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, KTH, Stockholm, Sweden (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) at Division of Communication Systems, ISY, Linköping University, Linköping, 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 Traffic

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

Source: Personal Communications in 2025, Martin Cooper

Martin Cooper
Inventor of handheld cellular phones

Predictions for the Future

- 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

210 MB/month/person

2.2 GB/person/month

Source: Cisco VNI Mobile, 2014
Evolving Networks for Higher Traffic

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

- Formula for Network Throughput:
  \[ \text{Throughput} = \frac{\text{Available spectrum}}{\text{bit/s in area}} \cdot \frac{\text{Cell density}}{\text{Cell/Area}} \cdot \frac{\text{Spectral efficiency}}{\text{bit/s/Hz/Cell}} \]

- Ways to achieve 1000x improvement:

<table>
<thead>
<tr>
<th></th>
<th>More spectrum</th>
<th>Higher cell density</th>
<th>Higher spectral efficiency</th>
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</thead>
<tbody>
<tr>
<td>Nokia (2011)</td>
<td>10x</td>
<td>10x</td>
<td>10x</td>
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<tr>
<td>SK Telecom (2012)</td>
<td>3x</td>
<td>56x</td>
<td>6x</td>
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New regulations, cognitive radio, higher frequencies
Smaller cells, heterogeneous deployments
Massive MIMO (Topic of today)
Introduction to

MASSIVE MIMO
Higher Spectral Efficiency

• Spectral Efficiency of Point-to-Point Transmission
  • Governed by Shannon’s capacity limit:
    \[
    \log_2 \left( 1 + \frac{\text{Received Signal Power}}{\text{Interference Power} + \text{Noise Power}} \right) \text{ [bit/s/Hz/User]}
    \]
  • Cannot do much: 4 bit/s/Hz \(\rightarrow\) 8 bit/s/Hz costs 17 times more power!

• Many Simultaneous Transmissions: *Spatially focused toward users*

![Diagram](image)
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
  • Analytic assumption: $N \rightarrow \infty$
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

- We Already have Many Antennas!

**Massive MIMO Characteristics**
- Active antennas: Many antenna ports
- Coherent flexible beamforming
- Multi-user MIMO with many users

*Image source: gigaom.com*
Massive MIMO Deployment

• When to Deploy Massive MIMO?
  • Improved 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
Example: Uplink Transmission

Two users channels: \( h_1, h_2 \sim CN(0, I_N) \)

Signals: \( s_1, s_2 \sim CN(0, P) \)

Noise: \( n \sim CN(0, I_N) \)

Received: \( y = h_1s_1 + h_2s_2 + n \)

Linear Processing for User 1: \( \tilde{y}_1 = w_1^H y = w_1^H h_1s_1 + w_1^H h_2s_2 + w_1^H n \)

Matched filter: \( w_1 = \frac{1}{N} h_1 \)

Signal remains: \( w_1^H h_1 = \frac{1}{N} ||h_1||^2 \xrightarrow{N \to \infty} E[|h_{11}|^2] = 1 \)

Interference vanishes: \( w_1^H h_2 = \frac{1}{N} h_1^H h_2 \xrightarrow{N \to \infty} E[h_{11}^H h_{21}] = 0 \)

Noise vanishes: \( w_1^H n = \frac{1}{N} h_1^H n \xrightarrow{N \to \infty} E[h_{11}^H n_1] = 0 \)

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

\[
\frac{|h_1^H h_2|^2}{\|h_1\|^2 \|h_2\|^2}\n\]

**Spectral Efficiency**

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


Difference: Analysis and Measurements

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

  \[ \text{Less true as } N \to \infty \]
  \[ (\text{Higher array resolution}) \]

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

\[ \frac{1}{N} h_1^H h_2 \to 0 \]
and convergence speed
Finite $N$: Anticipated Spectral Efficiency

- What Might Deliver Massive MIMO?

**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 user: $\approx$ 2 bit/s/Hz

Higher multiplexing gains possible!
Capitalizing on an Excessive Number of Antennas

THE MAGIC OF ASYMPTOTICS
Robust Interference Rejection

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

- Pilot-based CSI Estimation

\[ \text{Estimation overhead} \approx O(N) \]
\[ \text{Estimation overhead} \approx O(K) \]

**Key Property:** Robustness to Interference

*Imperfect CSI: Cannot reject all interference*

*Interference leakage vanishes as $N \to \infty$*
Robust Interference Rejection

- 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: Target SINR $\leq \frac{\text{Pathloss from transmitter}}{\sum \text{Pathloss from interferers}}$
Robust Interference Rejection

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

Key Property: High Spectral Efficiency

Loss from fractional pilot reuse

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

Distributed Coordination with Other Systems

• Heterogeneous Deployments
  • Massive MIMO: Coverage and mobility management
  • Small cells: Small path loss $\rightarrow$ High local area throughput

• Inter-Tier Interference
  • Major limiting factor!
  • Spatial transmitter coordination $\leftarrow$ Unreliable
  • Orthogonal in time/frequency $\leftarrow$ Inefficient

• Cognitive Radio Approach
  • Listen: Data signals from other systems
  • Compute: Spatial covariance matrix
  • Transmit: Orthogonal to matrix span

Complementary benefits!
Distributed Coordination with Other Systems

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

**Key Property:** Distributed Coordination

$N$ large: Subspace dimension $M \ll N$
Small signal loss, much less interference

Combine with user selection?

Optimizing 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
  • \[ EE = \frac{\text{Average Sum Rate [bit/s]}}{\text{Power Consumption [Joule/s]}} = \frac{KR}{\text{Transmit Power + Circuit Power}} \]
  • Maximize by selecting $N$, $K$, and $R$!
  • Detailed circuit power model is required:
  \[ C_{0,0} + C_{0,1}N + C_{1,0}K + C_{1,1}NK + C_{2,0}K^2 + C_{3,0}K^3 + C_{2,1}NK^2 + C_rKR \]

  - Fixed power (control signals, load-ind. processing, infrastructure)
  - Circuit power per transceiver chain
  - Cost of channel estimation and precoding computation
  - Coding/decoding data streams
Optimizing for Energy Efficiency (EE)

- What is the EE-Optimal Solution?
  - Depends on $C$-parameters
  - Used 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?

Resilience to 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 (e.g., OFDM-signal)

• Bussgang’s Theorem:
  \[ X \rightarrow \text{Non-Linear System} \rightarrow cX + V \]
  \( c \) equal over subcarriers (tracked)
  \( V \) is proportional to signal (e.g., inter-carrier interference)
  \( X, V \) are uncorrelated Gaussian variables
Resilience to 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 BS vanishes in space

(Unaffected: Distortion noise from user device)

**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 $N$!

Hardware-Friendly Signal Shaping

- Downlink Transmission
  - Received signal: \( y = h^H w + n \)

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

**Conventional:** Matched filter \( w \propto \frac{h}{||h||} s \)

**Pro:** Minimize transmit power \( ||w||^2 \)

**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**
Constant envelope: Consumed $\approx$ radiated power

Large $N$: Constant envelop is competitive!

**Key Property: Simplified Amplifiers**
Signals with low peak-to-average ratio
Easier amplifier designs
Cheaper to implement

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

• Important: Channel coherence interval
  • Limits multiplexing gain
  • Pilot contamination handled by smart pilot allocation

Magic of Asymptotics
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
THANK YOU FOR LISTENING!

QUESTIONS?

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