Massive MIMO

Bringing the Magic of Asymptotics to Wireless Networks

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Biography

- 1983: Born in Malmö, Sweden
- 2007: Master of Science in
  Engineering Mathematics, Lund, Sweden
- 2011: PhD in Telecommunications,
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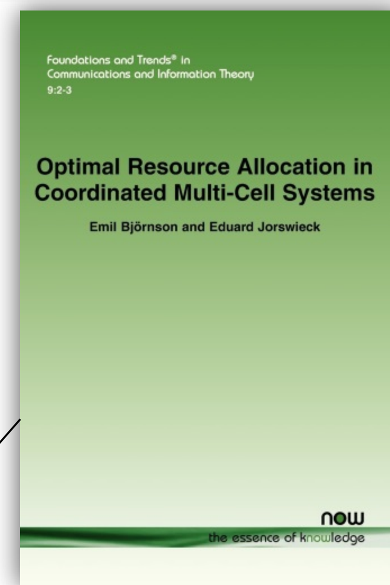
  (Advisors: *Björn Ottersten, Mats Bengtsson*)
- 2012-2014: International Postdoc Grant
  Host: *Mérouane Debbah*, Supélec, Paris
  Home university: KTH, Sweden
- 2014: Assistant Professor (swe: Bitr. lektor)
  Division of Communication Systems,
  Electrical Engineering, Linköping University, Sweden

Optimal Resource Allocation in Coordinated Multi-Cell Systems

Book by Emil Björnson, Eduard Jorswieck
FnT in Communications and Information Theory

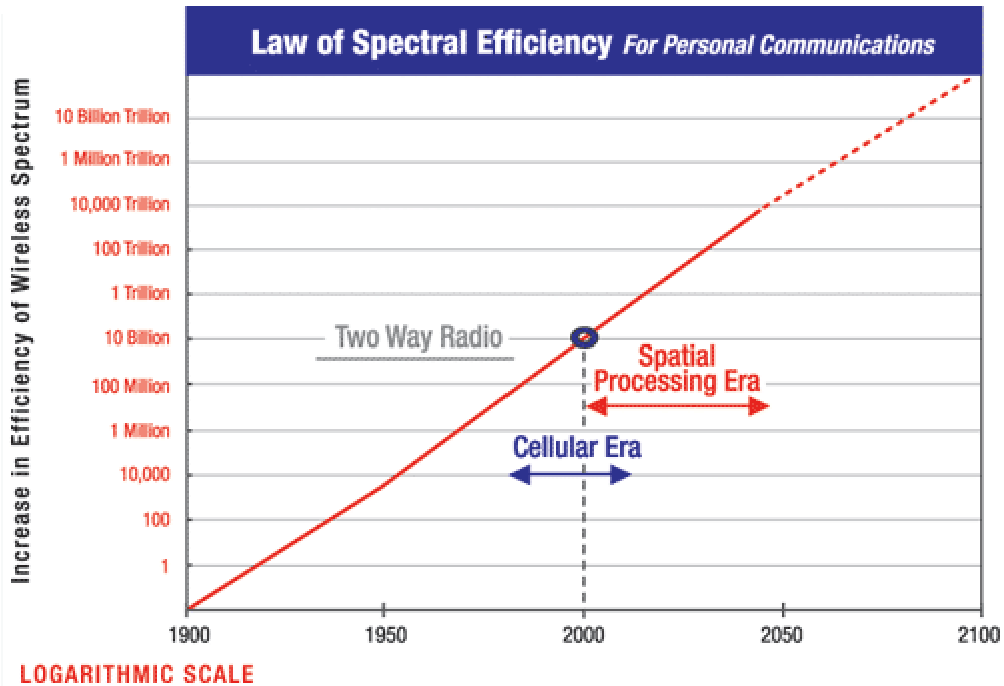


Introduction

WHAT CAN THE PAST TELL US ABOUT THE FUTURE?

Incredible Success of Wireless Communications

- Last 45 years: 1 Million Increase in Wireless Traffic



Source: Personal Communications in 2025, Martin Cooper

Martin Cooper's law

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

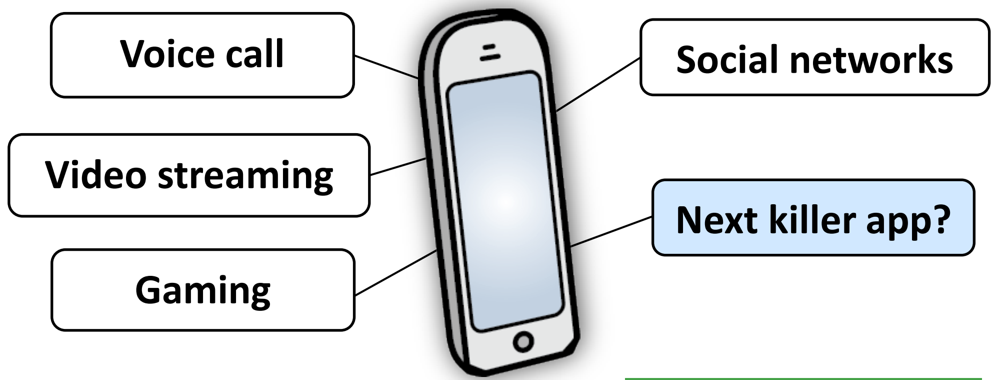
Martin Cooper

Inventor of handheld cellular phones

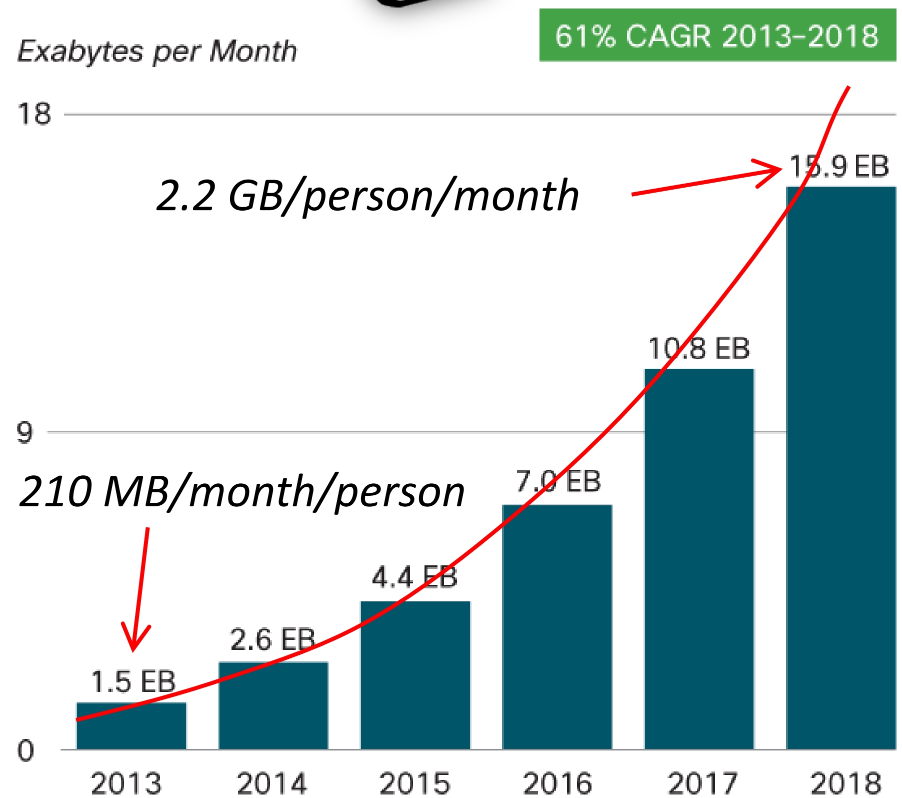
Source: Wikipedia

Predictions for the Future

- Wireless Connectivity
  - A natural part of our lives



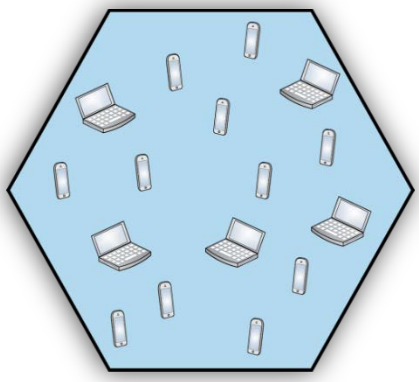
- Rapid Network Traffic Growth
  - 61% annual data traffic growth
  - Faster than in the past!
  - Exponential increase
  - Extrapolation: 20x until 2020
    200x until 2025
    2000x until 2030



Source: Cisco VNI Mobile, 2014

Evolving Networks for Higher Traffic

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



- Formula for Network Throughput:

$$\underbrace{\text{Throughput}}_{\text{bit/s in area}} = \underbrace{\text{Available spectrum}}_{\text{in Hz}} \cdot \underbrace{\text{Cell density}}_{\text{Cell/Area}} \cdot \underbrace{\text{Spectral efficiency}}_{\text{bit/s/Hz/Cell}}$$

- Ways to achieve 1000x improvement:

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

New regulations, cognitive radio, higher frequencies

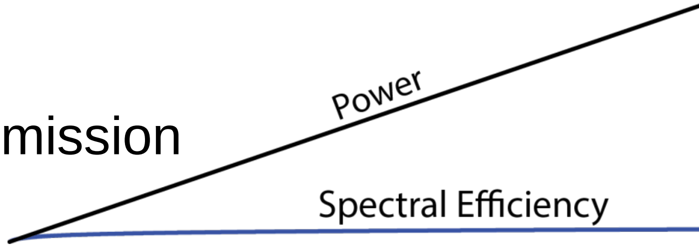
Smaller cells, heterogeneous deployments

Massive MIMO (Topic of this seminar) ?x

Introduction to

MASSIVE MIMO

Higher Spectral Efficiency

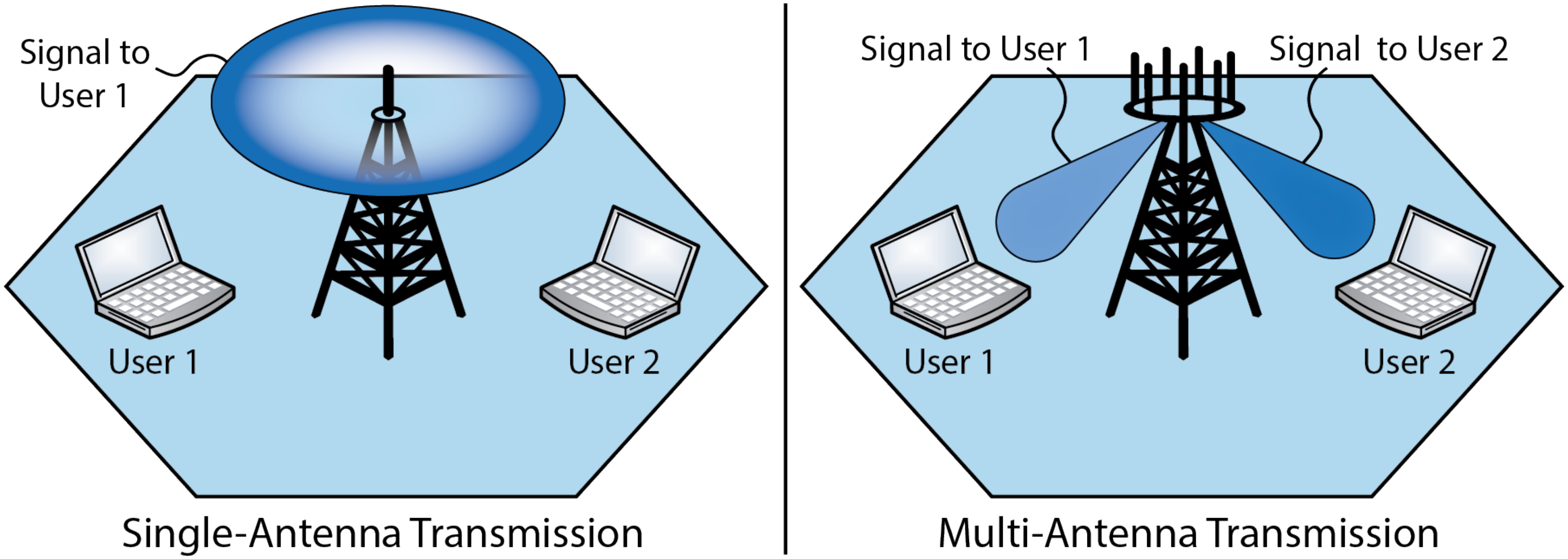


- Spectral Efficiency of Point-to-Point Transmission
  - Governed by Shannon's capacity limit:

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

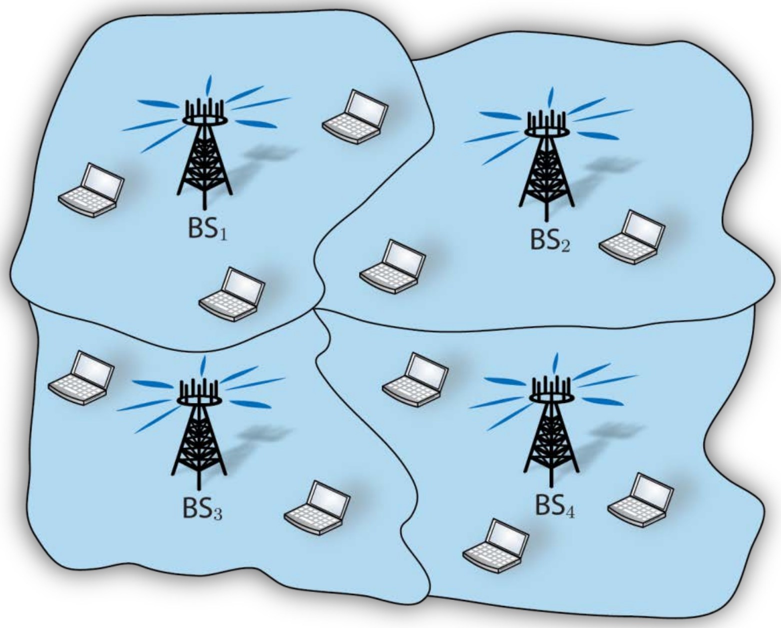
  - Cannot do much: 4 bit/s/Hz →8 bit/s/Hz costs 17 times more power!

- Many Simultaneous Transmissions: *Spatially focused toward users*



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

- Multi-Cell Multi-User MIMO
  - Base stations (BSs) with N antennas
  - Parallel uplink/downlink for K users
  - Channel coherence interval: T symbols



- Theory: Hardware is Limiting
  - Spectral efficiency roughly prop. to

$$\min\left(N, K, \frac{T}{2}\right)$$

  - 2x improvement = 2x antennas and users (since $T \in [100, 10000]$)

- Practice: Interference is Limiting
  - Multi-user MIMO in LTE-A: Up to 8 antennas
  - Interference since: Hard to learn users' channels
    Hard to coordinate BSs

End of MIMO road?

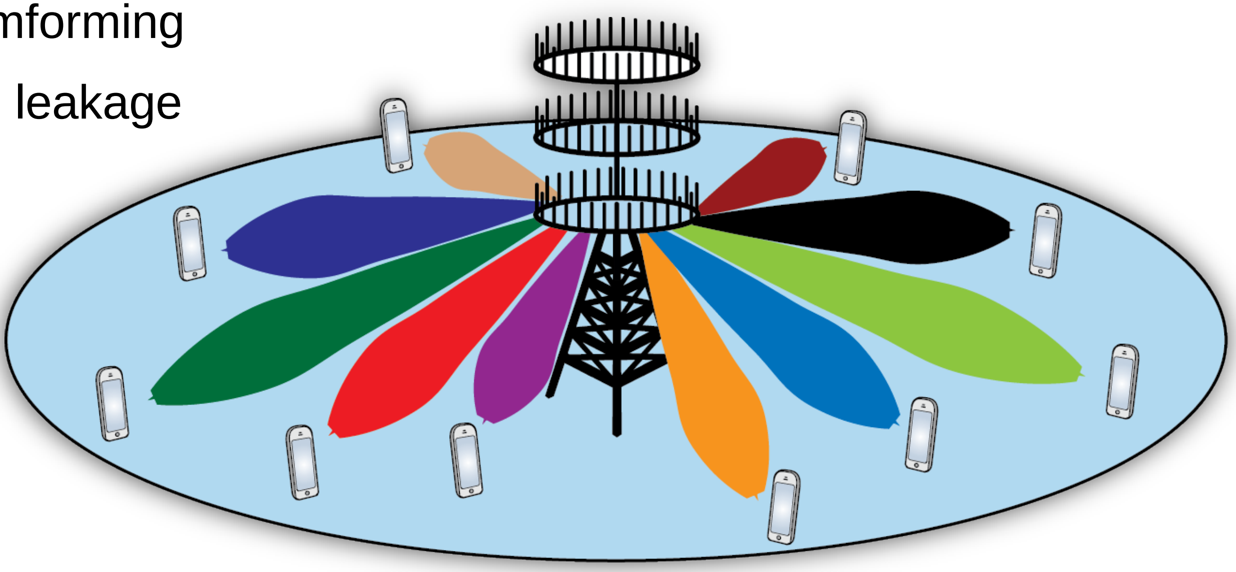
No reason to add more antennas/users?

Taking Multi-User MIMO to a New Level

- Network Architecture: Massive MIMO
  - Use large arrays at BSs; e.g., $N \approx 200$ antennas, $K \approx 40$ users
  - Key: Excessive number of antennas, $N \gg K$
  - Very narrow beamforming
  - Little interference leakage

Spectral efficiency prop. to number of users!

$$\min\left(N, K, \frac{T}{2}\right) \approx K$$



- 2013 IEEE Marconi Prize Paper Award

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

  - Analytic assumption: $N \to \infty$

What is the Key Difference?

- Number of 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 antenna ports

- We Already have Many Antennas!

Massive MIMO Characteristics

Active antennas: Many antenna ports

Coherent flexible beamforming

Multi-user MIMO with many users

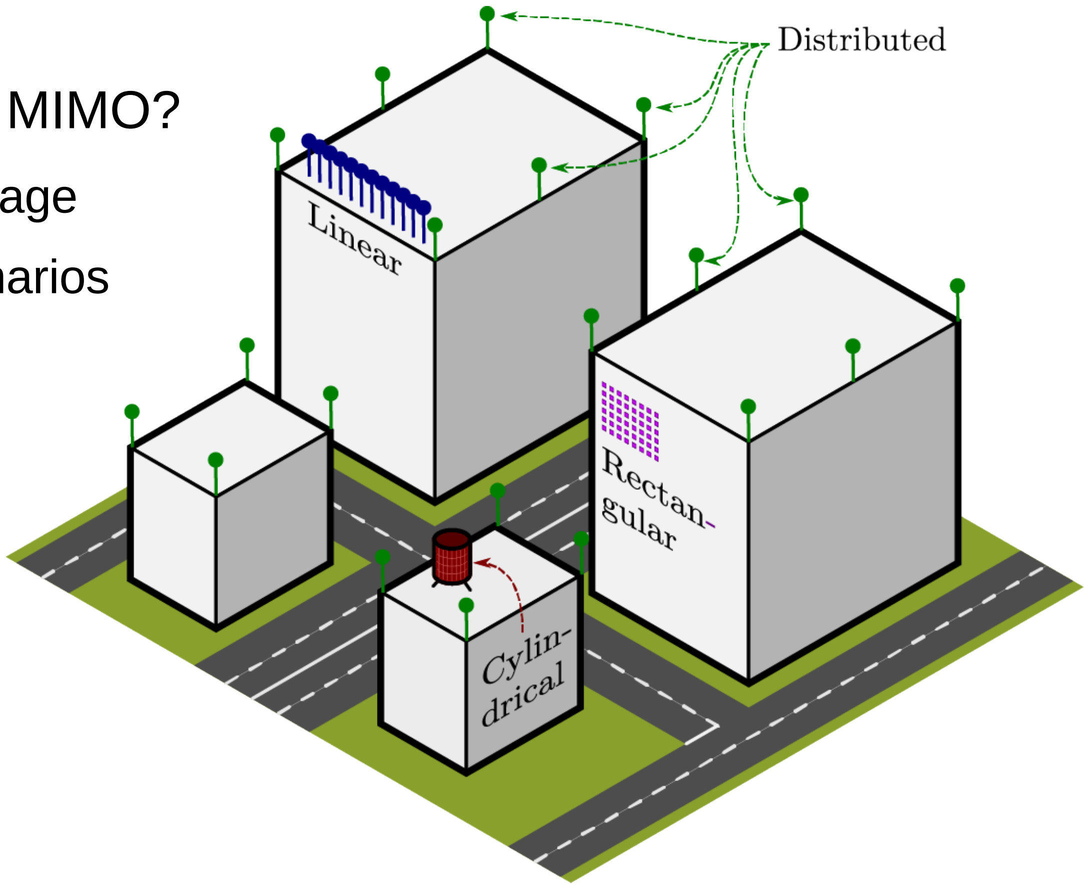
3 sectors, 4 vertical arrays per sector
Image source: gigaom.com

Massive MIMO Deployment

- When to Deploy Massive MIMO?
  - Improve wide-area coverage
  - Special superdense scenarios

- Co-located Deployment
  - 1D, 2D, or 3D arrays
  - One or multiple sectors

- Distributed Deployment
  - Remote radio heads
  - Cloud RAN

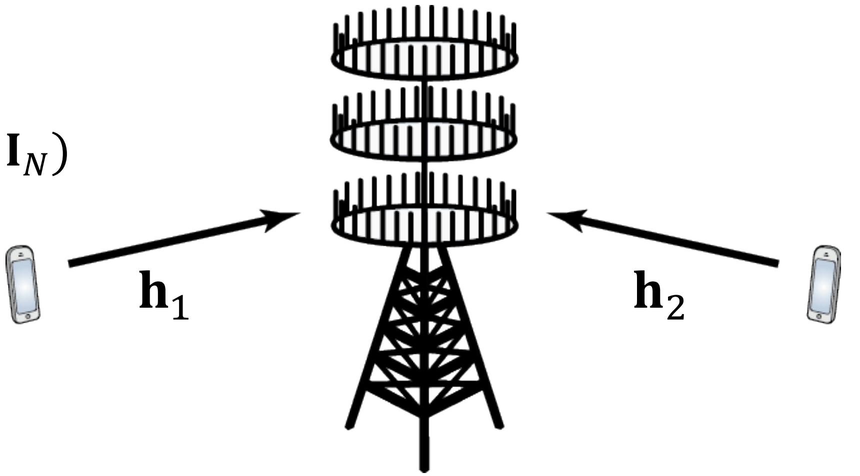


Basic Motivation

ASYMPTOTIC PROPERTIES

Asymptotic Channel Orthogonality

- Example: Uplink Transmission
  - Two users channels: $\mathbf{h}_1, \mathbf{h}_2 \sim CN(\mathbf{0}, \mathbf{I}_N)$
  - Signals: $s_1, s_2 \sim CN(0, P)$
  - Noise: $\mathbf{n} \sim CN(\mathbf{0}, \mathbf{I}_N)$
  - Received: $\mathbf{y} = \mathbf{h}_1 s_1 + \mathbf{h}_2 s_2 + \mathbf{n}$



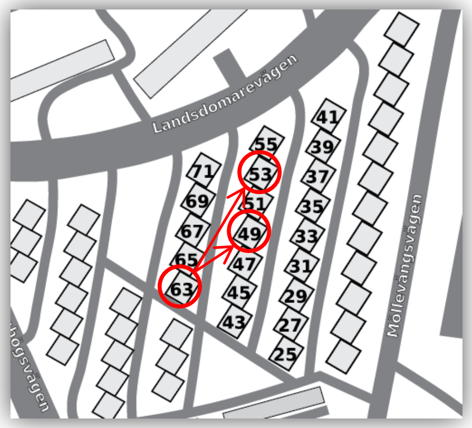
- Linear Processing for User 1: $\tilde{y}_1 = \mathbf{w}_1^H \mathbf{y} = \mathbf{w}_1^H \mathbf{h}_1 s_1 + \mathbf{w}_1^H \mathbf{h}_2 s_2 + \mathbf{w}_1^H \mathbf{n}$
  - Matched filter: $\mathbf{w}_1 = \frac{1}{N} \mathbf{h}_1$
  - Signal remains: $\mathbf{w}_1^H \mathbf{h}_1 = \frac{1}{N} ||\mathbf{h}_1||^2 \xrightarrow{N\to\infty} \mathrm{E}\left[|h_{11}|^{\mathbf{2}}\right] = 1$
  - Interference vanishes: $\mathbf{w}_1^H \mathbf{h}_2 = \frac{1}{N} \mathbf{h}_1^H \mathbf{h}_2 \xrightarrow{N\to\infty} \mathrm{E}[h_{11}^H h_{21}] = 0$
  - Noise vanishes: $\mathbf{w}_1^H \mathbf{n} = \frac{1}{N} \mathbf{h}_1^H \mathbf{n} \xrightarrow{N\to\infty} \mathrm{E}[h_{11}^H n_1] = 0$

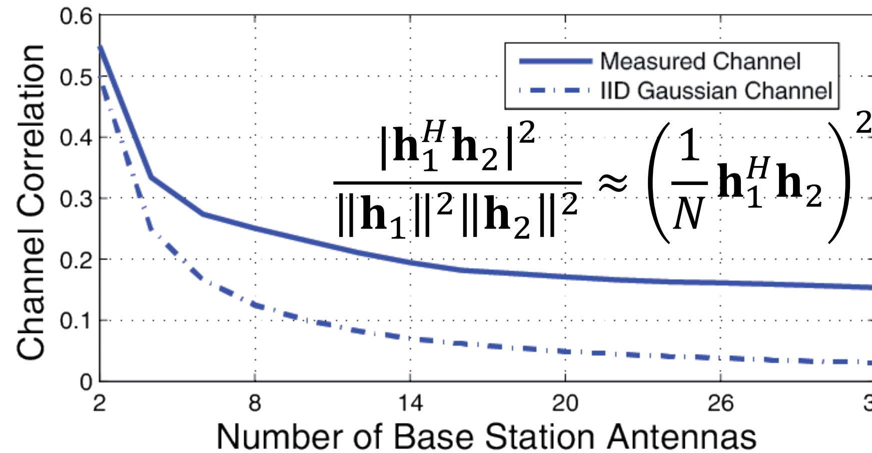
Asymptotically noise/interference-free communication: $\tilde{y}_1 \xrightarrow{N\to\infty} s_1$

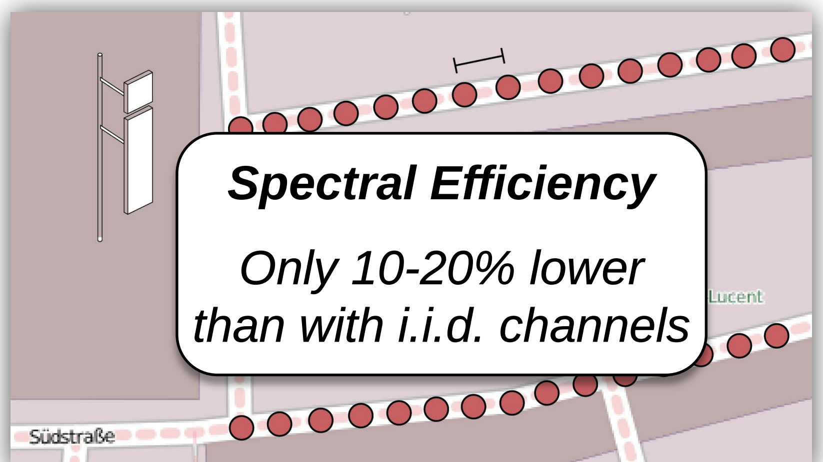
Does This Hold for Practical Channels?

- Initial Measurements: Show similar results

Source: X. Gao, O. Edfors, F. Rusek, and F. Tufvesson, "Linear Pre-Coding Performance in Measured Very-Large MIMO Channels," VTC 2011.

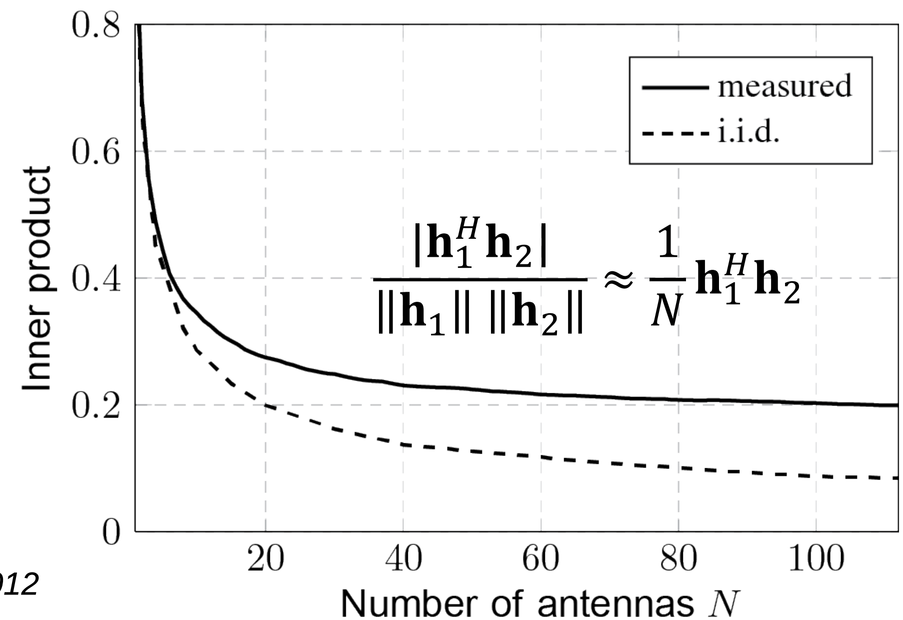






Spectral Efficiency

Only 10-20% lower than with i.i.d. channels



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

Difference: Analysis and Measurements

- Analysis with i.i.d. Rayleigh Fading
  - No line-of-sight propagation
  - Many scattering objectives
  - No dominant directivity

Less true as $N \rightarrow \infty$
(Higher array resolution)

- Alternative Channel Properties
  - Scattering "less" rich: Other random distributions
  - Spatial correlation: Directivity and user-correlation
  - Line-of-sight components
  - Spherical wavefronts

Affect if
$$\frac{1}{N}\mathbf{h}_1^H\mathbf{h}_2 \rightarrow \mathbf{0}$$
and convergence speed

Finite N: Anticipated Spectral Efficiency

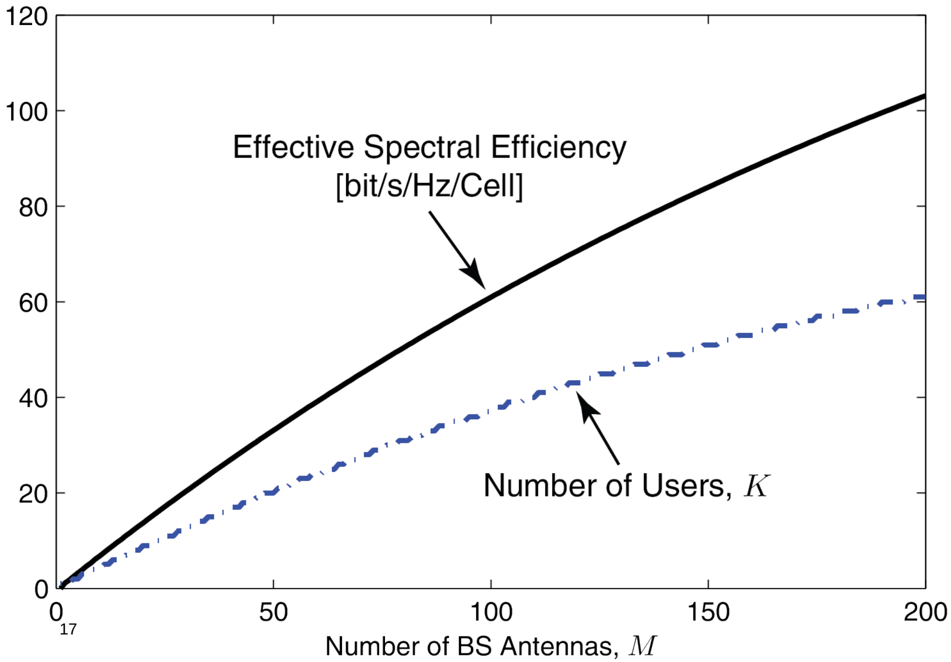
- What Might Massive MIMO Deliver?

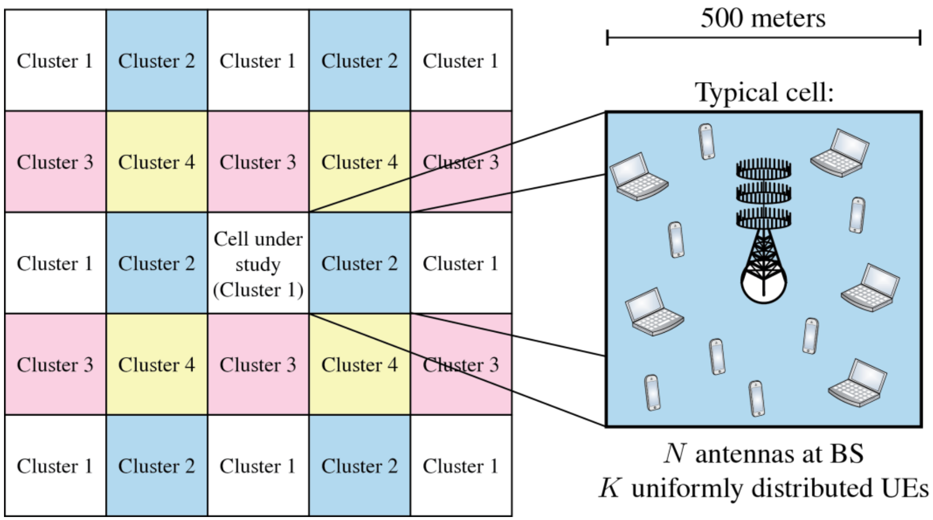
Simulation

LTE-like system parameters

Coherence interval: $T = 1000$

Channels: i.i.d. Rayleigh fading





Observations

Baseline: 3 bit/s/Hz/cell (IMT-Advanced)

Massive MIMO, $N = 100$*: x20 gain*

Massive MIMO, $N = 200$*: x34 gain*

Per scheduled user: ≈ 2 *bit/s/Hz*

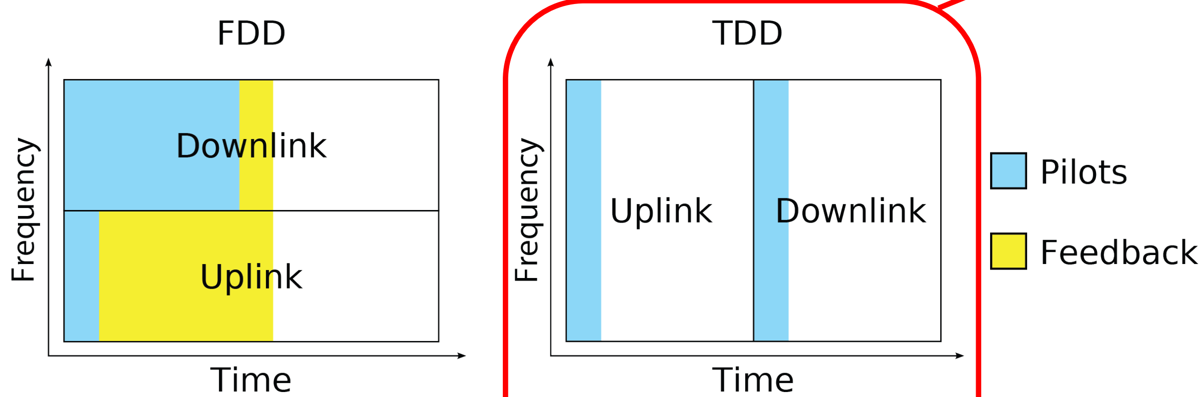
Higher multiplexing gains are possible!

Recent and Fundamental Research Results

“THE MAGIC OF ASYMPTOTICS”

Interference Management

- Interference Vanishes as $N \to \infty$ Using Linear Processing
  - Finite N: Reject remaining interference with zero-forcing processing
  - Requires channel state information (CSI) at BSs
- Pilot-based CSI Estimation



Estimation overhead $\approx O(N)$

Estimation overhead $\approx O(K)$

Time division duplex (TDD)

Much less overhead!

Key Property: *Robustness to Interference*

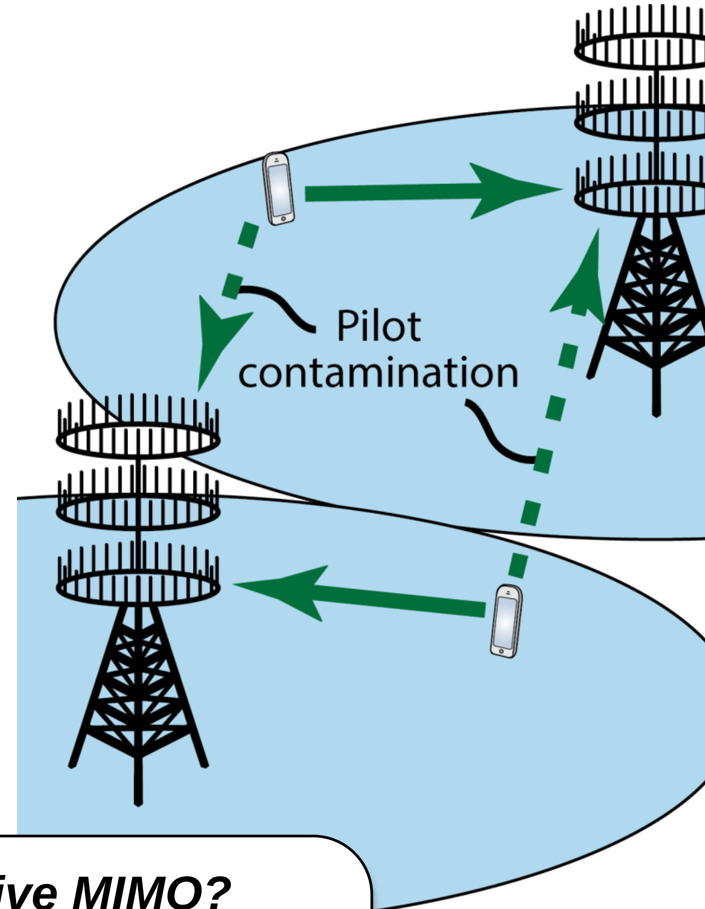
Imperfect CSI: Cannot reject all interference

Interference acts as noise: Vanishes as $N \to \infty$

Interference Management

- Limiting Factor: Coherence Interval T
  - Not more than T orthogonal pilots
  - Full frequency reuse for data transmission
  - Multi-cell: Must reuse pilots across cells

- Pilot Contamination
  - BS cannot tell difference between users
  - Channel estimates are correlated
  - This interference doesn't vanish as $N \to \infty$



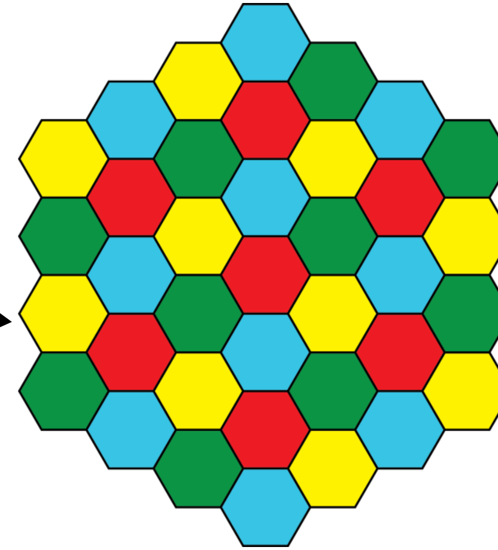
Will Pilot Contamination Kill Massive MIMO?

No, but treat it with much respect!

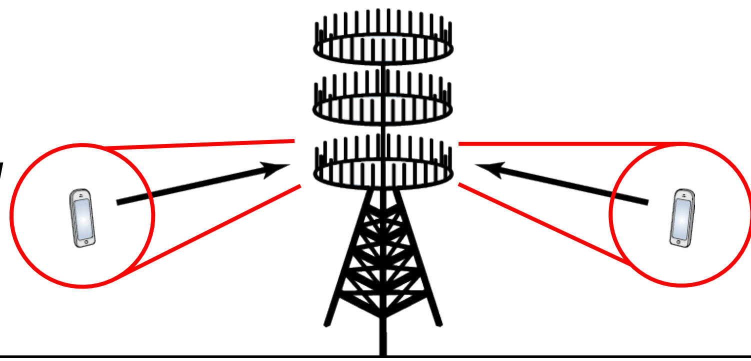
Make: $\text{Target SINR} \ll \dfrac{\text{Pathloss}^2 \text{ from transmitter}}{\sum \text{Pathloss}^2 \text{from interferers}}$

Interference Management

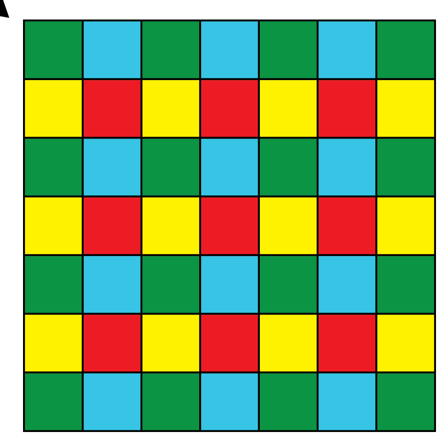
- Solution: Smart Pilot Allocation
  - Fractional pilot reuse
  - Simple: Distance-based patterns
  - Advanced: Exploit spatial correlation



Different statistical angles of arrival



Pilot reuse: $\boldsymbol{\beta = 4}$



Key Property: *High Area Spectral Efficiency*

Multiplicative gain $\approx \min\left(N, K, \frac{T}{2\beta}\right) \leq \frac{T}{2\beta}$ *per cell?*

Higher rates per user → Higher pilot reuse factor

Reference: H. Huh, G. Caire, H. C. Papadopoulos, and S. A. Ramprashad, "Achieving "Massive MIMO" Spectral Efficiency with a Not-so-Large Number of Antennas," IEEE Trans. Wireless Communications, 2012.

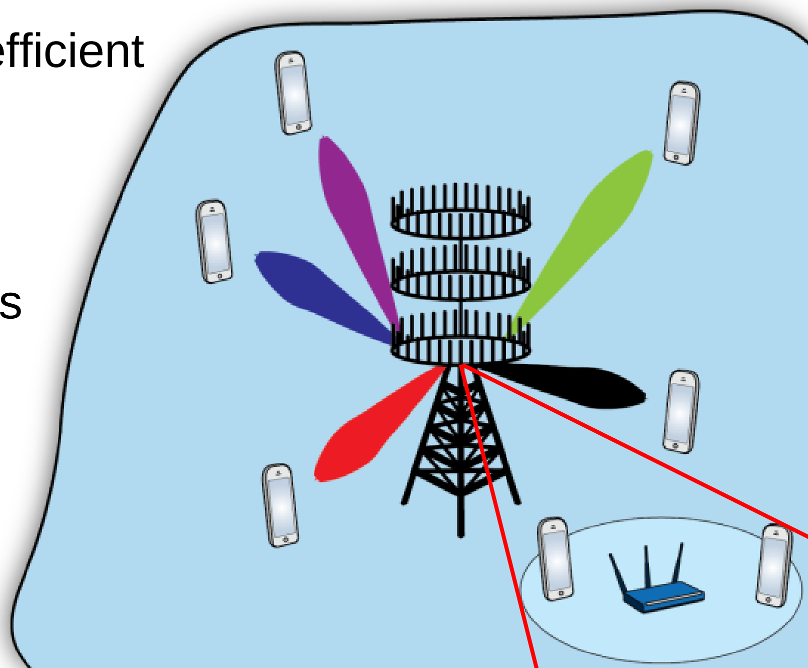
H. Yin, D. Gesbert, M. Filippou, and Y. Liu, "A coordinated approach to channel estimation in large-scale multiple-antenna systems," IEEE J. Sel. Areas Commun., 2013.

Distributed Coordination with Other Systems

- Heterogeneous Deployments
  - Massive MIMO: Coverage and mobility management
  - Small cells: Small path loss → High local area throughput

Complementary benefits!

- Inter-Tier Interference
  - Major limiting factor!
  - Spatial transmitter coordination ← Unreliable
  - Orthogonal in time/frequency ← Inefficient
- Cognitive Radio Approach
  - Listen: Data signals from other systems
  - Estimate: Spatial covariance matrix
  - Transmit: Orthogonal to matrix span



Distributed Coordination with Other Systems

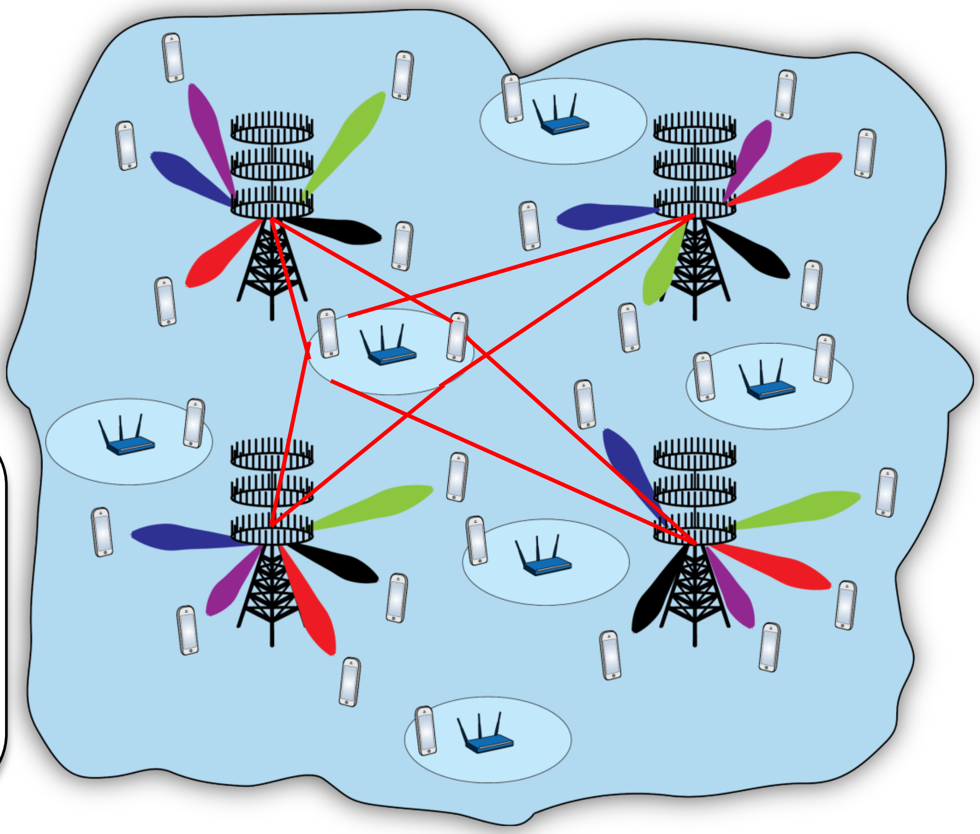
- TDD Coordination Protocol
  - Estimate received interference subspace
  - Transmit orthogonal to the M dominating interferers

Fully Distributed

Use only local information

No feedback or exchange

Scalable!



Key Property: *Distributed Coordination*

N large: Subspace dimension $M \ll N$

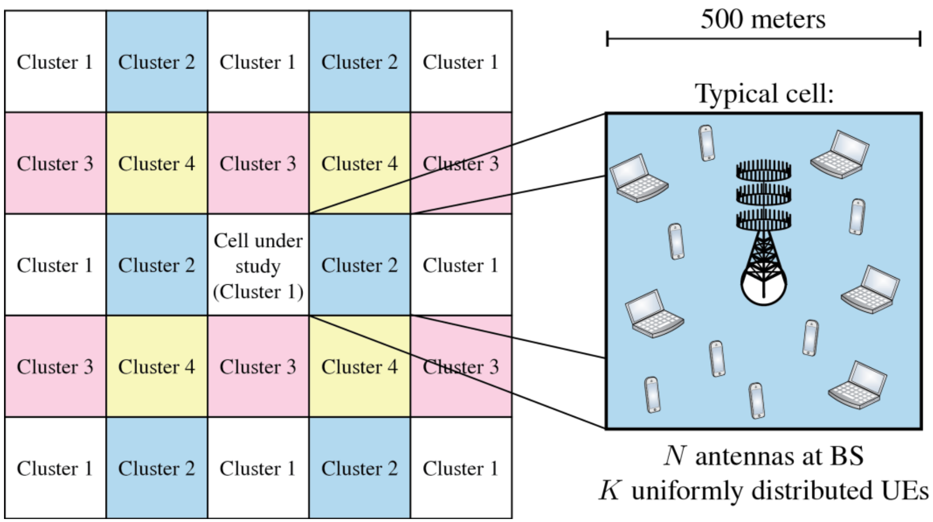
Small signal loss, much less interference

Combine with user selection?

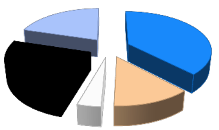
Reference: J. Hoydis, K. Hosseini, S. ten Brink, and M. Debbah, Making Smart Use of Excess Antennas: Massive MIMO, Small Cells, and TDD, Bell Labs Technical Journal, 2013

Optimizing Networks for Energy Efficiency (EE)

- Designing Cells for EE
  - Given symmetric cell topology
  - Guarantee a rate R per user
  - How to achieve optimal EE?



- Energy Efficiency in bit/Joule
  - $$EE = \frac{\text{Average Sum Rate [bit/s]}}{\text{Power Consumption [Joule/s]}} = \frac{K\,R}{\text{Transmit Power} + \text{Circuit Power}}$$
  - Maximize by selecting N, K, and R!
  - Detailed circuit power model is required:



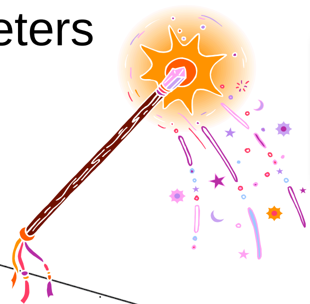
$$C_{0,0} + \underbrace{C_{0,1}N + C_{1,0}K}_{\textit{Circuit power per transceiver chain}} + \underbrace{C_{1,1}NK + C_{2,0}K^2 + C_{3,0}K^3 + C_{2,1}NK^2}_{\textit{Cost of channel estimation and precoding computation}} + C_r KR$$

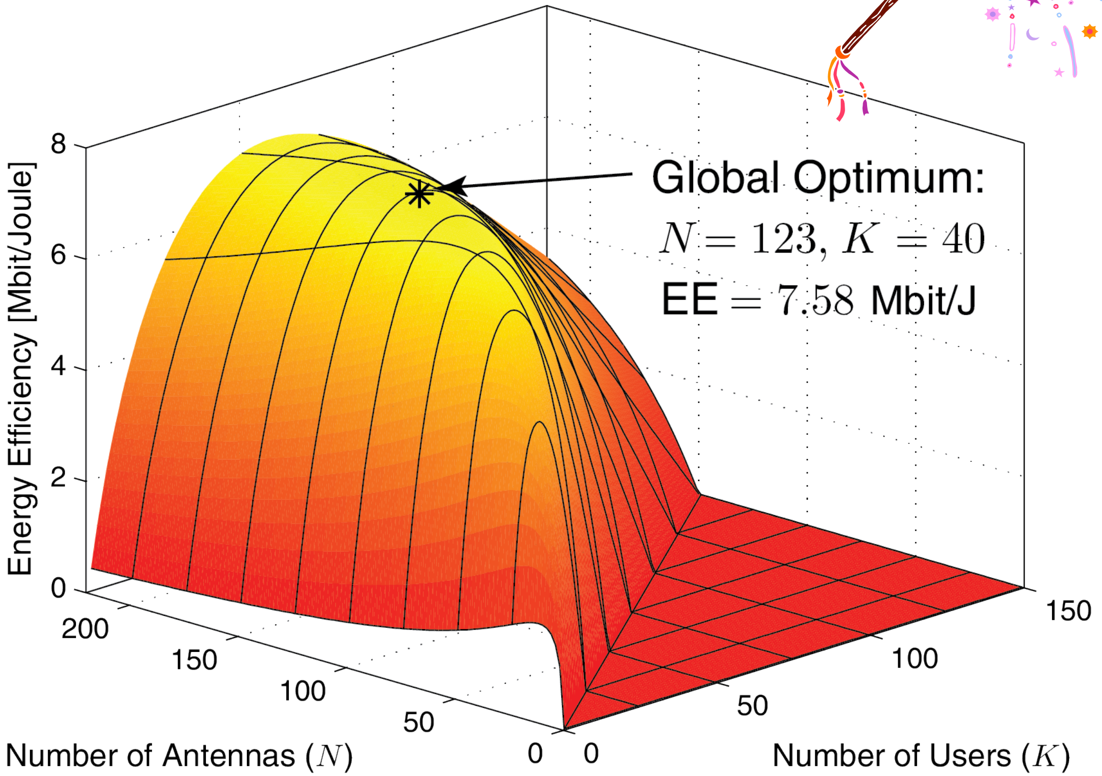
Fixed power (control signals, infrastructure, etc.)

Coding/decoding data streams

Optimizing Networks for Energy Efficiency (EE)

- What is the EE-Optimal Solution?
  - Depends on the $\mathcal{C}$-parameters
  - We use values from 2012





Key Property: *EE-optimality*

Massive MIMO is the solution

Golden Combination

Large array gain

Many simultaneous users

Fractional pilot reuse

Transmit Power

Total: Similar to today

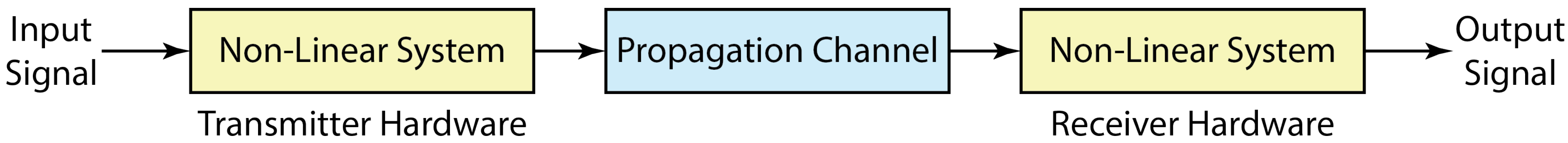
Per antenna: Much smaller

Use handset technology?

Reference: E. Björnson, L. Sanguinetti, J. Hoydis, M. Debbah, "Optimal Design of Energy-Efficient Multi-User MIMO Systems: Is Massive MIMO the Answer?," Submitted to IEEE Trans. Wireless Communications.

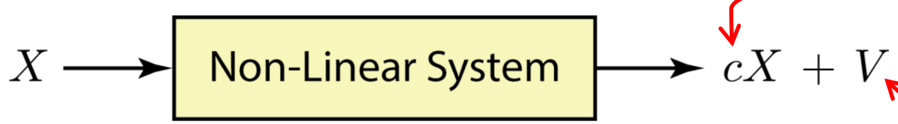
Impact of Hardware Impairments

- Real Hardware is Non-Ideal
  - Hardware impairments: Phase noise, I/Q-imbalance, non-linearities, etc.
  - Impact reduced by calibration/compensation (not fully removed!)
- Simple Hardware Model:



- Assume: Gaussian Input Signal
  - Example: OFDM signal
  - Bussgang's Theorem:

c equal over subcarriers (tracked)



V is proportional to signal (e.g., inter-carrier interference)

X, V are uncorrelated Gaussian variables

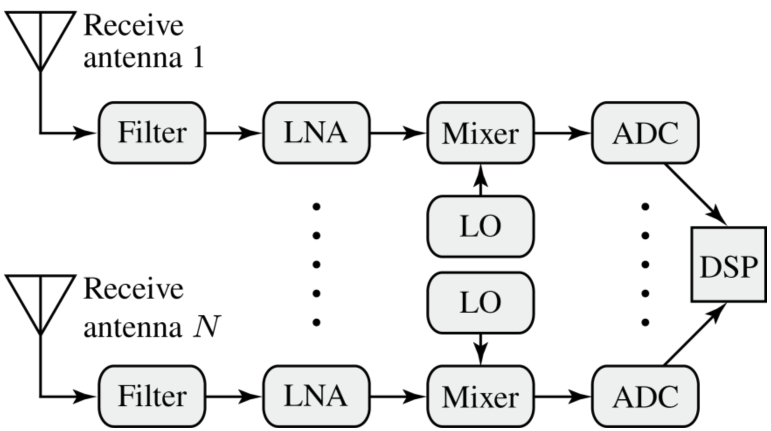
Impact of Hardware Impairments

- Impact of Hardware Impairments
  - Additive distortion noise at BS and user
  - Recall: Regular noise/interference vanish as $N \to \infty$

Key Property: *Small Impact of Hardware Impairments*

Distortion noise from BSs vanish in "space"

(Unaffected: Distortion noise from user devices)



Low Impairments vs. Low Cost and Power

Tolerate larger impairments → Cheap and energy-efficient hardware

N antenna ports: Cost and circuit power increase sublinearly in N!

Reference: E. Björnson, J. Hoydis, M. Kountouris, M. Debbah, "Massive MIMO Systems with Non-Ideal Hardware: Energy Efficiency, Estimation, and Capacity Limits," Submitted to IEEE Trans. Information Theory.

Hardware-Friendly Signal Shaping

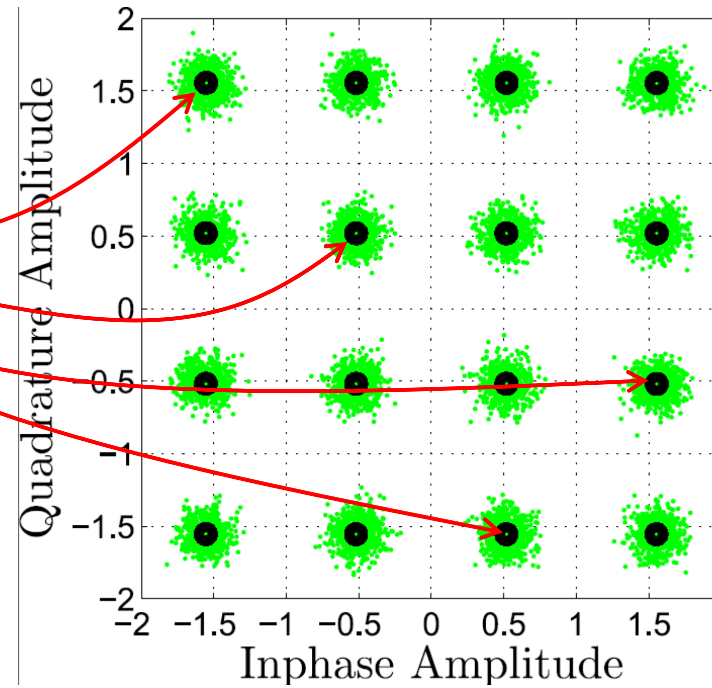
Channel

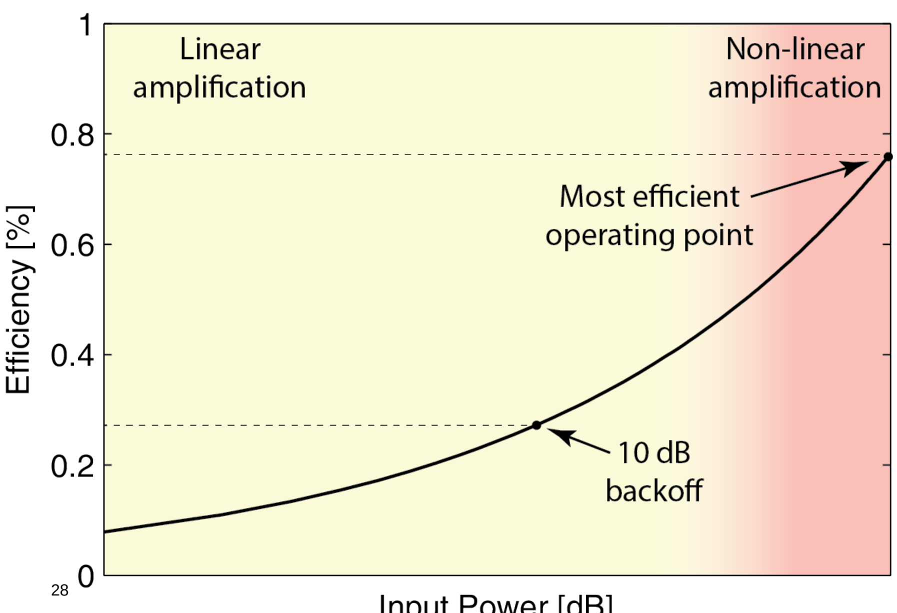
Noise

- Downlink Transmission
  - Received signal: $y = \underbrace{\mathbf{h}^H\mathbf{w}}_{\text{Effective Signal } s} + n$

Effective Signal s

- Signal Shaping: Given $s = \mathbf{h}^H\mathbf{w}$
  - How to pick $\mathbf{w}$? (N degrees of freedom)





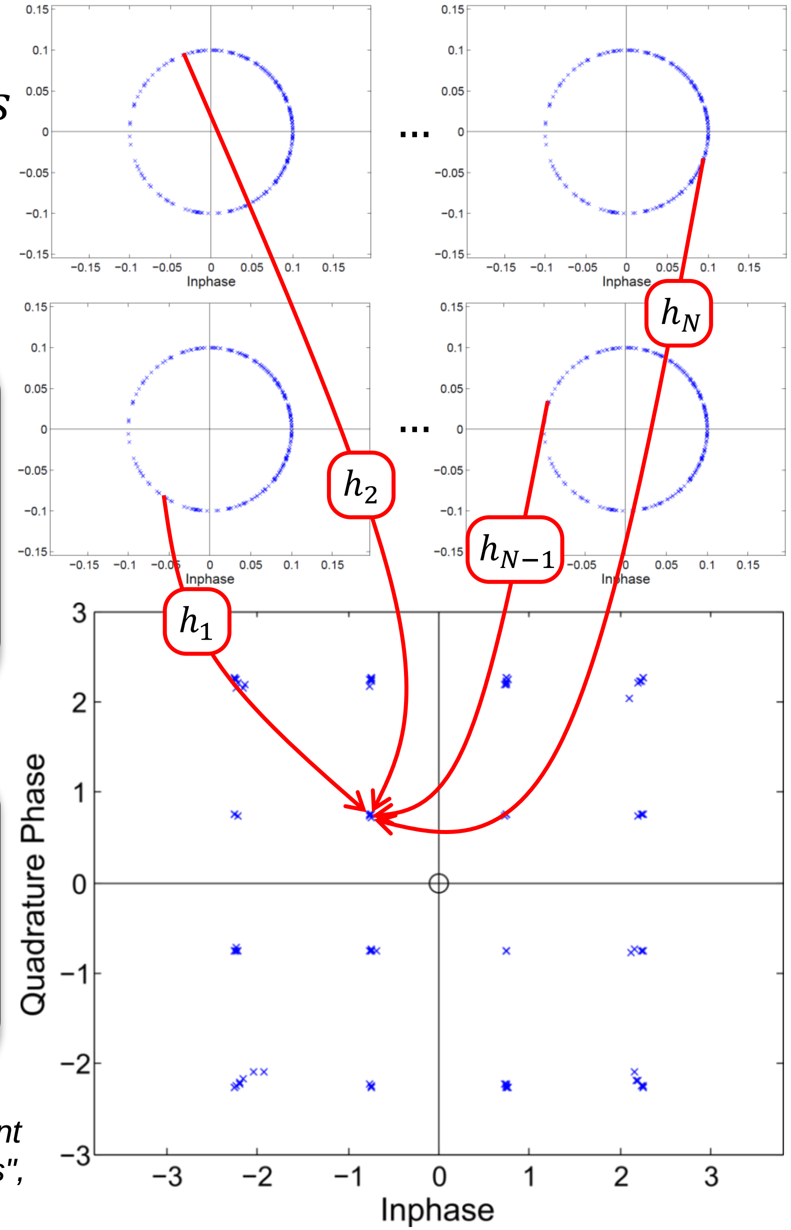
Conventional: Matched filter $\mathbf{w} \propto \frac{\mathbf{h}}{\|\mathbf{h}\|} s$

Pro: Minimize transmit power $\|\mathbf{w}\|^2$

Con: Large power variations (~ 10 dB) over antennas and time

Hardware-Friendly Signal Shaping

- Alternative: $|w_1|^2 = \cdots = |w_N|^2$ for all s
  - Pro: Constant envelope at antennas
  - Con: Requires more radiated power



Metric: Total Consumed Power

Conventional: Total = radiated + inefficiencies

Constant envelope: Total ≈ radiated

Large N: Constant envelop is competitive!

***Key Property:** Simplified Amplifiers*

Signals with low peak-to-average ratio

Easier to design amplifiers

Cheaper to implement

Reference: S.K. Mohammed, Erik G. Larsson, "Per-Antenna Constant Envelope Precoding for Large Multi-User MIMO Systems", IEEE Transactions on Communications, 2013.

SUMMARY

Summary

- Massive MIMO: A technique to increase spectral efficiency
  - Massive multi-user MIMO: Potentially 20x-40x gain over IMT-Advanced
  - Many different deployment strategies
- Excessive Number of Antennas
  - Quasi-orthogonal user channels
  - Robust interference rejection
  - Distributed coordination with other systems
  - High energy efficiency
  - Resilience to hardware impairments
  - Hardware-friendly signal shaping

Magic of asymptotics

- Important: *Channel coherence interval*
  - Limits multiplexing gain and per-user performance
  - Pilot contamination mitigated by smart pilot allocation

Bringing the Magic to Reality

- FP7 MAMMOET project (Massive MIMO for Efficient Transmission)
  - Bridge gap between “theoretical and conceptual” massive MIMO
  - Develop: Flexible, effective and efficient solutions

WP4 Validation and proof-of-concept

WP2 Efficient FE solutions
(IC solutions,
Comp/Calibration)

WP3 Baseband Solutions
(Algorithms,
Architectures & Design)

WP1 System approach, scenarios and requirements

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THANK YOU FOR LISTENING!

QUESTIONS?

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