Optimizing 5G Networks for Energy-Efficiency

Dense or Massive MIMO or Both?

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LiU EXPANDING REALITY

Biography – Emil Björnson

- 1983: Born in Malmö, Sweden
- 2007: Master in Engineering Mathematics, Lund University, Sweden
- 2011: PhD in Telecommunications, KTH, Stockholm, Sweden
- 2012-2014: Joint post-doc at Supélec, Paris, France, and at KTH, Sweden.
- 2014-: Assistant Professor and Docent in Communication Systems, Linköping University, Sweden
- 2014 Outstanding Young Researcher Award, IEEE ComSoc EMEA

Biography – Luca Sanguinetti

- 1977: Born in Florence, Italy
- 2002: Master in Telecommunications, University of Pisa, Italy
- 2006: PhD in Wireless Communications, University of Pisa, Pisa, Italy
- 2007-2008: Post-doc at Princeton, USA
- 2010-: Assistant Professor in Wireless Communication Systems, University of Pisa, Pisa, Italy
- 2013-2015: Assistant Professor at SUPELEC, Paris, France (funded by Marie-Curie Fellowship)

Outline

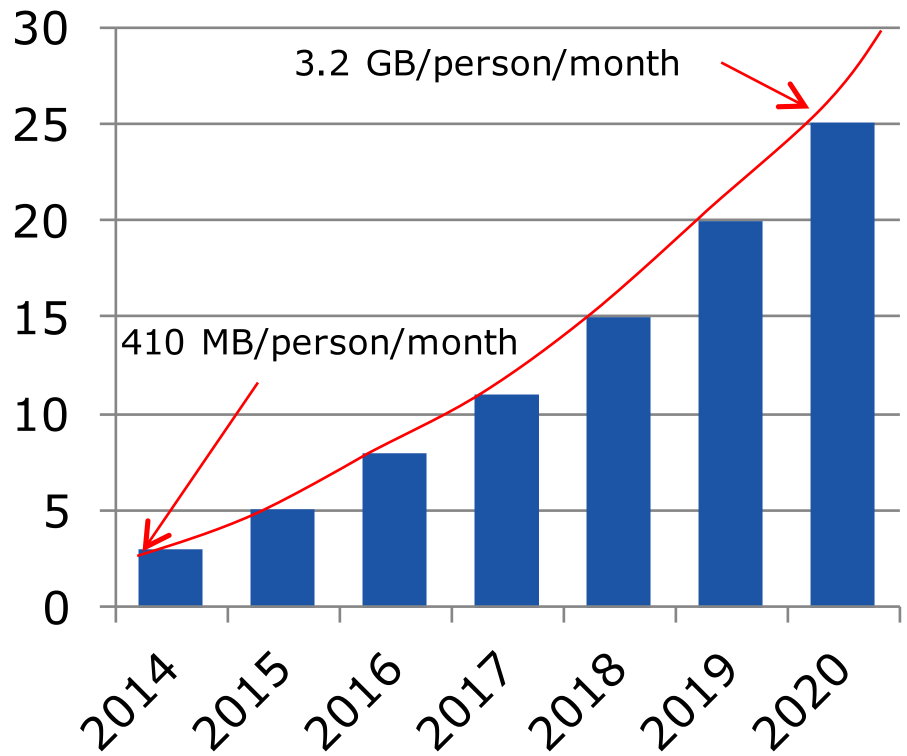
- Part 1: Introduction & Background
  - Energy Efficiency, small cells, and massive MIMO
- Part 2: General Problem Formulation
  - Mathematical models and concepts
- Optimization of Energy Efficiency
  - Part 3: Fixed Regular Deployment
  - Part 4: Heterogeneous Deployment
  - Insights on optimal network design
- Part 5: Optimizing Multiple Metrics at the Same Time
  - Beyond pure energy efficiency optimization
- Conclusion

Part 1

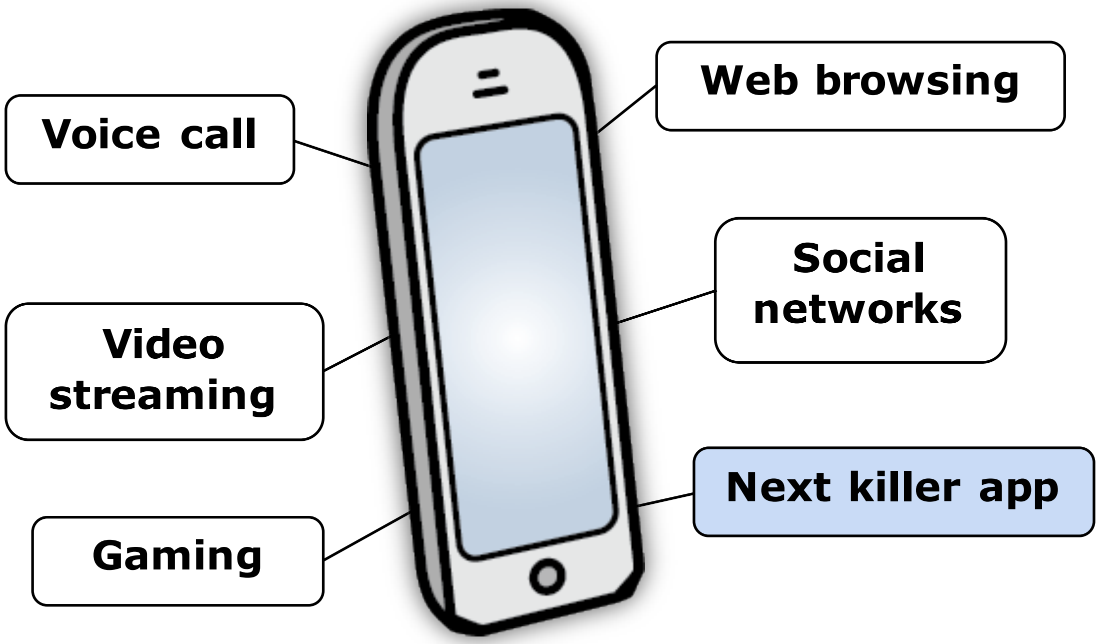
Introduction & Background

Introduction

- Wireless Connectivity
  - A natural part of our lives



Source: Ericsson (November 2014)



- Rapid Network Traffic Growth
  - 38% annual growth
  - Exponential increase!
  - Extrapolation: 5x until 2020
    25x until 2025
    125x until 2030

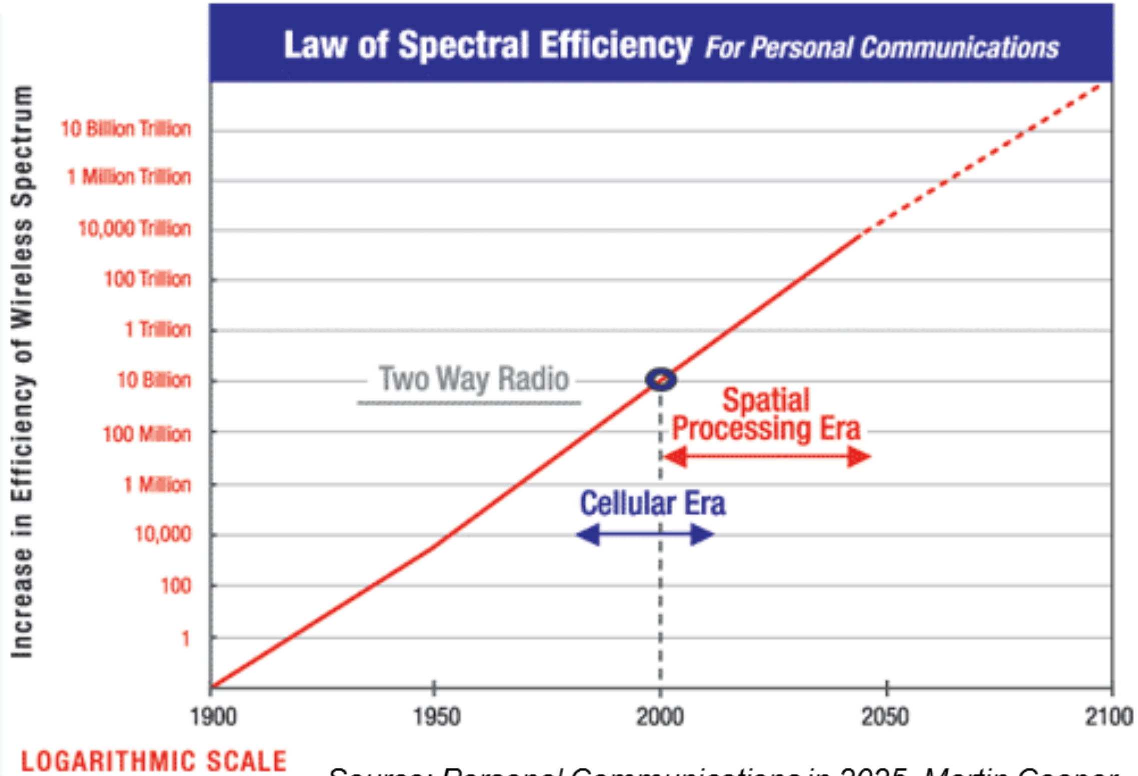
Exponential Traffic Growth

- Is this Growth Sustainable?
  - User *demand* will increase – users expect more for same price
  - Traffic supply – increases only if business models allow it!

- Exponential Growth is Nothing New!
  - 10^6 increase in last 45 years!

Martin Cooper's law

The number of simultaneous voice/data connections has doubled every 2.5 years since the beginning of wireless

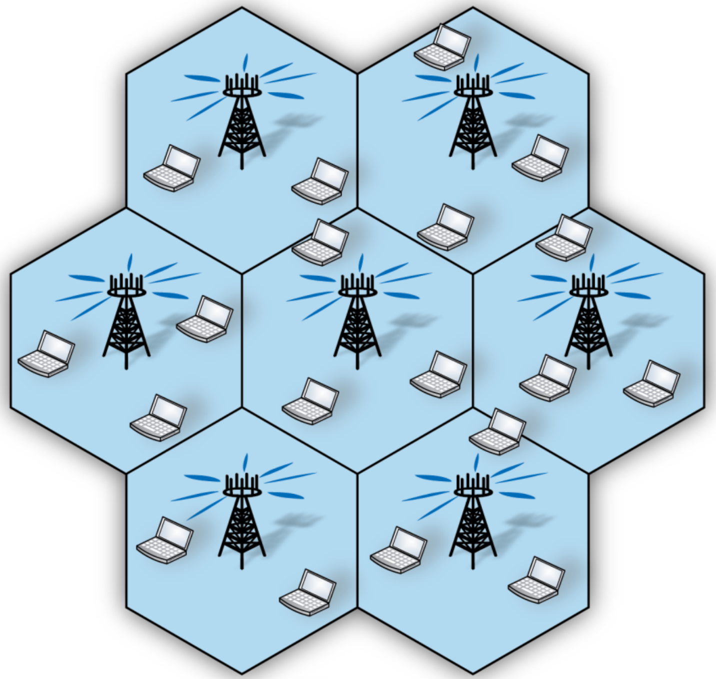


Source: Personal Communications in 2025, Martin Cooper

- Coopers law: 32%/year
- New predictions: 38%/year
- Growth likely to continue!

Cellular Networks

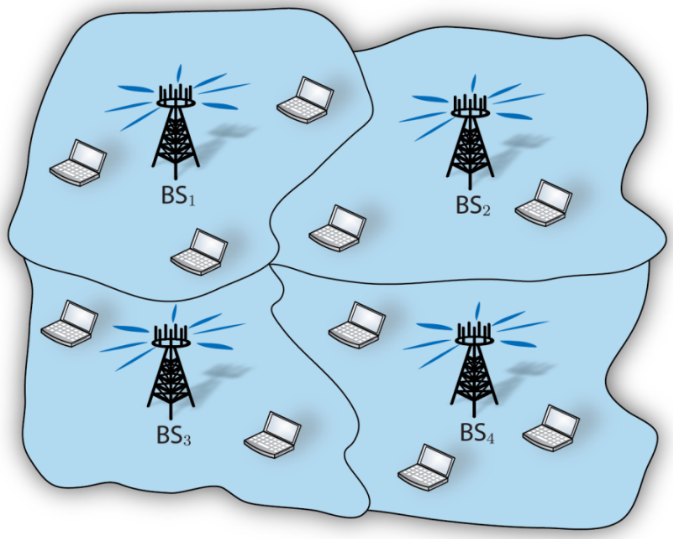
- Cellular Network Architecture
  - Coverage area divided into cells
  - One fixed base station (BS) per cell
  - Serves all users in the cell
  - Uplink: User→BS
  - Downlink: BS→User



- Different Standards
  - 2G (GSM), 3G (UMTS), 4G (LTE/LTE-A)

More and more focus on data traffic

- Traditional Ways to Handle More Traffic
  - Higher cell density (variable cell sizes)
  - More spectrum (carrier aggregation)
  - Higher spectral efficiency (spatial processing)

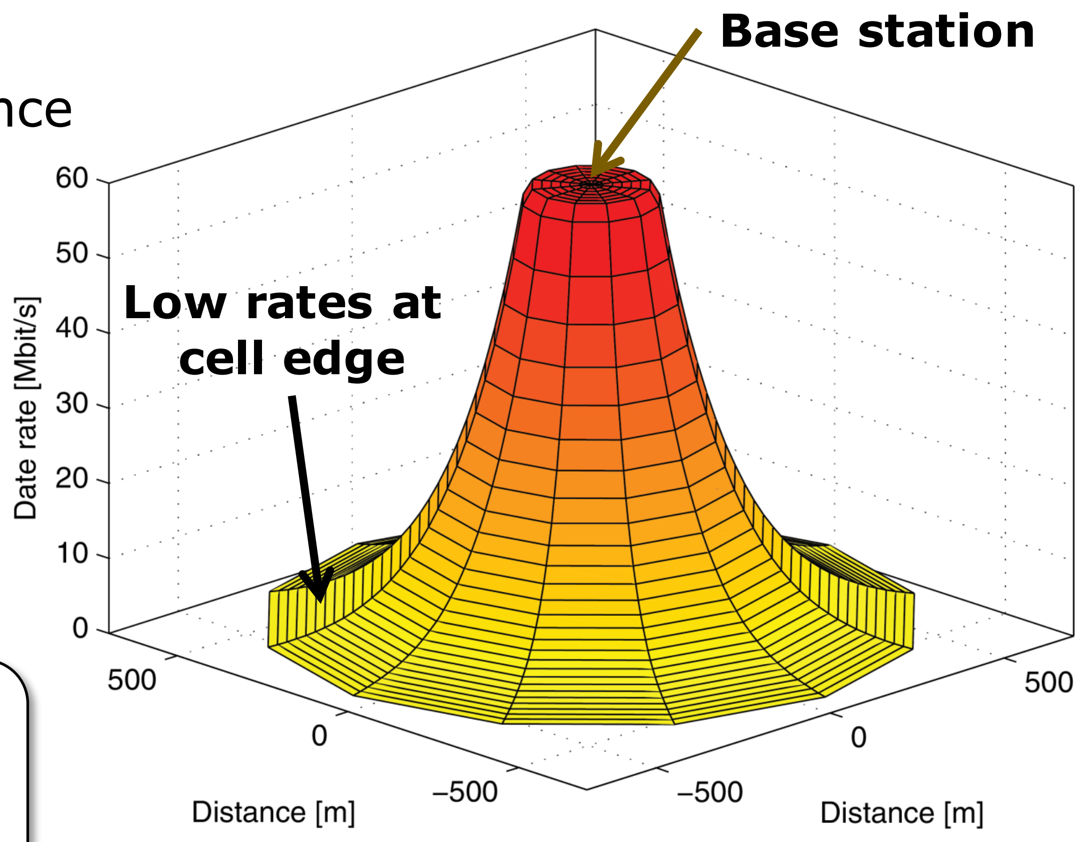


High Data Rates

- Traditional Design Metric
  - High *peak* and/or *average* rates [bit/s/active user]

- Basic Signal Propagation
  - Signal energy decays with distance
  - Peak rates in cell center
  - Far from peak rates at cell edge

- Traffic Independent of Location
  - Easily satisfied in cell center
  - Highest demand at cell edge!



Need for Additional Metrics

To optimize and design our networks properly!

Expectations for 5G Networks

- 5G – The Next Cellular Network Generation
  - Expected to be introduced by 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

Source: METIS project (www.metis2020.com)

Parts 2-4

What if we optimize a network only for energy-efficiency?

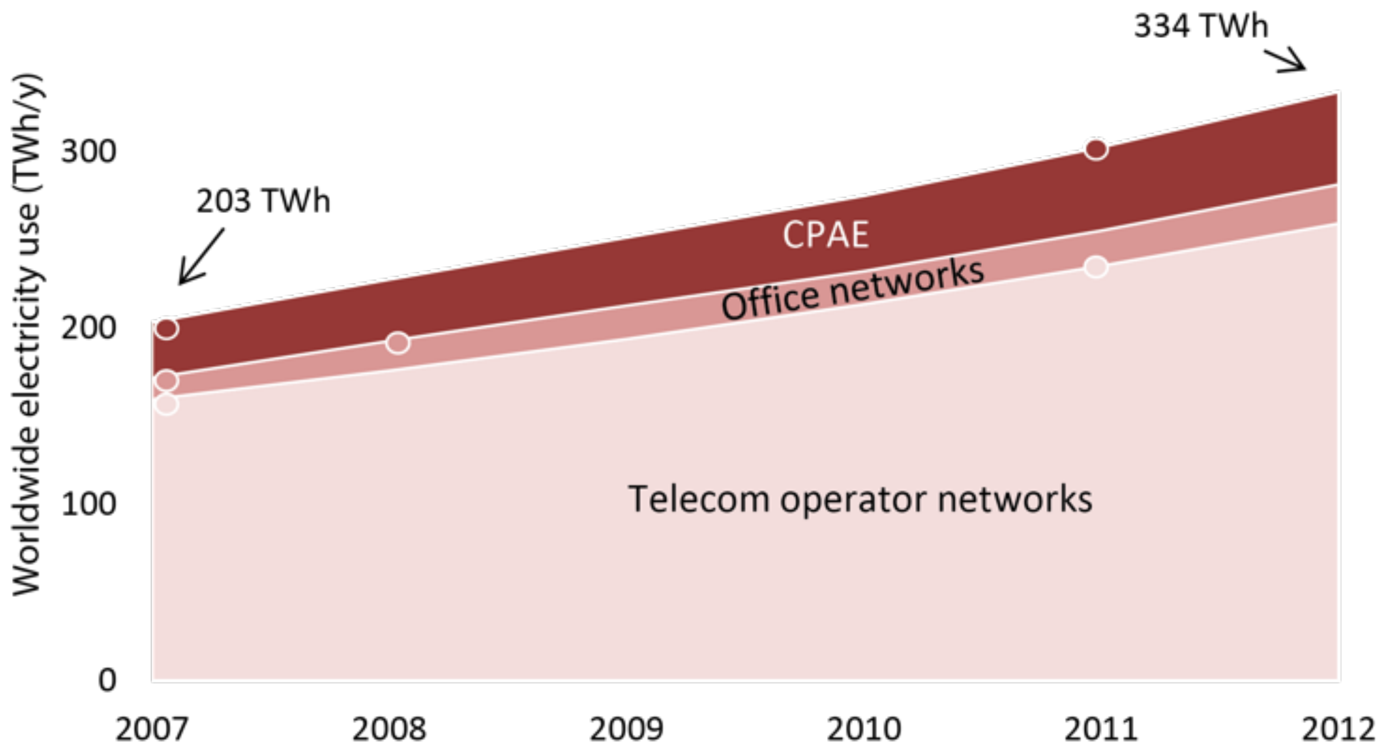
What will it look like?

Part 5

Is it possible to optimize a network with respect to multiple metrics?

What does "optimality" mean then?

Why Focus on Energy Efficiency?



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
  - Benefit: Sum Data Rate [bit/s]
  - Cost: Consumption of Energy [Watt = Joule/s] and Money [€/s]

- Definition: Energy Efficiency (EE):

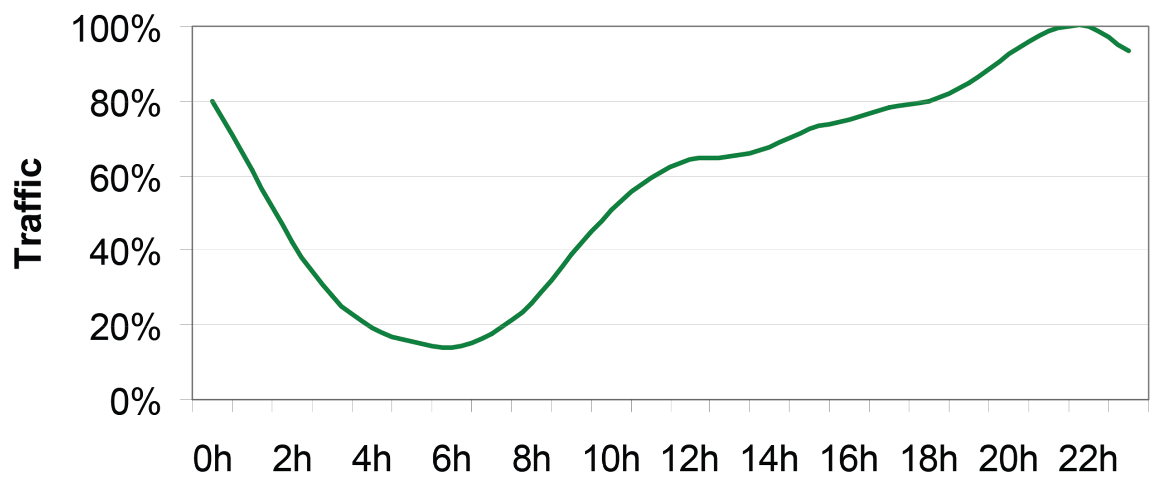
$$\mathrm{EE} = \frac{\text{Average Sum Rate [bit/s/cell]}}{\text{Power Consumption [Joule/s/cell]}}$$

  - "Amount of data transmitted over consumed energy" (naturally per cell)
  - A detailed model is developed in this tutorial!

- Economical Costs not Explicitly Included
  - Examples: Hardware cost, site renting, network management
  - Can be added by transforming into equivalent energy consumption
  - Use energy price [Joule/€] as transformation factor

Load-Independent Efficiency

- User Load Variations
  - Evening: Peak traffic
  - Late night: Lowest traffic
  - Same trends in the future



Source: Auer et al., "Cellular Energy Efficiency Evaluation Framework", VTC, 2011.

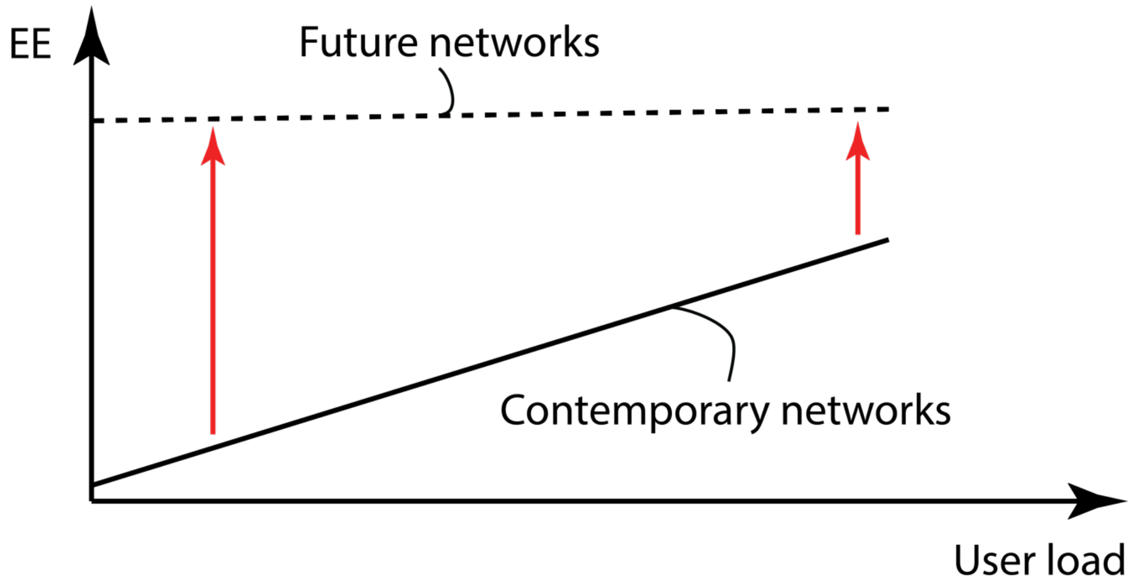
Contemporary networks

Relatively efficient at high user load

Very inefficient at low user load

Future networks

Must be more energy efficient, irrespective of current load



Network Densification

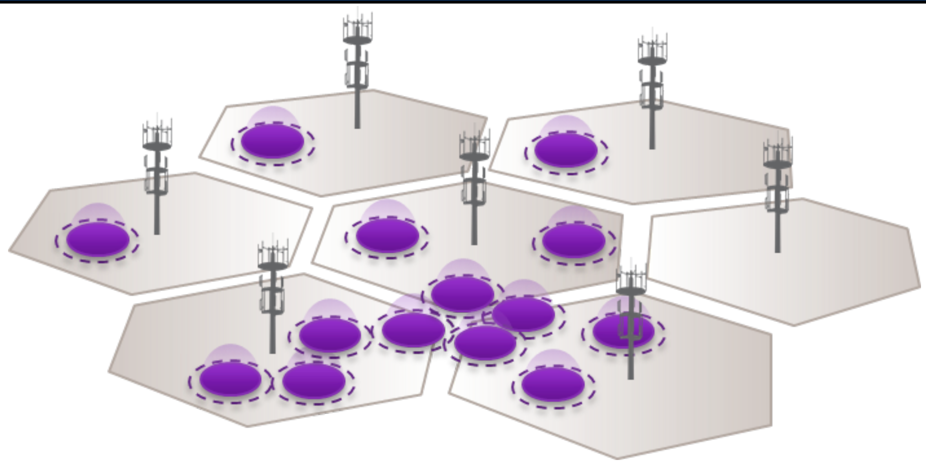
- Ideas: How can we improve EE?
  - Reduce propagation losses (-100 dB is common in wireless)
  - Serve multiple users per cell (share the load-independent costs)
  - **How to design new networks to achieve this?**

- Two Main Solution Paradigms
  - Smaller cells: Reduce propagation distances
  - Massive MIMO: Spatially directed transmission, multiplexing of users

Network densification:
More service antennas per km^2

Which solution should we choose?

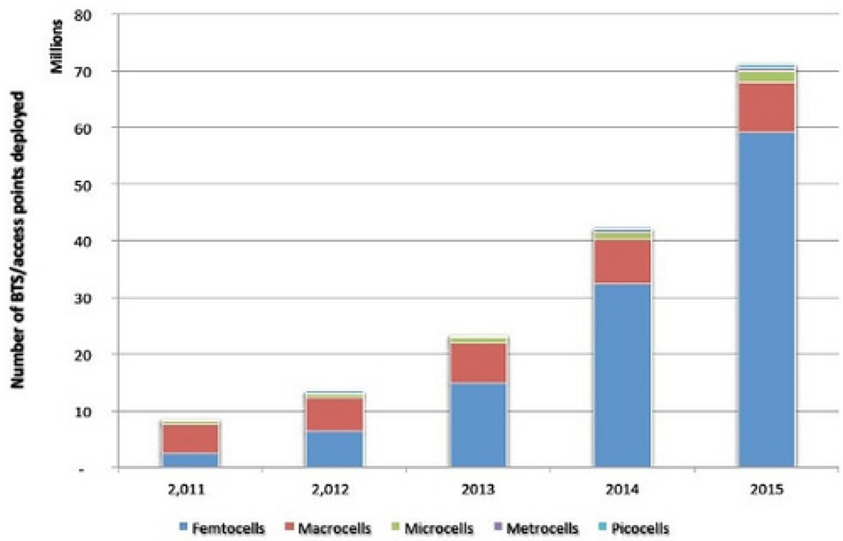
What are Small Cells?



- "Small cells" is an Umbrella Term:
  - Operator-controlled, low-powered BS operating in licensed spectrum

- Small Cells of Different Size
  - Femtocells (up to 100 m)
  - Picocells (up to 200 m)
  - Microcells (up to 500 m)

  - Centralized BSs or remote radio heads
  - Wired or wireless with core network



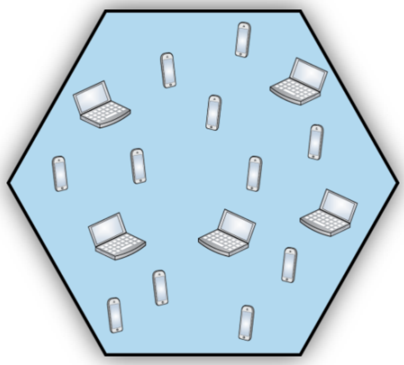
Source: Informa Telecoms & Media

Access Policies

- Three Access Policies
  - Closed access
    - Only users in a closed subscriber group can connect
  - Open access
    - All users can connect
  - Hybrid access
    - All users + priority to some
  - Important factors:
    - Interference from other cells depend on spectrum license
    - Different cost and backhaul conditions
- **Femtocells**: closed, open or hybrid access
- **Picocells**: open access, offload traffic from larger cells

Why Small Cells?

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



- Simple Formula for Area Rate:

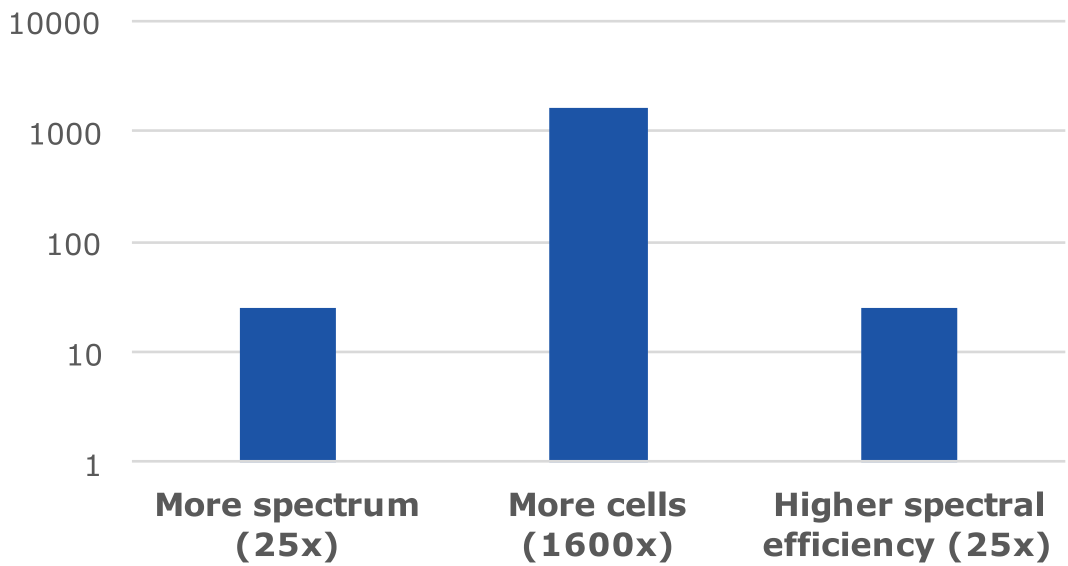
$$\underbrace{\text{Area rate}}_{\text{bit/s/km}^2} = \underbrace{\text{Available spectrum}}_{\text{Hz}} \cdot \underbrace{\text{Cell density}}_{\text{Cell/km}^2} \cdot \underbrace{\text{Spectral efficiency}}_{\text{bit/s/Hz/Cell}}$$

Cell-Size Reduction

Traditional way to increase rates

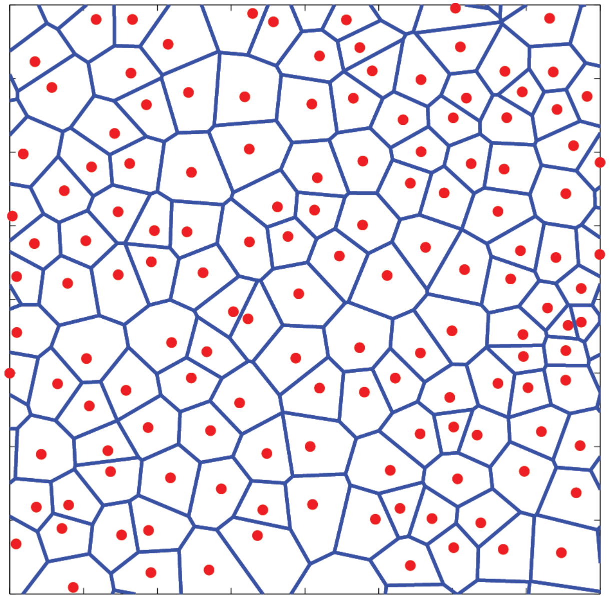
Most efficient approach in the past

No need to develop new radio interfaces

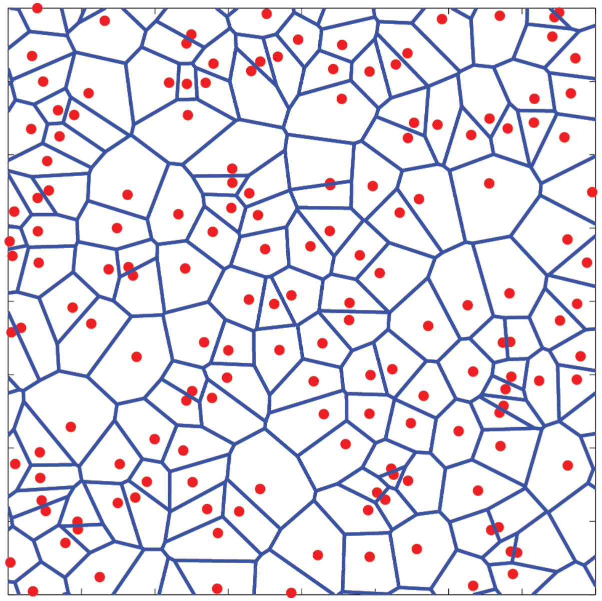


Asymmetric Deployment

- Shape of Cellular Networks
  - Classically modeled as symmetric hexagons grid
  - Real networks are highly asymmetric
  - Asymmetry plays key role as cells shrink



Real BS deployment



Poisson point deployment

Spatial Stochastic Point Processes

Tractable way to model randomness

Models random independent deployment:

Lower bound on practical performance

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

Small Cells – Main Benefits

- Improved Coverage
  - Especially outdoor-to-indoor and indoor-to-indoor coverage
  - Majority of wireless traffic originates from indoor users
- Improved Area Rates
  - Without need for more spectrum or advanced processing techniques
- Improved Battery Life
  - Lower propagation loss → Less transmit power from devices
- Reduced Energy Consumption
  - A small cell consumes 5 W → 100 millions small cells consume 4.4 TWh in 2020 (small part of network consumption)
- More Tailored to User Load
  - Hotspots in malls and subway stations

Small Cells – Energy Efficiency

- Advantages
  - Shorter distances: Major reductions in propagation losses
  - Can be applied along with any transmission protocol
  - Cells can be turned on/off without destroying coverage

- Disadvantages
  - Cell edge conditions are not improved (interference limited)
  - Hard to coordinate transmissions across cells
  - Deploy more BSs per km^2 – very expensive?

Small Cells – Standardization

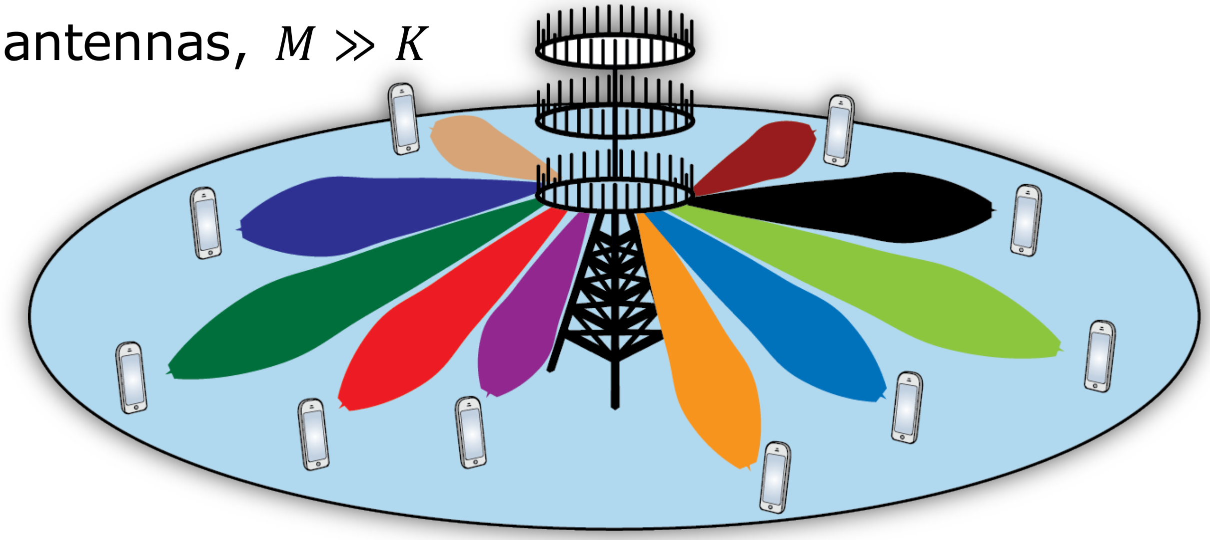
- Small Cell Forum (formerly Femto Forum)
  - Non-profit organization founded in 2007
  - Goal: Enable and promote small cells worldwide
  - Standardization, regulation & interoperability
  - Marketing, promotion & business case

67 operators covering 3 billion mobile subscribers – 46% of total

74 providers of small cell technology representing all parts of the ecosystem

What is Massive MIMO?

- New Network Architecture
  - Multi-user MIMO (multiple-input, multiple output) technology
  - Many antennas at BSs: e.g., $M = 100$ antennas
  - Serve many users in parallel: $K = 10$ users
  - Key: Excessive number of antennas, $M \gg K$
  - Very directive signals
  - Little interference leakage



2013 IEEE Marconi Prize Paper Award

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

Analysis based on $M \to \infty$ and K fixed, but concept applicable at any $M \gg K$

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

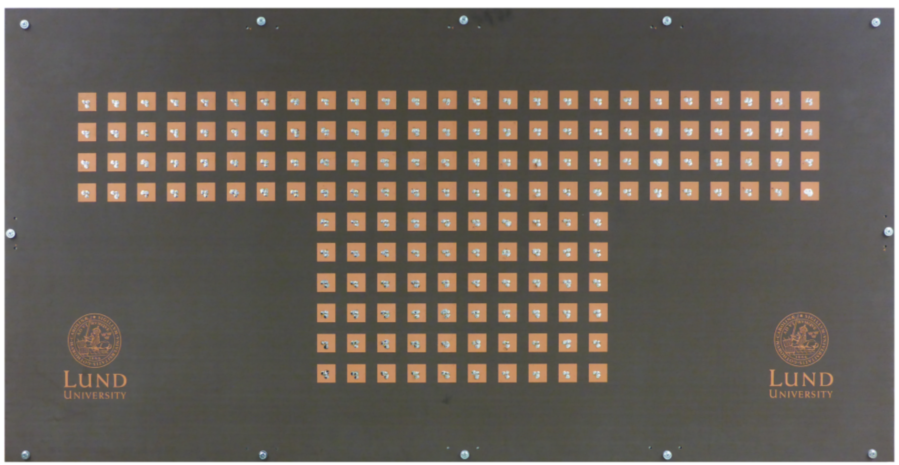
Many small dipoles with transceiver chains

Spatial multiplexing of tens of users

Massive numbers – not massive size

Typical vertical array:
10 antennas x 2 polarizations
Only 1-2 transceiver chains

60 cm



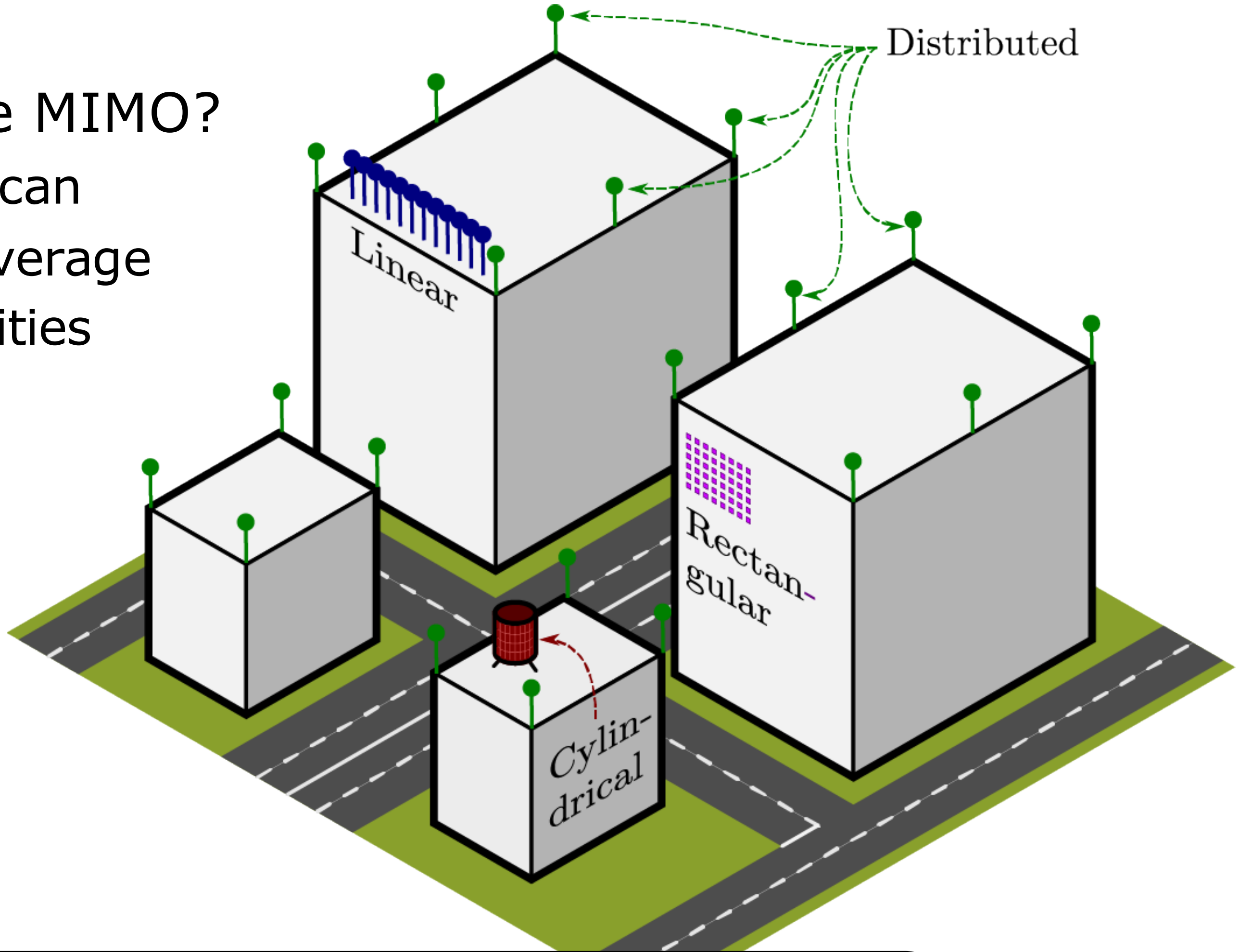
120 cm

160 dual-polarized antennas, 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 high user densities



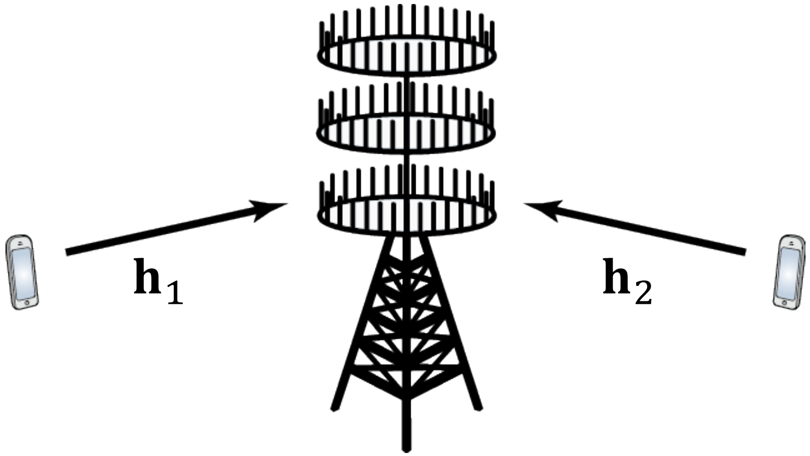
- Co-located Deployment
  - 1D, 2D, or 3D arrays
- Distributed Deployment
  - Remote radio heads

Benefits with Massive MIMO

Outdoor users:	Handle mobility and provide coverage
Indoor users:	No need to put BSs inside buildings

Original Motivation: Asymptotic Channel Orthogonality

- Example: Uplink Transmission
  - Two users, channels: $\mathbf{h}_1, \mathbf{h}_2 \sim CN(\mathbf{0}, \mathbf{I}_M)$
  - Signals: $s_1, s_2 \sim CN(0, P)$
  - Noise: $\mathbf{n} \sim CN(\mathbf{0}, \mathbf{I}_M)$
  - Received: $\mathbf{y} = \mathbf{h}_1 s_1 + \mathbf{h}_2 s_2 + \mathbf{n}$

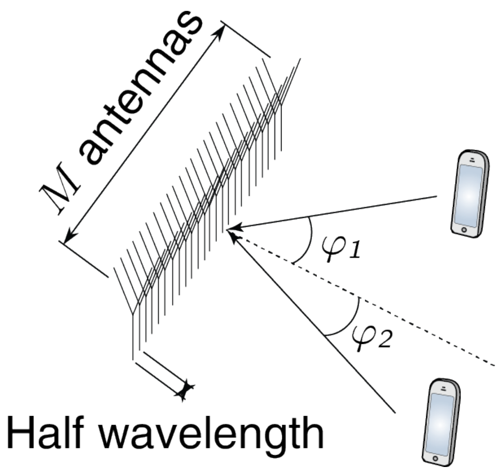


- Linear Processing for User 1: $\tilde{y}_1 = \mathbf{g}_1^H \mathbf{y} = \boxed{\mathbf{g}_1^H \mathbf{h}_1} s_1 + \boxed{\mathbf{g}_1^H \mathbf{h}_2} s_2 + \boxed{\mathbf{g}_1^H \mathbf{n}}$
  - Maximum ratio filter: $\mathbf{g}_1 = \frac{1}{M} \mathbf{h}_1$
  - Signal remains: $\mathbf{g}_1^H \mathbf{h}_1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

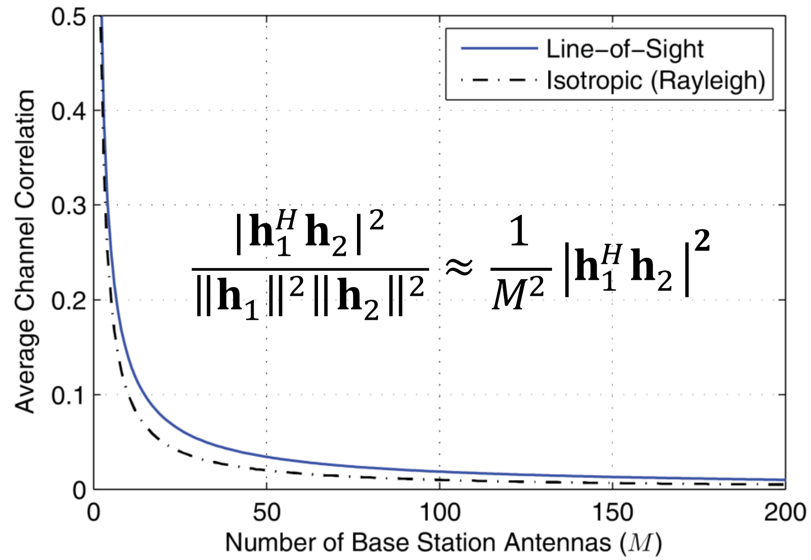
Asymptotically noise/interference-free communication: $\tilde{y}_1 \xrightarrow{M \to \infty} s_1$

Only for i.i.d. Rayleigh Fading Channels?

- Line-of-Sight Propagation

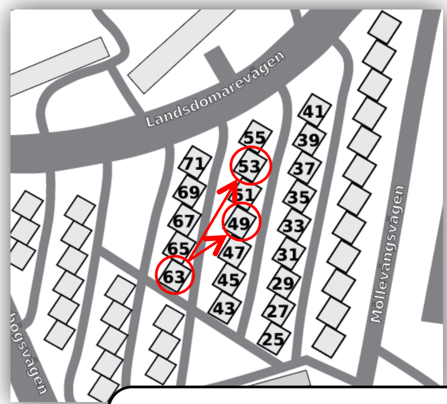


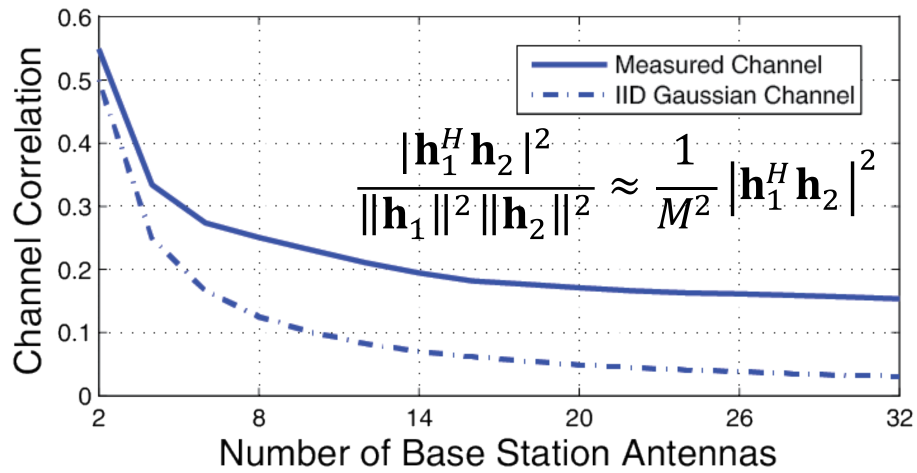
- Uniform linear array
- Random user angles
- M observations:
  - Stronger signal
  - Suppressed noise
- What is $\mathbf{h}_1^H \mathbf{h}_2 \rightarrow ?$



- Channel Measurements

Source: X. Gao, O. Edfors, F. Rusek, and F. Tufvesson, "Linear Pre-Coding Performance in Measured Very-Large MIMO Channels," VTC 2011.

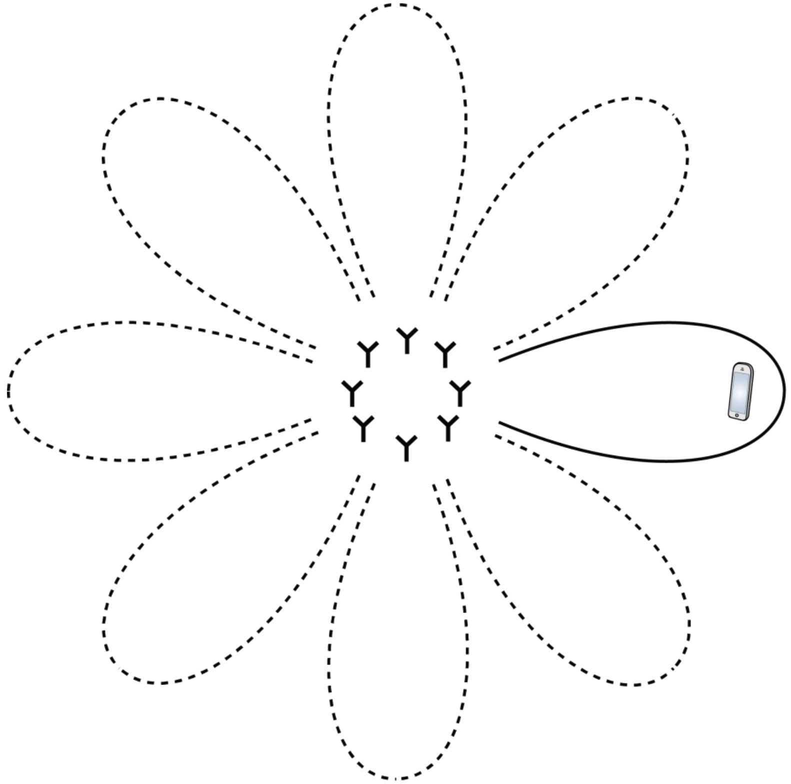


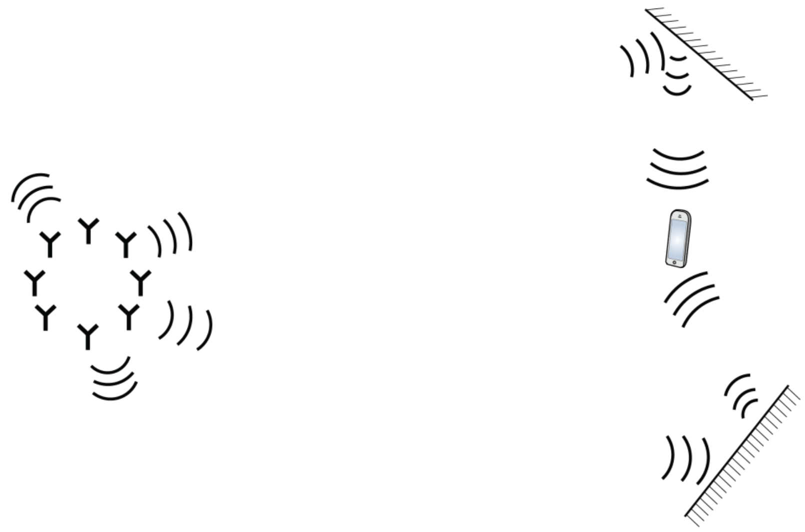


Different scenarios:
Determine how quickly interference is suppressed

MIMO Transmission

Same principles for uplink





Line-of-Sight

Channels determined by angles

1-2 parameters to estimate per user

Precoding = Beamforming

Non-Line-of-Sight

Rich multipath propagation

M parameters to estimate per user

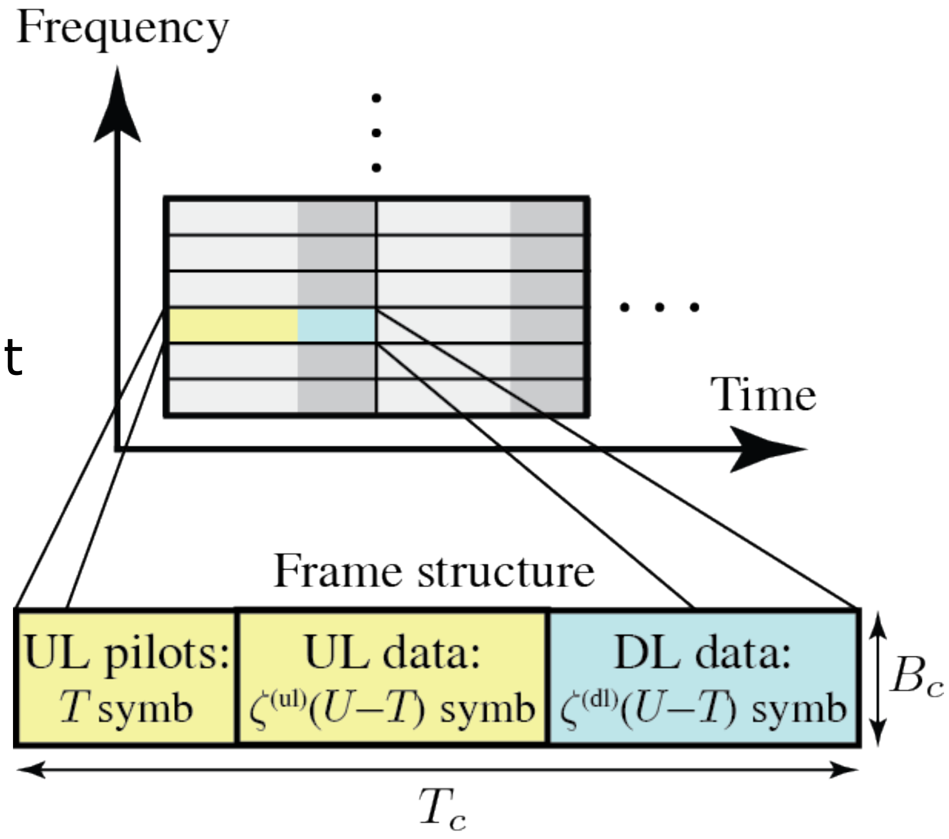
Precoding $\neq$ Beamforming

Massive MIMO aims at handling both cases!

Need to estimate M parameters efficiently even if M is large

Massive MIMO Transmission Protocol

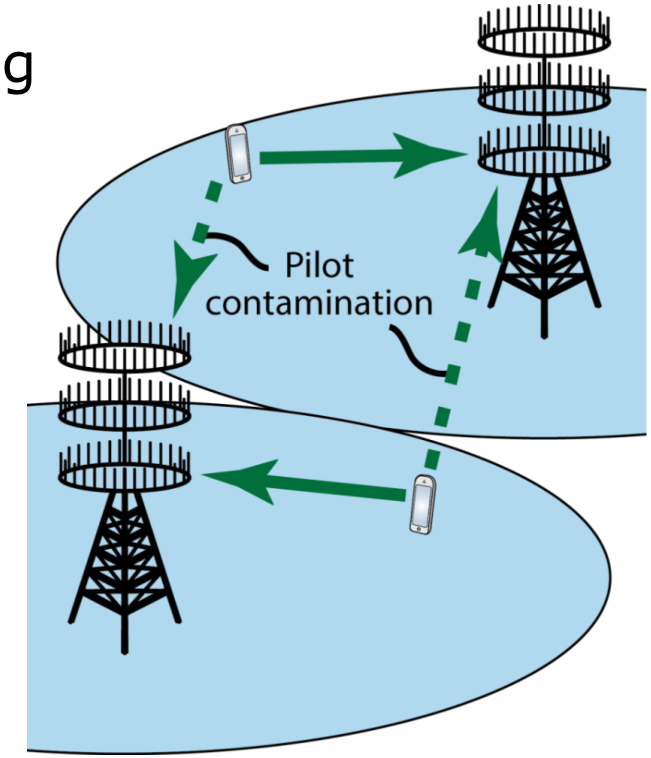
- Coherence Blocks
  - Fixed channel responses
  - Coherence time: T_c s
  - Coherence bandwidth: B_c Hz
  - Depends on mobility and environment
  - Block length: $U = T_c B_c$ symbols
  - Typically: $U \in [100,10000]$



- Time-Division Duplex (TDD)
  - Switch between downlink and uplink on all frequencies
  - T symbols/block for uplink pilots – to estimate channel responses
  - Number of pilots proportional to number of users K, independent of M
  - $U - T$ symbols/block for uplink and/or downlink payload data

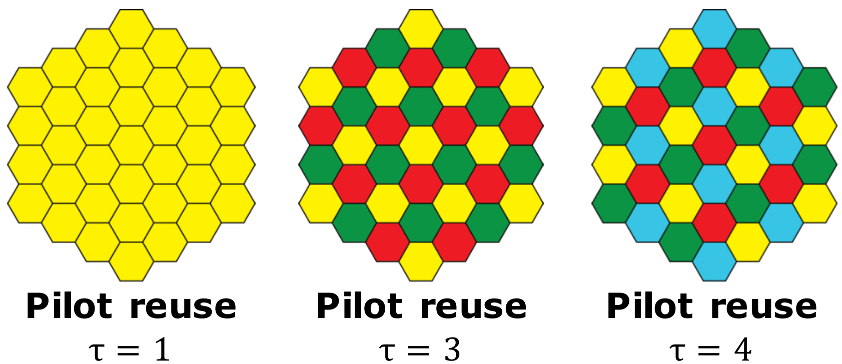
Channel Acquisition in Cellular Networks

- Each BS Needs to Know Channels for Processing
  - Estimate using uplink pilot symbols
  - Only T pilot symbols available (pick $K \leq T \leq U$)
  - Must use same pilot symbols in different cells!
  - Base stations cannot tell some users apart



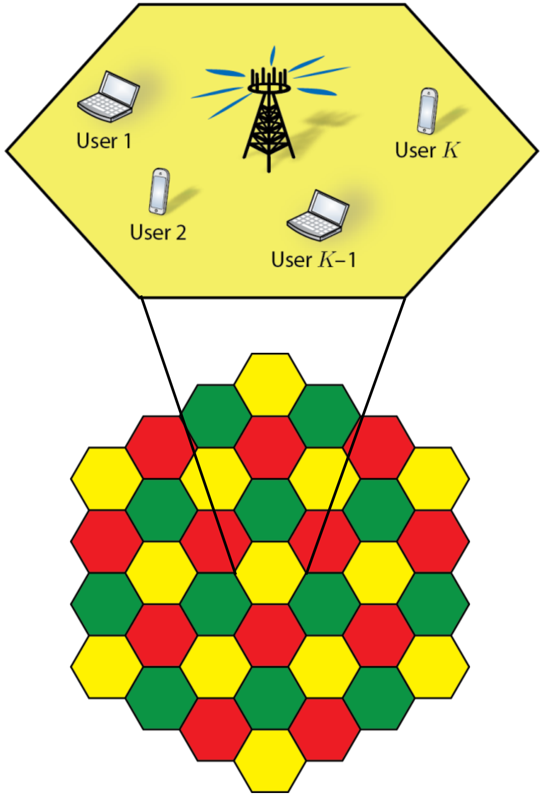
- Called: Pilot Contamination
  - Recall: Noise and interference vanish as $M \to \infty$
  - Not interference between users with same pilot!

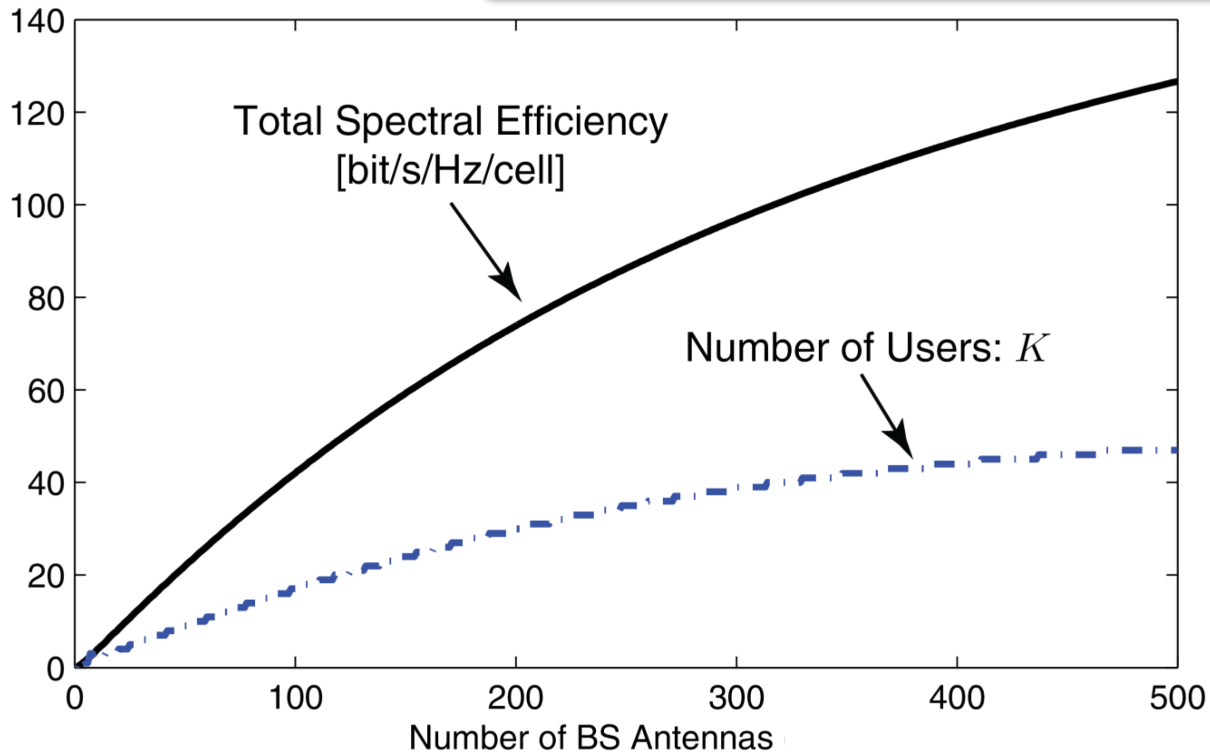
- Solution: Select how often pilots are reused
  - Pilot reuse factor $\tau \geq 1$
  - Users per cell: $K = \frac{T}{\tau}$
  - Higher τ → Fewer users per cell,
    but interferers further away



How Much can Spectral Efficiency be Improved?

Similar results for downlink





Uplink Simulation

LTE-like system parameters

Coherence block: $U = 500$

SNR 5 dB, i.i.d. Rayleigh fading

ZF detector and pilot reuse $\tau = 3$

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

Massive MIMO and Energy Efficiency

- Advantages
  - Better energy focusing (transmit power per user can scale as $1/\sqrt{M}$)
  - Improved cell edge conditions (only desired signals are amplified)
  - Multiple users share the load-independent "costs" per BS

- Disadvantages
  - More transceiver hardware per BS
  - Reduction in transmit power is modest
  - TDD protocols needed to enable precoding for large M

Summary

- Energy Efficiency is Important for Future Networks
  - Can be improved by network densification
  - Two approaches: Small cells and Massive MIMO

- Which Approach to Choose?
  - Cannot only be answered by proper EE modeling and optimization
  - **Methodology and key observations provided in this tutorial!**

Part 1

Questions?

Part 2

General Problem Formulation

How to Measure Energy-Efficiency?

- Recall: Energy-Efficiency (EE) in bit/Joule

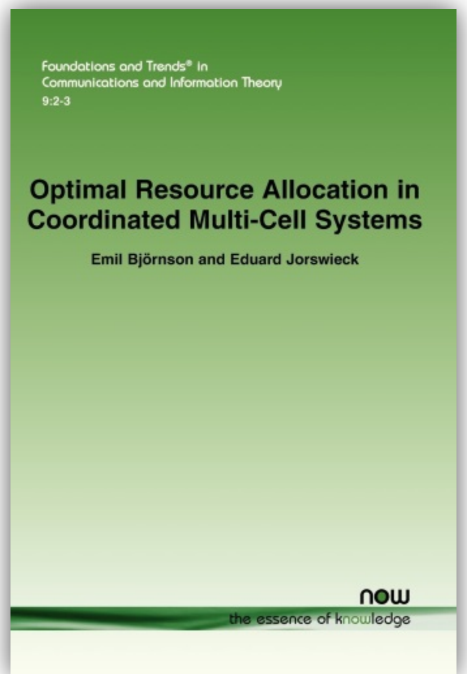
$$\mathrm{EE} = \frac{\text{Average Sum Rate [bit/s/cell]}}{\text{Power Consumption [Joule/s/cell]}}$$

- Conventional Academic Approaches:
  - Maximize rates with fixed power
  - Minimize transmit power for fixed rates
  - See for example:

Optimal Resource Allocation in Coordinated Multi-Cell Systems

Book from 2013 by Emil Björnson and Eduard Jorswieck

E-book is free to download



New Problem: Balance rates and power consumption

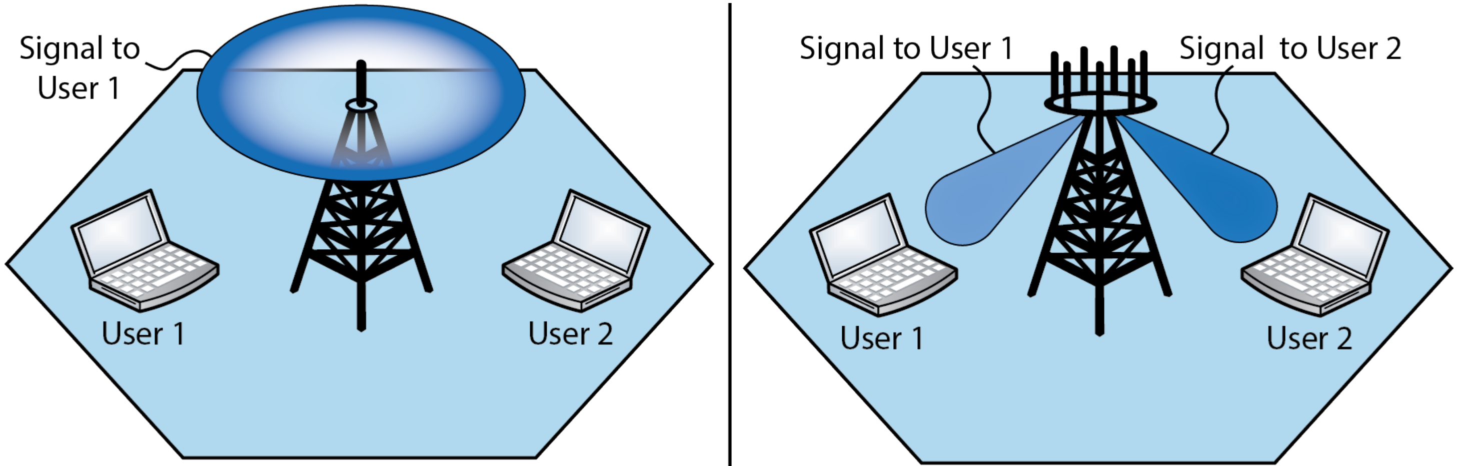
Ratio: Important to account for overhead signaling and circuit power!

Basic Information Theory

Achievable Rate per Active User [Lower Bound on Shannon Capacity]

$$\text{Bandwidth} \cdot \log_2\left(1 + \underbrace{\frac{\text{Received Signal Power}}{\text{Interference Power} + \text{Noise Power}}}_{\text{Signal-to-interference-and-noise ratio (SINR)}}\right) \quad \text{[bit/s/active user]}$$

- Can we Have Multiple Active User per Cell?
  - Yes, but causes inter-user interference
  - Traditional approach: Orthogonal in time/frequency (TDMA, OFDMA)
  - New multi-antenna approach: Space-division multiple access (SDMA)



Single-Antenna Transmission | Multi-Antenna Transmission

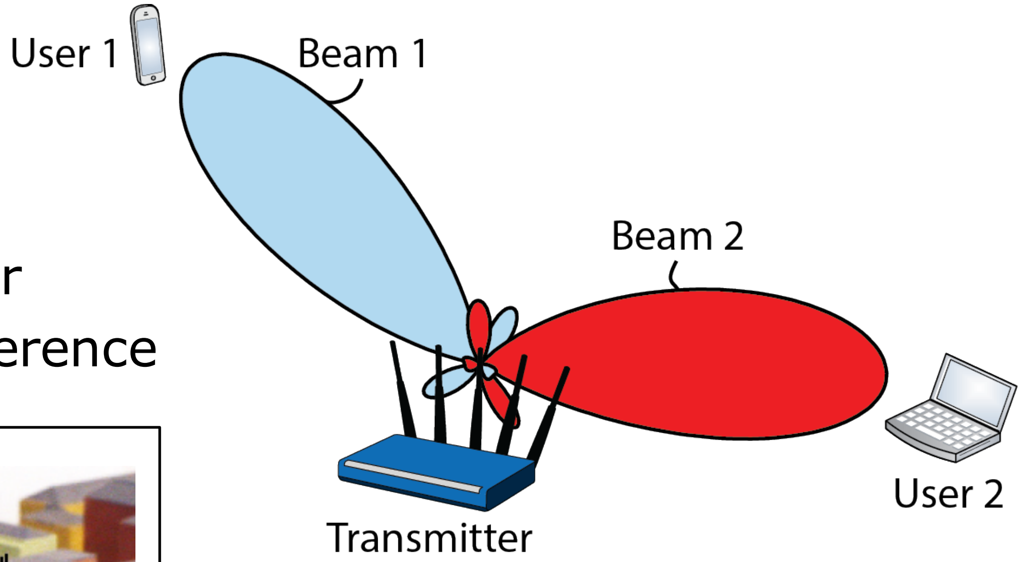
Known as

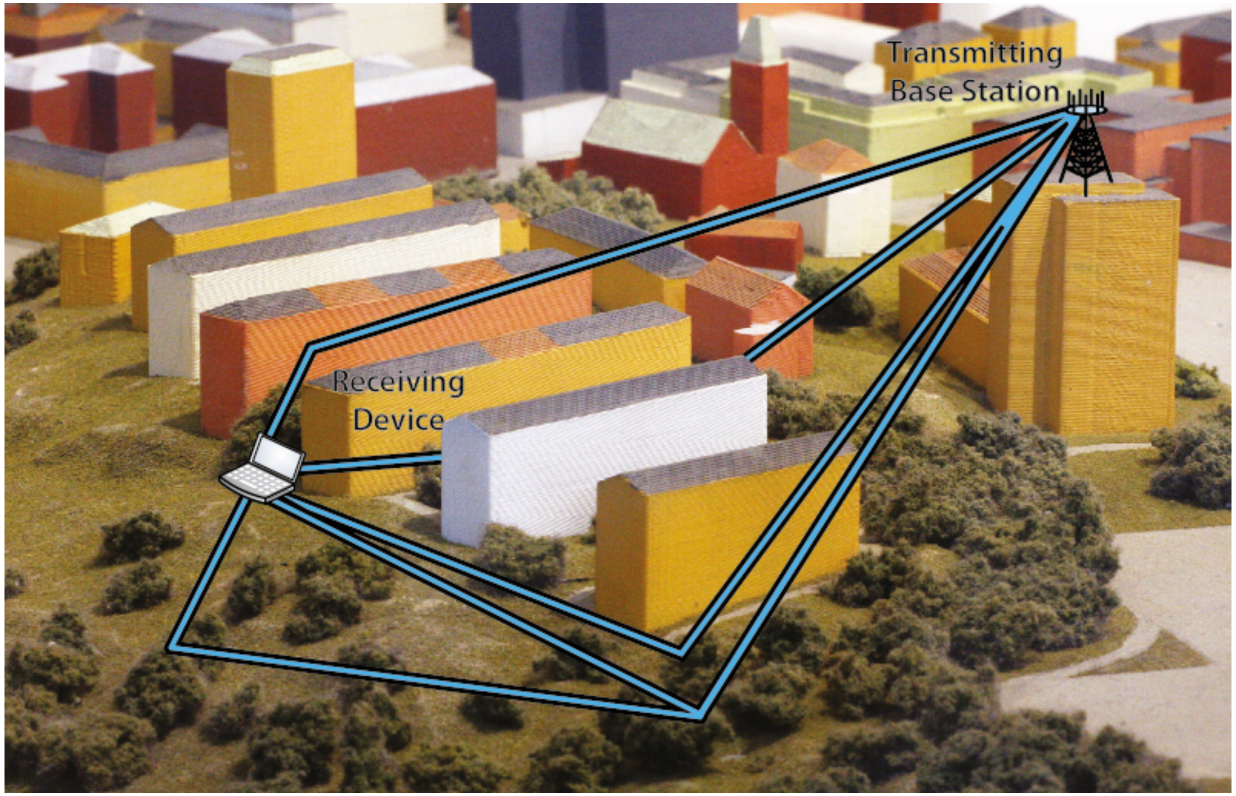
Multi-user MIMO

(massive if very many antennas)

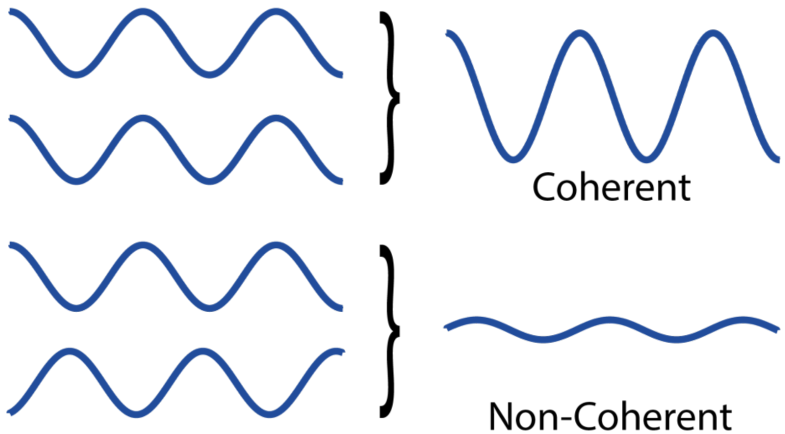
Recall: Precoding in Line-of-Sight and Non-Line-of-Sight

- Line-of-Sight
  - Adapt signal phases at antennas
  - Steer beam towards receiving user
  - Not laser beams: inter-user interference

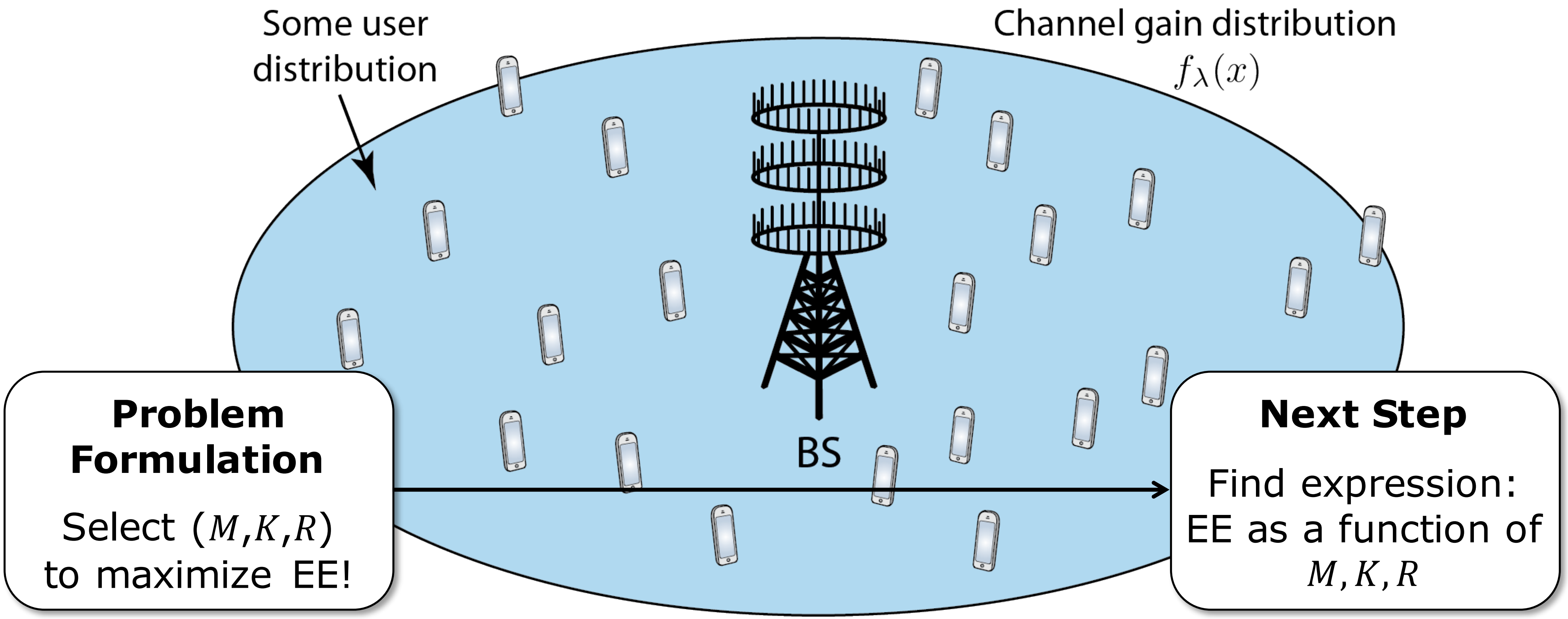




- Non-Line-of-Sight
  - Multipath propagation
  - Add components coherently



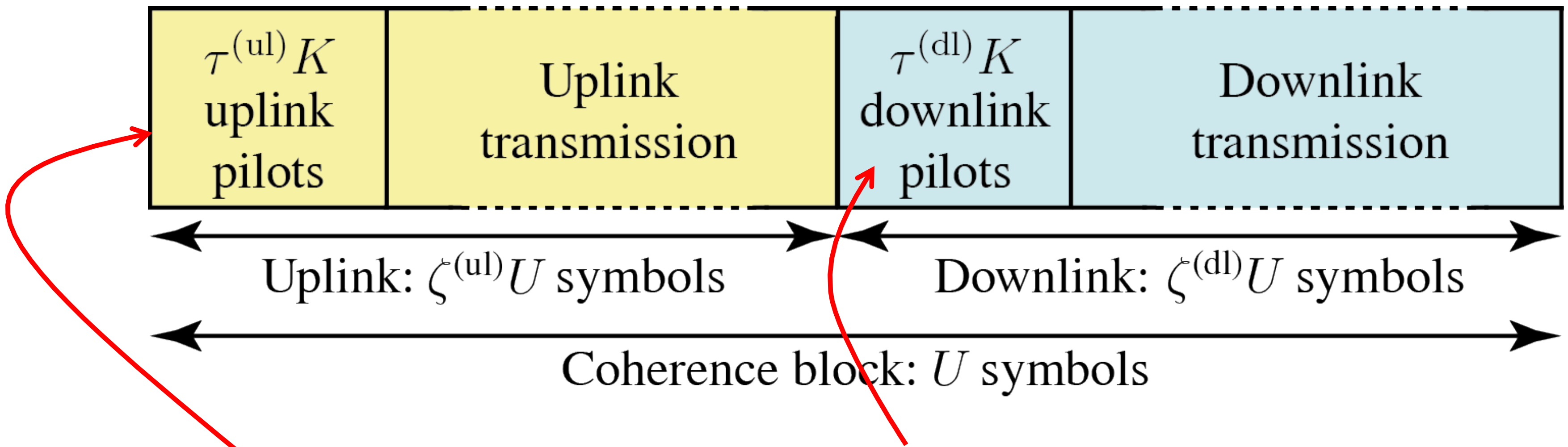
- Clean Slate Design
  - Single Cell: One base station (BS) with M antennas
  - Geometry: Random distribution for user locations and pathlosses
  - Multiple users: Pick K users randomly and serve with some rate R



System Model: Protocol

- Time-Division Duplex (TDD) Protocol
  - Uplink and downlink separated in time
  - Uplink fraction $\zeta^{(\mathrm{ul})}$ and downlink fraction $\zeta^{(\mathrm{dl})}$

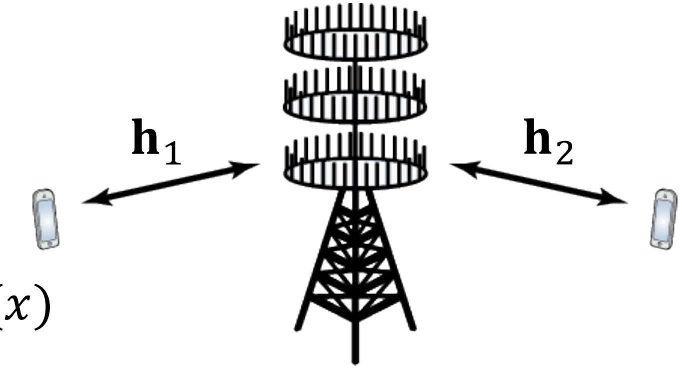
- Symbol Time and Coherence Block
  - B Hz bandwidth = B "channel uses" per second (symbol time $1/B$)
  - Channel stays fixed for U channel uses (symbols) = Coherence block
  - Determines how often we send pilot signals to estimate channels



Assumption: Perfect channel estimation (relaxed later)

System Model: Uplink Channels

- Flat-Fading Channels
  - Channel between BS and User k: $\mathbf{h}_k \in \mathbb{C}^M$
  - Rayleigh fading: $\mathbf{h}_k \sim \mathcal{CN}(\mathbf{0}, \lambda_k \mathbf{I})$
  - Channel variances λ_k: Random variables, pdf $f_\lambda(x)$



- Uplink Transmission
  - User k transmits signal s_k with power $\mathbb{E}\{|s_k|^2\} = \mathrm{p}_k^{(\mathrm{ul})}$ [Joule/channel use]
  - Received signal at BS:

$$\underbrace{\boldsymbol{y} = \mathbf{h}_k s_k}_{\text{Signal of User } k} + \underbrace{\sum_{i=1,\, i\neq k}^{K} \mathbf{h}_i s_i}_{\text{Signals from other users (interference)}} + \underbrace{\mathbf{n}}_{\text{Noise} \sim \mathcal{CN}(\mathbf{0}, \sigma^2 \mathbf{I})}$$

Signals from other users (interference)

Signal of User k

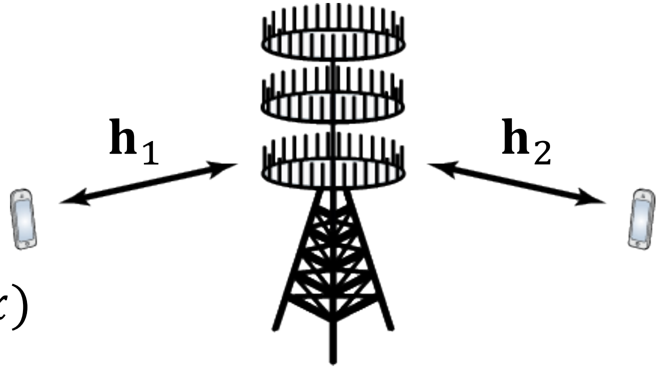
Noise $\sim \mathcal{CN}(\mathbf{0}, \sigma^2 \mathbf{I})$

  - Recover s_k by receive combining $\mathbf{g}_k$ as $\mathbf{g}_k^H \boldsymbol{y}$:

$$\mathrm{SINR}_k^{(\mathrm{ul})} = \frac{\mathbb{E}\left\{|s_k|^2 \left|\mathbf{g}_k^H \mathbf{h}_k\right|^2\right\}}{\sum_{i\neq k} \mathbb{E}\left\{|s_i|^2 \left|\mathbf{g}_k^H \mathbf{h}_i\right|^2\right\} + \mathbb{E}\left\{\left|\mathbf{g}_k^H \mathbf{n}\right|^2\right\}} = \frac{\mathrm{p}_k^{(\mathrm{ul})} |\mathbf{g}_k^H \mathbf{h}_k|^2}{\sum_{i\neq k} \mathrm{p}_i^{(\mathrm{ul})} |\mathbf{g}_k^H \mathbf{h}_i|^2 + \sigma^2 \|\mathbf{g}_k\|^2}$$

System Model: Downlink Channels

- Flat-Fading Channels
  - Channel between BS and User k: $\mathbf{h}_k \in \mathbb{C}^M$
  - Rayleigh fading: $\mathbf{h}_k \sim \mathcal{CN}(\mathbf{0}, \lambda_k \mathbf{I})$
  - Channel variances λ_k: Random variables, pdf $f_\lambda(x)$



- Downlink Transmission
  - BS transmits d_k to User k with power $\mathbb{E}\{|d_k|^2\} = \mathrm{p}_k^{(\mathrm{dl})}$ [Joule/channel use]
  - Spatial directivity by precoding vector $\mathbf{v}_k$
  - Received signal at User k:

Signals from other users (interference)

$$y_k = \mathbf{h}_k^H \frac{\mathbf{v}_k}{\|\mathbf{v}_k\|} d_k + \sum_{i=1,\, i\neq k}^{K} \mathbf{h}_k^H \frac{\mathbf{v}_i}{\|\mathbf{v}_i\|} d_i + n_k$$

Signal to User k

Noise $\sim \mathcal{CN}(0, \sigma^2)$

  - Recover d_k at User k:

$$\mathrm{SINR}_k^{(\mathrm{dl})} = \frac{\mathrm{p}_k^{(\mathrm{dl})} |\mathbf{h}_k^H \mathbf{v}_k|^2 / \|\mathbf{v}_k\|^2}{\sum_{i\neq k} \mathrm{p}_i^{(\mathrm{dl})} |\mathbf{h}_k^H \mathbf{v}_i|^2 / \|\mathbf{v}_i\|^2 + \sigma^2}$$

System Model: How Much Transmit Power?

- Design Parameter: *Gross* rate R
  - Make sure that $R = \begin{cases} B\log_2(1+\mathrm{SINR}_k^{(\mathrm{ul})}) & \text{for all } k \text{ in uplink} \\ B\log_2(1+\mathrm{SINR}_k^{(\mathrm{dl})}) & \text{for all } k \text{ in downlink} \end{cases}$
  - Select processing vectors $\mathbf{g}_k$ and $\mathbf{v}_k$, adapt transmit power $\mathrm{p}_k^{(\mathrm{ul})}$ and $\mathrm{p}_k^{(\mathrm{dl})}$

- Gives K equations:

$$\begin{cases} \mathrm{p}_k^{(\mathrm{ul})}|\mathbf{g}_k^H\mathbf{h}_k|^2 = (2^{R/B}-1)\left(\sum_{i\neq k}\mathrm{p}_i^{(\mathrm{ul})}\left|\mathbf{g}_k^H\mathbf{h}_i\right|^2 + \sigma^2\|\mathbf{g}_k\|^2\right) & \text{for } k=1,\ldots,K \\ \mathrm{p}_k^{(\mathrm{dl})}\frac{\left|\mathbf{h}_k^H\mathbf{v}_k\right|^2}{\|\mathbf{v}_k\|^2} = (2^{R/B}-1)\left(\sum_{i\neq k}\mathrm{p}_i^{(\mathrm{dl})}\frac{\left|\mathbf{h}_k^H\mathbf{v}_i\right|^2}{\|\mathbf{v}_i\|^2} + \sigma^2\right) & \text{for } k=1,\ldots,K \end{cases}$$

- Linear equations in transmit powers → Solve by Gaussian elimination!

Total Transmit Power [Joule/s] for $\mathbf{g}_k = \mathbf{v}_k$

Uplink energy/symbol: $\sigma^2\mathbf{D}^{-H}\mathbf{1}$

Downlink energy/symbol: $\sigma^2\mathbf{D}^{-1}\mathbf{1}$

Same total power: $P_{\mathrm{trans}} = B\mathbb{E}\{\sigma^2\mathbf{1}^H\mathbf{D}^{-1}\mathbf{1}\} = B\mathbb{E}\{\sigma^2\mathbf{1}^H\mathbf{D}^{-H}\mathbf{1}\}$

where $[\mathbf{D}]_{k,l} = \begin{cases} \frac{\left|\mathbf{h}_k^H\mathbf{v}_k\right|^2}{(2^{R/B}-1)\|\mathbf{v}_k\|^2} & \text{for } k=l \\ -\frac{\left|\mathbf{h}_k^H\mathbf{v}_l\right|^2}{\|\mathbf{v}_l\|^2} & \text{for } k\neq l \end{cases}$

System Model: How Much Transmit Power? (2)

- What did we Derive?
  - Optimal power allocation for fixed linear processing vectors

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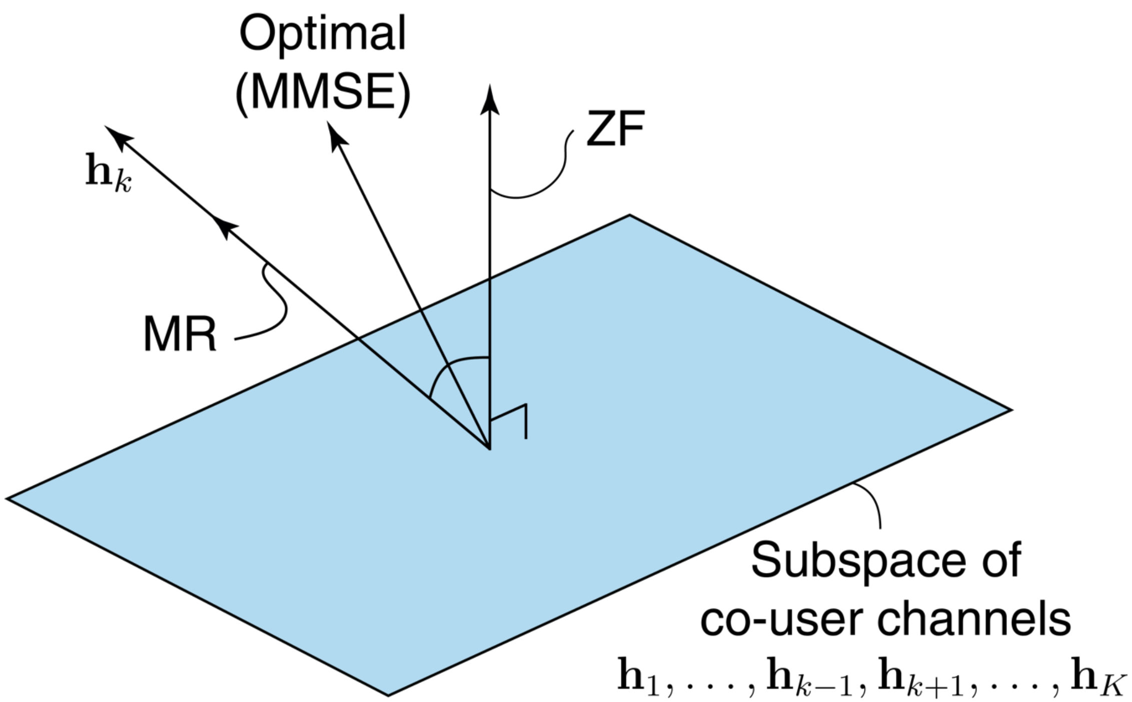
- Different Linear Processing
  - Notation: $\mathbf{G} = [\mathbf{g}_1, \dots, \mathbf{g}_K]$

    $\mathbf{V} = [\mathbf{v}_1, \dots, \mathbf{v}_K]$,

    $\mathbf{H} = [\mathbf{h}_1, \dots, \mathbf{h}_K]$,

    $\mathbf{P}^{(\mathrm{ul})} = \mathrm{diag}(p_1^{(\mathrm{ul})}, \dots, p_K^{(\mathrm{ul})})$



Minimize interference

Maximize signal

  - Maximum ratio (MR): $\mathbf{G} = \mathbf{V} = \mathbf{H}$
  - Zero-forcing (ZF): $\mathbf{G} = \mathbf{V} = \mathbf{H}(\mathbf{H}^H\mathbf{H})^{-1}$
  - Optimal (MMSE): $\mathbf{G} = \mathbf{V} = \left(\sigma^2\mathbf{I} + \mathbf{H}\,\mathbf{P}^{(\mathrm{ul})}\mathbf{H}^H\right)^{-1}\mathbf{H}$

Balance signal and interference (iteratively!)

System Model: How Much Transmit Power? (3)

- Simplified Expressions for ZF ($M \geq K+1$)
  - Main property: $\mathbf{H}^H \mathbf{V} = \mathbf{H}^H \mathbf{H}(\mathbf{H}^H \mathbf{H})^{-1} = \mathbf{I}$
  - Hence: $$[\mathbf{D}]_{k,l} = \begin{cases} \frac{|\mathbf{h}_k^H \mathbf{v}_k|^2}{(2^{R/B}-1)\|\mathbf{v}_k\|^2} & \text{for } k = l \\ -\frac{|\mathbf{h}_k^H \mathbf{v}_l|^2}{\|\mathbf{v}_l\|^2} & \text{for } k \neq l \end{cases} = \begin{cases} \frac{1}{(2^{R/B}-1)\|\mathbf{v}_k\|^2} & \text{for } k = l \\ 0 & \text{for } k \neq l \end{cases}$$
  - Total transmit power: $$P_{\text{trans}} = \mathbb{E}\{B\sigma^2 \mathbf{1}^H \mathbf{D}^{-1} \mathbf{1}\} = B\sigma^2 (2^{R/B}-1) \underbrace{\sum_k \mathbb{E}\{\|\mathbf{v}_k\|^2\}}_{= \operatorname{tr}\left(\left(\mathbf{H}^H\mathbf{H}\right)^{-1}\right)} = B\sigma^2(2^{R/B}-1)\frac{K}{M-K}\underbrace{\mathbb{E}\left\{\frac{1}{\lambda}\right\}}_{\text{Call this } \mathcal{S}_\lambda \text{ (depends on cell)}}$$

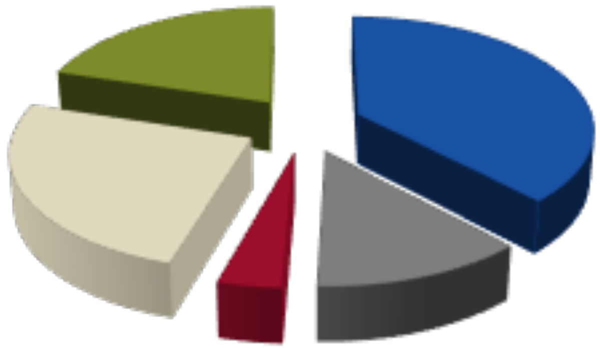
Property of Wishart matrices

Summary: Transmit Power with ZF

Parameterize gross rate as $R = B\log_2(1+\rho(M-K))$ for some ρ

Total transmit power: $P_{\text{trans}} = \rho B \sigma^2 \mathcal{S}_\lambda K$ [Joule/s]

Detailed Power Consumption Model



- What Consumes Power?
  - Not only radiated transmit power
  - Circuits, signal processing, backhaul, etc.
  - Must be specified as functions of M, K, R

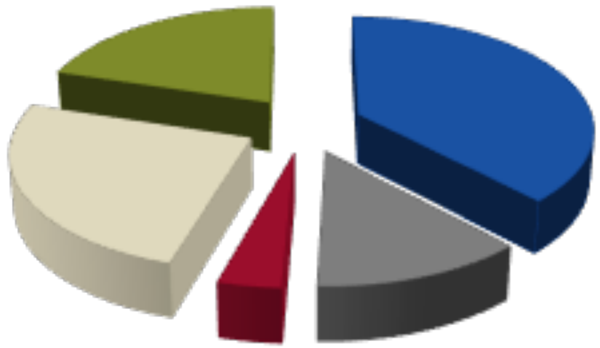
- Power Amplifiers
  - Amplifier efficiencies: $\eta^{(\mathrm{ul})}, \eta^{(\mathrm{dl})} \in (0,1]$
  - Average inefficiency: $\frac{\zeta^{(\mathrm{ul})}}{\eta^{(\mathrm{ul})}} + \frac{\zeta^{(\mathrm{dl})}}{\eta^{(\mathrm{dl})}} = \frac{1}{\eta}$

Summary: $\frac{P_{\mathrm{trans}}}{\eta}$

- Active Transceiver Chains
  - P_{FIX} = Fixed power (control signals, oscillator at BS, standby, etc.)
  - P_{BS} = Circuit power / BS antenna (converters, mixers, filters)
  - P_{UE} = Circuit power / user (oscillator, converters, mixer, filters)

Summary: $P_{\mathrm{FIX}} + M \cdot P_{\mathrm{BS}} + K \cdot P_{\mathrm{UE}}$

Detailed Power Consumption Model (2)



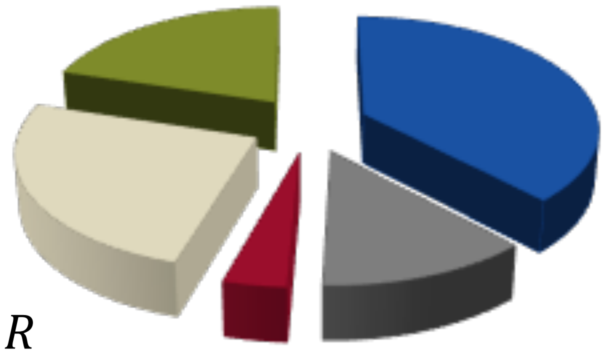
- Signal Processing
  - Channel estimation and precoding/combining
  - Efficiency: $L_{\mathrm{BS}}, L_{\mathrm{UE}}$ arithmetic operations / Joule

- Channel Estimation: $\frac{B}{U}\left(\frac{2\tau^{(\mathrm{ul})}MK^2}{L_{\mathrm{BS}}} + \frac{4\tau^{(\mathrm{dl})}K^2}{L_{\mathrm{UE}}}\right)$
  - Once in uplink/downlink per coherence block
  - Pilot signal lengths: $\tau^{(\mathrm{ul})}K, \tau^{(\mathrm{dl})}K$ for some $\tau^{(\mathrm{ul})}, \tau^{(\mathrm{dl})} \geq 1$

- Linear Processing (for $\mathbf{G} = \mathbf{V}$): $\frac{B}{U}\frac{C_{\mathrm{precoding}}}{L_{\mathrm{BS}}} + B\left(1 - \frac{(\tau^{(\mathrm{ul})} + \tau^{(\mathrm{ul})})K}{U}\right)\frac{2MK}{L_{\mathrm{BS}}}$
  - Compute precoding/combining vectors once per coherence block
  - Use same vectors for all $B\left(1 - \left(\tau^{(\mathrm{ul})} + \tau^{(\mathrm{ul})}\right)K/U\right)$ symbols
  - Types of precoding: $$C_{\mathrm{precoding}} = \begin{cases} 3MK & \text{for MR} \\ 3MK^2 + MK + K^3/3 & \text{for ZF} \\ Q(3MK^2 + MK + K^3/3) & \text{for MMSE} \end{cases}$$

Q = Number of iterations

Detailed Power Consumption Model (3)

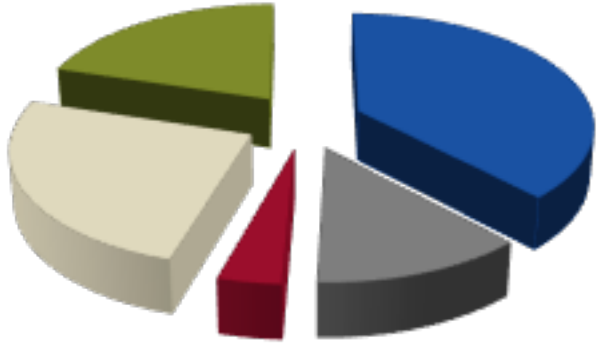


- Coding and Decoding: $R_{\text{sum}}(P_{\text{COD}} + P_{\text{DEC}})$
  - P_{COD} = Energy for coding data / bit
  - P_{DEC} = Energy for decoding data / bit
  - Sum rate: $R_{\text{sum}} = K\left(\zeta^{(\text{ul})} - \frac{\tau^{(\text{ul})}K}{U}\right)R + K\left(\zeta^{(\text{dl})} - \frac{\tau^{(\text{dl})}K}{U}\right)R$

$$= K\left(1 - \frac{(\tau^{(\text{ul})} + \tau^{(\text{dl})})K}{U}\right)R$$

- Backhaul Signaling: $P_{\text{BH}} + R_{\text{sum}} P_{\text{BT}}$
  - P_{BH} = Load-independent backhaul power
  - P_{BT} = Energy for sending data over backhaul / bit

Detailed Power Consumption Model: Summary



- Many Things Consume Power
  - Parameter values (e.g., $P_{\mathrm{BS}}, P_{\mathrm{UE}}$) change over time
  - Structure is important for analysis

Fixed power

A Generic Power Model

$$\frac{P_{\mathrm{trans}}}{\eta} + C_{0,0} + \underbrace{C_{0,1}M + C_{1,0}K}_{\text{Circuit power per transceiver chain}} + \underbrace{C_{1,1}MK + C_{2,0}K^2 + C_{3,0}K^3 + C_{2,1}MK^2}_{\text{Cost of signal processing}} + \underbrace{AK\left(1 - \frac{(\tau^{(\mathrm{ul})} + \tau^{(\mathrm{dl})})K}{U}\right)R}_{\text{Coding/decoding/backhaul}}$$

Transmit with amplifiers

for some parameters $C_{l,m}$ and A

- Observations
  - Polynomial in M and K → Increases faster than linear with K
  - Depends on cell geometry only through P_{trans}

Finally: Problem Formulation

- Maximize Energy-Efficiency:

Average Sum Rate [bit/s/cell]

$$\underset{M,K,R}{\text{maximize}} \quad \frac{K\left(1-\frac{(\tau^{(\mathrm{ul})}+\tau^{(\mathrm{dl})})K}{U}\right)R}{\underbrace{\frac{P_{\text{trans}}}{\eta}+\sum_{i=0}^{3} C_{i,0}K^{i}+\sum_{i=0}^{2} C_{i,1}MK^{i}+AK\left(1-\frac{(\tau^{(\mathrm{ul})}+\tau^{(\mathrm{dl})})K}{U}\right)R}_{\text{Power Consumption [Joule/s/cell]}}}$$

Closed Form Expressions with ZF – Part 3

Recall: $R = B\log_2(1+\rho(M-K))$ for some ρ and $P_{\text{trans}} = \rho B\sigma^2 \mathcal{S}_\lambda K$

Define: $\tau = \tau^{(\mathrm{ul})} + \tau^{(\mathrm{dl})}$

$$\underset{M,K,\rho}{\text{maximize}} \quad \frac{K\left(1-\frac{\tau K}{U}\right)B\log_2(1+\rho(M-K))}{\frac{\rho B\sigma^2\mathcal{S}_\lambda K}{\eta}+\sum_{i=0}^{3} C_{i,0}K^{i}+\sum_{i=0}^{2} C_{i,1}MK^{i}+AK\left(1-\frac{\tau K}{U}\right)B\log_2(1+\rho(M-K))}$$

Simple ZF expression: Used for analysis, other schemes by simulation

Why Such a Detailed/Complicated Model?

- Simplified Model → Unreliable Optimization Results
  - Two examples based on ZF
  - Beware: Both have appeared in the literature!

- Example 1: Fixed circuit power and no coding/decoding/backhaul

$$\underset{M,K,\rho}{\text{maximize}} \quad \frac{K\left(1-\frac{\tau K}{U}\right) B \log_2(1+\rho(M-K))}{\frac{\rho B \sigma^2 \mathcal{S}_\lambda K}{\eta} + C_{0,0}}$$

  - If $M \to \infty$, then $\log_2(1+\rho(M-K)) \to \infty$ and thus $\mathrm{EE} \to \infty$!

- Example 2: Ignore pilot overhead and signal processing

$$\underset{M,K,\rho}{\text{maximize}} \quad \frac{KB \log_2(1+\rho(M-K))}{\frac{\rho B \sigma^2 \mathcal{S}_\lambda K}{\eta} + C_{0,0} + C_{1,0}K + C_{0,1}M} = \frac{B \log_2(1+\rho K(\frac{M}{K}-1))}{\frac{\rho B \sigma^2 \mathcal{S}_\lambda}{\eta} + \frac{C_{0,0}}{K} + C_{1,0} + C_{0,1}\frac{M}{K}}$$

  - If $M, K \to \infty$ with $\frac{M}{K} = \text{constant} > 1$, then $\log_2(1+\rho K(\frac{M}{K}-1)) \to \infty$ and $\mathrm{EE} \to \infty$!

Summary

- Modeling of the EE metric
  - EE is a rate/power ratio → Sensitive to modeling inaccuracies
  - Rate: Overhead signaling must be included
  - Power: Both transmit and circuit power are important

- Main Result: General EE Maximization Formulation

$$\underset{M,K,R}{\text{maximize}} \quad \frac{K\left(1-\frac{(\tau^{(\text{ul})}+\tau^{(\text{dl})})K}{U}\right)R}{\frac{P_{\text{trans}}}{\eta}+\sum_{\boldsymbol{i=0}}^{\boldsymbol{3}} C_{i,0}K^{i}+\sum_{\boldsymbol{i=0}}^{\boldsymbol{2}} C_{i,1}MK^{i}+AK\left(1-\frac{(\tau^{(\text{ul})}+\tau^{(\text{dl})})K}{U}\right)R}$$

  - Solvable numerically for any processing scheme (since M, K integers)
  - Numerical observations might not hold for other parameter values

  - Analytic solutions: Reveal fundamental behaviors and tradeoffs!
  - **Part 3: Analytic solution with ZF, numerical for other schemes**

Part 2

Questions?

Part 3

Optimization of Energy-Efficiency:

Fixed Regular Deployment

Preliminaries

- Our Goal
  - Optimize number of antennas M
  - Optimize number of active users K
  - Optimize the (normalized) transmit power ρ

For ZF processing: **Analytically solvable!**

- Outline
  - Optimize each variable separately
  - Devise an alternating optimization algorithm

Definition (Lambert W function)

- Lambert W function, $W(x)$, solves equation $W(x)e^{W(x)} = x$
- The function is increasing and satisfies $W(0) = 0$
- $e^{W(x)}$ behaves as a linear function (i.e., $e^{W(x)} \approx x$):

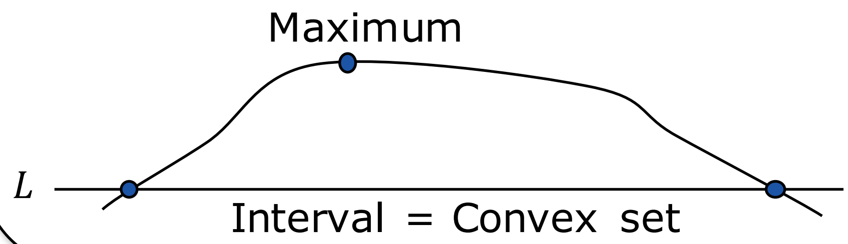
$$\frac{x\, e}{\log_e(x)} \leq e^{W(x)+1} \leq \frac{x}{\log_e(x)}(1+e) \quad \text{for} \quad x \geq e.$$

Solving Optimization Problems

- How to Solve an Optimization Problem?
  - Simple if the function is "nice" → "Looks like a mountain"

Quasi-Concave Function $\varphi(x)$

For any value L, the x that gives $\varphi(x) \geq L$ is a convex set:
For any x_1, x_2 with $\varphi(x_1) = \varphi(x_2)$, line between x_1 and x_2 is below the graph



Property: Goes up and then down

Examples: $-x^2, \log(x), [x]$

- Maximization of Continuous Quasi-Concave Function $\varphi(x)$:
  1. Compute the first derivative $\frac{d}{dx}\varphi(x)$
  2. Find switching point by setting $\frac{d}{dx}\varphi(x) = 0$
  3. Only one solution → It is the unique maximum!

Optimal Number of BS Antennas

- Find M that maximizes EE with ZF (recall $M > K$):

$$\underset{M \geq K+1}{\text{maximize}} \quad \frac{K\left(1-\frac{\tau K}{U}\right) B \log_2(1+\rho(M-K))}{\frac{\rho B \sigma^2 \mathcal{S}_\lambda K}{\eta} + \sum_{i=0}^{3} \mathcal{C}_{i,0} K^i + \sum_{i=0}^{2} \mathcal{C}_{i,1} M K^i + AK\left(1-\frac{\tau K}{U}\right) B \log_2(1+\rho(M-K))}$$

Theorem 1 (Optimal M)

EE is quasi-concave w.r.t. M and maximized by

$$M^* = \frac{e^{W\left(\frac{\rho(B\sigma^2 \mathcal{S}_\lambda K/\eta + \sum_{i=0}^{3} \mathcal{C}_{i,0} K^i)}{e \sum_{i=0}^{2} \mathcal{C}_{i,1} K^i} + \frac{\rho K - 1}{e}\right)+1} + \rho K - 1}{\rho}$$

- Observations
  - Increases with circuit coefficients independent of M (e.g., $P_{\text{FIX}}, P_{\text{UE}}$)
  - Decreases with circuit coefficients multiplied with M (e.g., $P_{\text{BS}}, 1/L_{BS}$)
  - Independent of cost of coding/decoding/backhaul
  - Increases with power ρ approx. as $\frac{\rho}{\log \rho}$ (almost linear)

Optimal Transmit Power

- Find ρ that maximizes EE with ZF:

$$\underset{\rho \geq 0}{\text{maximize}} \quad \frac{K\left(1-\frac{\tau K}{U}\right) B \log_2(1+\rho(M-K))}{\frac{\rho B \sigma^2 \mathcal{S}_\lambda K}{\eta} + \sum_{i=0}^{3} \mathcal{C}_{i,0} K^i + \sum_{i=0}^{2} \mathcal{C}_{i,1} M K^i + \mathcal{A} K \left(1-\frac{\tau K}{U}\right) B \log_2(1+\rho(M-K))}$$

Theorem 2 (Optimal ρ)

EE is quasi-concave w.r.t. ρ and maximized by

$$\rho^* = \frac{e^{W\left(\frac{\eta}{B\sigma^2 \mathcal{S}_\lambda} \frac{(M-K)\left(\sum_{i=0}^{3} \mathcal{C}_{i,0} K^i + \sum_{i=0}^{2} \mathcal{C}_{i,1} M K^i\right)}{e} - \frac{1}{e}\right)+1} - 1}{M-K}$$

- Observations
  - Increases with all circuit coefficients (e.g., $P_{\mathrm{FIX}}, P_{\mathrm{BS}}, P_{\mathrm{UE}}, 1/L_{BS}$)
  - Independent of cost of coding/decoding/backhaul
  - Increases with M approx. as $\frac{M}{\log M}$ (almost linear)

More circuit power → More transmit power

Power/antenna decreases $\frac{1}{\log M}$

Optimal Number of Users

- Find K that maximizes EE with ZF:

$$\underset{K \geq 0}{\text{maximize}} \quad \frac{K\left(1-\frac{\tau K}{U}\right) B \log_2(1+\bar{\rho}(\bar{\beta}-1))}{\frac{\bar{\rho} B \sigma^2 \mathcal{S}_\lambda}{\eta} + \sum_{\boldsymbol{i=0}}^{\boldsymbol{3}} C_{i,0} K^i + \sum_{\boldsymbol{i=0}}^{\boldsymbol{2}} C_{i,1} \bar{\beta} K^{i+1} + AK\left(1-\frac{\tau K}{U}\right) B \log_2(1+\bar{\rho}(\bar{\beta}-1))}$$

where $\bar{\rho} = \rho K$ and $\bar{\beta} = \frac{M}{K}$ are fixed

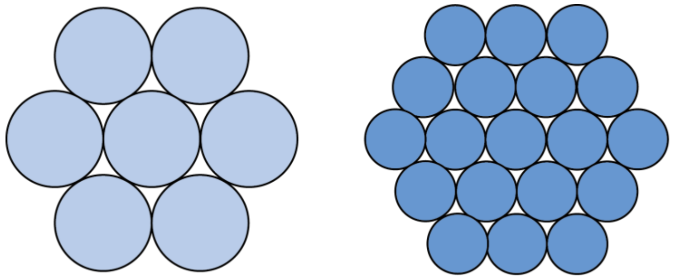
Theorem 3 (Optimal K)

EE is quasi-concave w.r.t. K

Maximized by the root of a quartic polynomial:
Closed form for K^* but very “large” expressions

- Observations
  - Increases with fixed circuit power (e.g., P_{FIX})
  - Decreases with circuit coefficients multiplied with M or K ($P_{\text{BS}}, P_{\text{UE}}, 1/L_{BS}$)

Impact of Cell Size



- Are Smaller Cells More Energy Efficient?
  - Recall: $\mathcal{S}_\lambda = \mathbb{E}\left\{\frac{1}{\lambda}\right\}$
  - Smaller cells → λ is larger → $\mathcal{S}_\lambda$ is smaller

- For any given parameters M, ρ, K
  - Smaller $\mathcal{S}_\lambda$ → smaller transmit power $\rho B \sigma^2 \mathcal{S}_\lambda K$
  - Higher EE! Yes, small cells are better!

- Expressions for M^*, ρ^*, K^*
  - M^* and K^* increases with $\mathcal{S}_\lambda$
  - ρ^* decreases with $\mathcal{S}_\lambda$

Smaller cells:
Less hardware and fewer users per cell
Use shorter distances to reduce power

Dependence on Other Parameters

Many other observations can be made from the expressions
Example: Impact of bandwidth B, coherence block length U, etc.

Alternating Optimization Algorithm

- Joint EE Optimization
  - EE is a function of M, ρ, and K
  - Theorems 1-3 optimize one parameter, when the other two are fixed
  - Can we optimize all of them?

Algorithm: Alternating Optimization

1. Assume that an initial set (M, ρ, K) is given
2. Update number of users K (and implicitly M and ρ) using Theorem 3
3. Update number of antennas M using Theorem 1
4. Update transmit power (ρ) using Theorem 2
5. Repeat 2.-5. until convergence

Theorem 4

The algorithm convergences to a local optimum to the joint EE optimization problem

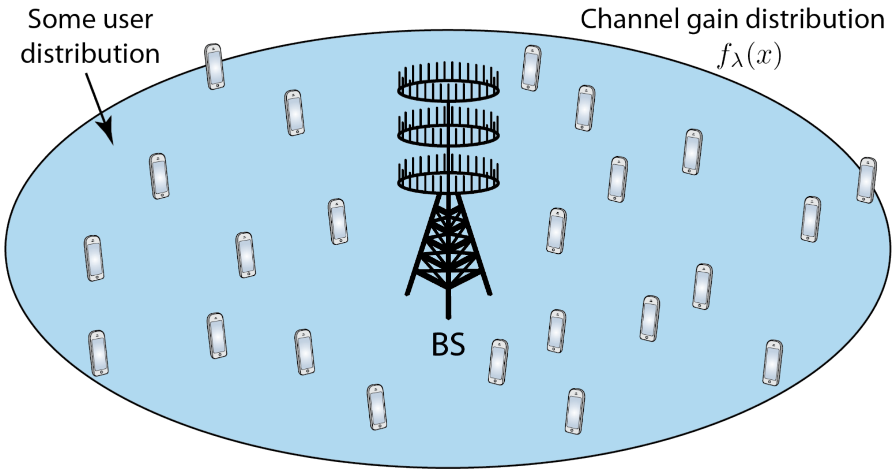
Disclaimer

M and K should be integers

Theorems 1 and 3 give real numbers → Take one of the closest integer points

Single-Cell Simulation Scenario

- Main Characteristics
  - Circular cell with radius 250 m
  - Uniform user distribution
  - Uncorrelated Rayleigh fading
  - Typical 3GPP pathloss model



- Many Parameters in the System Model
  - We found numbers from ≈ 2012 in the literature:

Parameter	Value	Parameter	Value
Cell radius (single-cell): $d_{\max}$	250 m	Fraction of downlink transmission: $\zeta^{(\mathrm{dl})}$	0.6
Minimum distance: $d_{\min}$	35 m	Fraction of uplink transmission: $\zeta^{(\mathrm{ul})}$	0.4
Large-scale fading model: $l(\mathbf{x})$	$10^{-3.53}/\|\mathbf{x}\|^{3.76}$	PA efficiency at the BSs: $\eta^{(\mathrm{dl})}$	0.39
Transmission bandwidth: B	20 MHz	PA efficiency at the UEs: $\eta^{(\mathrm{ul})}$	0.3
Channel coherence bandwidth: B_{C}	180 kHz	Fixed power consumption (control signals, backhaul, etc.): P_{FIX}	18 W
Channel coherence time: T_{C}	10 ms	Power consumed by local oscillator at BSs: P_{SYN}	2 W
Coherence block (channel uses): U	1800	Power required to run the circuit components at a BS: P_{BS}	1 W
Total noise power: $B\sigma^2$	-96 dBm	Power required to run the circuit components at a UE: P_{UE}	0.1 W
Relative pilot lengths: $\tau^{(\mathrm{ul})}, \tau^{(\mathrm{dl})}$	1	Power required for coding of data signals: P_{COD}	0.1 W/(Gbit/s)
Computational efficiency at BSs: L_{BS}	12.8 Gflops/W	Power required for decoding of data signals: P_{DEC}	0.8 W/(Gbit/s)
Computational efficiency at UEs: L_{UE}	5 Gflops/W	Power required for backhaul traffic: P_{BT}	0.25 W/(Gbit/s)

Optimal Single-Cell System Design: ZF Precoding

Optimum

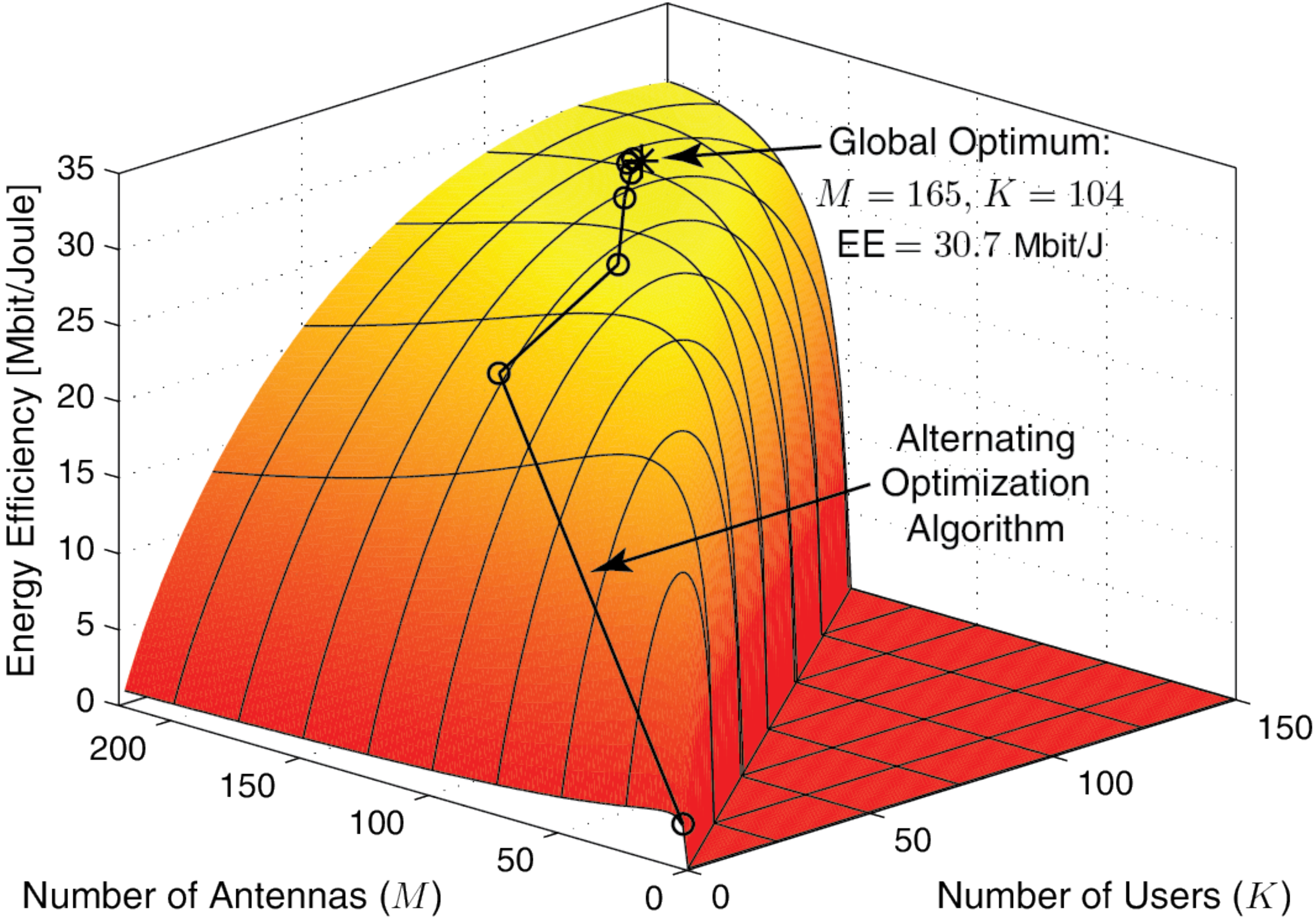
$M = 165$
$K = 104$
$\rho = 0.87$

User rates:
≈64-QAM

Massive MIMO!

Many users and antennas

$M \gg K$
suppresses interference



Optimal Single-Cell System Design: “Optimal” Processing

Optimum

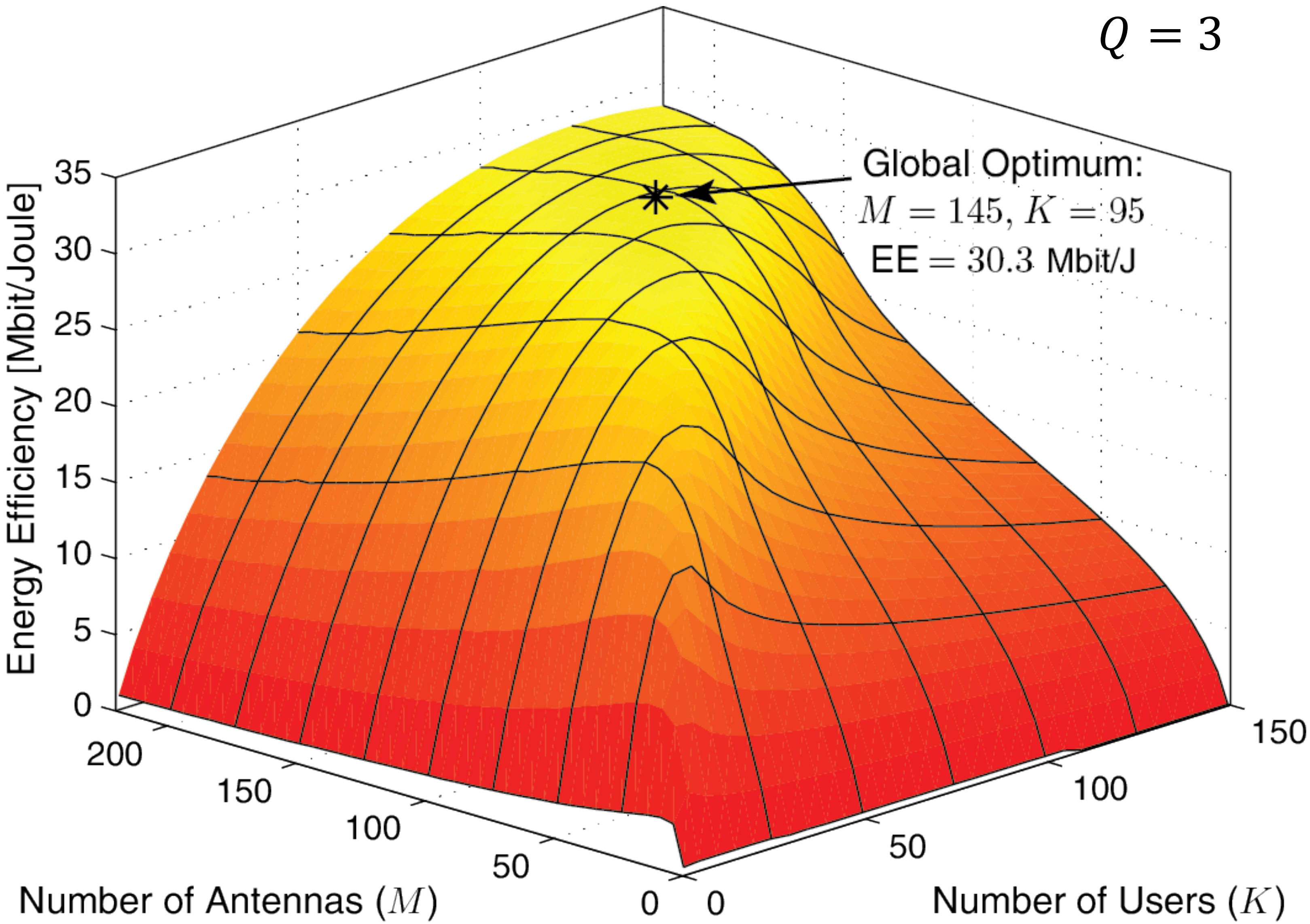
$M = 145$
$K = 95$
$\rho = 0.91$

User rates:
≈64-QAM

MMSE is Not Optimal!

Optimal linear processing but too costly computations

$Q = 3$



Optimal Single-Cell System Design: MR Processing

Optimum

$M = 81$
$K = 77$
$\rho = 0.24$

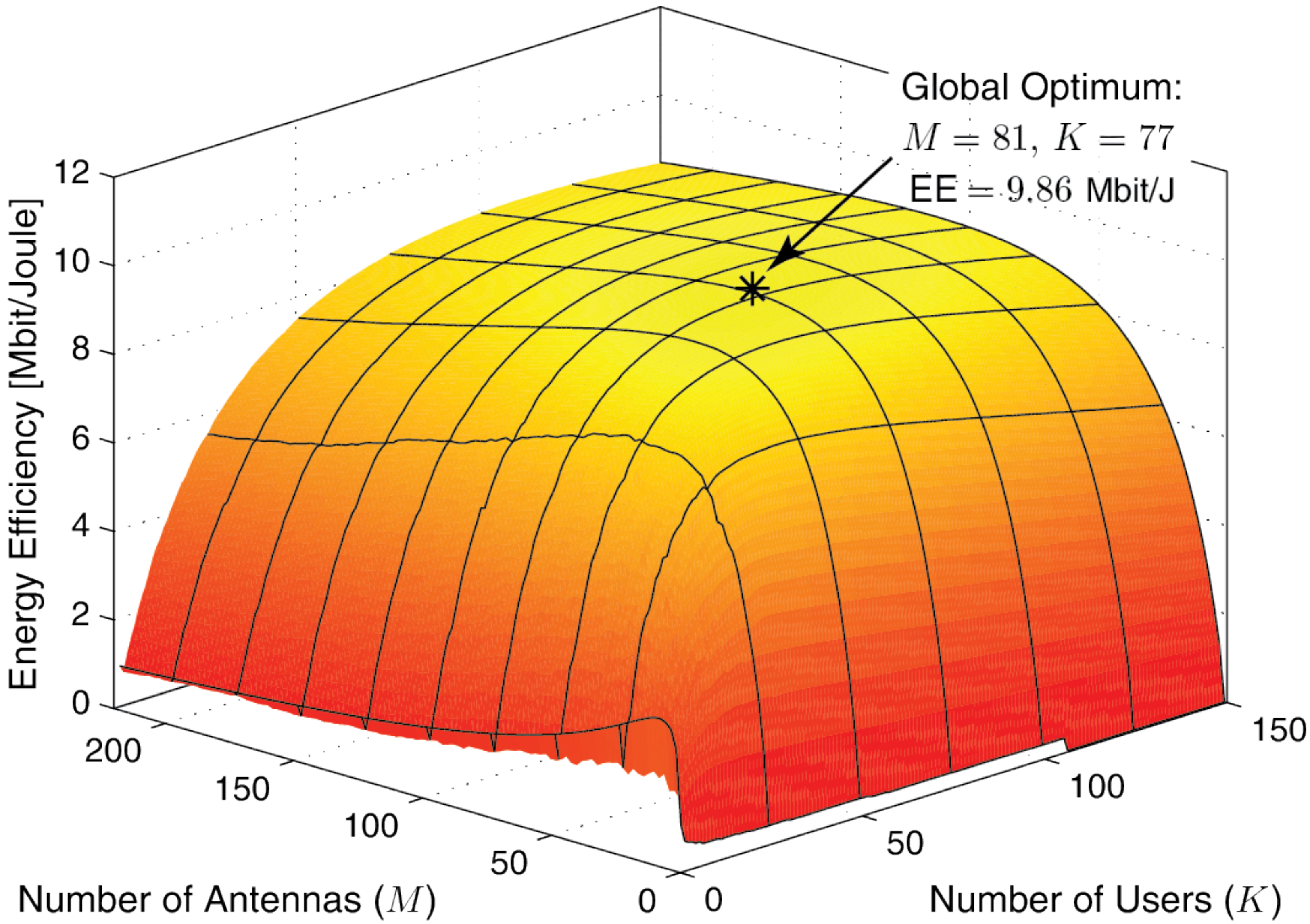
User rates:
≈2-PSK

Observation

Lower EE than with ZF

Also Massive MIMO setup

Low rates



Optimal Single-Cell System Design: MR Processing (2)

Paper at WCNC'14

Lower P_{BT} and $P_{\mathrm{C/D}}$ proportional to K

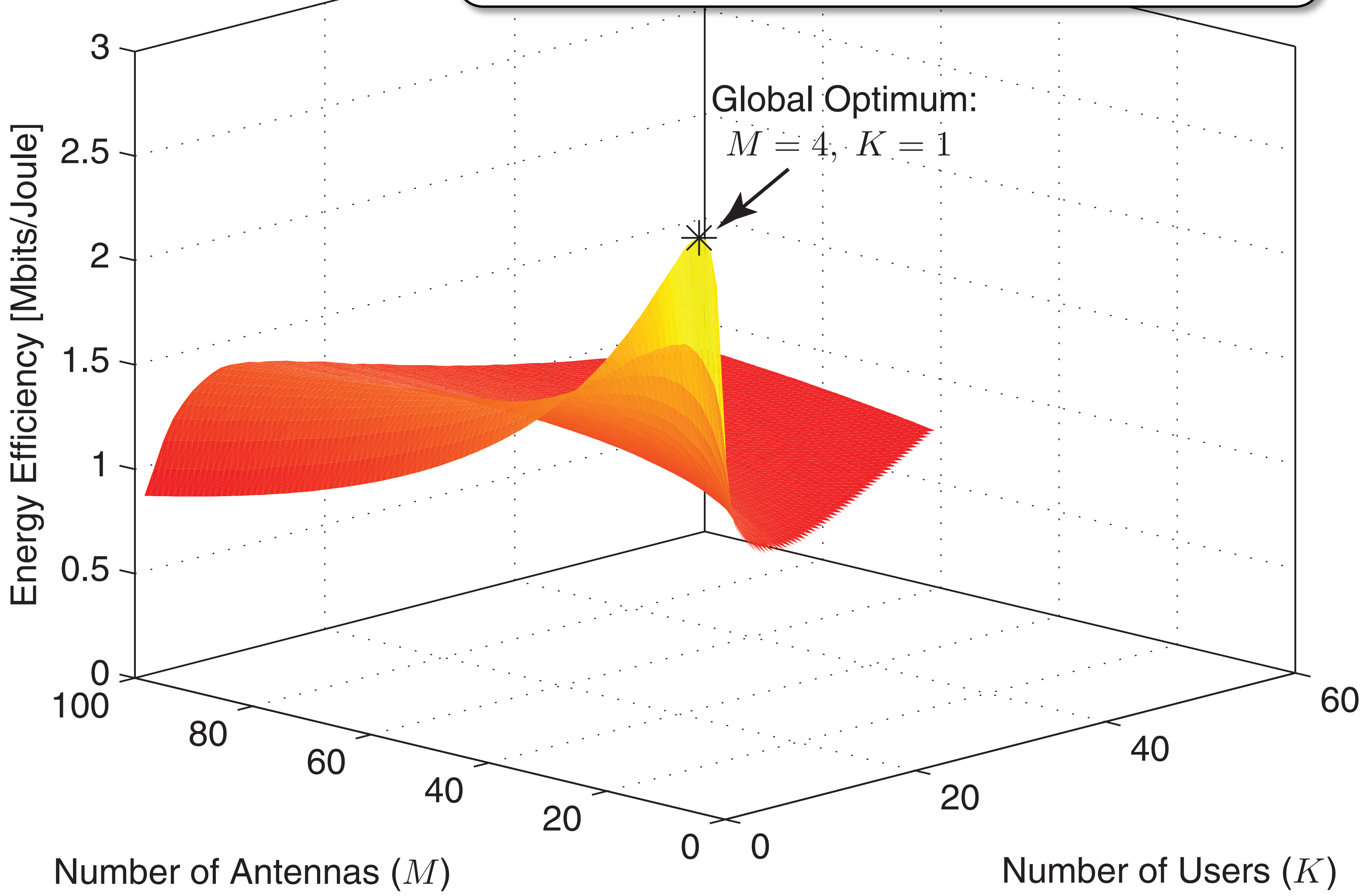
Optimum:
Single-user transmission

$M = 4$
$K = 1$

Simulations

Depends on parameters

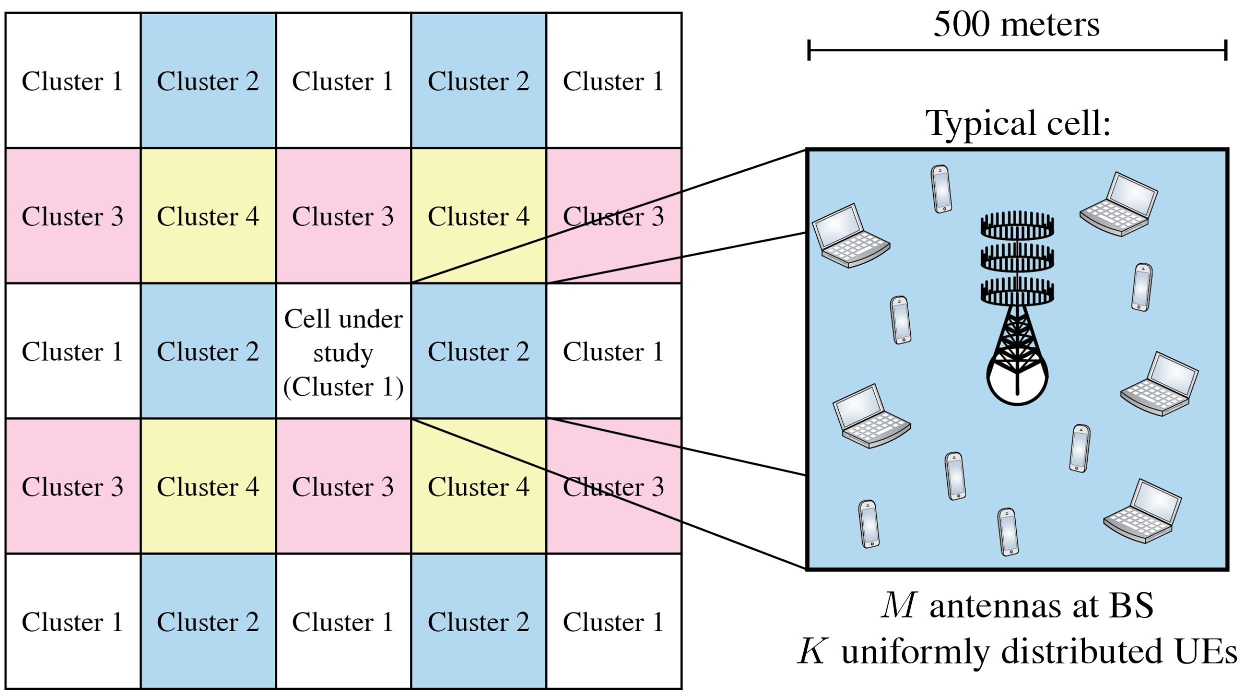
Download Matlab code to try other values!



Multi-Cell Scenario and Imperfect Channel Knowledge

- Limitations in Previous Analysis
  - Perfect channel knowledge
  - No interference from other cells

- Consider a Symmetric Multi-Cell Scenario:



Assumptions

All cells look the same → Jointly optimized

All cells transmit in parallel

Fractional pilot reuse: Divide cells into clusters

Uplink pilot length $\tau^{(\mathrm{ul})}K$ for $\tau^{(\mathrm{ul})} \in \{1,2,4\}$

Multi-Cell Scenarios and Imperfect Channel Knowledge (2)

- Inter-Cell Interference
  - λ_{jl} = Channel attenuation between a random user in cell l and BS j
  - $\mathcal{I} = \sum_{l \neq j} \mathbb{E}\left\{\frac{\lambda_{jl}}{\lambda_{jj}}\right\}$ is relative severity of inter-cell interference

Lemma (Achievable Rate)

Consider same transmit power as before: $P_{\text{trans}} = \rho B \sigma^2 \mathcal{S}_{\lambda} K$

Achievable rate under ZF and pilot-based channel estimation:

$$R = B \log_2 \left(1 + \frac{\rho(M-K)}{\rho(M-K)\mathcal{I}_{\text{PC}} + \underbrace{\left(1 + \mathcal{I}_{\text{PC}} + \frac{1}{\rho K \tau^{(\text{ul})}}\right)(1+\rho K \mathcal{I}) - \rho K (1 + \mathcal{I}_{\text{PC}^2})}} \right)$$

where $\mathcal{I}_{\text{PC}} = \sum_{l \neq j \text{ only in cluster}} \mathbb{E}\left\{\frac{\lambda_{jl}}{\lambda_{jj}}\right\}$ and $\mathcal{I}_{\text{PC}^2} = \sum_{l \neq j \text{ only in cluster}} \mathbb{E}\left\{\left(\frac{\lambda_{jl}}{\lambda_{jj}}\right)^2\right\}$

Pilot contamination (PC)
(Amplified by M)

Intra/inter-cell interference
(Not amplified by M)

Multi-Cell Scenarios and Imperfect Channel Knowledge (3)

- Multi-Cell Rate Expression not Amenable for Analytical Analysis
  - No closed-form optimization in multi-cell case
  - Numerical analysis still possible

- Similarities and Differences
  - Power consumption is exactly the same
  - Rates are smaller: Upper limited by pilot contamination:

$$R = B \log_2 \left(1 + \frac{\rho(M-K)}{\rho(M-K)\mathcal{J}_{\mathrm{PC}} + \left(1+\mathcal{J}_{\mathrm{PC}}+\frac{1}{\rho K \tau^{(\mathrm{ul})}}\right)(1+\rho K \mathcal{J}) - \rho K \left(1+\mathcal{J}_{\mathrm{PC}^{2}}\right)} \right) \leq B \log_2 \left(1 + \frac{1}{\mathcal{J}_{\mathrm{PC}}} \right)$$

  - Overly high rates not possible (but single-cell solution didn't give that…)
  - Clustering (fractional pilot reuse) might be good to reduce interference

Optimal Multi-Cell System Design: ZF Processing

Optimum

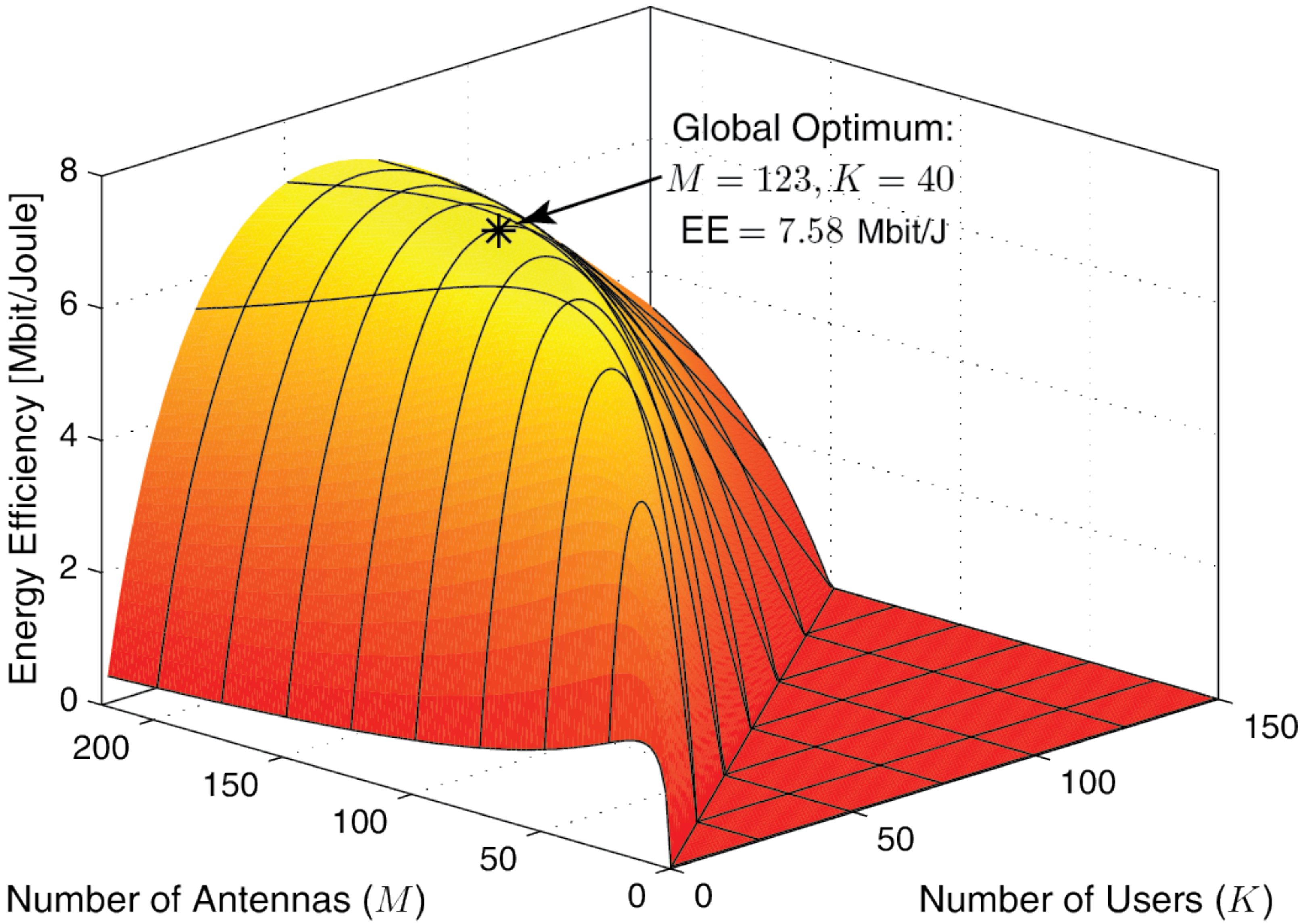
$M = 123$
$K = 40$
$\rho = 0.28$
$\tau^{(\mathrm{ul})} = 4$

User rates:
≈4-QAM

Massive MIMO!

Many BS antennas

Note that $M/K \approx 3$

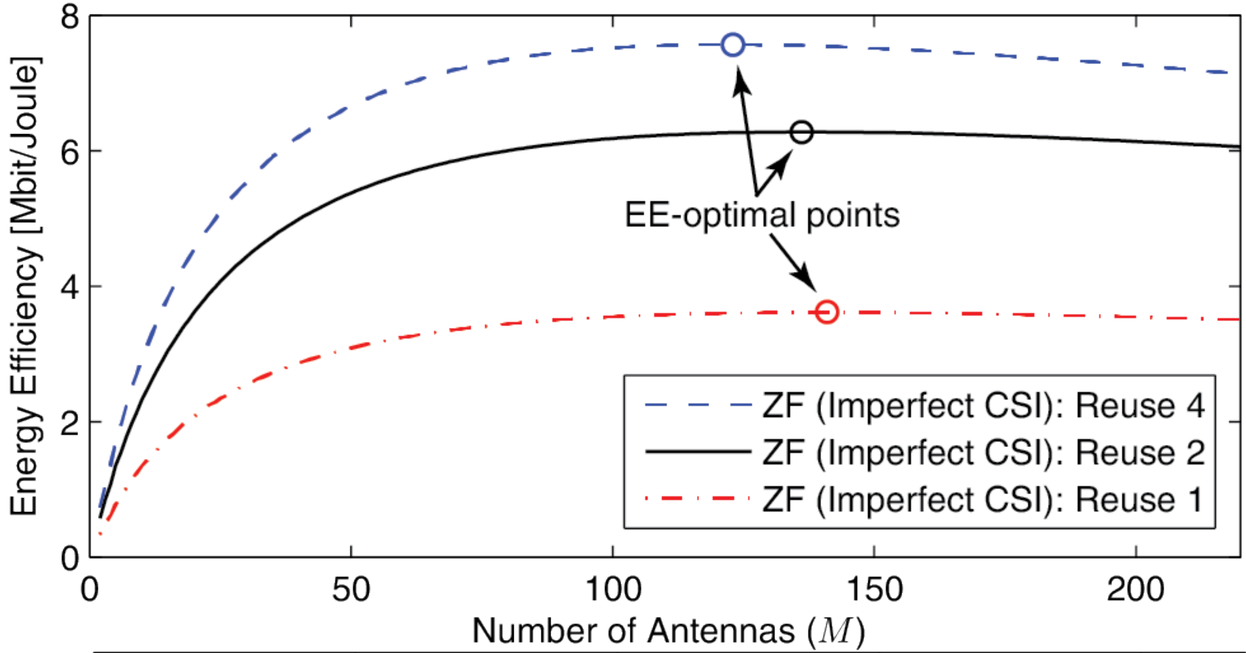


Different Pilot Reuse Factors

Higher Pilot Reuse

Higher EE *and* rates!

Controlling inter-cell interference is very important!

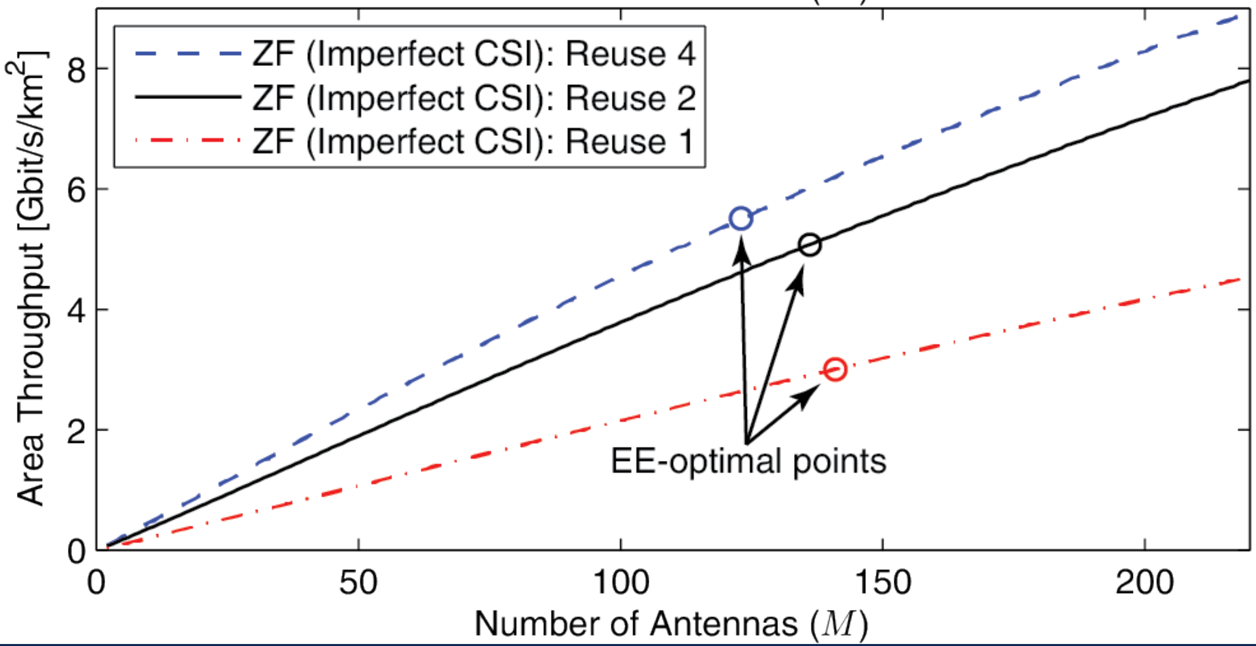


Area Throughput

We only optimized EE

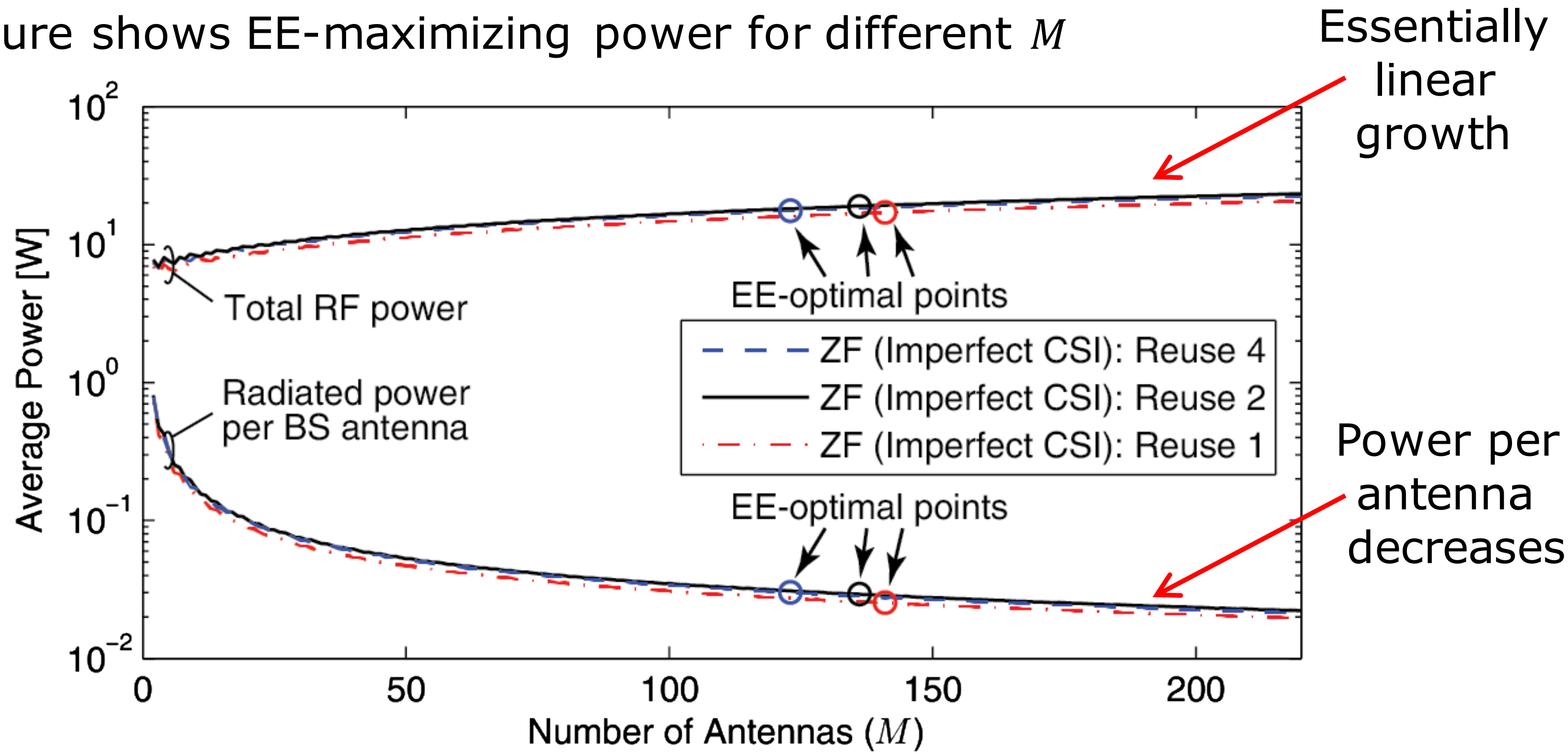
Achieved 6 Gbit/s/km^2 over 20 MHz bandwidth

METIS project mentions 100 Gbit/s/km^2 as 5G goal
→ Need 15x higher bandwidth!



Energy Efficient to Use More Transmit Power?

- Recall from Theorem 2: Transmit power increases M
  - Figure shows EE-maximizing power for different M



- Intuition: More Circuit Power → Use More Transmit Power
  - Different from $1/\sqrt{M}$ scaling law in Massive MIMO literature
  - Power per antennas decreases, but only logarithmically

Summary

- Optimization Results
  - EE is a quasi-concave function of (M, K, ρ)
  - Closed-form optimal M, K, or ρ for single-cell
  - Alternating optimization algorithm

Simulations

Depends on parameters

Download Matlab code to try other values!

Reveals how variables are connected

	Increases with	Decreases with
Antennas M	Power ρ, coverage area $\mathcal{S}_\lambda$, and M-independent circuit power	M-related circuit power
Users K	Fixed circuit power $\mathcal{C}_{0,0}$ and coverage area $\mathcal{S}_\lambda$	K-related circuit power
Transmit power $\rho B \sigma^2 \mathcal{S}_\lambda K$	Circuit power, coverage area $\mathcal{S}_\lambda$, antennas M, and users K	Smaller cells

Large Cell

More antennas, users, RF power

Massive MIMO Appears Naturally

Fractional pilot reuse is important!

More Circuit Power

Use more transmit power

Limits of M, K

Circuit power that scales with M,K

Part 3

Questions?

Part 4

Optimization of Energy-Efficiency:
Heterogeneous Deployment

Symmetric or Asymmetric Network Deployment?

- Recall: Shape of Real Networks
  - Highly asymmetric shape
  - Deployed for asymmetric user load
- Inter-Cell Interference
  - Symmetric: All cells equally exposed
    → Easy to define pilot reuse patterns
  - Asymmetric: Interference variations
    → Hard to pick pilot reuse patterns

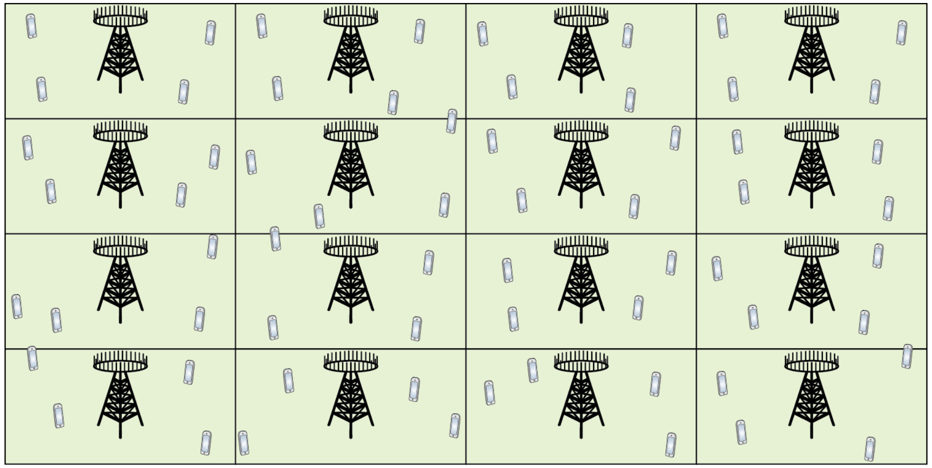
Pessimistic Approach

Some abstraction needed for analysis!

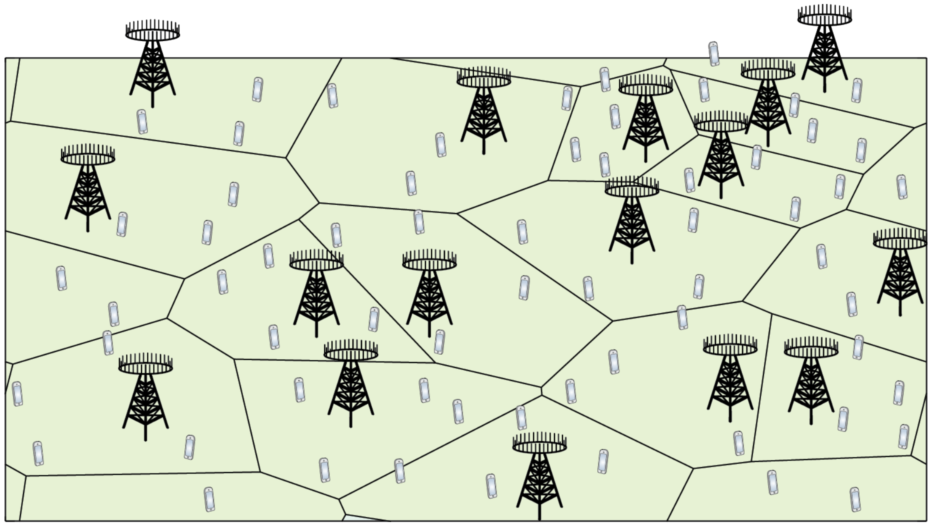
Hard to deploy intricate interference control

Good to design networks without relying on it

Tractable analysis with stochastic deployment?



Overly symmetric deployment



Independent stochastic deployment

Multi-Cell Modeling with Stochastic Geometry

- Stochastic Spatial Point Process Ψ
  - Ψ is a set of random locations in $\mathbb{R}^n$ for some integer n
  - Used here to model random BS locations in $\mathbb{R}^2$

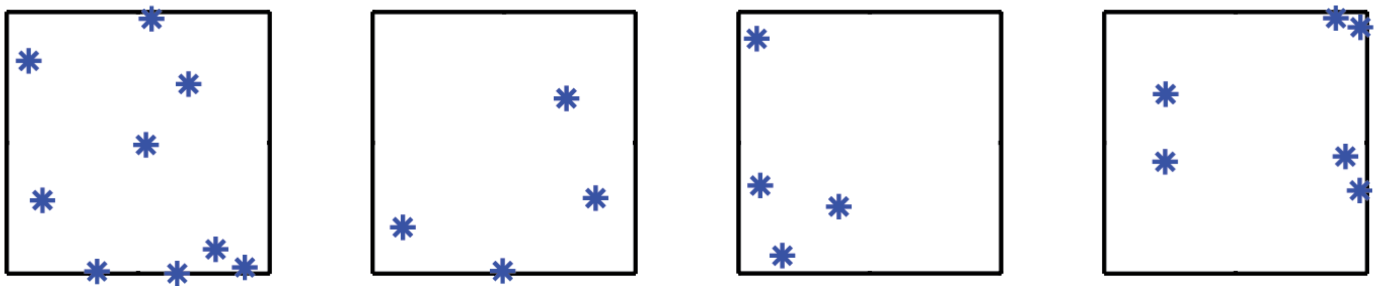
Homogeneous Poisson point process (PPP)

Independent and equally distributed points in $\mathbb{R}^2$

Density: λ BSs per km^2

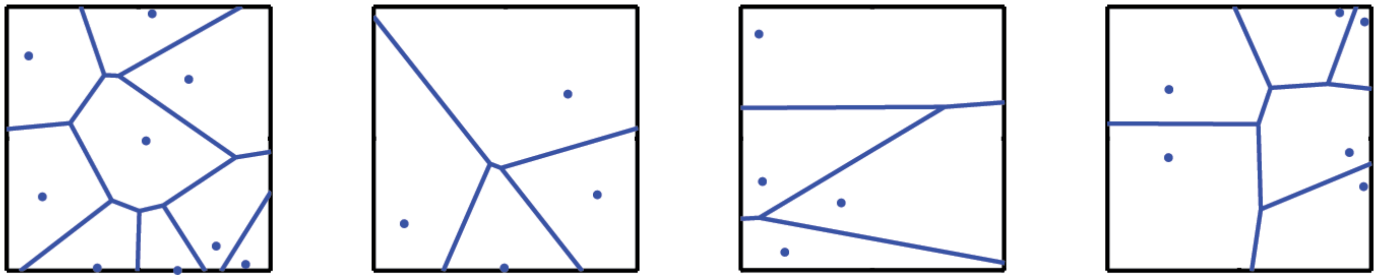
Po($\lambda\mathcal{A}$) BSs in any area of size $\mathcal{A}$ km^2:
These are uniformly distributed in the area

- 4 realizations with $\lambda\mathcal{A} = 6$ BSs in the area:



Network Modeling Assumptions

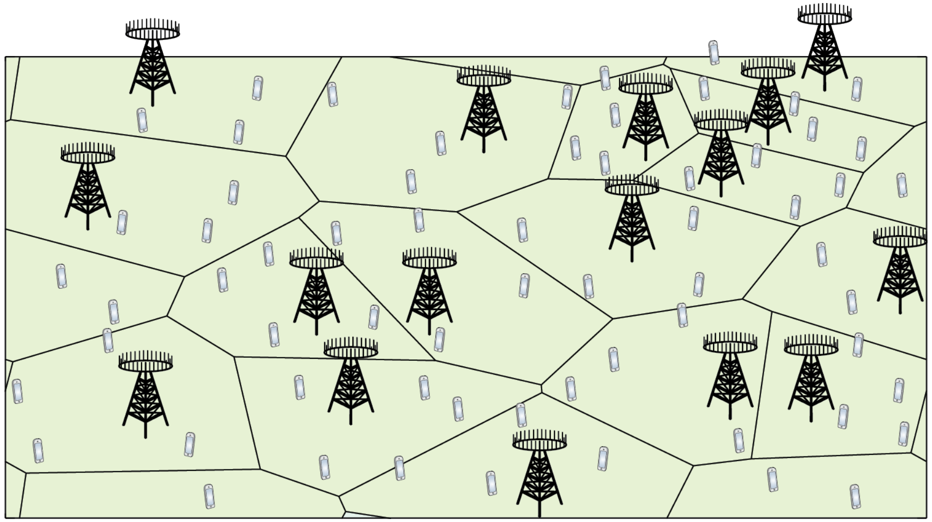
- BSs Distributed as PPP: λ BS/km^2
  - M antennas per BSs
  - Closest BS association: Poisson-Voronoi cells
  - K uniformly distributed users per cell → Asymmetric user density



- Propagation Model
  - Channel from User k in cell j to BS l:

$$\mathbf{h}_{jk}^{l} \sim \mathcal{CN}(\mathbf{0}, \lambda_{jk}^{l}\mathbf{I})$$

  - Pathloss: $\lambda_{jk}^{l} = \omega^{-1}(\text{distance [km]})^{-\alpha}$
  - Pathloss exponent: $\alpha > 2$
  - Loss at reference distance 1 km: ω



Uplink-Downlink Duality

Duality Theorem

The uplink rates are achievable in the downlink using same total power

Same precoding/combining vectors, but different power allocation

Provable with perfect CSI (as earlier) but also in general networks

Focus on Uplink

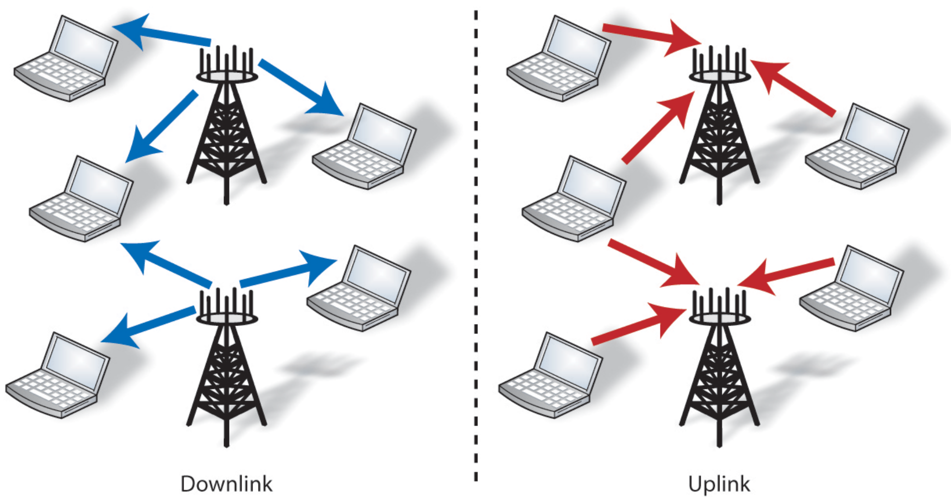
Only to simplify notation!

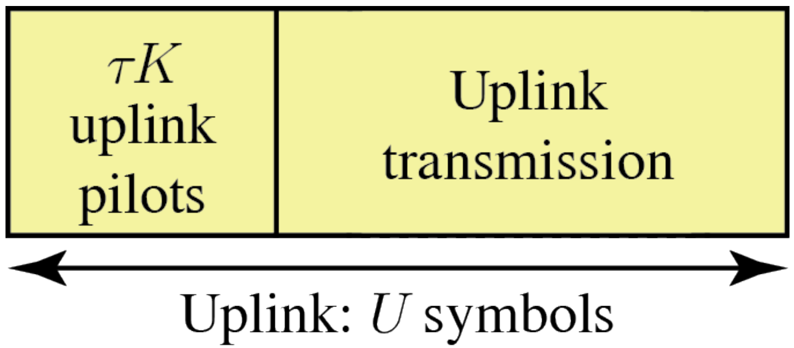
Pilot Assumptions

τK pilots: Reuse factor τ

No coordination: Pilots selected randomly in each cell

Imperfect CSI in this part!





Average Uplink Rate

- Randomness and Typical User
  - All users in the system is surrounded by BSs having same distribution
  - Property: Any user is "*typical user*" ← Only need to analyze one user!

- Power Control: Statistical channel inversion
  - User k in cell j: $p_{jk}^{j} = \rho/\lambda_{jk}^{j}$
  - Avoid near-far issues in the cells
  - Same average SNR ρ/σ^2 for everyone

Power per user:

$$\mathbb{E}\left\{\frac{\rho}{\lambda_{jk}^{j}}\right\} = \rho\omega\frac{\Gamma(\alpha/2-1)}{(\pi\lambda)^{\alpha/2}}$$

Lemma (Lower Bound on Average Rate with MR Processing)

$$\underline{\mathrm{R}} = B\left(1-\frac{\tau K}{U}\right)\log_2\left(1+\underline{\mathrm{SINR}}\right)$$

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

Maximizing Energy Efficiency

- Recall: $\mathrm{EE} = \frac{\text{Average Sum Rate [bit/s/cell]}}{\text{Power Consumption [Joule/s/cell]}}$
  - Sum rate is $\mathrm{K} \cdot \underline{\mathrm{R}}$ with $\underline{\mathrm{R}}$ from previous lemma
  - Power consumption modeled as before:

Cost of MR signal processing

$$\mathrm{P}_{\text{total}} = \frac{B\rho\omega}{\eta} \underbrace{\frac{\Gamma(\alpha/2-1)}{(\pi\lambda)^{\alpha/2}}}_{\text{Power control}} \left(1 - \frac{\tau K - 1}{U}\right) + C_{0,0} + \underbrace{C_{0,1}M + C_{1,0}K}_{\text{Circuit power per transceiver chain}} + C_{1,1}MK + \underbrace{AK\underline{\mathrm{R}}}_{\text{Coding/decoding/ backhaul}}$$

Transmit power with amplifiers

Fixed power

EE Maximization Problem

$$\begin{array}{ll} \underset{M,K,\rho,\lambda,\tau}{\text{maximize}} & \frac{K\underline{\mathrm{R}}}{\mathrm{P}_{\text{total}}} \\ \text{subject to} & \underline{\mathrm{SINR}} = \gamma \end{array}$$

- Average SINR constraint γ needed to not get too low rates

Solving Multi-Cell EE Maximization

- Optimization Variables:
  - M = Number of BS antennas
  - K = Number of users per cell
  - ρ = Normalized transmit power
  - λ = BS density
  - τ = Pilot reuse factor ($\tau \geq 1$)

Unique feature of this stochastic framework

Theorem 5 (Optimal reuse factor)

SINR constraint is satisfied by setting $\tau^* = \frac{D_1 \gamma}{M - D_2 \gamma}$

where $D_1 = \frac{4K}{(\alpha-2)^2} + \frac{K+M}{\alpha-1} + \frac{2\left(K+\frac{\sigma^2}{\rho}\right)}{\alpha-2}$ and $D_2 = \left(K + \frac{\sigma^2}{\rho} + \frac{2K}{\alpha-2}\right)\left(1 + \frac{\sigma^2}{\rho}\right)$

- Observations
  - Increases with K, but decreases with M or ρ
  - Independent of λ and hardware characteristics

Optimizing BS Density

- Impact of BS Density
  - Rate $\underline{\mathrm{R}}$ is independent of λ, due to power control
  - Transmit power scales as $\rho/\lambda^{\alpha/2}$

Theorem 6 (Optimal λ and ρ)

EE is monotonically increasing in λ

Set $\rho = \rho_0\lambda$. For any $\rho_0 > 0$, the EE is monotonically increasing in λ:
EE is maximized as $\lambda \to \infty$

Does it make sense to let $\lambda \to \infty$?

Physically: No, density is finite (depends on BS dimension)
Conceptually: Maybe (depends on convergence speed)

Simulation Parameters

Parameter	Symbol	Value
Coherence block length	U	400
Pathloss exponent	α	3.76
Pathloss over noise at 1 km	ω/σ^2	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
Coding/decoding/backhaul	$\mathcal{A}$	$1.15 \cdot 10^{-9}$ J/bit

Average inter-BS distance: On average λ BSs per km^2

Deployment	λ	$\lambda = 10$
Square grid	$1/\sqrt{\lambda}$ km	316 m
PPP (average)	$1/(2\sqrt{\lambda})$ km	158 m

Simulation: Impact of BS Density

Simulation

Different BS densities

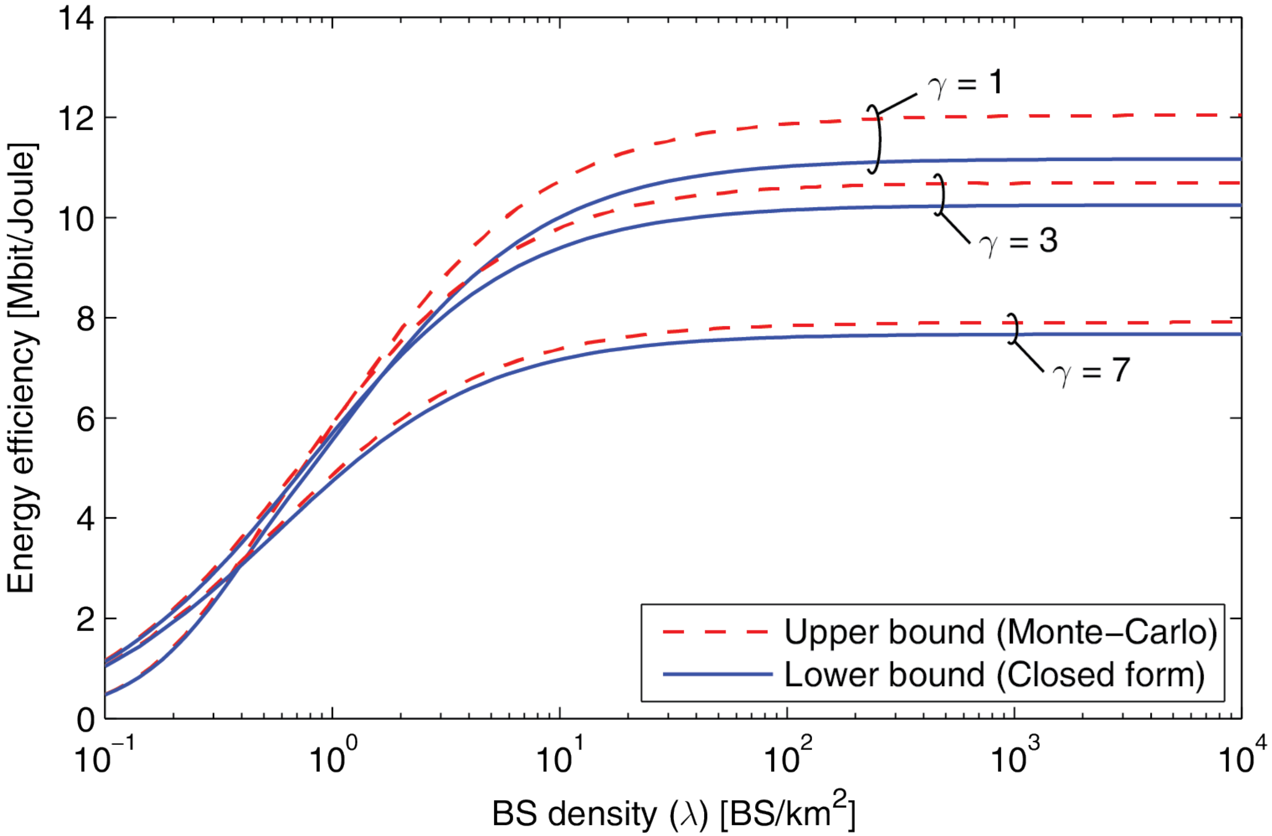
All other variables optimized

Observations

Lower bound is tight

Higher EE with lower γ

EE increases with λ



Saturation Property

EE saturates at $\lambda = 10$ (few hundred meters between BSs)

Satisfied in urban deployments – already today!

We can safely let $\lambda \to \infty$ in the analysis

Remaining Optimization Problem

- EE Maximization Problem Simplified by Theorems 5 and 6:

Remaining EE Maximization Problem

$$\underset{M,K}{\text{maximize}} \quad \frac{KB\left(1-\frac{K}{U}\frac{\bar{D}_1\gamma}{M-\bar{D}_2\gamma}\right)\log_2(1+\gamma)}{\mathcal{C}_{0,0}+\mathcal{C}_{0,1}M+\mathcal{C}_{1,0}K+\mathcal{C}_{1,1}MK+AKB\left(1-\frac{K}{U}\frac{\bar{D}_1\gamma}{M-\bar{D}_2\gamma}\right)\log_2(1+\gamma)}$$

$$\text{subject to} \quad \frac{\bar{D}_1\gamma}{M-\bar{D}_2\gamma} \geq 1$$

$$\text{where } \bar{D}_1 = \frac{4K}{(\alpha-2)^2} + \frac{K+M}{\alpha-1} + \frac{2K}{\alpha-2} \text{ and } \bar{D}_2 = K\left(1+\frac{2}{\alpha-2}\right)$$

- Feasible if $\left(1-\frac{K}{U}\frac{\bar{D}_1\gamma}{M-\bar{D}_2\gamma}\right) > 0$: $\gamma < \frac{UM}{K\bar{D}_1+\bar{D}_2} \leq U(\alpha-1)$
- Example: $U = 200$ and $\alpha = 3$ give $\gamma \leq 400$ (more than 256-QAM)

- Feasibly in most practical cases!

Optimizing Number of Users

- Find real-valued K that maximizes EE
  - Assuming $\bar{\beta} = \frac{M}{K}$ antennas per user

Theorem 7 (Optimal K)

EE is quasi-concave w.r.t. K and maximized by

$$K^* = \frac{\sqrt{(GC_{0,0})^2 + C_{0,0}C_{1,1}\bar{\beta} + C_{0,0}G(C_{1,0} + C_{0,1}\bar{\beta})} - GC_{0,0}}{C_{1,1}\bar{\beta} + G(C_{1,0} + C_{0,1})}$$

where $G = \frac{1}{U} \frac{\frac{4\gamma}{(\alpha-2)^2} + \frac{\gamma(1+\bar{\beta})}{\alpha-1} + \frac{2\gamma}{\alpha-2}}{\bar{\beta} - \left(1 + \frac{2}{\alpha-2}\right)\gamma}$

- Observations
  - Increases with fixed circuit power (e.g., P_{FIX})
  - Decreases with circuit coefficients multiplied with M or K ($P_{\text{BS}}, P_{\text{UE}}, 1/L_{BS}$)
  - Independent of cost of coding/decoding/backhaul

Optimizing Number of Antennas

- Find real-valued M that maximizes EE

Theorem 8 (Optimal M)

EE is quasi-concave w.r.t. K and maximized by

$$M^* = K \frac{\nu_1 K + \nu_2 + \sqrt{\nu_1 \nu_2 K + \nu_1^2 K^2 + (1 - \nu_0 K)(\nu_1 K + \nu_0 \nu_2 K) \frac{C_{0,0} + C_{1,0} K}{C_{0,1} K + C_{1,1} K^2} + \nu_0 \nu_1 \nu_2 K^2 + \nu_0 \nu_2^2 K}}{1 - \nu_0 K}$$

where $\nu_0 = \frac{\gamma}{U(\alpha-1)}$, $\nu_1 = \frac{1}{U}\left(\frac{4\gamma}{(\alpha-2)^2} + \frac{\gamma}{\alpha-1} + \frac{2\gamma}{\alpha-2}\right)$, $\nu_2 = \gamma\left(1 + \frac{2}{\alpha-2}\right)$.

- Observations
  - Increases with circuit coefficients independent of M (e.g., $P_{\mathrm{FIX}}, P_{\mathrm{UE}}$)
  - Decreases with circuit coefficients multiplied with M (e.g., $P_{\mathrm{BS}}, 1/L_{BS}$)
  - Independent of cost of coding/decoding/backhaul
  - Increases with γ due to interference suppression

Impact of Number of Antennas and Users

Simulation

Optimized τ, λ, ρ

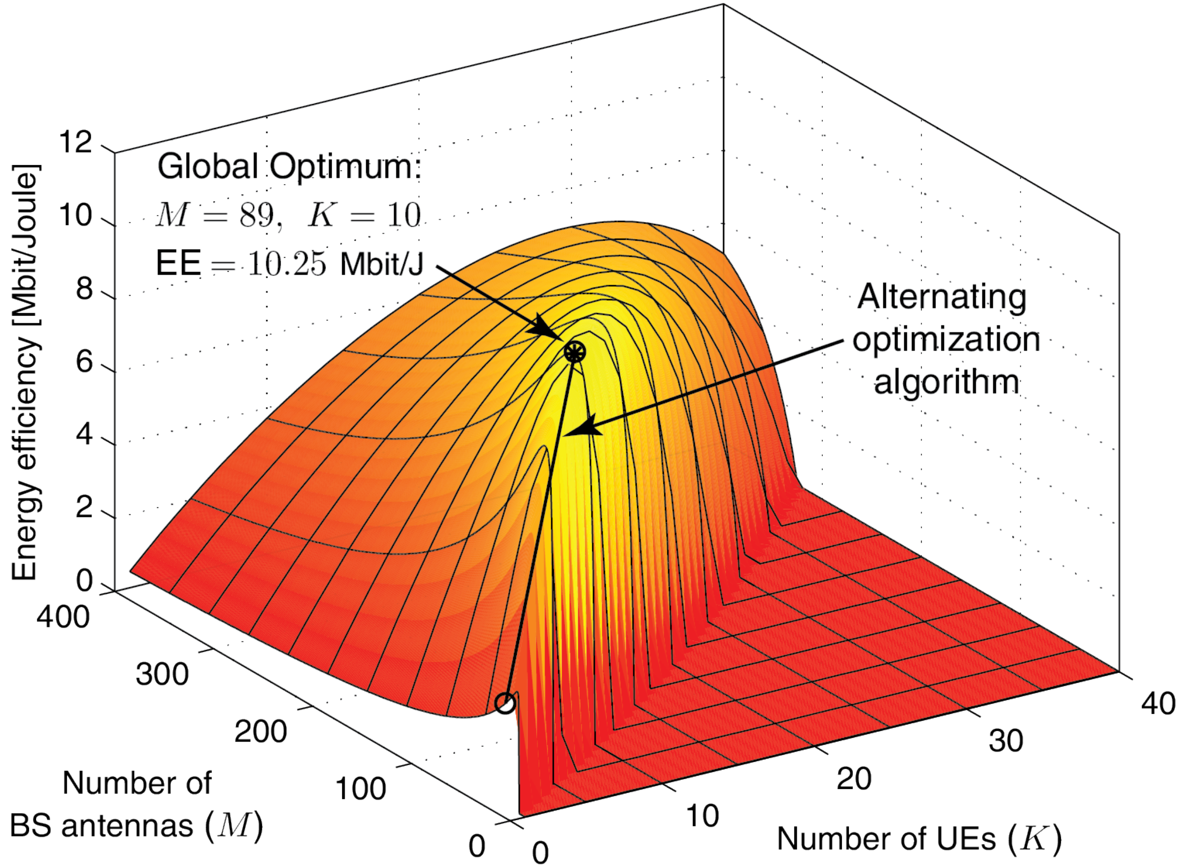
SINR constraint: $\gamma = 3$

Observations

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

Massive MIMO with reuse factor $\tau \approx 7$

Other (M, K) around the optimum are also good



Why Massive MIMO and Not Only Small Cells?

Small cells improve SNR, but not SINR

Massive MIMO improves cell-edge SINR by interference control

Other added benefit: Circuit power costs are shared between user

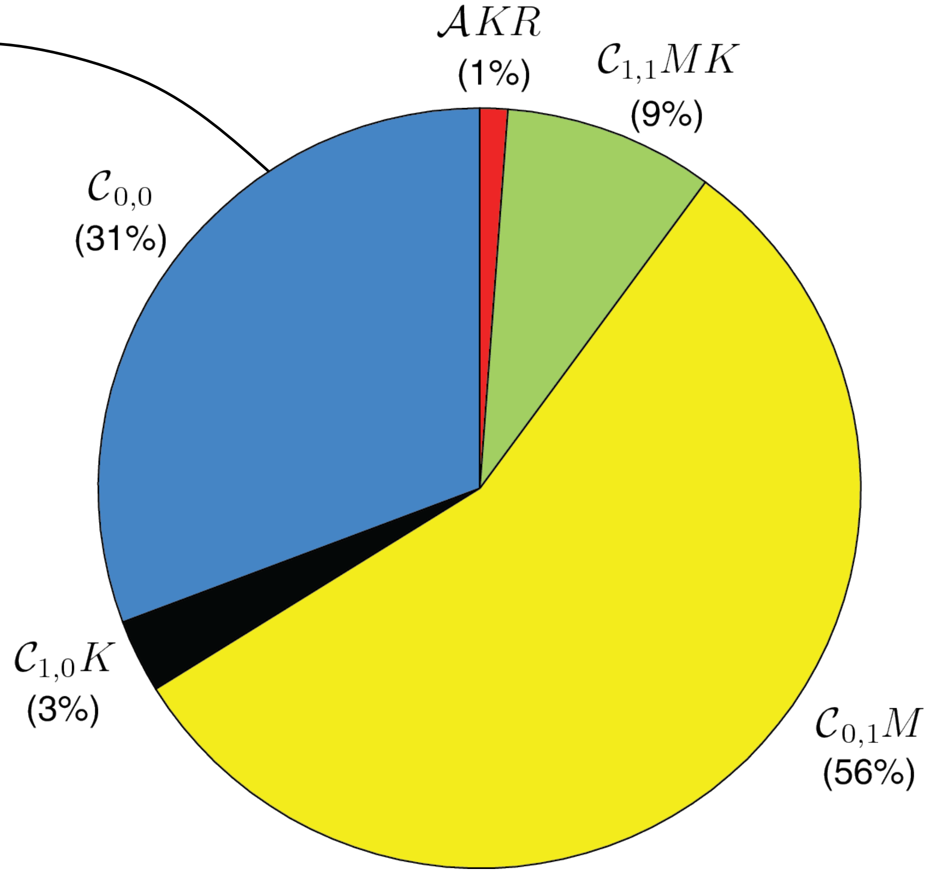
Power Distribution at Optimal Solution

What Consumes Power?

Consider optimum: $M^* = 89$, $K^* = 10$

Recall model:

$C_{0,0} + C_{0,1}M + C_{1,0}K + C_{1,1}MK + AK\underline{R}$



Dominating Parts

Power of BS transceivers: $C_{0,1}M$

Fixed power consumption: $C_{0,0}$

How to Improve Future Hardware?

Improve the dominating parts

Good design: No part has a large percentage

Designing with Given User Density

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

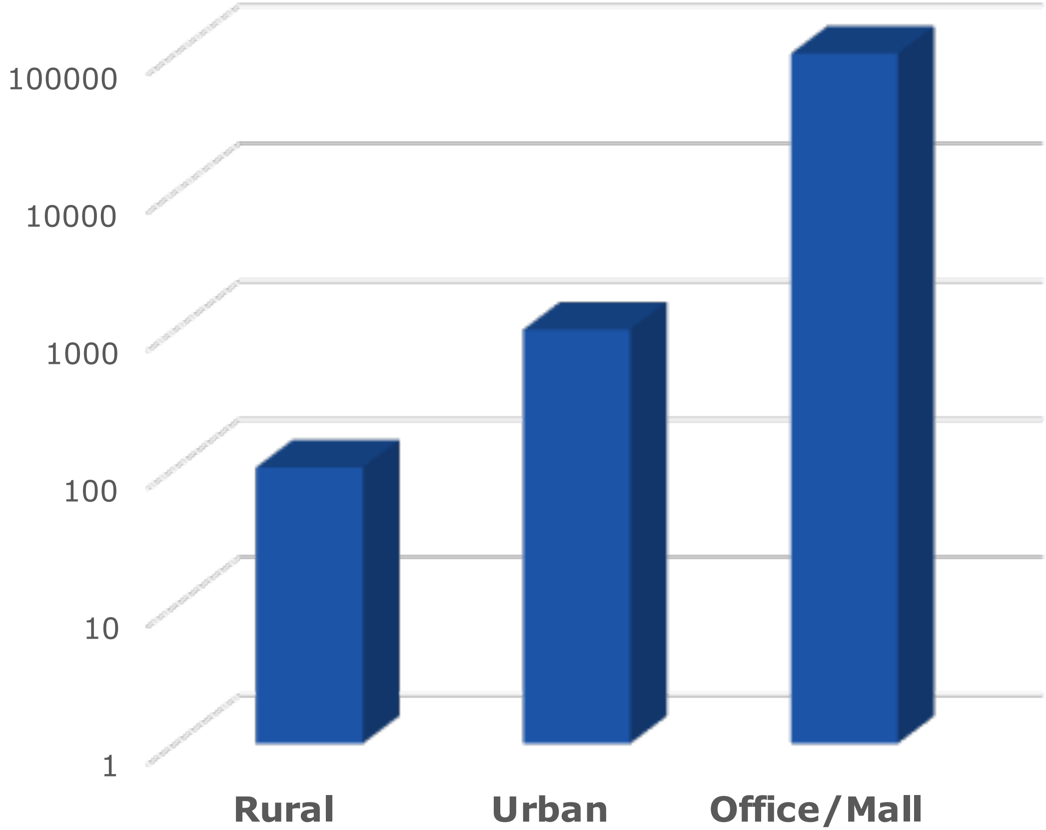
Can we Optimize this Density?

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/km^2

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

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

Low User Density

Many cells with $K \approx 1$

Most important to reduce pathloss

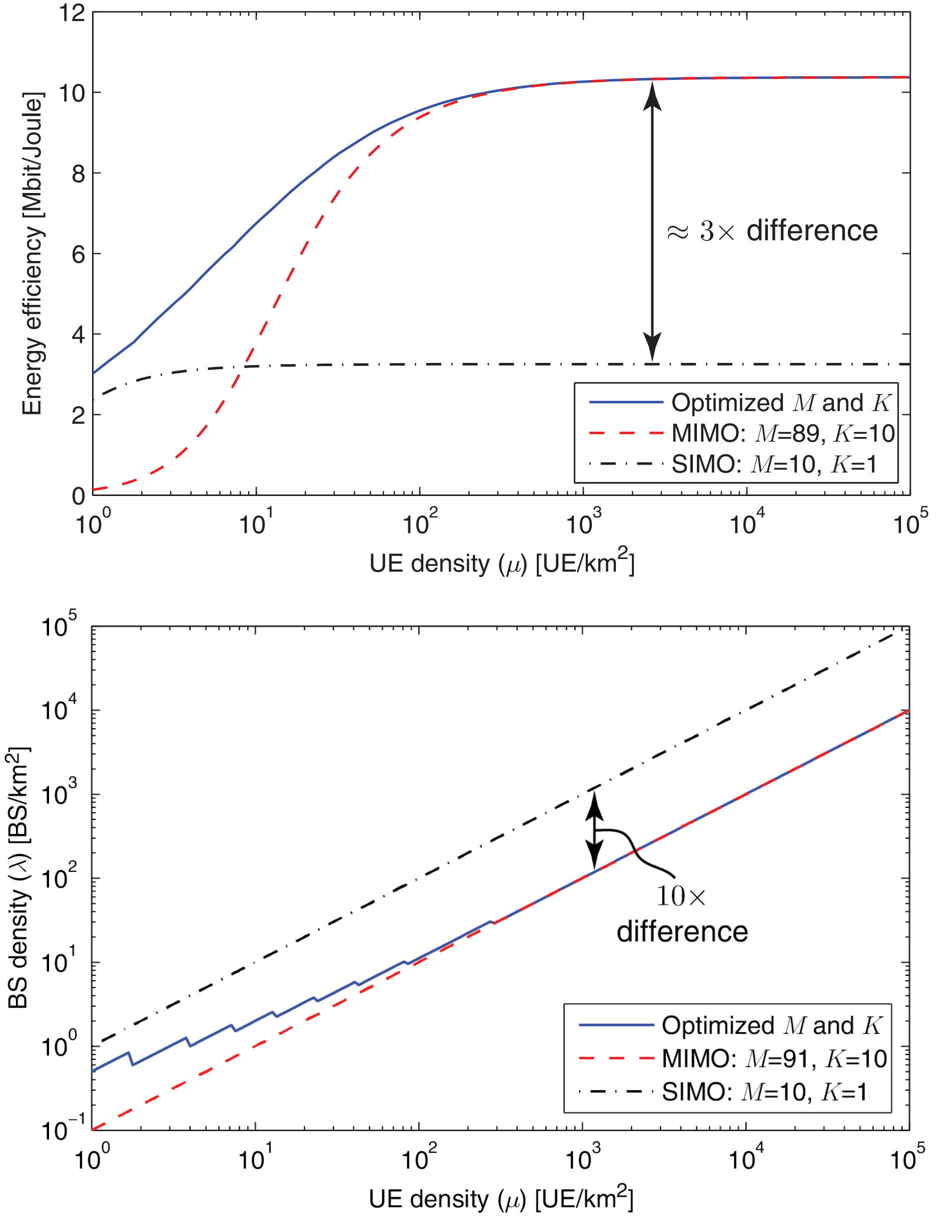
High User Density

Massive MIMO is optimal

Saturation for $\mu \geq 100$

Covers most practical scenarios:
EE independent of user load!

Share circuit power and cost over users



Summary

- EE Optimization with Stochastic Deployment
  - Stochastic geometry: Resembles real deployments, tractable formulas
- Optimized Network Densification
  - Large cells: First step is to reduce cell size
  - Smaller cells: Transmit power is negligible → Use also Massive MIMO
  - Optimal solution is a combination of small cells and Massive MIMO
- Intuition:
  - Smaller cells: Greatly improves SNR, but no interference improvement
  - More antennas/users per cell: Suppress interference
    Share circuit power cost among users
- Future Work
  - Other processing schemes and point distributions
  - Coordinated resource management, multi-tier networks

Part 4

Questions?

Part 5

Multi-Objective Network Optimization

Optimize more than Energy-Efficiency

- Recall: Many Metrics in 5G Discussions
  - Average rate (Mbit/s/active user)
  - Average area rate (Mbit/s/km^2)
  - Energy-efficiency (Mbit/Joule)
  - Active devices (per km^2)
  - Delay constraints (ms)

Communications

- So Far: Only cared about EE
  - Ignored all other metrics

Optimize Multiple Metrics

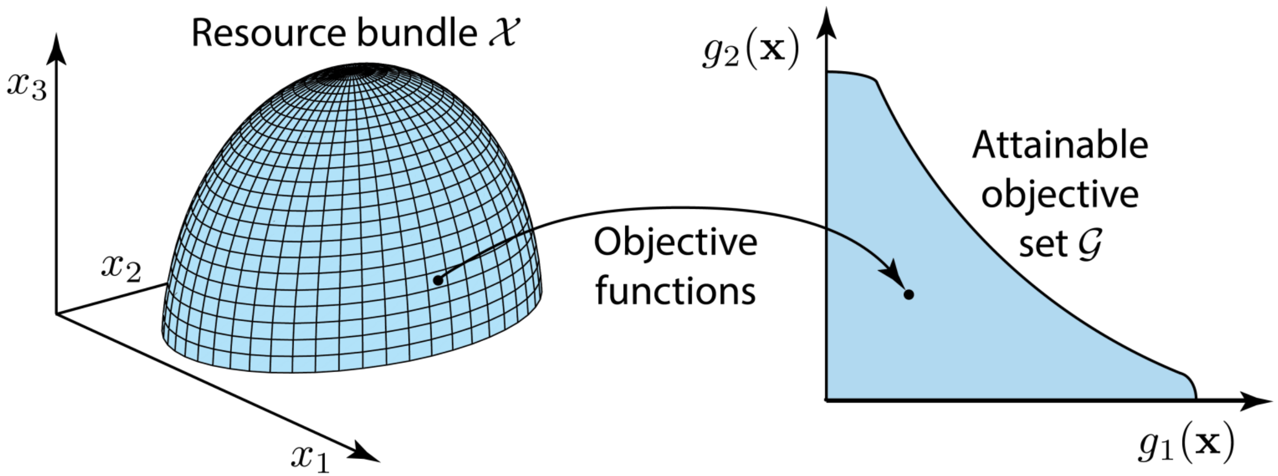
We want efficient operation w.r.t. all objectives!

Is this possible?
For all at the same time?

Basic Assumptions: Multi-Objective Optimization

- Consider N Performance Metrics
  - Objectives to be maximized
  - Notation: $g_1(\mathbf{x}), g_2(\mathbf{x}), \ldots, g_N(\mathbf{x})$
  - Example: individual user rates, area rates, energy-efficiency

- Optimization Resources
  - Resource bundle: $\mathcal{X}$
  - Example: power, resource blocks, network architecture, antennas, users
  - Feasible allocation: $\mathbf{x} \in \mathcal{X}$



Single or Multiple Performance Metrics

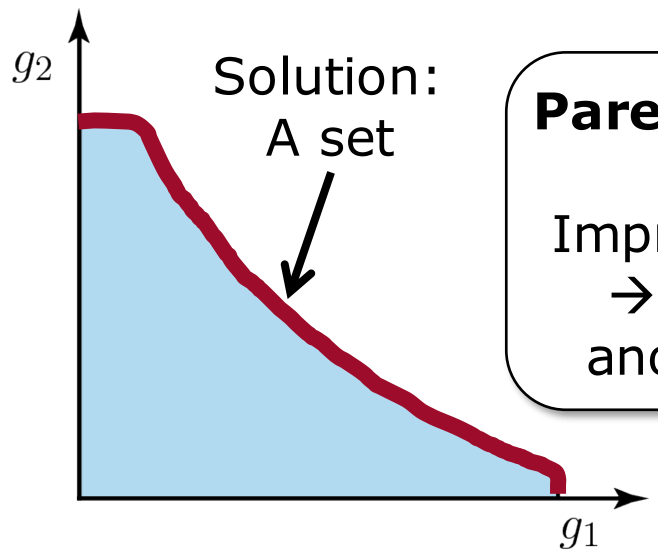
- Conventional Optimization
  - Pick one prime metric: $g_1(\mathbf{x})$
  - Turn $g_2(\mathbf{x}), \ldots, g_N(\mathbf{x})$ into constraints
  - Optimization problem:

$$\begin{aligned} \underset{\mathbf{x}}{\text{maximize}} \quad & g_1(\mathbf{x}) \\ \text{subject to} \quad & \mathbf{x} \in \mathcal{X}, \\ & g_2(\mathbf{x}) \geq A_2, \ldots, g_N(\mathbf{x}) \geq A_N. \end{aligned}$$

  - Solution: A scalar number
  - Cons: Is there a prime metric? How to select constraints?

- Multi-Objective Optimization
  - Consider all N metrics
  - No order or preconceptions!
  - Optimization problem:

$$\begin{aligned} \underset{\mathbf{x}}{\text{maximize}} \quad & [g_1(\mathbf{x}), g_2(\mathbf{x}), \ldots, g_N(\mathbf{x})] \\ \text{subject to} \quad & \mathbf{x} \in \mathcal{X}. \end{aligned}$$



Pareto Boundary

Improve a metric → Degrading another metric

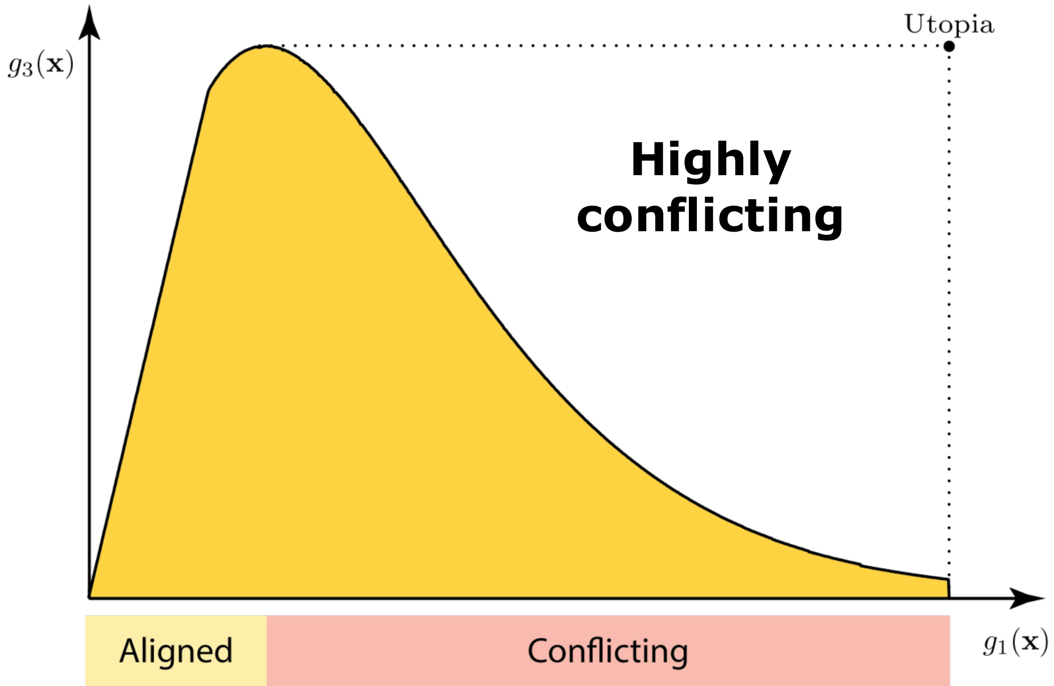
Why Multi-Objective Optimization?

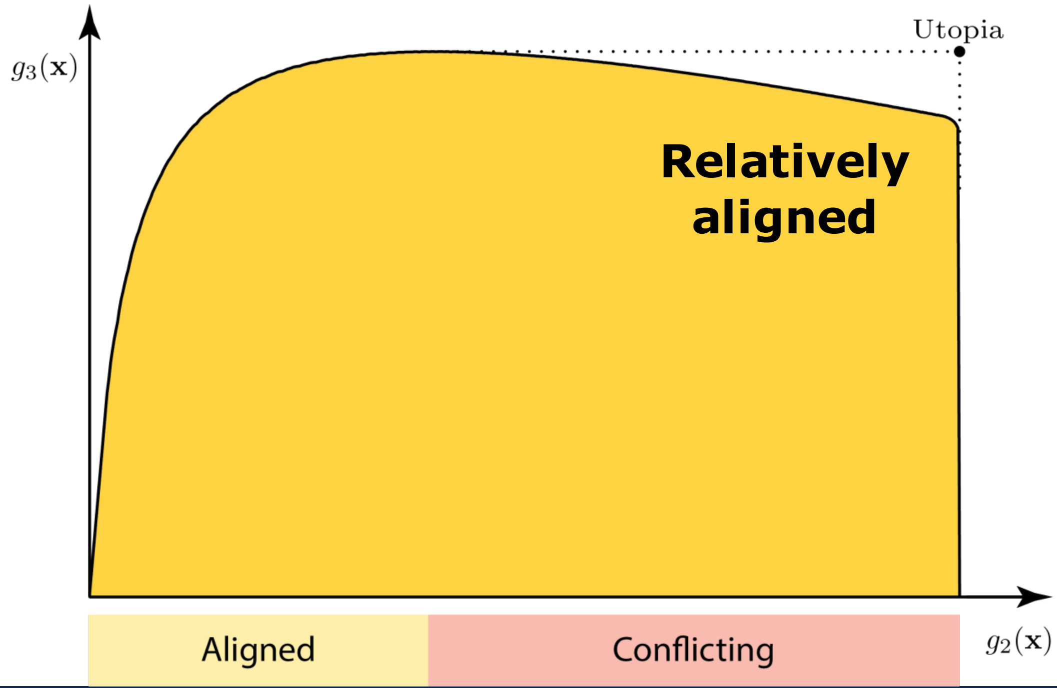
- Study Tradeoffs Between Metrics
  - When are metrics aligned or conflicting?
  - Common in engineering and economics – new in communication theory

A Posteriori Approach

Generate region (computationally demanding!)

Look at region and select operating point





A Priori Approach

- No Objectively Optimal Solution
  - Utopia point outside of region → Only subjectively "good" solutions exist
- System Designer Selects Utility Function $f : \mathbb{R}^N \to \mathbb{R}$
  - Describes subjective preference (larger is better)
- Examples:
  - Sum performance: $f(\mathbf{g}) = \sum_k g_k$
  - Proportional fairness: $f(\mathbf{g}) = \prod_k g_k$
  - Harmonic mean: $f(\mathbf{g}) = K_r \left(\sum_k g_k^{-1}\right)^{-1}$
  - Max-min fairness: $f(\mathbf{g}) = \min_k g_k$

Aggregate metric

Fairness of metrics

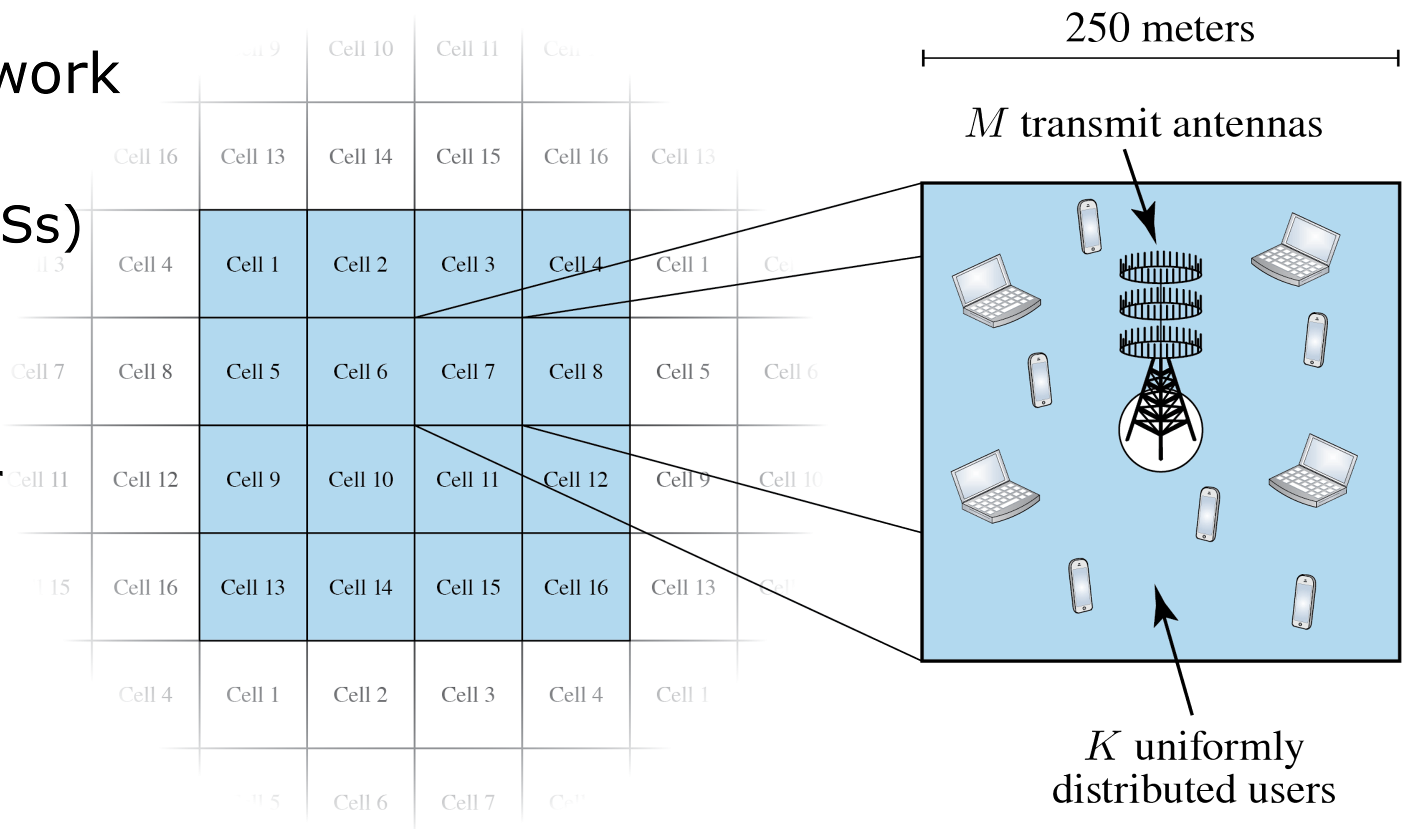
We obtain a simplified problem:

$$\begin{aligned} \underset{\mathbf{x}}{\text{maximize}} \quad & f(g_1(\mathbf{x}), g_2(\mathbf{x}), \dots, g_N(\mathbf{x})) \\ \text{subject to} \quad & \mathbf{x} \in \mathcal{X} \end{aligned}$$

- Solution: A scalar number
  (Gives one Pareto optimal point)
- Takes all metrics into account!

Example: Optimization of 5G Networks

- Design Cellular Network
  - Symmetric system
  - 16 base stations (BSs)
  - Select:
    M = # BS antennas
    K = # users
    P = transmit power



- Resource bundle:

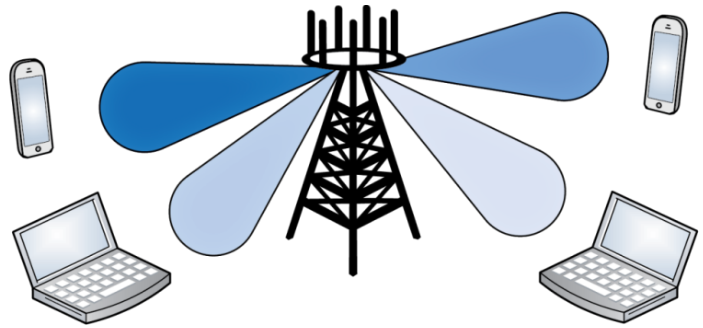
$$\mathcal{X} = \left\{ [K \ M \ P]^T : \begin{array}{c} 1 \leq K \leq \frac{M}{2}, \\ 2 \leq M \leq M_{\max}, \\ 0 \leq P \leq M P_{\max} \end{array} \right\}$$

500

20 W

Example: Optimization of 5G Networks (2)

- Downlink Multi-Cell Transmission
  - Each BS serves only its own K users
  - Coherence block length: U
  - BS knows channels within the cell (cost: K/U)
  - ZF precoding: no intra-cell interference
  - Interference leaks between cells



- Average User Rate

Power/user

Array gain

$$R_{\text{average}} = B\left(1 - \frac{K}{U}\right)\log_2\left(1 + \frac{\frac{P}{K}\overbrace{(M-K)}}{\mathcal{S}_\lambda \sigma^2 + \mathcal{J}}\right)$$

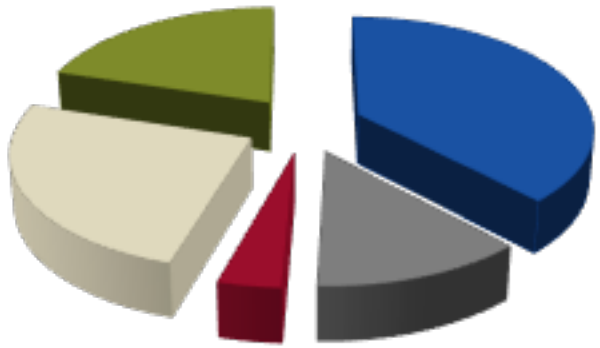
Bandwidth (10 MHz)

CSI estimation overhead ($U = 1000$)

Noise / pathloss ($1.72 \cdot 10^{-4}$)

Relative inter-cell interference (0.54)

Example: Optimization of 5G Networks (3)



- What Consumes Power?
  - Transmit power (+ losses in amplifiers)
  - Circuits attached to each antenna
  - Baseband signal processing
  - Fixed load-independent power

- Total Power Consumption

$$P_{\text{total}} = \frac{P_{\text{trans}}}{\eta} + C_{0,0} + C_{1,0}K + C_{0,1}M + \frac{B \cdot C_{\text{precoding}}}{U\, L_{\text{BS}}}$$

Amplifier efficiency (0.31)

Fixed power $(10\ \mathrm{W})$

Circuit power per user $(0.3\ \mathrm{W})$

Circuit power per antenna $(1\ \mathrm{W})$

Compute ZF precoding $(2.3 \cdot 10^{-6} \cdot MK^2)$

Example: Results

3 Objectives

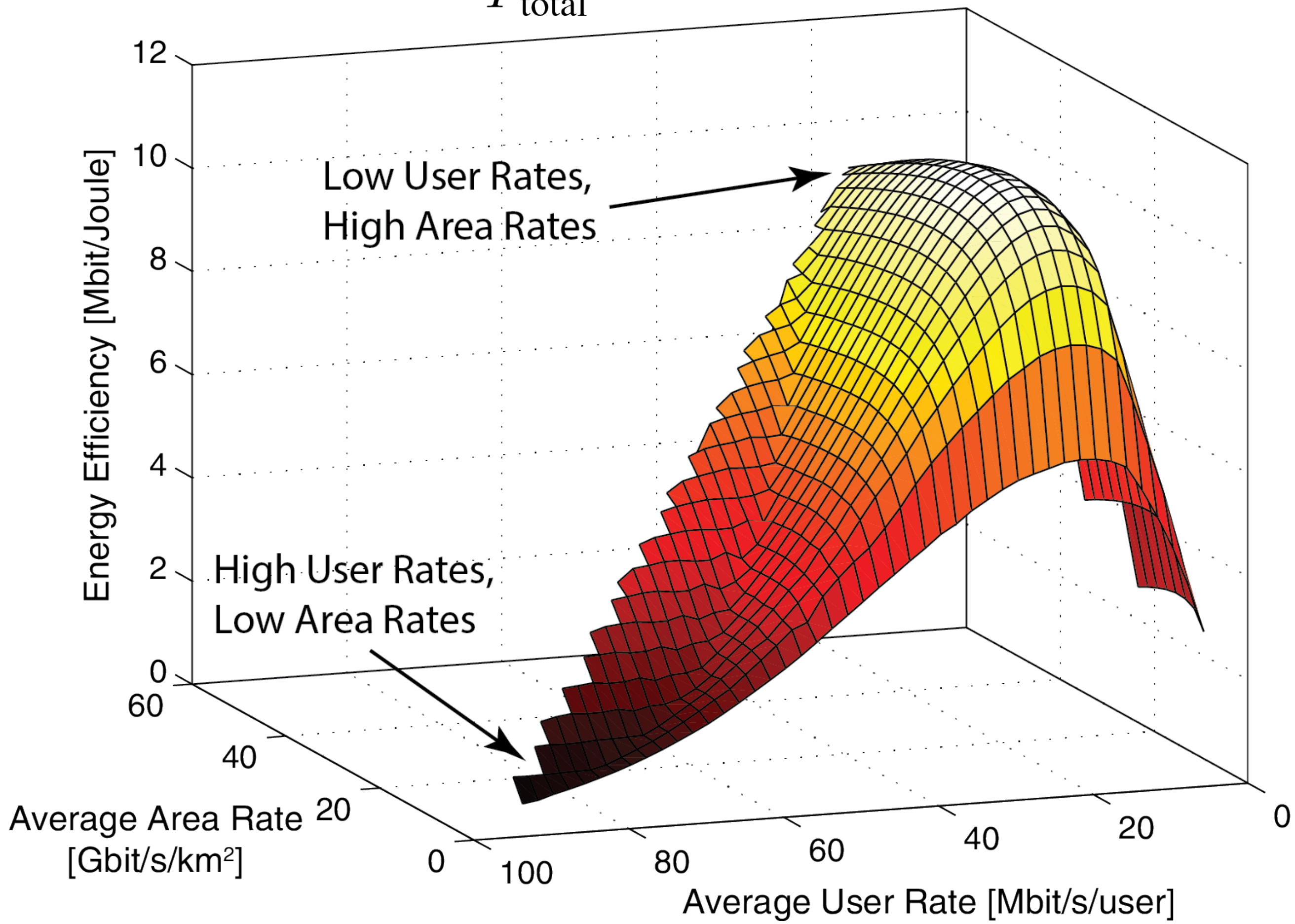
1. Average user rate $g_1(\mathbf{x}) = R_{\text{average}}$ [bit/s/user]
2. Total area rate $g_2(\mathbf{x}) = \frac{K}{A} R_{\text{average}}$ [bit/s/km^2]
3. Energy-efficiency $g_3(\mathbf{x}) = \frac{K R_{\text{average}}}{P_{\text{total}}}$ [bit/J]

Observations

Area and user rates are conflicting objectives

Only energy efficient at high area rates

Different number of users



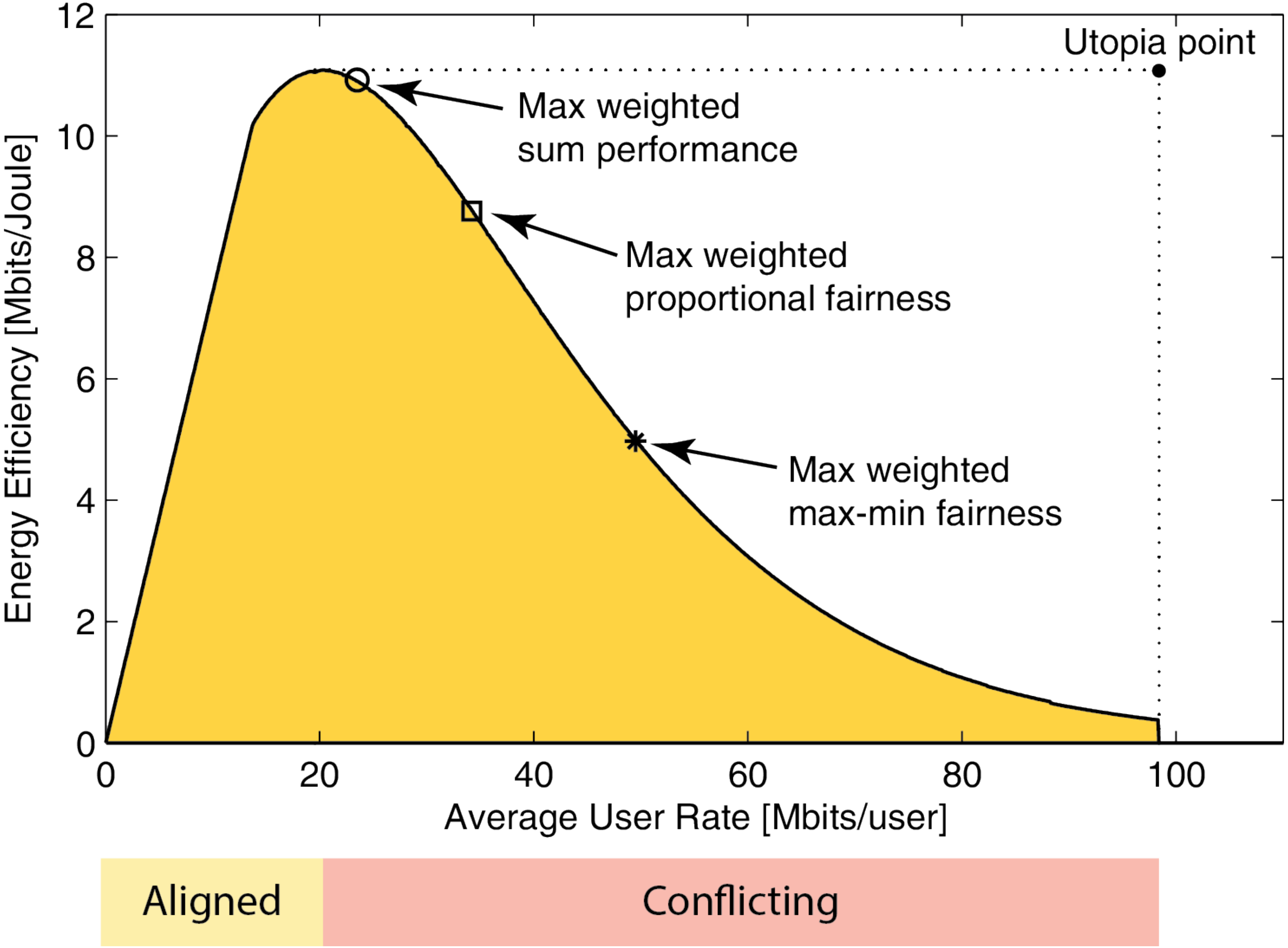
Example: Results (2)

- Energy-Efficiency vs. User Rates
  - Utility functions normalized by utopia point

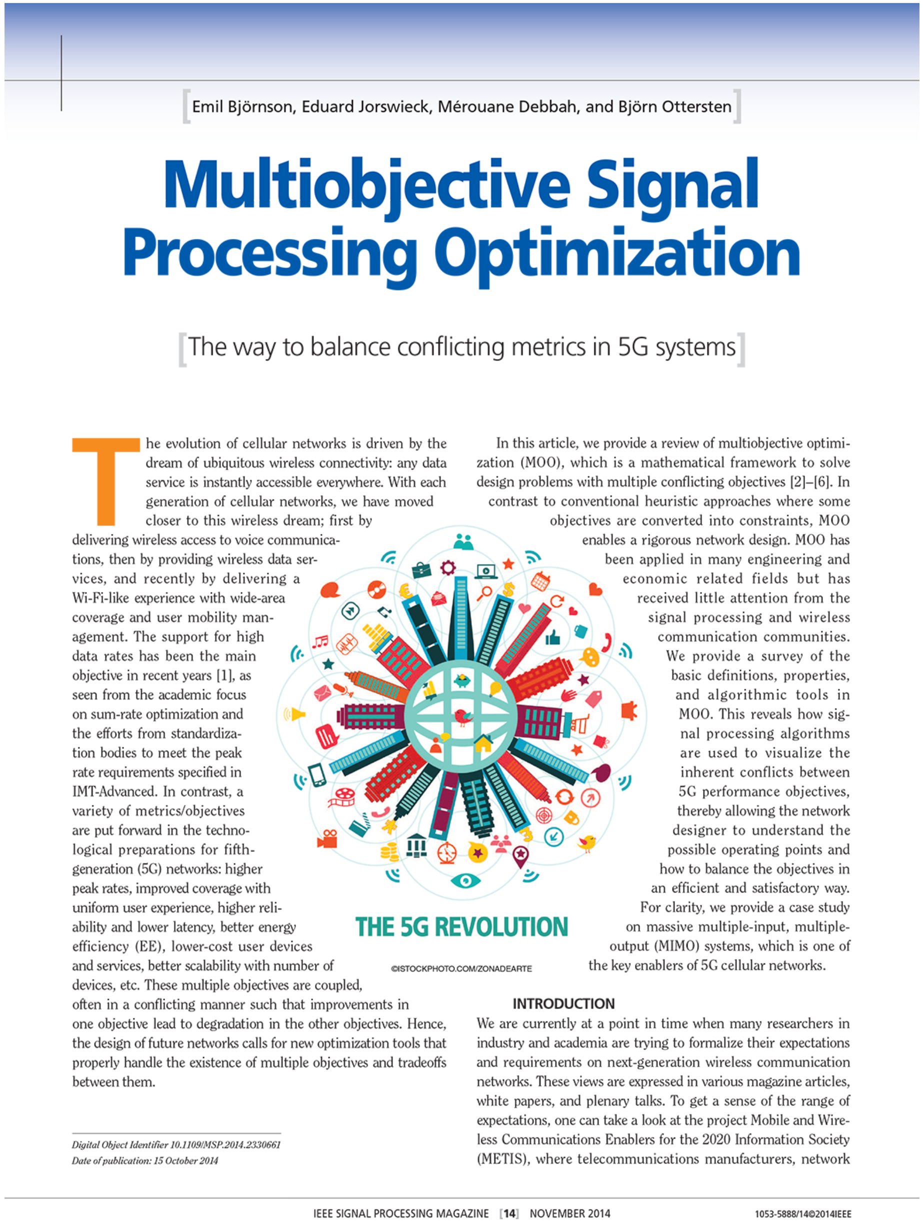
Observations

Aligned for small user rates

Conflicting for high user rates



Summary



[Emil Björnson, Eduard Jorswieck, Mérouane Debbah, and Björn Ottersten]

Multiobjective Signal Processing Optimization

[The way to balance conflicting metrics in 5G systems]

The evolution of cellular networks is driven by the dream of ubiquitous wireless connectivity: any data service is instantly accessible everywhere. With each generation of cellular networks, we have moved closer to this wireless dream; first by delivering wireless access to voice communications, then by providing wireless data services, and recently by delivering a Wi-Fi-like experience with wide-area coverage and user mobility management. The support for high data rates has been the main objective in recent years [1], as seen from the academic focus on sum-rate optimization and the efforts from standardization bodies to meet the peak rate requirements specified in IMT-Advanced. In contrast, a variety of metrics/objectives are put forward in the technological preparations for fifth-generation (5G) networks: higher peak rates, improved coverage with uniform user experience, higher reliability and lower latency, better energy efficiency (EE), lower-cost user devices and services, better scalability with number of devices, etc. These multiple objectives are coupled, often in a conflicting manner such that improvements in one objective lead to degradation in the other objectives. Hence, the design of future networks calls for new optimization tools that properly handle the existence of multiple objectives and tradeoffs between them.

THE 5G REVOLUTION

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In this article, we provide a review of multiobjective optimization (MOO), which is a mathematical framework to solve design problems with multiple conflicting objectives [2]–[6]. In contrast to conventional heuristic approaches where some objectives are converted into constraints, MOO enables a rigorous network design. MOO has been applied in many engineering and economic related fields but has received little attention from the signal processing and wireless communication communities. We provide a survey of the basic definitions, properties, and algorithmic tools in MOO. This reveals how signal processing algorithms are used to visualize the inherent conflicts between 5G performance objectives, thereby allowing the network designer to understand the possible operating points and how to balance the objectives in an efficient and satisfactory way. For clarity, we provide a case study on massive multiple-input, multiple-output (MIMO) systems, which is one of the key enablers of 5G cellular networks.

INTRODUCTION

We are currently at a point in time when many researchers in industry and academia are trying to formalize their expectations and requirements on next-generation wireless communication networks. These views are expressed in various magazine articles, white papers, and plenary talks. To get a sense of the range of expectations, one can take a look at the project Mobile and Wireless Communications Enablers for the 2020 Information Society (METIS), where telecommunications manufacturers, network

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- Multi-Objective Optimization
  - Rigorous way to study problems with multiple performance metrics
- 5G Characterized by Multiple Metrics
  - Calls for multi-objective network design
  - Framework to derive interplay between EE and other performance metrics
  - A way to make informed decisions!

Further Reading

E. Björnson, E. Jorswieck, M. Debbah, B. Ottersten, "*Multi-Objective Signal Processing Optimization: The Way to Balance Conflicting Metrics in 5G Systems*," IEEE SPM, Nov. 2014.

Part 5

Questions?

Conclusion

Conclusions

- What if a Cellular Network is Designed for High Energy-Efficiency?
  - Energy-efficiency [bit/Joule] $= \dfrac{\text{Average Sum Rate [bit/s/cell]}}{\text{Power Consumption [Joule/s/cell]}}$
  - Necessary: Accurate expressions for rate and power consumption
  - Design parameters: Number of users, BS antennas, transmit power, BS density, and pilot reuse factor

- Analytical and Numerical Results
  - Tractable problem formulation was developed
  - Fundamental interplay between system parameters obtained by analysis
  - Network densification is the way to high EE
  - Small cells and Massive MIMO have complementary benefits
  - Feasible to combine these techniques: Massive MIMO $\neq$ large size

- Multi-Objective Optimization
  - Framework to jointly optimize energy-efficiency and other 5G metrics

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THANKS!

Papers, Presentations, and Simulation Code are Available on our Homepages:

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

http://www.iet.unipi.it/l.sanguinetti/