Energy-Efficient Communication in Wireless Networks

Small or massive MIMO?

Dr. Emil Björnson

Seminar at 5GrEEn Summer School, KTH Kista, Stockholm
26 August 2014

LiU EXPANDING REALITY

Biography

- 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, and KTH, based on International postdoc grant “Optimization of Green Small-Cell Networks”
- 2014: Assistant Professor in Communication Systems, Linköping University, Sweden

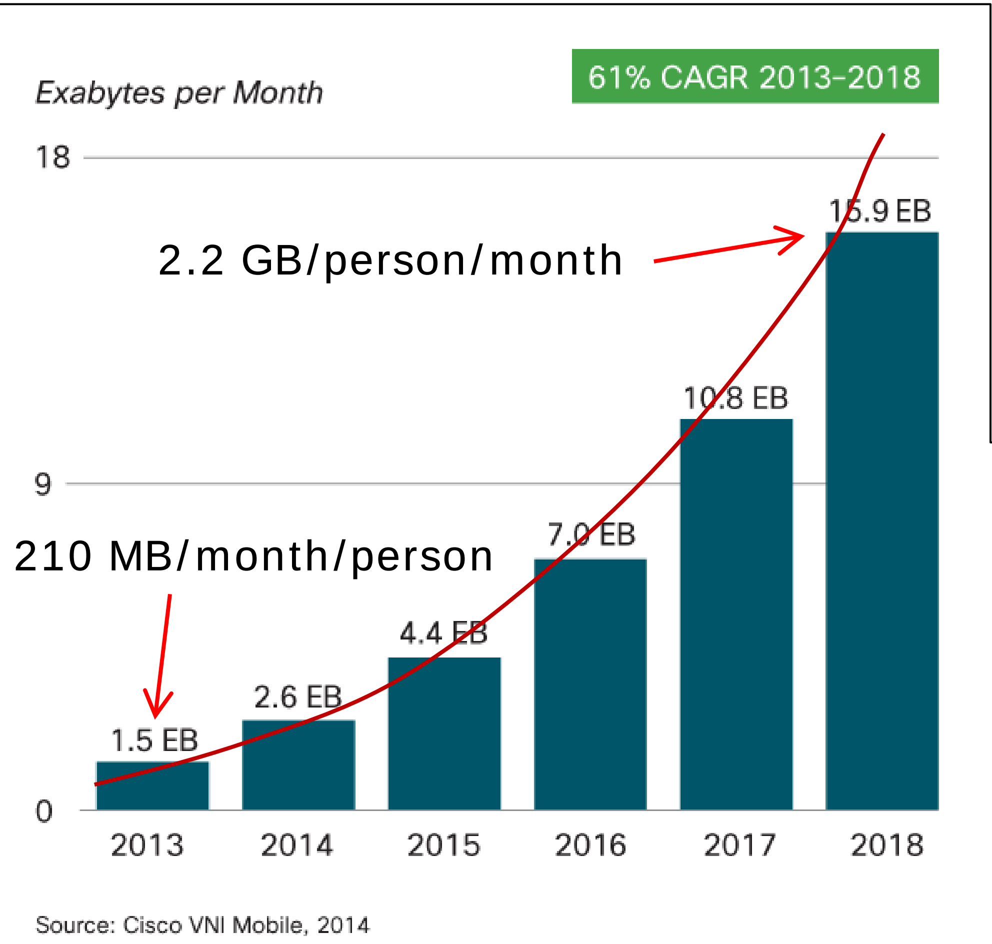
Outline

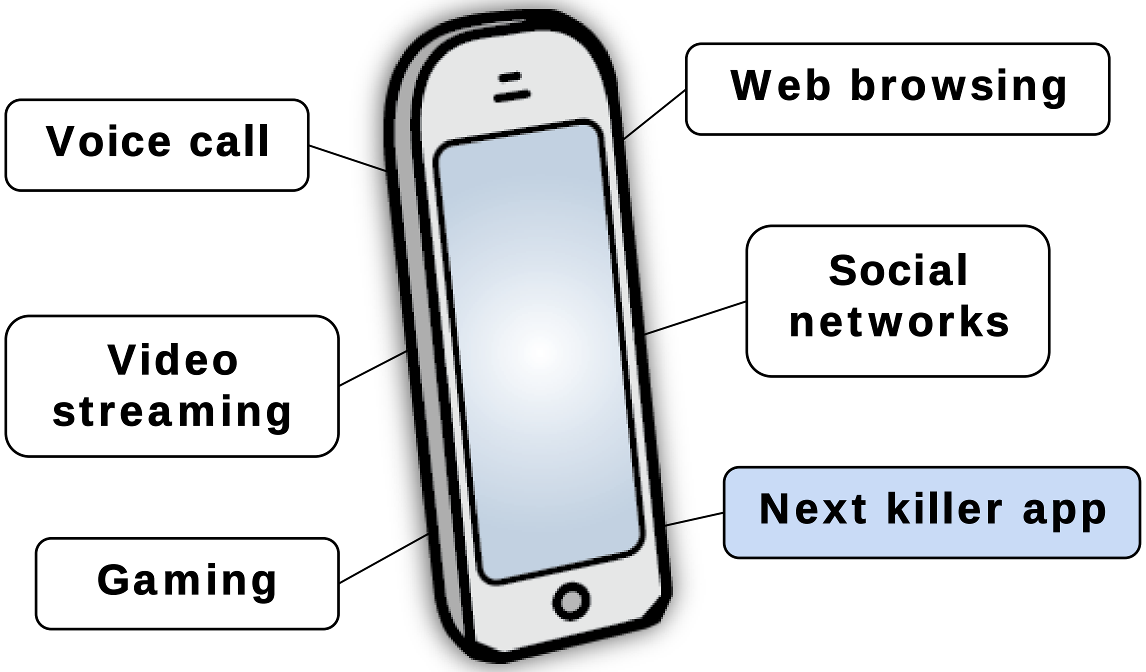
- Introduction & Background
- Part 1: Problem Formulation
  - Detailed system model (energy-efficiency, rates and power consumption)
- Part 2: Optimization of Energy-Efficiency
  - Optimal system parameters: Reveal fundamental interplay
  - Numerical results: Single-cell and multi-cell
- Part 3: Massive MIMO
  - Main properties and deployment ideas
- Part 4: Multi-Objective Network Optimization
  - Optimizing energy-efficiency and other metrics *in parallel*

Introduction & Background

Introduction

- Wireless Connectivity
  - A natural part of our lives





- Rapid Network Traffic Growth
  - 61% annual growth
  - Exponential increase!
  - Extrapolation: 20x until 2020
    200x until 2025
    2000x until 2030

Exponential Traffic Growth

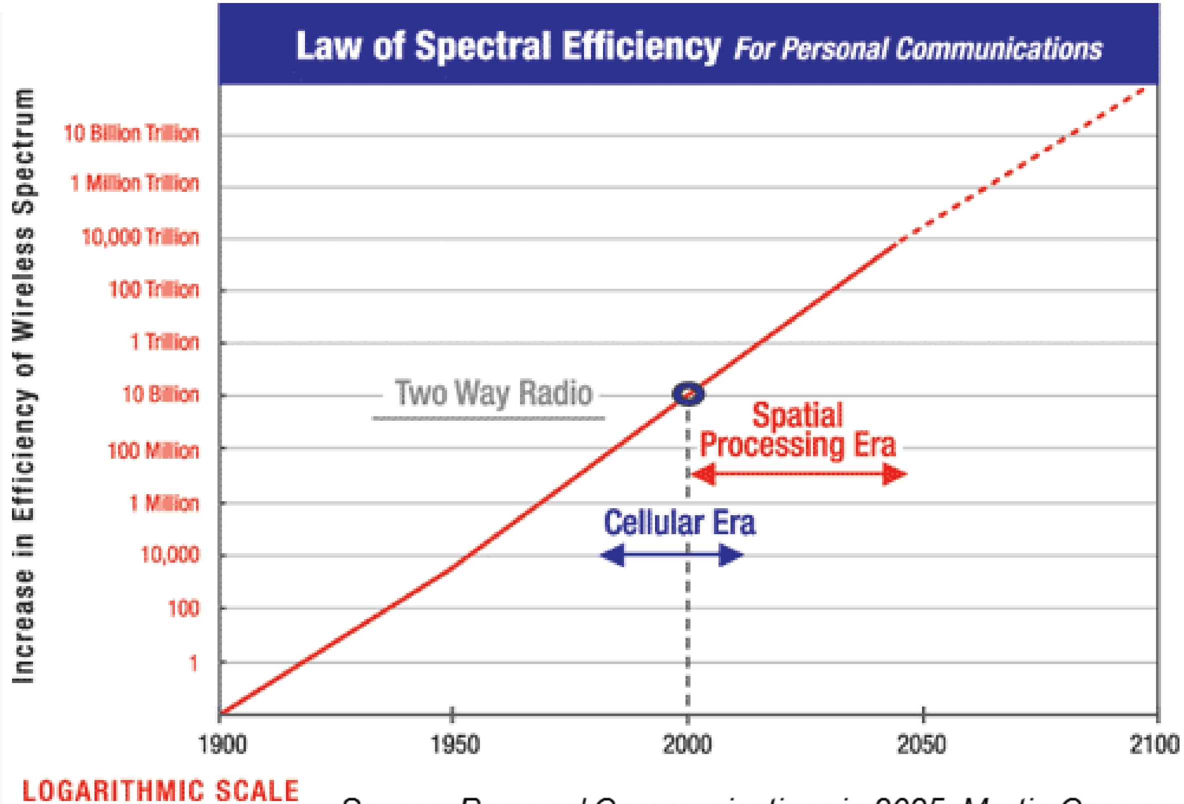
- Is this Growth Sustainable?
  - User *demand* will increase – users expect more for same price
  - Traffic supply – increases only if business models allow it!

- 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

- Coopers law: 32%/year
- New predictions: 61%/year



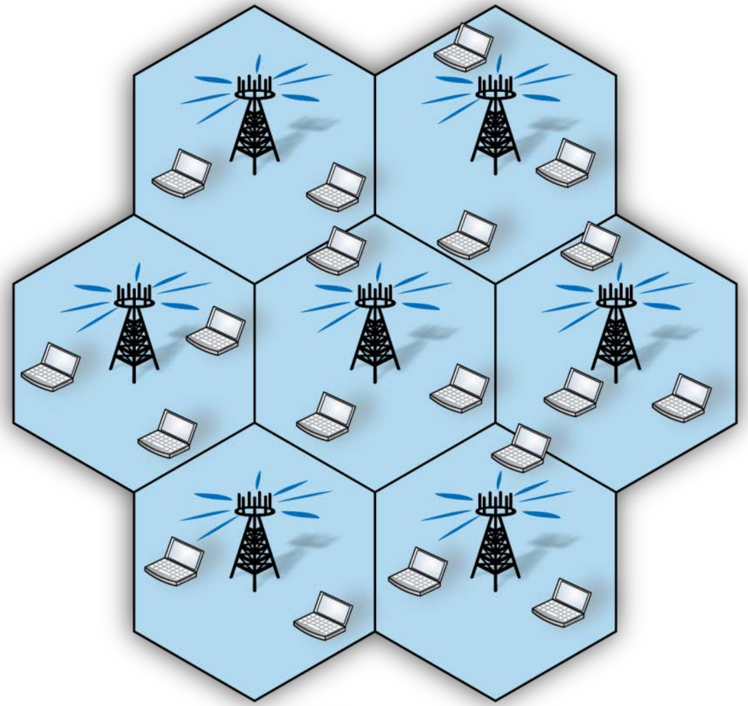
Source: *Personal Communications in 2025, Martin Cooper*

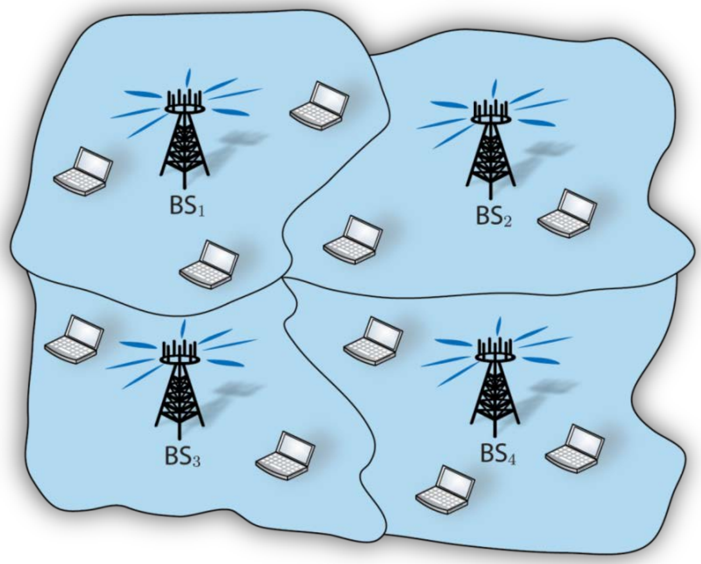
Wireless Networks

- Cellular Network Architecture
  - Coverage Area divided into cells
  - One fixed base station per cell
  - Serves all users in the cell
- 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)



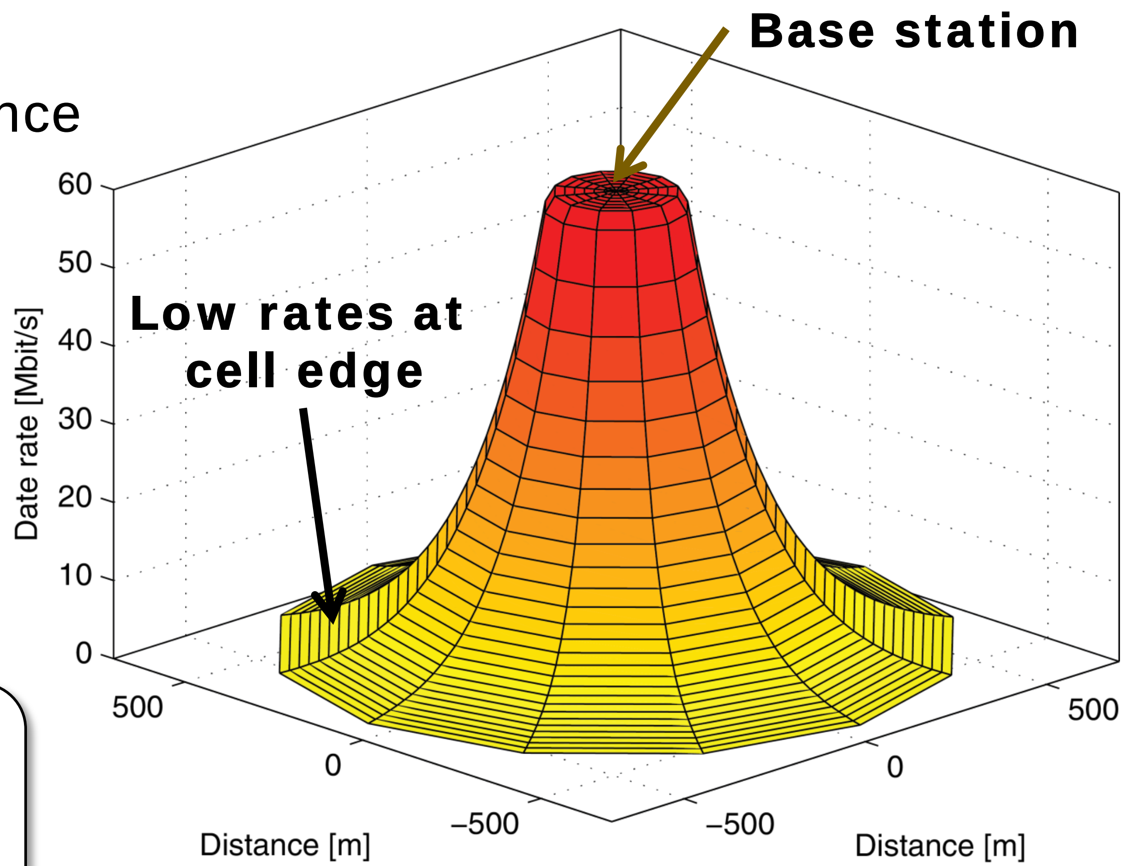


High Data Rates

- 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 Network Generation
  - Expected to be introduced by year 2020
  - Design objectives are currently being defined

5G Performance Metrics	**Expectation**
Average Rate (Mbit/s/active user)	10-100x
Average Area Rate (Mbit/s/km^2)	1000x
Active devices (per km^2)	10-100x
Energy-Efficiency (Mbit/Joule)	1000x

Source: METIS project (www.metis2020.com)

Parts 1-3

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

What will it look like?

Part 4

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

What does “optimality” mean then?

Part 1

Problem Formulation

How to Measure Energy-Efficiency?

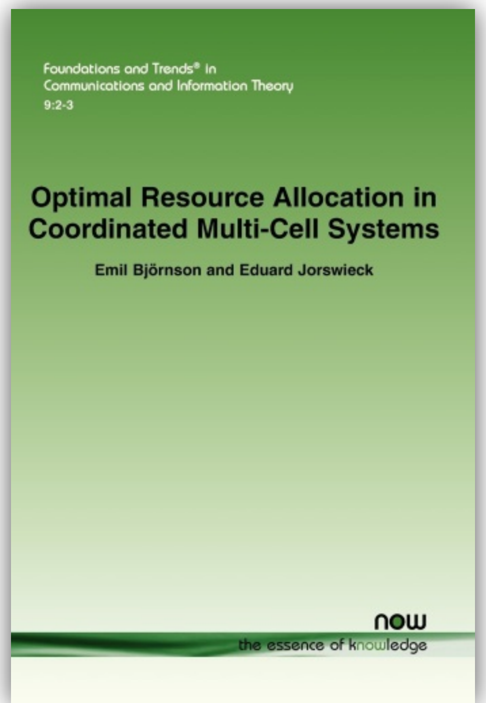
- Energy-Efficiency (EE) in bit/Joule

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

- 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
Free to download from my homepage



New Problem: Balance rates and power consumption

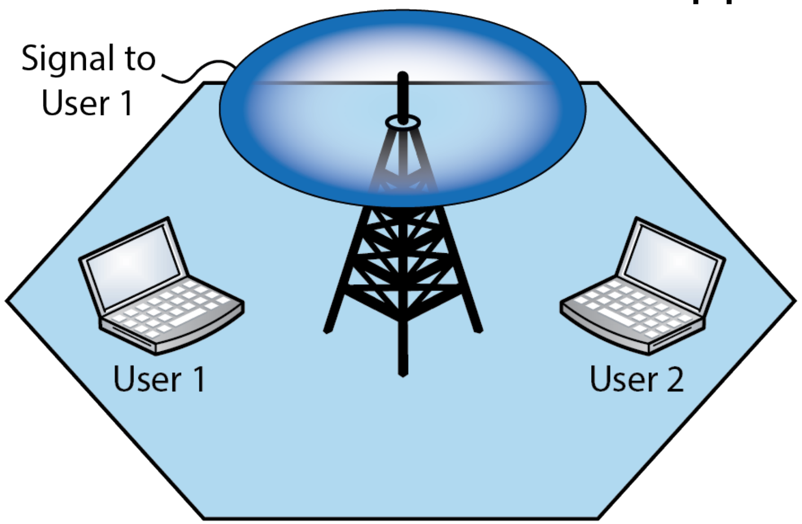
Important to account for overhead signaling and circuit power!

Basic Information Theory

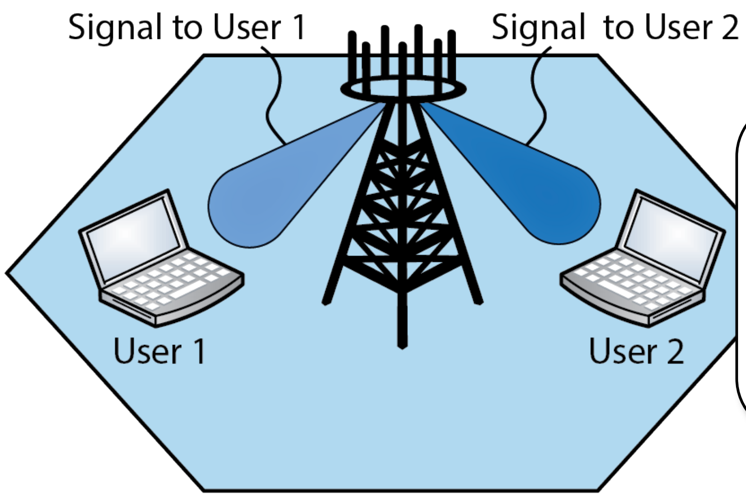
Achievable Rate per Active User [Lower Bound on Shannon Capacity]

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

- More than One 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



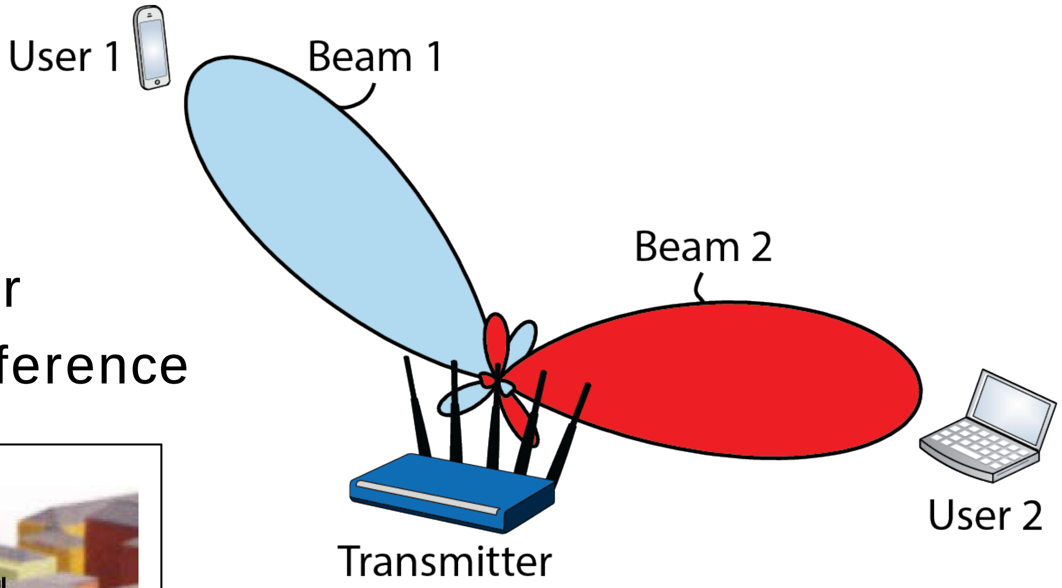
Multi-Antenna Transmission

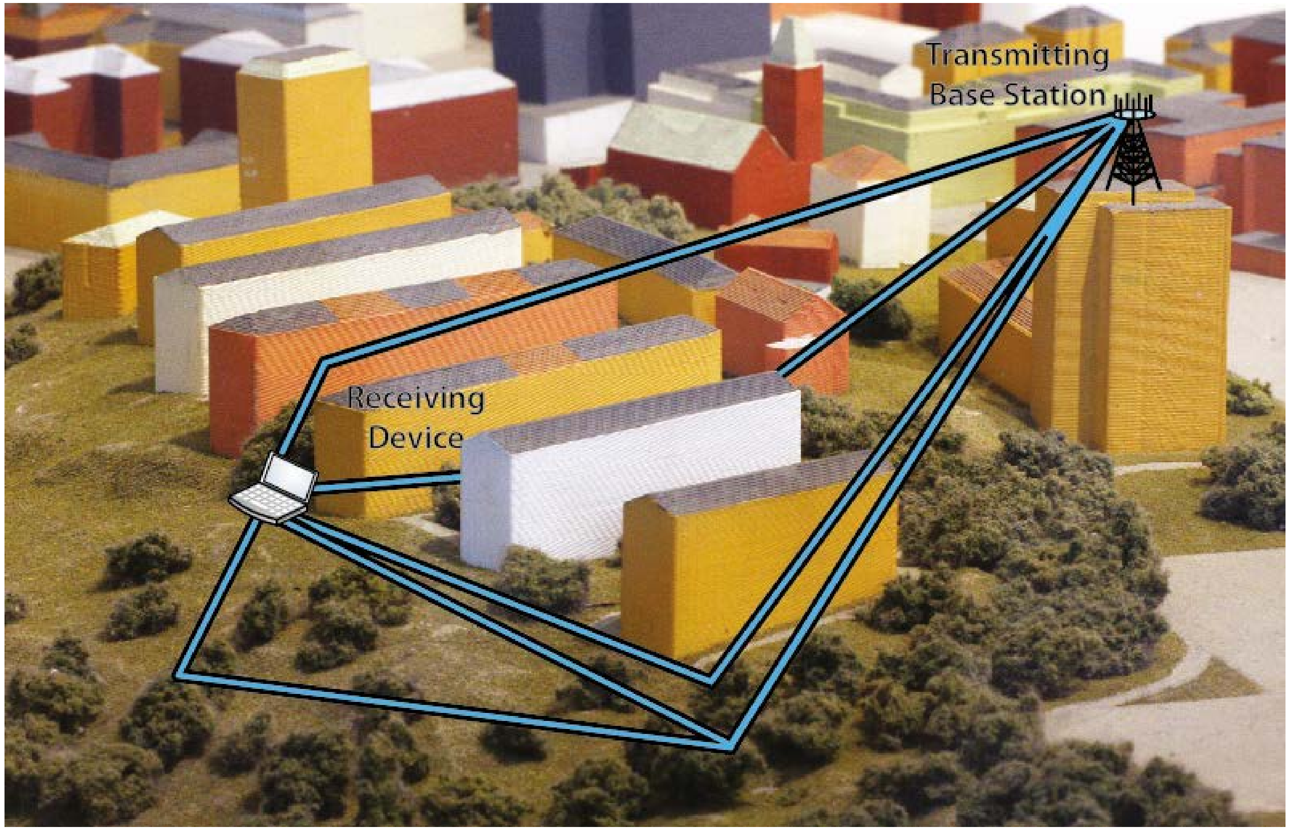
Known as

Multi-user MIMO (Multiple input multiple output)

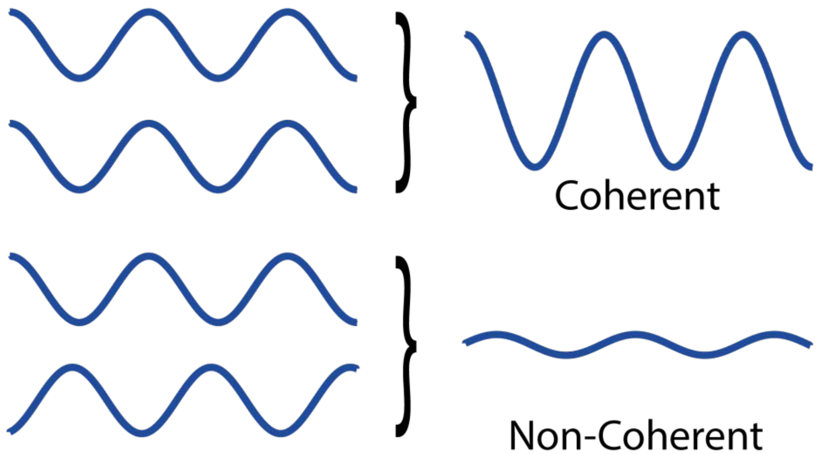
Beamforming in Line-of-Sight and Non-Line-of-Sight

- Line-of-Sight
  - Adapt signal phases at antennas
  - Steer beam towards receiving user
  - Imperfect beams: inter-user interference



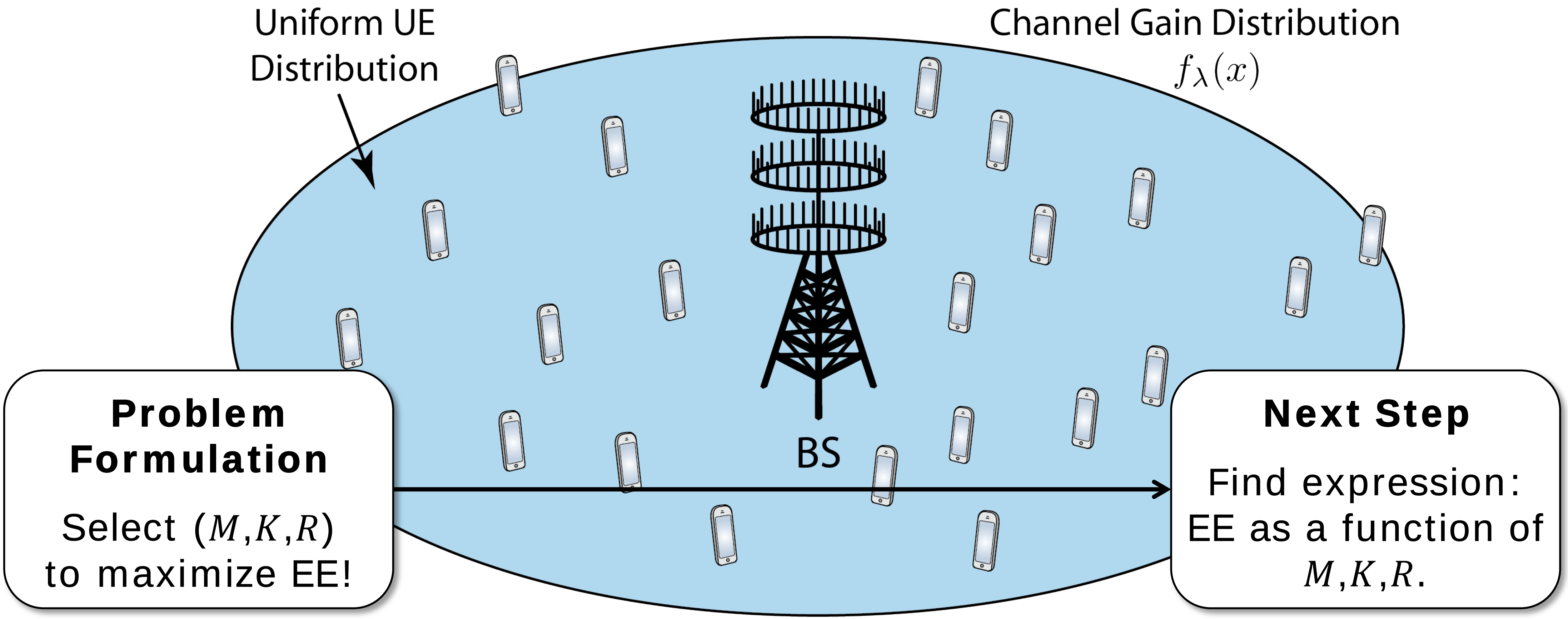


- Non-Line-of-Sight
  - Multipath propagation
  - Add components coherently



Single-Cell: Optimizing for Energy-Efficiency

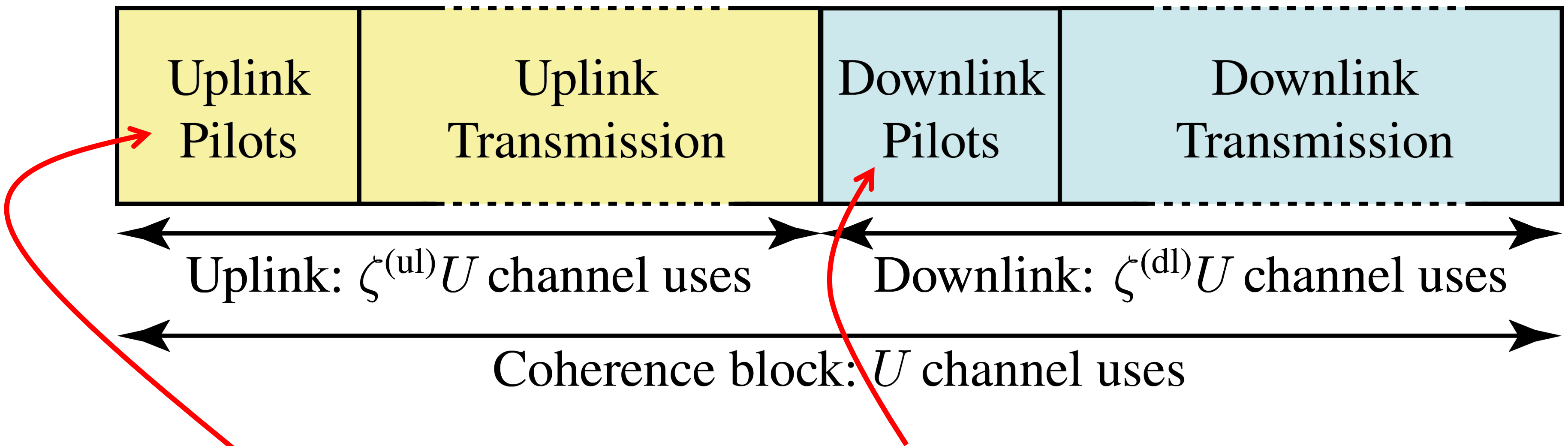
- Clean Slate Design
  - Single Cell: One base station (BS) with M antennas
  - Geometry: Random distribution for user locations and pathlosses
  - Multiple users: Pick K users randomly and serve with some rate R



System Model: Protocol

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

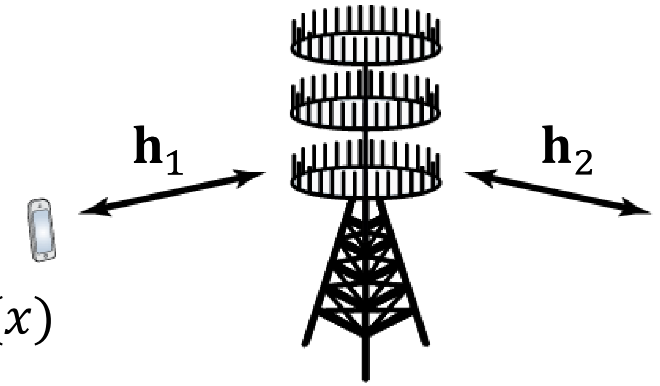
- Coherence Block
  - B Hz bandwidth = B "channel uses" per second (symbol time $1/B$)
  - Channel stays fixed for U channel uses (symbols) = Coherence block
  - Determines how often we send pilot signals to estimate channels



Assumption: Perfect channel estimation (relaxed later)

System Model: 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:

Signals from other users (interference)

$$\boldsymbol{y} = \mathbf{h}_k s_k + \sum_{i=1,\, i\neq k}^{K} \mathbf{h}_i s_i + \mathbf{n}$$

Signal of User k

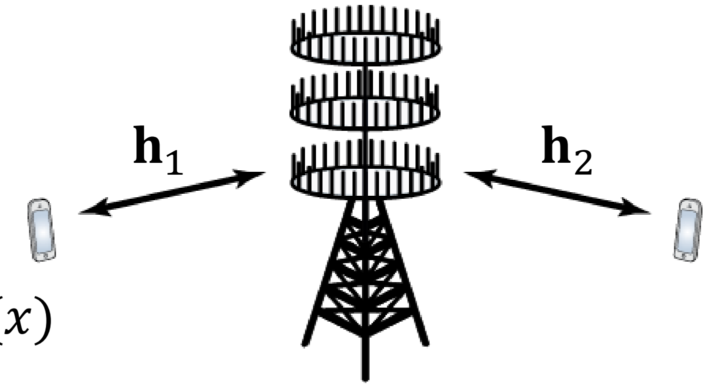
Noise $\sim \mathcal{CN}(\mathbf{0}, \sigma^2 \mathbf{I})$

  - Recover s_k by receive beamforming $\mathbf{g}_k$ 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: Channels (2)

- 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 beamforming 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 beamforming $\mathbf{g}_k$ 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: $\sigma^2\mathbf{D}^{-1}\mathbf{1}$

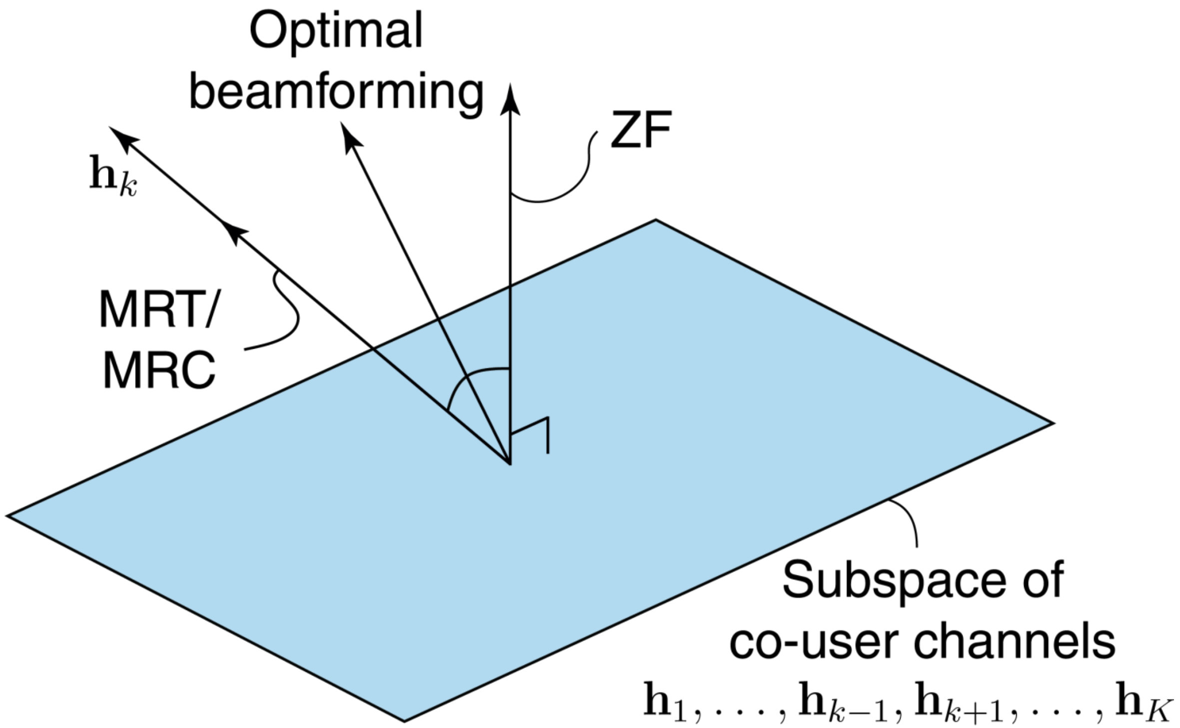
Same total power: $P_{\mathrm{trans}} = B\mathbb{E}\{\sigma^2\mathbf{1}^H\mathbf{D}^{-1}\mathbf{1}\} = B\mathbb{E}\{\sigma^2\mathbf{1}^H\mathbf{D}^{-H}\mathbf{1}\}$

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 beamforming vectors

- Different Beamforming
  - Notation: $\mathbf{G} = [\mathbf{g}_1, \dots, \mathbf{g}_K]$
    $\mathbf{V} = [\mathbf{v}_1, \dots, \mathbf{v}_K]$,
    $\mathbf{H} = [\mathbf{h}_1, \dots, \mathbf{h}_K]$,
    $\mathbf{P}^{(\mathrm{ul})} = \mathrm{diag}(\mathrm{p}_1^{(\mathrm{ul})}, \dots, \mathrm{p}_K^{(\mathrm{ul})})$



Minimize interference

Maximize signal

  - Maximum ratio trans./reception (MRT/MRC): $\mathbf{G} = \mathbf{V} = \mathbf{H}$
  - Zero-forcing (ZF) beamforming: $\mathbf{G} = \mathbf{V} = \mathbf{H}(\mathbf{H}^H\mathbf{H})^{-1}$
  - Optimal beamforming: $\mathbf{G} = \mathbf{V} = \left(\sigma^2\mathbf{I} + \mathbf{H}\,\mathbf{P}^{(\mathrm{ul})}\mathbf{H}^H\right)^{-1}\mathbf{H}$

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: $$[\mathbf{D}]_{k,l} = \begin{cases} \frac{\left|\mathbf{h}_k^H\mathbf{v}_k\right|^2}{(2^{R/B}-1)\|\mathbf{v}_k\|^2} & \text{for } k=l \\ -\frac{\left|\mathbf{h}_k^H\mathbf{v}_l\right|^2}{\|\mathbf{v}_l\|^2} & \text{for } k \neq l \end{cases} = \begin{cases} \frac{1}{(2^{R/B}-1)\|\mathbf{v}_k\|^2} & \text{for } k=l \\ 0 & \text{for } k \neq l \end{cases}$$
  - Total transmit power:

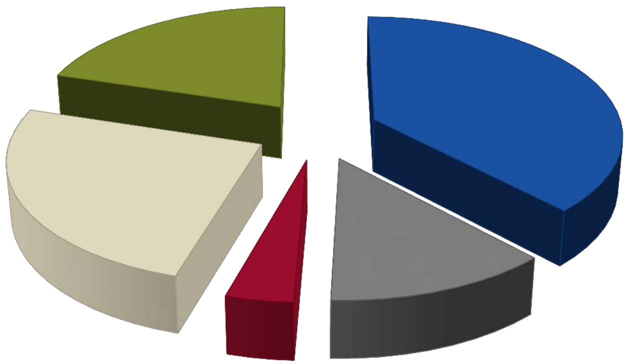
$$P_{\text{trans}} = \mathbb{E}\{B\sigma^2\mathbf{1}^H\mathbf{D}^{-1}\mathbf{1}\} = B\sigma^2(2^{R/B}-1)\underbrace{\sum_k \mathbb{E}\{\|\mathbf{v}_k\|^2\}}_{=\operatorname{tr}\left(\left(\mathbf{H}^H\mathbf{H}\right)^{-1}\right)} \overset{\text{Property of Wishart matrices}}{=} B\sigma^2(2^{R/B}-1)\frac{K}{M-K}\underbrace{\mathbb{E}\left\{\frac{1}{\lambda}\right\}}_{\text{Call this } \mathcal{S}_\lambda \text{ (depends on cell)}}$$

Summary: Transmit Power with ZF

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

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

Detailed Power Consumption Model



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

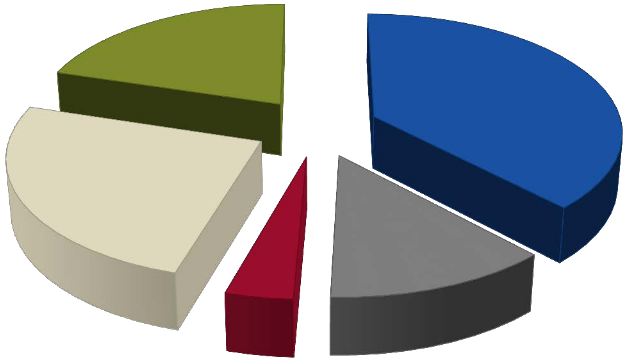
- Power Amplifiers
  - Amplifier efficiencies: $\eta^{(\mathrm{ul})}, \eta^{(\mathrm{dl})} \in (0,1]$
  - Average inefficiency: $\frac{\zeta^{(\mathrm{ul})}}{\eta^{(\mathrm{ul})}} + \frac{\zeta^{(\mathrm{dl})}}{\eta^{(\mathrm{dl})}} = \frac{1}{\eta}$

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)



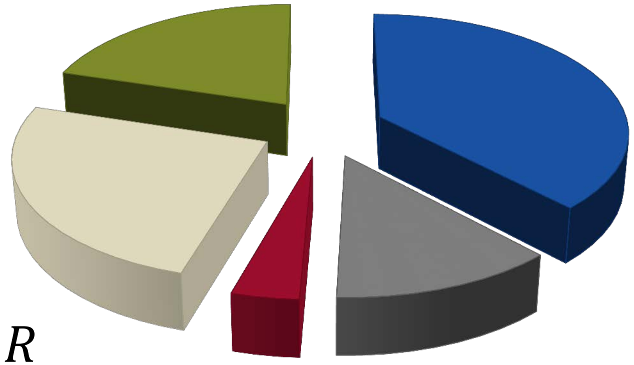
- Signal Processing
  - Channel estimation and beamforming
  - Efficiency: $L_{\text{BS}}, L_{\text{UE}}$ arithmetic operations / Joule

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

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

Number of iterations

Detailed Power Consumption Model (3)



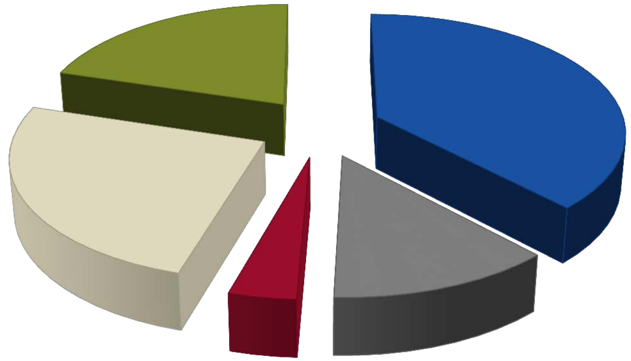
- Coding and Decoding: $R_{\text{sum}}(P_{\text{COD}} + P_{\text{DEC}})$
  - P_{COD} = Energy for coding data / bit
  - P_{DEC} = Energy for decoding data / bit
  - Sum rate: $R_{\text{sum}} = K\left(\zeta^{(\text{ul})} - \frac{\tau^{(\text{ul})}K}{U}\right)R + K\left(\zeta^{(\text{dl})} - \frac{\tau^{(\text{dl})}K}{U}\right)R$

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

- 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., $P_{\text{BS}}, P_{\text{UE}}$) change over time
  - Structure is important for analysis



Generic Power Model

Fixed power

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

Transmit with amplifiers

Circuit power per transceiver chain

Cost of signal processing

Coding/decoding/ backhaul

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]

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

Closed Form Expressions with ZF

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

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

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

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

Why Such a Detailed/Complicated Model?

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

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

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

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

- Example 2: Ignore pilot overhead and signal processing

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

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

Part 1

Questions?

Part 2

Optimization of Energy-Efficiency

Preliminaries

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

  For ZF processing

- 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., $e^{W(x)} \approx x$):

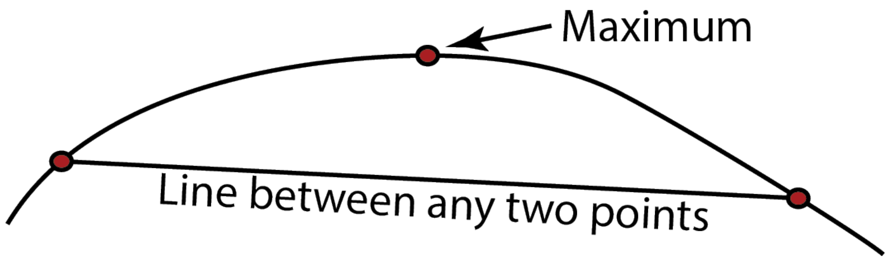
$$\frac{x\,e}{\log_e(x)} \leq e^{W(x)+1} \leq \frac{x}{\log_e(x)}(1+e) \quad \text{for} \quad x \geq e.$$

Solving Optimization Problems

- How to Solve an Optimization Problem?
  - Simple if the function is “nice”:

Quasi-Concave Function

For any two points on the graph of the function, the line between the points is below the graph



Property: Goes up and then down

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

- Maximization of a 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:

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

Theorem 1 (Optimal M)

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

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

- 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 α approx. as $\frac{\alpha}{\log \alpha}$ (almost linear)

Optimal Transmit Power

- Find α that maximizes EE with ZF:

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

Theorem 2 (Optimal α)

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

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

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

More circuit power → More transmit power

Optimal Number of Users

- Find K that maximizes EE with ZF:

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

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

Theorem 3 (Optimal K)

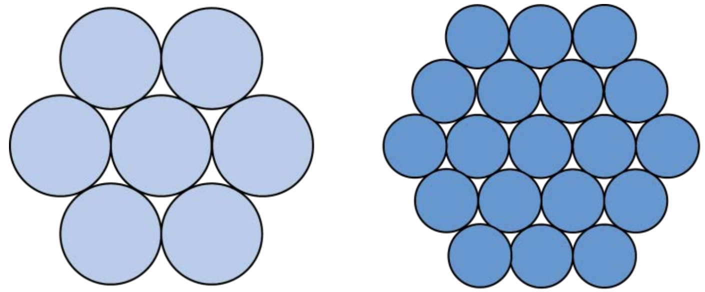
EE is quasi-concave w.r.t. K

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 ($P_{\mathrm{BS}}, P_{\mathrm{UE}}, 1/L_{BS}$)

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, α, K
  - Smaller $\mathcal{S}_\lambda$ → smaller transmit power $\alpha B \sigma^2 \mathcal{S}_\lambda K$
  - Higher EE!

- Expressions for M^*, α^*, K^*
  - M^* and K^* increases with $\mathcal{S}_\lambda$
  - α^* 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
Example: Impact of bandwidth B, coherence block length U, etc.

Alternating Optimization Algorithm

- Joint EE Optimization
  - EE is a function of M, α, 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, α, K) is given
2. Update number of users K (and implicitly M and α) using Theorem 3
3. Update number of antennas M using Theorem 1
4. Update transmit power (α) using Theorem 2
5. Repeat 2.-5. until convergence

Theorem 4

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

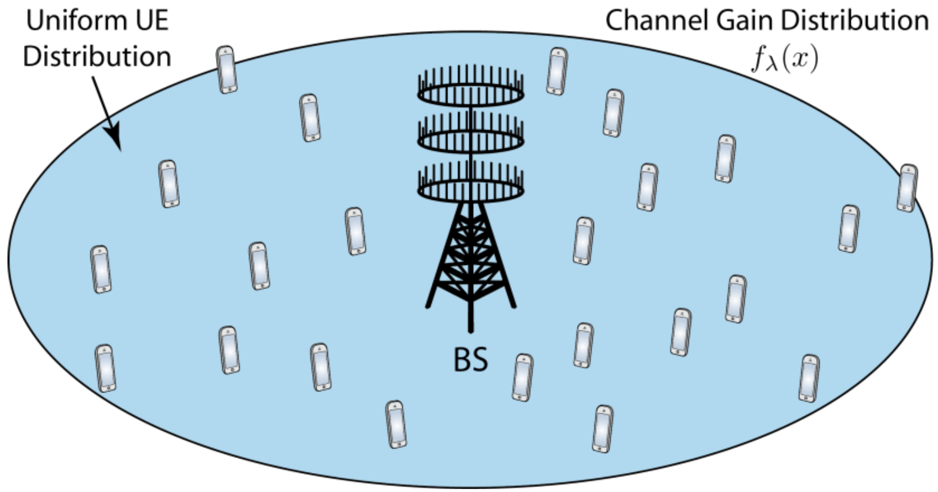
Disclaimer

M and K should be integers

Theorems 1 and 3 give real numbers
→ Take one of the 2 closest integers

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 Beamforming

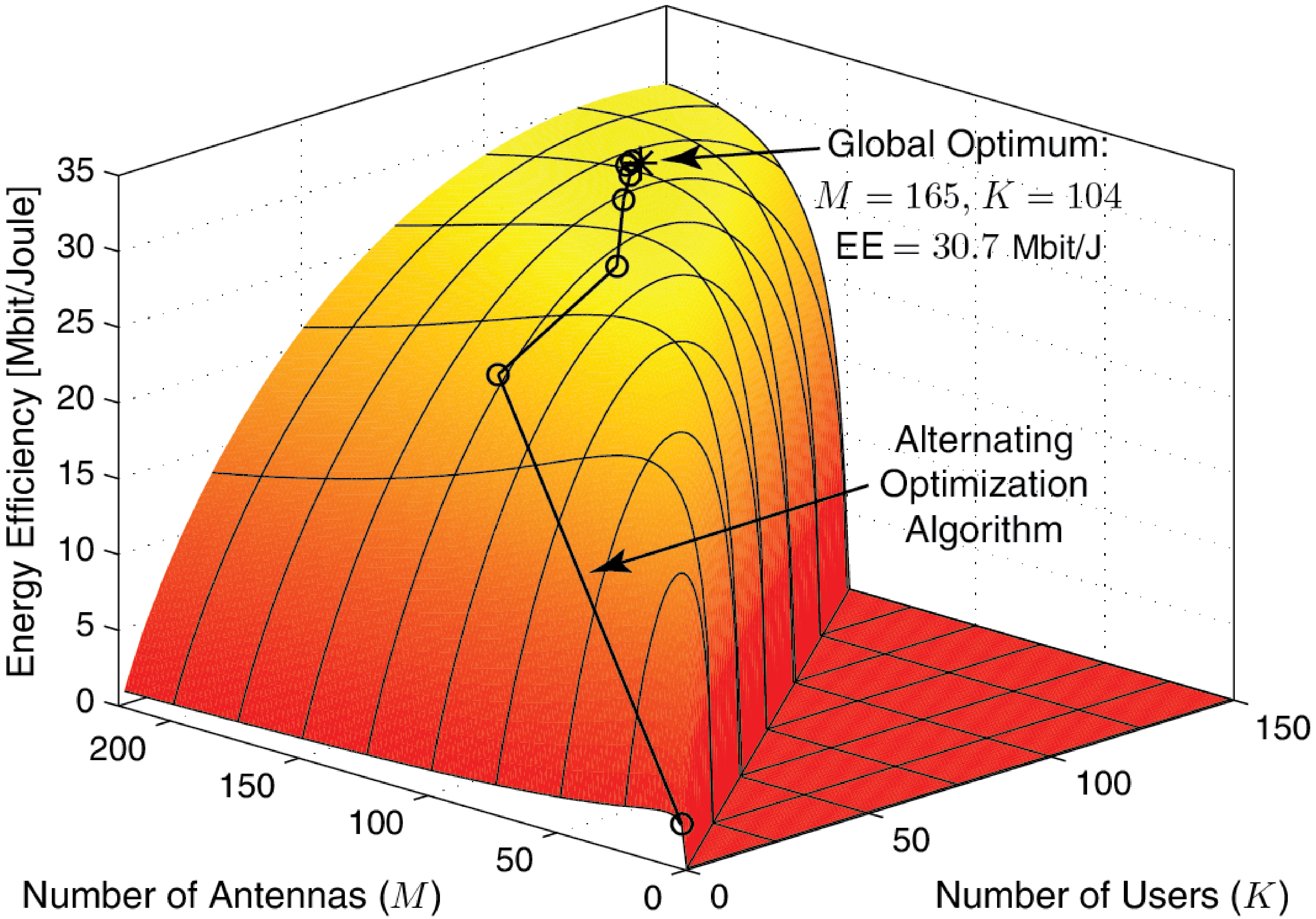
Optimum

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

User rates:
≈64-QAM

Massive MIMO!

Name for multi-user MIMO with very many antennas



Optimal Single-Cell System Design: “Optimal” Beamforming

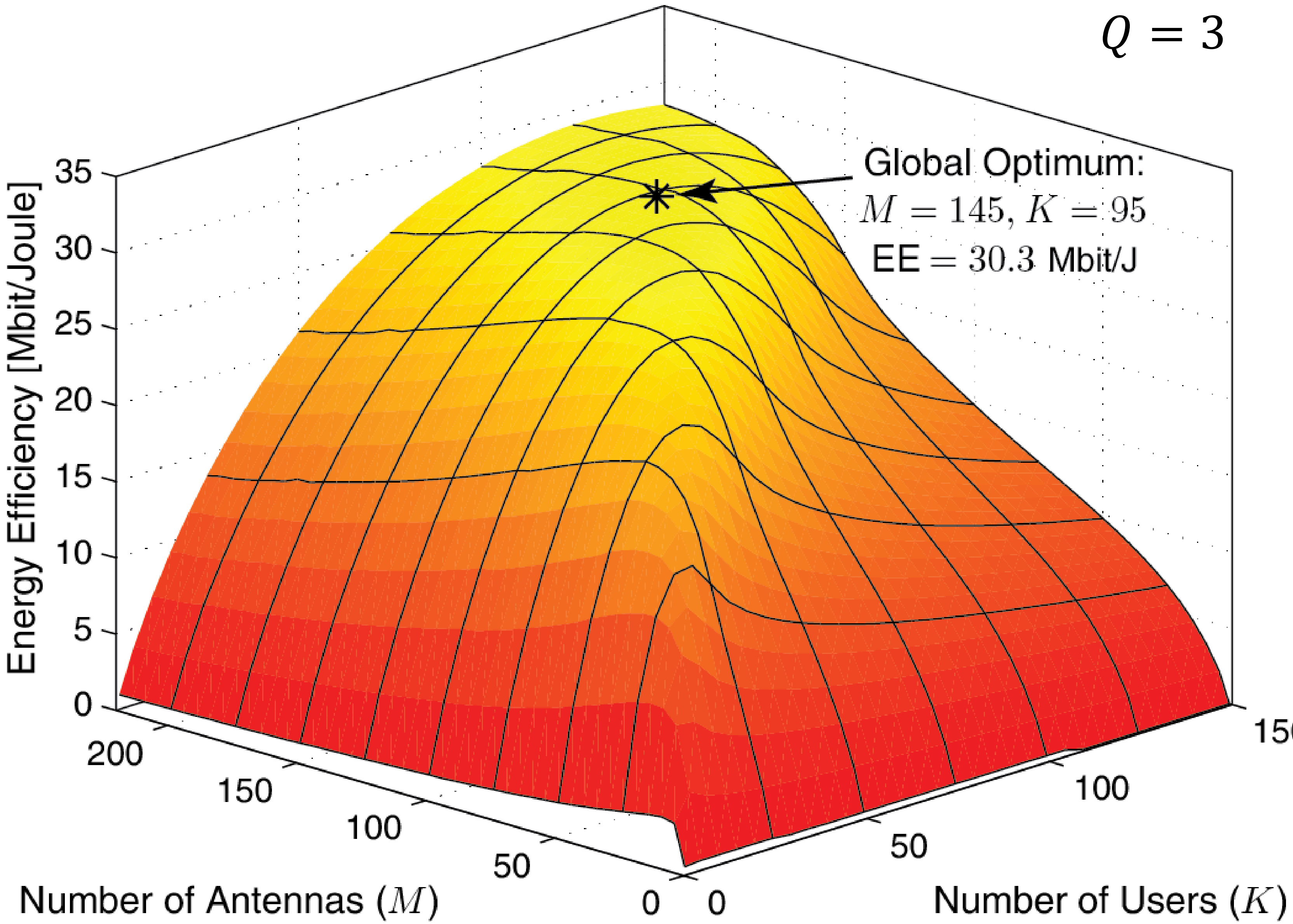
Optimum

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

User rates:
≈64-QAM

Not optimal!

Gives optimal beamforming but computations are too costly



Optimal Single-Cell System Design: MRT/MRC Beamforming

Optimum

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

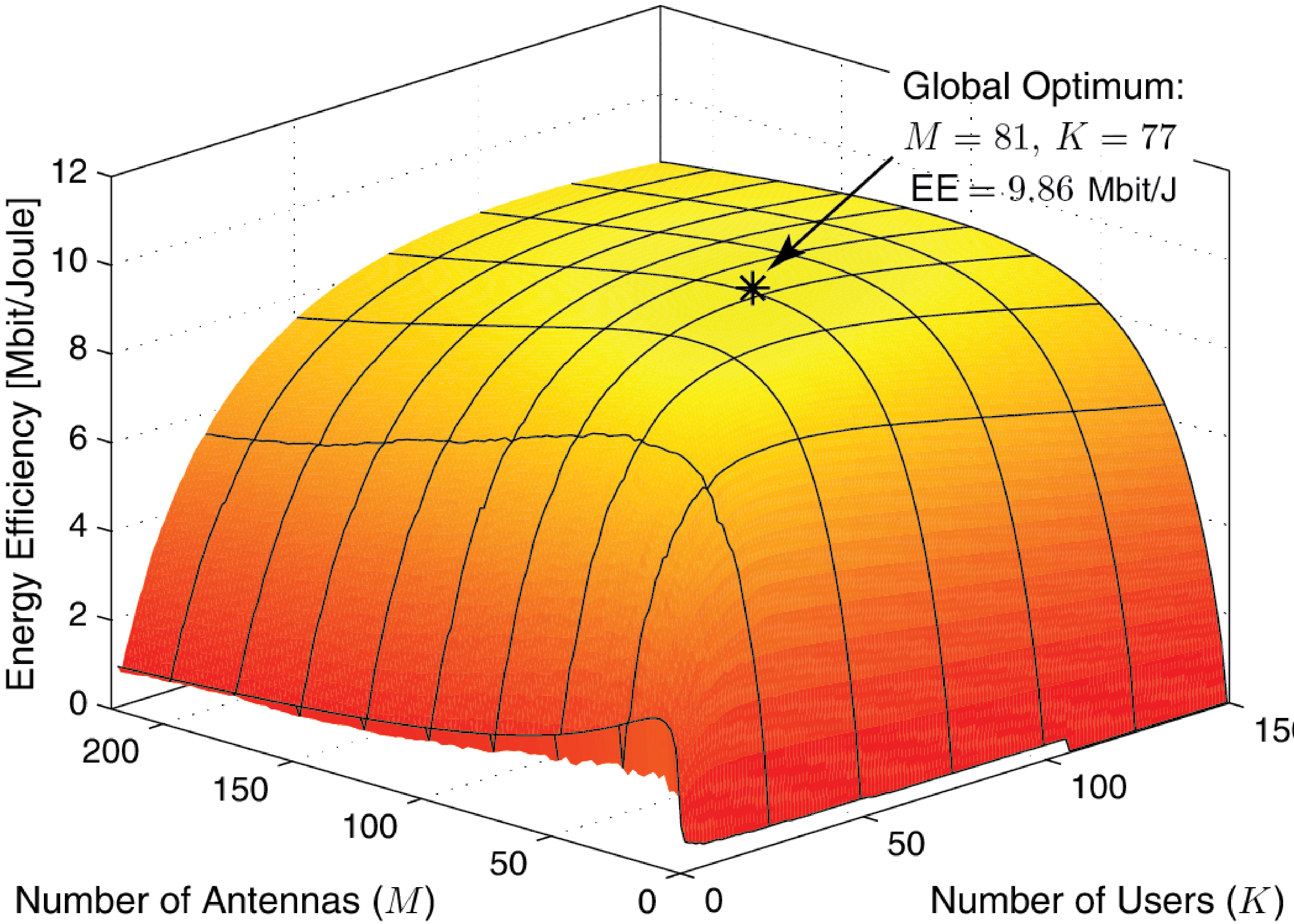
User rates:
≈2-PSK

Observation

Lower EE than with ZF

Also Massive MIMO setup

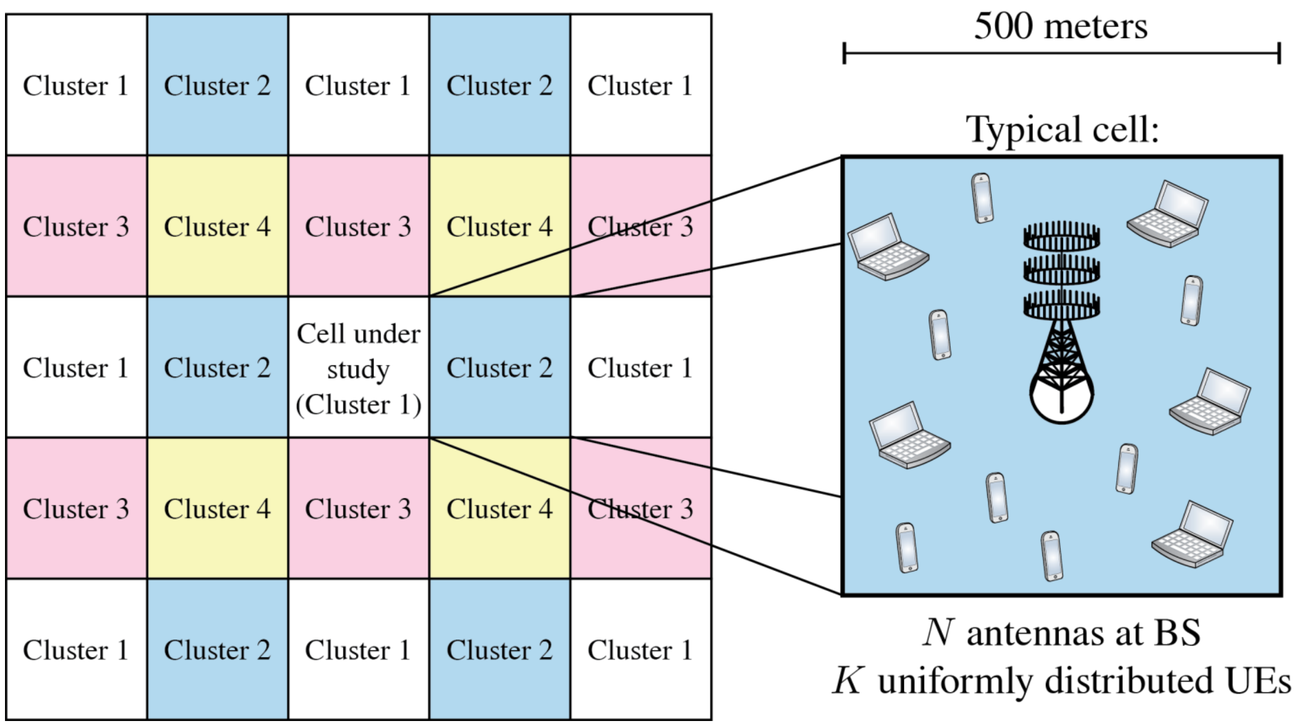
Low rates



Multi-Cell Scenarios 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: $P_{\text{trans}} = \alpha B \sigma^2 \mathcal{S}_\lambda K$

Achievable rate under ZF and pilot-based channel estimation:

$$R = B \log_2\left(1 + \frac{\alpha(M-K)}{\underbrace{\alpha(M-K)\mathcal{I}_{\text{PC}}}_{\text{Pilot contamination (PC) (Strong interference)}} + \underbrace{\left(1 + \mathcal{I}_{\text{PC}} + \frac{1}{\alpha K \tau^{(\text{ul})}}\right)(1 + \alpha K \mathcal{I}) - \alpha K (1 + \mathcal{I}_{\text{PC}^2})}_{\text{Intra/inter-cell interference (Weaker)}}}\right)$$

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

Multi-Cell Scenarios and Imperfect Channel Knowledge (3)

- Multi-Cell Rate Expression not Amenable for 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:

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

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

Optimal Multi-Cell System Design: ZF Beamforming

Optimum

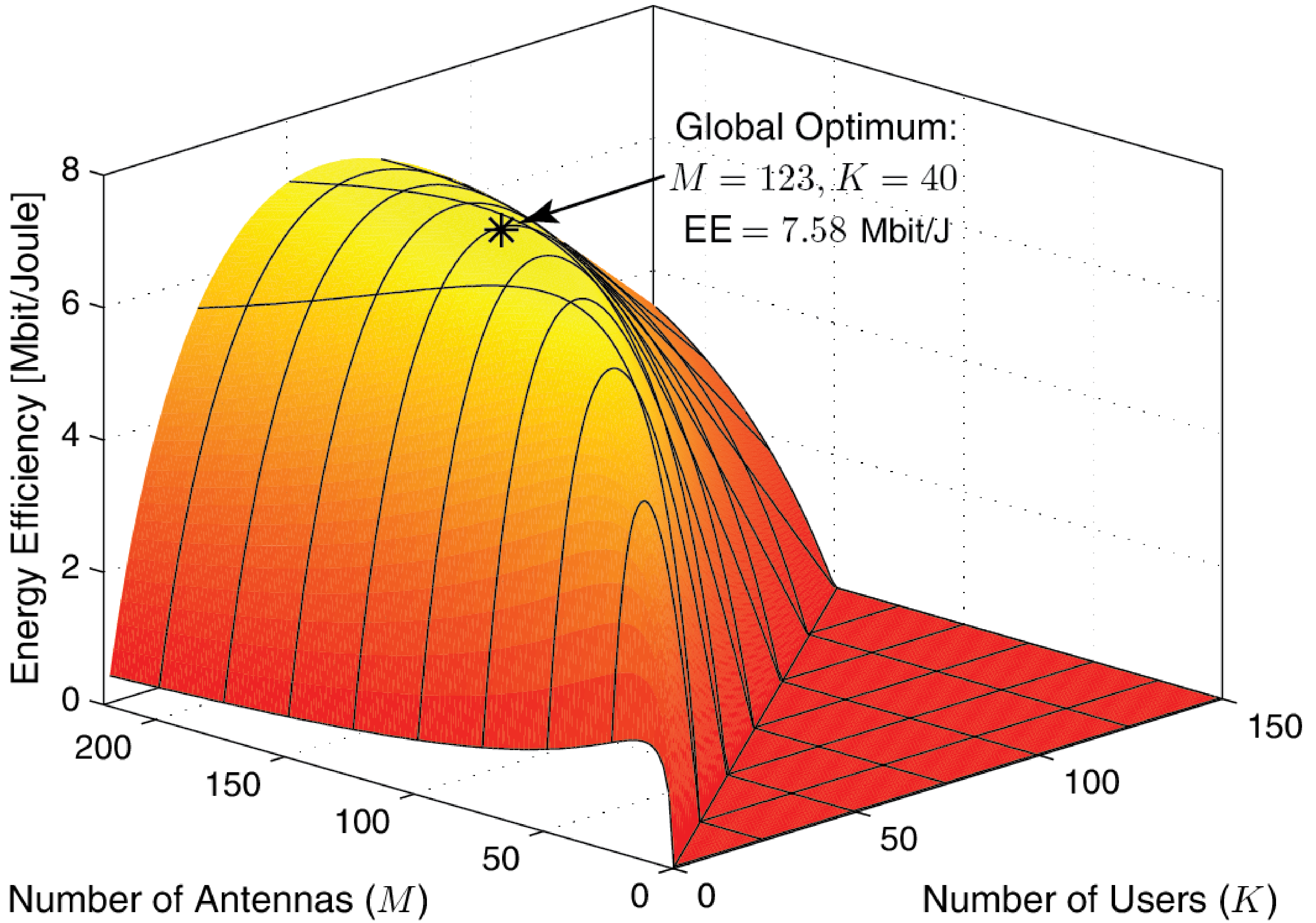
$M = 123$
$K = 40$
$\alpha = 0.28$
$\tau^{(\text{ul})} = 4$

User rates:
≈4-QAM

Massive MIMO!

Many BS antennas

Note that
$M/K \approx 3$

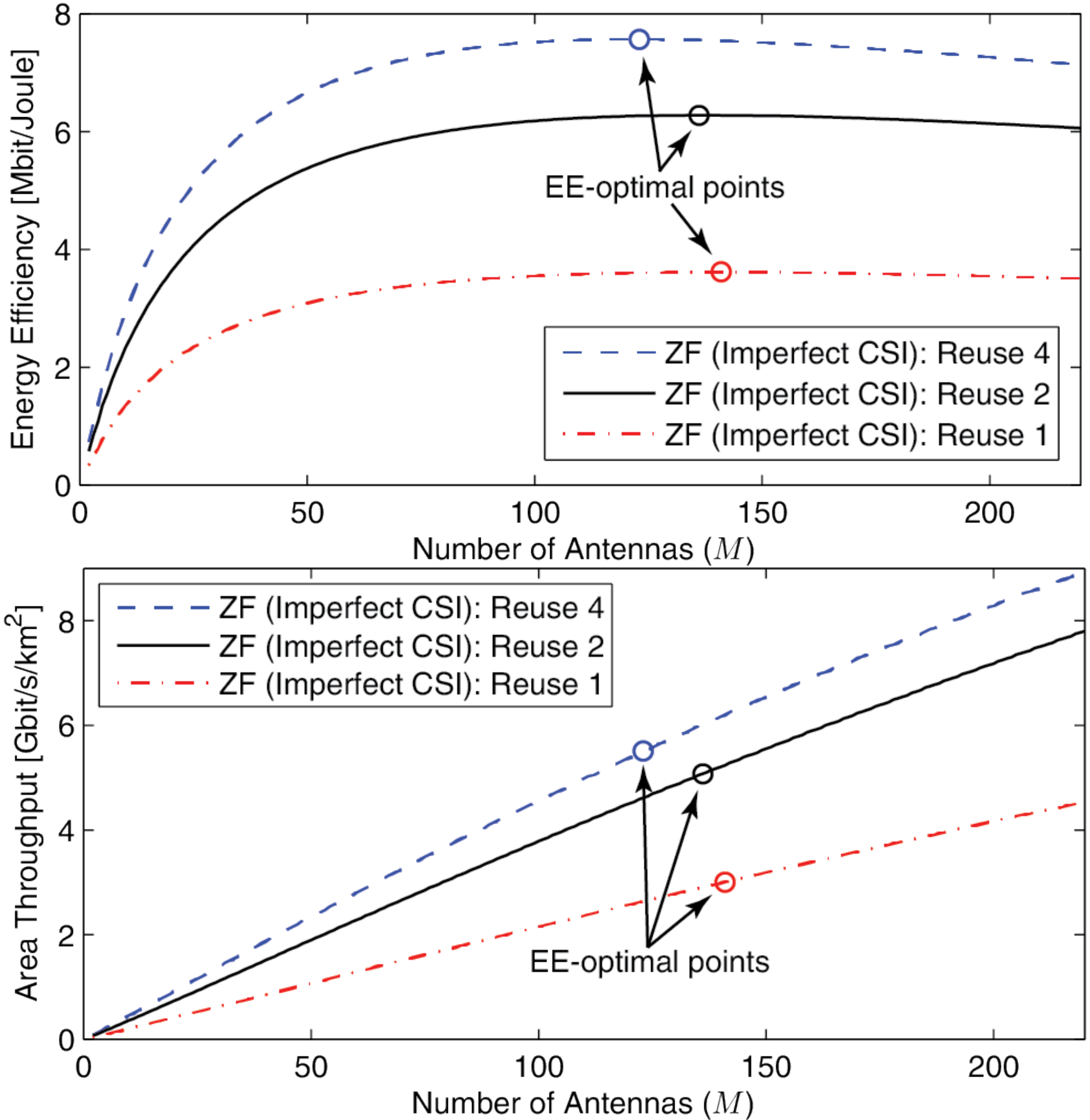


Different Pilot Reuse Factors

Higher Pilot Reuse

Higher EE *and* rates!

Controlling inter-cell interference is very important!



Area Throughput

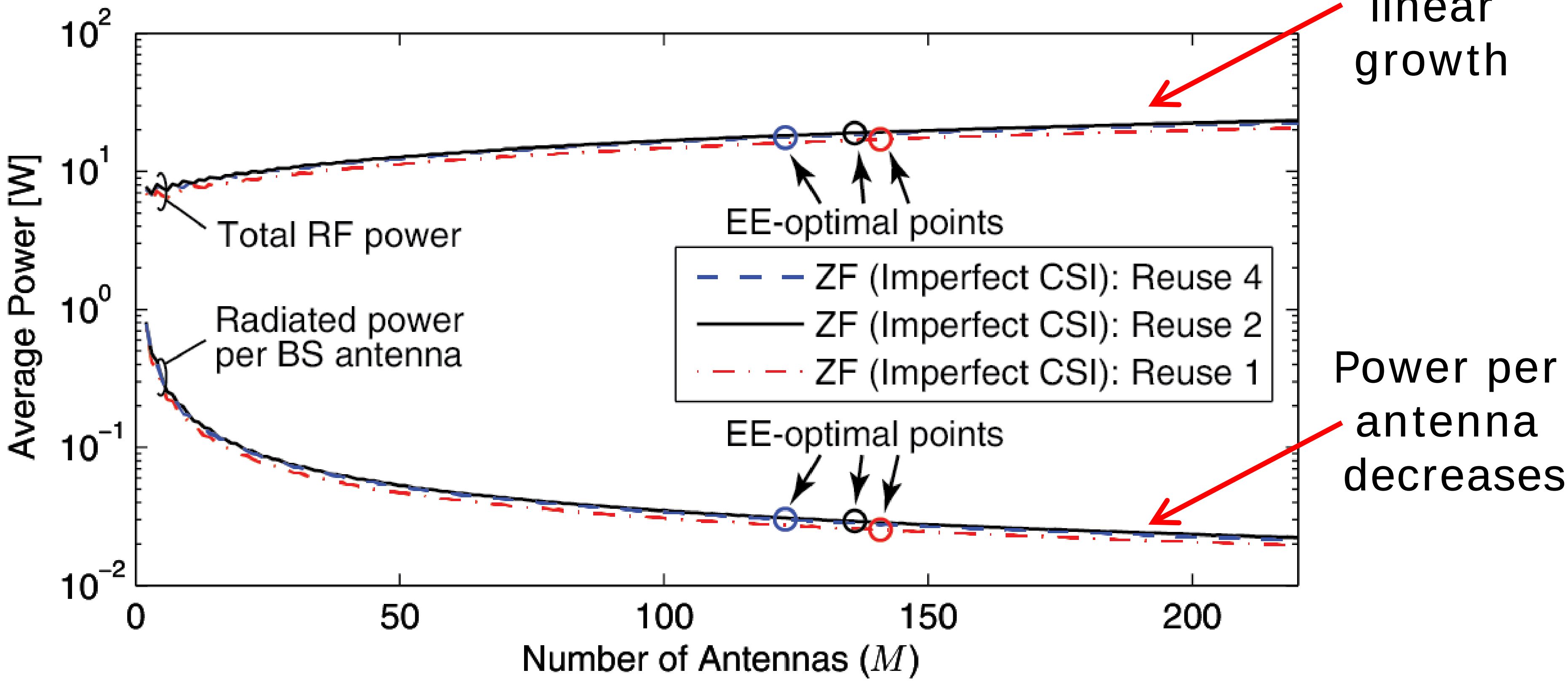
We only optimized EE

Achieved $6\ \mathrm{Gbit/s/km^2}$ over 20 MHz bandwidth

METIS project mentions $100\ \mathrm{Gbit/s/km^2}$ as 5G goal
→ Need 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 laws in recent massive MIMO literature
  - Power per antennas decreases, but only logarithmically

Summary

- Optimization Results
  - EE is a quasi-concave function of (M, K, α)
  - Closed-form optimal M, K, or α 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 α, 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 $\alpha B \sigma^2 \mathcal{S}_\lambda K$	Circuit power, coverage area $\mathcal{S}_\lambda$, antennas M, and users K	-

Large Cell

More antennas, users, RF power

Massive MIMO Appears Naturally

Fractional pilot reuse important!

More Circuit Power

Use more transmit power

Limits of M, K

Circuit power that scales with M,K

Part 2

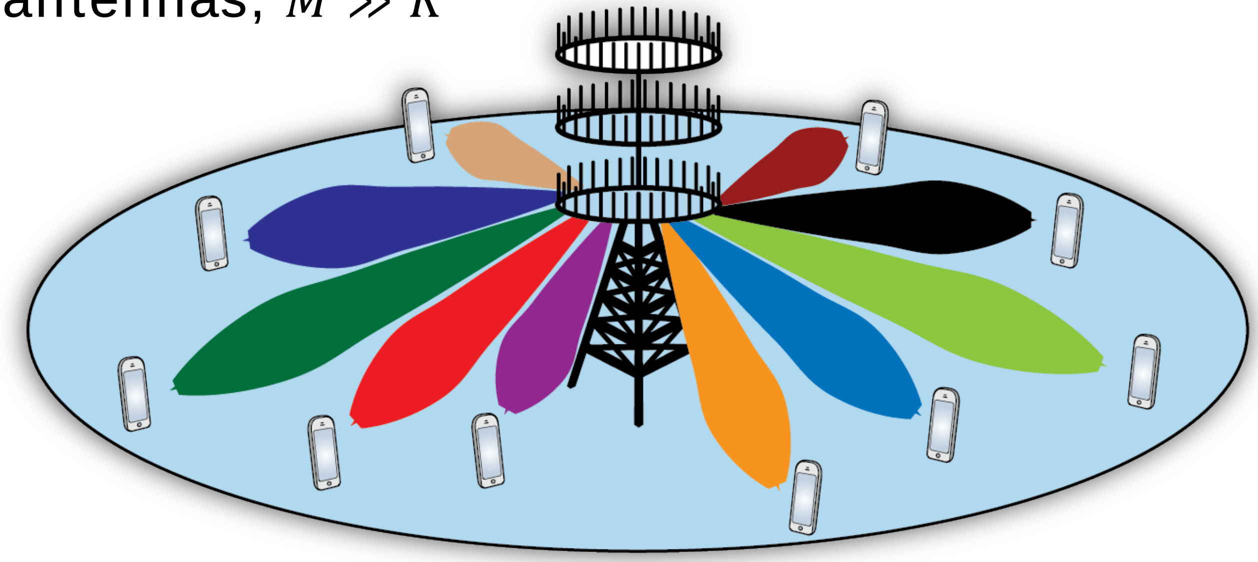
Questions?

Part 3

Massive MIMO

What is Massive MIMO?

- New Network Architecture
  - Use large arrays at BSs; e.g., $M = 123$ antennas, $K = 40$ users
  - Key: Excessive number of antennas, $M \gg K$
  - Very narrow beamforming
  - Little interference leakage



2013 IEEE Marconi Prize Paper Award

Thomas Marzetta, "*Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas*," IEEE Transactions on Wireless Communications, 2010.

Analytic assumption: $M \to \infty$

What is the Key Difference?

- Number of Antennas?
  - 3G/UMTS: 3 sectors x 20 element-arrays = 60 antennas
  - 4G/LTE-A: 4-MIMO x 60 = 240 antennas

- We Already have Many Antennas!

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

Massive MIMO Characteristics

Active antennas: Many antenna ports

Coherent flexible beamforming

Multi-user MIMO with many users

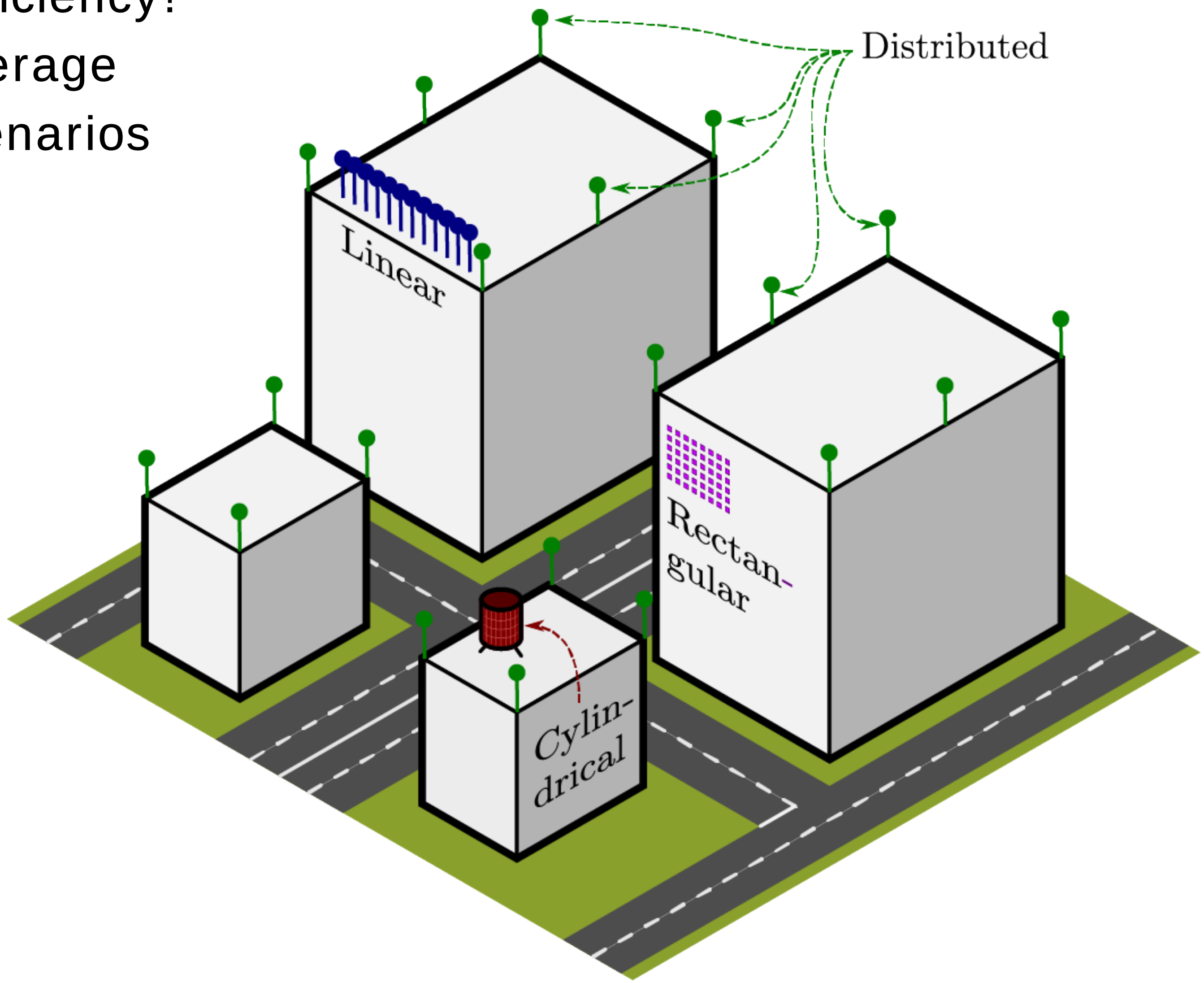
3 sectors, 4 vertical arrays per sector
Image source: gigaom.com

Massive MIMO Deployment

- When to Deploy Massive MIMO?
  - Achieve high energy-efficiency!
  - Improve wide-area coverage
  - Special super-dense scenarios

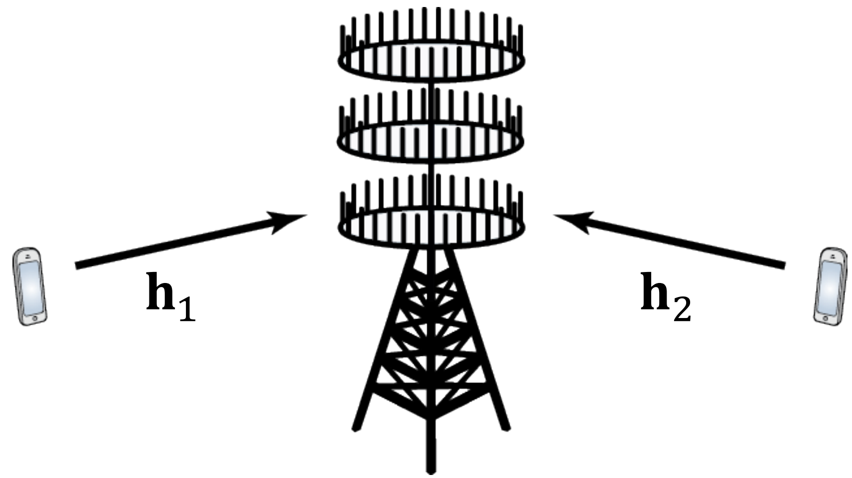
- Co-located Deployment
  - 1D, 2D, or 3D arrays
  - One or multiple sectors

- Distributed Deployment
  - Remote radio heads
  - Cloud RAN



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: $\mathbf{y} = \mathbf{h}_1 s_1 + \mathbf{h}_2 s_2 + \mathbf{n}$



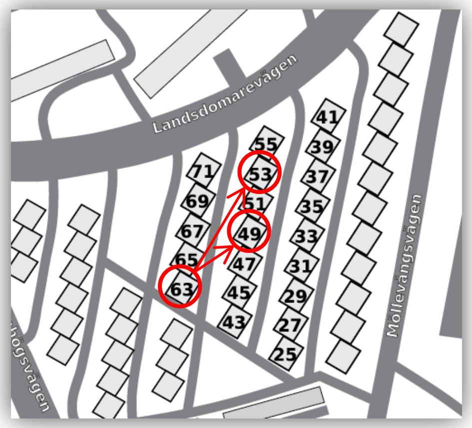
- Linear Processing for User 1: $\tilde{y}_1 = \mathbf{g}_1^H \mathbf{y} = \mathbf{g}_1^H \mathbf{h}_1 s_1 + \mathbf{g}_1^H \mathbf{h}_2 s_2 + \mathbf{g}_1^H \mathbf{n}$
  - Matched filter: $\mathbf{g}_1 = \frac{1}{M}\mathbf{h}_1$
  - Signal remains: $\mathbf{g}_1^H \mathbf{h}_1 = \frac{1}{M}||\mathbf{h}_1||^2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

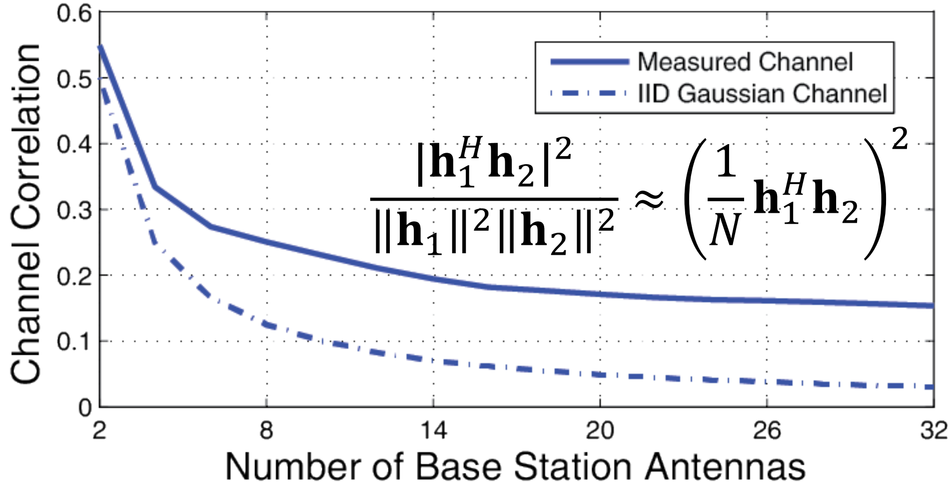
Asymptotically noise/interference-free communication: $\tilde{y}_1 \xrightarrow{M\to\infty} s_1$

Does This Hold for Practical Channels?

- Initial Measurements: Show similar results

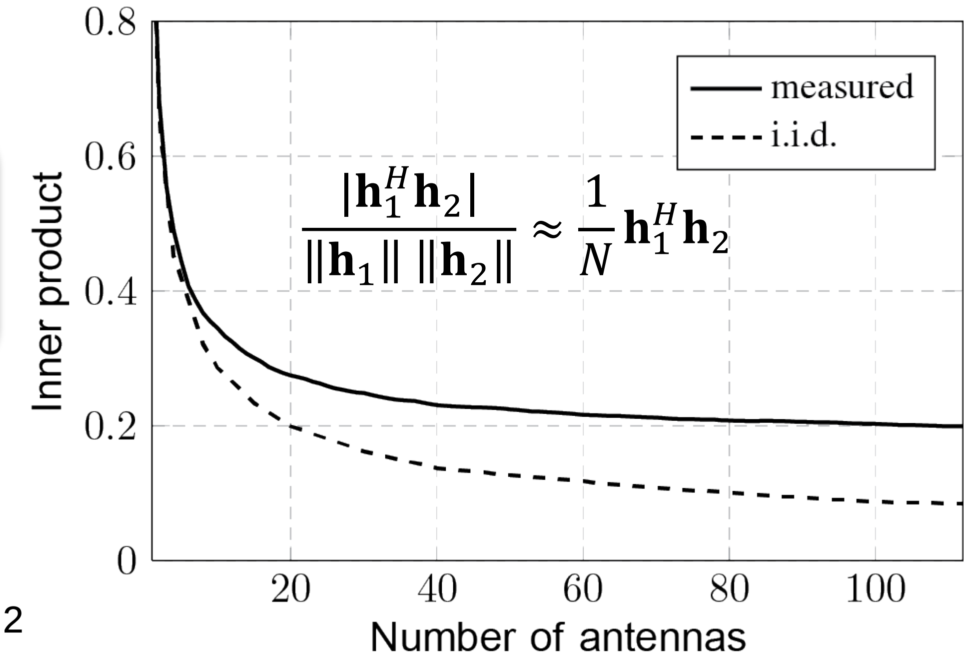
Source: X. Gao, O. Edfors, F. Rusek, and F. Tufvesson, “Linear Pre-Coding Performance in Measured Very-Large MIMO Channels,“ VTC 2011.





Achievable Rates

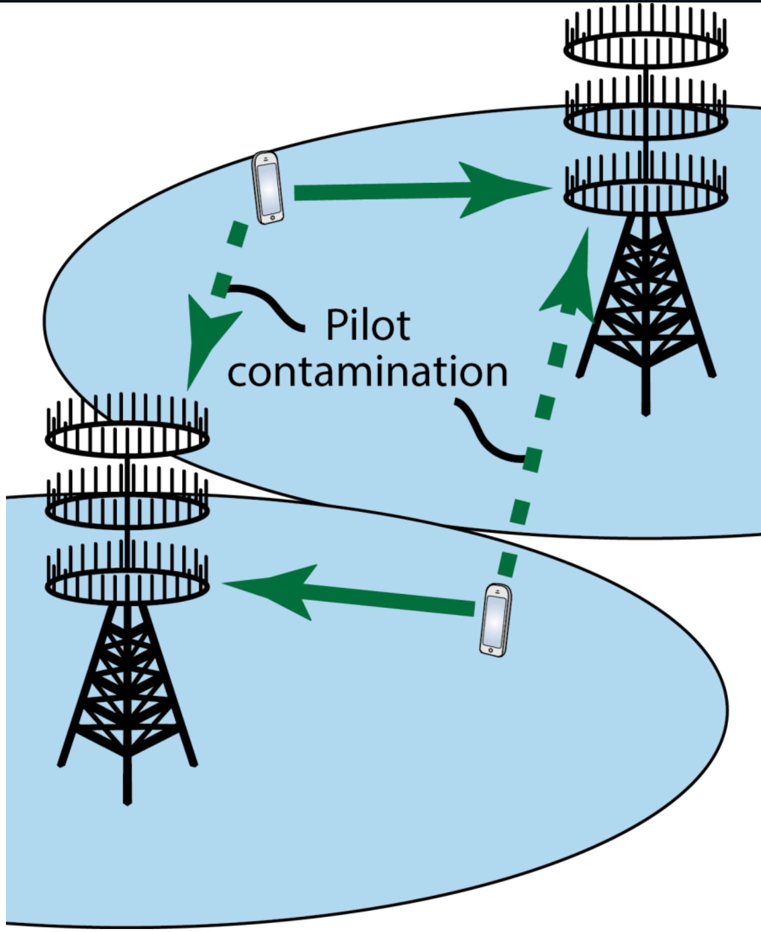
Only 10-20% lower than with i.i.d. channels



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

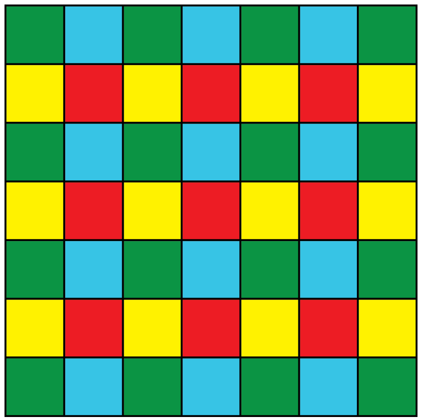
Main Research Challenges

- Acquisition of Channel State Information
  - Finite coherence block $U \in [100,10000]$
  - Only $\leq U$ unique pilots → Reuse across cells
  - BS cannot tell difference between users
  - Pilot contamination: Correlated estimates
  - This interference doesn't vanish as $M \to \infty$

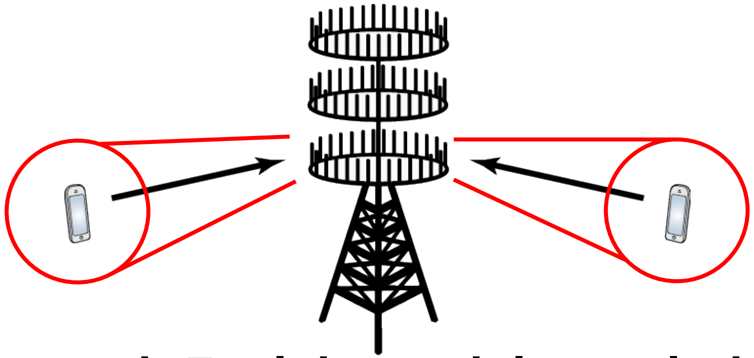


- Not a New Phenomenon
  - Pilot contamination always an issue
  - More pronounced when M and K are large

- Current Solutions:



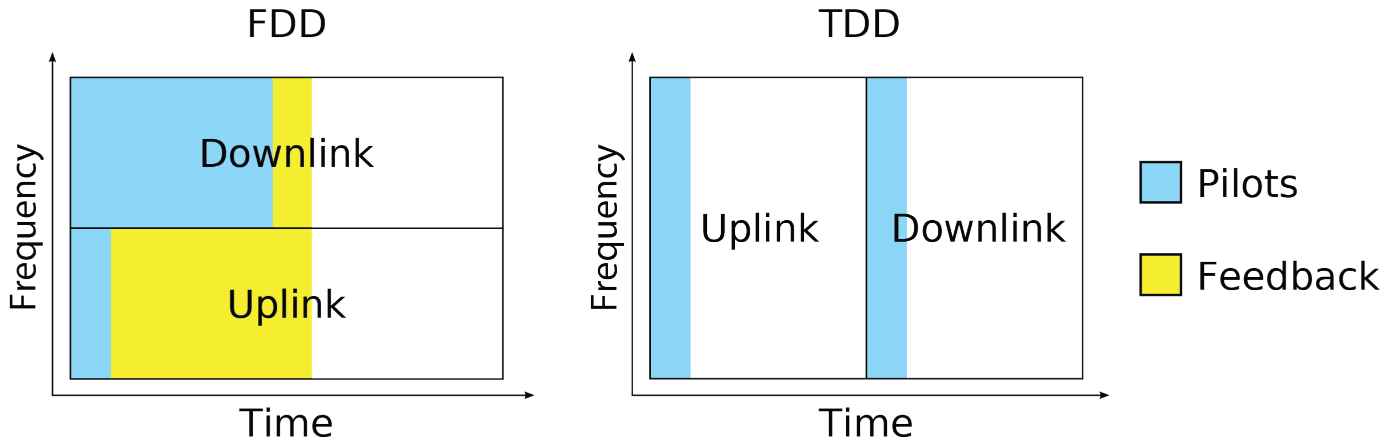
Simple: Fractional pilot reuse



Advanced: Exploit spatial correlation

Main Research Challenges (2)

- Frequency Division Duplex (FDD)
  - Many systems and spectrum bands are dedicated to FDD
  - Cannot rely on channel reciprocity → Is estimation overhead too large?



- Computational Complexity
  - ZF performs better than MRC/MRT but has higher complexity
  - Can complexity be reduced with retained performance?

- Circuit Design and Hardware Implementation
  - Cost and power increase in massive MIMO, but as N, $\sqrt{N}$, or slower?
  - Can waveforms be design to allow more efficient hardware?

MAMMOET Project

- 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

Part 3

Questions?

Part 4

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)

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

Optimize Multiple Metrics

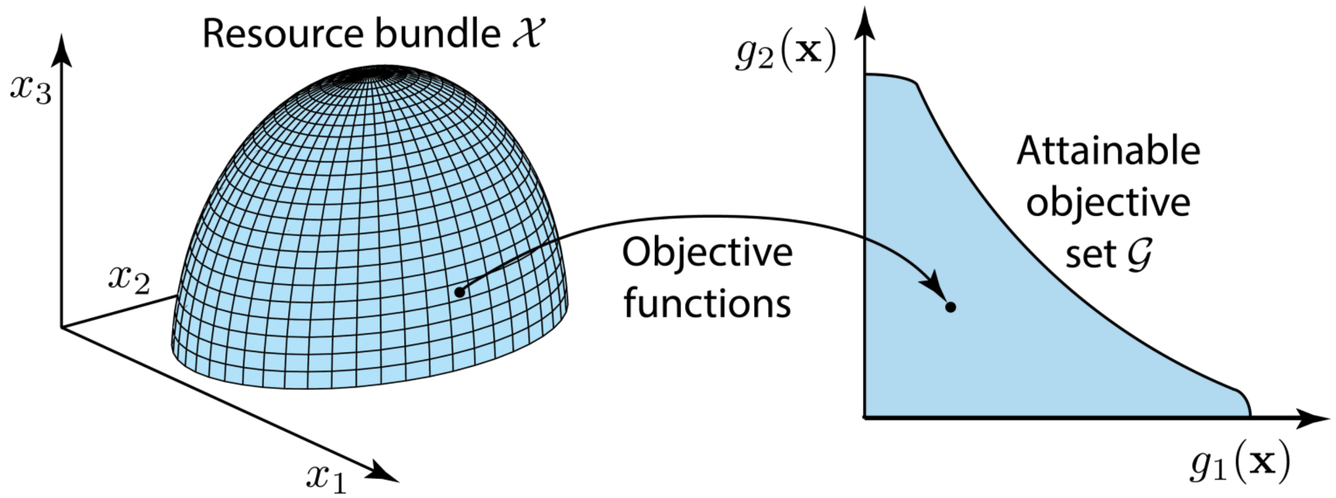
We want efficient operation w.r.t. all objectives

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

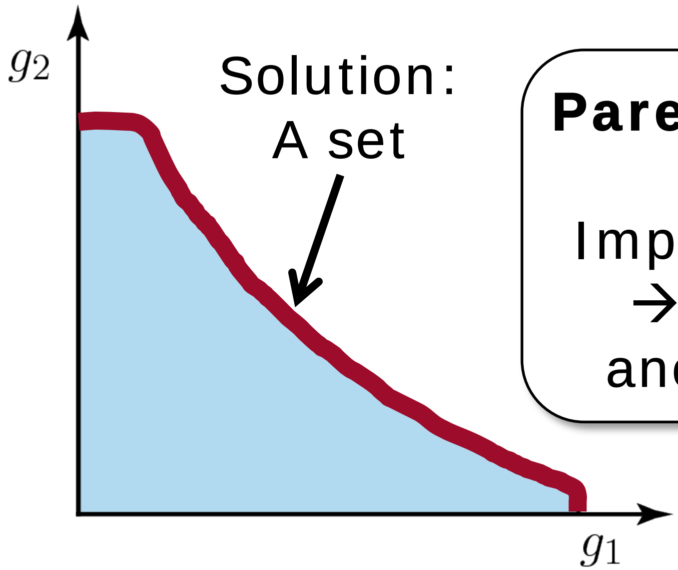
- Conventional Optimization
  - Pick one prime metric: $g_1(\mathbf{x})$
  - Turn $g_1(\mathbf{x}), g_2(\mathbf{x}), \dots, g_N(\mathbf{x})$ into constraints
  - Optimization problem:

$$\begin{aligned} \underset{\mathbf{x}}{\text{maximize}} \quad & g_1(\mathbf{x}) \\ \text{subject to} \quad & \mathbf{x} \in \mathcal{X}, \\ & g_2(\mathbf{x}) \geq C_2, \dots, g_N(\mathbf{x}) \geq C_N. \end{aligned}$$

  - 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:

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



Pareto Boundary

Improve a metric → Degrading another metric

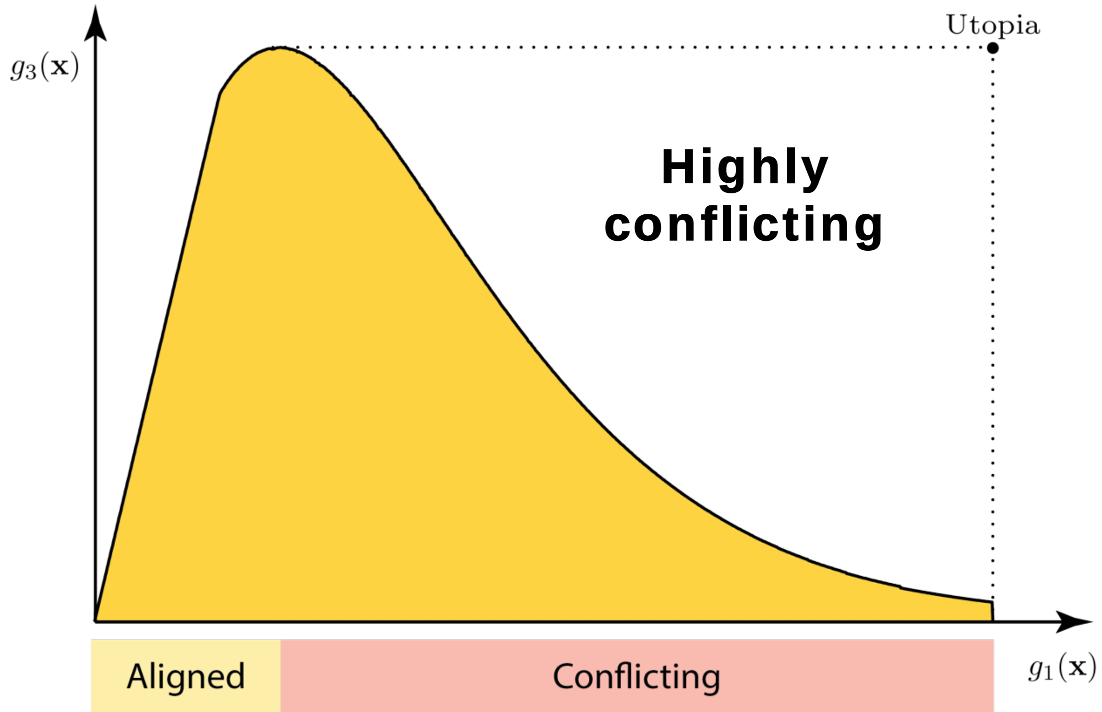
Why Multi-Objective Optimization?

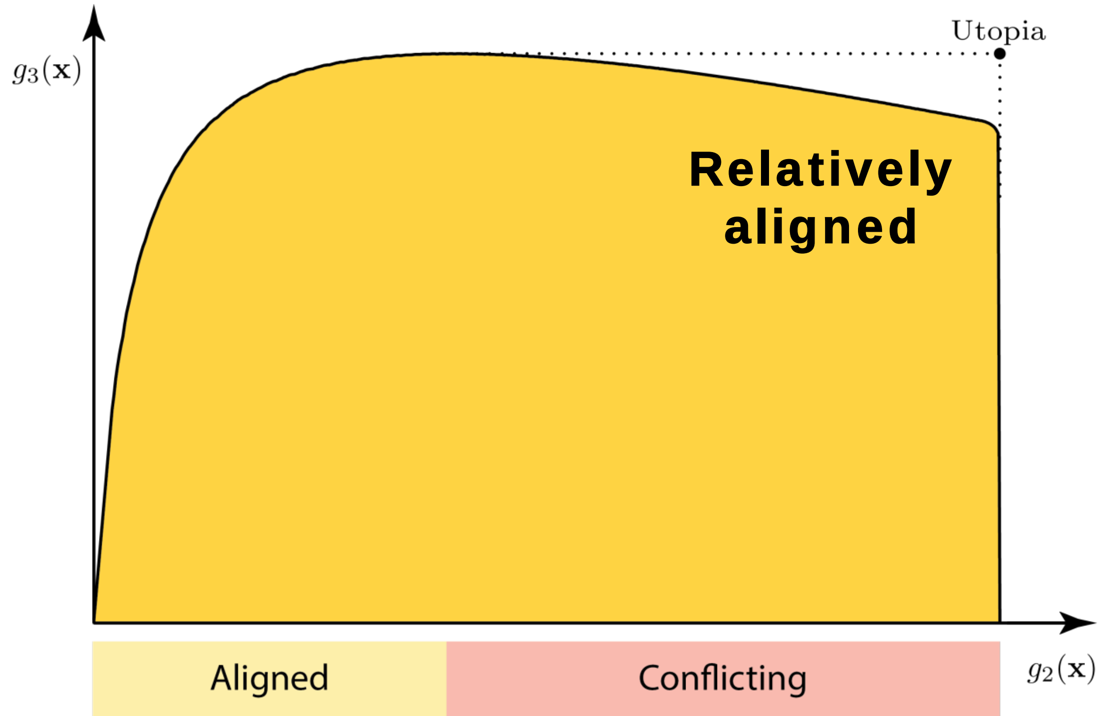
- Study Tradeoffs Between Metrics
  - When are metrics aligned or conflicting?
  - Common in engineering and economics – new in communication theory

***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

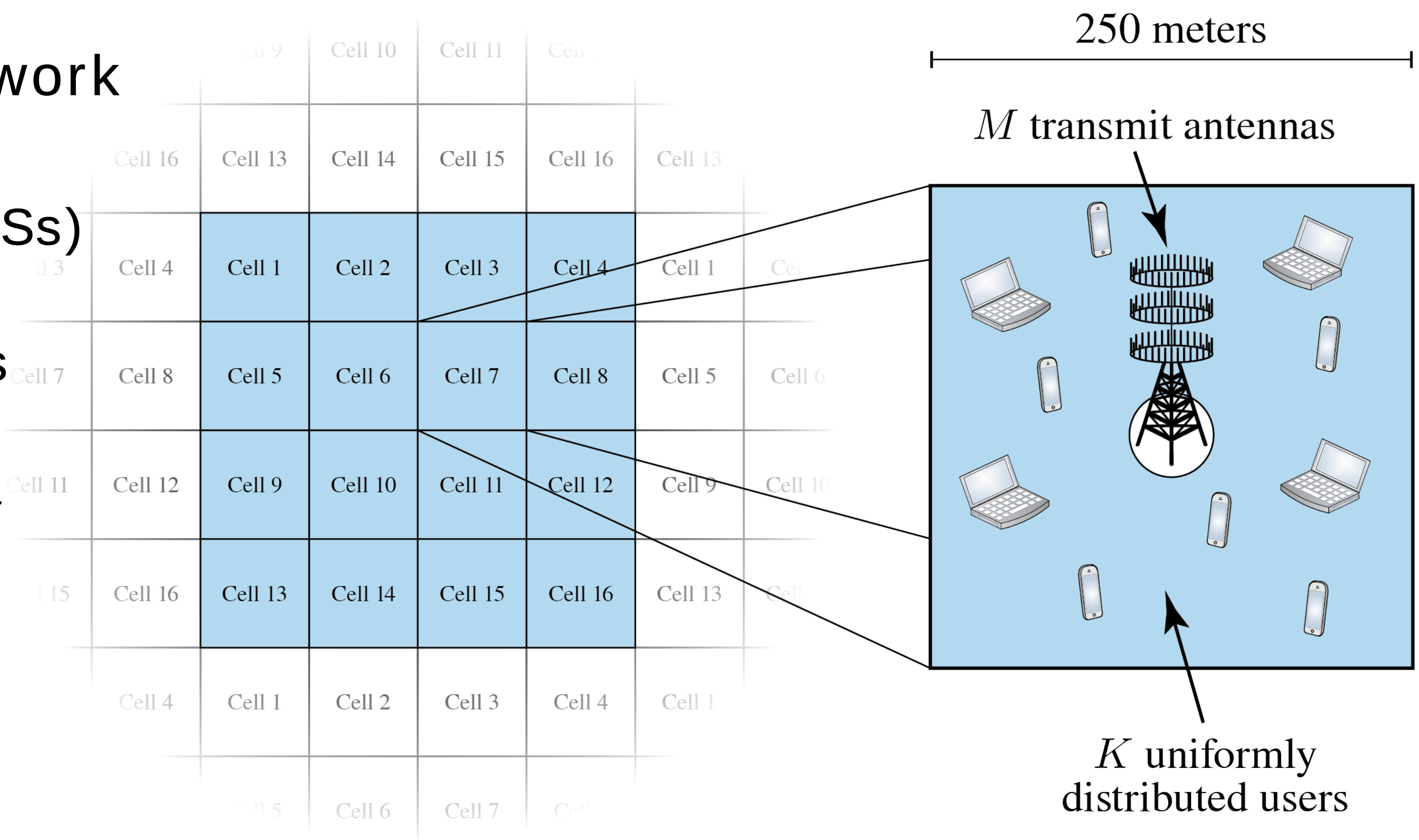
We obtain a simplified problem:

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

- 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 = power/antenna



- Resource bundle:

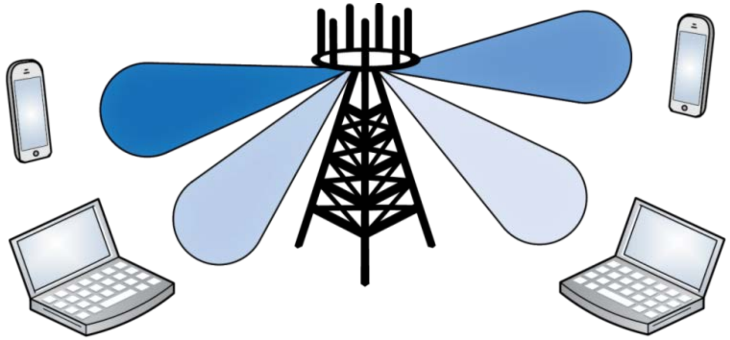
$$\mathcal{X} = \left\{ [K \;\; M \;\; P]^T : \begin{array}{c} 1 \leq K \leq \frac{M}{2}, \\ 2 \leq M \leq M_{\max}, \\ 0 \leq P \leq M P_{\max} \end{array} \right\}$$

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 beamforming: no intra-cell interference
  - Interference leaks between cells



- Average User Rate

Power/user

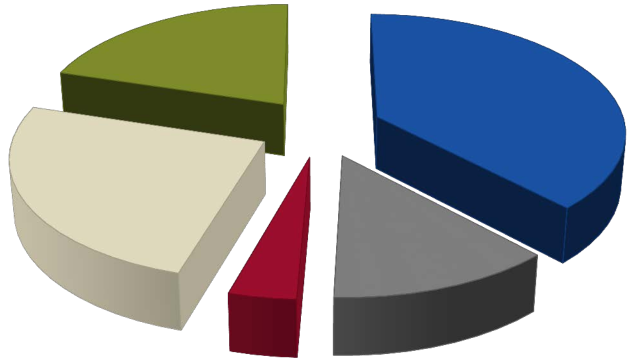
$$R_{\text{average}} = B \underbrace{\left(1 - \frac{K}{U}\right)}_{\text{CSI estimation overhead } (U = 1000)} \log_2\left(1 + \frac{\frac{P}{K}\overbrace{(M-K)}^{\text{Array gain}}}{\mathcal{S}_{\lambda}\sigma^2 + \mathcal{J}}\right)$$

Bandwidth (10 MHz)

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

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

Amplifier efficiency (0.31)

Fixed power (10 W)

Circuit power per user (0.3 W)

Circuit power per antenna (1 W)

Computing ZF beamforming ($2.3 \cdot 10^{-6} \cdot MK^2$)

Example: Results

3 Objectives

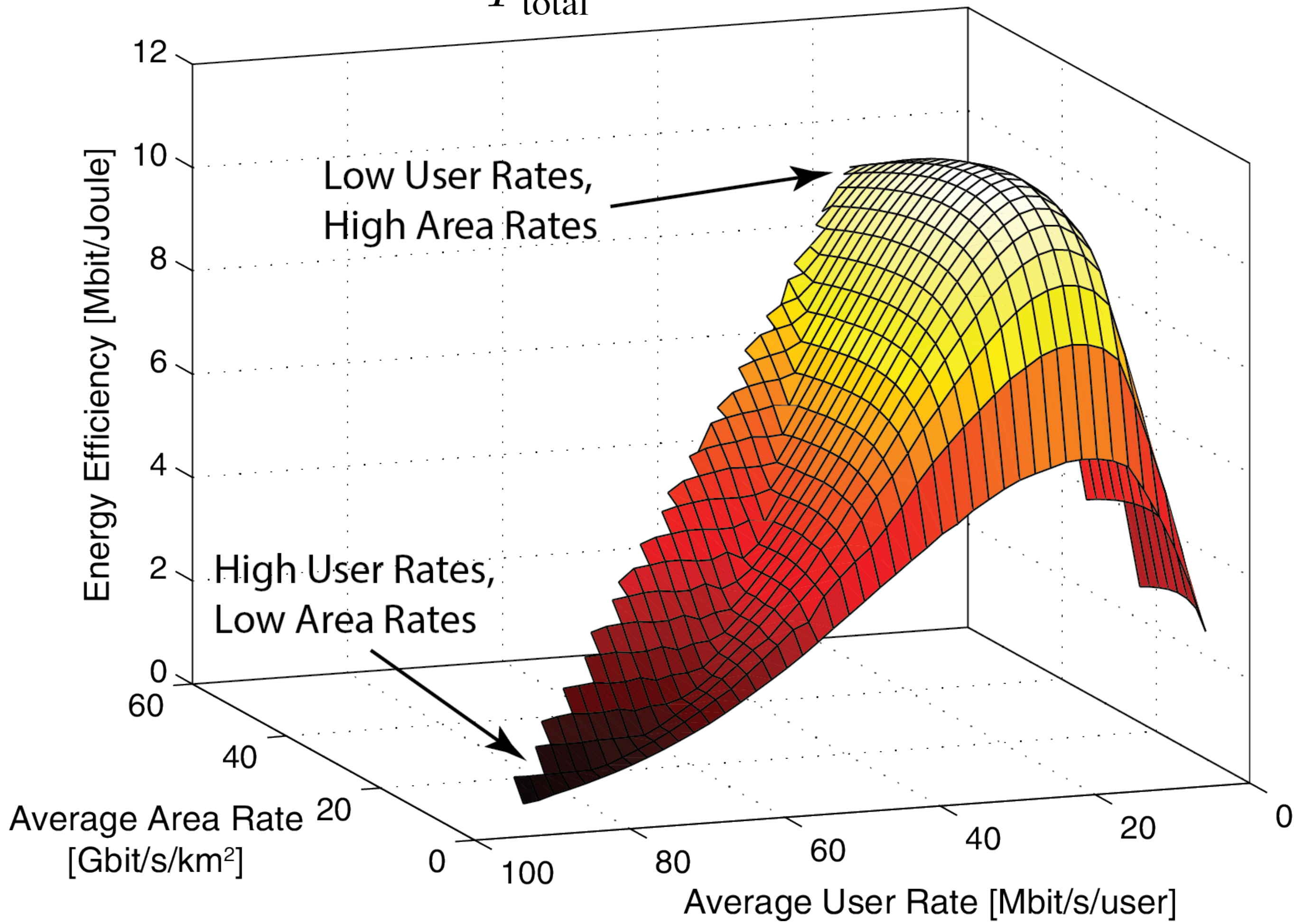
1. Average user rate $g_1(\mathbf{x}) = R_{\text{average}}$ [bit/s/user]
2. Total area rate $g_2(\mathbf{x}) = \frac{K}{A} R_{\text{average}}$ [bit/s/km^2]
3. Energy-efficiency $g_3(\mathbf{x}) = \frac{K R_{\text{average}}}{P_{\text{total}}}$ [bit/J]

Observations

Area and user rates are conflicting objectives

Only energy efficient at high area rates

Different number of users



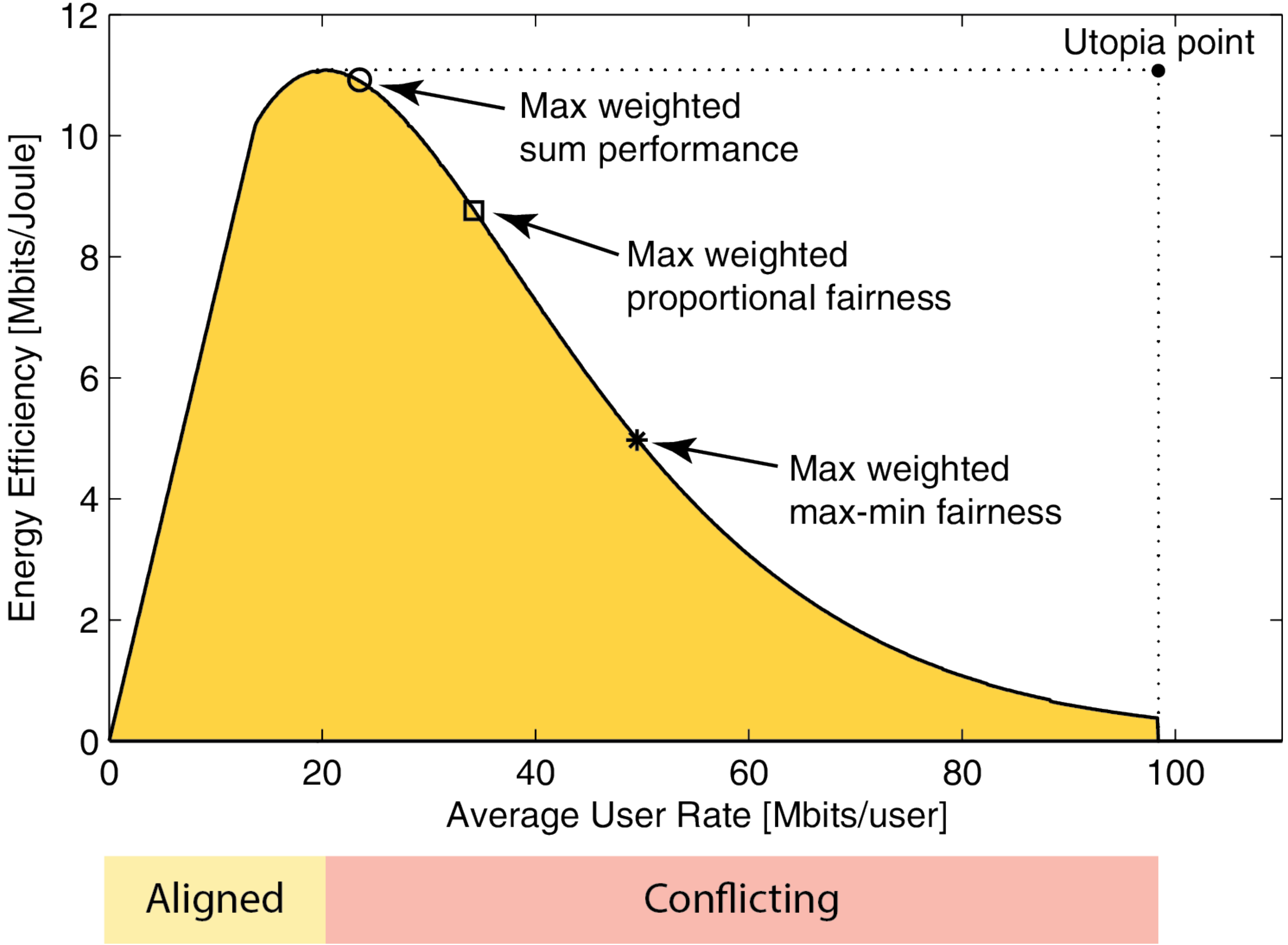
Example: Results (2)

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

Observations

Aligned for small user rates

Conflicting for high user rates



Part 4

Questions?

Summary

- 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 rate expressions and power consumption
  - Design parameters: Number of users, antennas, and transmit power
- Analytical and Numerical Results
  - Reveals interplay between system parameters
  - Shows that massive MIMO is the energy-efficient solution
- Main Properties of massive MIMO
  - Arrays with many *active* antennas and relatively many users
- Multi-Objective Optimization
  - Framework to jointly optimize energy-efficiency and other 5G metrics

References

1. S. Cui, Member, A. J. Goldsmith, A. Bahai, “Energy-Constrained Modulation Optimization,” IEEE Transactions on Wireless Communications, vol. 4, no. 5, pp. 2349-2360, 2005.

2. T. Marzetta, “Noncooperative cellular wireless with unlimited numbers of base station antennas,” IEEE Trans. Wireless Commun., vol. 9, no. 11, pp. 3590–3600, 2010.

3. Y. Chen, S. Zhang, S. Xu, and G. Li, “Fundamental trade-offs on green wireless networks,” IEEE Commun. Mag., vol. 49, no. 6, pp. 30–37, 2011.

4. G. Auer, V. Giannini, C. Desset, I. Godor, P. Skillermark, M. Olsson, M.A. Imran, D. Sabella, M.J. Gonzalez, O. Blume, A. Fehske, ” How much energy is needed to run a wireless network?,” IEEE Wireless Communications, vol. 18, no. 5, pp. 40-49, 2011.

5. S. Tombaz, A. Västberg, and J. Zander, “Energy- and cost-efficient ultrahigh- capacity wireless access,” IEEE Wireless Commun. Mag., vol. 18, no. 5, pp. 18–24, 2011.

6. F. Rusek, D. Persson, B. Lau, E. Larsson, T. Marzetta, O. Edfors, F. Tufvesson, “Scaling up MIMO: Opportunities and challenges with very large arrays,” IEEE Signal Process. Mag., vol. 30, no. 1, pp. 40-60, 2013.

References (2)

7. H. Ngo, E. Larsson, and T. Marzetta, “Energy and spectral efficiency of very large multiuser MIMO systems,” IEEE Trans. Commun., vol. 61, no. 4, pp. 1436–1449, 2013.

8. G. Miao, “Energy-efficient uplink multi-user MIMO,” IEEE Trans. Wireless Commun., vol. 12, no. 5, pp. 2302–2313, 2013.

9. E. Björnson, M. Kountouris, and M. Debbah, “Massive MIMO and small cells: Improving energy efficiency by optimal soft-cell coordination,” in Proc. Int. Conf. Telecommun. (ICT), 2013.

10. E. Björnson, L. Sanguinetti, J. Hoydis, M. Debbah, “Optimal Design of Energy-Efficient Multi-User MIMO Systems: Is Massive MIMO the Answer?,” IEEE Transactions on Wireless Communications, Submitted for publication.

11. E. Björnson, M. Bengtsson, B. Ottersten, ”Optimal Multiuser Transmit Beamforming: A Difficult Problem with a Simple Solution Structure,” IEEE Signal Processing Magazine, vol. 31, no. 4, pp. 142-148, July 2014.

12. E. Björnson, E. Jorswieck, M. Debbah, B. Ottersten, “Multi-Objective Signal Processing Optimization: The Way to Balance Conflicting Metrics in 5G Systems,” To Appear in IEEE Signal Processing Magazine, Special Issue on Signal Processing for the 5G Revolution.

Linköping University
expanding reality

QUESTIONS?

Papers, Presentations, and Simulation Code
All Available on my Homepage:
http://www.commsys.isy.liu.se/en/staff/emibj29