Massive MIMO for 5G

Recent Theory

Dr. Emil Björnson

Department of Electrical Engineering (ISY)
Linköping University, Linköping, Sweden

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Expectations for 5G Networks

- 5G – Next Network Generation
  - To be introduced around 2020
  - Design objectives are currently being defined

5G Performance Metrics	Expectation
Average rate (bit/s/active user)	10-100x
Average area rate (bit/s/km^2)	1000x
Active devices (per km^2)	10-100x
Energy efficiency (bit/Joule)	1000x
"Best experience follows you"	

Source: METIS project (www.metis2020.com)

What is the role of Massive MIMO here?

Outline, Part 2: Recent Theory

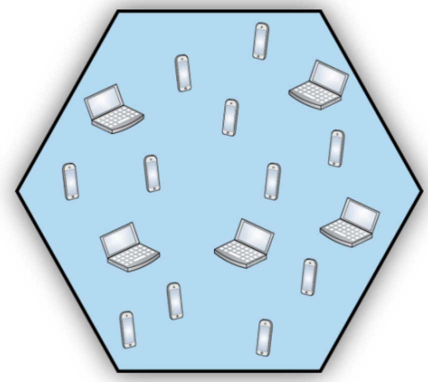
- Spectral Efficiency
  - Designing Massive MIMO for high spectral efficiency
  - What are the fundamental limits?
- Energy Efficiency
  - How is it defined?
  - Is Massive MIMO energy efficient?
- Hardware Efficiency
  - Does Massive MIMO require high-grade hardware?
  - Can it make more efficient use of hardware (lower cost, size, and power)?
- Open Problems

Massive MIMO and

SPECTRAL EFFICIENCY

Evolving Networks for Higher Traffic

- Increase Network Throughput [bit/s/km²]
  - Consider a given area →



- Simple Formula for Network Throughput:

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

- 5G goal: 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, mmWave bands

Smaller cells, heterogeneous deployments

Massive MIMO

How many ??x can we expect?

Optimization of Spectral Efficiency

- How Large Spectral Efficiency can be Achieved?
  - Problem Formulation:

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

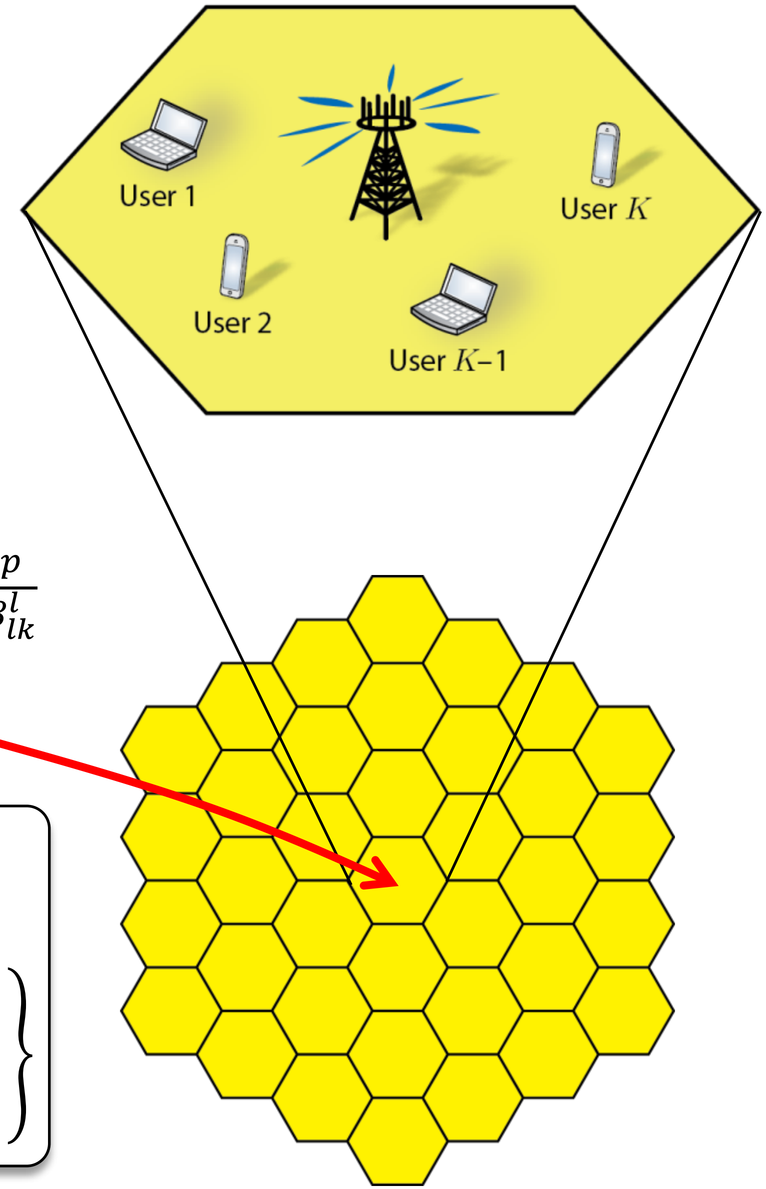
for a given M *and* τ_c.

- Issue: Hard to find tractable expressions
  - Interference depends on all users' positions!
  - Expressions from before: Fixed and explicit pathloss values (β)
  - We want quantitative results – averaged over user locations

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

Symmetric Multi-Cell Network

- Classic Multi-Cell Network
  - Infinite grid of hexagonal cells
  - M antennas at each BS
  - K active users in each cell
  - Same user distribution in each cell
  - Uncorrelated Rayleigh fading
  - Statistical channel inversion: $\rho_u \eta_{lk} = \frac{p}{\beta_{lk}^{l}}$



Every cell is "typical"

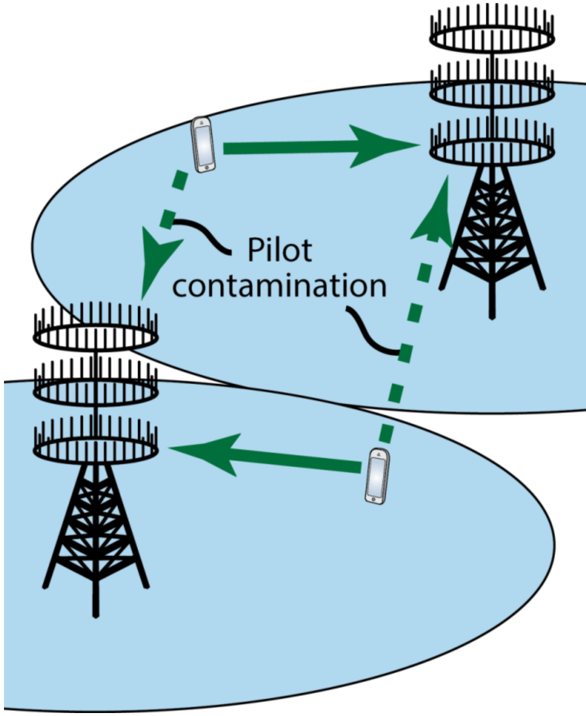
Propagation Parameters

(Average interference from cell l to BS j)

Compute $\mu_{jl}^{(1)} = \mathbb{E}\left\{\frac{\beta_{lk}^{j}}{\beta_{lk}^{l}}\right\}$ *and* $\mu_{jl}^{(2)} = \mathbb{E}\left\{\left(\frac{\beta_{lk}^{j}}{\beta_{lk}^{l}}\right)^2\right\}$

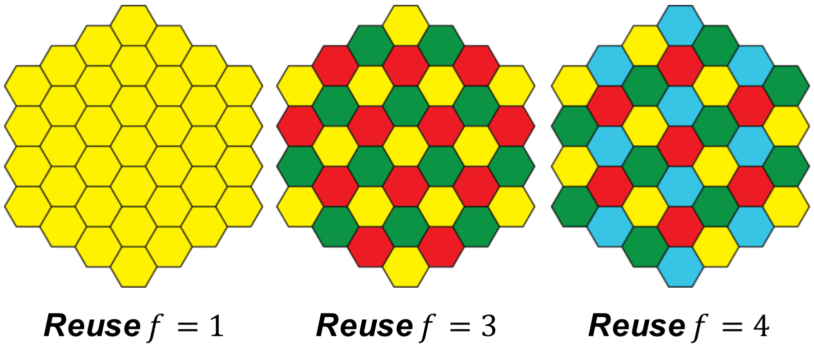
Coordinated Pilot Allocation

- Limited Number of Pilots: $\tau_p \leq \tau_c$
  - Must use same pilot sequence in several cells
  - Base stations cannot tell some users apart: *Essence of pilot contamination*



- Coordinated Pilot Allocation
  - Allocate pilots to users to reduce contamination
  - Scalability $\rightarrow$ No signaling between BSs

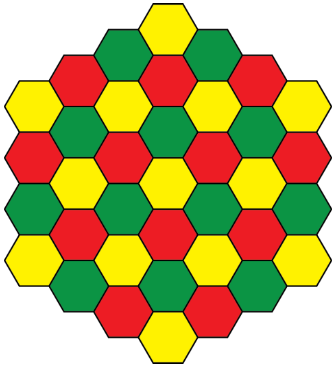
- Solution: Non-universal pilot reuse
  - Pilot reuse factor $f \geq 1$
  - Users per cell: $K = \frac{\tau_p}{f}$
  - $\mathcal{P}_j$ = Cells with same pilots as BS j
  - Higher $f \rightarrow$ Fewer users per cell, but fewer interferers in $\mathcal{P}_j$



Coordinated Precoding and Detection

- Coordinated Multi-Point (CoMP)
  - Avoid causing strong inter-cell interference
  - Scalability → No signaling between BSs
- Solution: Observe and react ($f \geq 1$)
  - Listen to pilot signals used only in other cells
  - Utilize to suppress inter-cell interference
  - Schemes: Multi-cell ZF and multi-cell MMSE

Reuse $f = 3$

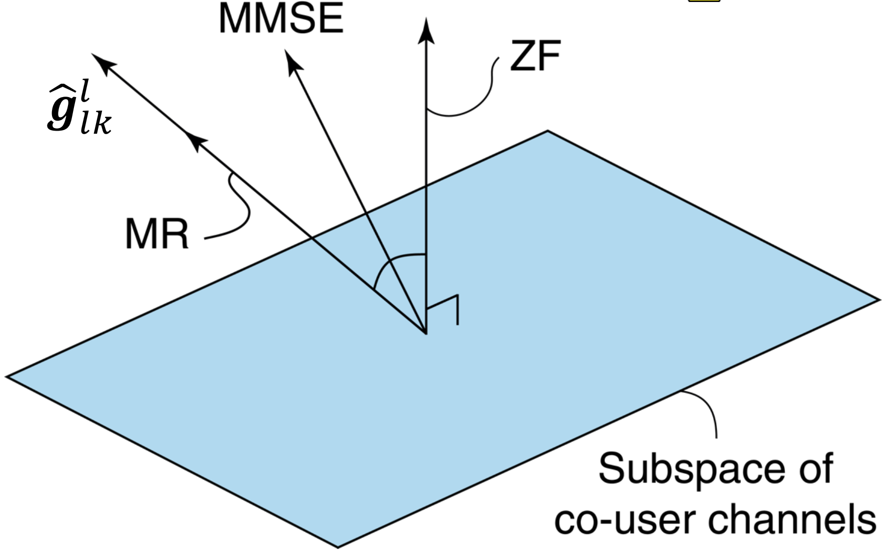


MMSE precoding/detection:

$$\boldsymbol{v}_{lk} = \left(\sum_{j,m} \rho_u \eta_{jm} \widehat{\boldsymbol{g}}^{l}_{jm} (\widehat{\boldsymbol{g}}^{l}_{jm})^H + \boldsymbol{E}_l + \boldsymbol{I} \right)^{-1} \widehat{\boldsymbol{g}}^{l}_{lk}$$

All estimated channels

Estimation error covariance matrix



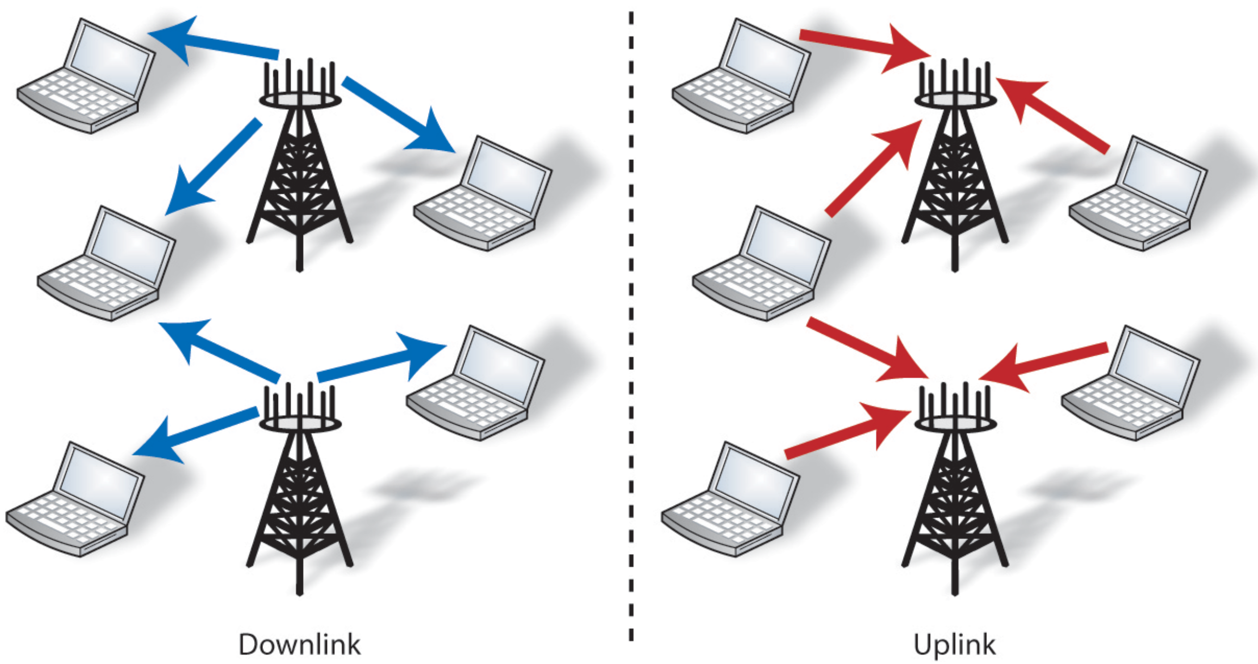
Uplink-Downlink Duality

Duality Theorem

The uplink SEs are achievable in the downlink using same sum transmit power

Same precoding/detection vectors, but different power allocation

Note: Equivalence between two lower bounds – uplink bound is looser!



Average Spectral Efficiency per Cell

- Lower Bound on Average Ergodic Capacity in Cell j:

$$\mathrm{SE}_j = K \underbrace{\left(1 - \frac{\tau_p}{\tau_c}\right)}_{\text{Loss from pilots}} \log_2\left(1 + \underbrace{\frac{1}{I_j}}_{\text{SINR}}\right)$$

- Interference term depends on processing:

$$I_j^{\mathrm{MR}} = \underbrace{\sum_{l \in \mathcal{P}_j(f)\setminus\{j\}} \left(\mu_{jl}^{(2)} + \frac{\mu_{jl}^{(2)} - (\mu_{jl}^{(1)})^2}{M}\right)}_{\text{Pilot contamination}} + \underbrace{\left(\frac{\sum_{l\in\mathcal{L}} \mu_{jl}^{(1)} K + \frac{1}{\rho}}{M}\right)}_{\text{Interference from all cells}} \underbrace{\left(\sum_{l\in\mathcal{P}_j(f)} \mu_{jl}^{(1)} + \frac{1}{\rho\tau_p}\right)}_{\text{1/(Estimation quality)}}$$

$$I_j^{\mathrm{ZF}} = \overbrace{\sum_{l \in \mathcal{P}_j(f)\setminus\{j\}} \left(\mu_{jl}^{(2)} + \frac{\mu_{jl}^{(2)} - (\mu_{jl}^{(1)})^2}{M-K}\right)} + \overbrace{\left(\frac{\sum_{l\in\mathcal{L}} \mu_{jl}^{(1)} K + \frac{1}{\rho}}{M-K}\right)} \overbrace{\left(\sum_{l\in\mathcal{P}_j(f)} \mu_{jl}^{(1)} + \frac{1}{\rho\tau_p}\right)} - \overbrace{\sum_{l\in\mathcal{P}_j(f)} \frac{\left(\mu_{jl}^{(1)}\right)^2 K}{M-K}}^{\text{Interference suppression}}$$

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

Asymptotic Limit on Spectral Efficiency

- Lower Bound on Average Ergodic Capacity as $M \to \infty$:

$$\mathrm{SE}_j \to K\left(1 - \frac{fK}{\tau_c}\right)\log_2\left(1 + \frac{1}{\sum_{l \in \mathcal{P}_j(f)\setminus\{j\}} \mu_{jl}^{(2)}}\right)$$

How Many Users to Serve?

Pre-log factor $K\left(1 - \frac{fK}{\tau_c}\right)$ *is maximized by* $K^* = \frac{\tau_c}{2f}$ *users*

Maximal SE: $\frac{\tau_c}{4f}\log_2\left(1 + \frac{1}{\sum_{l \in \mathcal{P}_j(f)\setminus\{j\}} \mu_{jl}^{(2)}}\right)$

Try different f *and* $\mathcal{P}_j(f)$ *to maximize the limit*

How Long Pilot Sequences?

$\tau_p = fK^* = \frac{\tau_c}{2}$ *: Spend half coherence interval on pilots!*

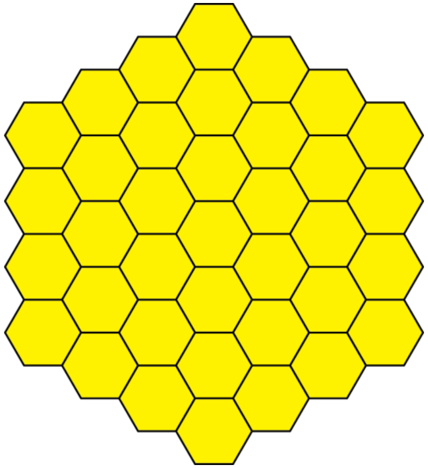
Numerical Results

- Problem Formulation:

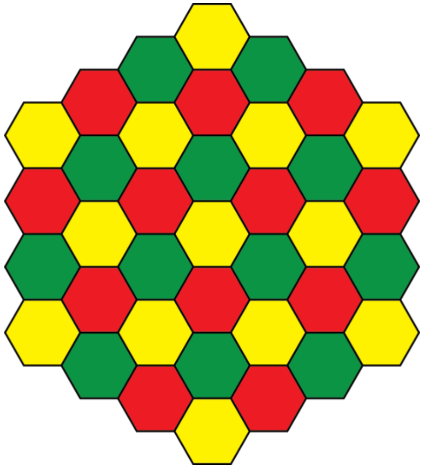
$$\underset{K,\,\tau_p}{\text{maximize}} \quad \text{total spectral efficiency} \qquad [\text{bit/s/Hz/cell}]$$

for a given M *and* τ_c.

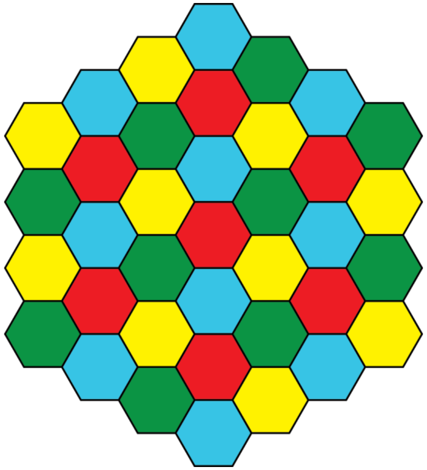
  - Use average spectral efficiency expressions
  - Compute average interference $\mu_{jl}^{(1)}$ and $\mu_{jl}^{(2)}$ (a few minutes)
  - Compute for different K and f and pick maximum (<1 minute)



Reuse $\boldsymbol{f=1}$



Reuse $\boldsymbol{f=3}$



Reuse $\boldsymbol{f=4}$

Assumptions

Pathloss exponent: 3.7

Coherence: $\tau_c = 400$

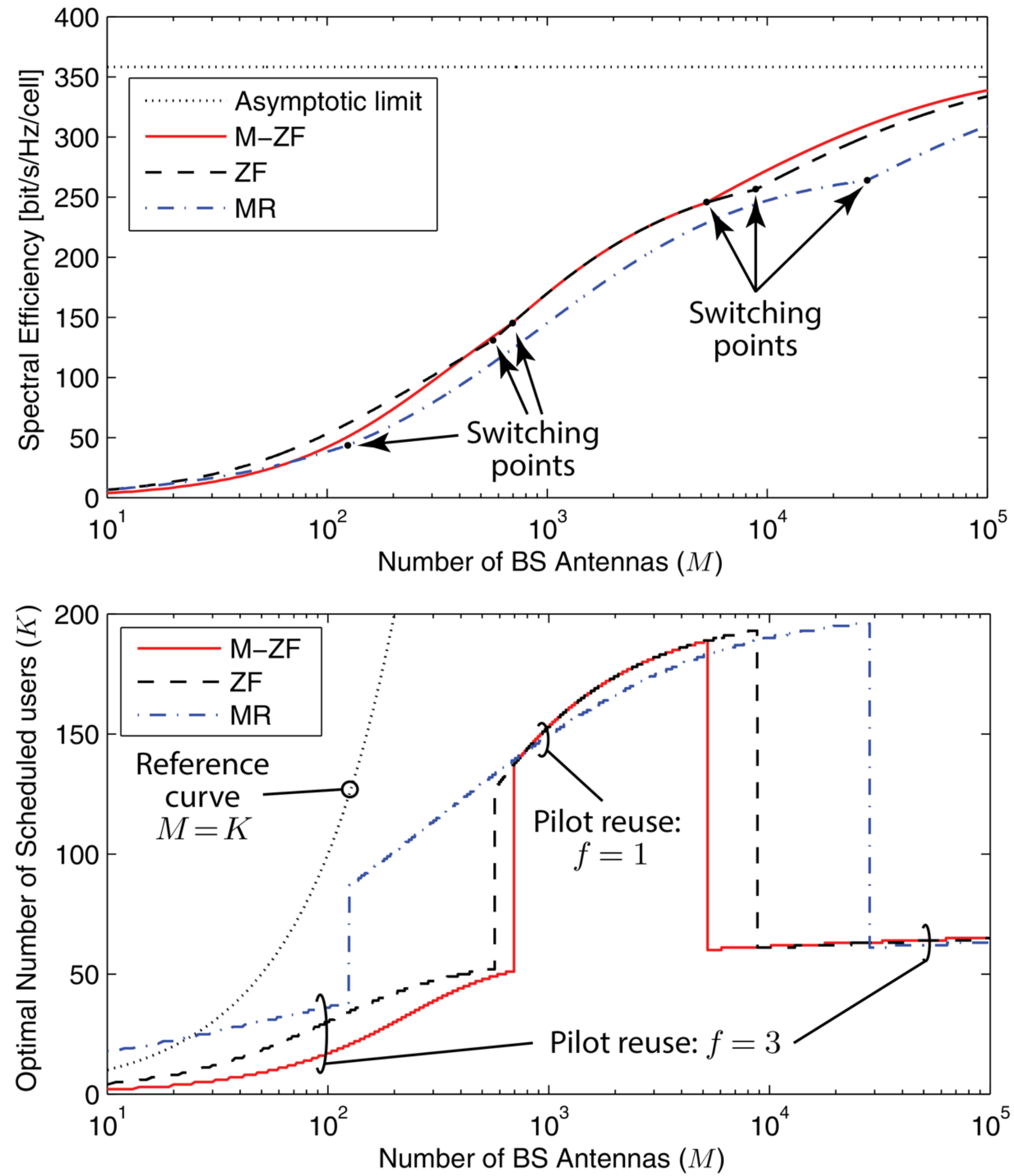
Rayleigh fading

SNR 5 dB

Asymptotic Behavior: Mean-Case Interference

Observations

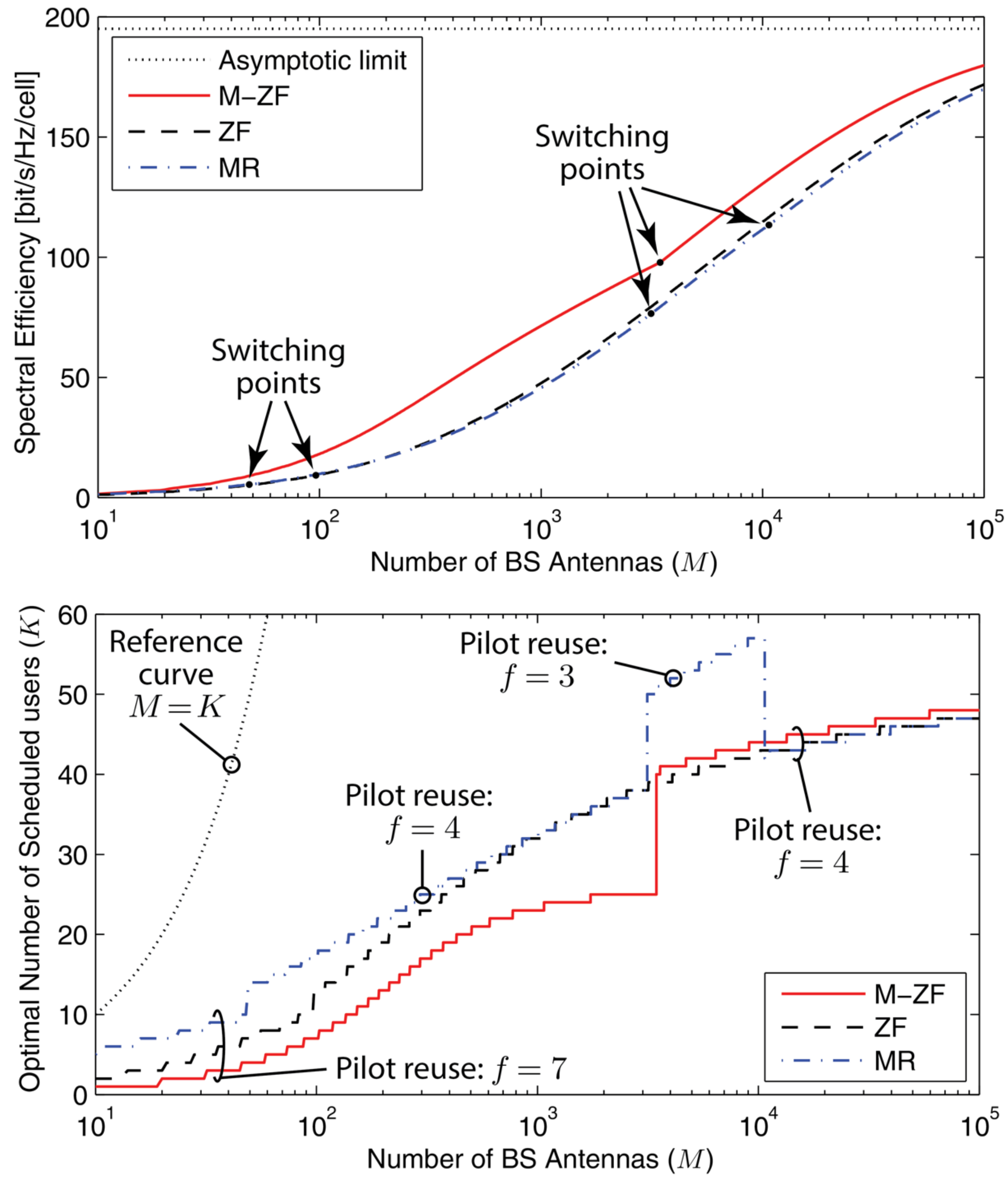
- *Uniform user distributions*
- *Asymptotic limits not reached*
- *Reuse factor $f = 3$ is desired*
- *K is different for each scheme*
- *Small difference between optimized schemes*
- *Coordinated beamforming: Better at very large M*



Asymptotic Behavior: Worst-Case Interference

Observations

- *Interferers at worst positions*
- *Asymptotic limits not reached*
- *Reuse factor $f = 4$ is desired*
- *K is different for each scheme*
- *Coordinated beamforming: Brings large gains for all M*



Flexible Number of Users

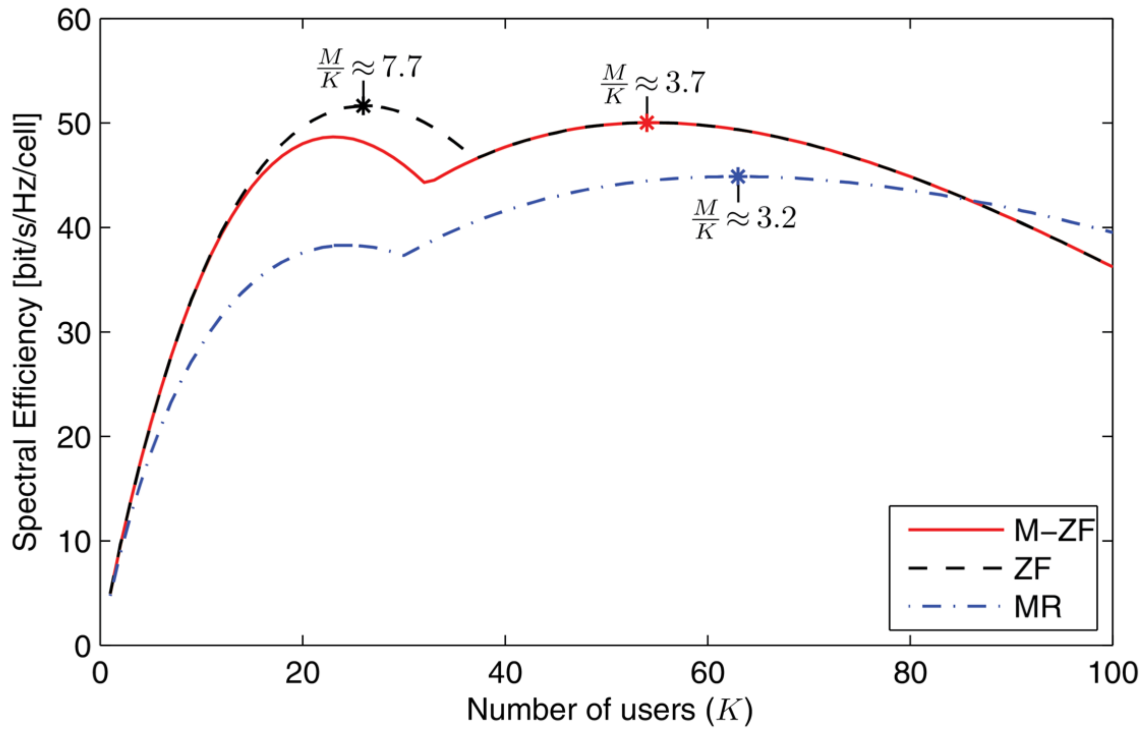
- SE w.r.t. number of users ($M = 200$ antennas)
  - Mean-case interference
  - Optimized reuse factors
  - Equal SNR (5 dB)

Observations

Stable SE for $K > 10$:
Trivial scheduling:
Admit everyone

M-ZF, ZF, and MR provide similar per-cell performance

$M/K < 10$ is fine!



Spectral Efficiency per User

- User Performance for Optimized System
  - Mean-case interference
  - Optimized reuse factors
  - Equal SNR (5 dB)

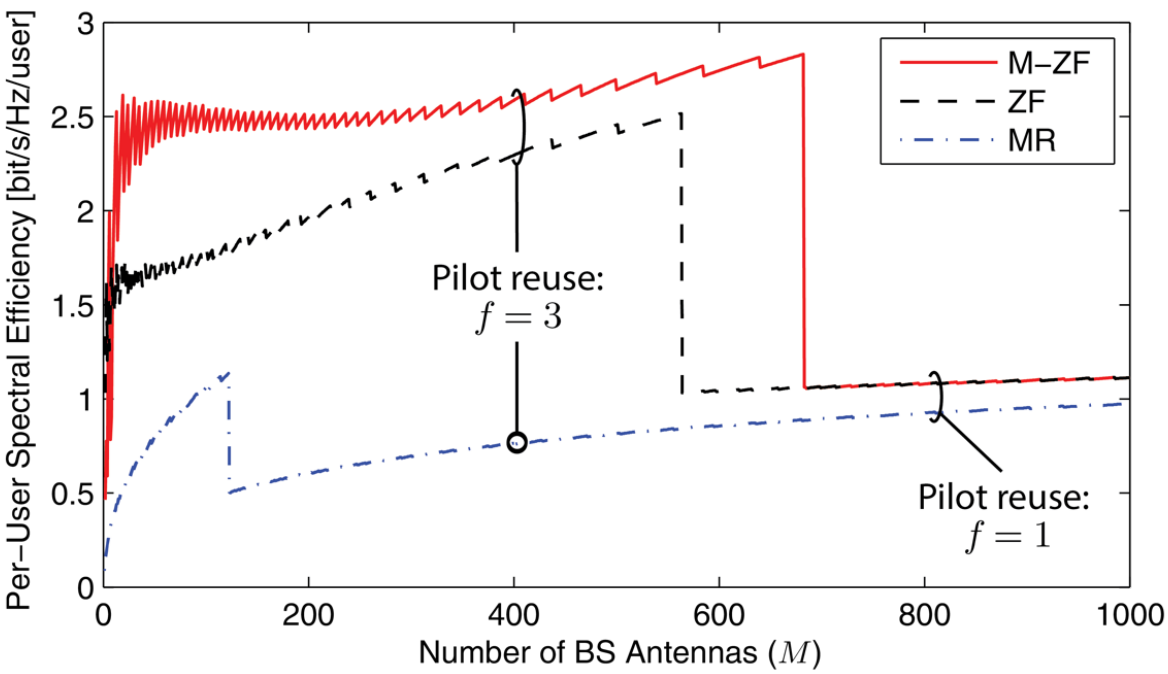
Observations

User performance is modest:

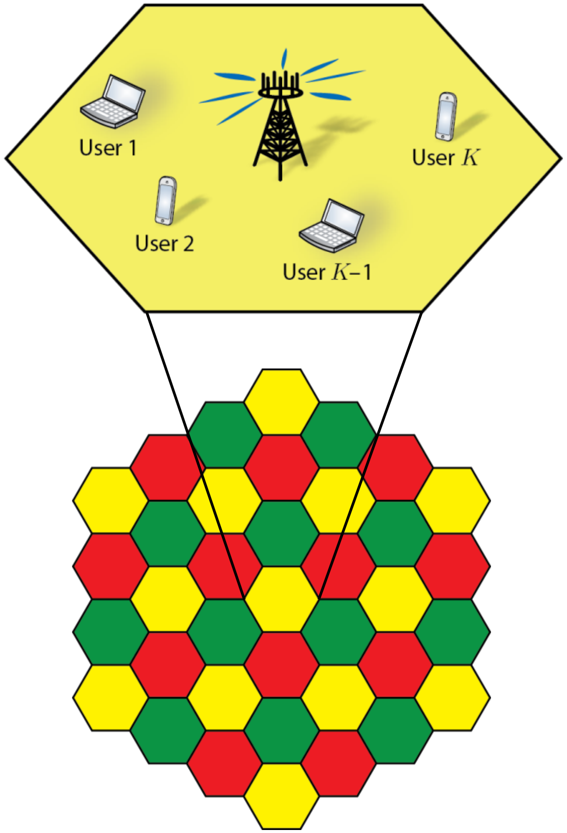
BPSK, Q-PSK, or 16-QAM

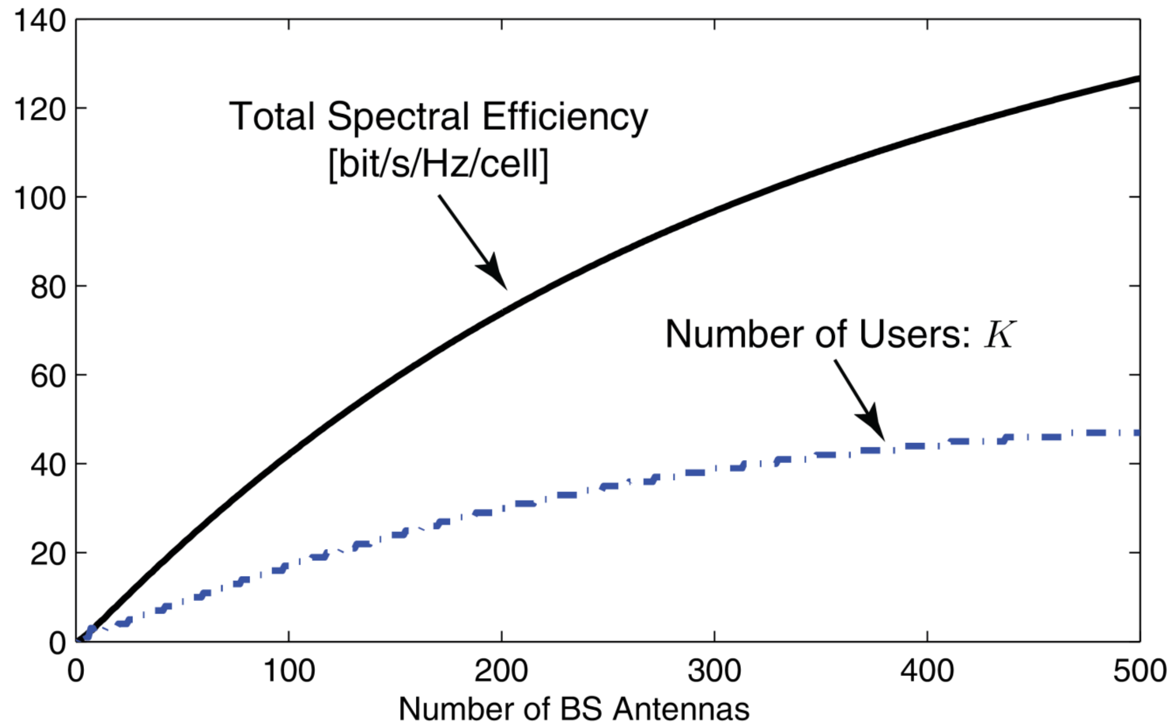
Schemes for different purposes:

M-ZF > ZF > MR



Anticipated Uplink Spectral Efficiency





Assumptions

ZF processing

Pilot reuse: $f = 3$

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*

Control Signaling

- Coherent Precoding and Detection Require CSI
  - How to initiate the transmission without array gain?

- User Initiates Transmission
  - Easy: Find an unused pilot and send a transmission request
  - Reserve some pilot sequences for such random access

- BS Initiates Transmission
  - Harder: Must contact the user without having CSI
  - Low-rate space-time coded transmission is feasible

Summary

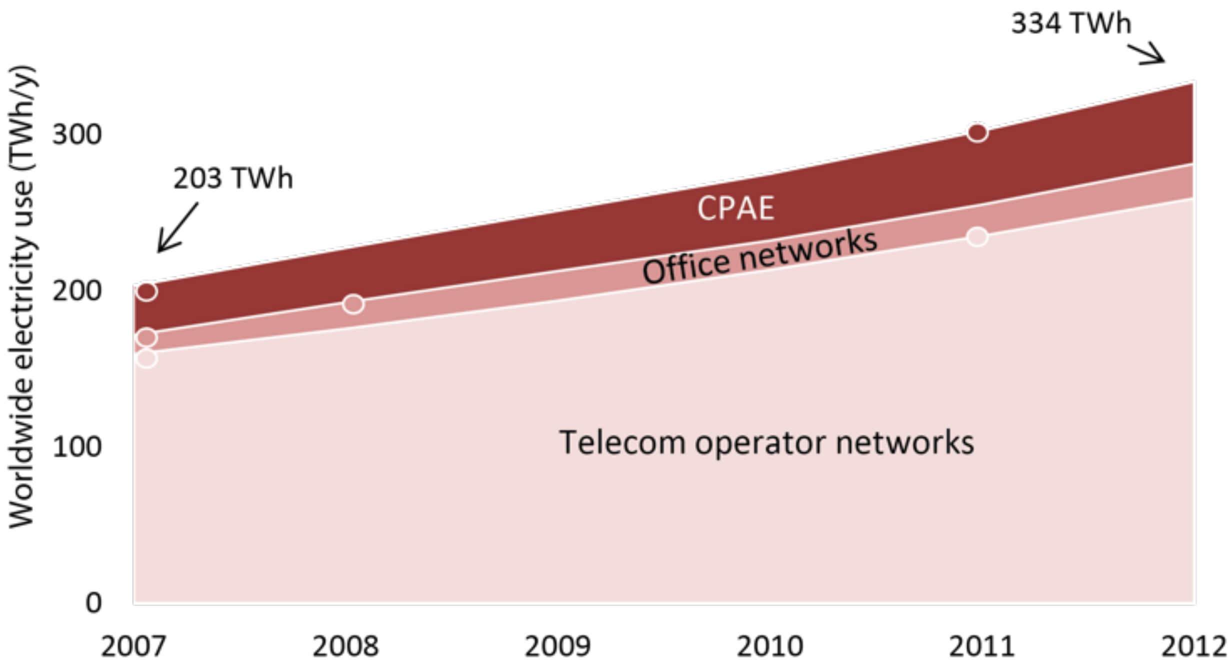
- Massive MIMO delivers High Spectral Efficiency
  - > 20x gain over IMT-Advanced is foreseen
  - Very high spectral efficiency per cell, not per user
  - Non-universal pilot reuse ($f = 3$) is often preferred
  - MR, ZF, M-ZF prefer different values on K and f
  - "An order of magnitude more antennas than users" is not needed

- Asymptotic limits
  - Coherence interval (τ_c symbols) limits multiplexing capability
  - Allocate up to $\tau_c/2$ symbols for pilots
  - We can handle very many users/cell – how many will there be?

Massive MIMO and

ENERGY EFFICIENCY

Energy Consumption



Source: Heddeghem et al. "Trends in worldwide ICT electricity consumption from 2007 to 2012"

- Network Electricity Consumption
  - Dominated by network infrastructure – increases continuously
  - 1000x higher data rates: Easy to achieve using 1000x more power
Hard to achieve without using more power
  - Calls for **much higher energy efficiency**!

What is Energy Efficiency?

- Benefit-Cost Analysis of Networks
  - Systematic approach to analyze strengths and weaknesses of networks

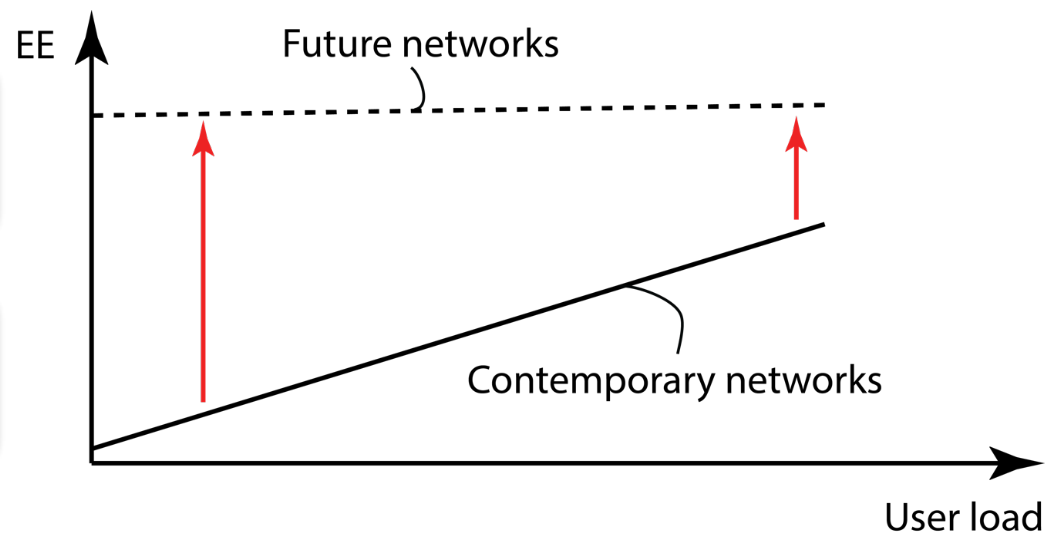
Cost: *Power Consumption [Watt = Joule/s]* → ***Network*** → ***Benefit:*** *Sum Data Rate [bit/s]*

- Definition: Energy Efficiency (EE):

$$\text{EE [bit/Joule]} = \frac{\text{Average Sum Rate [bit/s/cell]}}{\text{Power Consumption [Joule/s/cell]}}$$

Contemporary networks:
Very inefficient at low load

Future networks:
Must be more efficient at any load



Transmit Power Scaling Law

Power Scaling Law

If the transmit power ρ decreases as $1/M^{\alpha}$ for $\alpha \leq 1/2$:

SE will not go zero as $M \to \infty$

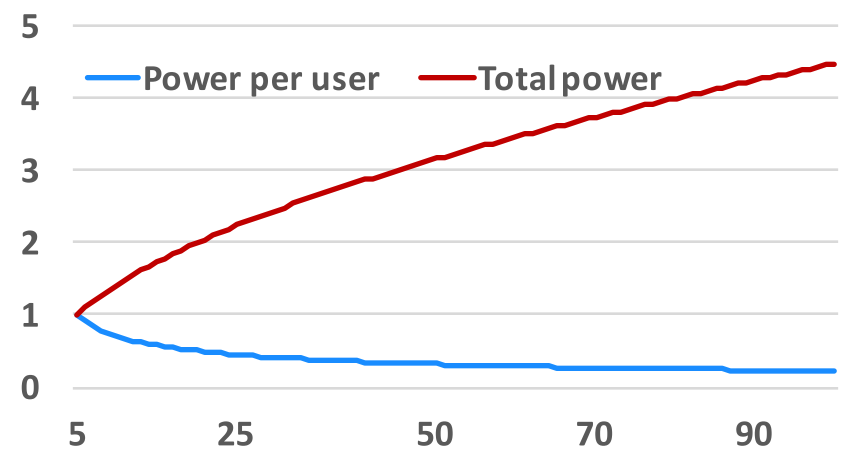
Example: Set $p = p_0/M^{\alpha}$ in $\mathrm{SE}_j = K\left(1 - \frac{\tau_p}{\tau_c}\right)\log_2\left(1 + \frac{1}{I_j}\right)$:

$$I_j^{\mathrm{MR}} = \sum_{l \in \mathcal{P}_j(f)\setminus\{j\}} \left(\mu_{jl}^{(2)} + \frac{\mu_{jl}^{(2)} - (\mu_{jl}^{(1)})^2}{M}\right) + \left(\frac{\sum_{l\in\mathcal{L}} \mu_{jl}^{(1)} K + \frac{M^{\alpha}}{p_0}}{M}\right)\left(\sum_{l\in\mathcal{P}_j(f)} \mu_{jl}^{(1)} + \frac{M^{\alpha}}{p_0 \tau_p}\right) = \sum_{l\in\mathcal{P}_j(f)\setminus\{j\}} \mu_{jl}^{(2)} + \mathcal{O}\left(\frac{M^{2\alpha}}{M}\right)$$

***Observations** ($\alpha = 1/2$)*

Power per antenna/user: Decreases as $\frac{1}{\sqrt{M}}$

Total power: $\frac{K}{\sqrt{M}}$ increases as $\sqrt{M}$ for fixed $\frac{M}{K}$



Radiated Energy Efficiency

- Energy Efficiency with Power Scaling:

$$\text{EE} = \frac{\text{Average Sum Rate [bit/s/cell]}}{\text{Power Consumption [Joule/s/cell]}} = \frac{B \cdot K \left(1 - \frac{\tau_p}{\tau_c}\right) \log_2\left(1 + \frac{1}{I_j}\right)}{\frac{K p_0}{M^{\alpha}} \mathbb{E}\left\{\frac{1}{\beta_{lk}^{l}}\right\}}$$

  - Bandwidth: B Hz

  - Consequence of scaling law as $M \to \infty$:
    1. Sum rate $\to$ constant > 0
    2. Transmit power $\to 0$

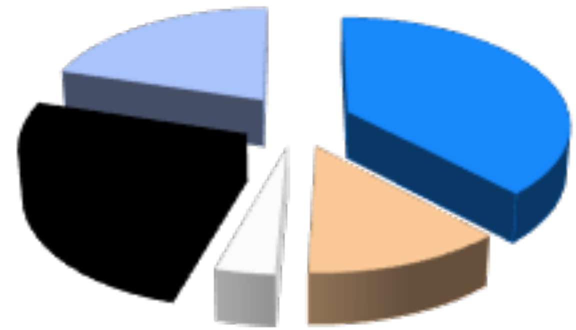
    } $\text{EE} \to \infty$

Is Massive MIMO Incredibly Energy Efficient?

Yes, in terms of bringing down the radiated transmit power

But not all consumed power is radiated!

Generic Power Consumption Model



- Many Components Consume Power
  - Radiated transmit power
  - Baseband signal processing (e.g., precoding)
  - Active circuits (e.g., converters, mixers, filters)

- Average Power Consumption Model:

$$\text{APC} = \frac{Kp}{\eta}\mathbb{E}\left\{\frac{1}{\beta_{lk}^{l}}\right\} + C_{0,0} + C_{0,1}M + C_{1,0}K + C_{1,1}MK$$

Power amplifier (η is efficiency)

Fixed power (control signals, backhaul, load-independent processing)

Circuit power per transceiver chain

Cost of digital signal processing (e.g., channel estimation and precoding computation)

***Nonlinear increasing function** of M and K*

***Many coefficients:** $\eta, C_{\mathrm{i,j}}$ for different i, j*

Optimizing a Cellular Network for High EE

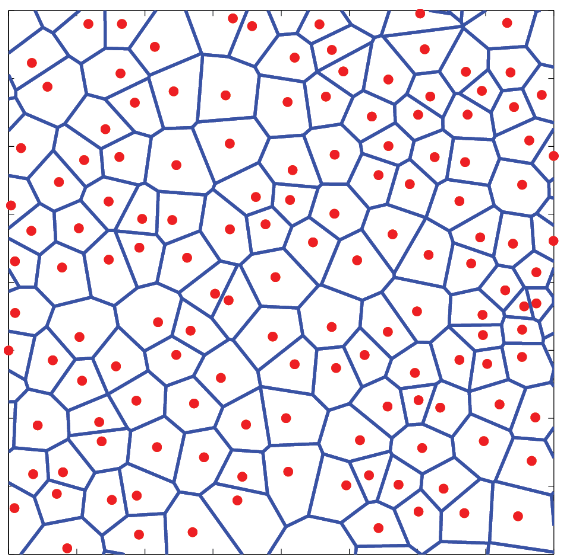
- Clean Slate Network Design
  - Select BS density: λ BSs per km²
  - Select M and K per cell
  - Asymmetric user load → asymmetric deployment

Spatial Point Processes

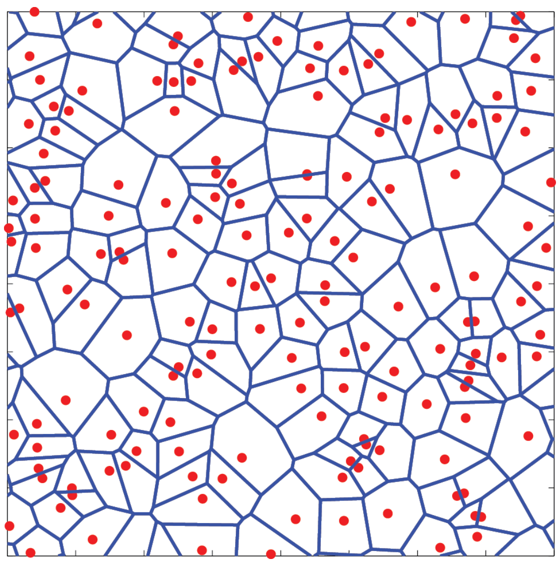
Tractable way to model randomness

Poisson point process (PPP):
Po(λA) *BSs in area of size A km²*

Random independent deployment:
Lower bound on practical performance



Real BS deployment



Poisson point deployment

Source: Andrews et al. "A Tractable Approach to Coverage and Rate in Cellular Networks"

Average Uplink Spectral Efficiency

Assumptions

BSs distributed as PPP: λ BS/km^2

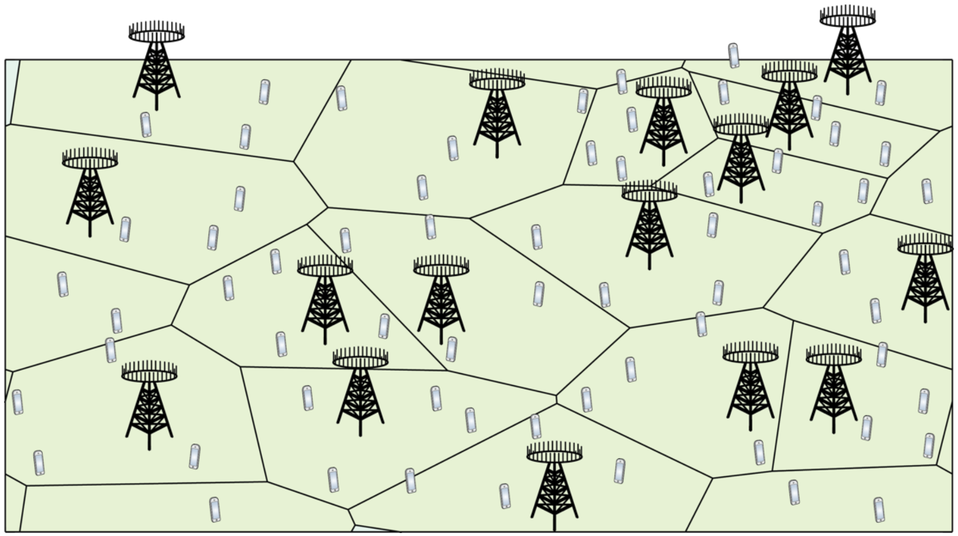
M antennas per BS, K users per cell

Random pilot allocation: $\tau_p = fK$

Statistical channel inversion: p/β_{lk}^{l}

Pathloss over noise:

$$\beta_{lk}^{j} = \omega^{-1}(\text{distance [km]})^{-\alpha}$$



Power per user: $\mathbb{E}\left\{\frac{p}{\beta_{lk}^{l}}\right\} = p\omega \frac{\Gamma(\alpha/2-1)}{(\pi\lambda)^{\alpha/2}}$

Lower Bound on Average SE with MR

$$\underline{\mathrm{SE}} = \left(1 - \frac{fK}{\tau_c}\right)\log_2(1 + \underline{\mathrm{SINR}})$$

$$\underline{\mathrm{SINR}} = \frac{M}{\left(K + \frac{1}{p}\right)\left(1 + \frac{2}{f(\alpha-2)} + \frac{1}{p}\right) + \frac{2K}{\alpha-2}\left(1 + \frac{1}{p}\right) + \frac{K}{f}\left(\frac{4}{(\alpha-2)^2} + \frac{1}{\alpha-1}\right) + \frac{M}{f(\alpha-1)}}$$

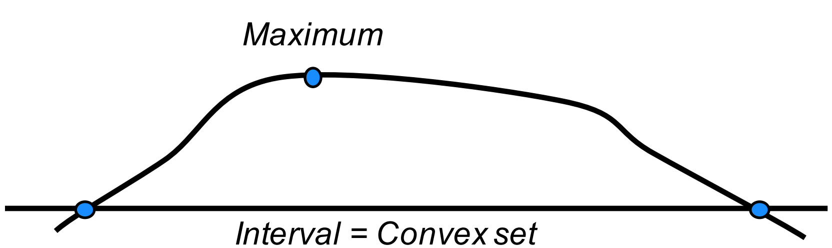
Maximizing Energy Efficiency

$$\underset{M,K,p,\lambda,f}{\text{maximize}} \quad \frac{B \cdot K \left(1 - \frac{fK}{\tau_c}\right) \log_2(1 + \underline{\text{SINR}})}{\text{APC}}$$
$$\text{subject to} \quad \underline{\text{SINR}} \geq \gamma$$

- Average SINR constraint γ needed to not get too low SE
- Is the solution small cells (high λ) or Massive MIMO (high M)?

- Main Properties
  1. Can pick f to satisfy SINR constraint
  2. By setting $p = p_0 \lambda$, the EE is increasing in λ
  3. Quasi-concave function w.r.t. M and K

Possible to solve the problem numerically



Simulation Parameters

Parameter	Symbol	Value
Coherence interval	τ_c	400
Pathloss exponent	α	3.76
Pathloss over noise at 1 km	ω	33 dBm
Amplifier efficiency	η	0.39
Bandwidth	B	20 MHz
Static power	$\mathcal{C}_{0,0}$	10 W
Circuit power per active user	$\mathcal{C}_{1,0}$	0.1 W
Circuit power per BS antenna	$\mathcal{C}_{0,1}$	1 W
Signal processing coefficient	$\mathcal{C}_{1,1}$	3.12 mW

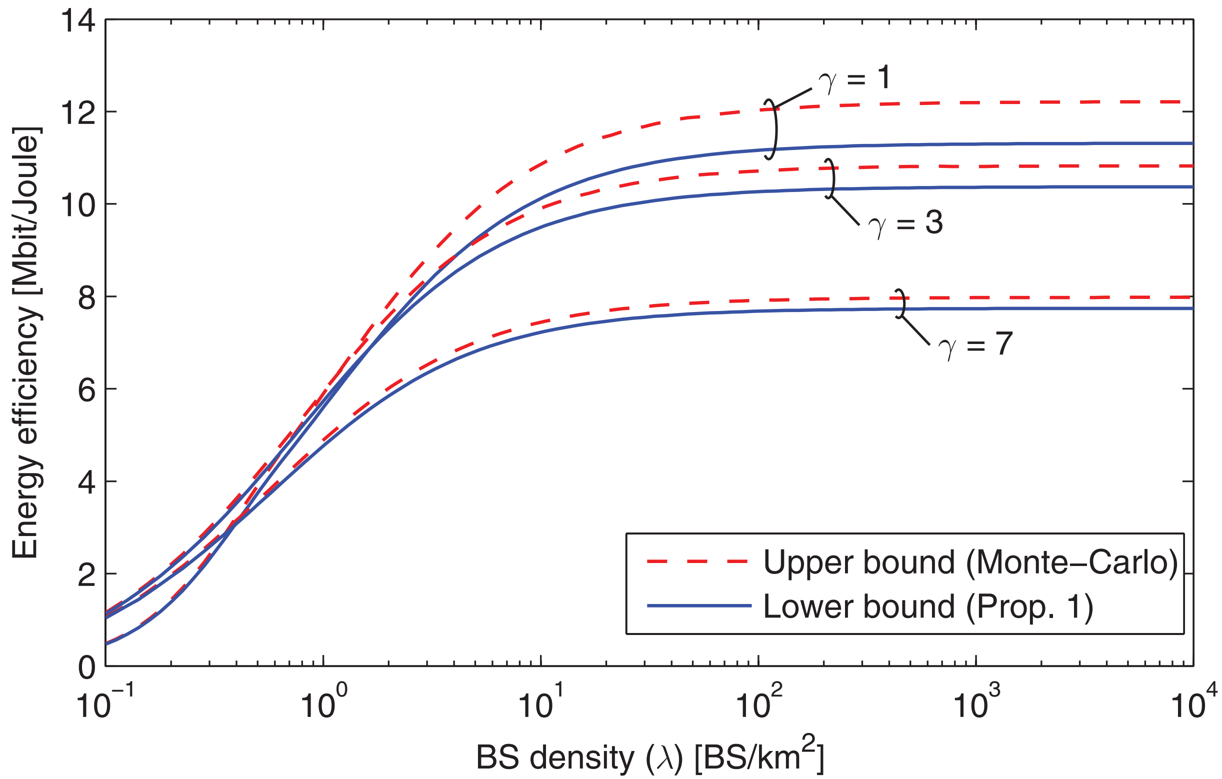
We publish simulation code to enable simple testing of other values!

Impact of BS Density

Simulation

Different BS densities

Other variables optimized



Observations

Lower bound is tight

Higher EE with lower γ

EE increases with λ

Saturation Property

EE gain from small cells saturates at $\lambda = 10$

This is satisfied in most urban deployments (300 m between BSs)

We can safely let $\lambda \rightarrow \infty$ *to simplify analysis*

Optimal Number of Antennas and Users

Real-valued Optimization

Optimal $K \in \mathbb{R}$ *found in closed-form for fixed* M/K

Optimal $M \in \mathbb{R}$ *found in closed-form for fixed* K

Alternating optimization reaches global maximum

Properties: *Optimal* K *and* M

↘: *Decrease as* $C_{0,1}$, $C_{1,0}$, *and* $C_{1,1}$ *increase*

↗: *Increase as* $C_{0,0}$ *increases*

Intuition: Activate more hardware if the relative cost is small

Impact of Number of Antennas and Users

Simulation

Optimized f, λ, p

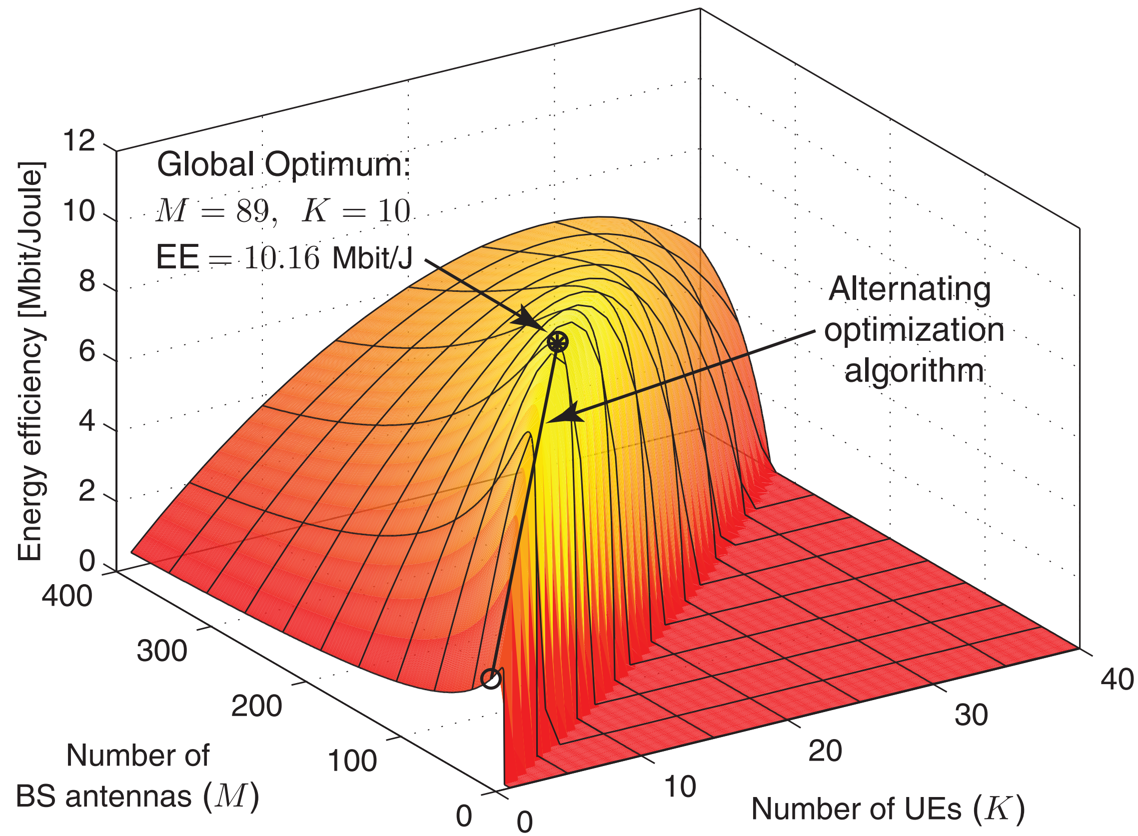
SINR constraint: $\gamma = 3$

Observations

Optimal: $M = 89$, $K = 10$

Massive MIMO with reuse factor $f \approx 7$

Many good solutions



Why is Massive MIMO Energy Efficient?

Interference suppression: Improve SINR, not only SNR as with small cells

Sharing cost: Fixed circuit power costs are shared

Optimization with Given User Density

- User Density
  - So far: K and λ design variables
  - Density: λK users per km^2
  - Heterogeneous user distribution

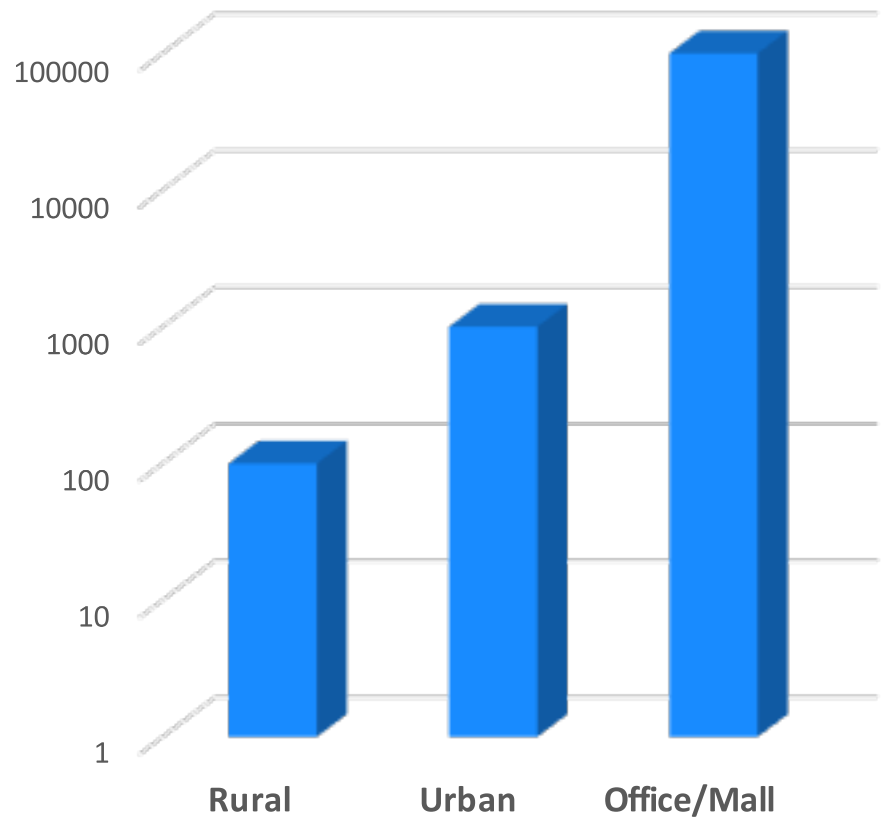
Can we Optimize this Density?

Increase: No, cannot "create" users

Decrease: Yes, by scheduling

Practical User Densities

Rural:	10^2 *per km*^{2}
Urban:	10^3 *per km*^{2}
Office/Mall:	10^5 *per km*^{2}



Source: METIS, "Deliverable D1.1: Scenarios, requirements and KPIs for 5G mobile and wireless system"

Impact of User Density

Simulation

Fixed user density μ users/km²

Rural: $\mu = 10^2$, Malls: $\mu = 10^5$

EE maximization with constraint $K\lambda = \mu$

Low User Density

Many cells with $K \approx 1$

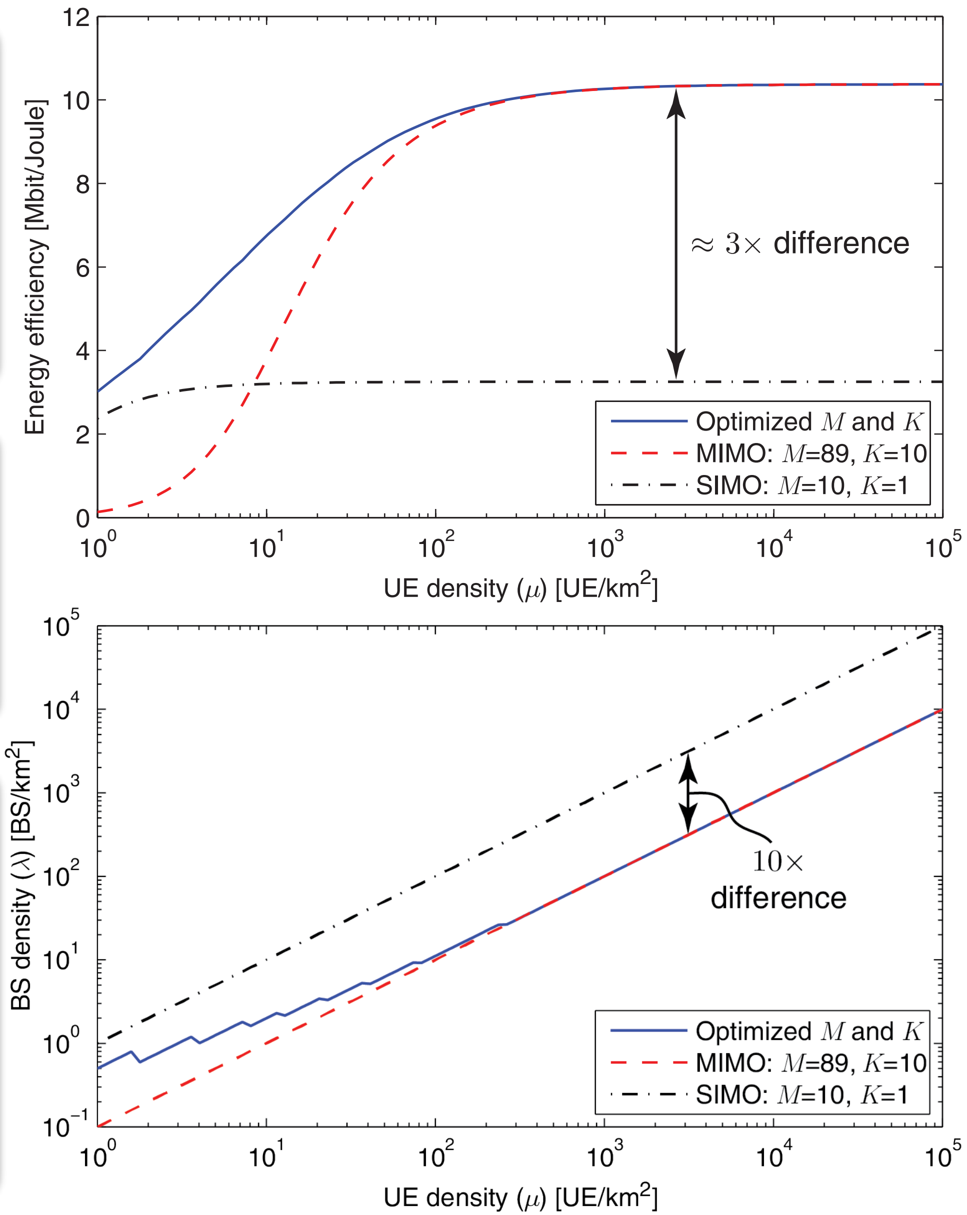
Most important to reduce pathloss

High User Density

Massive MIMO is optimal

Saturation for $\mu \geq 100$:
Covers both rural and shopping malls

Share circuit power and cost over users



Summary

- Transmit Power Scaling Law
  - Reduced as $1/\sqrt{M}$ per user, but total transmit power might increase
  - Reduced as $1/\sqrt{M}$ per BS antenna → Use handset technology?

- Designing Networks for Energy Efficiency
  - Large cells: First step is to reduce cell size
  - Smaller cells: Transmit power only a small part → Use Massive MIMO
  - Intuition: Suppress interference, share circuit power over many users
  - Non-universal pilot reuse is important in random deployments
  - Several Mbit/Joule achieved without coordination

Massive MIMO and

HARDWARE EFFICIENCY

Many Antennas and Transceiver Chains

- Many Antenna Elements
  - LTE 4-MIMO: $3 \cdot 4 \cdot 20 = 240$ antennas

    But only 12 transceiver chains!
  - Massive MIMO = M transceiver chains

- End-to-end Channels
  - Wireless propagation channel
  - Transceiver hardware
  - Simple model:

3 sectors, 4 arrays/sector, 20 antennas/array

Image source: gigaom.com

Can We Afford M High-Grade Transceiver Chains?

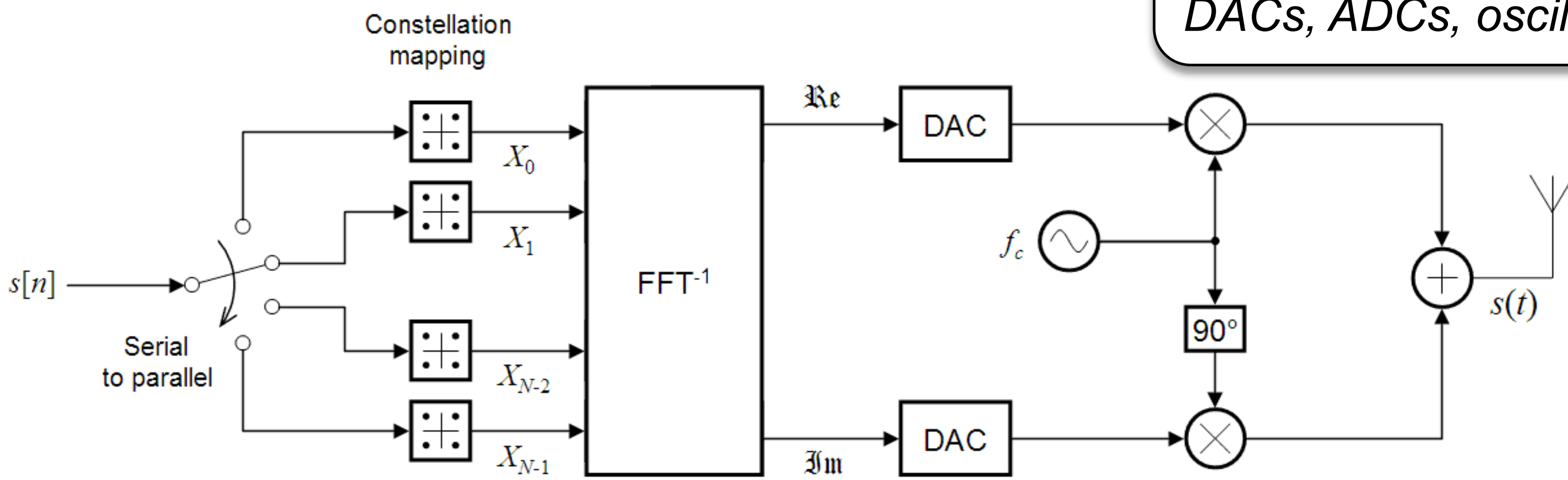
Can Massive MIMO utilize the hardware components more efficiently?

Orthogonal frequency-division multiplexing (OFDM)

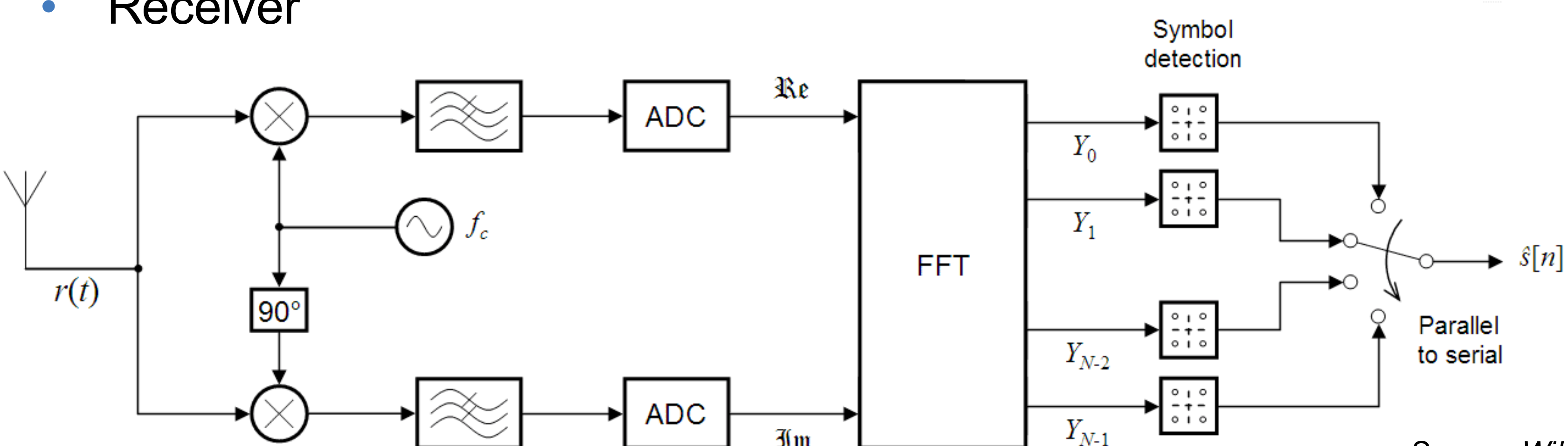
Main Components

Filters, I/Q mixers, DACs, ADCs, oscillators

- Transmitter



- Receiver



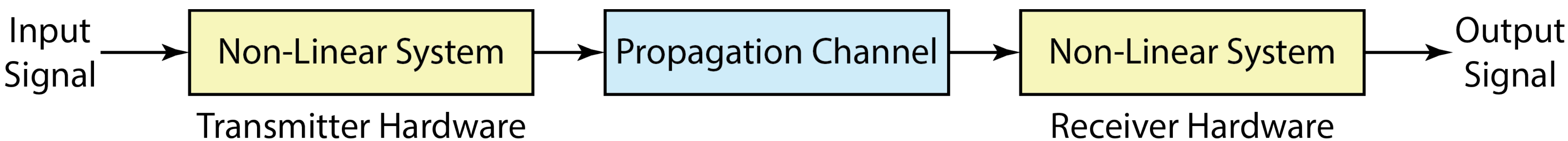
Source: Wikipedia

Modeling of Hardware Impairment

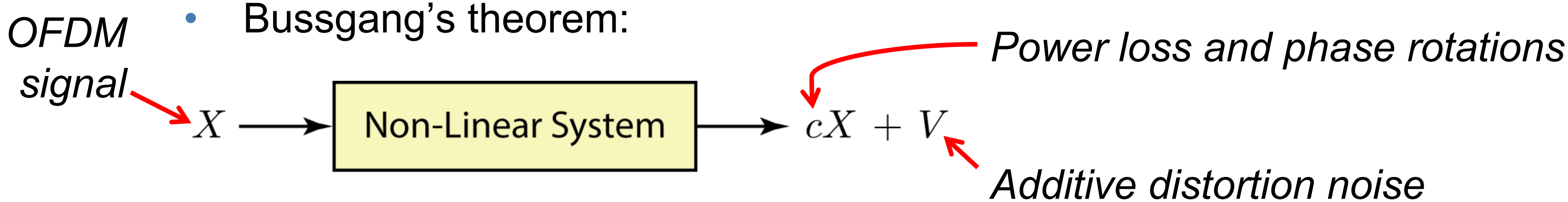
- Real Transceivers have Hardware Impairments
  - Ex: Phase noise, I/Q-imbalance, quantization noise, non-linearities, etc.
  - Each impairment can be modeled (for given hardware, waveform etc.)
  - But: Impact reduced by calibration and only combined effect matters!

More impairments = Lower price, lower power, smaller size

- High-Level Hardware Model:



  - Bussgang's theorem:



X, V are uncorrelated Gaussian variables

Classical Impact of Hardware Impairments

- Impact on Point-to-Point MIMO
  - Low SNR: Negligible impact on spectral efficiency
  - High SNR: Fundamental upper limit

Error Vector Magnitude

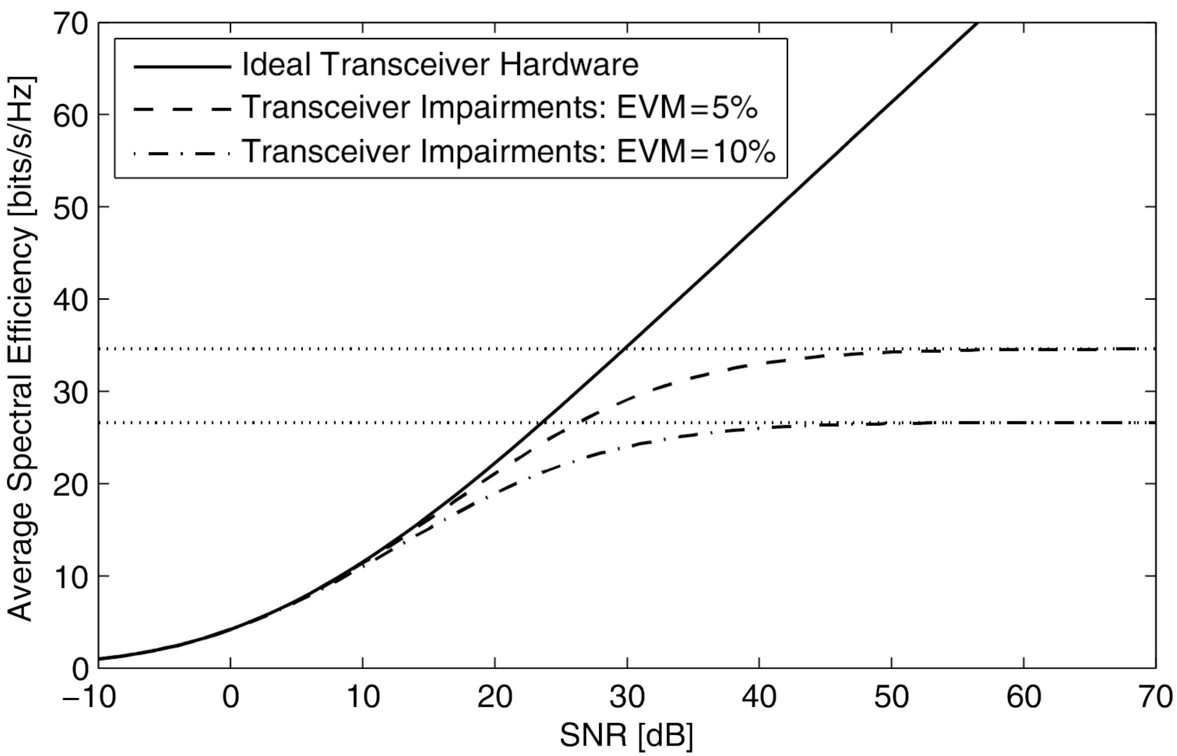
$$\text{EVM} = \frac{\text{Distortion magnitude}}{\text{Signal magnitude}}$$

Distortion scales with signal power

LTE EVM limits: 8%-17.5%

What about large M regime?

Large or small impact?



Example: 4x4 point-to-point MIMO, i.i.d. Rayleigh fading

Distortion Noise: Definition and Interpretation

- Uplink Signal (conventional):

$$\boldsymbol{y} = \sum_k \boldsymbol{g}_k x_k + \boldsymbol{w}$$

Distortion Noise Model

Gaussian distributed

Independent between users and antennas

Error Vector Magnitude

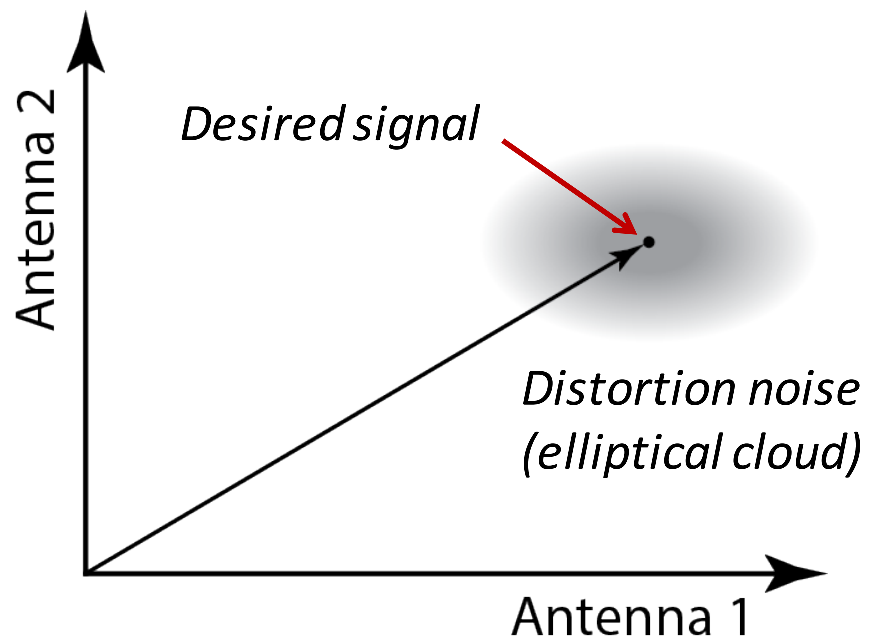
(at transmitter)

$$\mathrm{EVM}^{\mathrm{tx}} = \frac{\sqrt{\mathbb{E}\{|\xi_k^{\mathrm{tx}}|^2\}}}{\sqrt{\mathbb{E}\{|c_k^{\mathrm{tx}} x_k|^2\}}}$$

- Uplink Signal (with impairments):

$$\boldsymbol{y} = c^{\mathrm{rx}} \sum_k \boldsymbol{g}_k (c_k^{\mathrm{tx}} x_k + \xi_k^{\mathrm{tx}}) + \boldsymbol{\xi}^{\mathrm{rx}} + \boldsymbol{w}$$

Gain losses — *Transmitter distortion* — *Receiver distortion*



What is the Impact of Distortion Noise?

Uplink Single-User Scenario

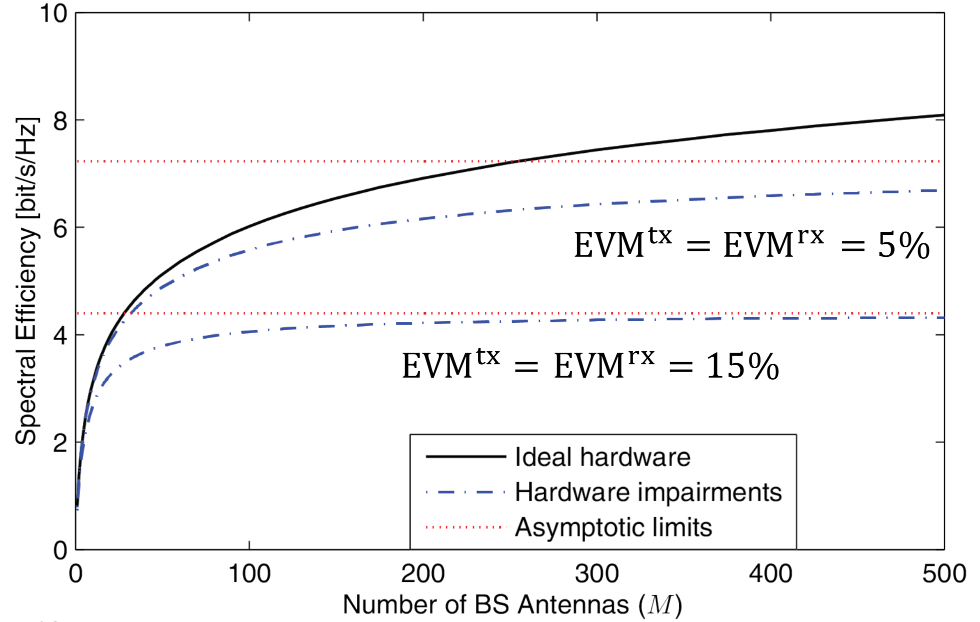
Rayleigh fading, SNR = 5 dB

Observations

Ideal: $\mathrm{SE} = \mathcal{O}(\log M)$

Non-ideal: Asymptotic limits

Higher EVM → Lower limit

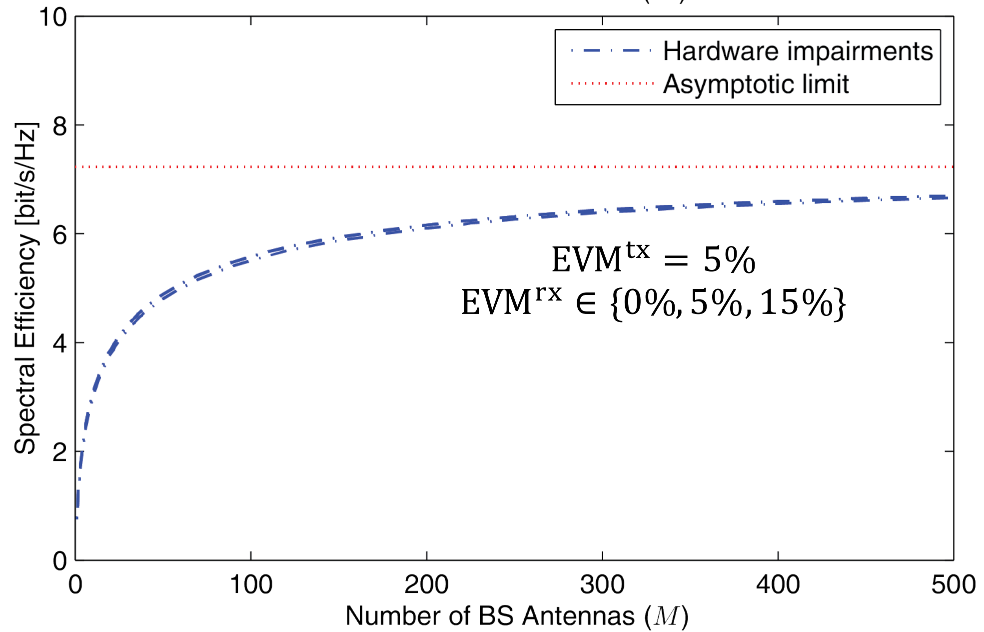


Observations

Impairments caused by user device determine the limit

Distortion noise caused by BS averages out as $M \to \infty$

(cf. inter-user interference)



Multi-Cell Scenario with Distortion Noise

Uplink Multi-Cell Scenario

Rayleigh fading, SNR = 5 dB

$K = 8$ *users per cell*

MR detection

Hardware Scaling Law

If BS distortion variance increases as M^{κ} *for* $\kappa \leq 1/2$*:*

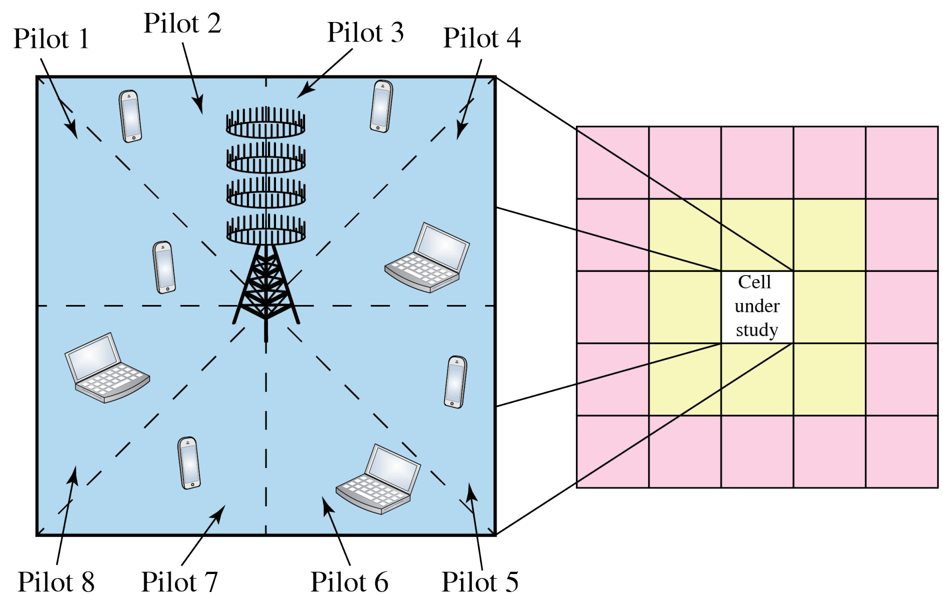
SE will not go zero as $M \rightarrow \infty$

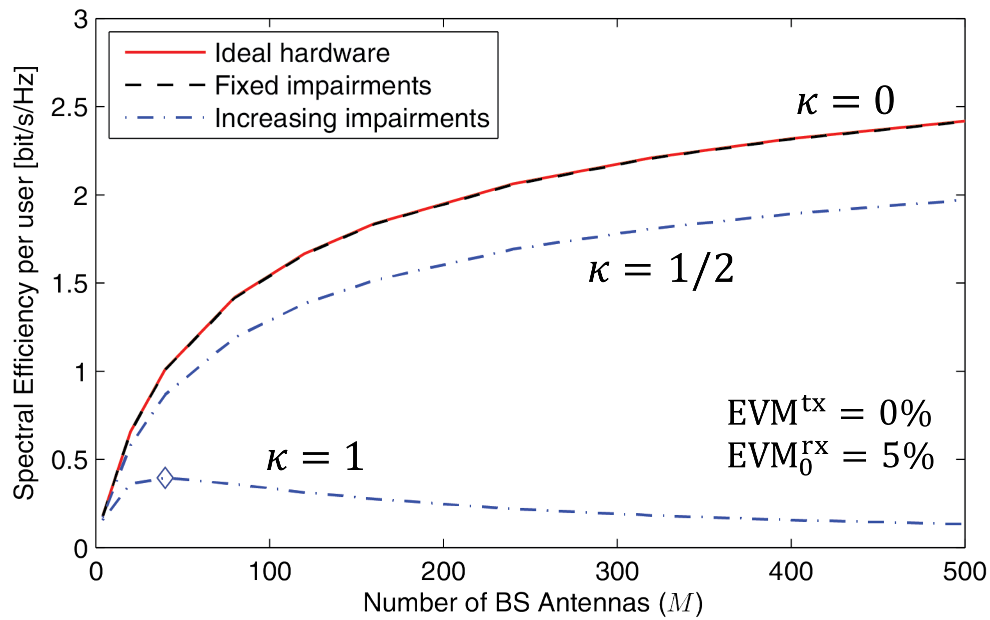
Can be proved rigorously!

Observations

Small loss if law is followed

Otherwise large loss!





Utilizing the Hardware Scaling Law

- Massive MIMO can use Lower-Grade Hardware
  - Reduced cost, power consumption, and size

- Example: Analog-to-Digital Converter (ADC)
  - One b-bit ADC per Transceiver Chain

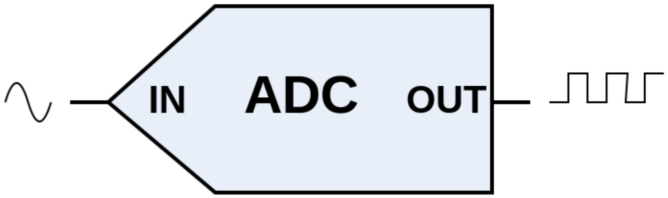


Image source: Wikipedia

  - Adds quantization noise roughly proportional to 2^{-2b}:

$$\sqrt{M} = c_0 \cdot 2^{-2b} \Rightarrow b = \frac{1}{2}\log_2(c_0) - \frac{1}{4}\log_2(M)$$

Ex: $M = 256$ requires 2 fewer bits than $M = 1$ (even 1-bit ADCs possible)

  - Circuit power roughly proportional to 2^{2b}:

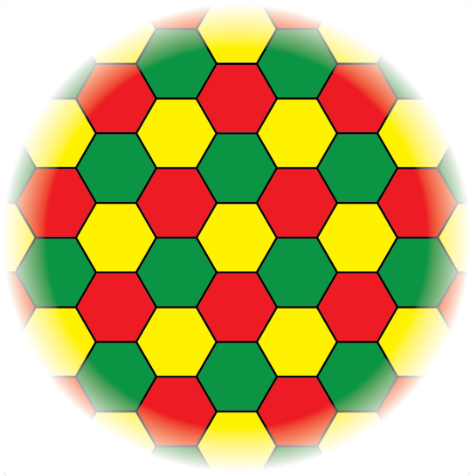
Ex: Power of M ADCs can scale as $\sqrt{M}$ rather than M

Interference Visibility Range

- Only Remaining Interference as $M \to \infty$:
  - Pilot contamination (reuse of pilot resources)
  - Hardware impairments (at user devices)

- Distortion Noise as Self-interference
  - Limits the visibility of inter-user interference

Strong self-interference



Weak self-interference

No reason to suppress inter-user interference below self-interference!

Summary

- Any Transceiver is Subject to Hardware Impairments
  - Massive MIMO is resilient to such imperfections
  - Distortion variance at BS may increase as $\sqrt{M}$
  - High-grade BS hardware is not required!
  - User hardware quality is the fundamental limitation

- Further Remarks
  - Analysis with more detailed hardware models show same behavior
  - Phase noise is not worse than in small MIMO systems
  - Reduced transmit power and relaxed impairment constraints
    $\rightarrow$ New compact transceiver designs?

Part 4

OPEN PROBLEMS

Open Problems and Active Research Topics

1. Channel measurements and modeling
2. Circuit and transceiver design
3. Implementation-aware algorithmic design
4. Dealing with hardware impairments and reciprocity calibration
5. Exploiting $M - K$ excess degrees of freedom
6. FDD operation for "low mobility" or "highly structured channels"
7. MAC-layer design, power control, and scheduling
8. Control signaling and BS transmission without CSI
9. New deployment scenarios (e.g., distributed arrays or cell-free)
10. Mitigation of pilot contamination
11. System-level studies and coexistence with HetNets or D2D
12. Massive MIMO in millimeter wave bands

SUMMARY

Summary

- Massive MIMO has Many Extraordinary Benefits
  - **High spectral efficiency**: >20x gains over IMT-Advanced are foreseen
    - High SE per cell, but modest per user
    - Important: Non-universal pilot reuse, pilots use large part of coherence interval
  - **High energy efficiency**: Tens of Mbit/Joule are foreseen
    - Reduced transmit power per user and antenna, maybe not per cell
    - Circuit power dominates power consumption in urban scenarios
    - Important: Interference control, sharing circuit power between users
  - **High hardware efficiency**: High-grade hardware is not needed
    - Variance of distortion noise at BS can scale with number of antennas
    - Important: Quality of user device is the limiting factor

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Bringing an Extraordinary Technology 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

MAMMOET Massive MIMO

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QUESTIONS?

Dr. Emil Björnson

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