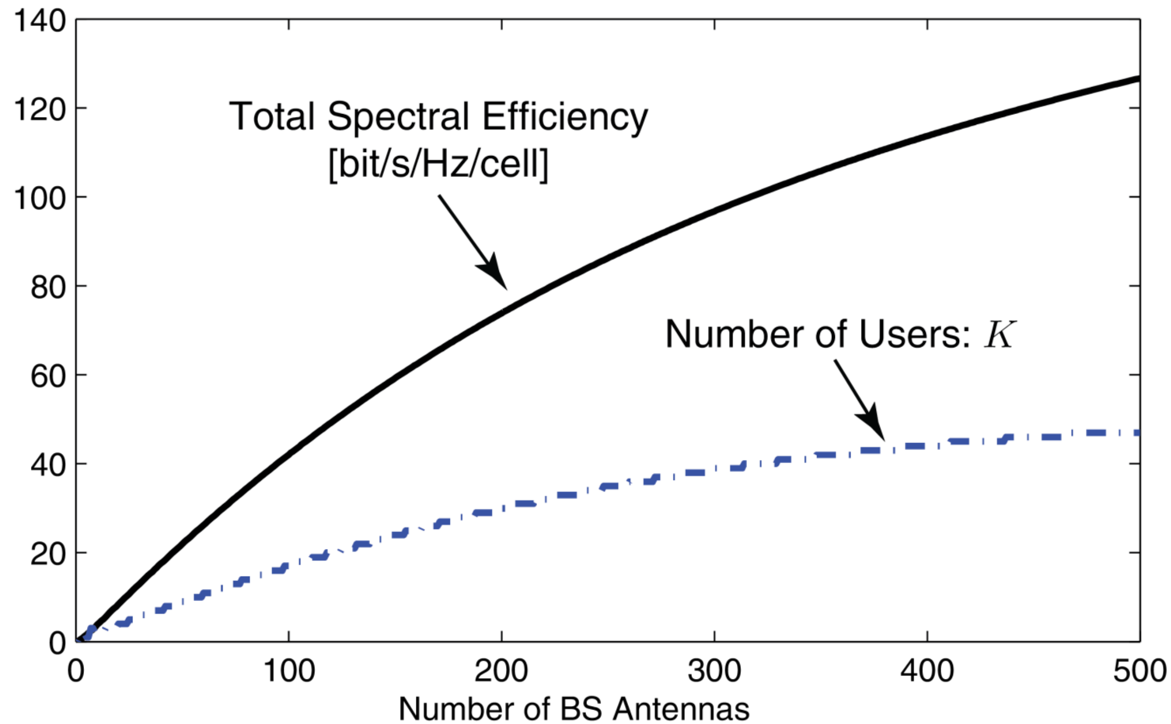
What is Different from Classic Multi-User MIMO?

- Multi-user MIMO has been around for decades:
  - J. Winters, "*Optimum combining for indoor radio systems with multiple users*," IEEE Trans. Commun., 1987.
  - S. Swales, M. Beach, D. Edwards, and J. McGeehan, "*The performance enhancement of multibeam adaptive base-station antennas for cellular land mobile radio systems*," IEEE Trans. Veh. Technol., 1990.
  - R. H. Roy and B. Ottersten. Spatial division multiple access wireless communication systems. US Patent, 1991. 5515378.

- Some new key characteristics
  - $M \gg K$: Favorable propagation
  - Frequency dependence and fast fading disappear
  - Scalability: Estimation overhead independent of M
  - Simple linear precoding and detection
  - Elegant ergodic capacity analysis

How Much can Spectral Efficiency be Improved?





Uplink Simulation

LTE-like system parameters

Coherence block: $S = 500$

SNR 5 dB, Rayleigh fading

ZF detection and pilot reuse 3

Observations

- *Baseline: 2.25 bit/s/Hz/cell (IMT-Advanced)*
- *Massive MIMO,* $M = 100$*: x20 gain*
- *Massive MIMO,* $M = 400$*: x50 gain*
- *Per scheduled user:* ≈ 2.5 *bit/s/Hz*

Originator of Massive MIMO Concept

- Thomas Marzetta, Bell Labs
  - Originator of Massive MIMO Concept

  - Key paper:

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

Massive MIMO: 50x Improvements!

Will FCC give him 10 MHz?

TEN MYTHS ABOUT MASSIVE MIMO

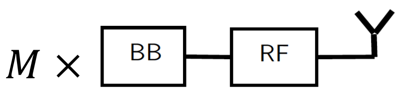
“It is only suitable for millimeter wave bands”

Cellular bands: ~ 2 GHz

Wavelength: $\lambda = 15$ cm

Form factor of $\lambda/2$ array:
400 elements in 1.5×1.5 m

Mature hardware

Example: 

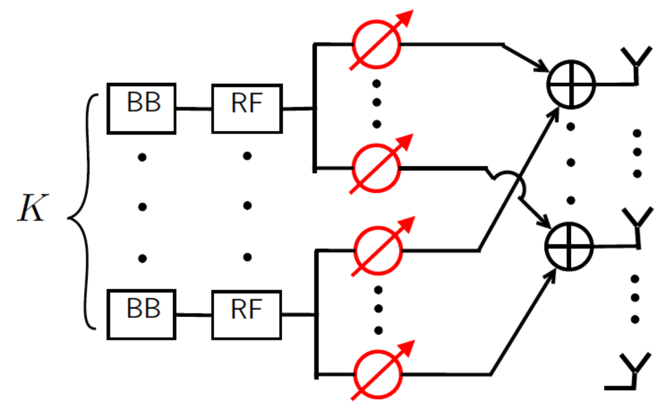
Coherence (suburban): $T_c B_c \sim 200$

mmWave bands: ~ 60 GHz

Wavelength: $\lambda = 5$ mm

Form factor of $\lambda/2$ array:
400 elements in 5×5 cm

Hardware? Awaiting spectrum?



Hybrid?

$30 \times$ Doppler $\rightarrow T_c$ reduces by $1/30$

Massive MIMO is ideal for cellular bands!

“It is only suitable for millimeter wave bands”

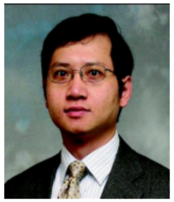
THE DEATH OF 5G PART 2: WILL ANALOG BE THE DEATH OF MASSIVE MIMO?

CTN Issue: June 2015

Jin Liu and Hlaing Minn, Guest Editors
Alan Gatherer, Editor in Chief, ComSoc Technology News

Editor's note: While we are on the topic of things that might kill 5G, or at least cause it to evolve into something other than we think it is today, I think the topic of the analog front-end of massive MIMO is worth a closer look. So many papers side-step this issue with a note that analog beam forming solutions will solve the problem. Though some very interesting work has been done in this area, this sounds like a punt down the field to me. History has taught us that analog never replaces digital for all that long. In order to step back and cast an impartial eye on the problem I recently drove down the road from my office in, what at that time was, a quite soggy Plano TX to an equally soggy Richardson and the home of UT Dallas. Below is the result of this effort; a nice little summary by Professors Liu and Minn on some of the issues that face ADC development if we are to implement 5G massive MIMO in production. I'm sure there are more issues than mentioned here and comments are always welcome.

Analog Front End Design Challenges for 5G Massive MIMO

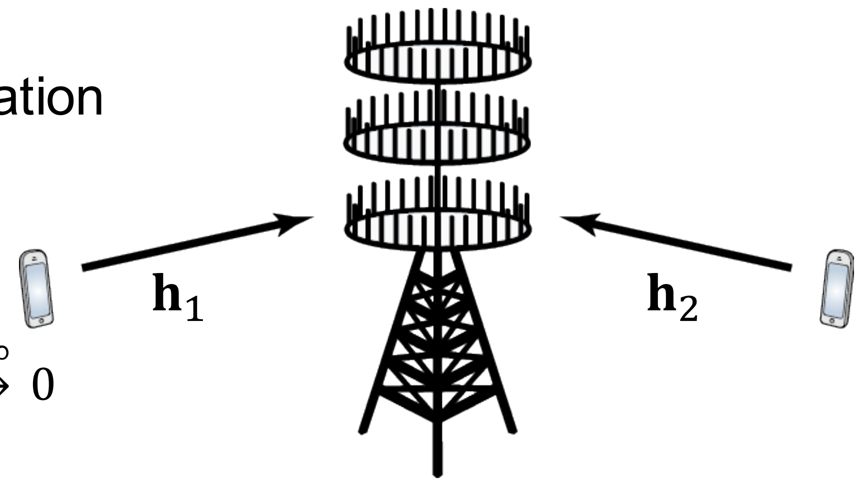


Jin Liu and Hlaing Minn

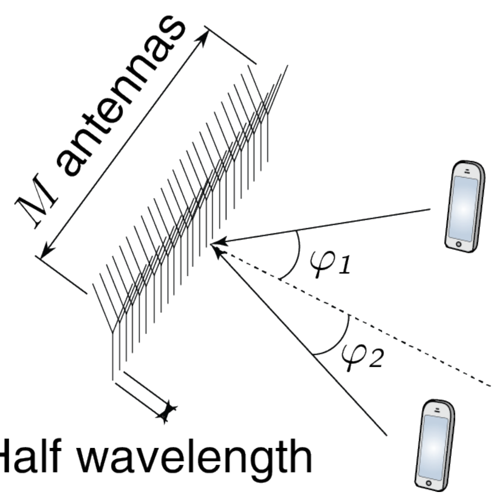
The exponential growth of data rate has led to the demand for 5G wireless systems with an expected data bandwidth of several GHz and carrier frequencies in the millimeter wave range (tens of GHz to 100GHz) [1-5]. Due to large propagation losses at this frequency range, beamforming with massive MIMO plays a central role in establishing reliable communication links. It is expected that the required number of antennas will be an order of magnitude larger than existing wireless systems. This presents significant challenges in the analog front end design.

“It only works in rich-scattering environments”

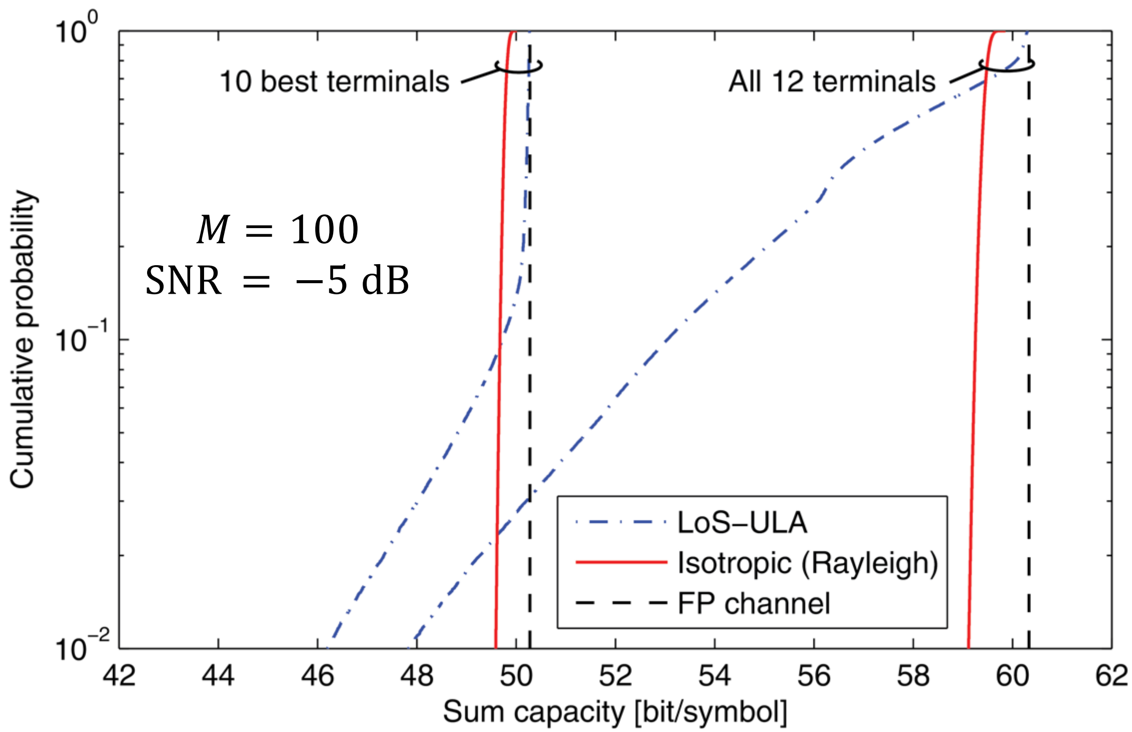
- Rich-scattering: Favorable propagation
  - Rayleigh fading: $\mathbf{h}_1, \mathbf{h}_2 \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}_M)$
  - Array gain: $\frac{1}{M} ||\mathbf{h}_1||^2 \xrightarrow{M\to\infty} 1$
  - Channel orthogonality: $\frac{1}{M} \mathbf{h}_1^H \mathbf{h}_2 \xrightarrow{M\to\infty} 0$



Opposite: Line-of-Sight



***Reality:** Works in diverse environments*

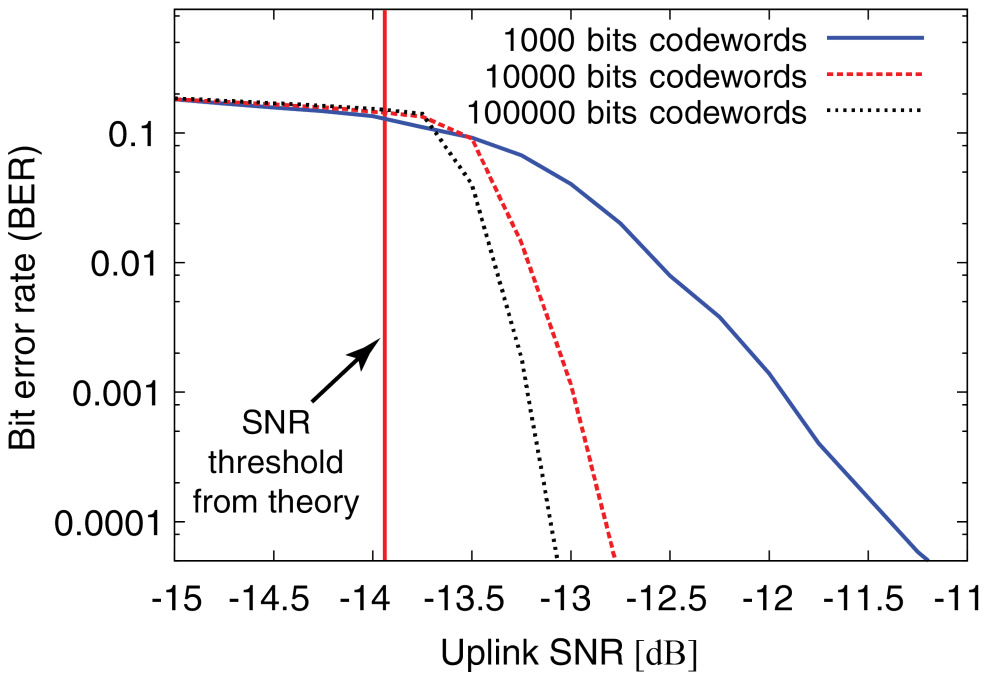


"Massive MIMO Relies on Asymptotic Results"

- Initial works: Closed-form results for $M \to \infty$
  - Nowadays: Performance expressions for any M, K, and pilot signaling
  - Consider achievable rate formula:

$$K \cdot \log_2\left(1 + \frac{c_{\text{CSI}} \cdot M \cdot \text{SNR}}{K \cdot \text{SNR} + 1}\right) \quad \text{where } c_{\text{CSI}} = \left(1 + \frac{1}{K \cdot \text{SNR}}\right)^{-1}$$

- **Example**:
  $M = 100, \; K = 30$
  QPSK with ½-LDPC code
  Total: 30 bit/s/Hz
- **Reality**:
  Closed-form rate formulas reached for modest M, K, and codeword lengths



“Massive MIMO Relies on Asymptotic Results”

Achievable rate of AWGN channel

$$y = g \cdot s + n$$

Constant gain: g

Signal: $CN(0, P)$

Noise: $CN(0, \sigma^2)$

$$R = \log_2(1 + P|g|^2/\sigma^2)$$

Achievable rate of Massive MIMO uplink channel

$$\boldsymbol{y} = \sum_{i=1}^{K} \boldsymbol{h}_i s_i + \boldsymbol{n}$$

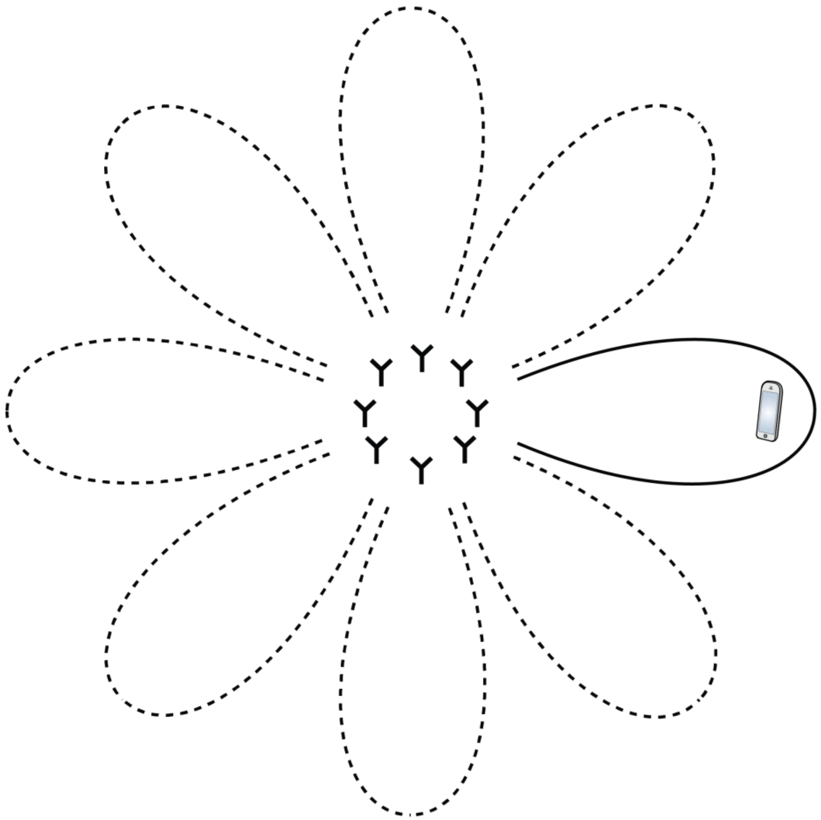
Uplink detector $\boldsymbol{v}_k$ for user k:

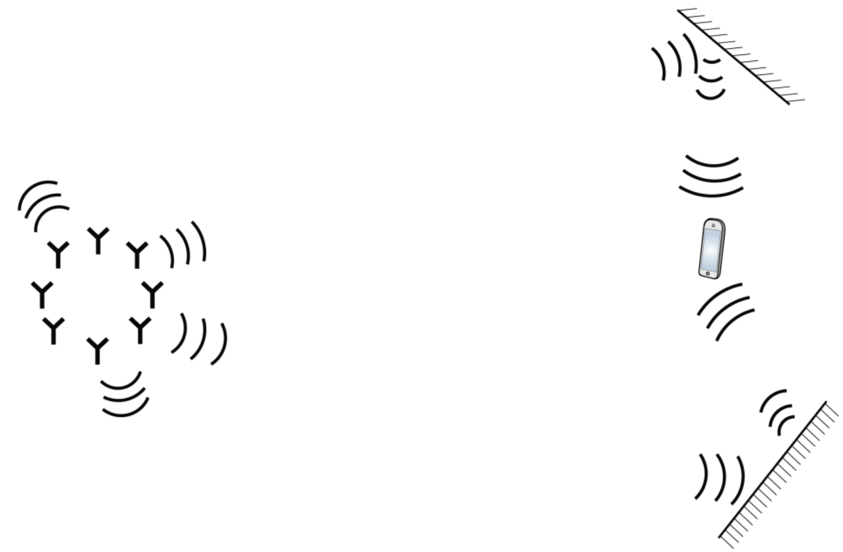
$$\boldsymbol{v}_k^H \boldsymbol{y} = \sum_{i=1}^{K} \boldsymbol{v}_k^H \boldsymbol{h}_i s_i + \boldsymbol{v}_k^H \boldsymbol{n} = \underbrace{\mathbb{E}\{\boldsymbol{v}_k^H \boldsymbol{h}_k\}}_{g_k\text{: Constant gain}} s_k + \underbrace{\left(\boldsymbol{v}_k^H \boldsymbol{h}_k - \mathbb{E}\{\boldsymbol{v}_k^H \boldsymbol{h}_k\}\right) s_k}_{a_k\text{: Uncorr. deviation}} + \underbrace{\sum_{i \neq k} \boldsymbol{v}_k^H \boldsymbol{h}_i s_i + \boldsymbol{v}_k^H \boldsymbol{n}}_{b_k\text{: Interference and noise}}$$

$$R_k = \log_2\left(1 + \frac{P|g_k|^2}{\mathbb{E}\{|a_k|^2\} + \mathbb{E}\{|b_k|^2\}}\right) = \begin{bmatrix}\text{Rayleigh fading} \\ \text{Maximum ratio combining}\end{bmatrix} = \log_2\left(1 + \frac{c_{\mathrm{CSI}} \cdot M \cdot \mathrm{SNR}}{K \cdot \mathrm{SNR} + 1}\right)$$

Behaves similar to an AWGN channel after processing!

"Massive MIMO is just beamforming"





Line-of-Sight

Channels determined by angles

1-2 parameters to estimate per user

Precoding = Beamforming

Easy: Codebooks can be used

Non-Line-of-Sight

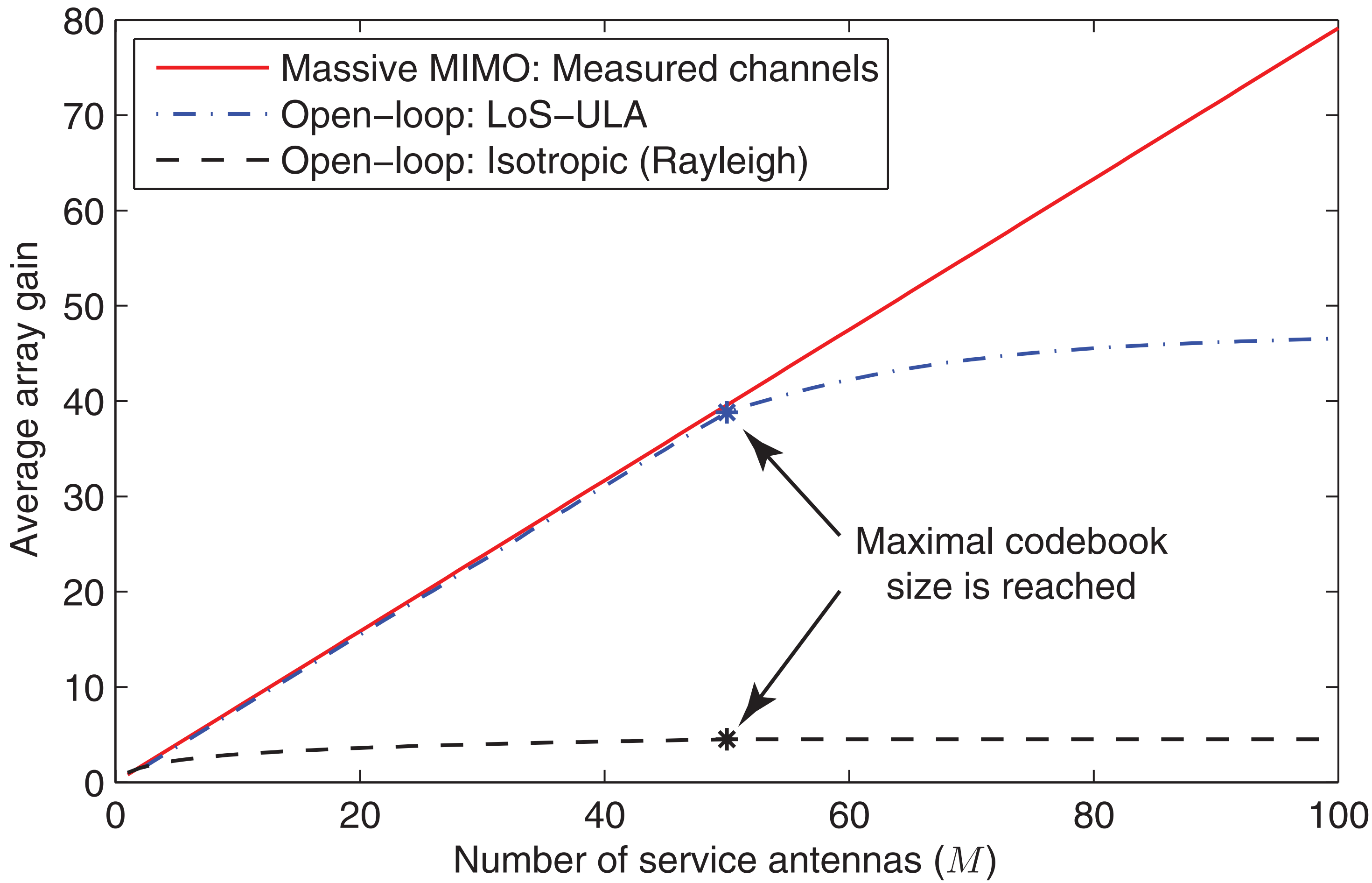
Rich multipath propagation

M parameters to estimate per user

Precoding ≠ Beamforming

Hard: Requires pilot transmission!

“Massive MIMO is just beamforming”



Scenario: $K = 12$ *terminals*

Massive MIMO: $\mathrm{SNR} = -5$ *dB*, $c_{\mathrm{CSI}} \approx 0.79$

Open-loop beamforming: *Codebook size* $L = \begin{cases} M, & M \leq 50 \\ 50, & M > 50 \end{cases}$

"Too much is lost by linear processing"

- Capacity-Achieving Non-linear Processing
  - Downlink: Dirty paper coding
  - Uplink: Successive interference cancellation

Why not use it in Massive MIMO?

Linear Processing

Bad when $M \approx K$

Good when $M/K > 2$

Relative low complexity

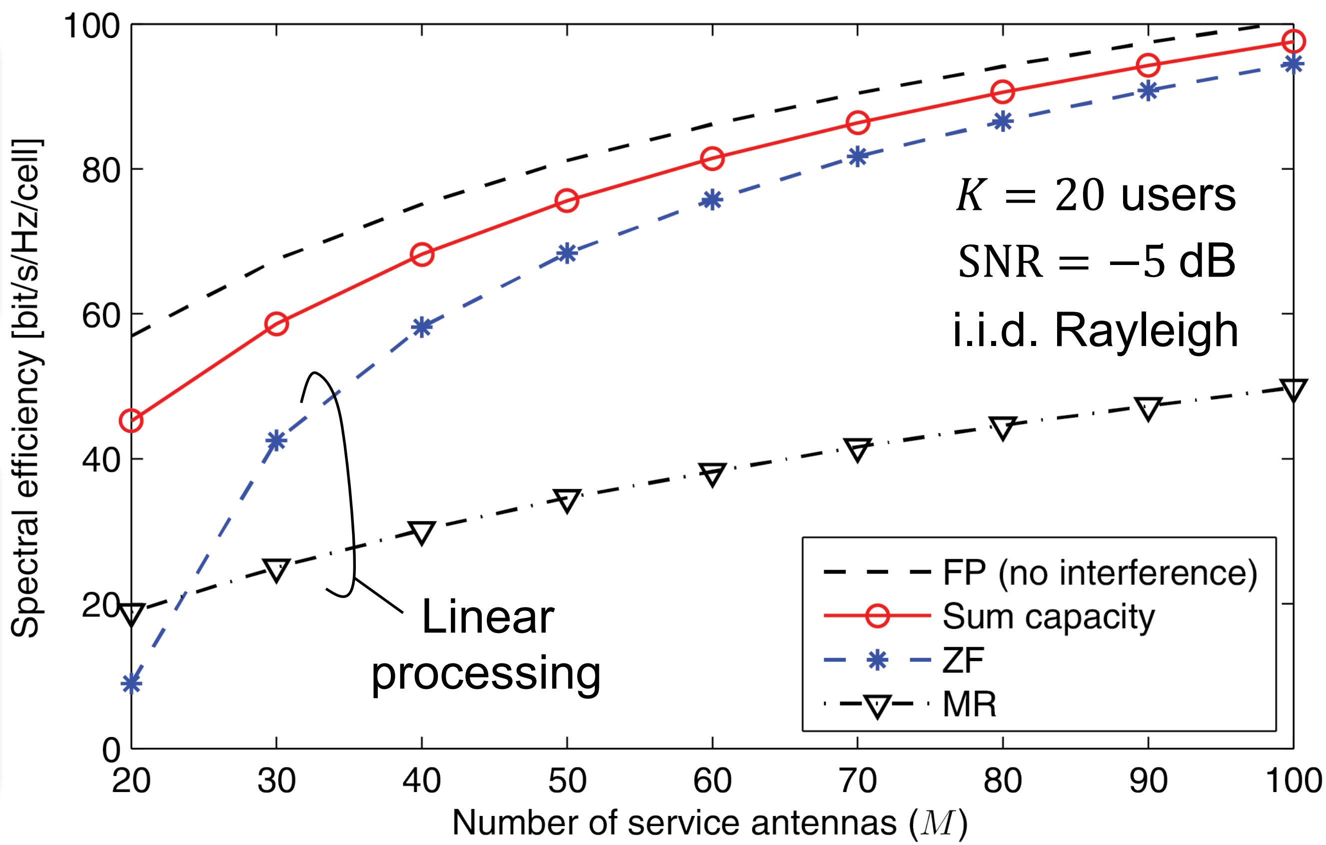
Massive MIMO

Uses linear processing:

Maximum ratio (MR)

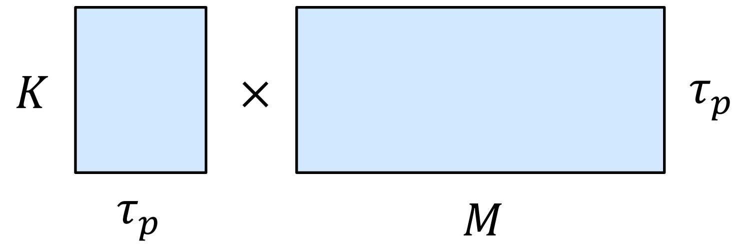
Zero-forcing (ZF)

Optimal: MMSE

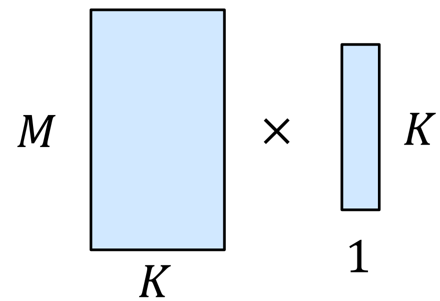


“Signal Processing Complexity is Overwhelming”

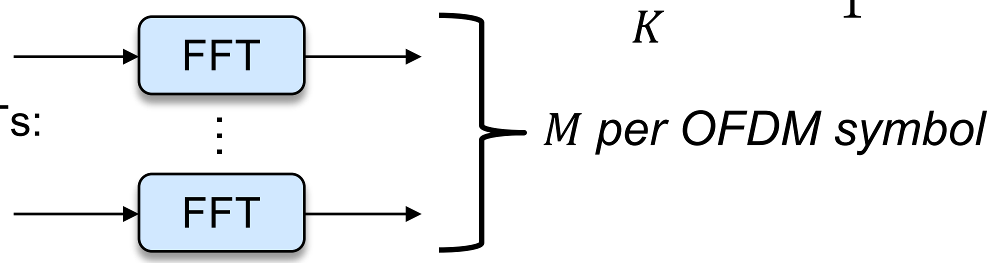
- **Reality:** It is higher, but appears to be manageable
  - Most processing can be parallelized per antenna
    - Channel estimation: $O(MK\tau_p)$ opers/frame



    - Precode/detect data: $O(MK)$ opers/symbol



    - N-point FFTs: $O(N \log N)$



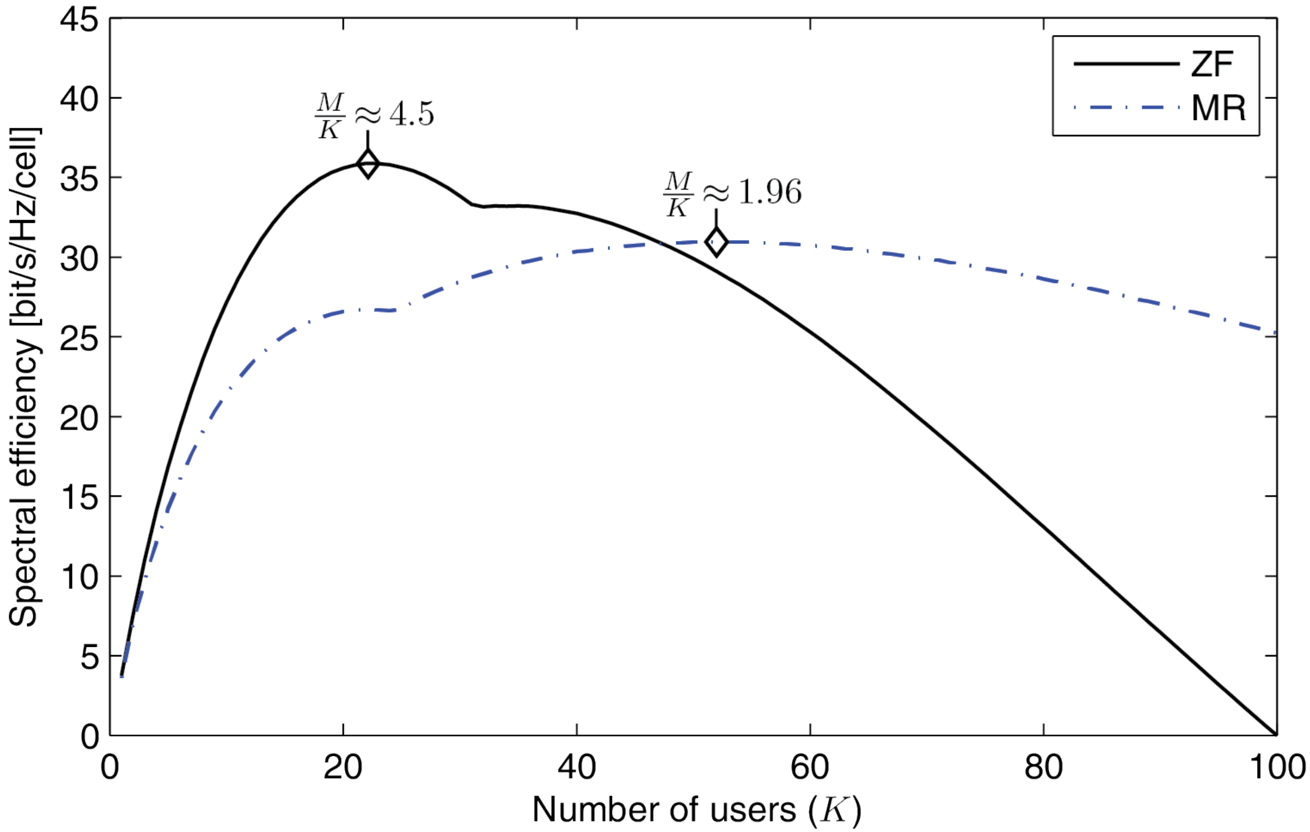
  - Not parallelizable: Computing ZF/MMSE matrix inversion, but:
    - Not the main complexity (happens only $1/S$ of the time)
    - Good inversion approximations (diagonal-dominant matrices)

“Need Orders of Magnitude More Antennas than Users”

- No! It depends on the metric
  - **Example**:
    $M = 100,\ S = 200$
    SNR = -5 dB from own BS

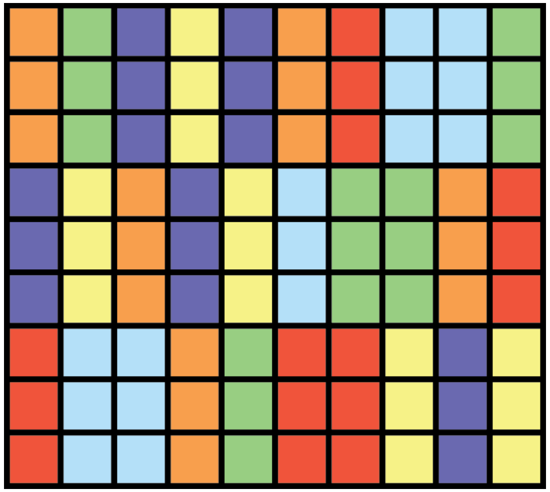
- **Reality**:
  Any $M/K > 2$ is desirable

  Choose between:
  Many or few users →
  Low or high rates/user

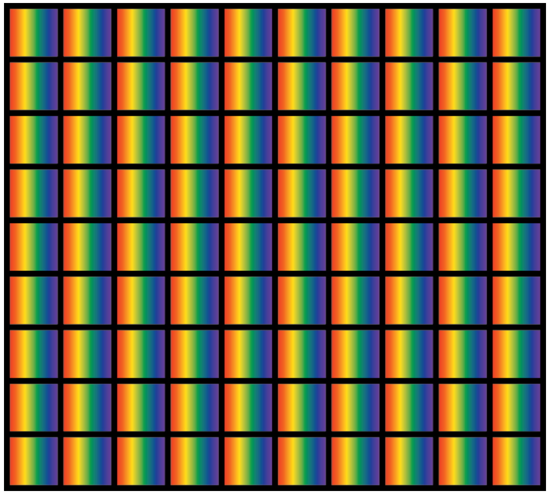


“Resource Allocation is Hugely Complicated”

- **Classic Resource Allocation**
  - Allocate time/frequency blocks to a user
  - Utilize: Current fading realization
  - Multiple users per block → Harder to allocate



- **Reality:** Not needed in Massive MIMO!
  - Same channel quality in all blocks
  - Everyone can get the whole bandwidth, whenever needed!



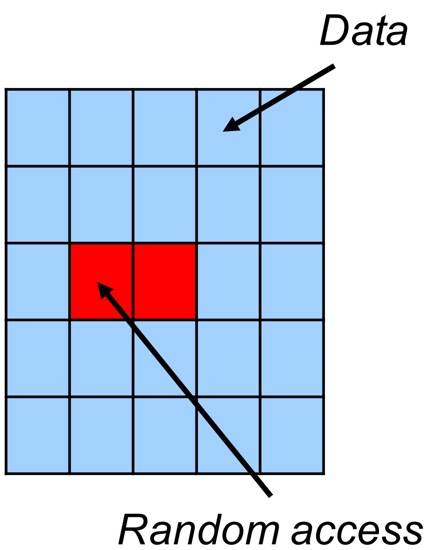
Power Control Still Needed!

Complexity independent of M

No need to adapt to small-scale fading

“Terminals cannot join since no initial array gain”

- Coherent transmission
  - Array gain $c_{\text{CSI}} \cdot M$: Tens of dB in improved SNR!
  - Requires channel estimates from pilot signals
- **Terminal** initiates
  - Select a pilot allocated for random access
  - Response: User gets a dedicated pilot signal
- **Base station** initiates
  - Broadcast pilot allocation: $c_{\text{CSI}} \cdot M/K$ times weaker than with precoding
  - Response: User uses its dedicated pilot signal

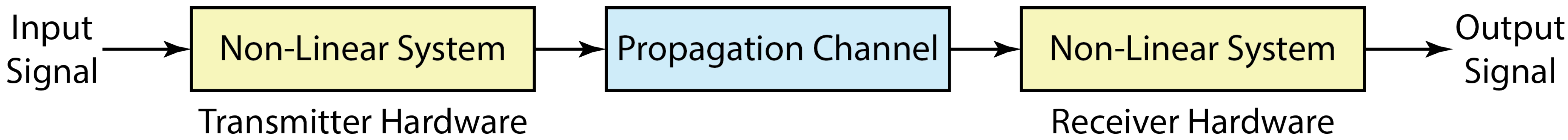


Broadcasting should mimic omni-antenna

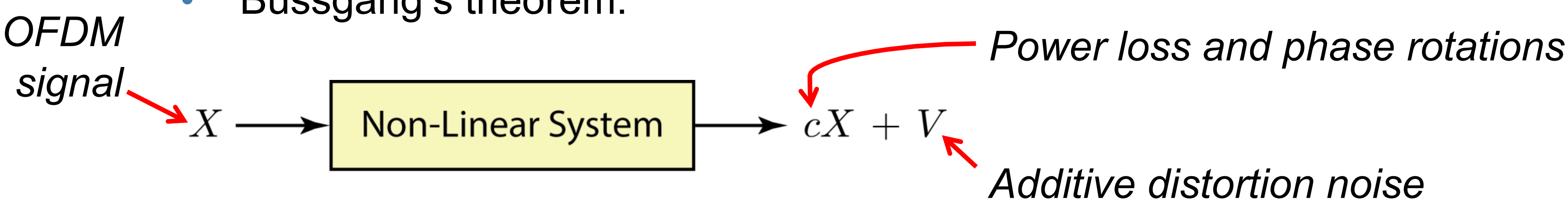
Form a broad beam or use space-time code

***Truth:** Massive MIMO might not increase coverage*

“Massive MIMO Needs High Precision Hardware”



- Real Transceivers have Hardware Impairments
  - Ex: Phase noise, I/Q-imbalance, quantization noise, non-linearities, etc.
  - Bussgang’s theorem:



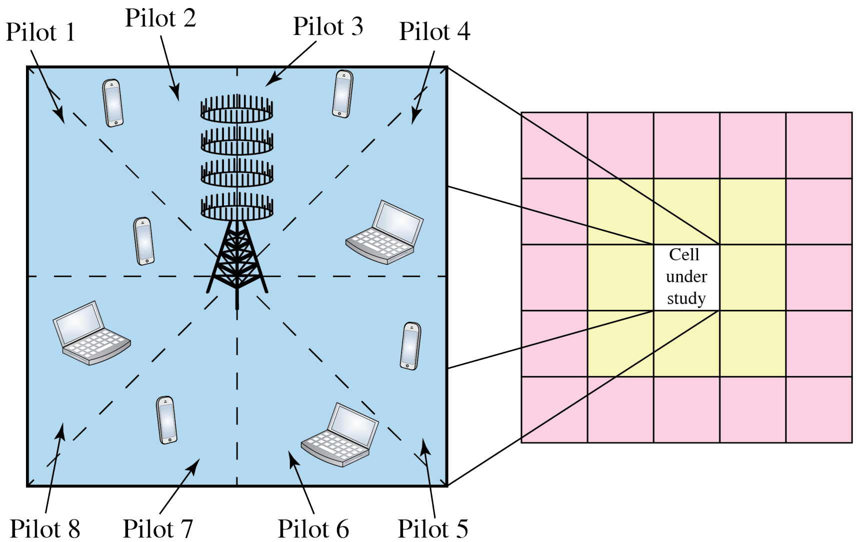
X, V are uncorrelated Gaussian variables

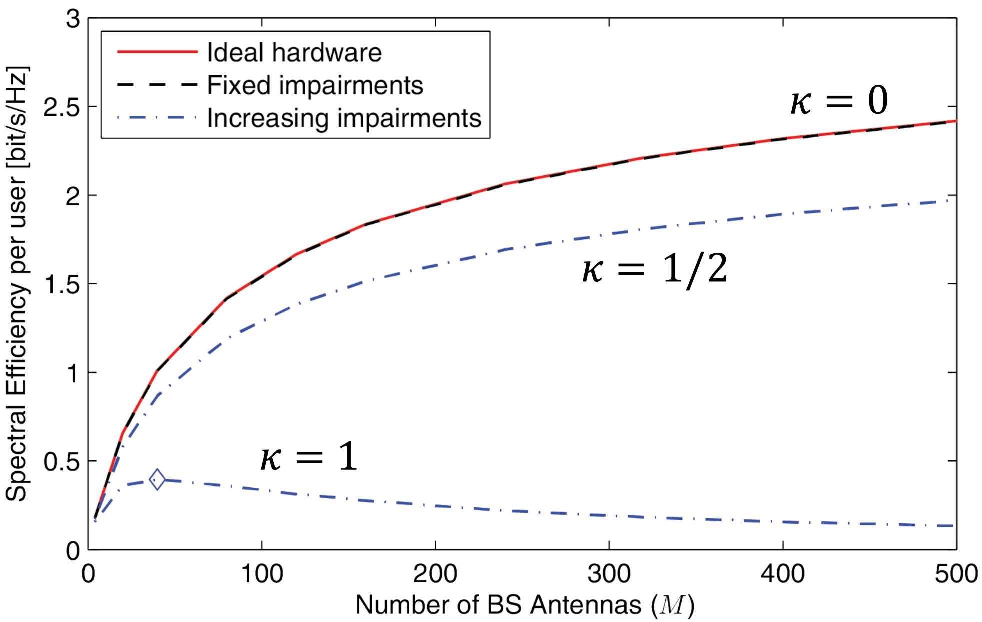
Additive Distortion: Just like interference

Suppressed by adding more antennas

Reality: *Massive MIMO supports lower-precision hardware!*

"Massive MIMO Needs High Precision Hardware"





Uplink Scenario

- Rayleigh fading, SNR = 5 dB
- $K = 8$ users per cell
- MR combining

Distortion Noise V

- $M = 1$: 5% of signal magnitude
- $M > 1$: Increases as M^{κ}
- Can handle $\kappa \leq 1/2$

ONE CRITICAL QUESTION

Can Massive MIMO work in FDD mode?

- Frequency-division duplex (FDD) is used in many systems
  - Different uplink/downlink frequencies → Two-way pilots & feedback needed

TDD versus FDD

Channel coherence limits both antennas and users in FDD, but only users in TDD

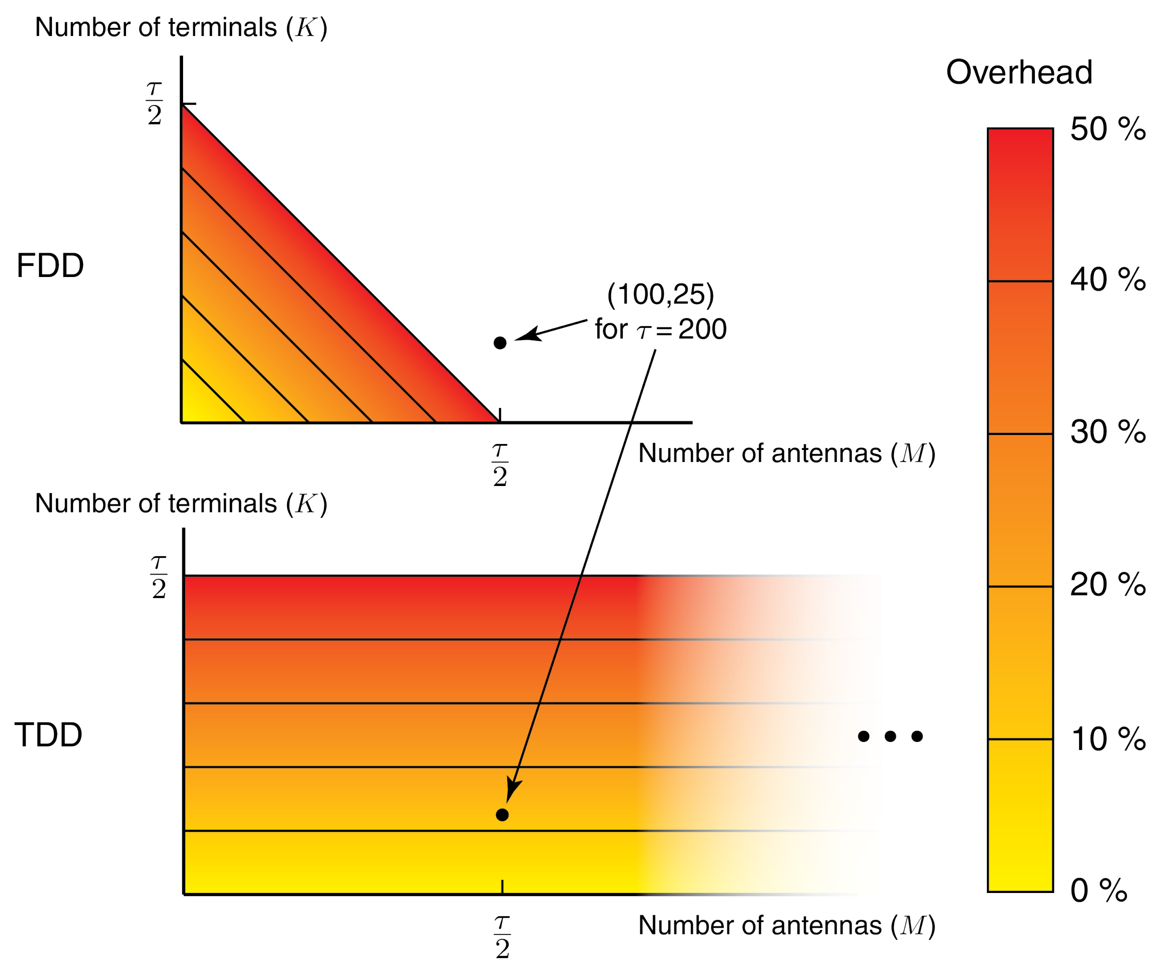
FDD possible with low mobility

Critical Question

Can we reduce estimation and feedback load?

Yes, with parameterizable channel sparsity!

Does it exist?



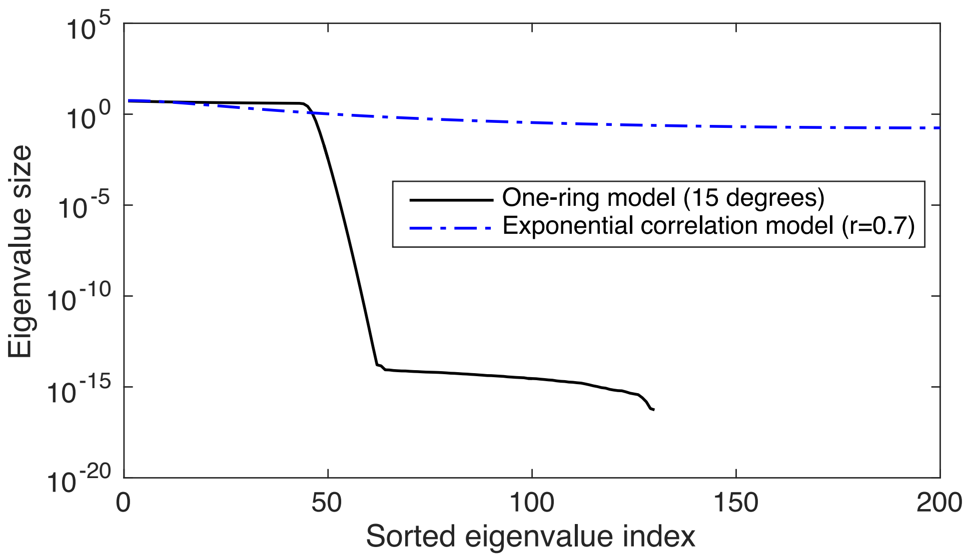
Sparsity Hypothesis: Does it hold?

Line-of-sight

- Beamdirection from calibrated array: Parameterizable with two angles
- Yes, it might hold!

Non-line-of-sight

- Depends on channel model
- One-ring model: Yes!
- Exponential corr: No!



Critical Question

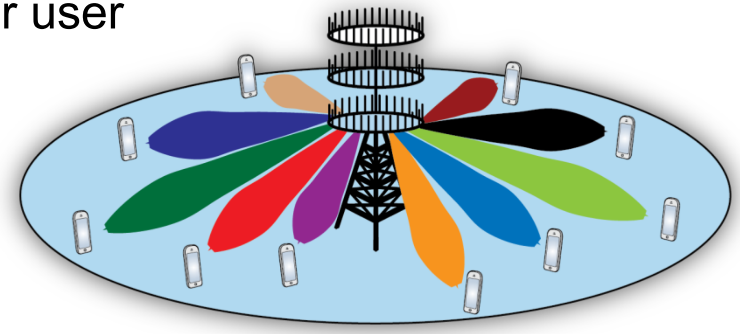
Does sparsity exist in general?

Can we exploit sparsity if it only exist for some users?

SUMMARY

Summary

- Massive MIMO: The way to increase spectral efficiency in 5G networks
  - >20x gain over IMT-Advanced are foreseen
  - BSs with many small antennas and transceiver chains
  - Higher spectral efficiency per cell, not per user



- Facts to Remember
  - Massive MIMO $\neq$ Massive size: TV sized panels at cellular frequencies
  - Favorable propagation in most propagation environments
  - Resource allocation and processing are simplified, not more complicated
- Further Reading
  - Emil Björnson, Erik G. Larsson, Thomas L. Marzetta, "*Massive MIMO: Ten Myths and One Critical Question*," To appear in IEEE Commun. Magazine.

Questions?

Emil Björnson

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Slides and papers available online:

http://www.commsys.isy.liu.se/en/staff/emibj29