Increasing the Spectral Efficiency of Future Wireless Networks

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Outline

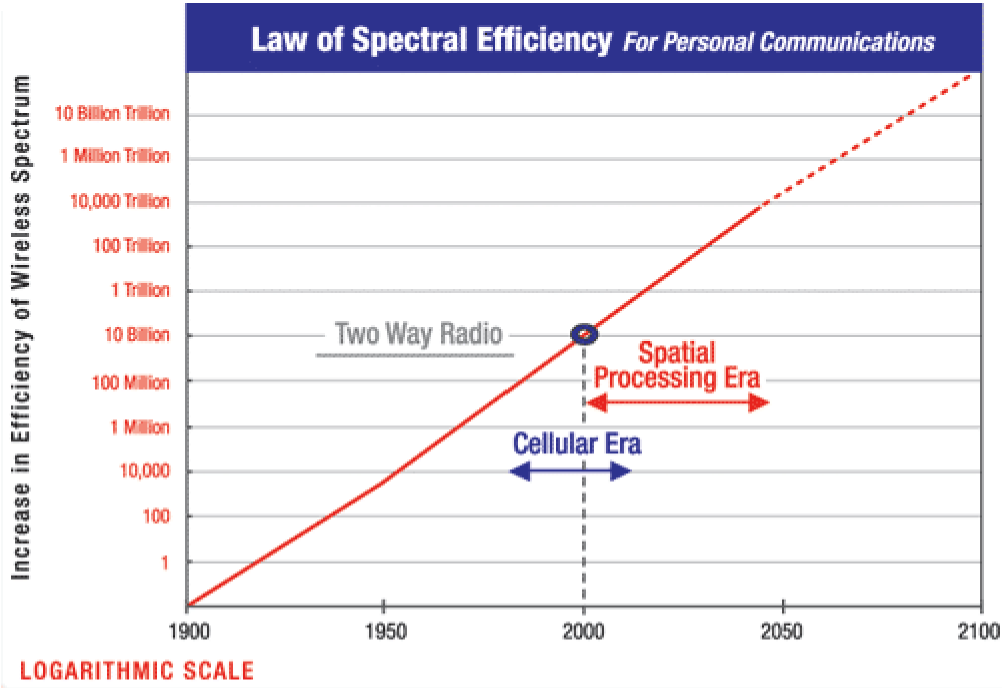
- Introduction: Past and Future of Wireless Communications
- Ways to Achieve Higher Spectral Efficiency
  - What does communication theory tell us?
- Basic Properties of Massive MIMO
  - Asymptotic behaviors and recent measurements
- What can we Expect from Massive MIMO?
  - New research results
- Summary

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



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

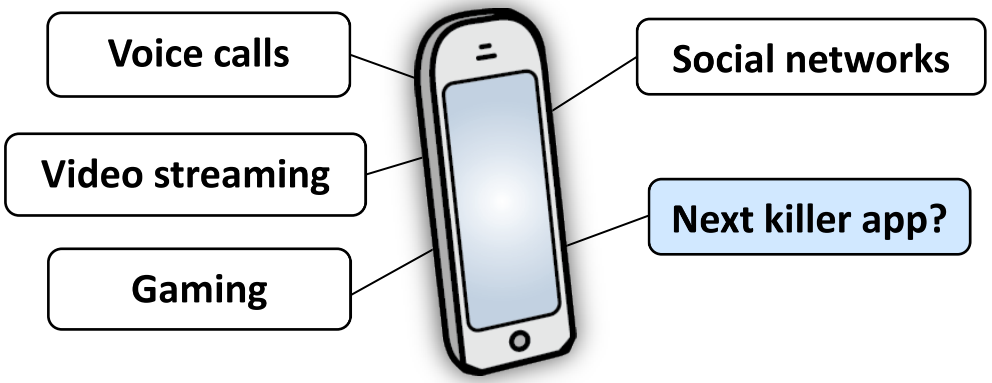
Martin Cooper

Inventor of handheld cellular phones

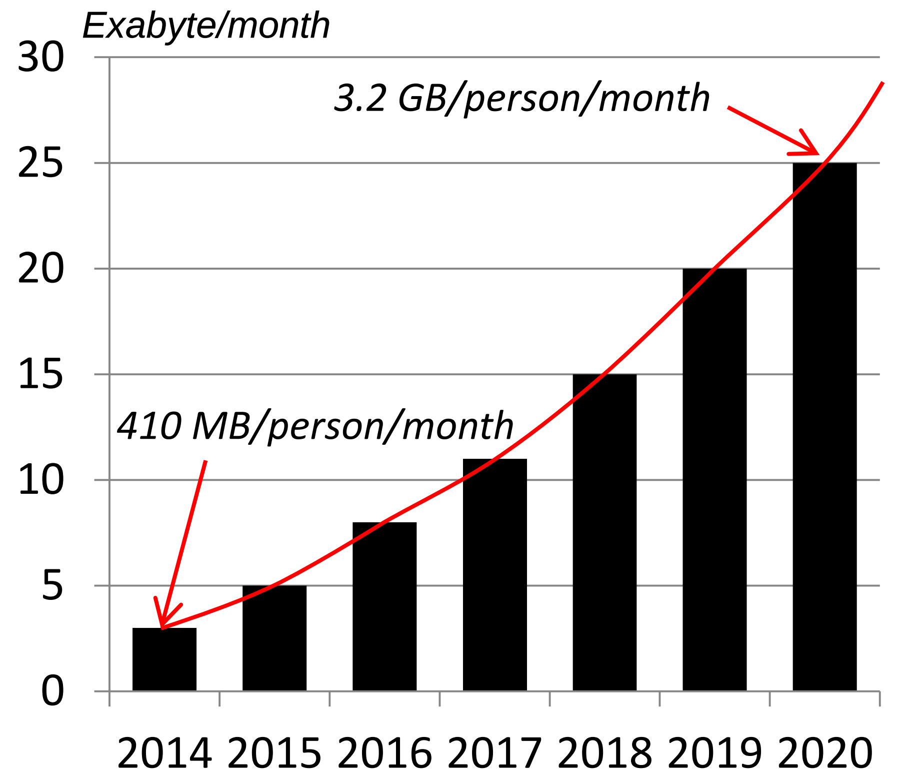
Source: Wikipedia

Predictions for the Future

- Wireless Connectivity
  - A natural part of our lives

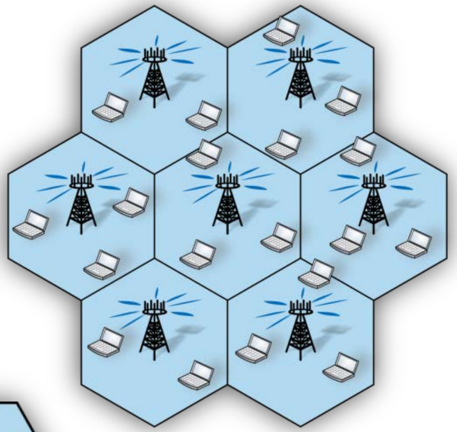


- Rapid Network Traffic Growth
  - 38% annual data traffic growth
  - Slightly faster than in the past!
  - Exponential increase
  - Extrapolation: 7x until 2020
    32x until 2025
    154x until 2030

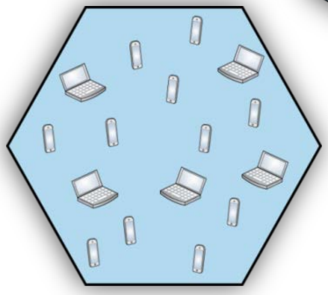


Source: Ericsson (November 2014)

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:

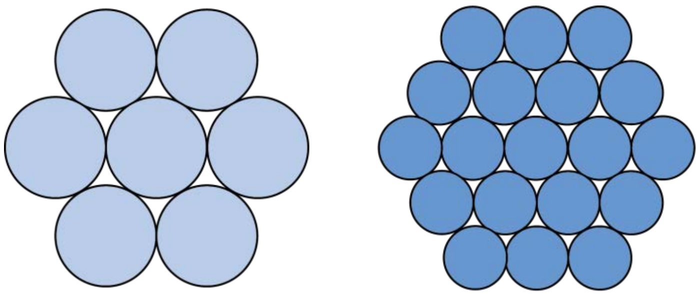
$$\underbrace{\text{Throughput}}_{\text{bit/s in area}} = \underbrace{\text{Cell density}}_{\text{Cell/Area}} \cdot \underbrace{\text{Available spectrum}}_{\text{in Hz}} \cdot \underbrace{\text{Spectral efficiency}}_{\text{bit/s/Hz/Cell}}$$

  - Ways to achieve 1000x improvement:

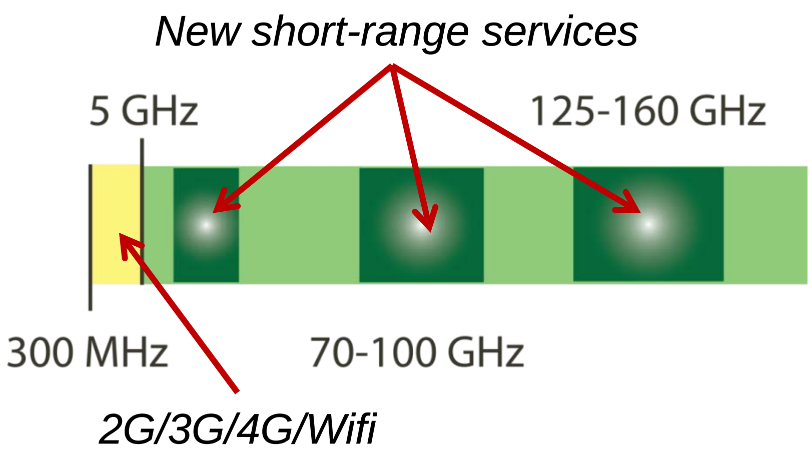
	Higher cell density	More spectrum	Higher spectral efficiency
Nokia (2011)	10x	10x	10x
SK Telecom (2012)	56x	3x	6x

Three Different Solutions

- Higher Cell Density
  - Traditional way to improve throughput
  - Divide cell radius by z → 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 → Mainly short-range WiFi?

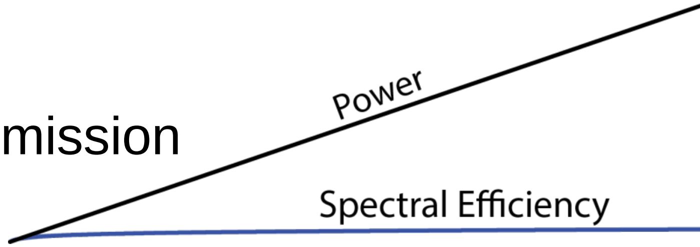


- Higher Spectral Efficiency
  - Not any large improvements in the past
  - **Can it be the driving force in future networks?**

Ways to Achieve

HIGHER SPECTRAL EFFICIENCY

Higher Spectral Efficiency

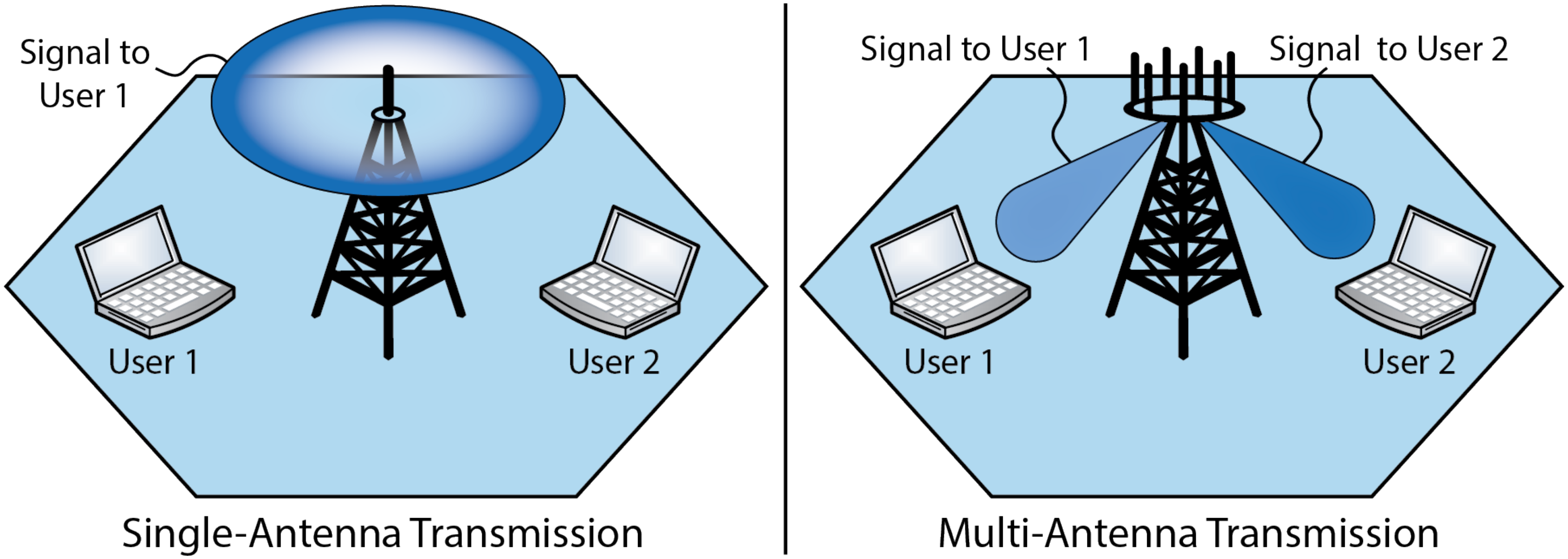


- Spectral Efficiency of Point-to-Point Transmission
  - Governed by Shannon's capacity limit:

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

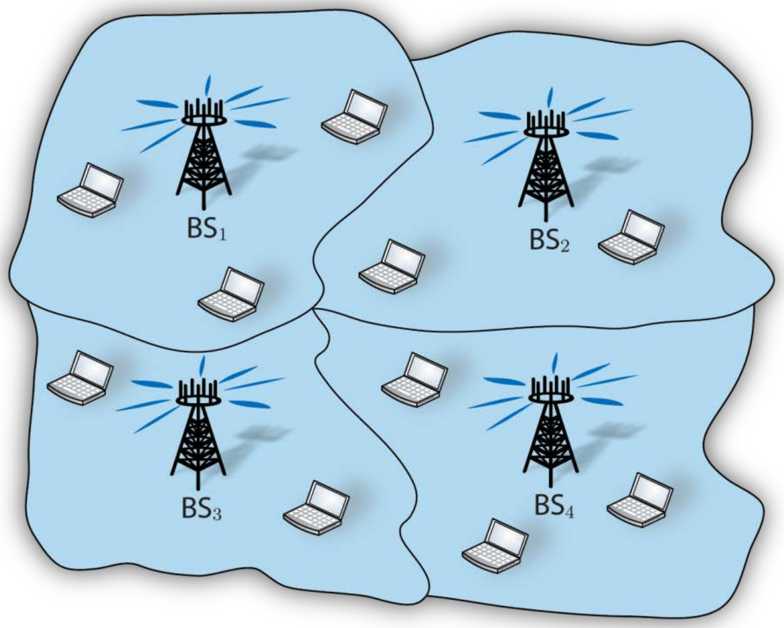
  - Cannot do much: 4 bit/s/Hz → 8 bit/s/Hz costs 17 times more power!

- Many Parallel Transmissions: *Spatially focused to each desired user*



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

End of the MIMO road?

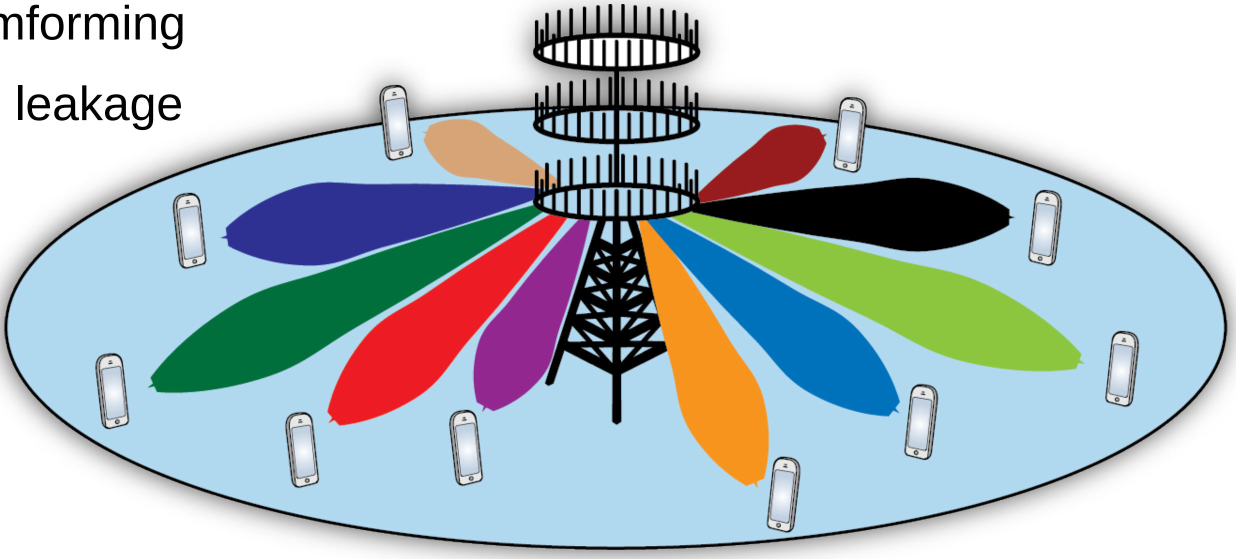
No reason to add more antennas/users?

Taking Multi-User MIMO to a New Level

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

Spectral efficiency prop. to number of users!

$$\min\left(M, K, \frac{S}{2}\right) \approx K$$



- 2013 IEEE Marconi Prize Paper Award

  Thomas Marzetta, "*Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas*," IEEE Trans. Wireless Communications, 2010.
  - Analysis based on asymptotics: $M \to \infty$
  - Concept applicable at any M

What is the Key Difference from Today?

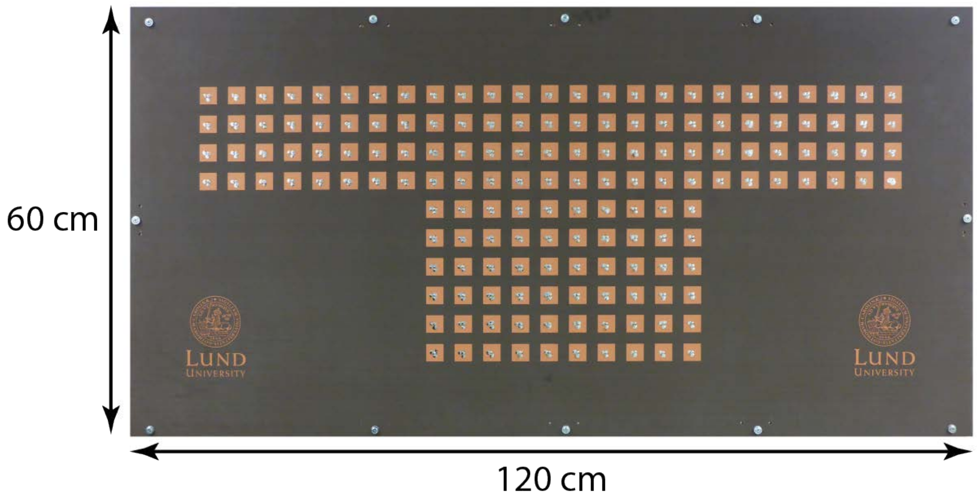
- Number of Antennas? **No, we already have many antennas!**
  - 3G/UMTS: 3 sectors x 20 element-arrays = 60 antennas
  - 4G/LTE-A: 4-MIMO x 60 = 240 antennas

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

Massive MIMO Characteristics

Active antennas: Many antenna ports

Coherent beamforming to tens of users

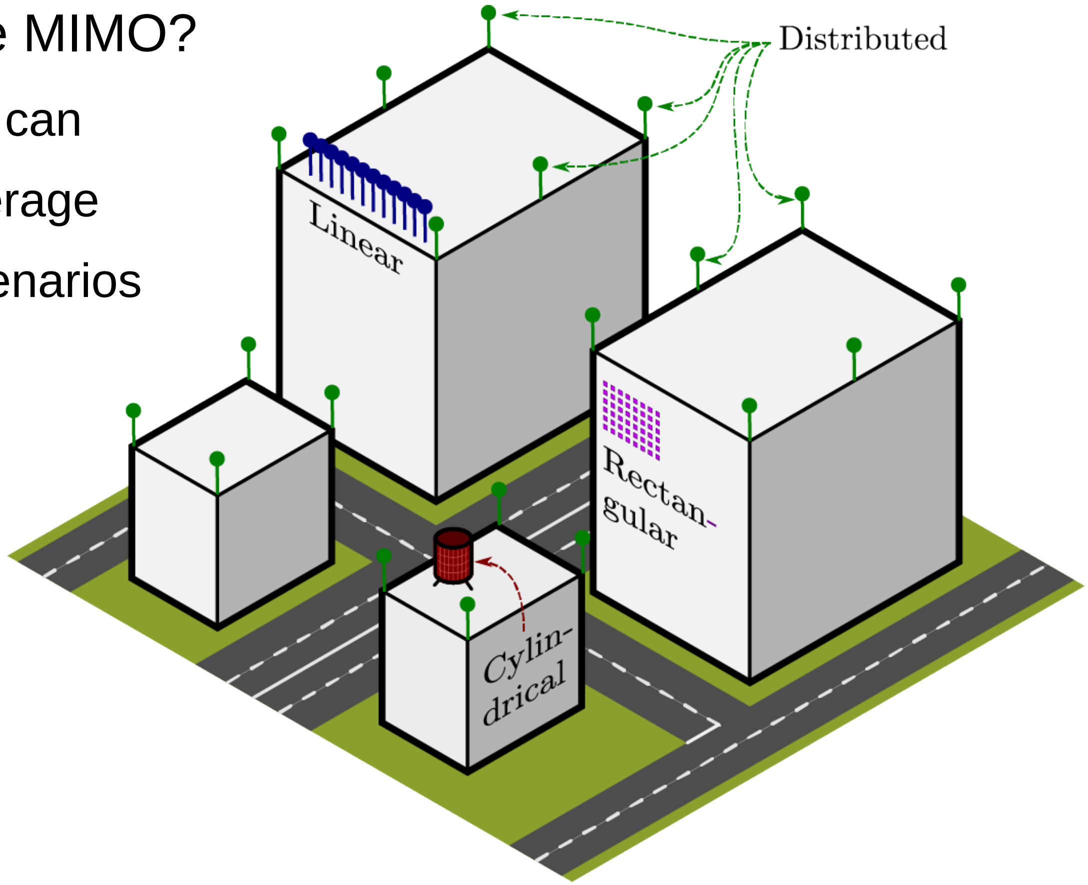


160 antenna elements, *LuMaMi testbed, Lund University*

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

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

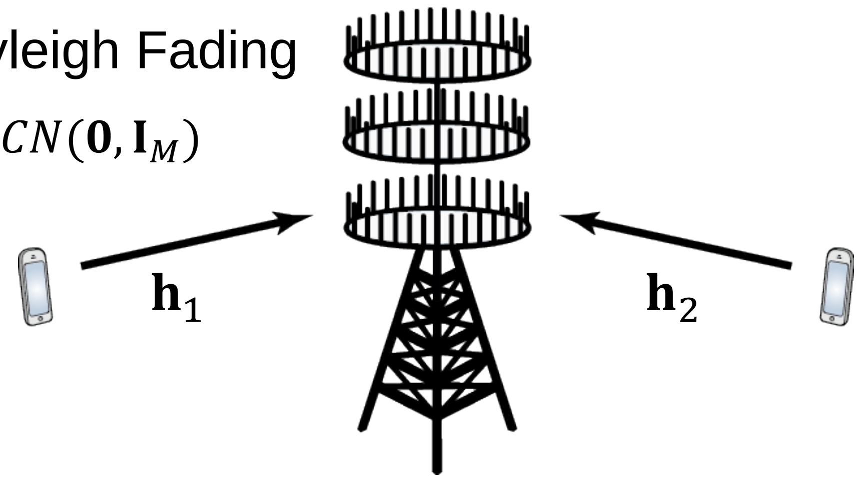


Basic Properties of

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: $\tilde{y}_1 = \mathbf{w}_1^H \mathbf{y} = \boxed{\mathbf{w}_1^H \mathbf{h}_1} s_1 + \boxed{\mathbf{w}_1^H \mathbf{h}_2} s_2 + \boxed{\mathbf{w}_1^H \mathbf{n}}$
  - Maximum ratio filter: $\mathbf{w}_1 = \frac{1}{M}\mathbf{h}_1$
  - Signal remains: $\mathbf{w}_1^H \mathbf{h}_1 = \frac{1}{M}||\mathbf{h}_1||^2 \xrightarrow{M\to\infty} \mathrm{E}\big[|h_{11}|^{\mathbf{2}}\big] = 1$
  - Interference vanishes: $\mathbf{w}_1^H \mathbf{h}_2 = \frac{1}{M}\mathbf{h}_1^H \mathbf{h}_2 \xrightarrow{M\to\infty} \mathrm{E}[h_{11}^H h_{21}] = 0$
  - Noise vanishes: $\mathbf{w}_1^H \mathbf{n} = \frac{1}{M}\mathbf{h}_1^H \mathbf{n} \xrightarrow{M\to\infty} \mathrm{E}[h_{11}^H n_1] = 0$

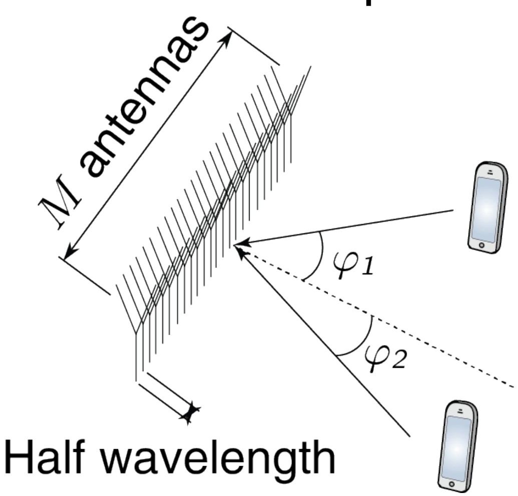
Asymptotically noise/interference-free communication: $\tilde{y}_1 \xrightarrow{M\to\infty} s_1$

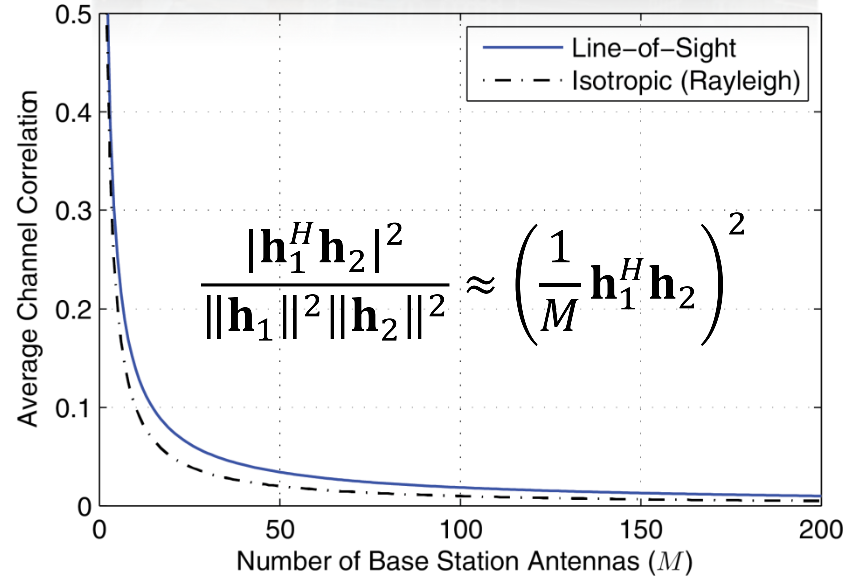
Is this Result Limited to Isotropic Fading?

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

$$\underbrace{\hphantom{\text{No dominant directivity, Very many scattering objectives}}}_{\textit{Less true as } M \to \infty}$$

- Example: Line-of-Sight Propagation
  - Uniform linear array
  - Random user angles
  - M observations:
    - Stronger signal
    - Suppressed noise
  - What is $\mathbf{h}_1^H \mathbf{h}_2 \to ?$





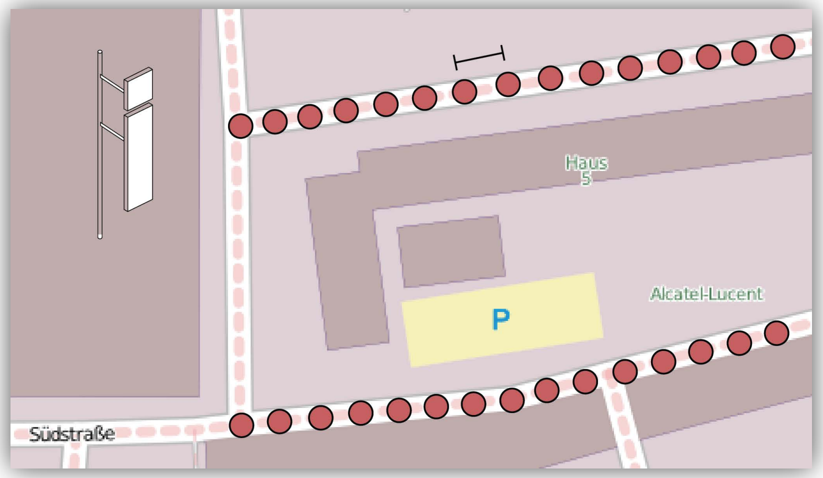
***Main difference**:*
How quickly interference is suppressed

How will Practical Channels Behave?

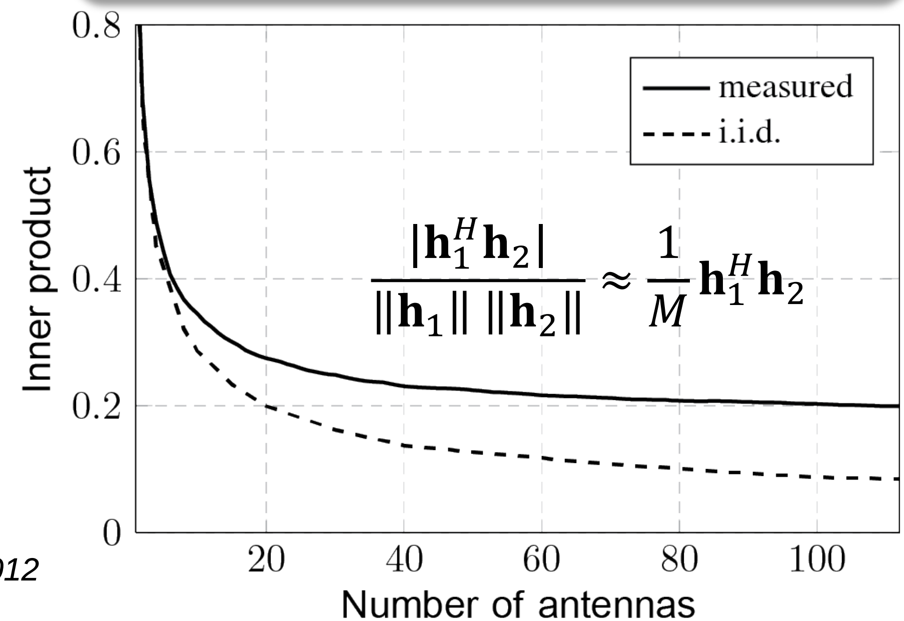
- Measurements show similar results

Spectral Efficiency

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



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



*There are no **experimentally** validated massive MIMO channel models!*

- Asymptotic Favorable Propagation: $\frac{1}{M} \mathbf{h}_1^H \mathbf{h}_2 \rightarrow 0$ as $M \rightarrow \infty$
  - Achieved in Rayleigh fading and line-of-sight – two extremes!
  - Same behavior expected and seen in practice

What can We Expect from

MASSIVE MIMO?

Improving Spectral Efficiency by Massive MIMO

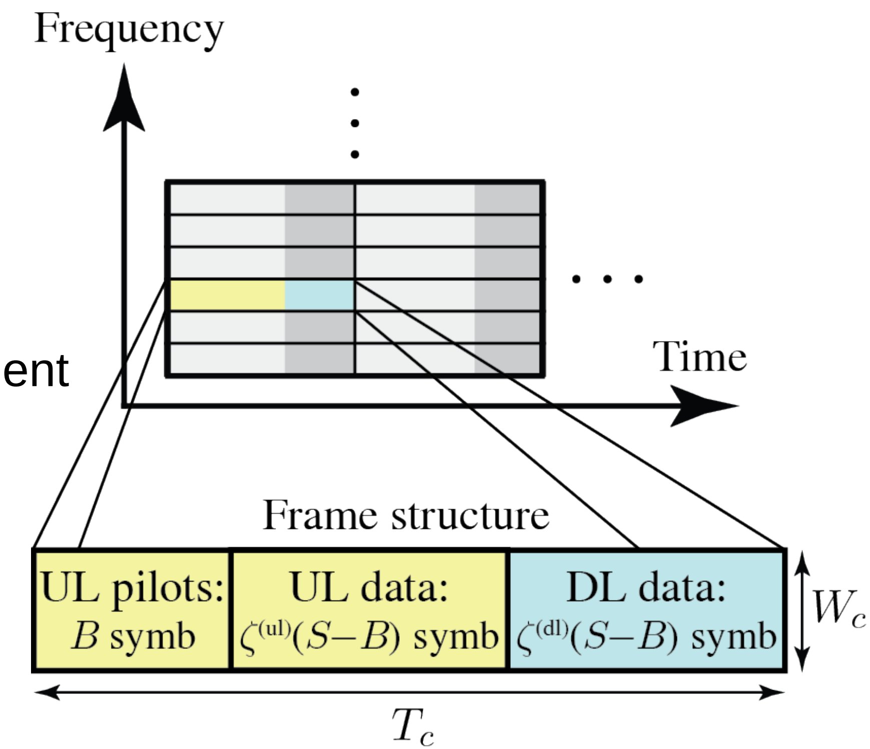
- Massive MIMO can Improve Spectral Efficiency
  - Question: How large improvement can we expect? (2x, 5x, 10x, …?)

- Answers in My Recent Research
  - E. Björnson, E. G. Larsson, M. Debbah, "*Optimizing Multi-Cell Massive MIMO for Spectral Efficiency: How Many Users Should Be Scheduled?*" Proceedings of IEEE GlobalSIP, Dec 2014.
  - E. Björnson, E. G. Larsson, M. Debbah, "*Massive MIMO for Maximal Spectral Efficiency: How Many Users and Pilots Should Be Allocated?*," Submitted to IEEE Transactions on Wireless Communications.

- 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 s
  - Coherence bandwidth: W_c 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

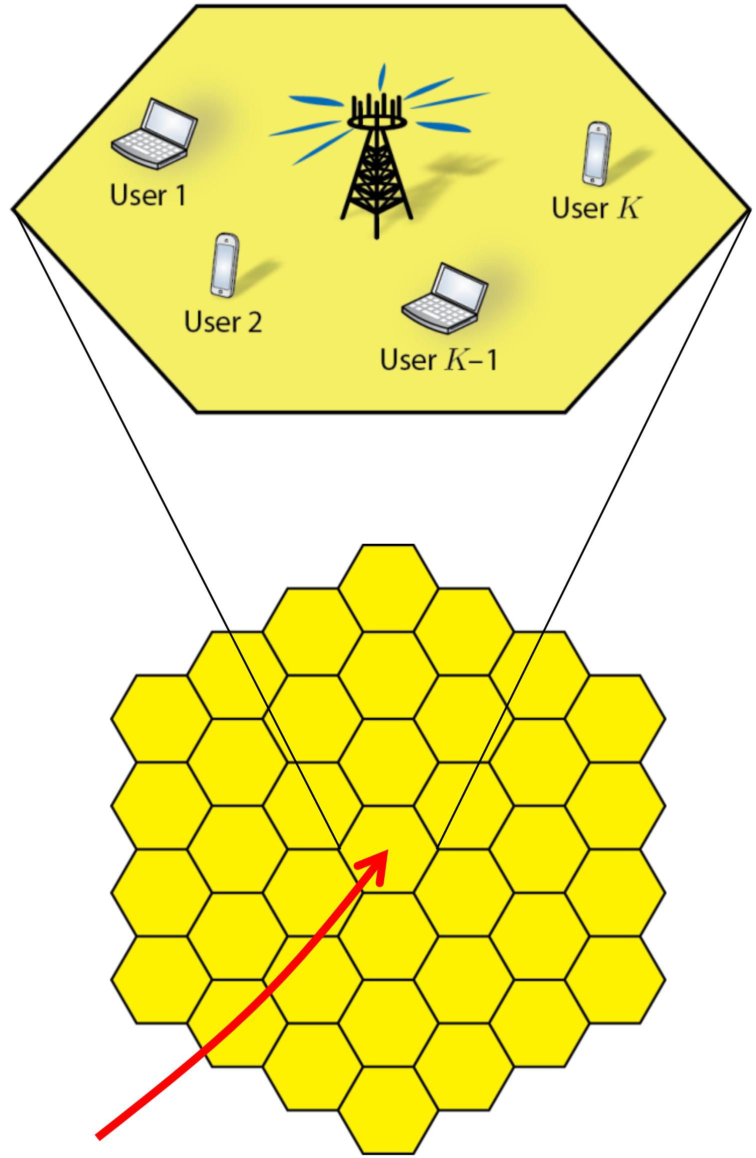
- Classic Hexagonal Cellular System
  - Infinitely large set of cells ($\mathcal{L}$)
  - M antennas at each BS
  - K active users in each cell

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

Relative inter-cell interference

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

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



Every cell is "typical"

Problem Formulation

- Problem Formulation:

$$\underset{K,B}{\text{maximize}} \quad \text{total spectral efficiency} \qquad [\text{bit/s/Hz/cell}]$$

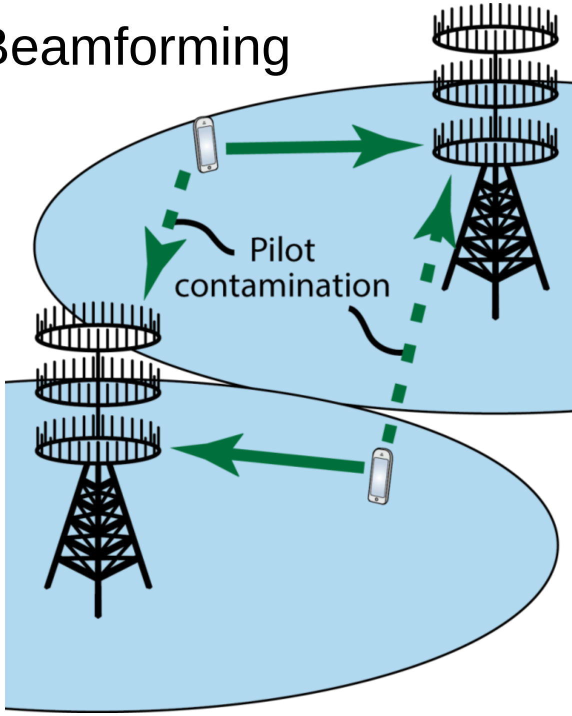
for a given M *and* S.

- 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

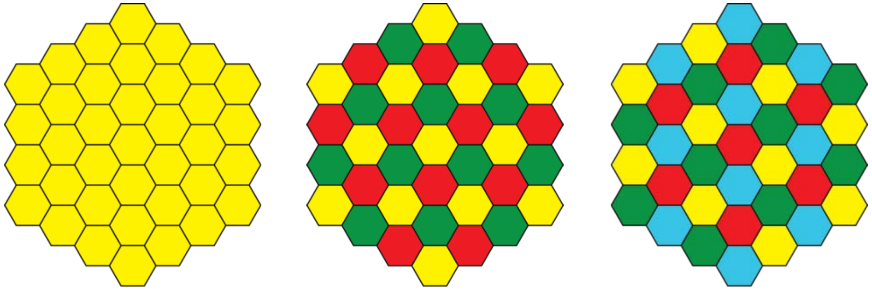
- Proposed Solution: Make every user "typical"
  - Same signal power: Power control inversely proportional to pathloss
  - Inter-cell interference: Code over variations in user locations in other cells

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 β → Fewer users per cell, but interferers further away



Pilot reuse $\beta = 1$ ***Pilot reuse*** $\beta = 3$ ***Pilot reuse*** $\beta = 4$

Computing Spectral Efficiency

Theorem: Lower bound on spectral efficiency in cell j:

$$\mathrm{SE}_j = \sum_{k=1}^{K} \underbrace{\left(1-\frac{B}{S}\right)}_{\textit{Loss from pilots}} \log_2\left(1+\underbrace{\frac{B}{I_{jk}}}_{\textit{SINR of user k}}\right)$$

- Interference term with maximum ratio (MR) processing:

Noise/Transmit Power

$$I_{jk}^{\mathrm{MR}} = \underbrace{\sum_{l\in\mathcal{L}} \sum_{\substack{m=1\\(l,m)\neq(j,k)}}^{K} \left(\mu_{jl}^{(2)} + \frac{\mu_{jl}^{(2)} - \left(\mu_{jl}^{(1)}\right)^2}{M}\right) \mathbf{v}_{i_{jk}}^{\mathrm{H}}\mathbf{v}_{i_{lm}}}_{\textit{Pilot contamination}} + \underbrace{\left(\sum_{l\in\mathcal{L}} \mu_{jl}^{(1)}\frac{K}{M} + \frac{\sigma^2}{M\rho}\right)}_{\textit{Interference from all cells}} \underbrace{\left(\sum_{\ell\in\mathcal{L}}\sum_{m=1}^{K}\mu_{jl}^{(1)} \mathbf{v}_{i_{jk}}^{\mathrm{H}} \mathbf{v}_{i_{\ell m}} + \frac{\sigma^2}{\rho}\right)}_{\textit{1/(Channel estimation quality)}}$$

***Only term that remains as** $M \rightarrow \infty$: Finite limit on SE*

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:

$$\underset{K,\beta}{\text{maximize}} \quad \text{spectral efficiency} \qquad [\text{bit/s/Hz/cell}]$$

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 β and pick maximum (<1 minute)

Simulation Assumptions

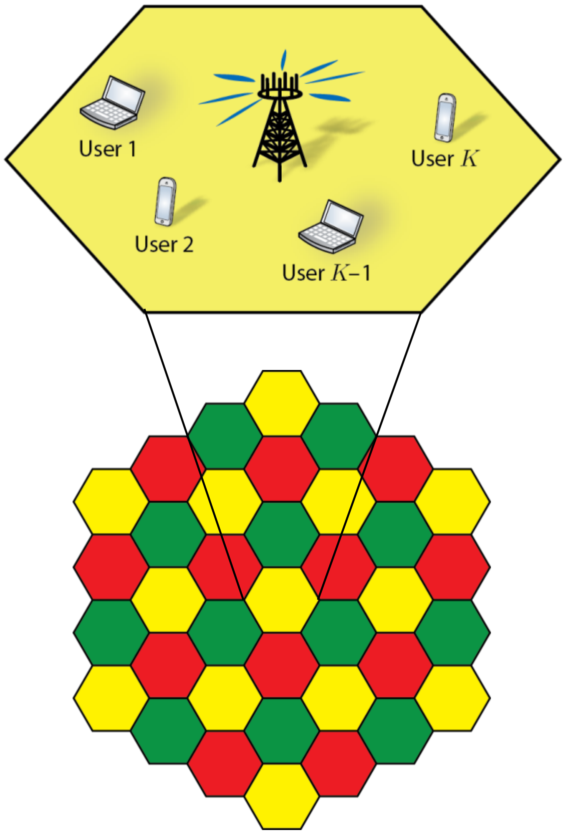
Uniform user distribution

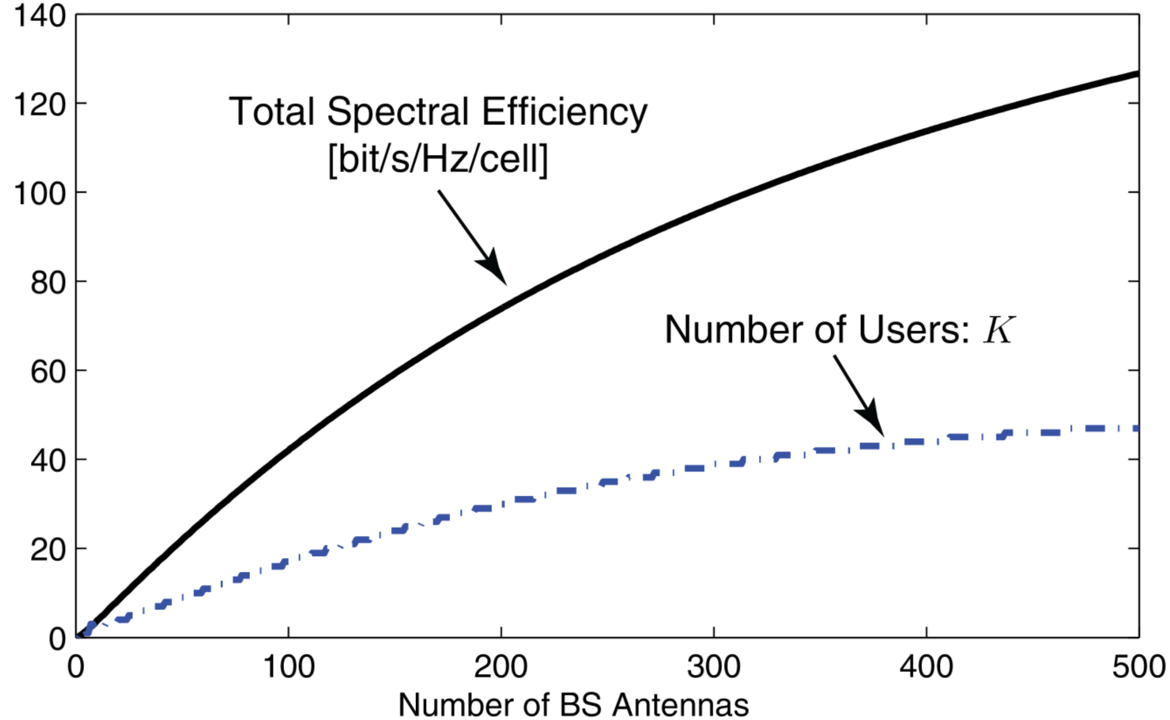
Pathloss exponent: 3.7

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: ≈ 2.5 bit/s/Hz*

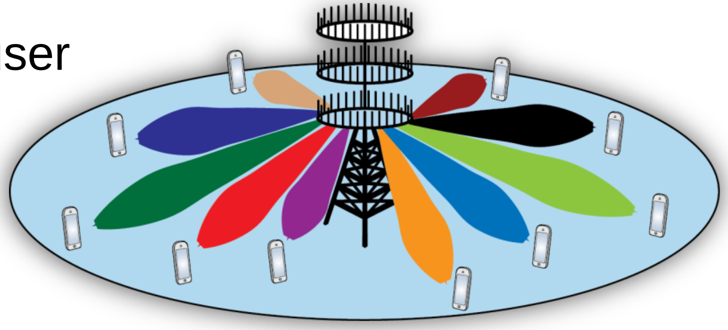
SUMMARY

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



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QUESTIONS?

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