Increasing the Spectral Efficiency of Future Wireless Networks

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Outline

• Introduction: Past and Future of Wireless Communications

• Ways to Achieve Higher Spectral Efficiency
  • What does communication theory tell us?

• Basic Properties of Massive MIMO
  • Asymptotic behaviors and recent measurements

• What can we Expect from Massive MIMO?
  • New research results

• Summary
Introduction

PAST AND FUTURE OF WIRELESS COMMUNICATIONS
Incredible Success of Wireless Communications

- Last 45 years: 1 Million Increase in Wireless Traffic
- Two-way radio, FM/AM radio, satellite services, cellular networks, WiFi

**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

• Wireless Connectivity
  • A natural part of our lives

• Rapid Network Traffic Growth
  • 38% annual data traffic growth
  • Slightly faster than in the past!
  • Exponential increase
  • Extrapolation: 7x until 2020
  • 32x until 2025
  • 154x until 2030

Source: Ericsson (November 2014)
Evolving Cellular Networks for More Traffic

- **Cellular Network Architecture**
  - Area divided into cells
  - One fixed base station serves all the users

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

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

  - **Ways to achieve 1000x improvement:**

<table>
<thead>
<tr>
<th></th>
<th>Higher cell density</th>
<th>More spectrum</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>
</tr>
<tr>
<td>SK Telecom (2012)</td>
<td>56x</td>
<td>3x</td>
<td>6x</td>
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Three Different Solutions

• **Higher Cell Density**
  • Traditional way to improve throughput
  • Divide cell radius by $z \rightarrow z^2$ more cells
  • Expensive: Rent and deployment cost

• **More Spectrum**
  • Suitable for coverage: Below 5 GHz
  • Already allocated for services!
    (cellular: 550 MHz, WiFi: 540 MHz)
  • Above 5 GHz: High propagation losses $\rightarrow$ Mainly short-range WiFi?

• **Higher Spectral Efficiency**
  • Not any large improvements in the past
  • Can it be the driving force in future networks?
Ways to Achieve

HIGHER SPECTRAL EFFICIENCY
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 Parallel Transmissions: *Spatially focused to each desired user*

![Single-Antenna Transmission](image1)

![Multi-Antenna Transmission](image2)
Multi-User MIMO (Multiple-input Multiple-output)

- **Multi-Cell Multi-User MIMO**
  - Base stations (BSs) with $M$ antennas
  - Parallel uplink/downlink for $K$ users
  - Channel coherence block: $S$ symbols

- **Theory: Hardware is Limiting**
  - Spectral efficiency roughly prop. to
    $$\min\left(M, K, \frac{S}{2}\right)$$
  - 2x improvement = 2x antennas and users (since $S \in [100,10000]$)

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

\[\text{End of the MIMO road?} \quad \text{No reason to add more antennas/users?}\]
Taking Multi-User MIMO to a New Level

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

2013 IEEE Marconi Prize Paper Award

- Analysis based on asymptotics: $M \rightarrow \infty$
- Concept applicable at any $M$
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

**Massive MIMO Characteristics**

*Active antennas: Many antenna ports*

*Coherent beamforming to tens of users*

**Typical vertical array:**
10 antennas x 2 polarizations
Only 1-2 antenna ports

*160 antenna elements, LuMaMi testbed, Lund University*
Massive MIMO Deployment

• When to Deploy Massive MIMO?
  • The future will tell, but it can
    1. Improve wide-area coverage
    2. Handle super-dense scenarios

• Co-located Deployment
  • 1D, 2D, or 3D arrays

• Distributed Deployment
  • Remote radio heads
Basic Properties of

MASSIVE MIMO
Asymptotic Channel Orthogonality

- Example: Uplink with Isotropic/Rayleigh Fading
  - Two users, i.i.d. channels: \( \mathbf{h}_1, \mathbf{h}_2 \sim CN(\mathbf{0}, \mathbf{I}_M) \)
  - Signals: \( s_1, s_2 \) with power \( P \)
  - 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 Processing for User 1: \( \hat{\mathbf{y}}_1 = \mathbf{w}_1^H \mathbf{y} = \mathbf{w}_1^H \mathbf{h}_1 s_1 + \mathbf{w}_1^H \mathbf{h}_2 s_2 + \mathbf{w}_1^H \mathbf{n} \)
  - Maximum ratio filter: \( \mathbf{w}_1 = \frac{1}{M} \mathbf{h}_1 \)
  - Signal remains: \( \mathbf{w}_1^H \mathbf{h}_1 = \frac{1}{M} ||\mathbf{h}_1||^2 \xrightarrow{M \to \infty} E[|h_{11}|^2] = 1 \)
  - Interference vanishes: \( \mathbf{w}_1^H \mathbf{h}_2 = \frac{1}{M} \mathbf{h}_1^H \mathbf{h}_2 \xrightarrow{M \to \infty} E[h_{11}^H h_{21}] = 0 \)
  - Noise vanishes: \( \mathbf{w}_1^H \mathbf{n} = \frac{1}{M} \mathbf{h}_1^H \mathbf{n} \xrightarrow{M \to \infty} E[h_{11}^H n_1] = 0 \)

Asymptotically noise/interference-free communication: \( \hat{\mathbf{y}}_1 \xrightarrow{M \to \infty} s_1 \)
Is this Result Limited to Isotropic Fading?

- Assumptions in i.i.d. Rayleigh Fading
  - No dominant directivity
  - Very many scattering objectives

  \[ \text{Less true as } M \rightarrow \infty \]

- Example: Line-of-Sight Propagation
  - Uniform linear array
  - Random user angles
  - \( M \) observations:
    - Stronger signal
    - Suppressed noise
  - What is \( h_1^H h_2 \rightarrow ? \)

**Main difference:**
How quickly interference is suppressed
How will Practical Channels Behave?

- Measurements show similar results.

Asymptotic Favorable Propagation:

\[ \frac{1}{M} \mathbf{h}_1^H \mathbf{h}_2 \to 0 \text{ as } M \to \infty \]

- Achieved in Rayleigh fading and line-of-sight – two extremes!
- Same behavior expected and seen in practice.

There are no experimentally validated massive MIMO channel models!

Spectral Efficiency

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

What can We Expect from MASSIVE MIMO?
Improving Spectral Efficiency by Massive MIMO

• Massive MIMO can Improve Spectral Efficiency
• Question: How large improvement can we expect? \((2x, 5x, 10x, \ldots?)\)

• Answers in My Recent Research

• Methodology
  1. Define a theoretical communication model (using practical properties)
  2. Formulate the question in mathematical terms
  3. Derive communication-theoretic performance expressions
  4. Obtain the answer by analytic results and numerical simulations
Transmission Protocol

- **Coherence Blocks**
  - Fixed channel responses
  - Coherence time: $T_c \text{ s}$
  - Coherence bandwidth: $W_c \text{ Hz}$
  - Depends on mobility and environment
  - Block length: $S = T_c W_c$ symbols
  - Typically: $S \in [100,10000]$

- **Time-Division Duplex (TDD)**
  - Switch between downlink and uplink on all frequencies
  - $B$ symbols/block for uplink pilots – to estimate channel responses
  - $S - B$ symbols/block for uplink and/or downlink payload data
Hexagonal Cellular Network

- Classic Hexagonal Cellular System
  - Infinitely large set of cells ($\mathcal{L}$)
  - $M$ antennas at each BS
  - $K$ active users in each cell

- Assumptions
  - Uniform user distribution in cells
  - Uncorrelated Rayleigh fading

**Relative inter-cell interference**

$$\mu_{jl}^{(1)} = \text{Average interference power from cell } l \text{ to cell } j$$

$$\mu_{jl}^{(2)} = \text{Second moment of same thing}$$

*Every cell is “typical”*
Problem Formulation

• Problem Formulation:

\[
\text{maximize } \frac{K}{B} \text{ total spectral efficiency } \quad [\text{bit/s/Hz/cell}]
\]

for a given \textit{M and S}.

• Main Issue: Hard to Find Tractable Expressions
  • Interference depends on user positions (in all cells!)
  • Prior works: Fixed pathloss values
  • We want reliable quantitative results – independent of user locations

• Proposed Solution: Make every user “typical”
  • Same signal power: Power control inversely proportional to pathloss
  • Inter-cell interference: Code over variations in user locations in other cells
Channel Acquisition

- Base Station Need Channel Responses to do Beamforming
  - Estimate using uplink pilot symbols
  - Only $B$ pilot symbols available (pick $B \leq S$)
  - Must use same pilot symbols in different cells
  - Base stations cannot tell some users apart

- Called: Pilot Contamination
  - Recall: Noise and interference vanish as $M \to \infty$
  - Not interference between users with same pilot!

- Solution: Select how often pilots are reused
  - Pilot reuse factor $\beta \geq 1$
  - Users per cell: $K = \frac{B}{\beta}$
  - Higher $\beta$ → Fewer users per cell, but interferers further away
Computing Spectral Efficiency

**Theorem:** Lower bound on spectral efficiency in cell $j$:

$$ SE_j = \sum_{k=1}^{K} \left( 1 - \frac{B}{S} \right) \log_2 \left( 1 + \frac{B}{I_{jk}} \right) $$

- **Interference term with maximum ratio (MR) processing:**

$$ I_{jk}^{\text{MR}} = \sum_{l \in \mathcal{L}} \sum_{m=1, m \neq (j,k)}^{K} \left( \mu_{jl}^{(2)} + \frac{\mu_{jl}^{(2)} - (\frac{\mu_{jl}^{(1)}}{M})^2}{M} \right) v_{i,lm}^{\Pi} v_{i,m}^{\Pi} + \left( \frac{\sum_{l \in \mathcal{L}} \mu_{jl}^{(1)} K}{M} + \frac{\sigma^2}{M \rho} \right) \left( \frac{\sum_{l \in \mathcal{L}} \sum_{m=1}^{K} \mu_{jl}^{(1)} v_{i,jk}^{\Pi} v_{i,\ell,m}^{\Pi} + \frac{\sigma^2}{\rho} }{1/(\text{Channel estimation quality})} \right) $$

**Proof (outline):**

1. **Compute the MMSE channel estimator for arbitrary pilots**
2. **Derive a lower bound on mutual information by treating interference as noise**
3. **Compute lower bound on average mutual information for random interferers**

**Same thing for zero-forcing (ZF) processing:** Cancel interference spatially
Numerical Results

• Problem Formulation:

\[
\begin{align*}
\text{maximize} & \quad K, \beta \\
\text{spectral efficiency} & \quad [\text{bit/s/Hz/cell}]
\end{align*}
\]

for a given \( M \) and \( S \).

• Use new closed-form spectral efficiency expressions
• Compute interference \( \mu_{jl}^{(1)} \) and \( \mu_{jl}^{(2)} \) between cells (a few minutes)
• Simply compute for different \( K \) and \( \beta \) and pick maximum (<1 minute)

Simulation Assumptions

- Uniform user distribution
- Pathloss exponent: 3.7
- Coherence block: \( S = 400 \)
- SNR 5 dB, Rayleigh fading
Anticipated Uplink Spectral Efficiency

**Optimized Results**

ZF slightly better than MR processing (and use smaller $K$)

Pilot reuse $\beta = 3$ is best

**Observations**

- Baseline: 2.25 bit/s/Hz/cell (IMT-Advanced)
- Massive MIMO, $M = 100$: x20 gain ($M/K \approx 6$)
- Massive MIMO, $M = 400$: x50 gain ($M/K \approx 9$)
- Per scheduled user: $\approx 2.5$ bit/s/Hz
SUMMARY
Summary

• Wireless Communication is an Incredible Success Story
  • Usage has increased exponentially for a century!
  • This trend is expected to continue in the foreseeable future
  • Wireless networks must improve:
    More bandwidth, Higher cell density, More spectral efficiency

Main driving forces in the past  Can be improved in the future!

• Massive MIMO: A technique to increase spectral efficiency
  • >20x gain over IMT-Advanced are foreseen
  • Base stations with many active antenna elements
  • High spectral efficiency per cell, not per user
  • Many potential deployment strategies
QUESTIONS?

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