Introduction to Massive MIMO

Communication system concepts

Dr. Emil Björnson

Associate Professor

Department of Electrical Engineering (ISY)

Linköping University, Sweden

LINKÖPING UNIVERSITY

Outline

- Introduction
- How to Achieve Higher Spectral Efficiency
- Basic Properties of Massive MIMO
- Massive MIMO Transmission Protocol
- Summary

INTRODUCTION

Incredible Success of Wireless Communications

Martin Cooper's law

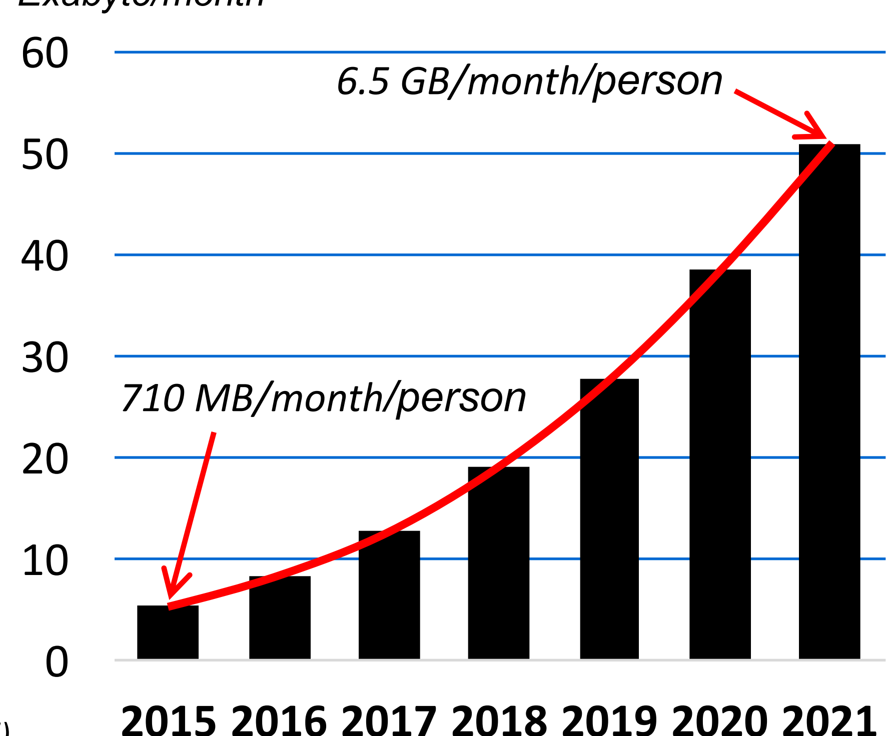
The number of voice/data connections has doubled every 2.5 years (+32% per year) since the beginning of wireless

Last 45 years: 1 Million increase in wireless traffic

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

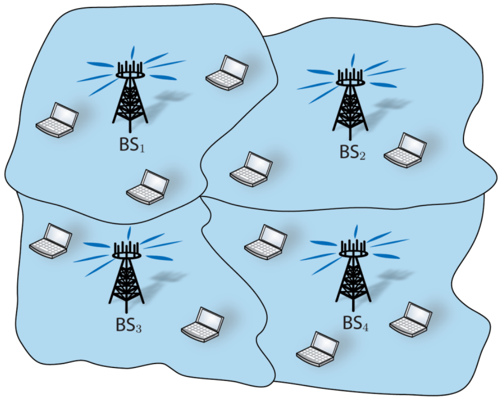
Source: Wikipedia

- Future Network Traffic Growth
  - 45% annual data traffic growth
  - Slightly faster than in the past!
  - Exponential increase
  - Extrapolation: 6x in 5 years
    40x in 10 years
    260x in 15 years



Data source: Ericsson (November 2015)

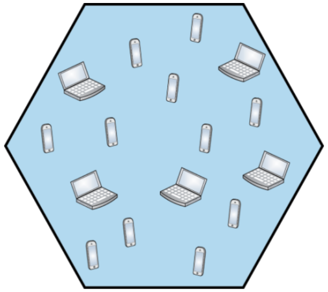
Evolving Networks for Higher Traffic



Cellular networks

Coverage area divided into cells
Users served by a base station

- Increase Network Throughput [bit/s/km^2]
  - Consider a given area →



- Simple Formula for Network Throughput:

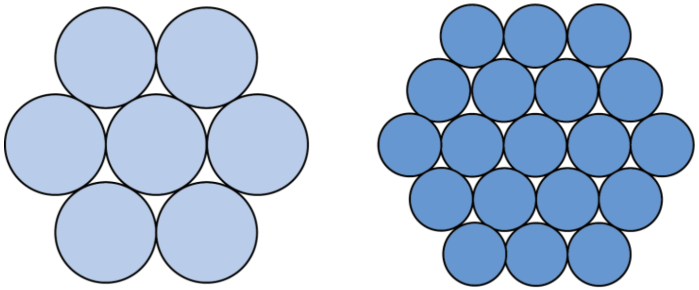
$$\underbrace{\text{Throughput}}_{\text{bit/s/km}^2} = \underbrace{\text{Cell density}}_{\text{Cell/km}^2} \cdot \underbrace{\text{Available spectrum}}_{\text{Hz}} \cdot \underbrace{\text{Spectral efficiency}}_{\text{bit/s/Hz/Cell}}$$

  - Ways to achieve 1000x improvement:

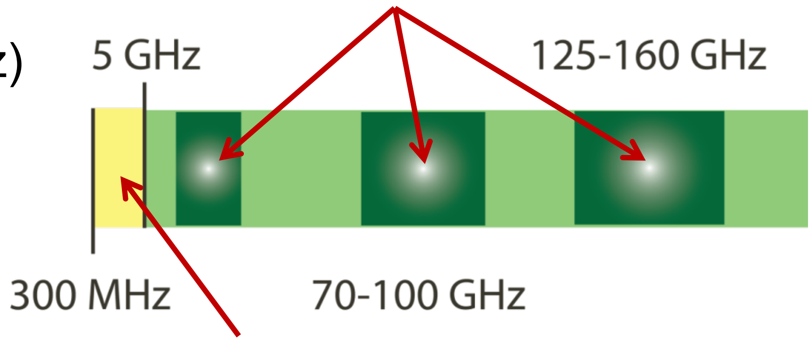
	Higher cell density	More spectrum	Higher spectral efficiency
Nokia (2011)	10x	10x	10x
SK Telecom (2012)	56x	3x	6x

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 getting worse
    WiFi + Cellular is already dense: *Coverage is the issue*!



- More Spectrum
  - Range suitable for coverage: < 5 GHz
  - Already allocated for services!
    (Cellular: ~ 550 MHz, WiFi: ~ 550 MHz)
  - Far above 5 GHz: High propagation losses → Mainly short-range hotspots



Higher Spectral Efficiency

"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

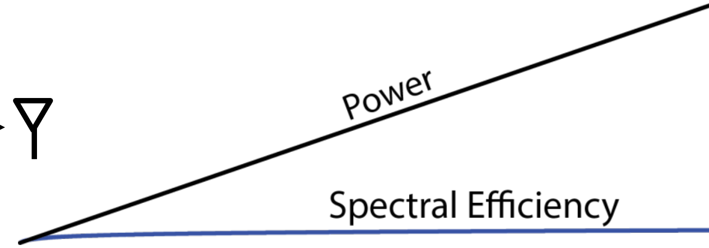
January 2015: FCC sold 65 MHz at 1.7-2.1 GHz for $45 billion

Can FCC's $50\times$ goal be reached?

How to achieve

HIGHER SPECTRAL EFFICIENCY

Higher Spectral Efficiency

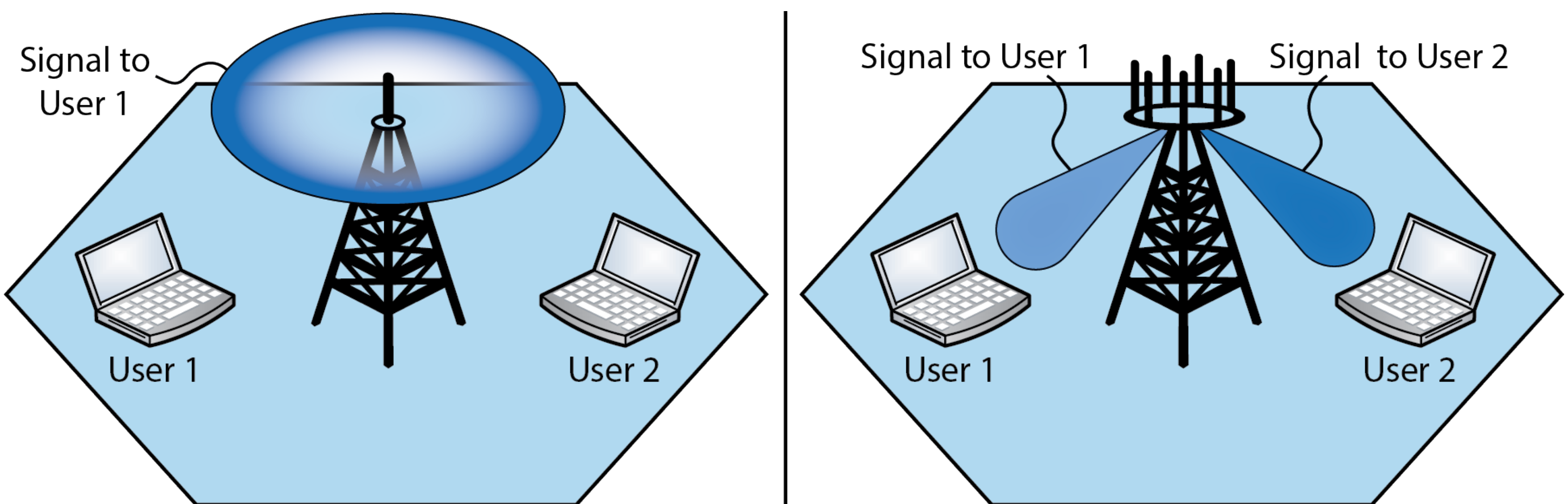


- Point-to-Point Spectral Efficiency:
  - Governed by Shannon's capacity limit:

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

  - Issue: 4 bit/s/Hz → 8 bit/s/Hz requires $17\times$ more power!

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

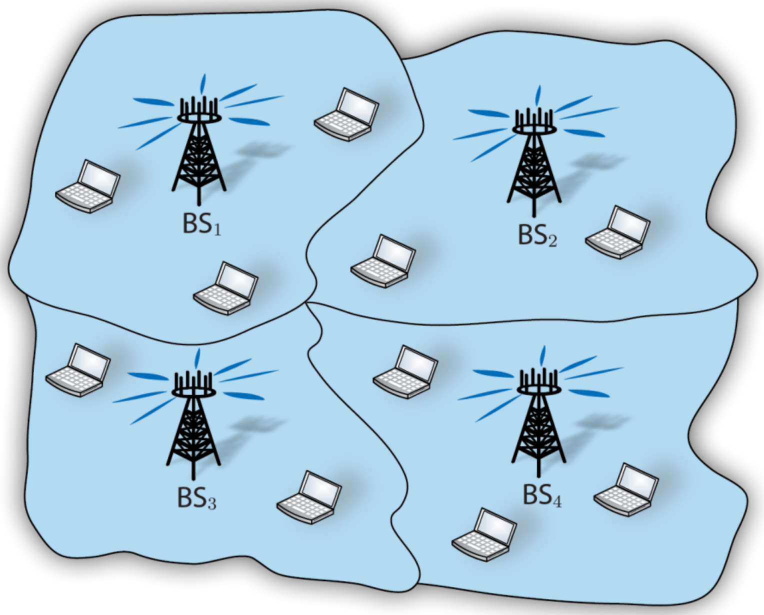


Single-Antenna Transmission

Multi-Antenna Transmission

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

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



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

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

  - $2\times$ improvement $= 2\times$ antennas and users $(\tau_c \in [100{,}10000])$

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

End of the MIMO road?

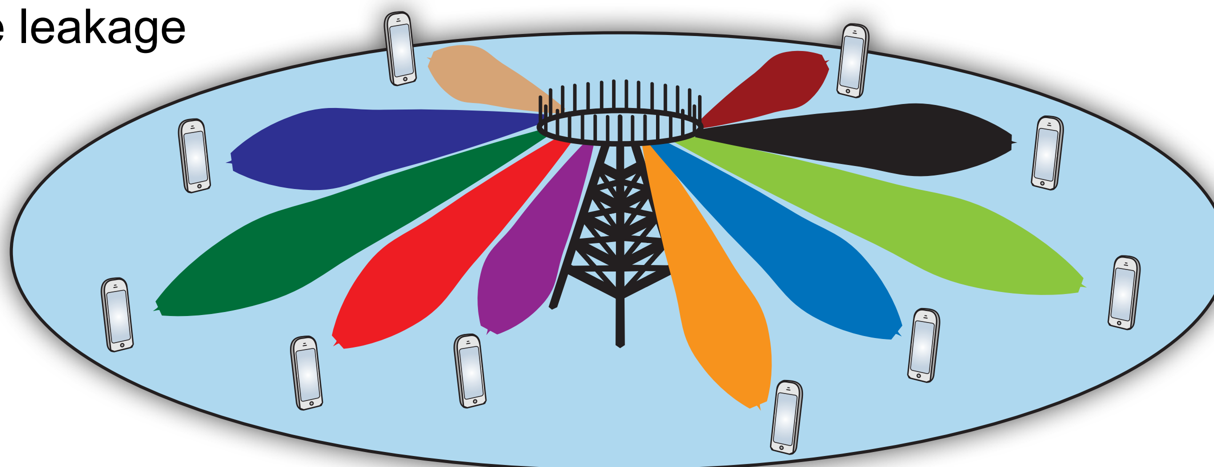
No reason to add more antennas/users?

Taking Multi-User MIMO to the Next Level

- Network Architecture: Massive MIMO
  - Many BS antennas; e.g., $M \approx 200$ antennas, $K \approx 40$ single-antenna users
  - Key: Many more antennas than users: $M \gg K$
  - Very directive signals
  - Little interference leakage

Spectral efficiency prop. to number of users!

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



- Seminal work:

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

  - 2013 IEEE Guglielmo Marconi Prize Paper Award
  - 2015 IEEE W. R. G. Baker Award

What is the Key Difference from Today?

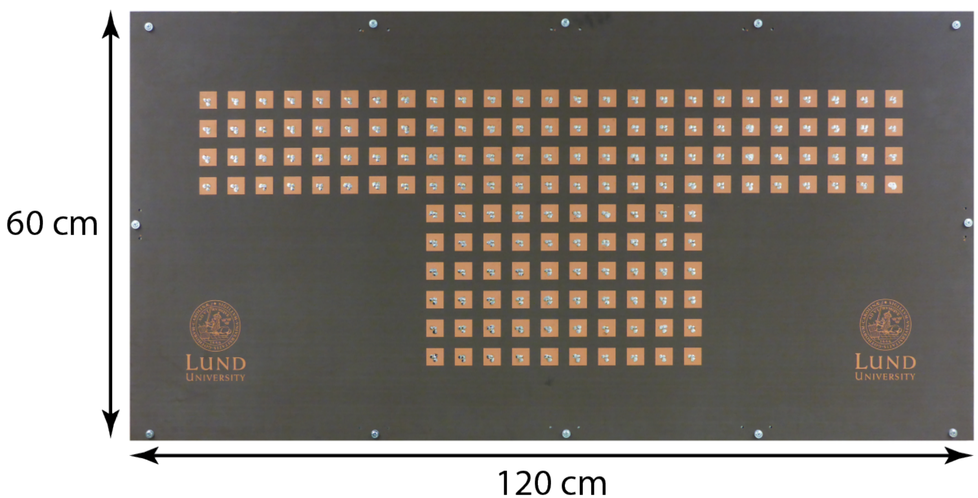
- Number of Antennas? **No, we already have many antennas!**
  - 3G/UMTS: 3 sectors x 20 element-arrays = 60 antennas
  - 4G/LTE-A: 8-MIMO x 30 = 240 antennas

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

Massive MIMO Characteristics

Many fully digital steerable antennas

Massive in numbers – not massive in size



160 antenna elements, *LuMaMi testbed, Lund University*

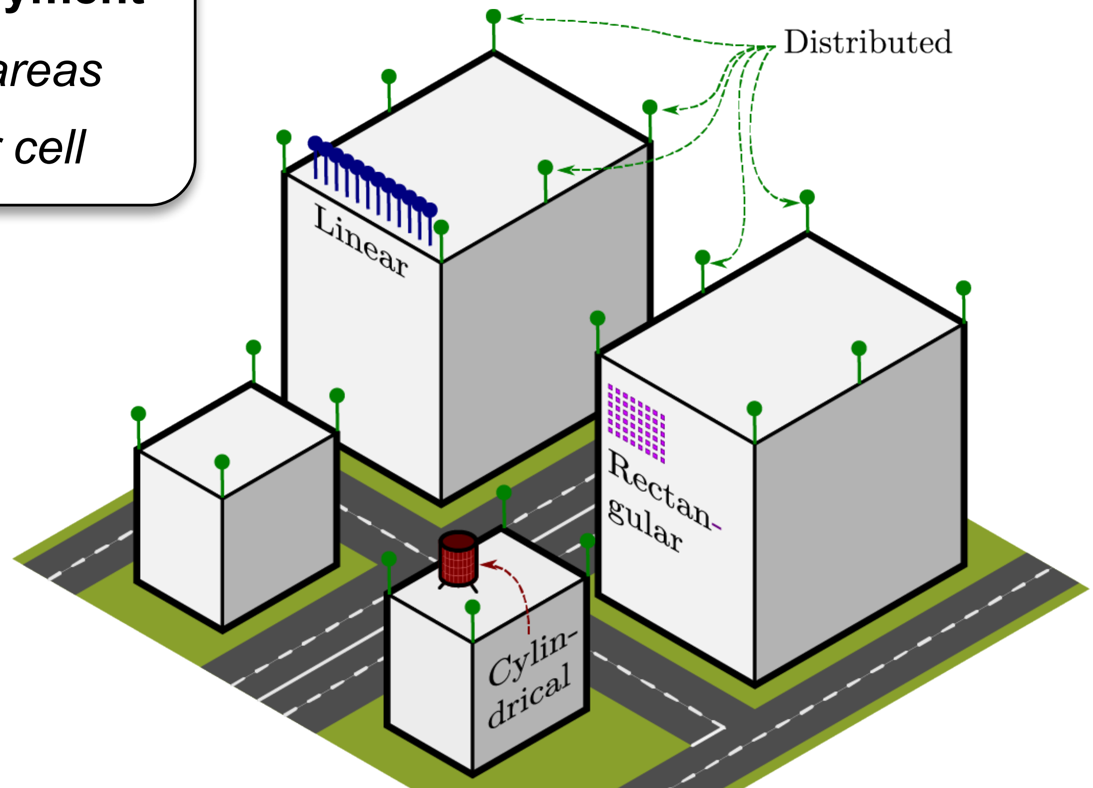
3 sectors, 4 vertical arrays per sector

How to Deploy Massive MIMO?

Conventional Cellular Deployment

Non-overlapping coverage areas

One or multiple sectors per cell



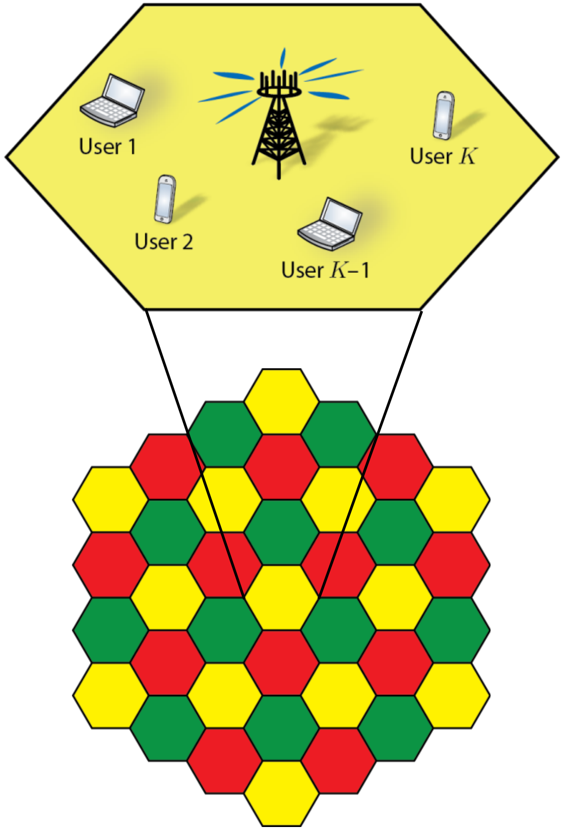
- Co-located Deployment
  - 1D, 2D, or 3D arrays
  - No need for sectors
- Distributed Deployment
  - Remote radio heads

Key Benefits of Massive MIMO

Outdoor users: Handle mobility and guarantee coverage

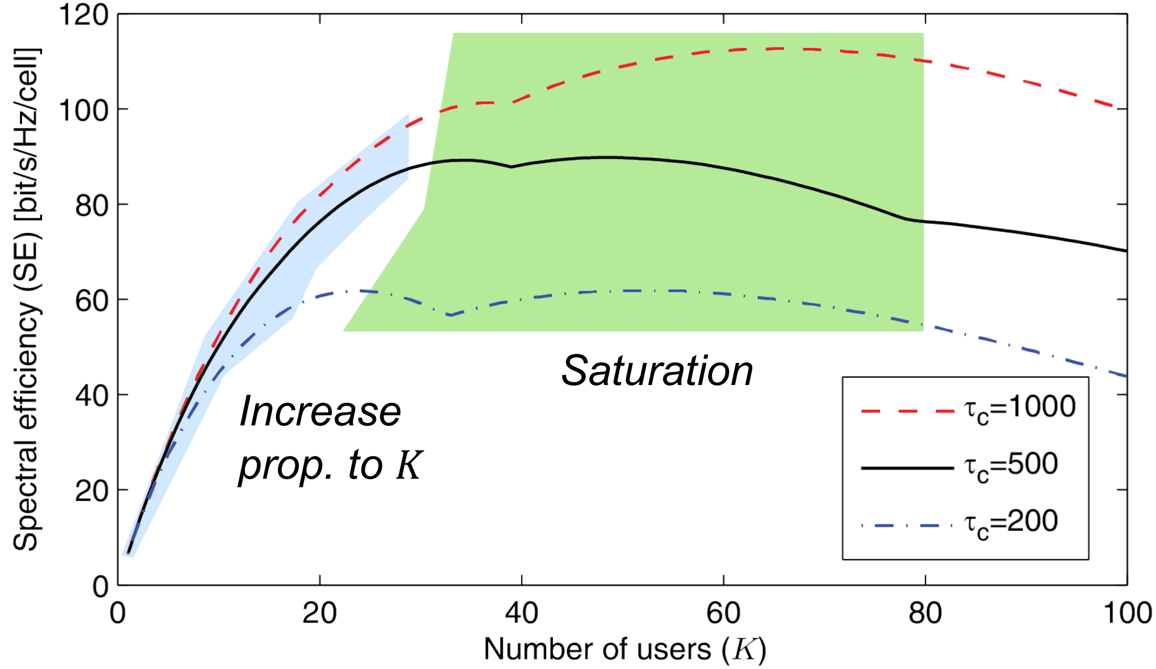
Indoor users: No need to put BSs inside buildings

How Much can Spectral Efficiency be Improved?



Uplink simulation

$M = 200$ antennas, SNR 0 dB, Rayleigh fading



- *Baseline:* 2.25 bit/s/Hz/cell (IMT-Advanced)
- *Massive MIMO:* $25\times - 50\times$ improvement
- Large coherence τ_c is key → Use lower frequencies

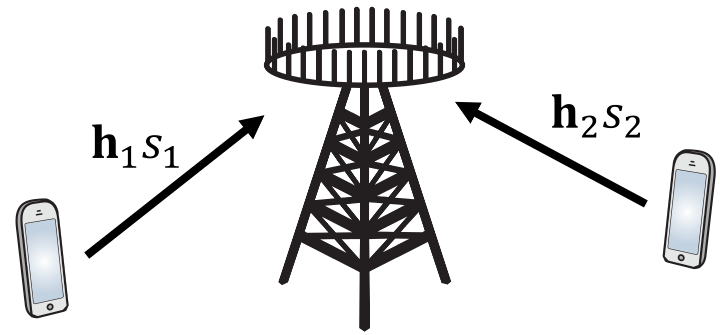
Yes, FCC's $50\times$ goal is within reach!

Basic Properties of

MASSIVE MIMO

Asymptotic Channel Orthogonality

- Example: Uplink with i.i.d. Rayleigh Fading
  - Two users, send signals s_k for $k = 1,2$
  - Channels: $\boldsymbol{h}_k = [h_{k1} \dots h_{kM}]^T \sim CN(\mathbf{0}, \mathbf{I}_M)$
  - Noise: $\mathbf{n} \sim CN(\mathbf{0}, \mathbf{I}_M)$
  - Received: $\mathbf{y} = \mathbf{h}_1 s_1 + \mathbf{h}_2 s_2 + \mathbf{n}$



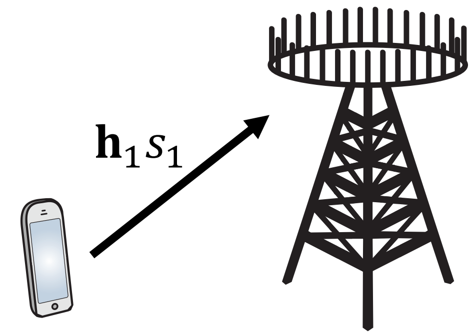
- Linear Detector $\mathbf{w}_1$ for User 1: $\tilde{y}_1 = \mathbf{w}_1^H \mathbf{y} = \boxed{\mathbf{w}_1^H \mathbf{h}_1} s_1 + \boxed{\mathbf{w}_1^H \mathbf{h}_2} s_2 + \boxed{\mathbf{w}_1^H \mathbf{n}}$
  - Maximum ratio filter: $\mathbf{w}_1 = \frac{1}{M} \mathbf{h}_1$
  - Signal remains: $\mathbf{w}_1^H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

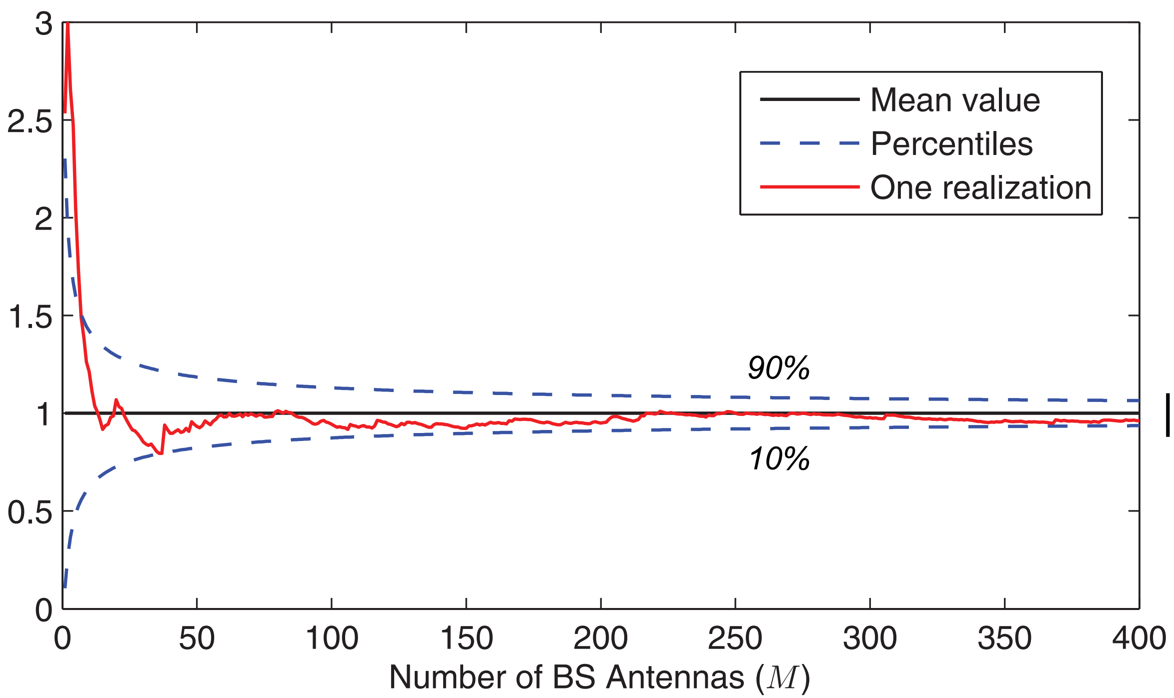
Asymptotic Channel Hardening

Variations of effective channel reduce with M:

$$\frac{1}{M}\|\mathbf{h}_1\|^2 \text{ has } \begin{cases} \text{Mean: } 1 \\ \text{Variance: } 1/M \end{cases}$$



$\mathbf{h}_1 \sim CN(\mathbf{0}, \mathbf{I}_M)$



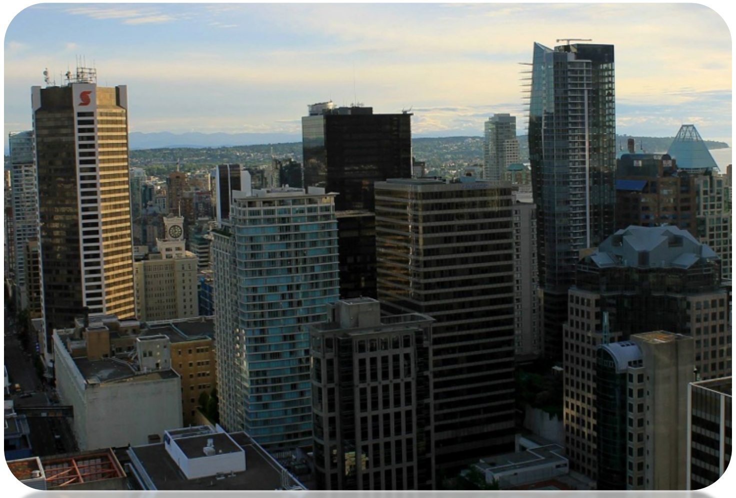
$\|\mathbf{h}_1\|^2 \approx \mathrm{E}\{\|\mathbf{h}_1\|^2\}$

Double benefits: *$\|\mathbf{h}_1\|^2$ scales with M, variations reduces*

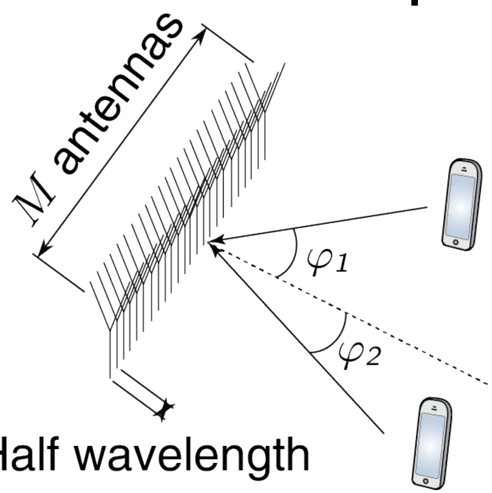
Orthogonality Only in Isotropic Fading?

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

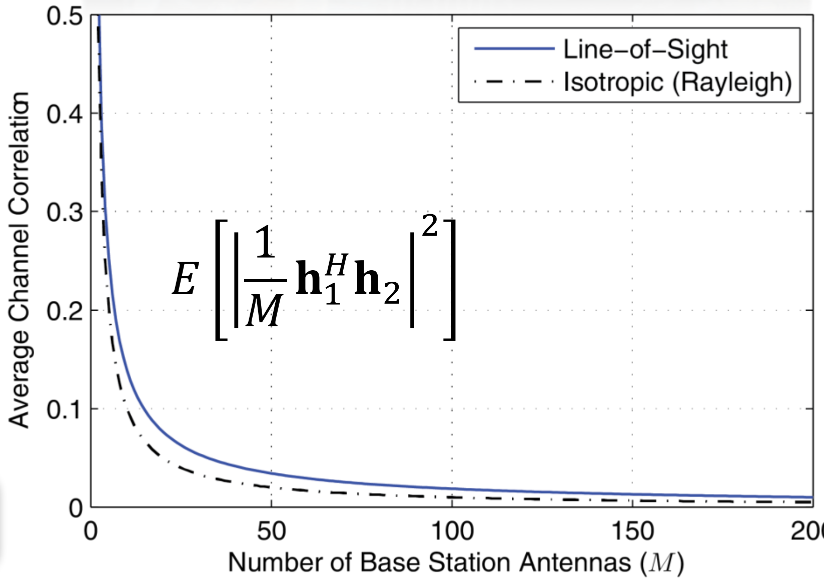
Less true as $M \to \infty$



Example: Line-of-Sight Channels



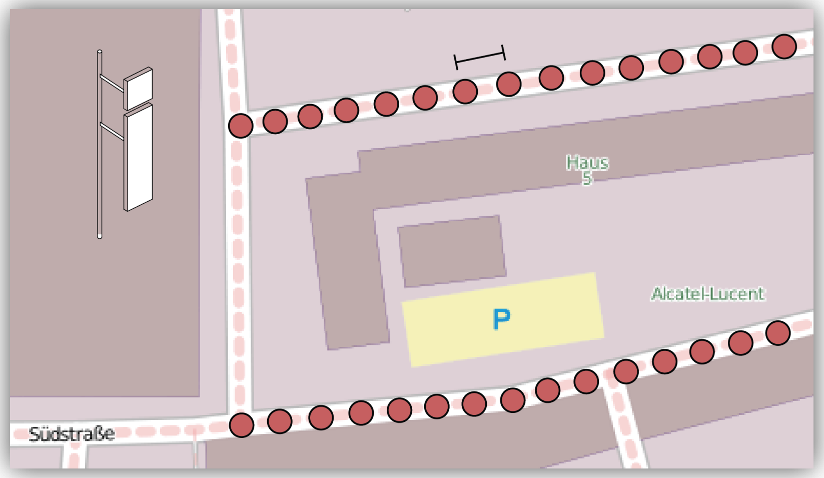
- Random user angles
- M observations:
  - Stronger signal
  - Suppressed noise
- What is $\mathbf{h}_1^H \mathbf{h}_2$?



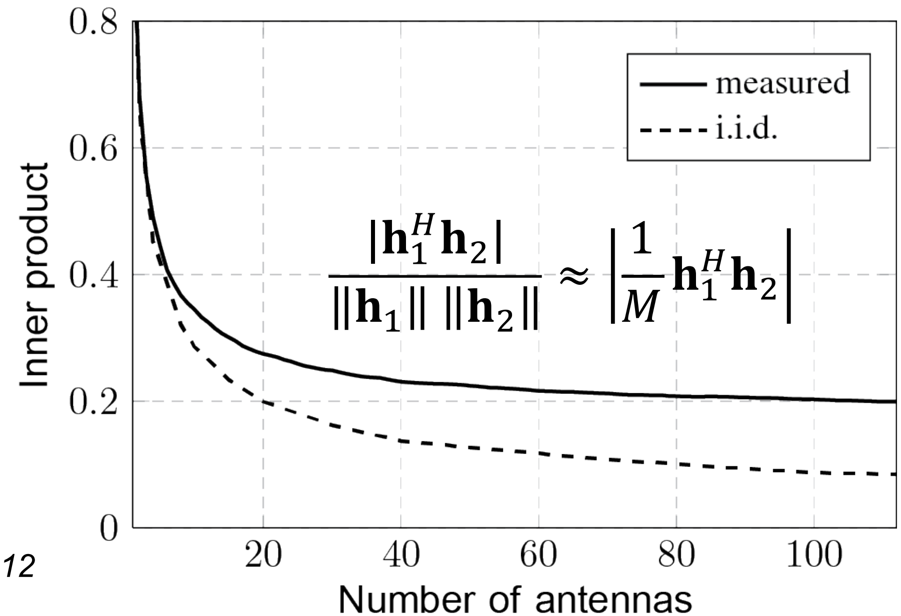
***Difference**: How quickly orthogonality appears*

How Do Practical Channels Behave?

- Measurements show similar results



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

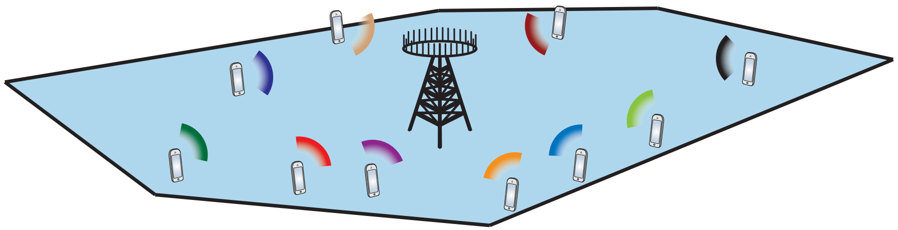


- Asymptotic Favorable Propagation: $\frac{1}{M} \mathbf{h}_1^H \mathbf{h}_2 \rightarrow 0$ as $M \rightarrow \infty$
  - Achieved in Rayleigh fading and line-of-sight – two extremes!
  - Same behavior expected and observed in practice

Massive MIMO

TRANSMISSION PROTOCOL

Classical Multi-User MIMO vs. Massive MIMO

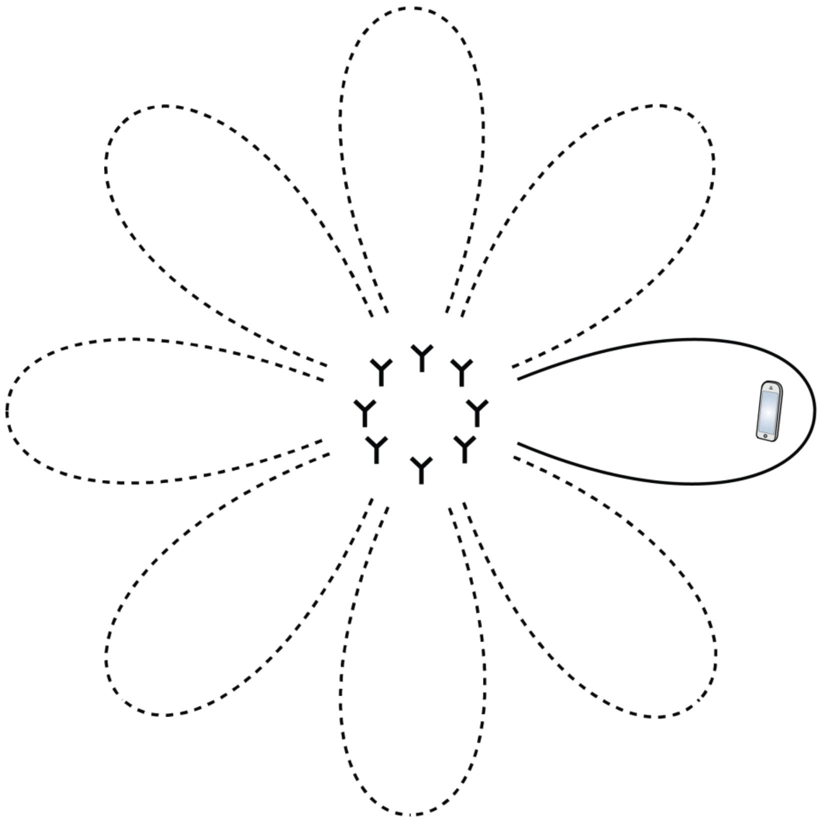


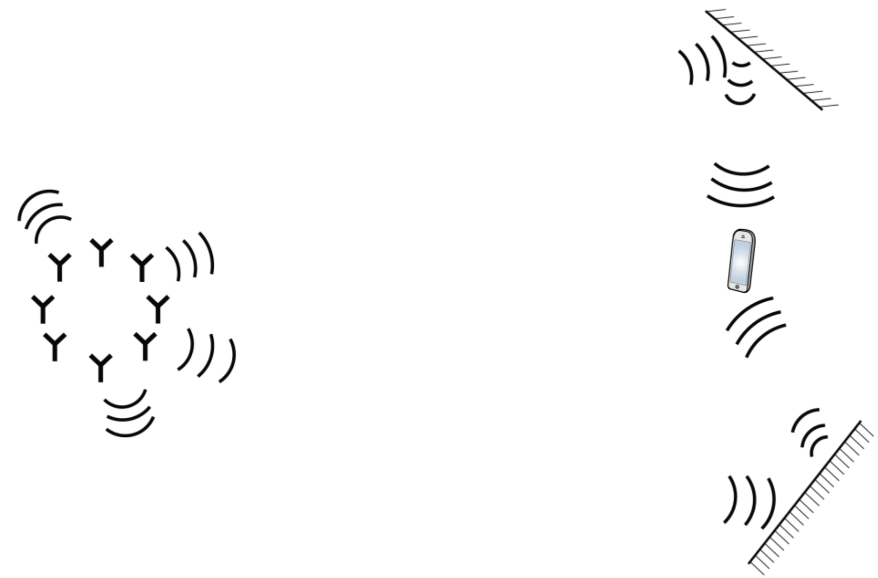
	Classic multi-user MIMO	Massive MIMO (Canonical)
Antennas M, users K	$M \approx K$	$M \gg K$
Signal processing	Non-linear is preferred	Linear is near optimal
Duplexing mode	Designed for TDD and FDD	Designed for TDD w. reciprocity
Instantaneous channel	Known at BS and user	Only needed at BS (hardening)
Channel quality	Affected by frequency-selective and fast fading	Almost no channel quality variations (hardening)
Variations in user load	Scheduling needed if $K > M$	Scheduling seldom needed
Resource allocation	Rapid due to fading	Only on a slow time scale
Cell-edge performance	Only good if BSs cooperate	Improved by array gain of M
BS cooperation	Highly beneficial if rapid	Only long-term coordination

FDD = Frequency-division duplex, *TDD = Time-division duplex*

Downlink MIMO Precoding

Same principle for MIMO detection





Line-of-Sight

Channels characterized by angles

1-2 parameters to estimate per user

Precoding = Angular beamforming

Non-Line-of-Sight

Rich multipath propagation

M parameters to estimate per user

Precoding $\neq$ Angular beamforming

Easy: Codebooks usable (phased array)

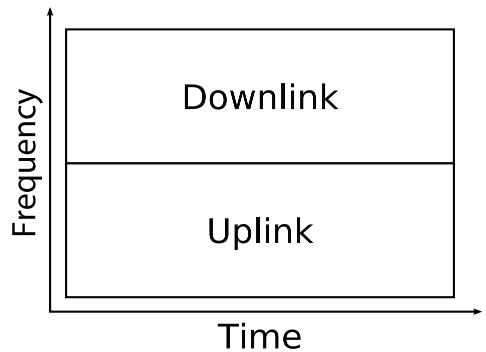
Hard: Requires pilot transmission!

How to Limit the Pilot Overhead?

Frequency-division duplex (FDD)

Downlink: M pilots + K feedback

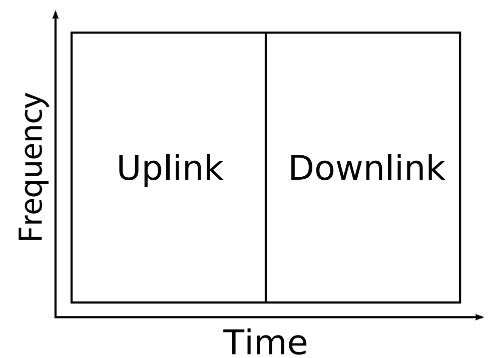
Uplink: K pilots + M feedback

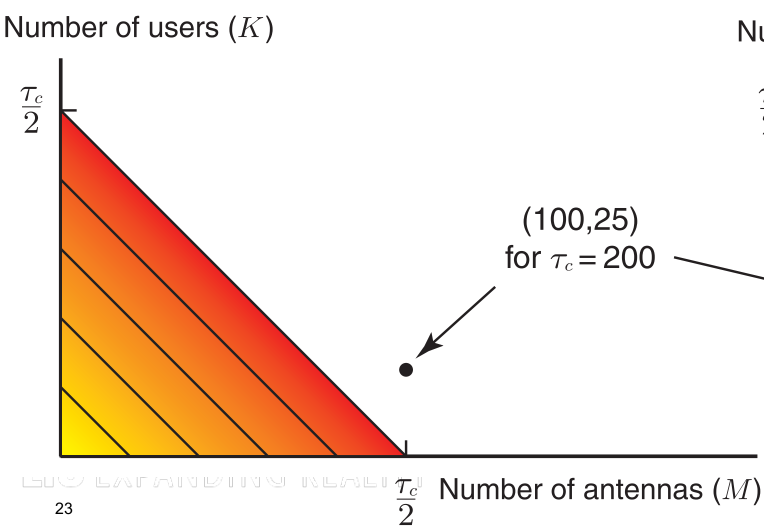


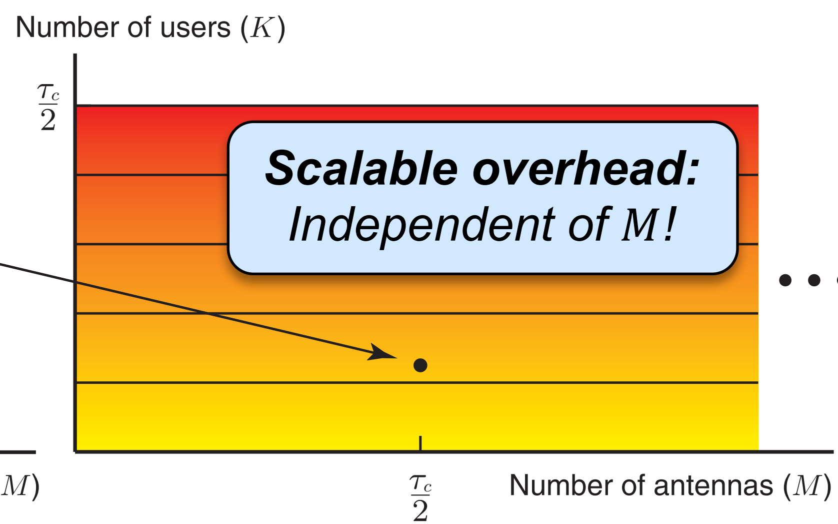
Time-division duplex (TDD)

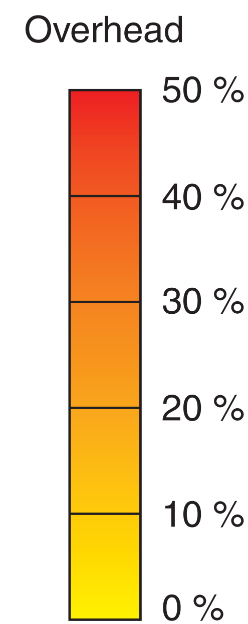
Uplink: K pilots, exploit channel reciprocity

Downlink: K precoded pilots (optional)



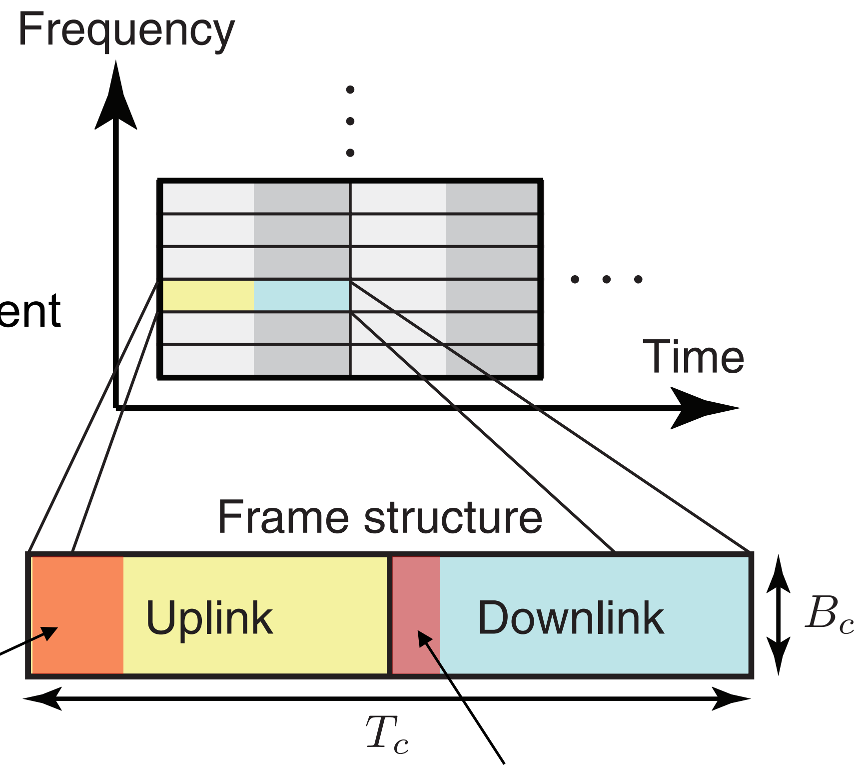






Massive MIMO TDD Protocol

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

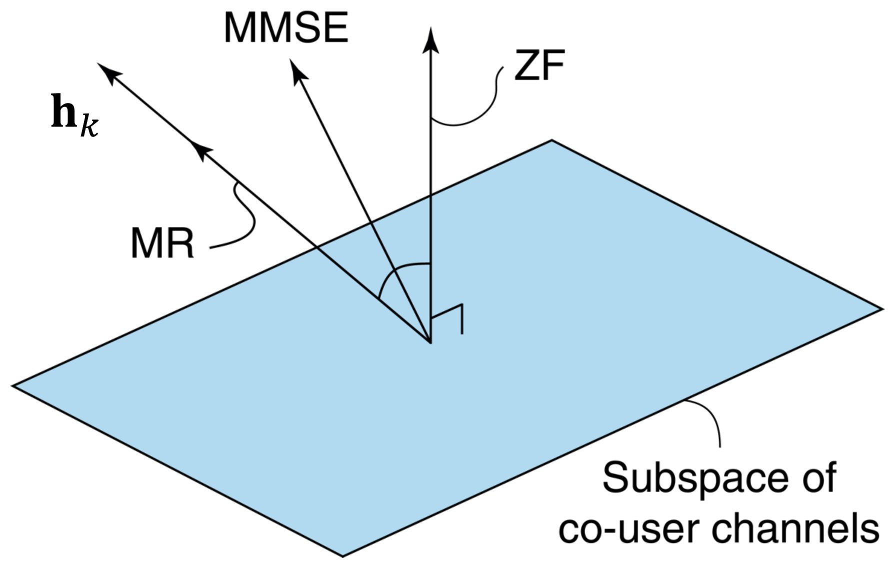


***Uplink pilots**:*
τ_p symbols/block
($\tau_p \geq K$)

Optional:
downlink pilots
(recall hardening)

Uplink and/or downlink payload data
$\tau_c - \tau_p$ symbols/block

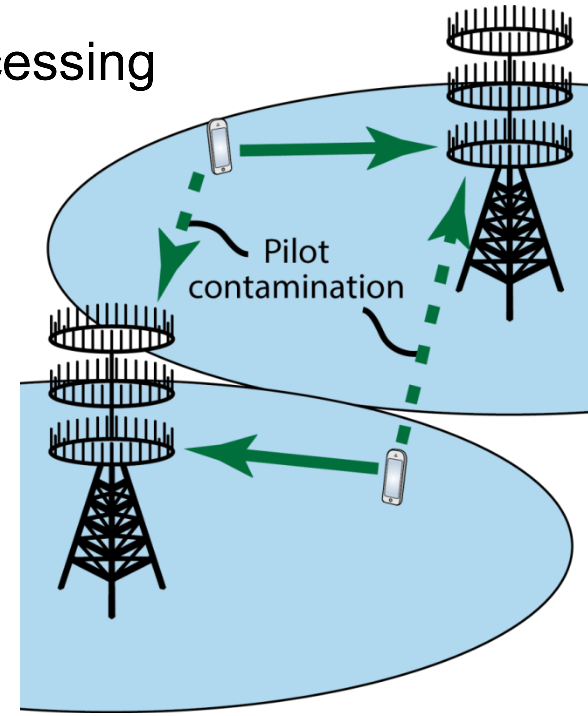
Linear Processing Schemes



- Three Options for Downlink Precoding and Uplink Detection
  - Maximum ratio (MR): Maximize received signal power
  - Zero-forcing (ZF): Minimize interference
  - Maximum mean-squared error (MMSE): Balance to signal/interference to minimize uplink MSE

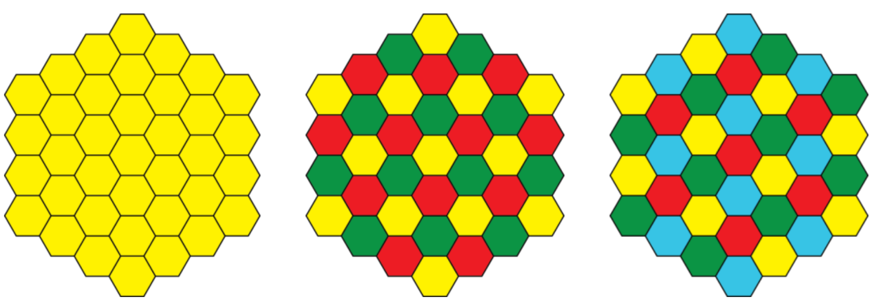
Channel Acquisition in Massive MIMO

- BS Needs Channel Responses for Linear Processing
  - Estimate using $\tau_p \leq \tau_c$ pilot symbols
  - Must reuse pilot sequences in different cells



- Called: Pilot Contamination
  - BSs cannot tell some users apart
  - Recall: Noise and interference vanish as $M \rightarrow \infty$
  - Not interference between users with same pilot!

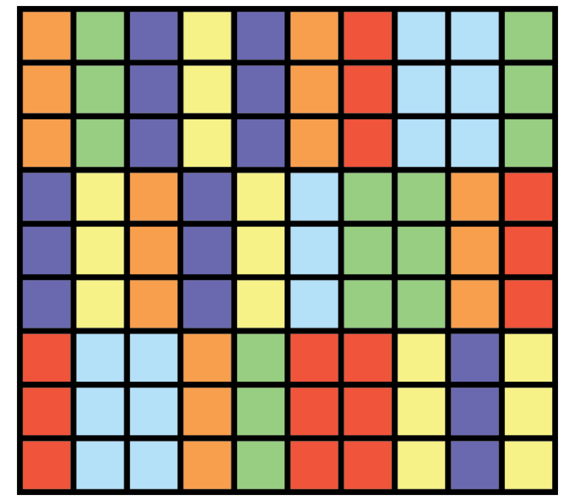
- Scalable Solution: Select how often pilots are reused
  - Pilot reuse factor $f \geq 1$
  - Users per cell: $K \leq \tau_p / f$
  - Higher f $\rightarrow$ Fewer users per cell, but interferers further away



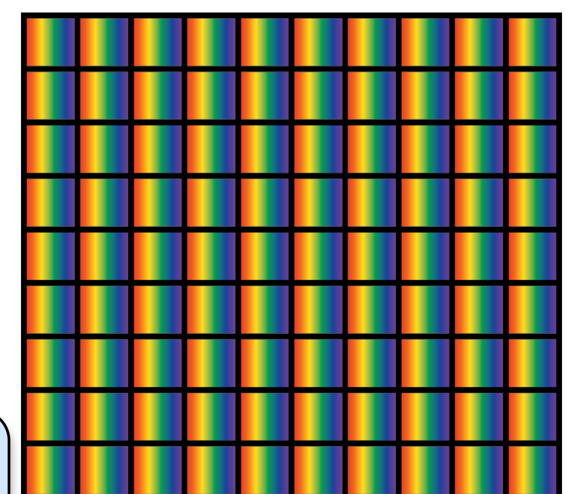
***Pilot reuse** $f = 1$* ***Pilot reuse** $f = 3$* ***Pilot reuse** $f = 4$*

Simple Resource Allocation

- Resource Allocation in 4G
  - Give each time/frequency block to one user
  - Utilize current fading realization
  - *Not needed in Massive MIMO*



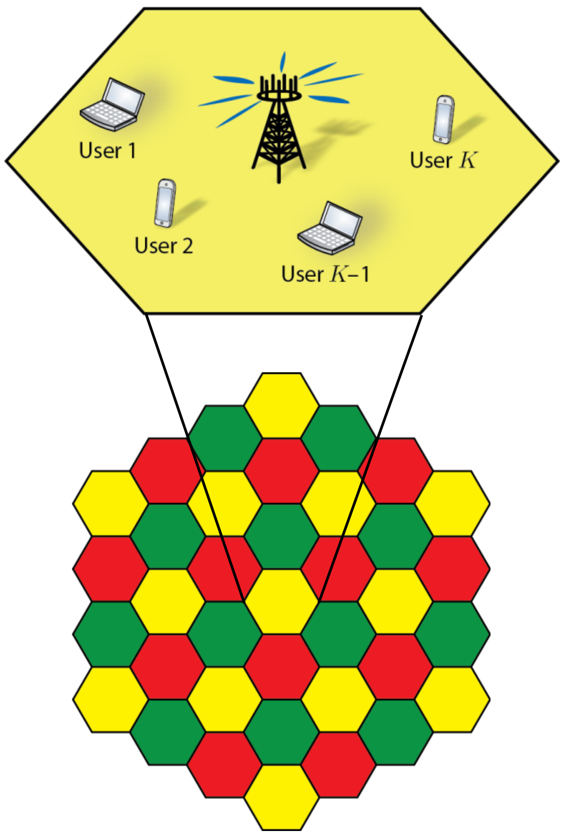
- Spatial Resource Allocation
  - Each user get the whole bandwidth, whenever needed!
  - Separate users spatially
  - Same channel quality in all blocks



Scalable resource allocation:

Only power control based on long-term channel quality

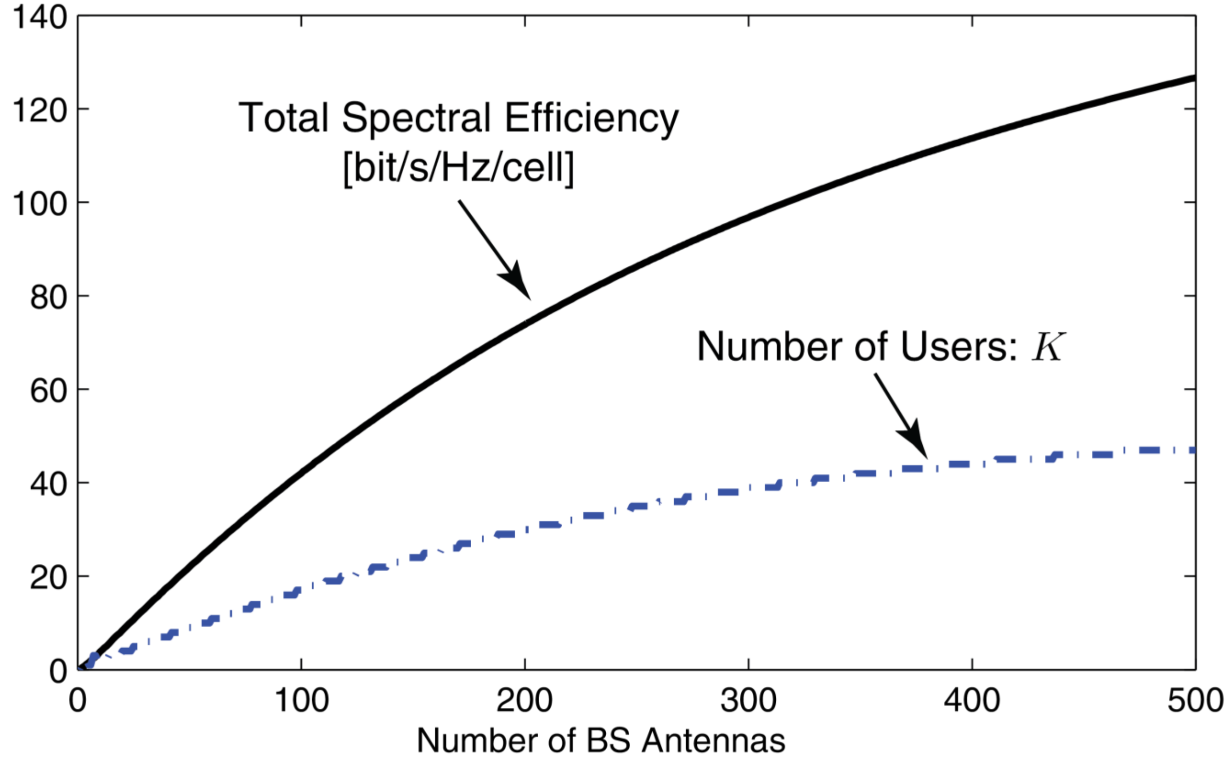
How Many Antennas Are Needed?



Uplink simulation

SNR 5 dB, Rayleigh fading,

ZF detection, $\tau_c = 500$, *pilot reuse* $f = 3$

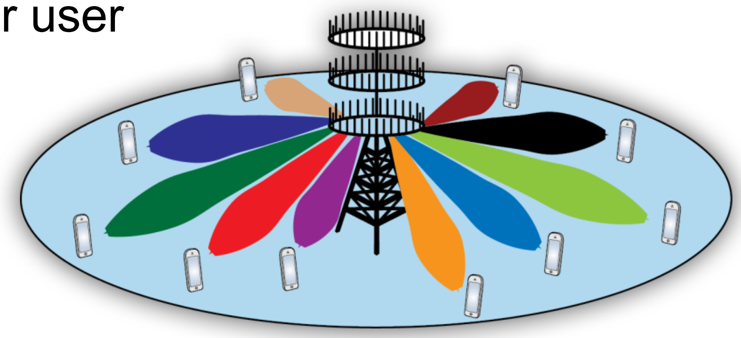


Massive MIMO is an incredibly scalable technology!

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
  - Many potential deployment strategies



- Facts to Remember
  - Massive MIMO ≠ Massive size: TV sized panels at cellular frequencies
  - Favorable propagation in most propagation environments
  - Resource allocation and processing are simplified, not complicated
- Further Reading
  - Emil Björnson, Erik G. Larsson, Thomas L. Marzetta, "*Massive MIMO: 10 Myths and One Critcal Question*," IEEE Commun. Magazine, Feb. 2016.

Thank you!

Emil Björnson

Slides and papers available online:

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

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