Optimal Design of Energy-Efficient Multi-User MIMO Systems\textsuperscript{1}

Is Massive MIMO the Answer?

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Network of Excellence in Wireless COMmunications#

Introduction
What are the 5G expectations?

Tons of Plenary Talks and Overview Articles
- Fulfilling dream of ubiquitous wireless connectivity

Expectation: Many Metrics Should Be Improved in 5G
- Higher user data rates
- Higher area throughput
- Great scalability in number of connected devices
- Higher reliability and lower latency
- Better coverage with more uniform user rates
- Improved energy efficiency (green cellular networks)

Conflicting Metrics!
- Impossible to maximize all metrics simultaneously
- Our goal: High energy efficiency (EE) with uniform user rates
Introduction
How to measure energy efficiency?

Energy Efficiency in bits/Joule

\[ EE = \frac{\text{Average Sum Throughput [bit/second]}}{\text{Power Consumption [Watt]}} \]

Conventional Academic Approaches

- Maximize throughput with fixed power
- Minimize transmit power for fixed throughput

New Problem: Balance Throughput and Power Consumption

- Crucial: Account for overhead signaling
- Crucial: Use reasonable power consumption model
PART I
The EE Optimization Problem
Multi-User Multiple-Input Multiple-Output (MIMO)
- One BS with array of $M$ antennas
- $K$ single-antenna UEs with random locations $x_k \in \mathbb{R}^2$ (in meters)
- Share a flat-fading carrier

Main Question:
- How should a multi-user MIMO system be designed to maximize energy efficiency?
- Optimization variables: $M, K$ and $\bar{R}$ (user rate)
TDD mode

- Uplink pilots enable the BS to estimate the UE channels
- Channels are considered reciprocal
- BS uses uplink estimates for precoding
- Downlink pilots let each UE estimate its effective channel

Parameters

- \( U = B_C T_C \) channel uses – \( B_C \) coherence bandwidth and \( T_C \) coherence time
- \( \zeta^{(ul)} \) and \( \zeta^{(dl)} \) – Ratio of uplink and downlink transmission (\( \zeta^{(ul)} + \zeta^{(dl)} = 1 \))
- \( \tau^{(ul)} K \) and \( \tau^{(dl)} K \) – Pilot signaling

Rate (in bit/second) per each UE

- Uplink rate \( \zeta^{(ul)} \bar{R} \)
- Downlink rate \( \zeta^{(dl)} \bar{R} \)
System Model
Channel model and linear Processing

Channel Model

- \( h_k \in \mathbb{C}^{M \times 1} - \{h_{k,n}\} \) channel between antenna \( n \) and UE \( k \)
- \( h_k \sim \mathcal{CN}(0_M, l(x_k)I_M) \) – Rayleigh small-scale fading distribution
- \( l(\cdot) : \mathbb{R}^2 \to \mathbb{R} \) – Large-scale channel fading (we keep it generic)
System Model

Channel model and linear Processing

Channel Model

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Linear processing with perfect knowledge of \( \mathbf{H} = [\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_K] \)

- Uplink (MRC, ZF, and MMSE)
  \[
  \mathbf{G} = \begin{cases} 
  \mathbf{H} & \text{for MRC} \\
  \mathbf{H} (\mathbf{H}^H \mathbf{H})^{-1} & \text{for ZF} \\
  (\mathbf{H} \mathbf{P}^{(ul)} \mathbf{H}^H + \sigma^2 \mathbf{I}_M)^{-1} \mathbf{H} & \text{for MMSE}
  \end{cases}
  \] (1)

- Downlink (MRT, ZF, and MMSE)
  \[
  \mathbf{V} = \begin{cases} 
  \mathbf{H} & \text{for MRT} \\
  \mathbf{H} (\mathbf{H}^H \mathbf{H})^{-1} & \text{for ZF} \\
  (\mathbf{H} \mathbf{P}^{(ul)} \mathbf{H}^H + \sigma^2 \mathbf{I}_M)^{-1} \mathbf{H} & \text{for MMSE}
  \end{cases}
  \] (2)

Setting \( \mathbf{V} = \mathbf{G} \) reduces computational complexity! (But not necessary)
Uplink
Achievable rates

Under the assumptions of Gaussian codebooks, the achievable uplink rate (in bit/second) of the \( k \)th UE is

\[
R^{(ul)}_k = \zeta^{(ul)} \left( 1 - \frac{\tau^{(ul)} K}{U \zeta^{(ul)}} \right) \tilde{R}^{(ul)}_k
\]  

(3)

where the pre-log factor \( \left( 1 - \frac{\tau^{(ul)} K}{U \zeta^{(ul)}} \right) \) accounts for pilot overhead and

\[
\tilde{R}^{(ul)}_k = B \log \left( 1 + \frac{p^{(ul)}_k |g_k^H h_k|^2}{\sum_{\ell=1, \ell \neq k}^{K} p^{(ul)}_{\ell} |g_k^H h_{\ell}|^2 + \sigma^2 \|g_k\|^2} \right)
\]  

(4)

is the uplink gross rate (in bit/second) of UE \( k \).
Uplink

Average RF power to guarantee the same $\bar{R}$

If $\bar{R}_k^{(ul)} = \bar{R}$ for $k = 1, 2, \ldots, K$ then

\[
p^{(ul)} = \sigma^2 (D^{(ul)})^{-1} 1_K
\]

with

\[
\begin{cases}
|g_k^H h_k|^2 & \text{for } k = \ell, \\
\frac{|g_k^H h_\ell|^2}{\|g_k\|^2} & \text{for } k \neq \ell.
\end{cases}
\]

The average uplink RF power (in Watt) is

\[
P_{TX}^{(ul)} = \sigma^2 \frac{B \zeta^{(ul)}}{\eta^{(ul)}} \mathbb{E} \left\{ 1_K^T (D^{(ul)})^{-1} 1_K \right\}
\]

where $0 < \eta^{(ul)} \leq 1$ is the LPA efficiency at the UEs.

The same can be done for the downlink!
**Problem statement**

**EE optimization**

The EE optimization problem is mathematically defined as:

\[
\max_{M \in \mathbb{Z}^+, K \in \mathbb{Z}^+, \bar{R} \geq 0} \quad \text{EE} = \frac{\sum_{k=1}^{K} \left( \mathbb{E} \left\{ R_k^{(ul)} \right\} + \mathbb{E} \left\{ R_k^{(dl)} \right\} \right)}{P_{TX}^{(ul)} + P_{TX}^{(dl)} + P_{CP}}
\]

where \( P_{CP} \) accounts for the circuit power consumption (missing term so far!).

Solvable through exhaustive search:
- All combinations of \( K \) and \( M \) (integers)
- Optimal \( \bar{R} \) for each pair
- Good only for off-line cell planning

**Conventional approach** \( P_{CP} = P_{FIX} \ [1] \)
- \( P_{FIX} \) is **fixed** (control signaling, load-independent backhaul, baseband processors...)
- EE\((ZF)\) \(\rightarrow \infty \) if \( M \rightarrow \infty \)
- EE\((ZF)\) \(\rightarrow \infty \) if \( K \rightarrow \infty \)

An accurate model for \( P_{CP} \) is very much important!
Circuit power consumption
A realistic (or reasonable) model

Our model:

\[ P_{CP} = P_{FIX} + P_{TC} + P_{C/D} + P_{BH} + P_{CE} + P_{LP} \] (9)

where the different terms account for:

- \( P_{FIX} \) – control signaling, load-independent backhaul, baseband processors…
- \( P_{TC} \) – transceiver chains
- \( P_{C/D} \) – channel coding and decoding
- \( P_{BH} \) – load-dependent backhaul
- \( P_{CE} \) – channel estimation (performed once per coherence block)
- \( P_{LP} \) – linear processing at the BS

Objective: simple and realistic models for how each term depends on \( (M, K, \bar{R}) \)!
Circuit power consumption

Transceiver chains

The power consumption $P_{TC}$ can be quantified as $[2, 3]^2$

$$P_{TC} = (MP_{BS} + P_{SYN}) + KP_{UE} \quad \text{Watt}$$

(10)

where

- $P_{BS}[=1\text{W}]$ – circuit components (such as converters, mixers, and filters)
- $P_{SYN}[=2\text{W}]$ – local oscillator
- $P_{UE}[=0.1\text{W}]$ – circuits components of each single-antenna UE

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Circuit power consumption
Coding and decoding

The power consumption $P_{C/D}$ is proportional to the number of bits per second \[4\]^3:

$$P_{C/D} = \sum_{k=1}^{K} \left( \mathbb{E}\{R_k^{(ul)} + R_k^{(dl)}\} \right) (P_{COD} + P_{DEC}) \text{ Watt}$$

(11)

where $P_{COD}$ and $P_{DEC}$ are the coding and decoding powers (in Watt per bit/s).

For simplicity, $P_{COD}[= 0.1 \text{ W/Gbit/s}]$ and $P_{DEC}[= 0.8 \text{ W/Gbit/s}]$ are the same in the uplink and downlink.

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^3 A. Mezghani and J. A. Nossek, ”Power efficiency in communication systems from a circuit perspective,” ISCAS ’11.
Circuit power consumption

Backhaul

The load-dependent term $P_{BH}$ can be computed as [5] 4

$$P_{BH} = \sum_{k=1}^{K} \left( \mathbb{E} \left\{ R_{k}^{(ul)} + R_{k}^{(dl)} \right\} \right) P_{BT} \text{ Watt}$$

(12)

where $P_{BT} = 0.25 \text{ W/Gbit/s}$ is the backhaul traffic power (in Watt per bit/second).

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Circuit power consumption

Channel estimation

The power $P_{CE}$ for channel estimation is

$$P_{CE} = P_{CE}^{(ul)} + P_{CE}^{(dl)}$$  \hfill (13)

where

$$P_{CE}^{(dl)} = \frac{B}{U} \frac{4\tau^{(dl)} K^2}{L_{UE}}$$ \hfill (14)$$

$$P_{CE}^{(ul)} = \frac{B}{U} \frac{2\tau^{(ul)} M K^2}{L_{BS}}$$ \hfill (15)$$

with $L_{BS} [= 12.8 \text{ GFlops/W}]$ and $L_{UE} [= 5 \text{ GFlops/W}]$ being the computational efficiency in flops/Watt (reasonably $L_{BS} \gg L_{UE}$).
Circuit power consumption

Linear Processing

This costs [6]

\[
P_{LP} = B \left(1 - \frac{(\tau^{(ul)} + \tau^{(dl)})K}{U}\right) \frac{2MK}{L_{BS}} + P_{LP-C} \quad \text{Watt} \tag{16}
\]

where \(P_{LP-C}\) accounts for the power required for the computation of \(G\) and \(V\).

- With MRT/MRC

\[
P_{LP-C}^{(MRT/MRC)} = \frac{B}{U} \frac{3MK}{L_{BS}} \quad \text{Watt} \tag{17}
\]

- With ZF

\[
P_{LP-C}^{(ZF)} = \frac{B}{U} \left(\frac{K^3}{3L_{BS}} + \frac{3MK^2 + MK}{L_{BS}}\right) \quad \text{Watt} \tag{18}
\]

- With MMSE

\[
P_{LP-C}^{(MMSE)} = Q P_{LP-C}^{(ZF)} \quad \text{Watt} \tag{19}
\]

where \(Q\) is design parameter (number of iterations for fixed point computation).
System parameters
EARTH Project\textsuperscript{5}

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

PART II
Optimal EE parameters for ZF processing
Uplink and Downlink

ZF processing

- If a ZF detector is employed with $M \geq K + 1$, then

$$R_{k}^{(ul-ZF)} = \bar{R} = B \log (1 + \alpha (M - K)) \quad (20)$$

where $\alpha$ is a design parameter and

$$P_{TX}^{(ul-ZF)} = \frac{B \zeta^{(ul)} \sigma^2 S_x}{\eta^{(ul)}} \alpha K \quad (21)$$

where $S_x = \mathbb{E}_x \{ (l(x))^{-1} \}$ accounts for user distribution and propagation environment.

- If ZF precoding is used with $M \geq K + 1$, then

$$R_{k}^{(dl-ZF)} = \bar{R} = B \log (1 + \alpha (M - K)) \quad (22)$$

and

$$P_{TX}^{(dl-ZF)} = \frac{B \zeta^{(dl)} \sigma^2 S_x}{\eta^{(dl)}} \alpha K \quad (23)$$

- Letting $\eta = \left( \frac{\zeta^{(ul)}}{\eta^{(ul)}} + \frac{\zeta^{(dl)}}{\eta^{(dl)}} \right)^{-1}$

$$P_{TX}^{(ZF)} = P_{TX}^{(ul-ZF)} + P_{TX}^{(dl-ZF)} = \frac{B \sigma^2 S_x}{\eta} \alpha K \quad (24)$$
EE optimization
ZF Processing

If ZF is used on UL and DL, then

\[
\begin{align*}
\text{maximize} & \quad M \in \mathbb{Z}_+, K \in \mathbb{Z}_+, \alpha \geq 0 \\
\text{EE}^{(ZF)} &= \frac{K \left(1 - \frac{(\tau^{(ul)} + \tau^{(dl)}) K}{U}\right) \bar{R}}{B \sigma^2 \alpha S_x K + P^{(ZF)}_{CP}} \\
\text{subject to} & \quad M \geq K + 1
\end{align*}
\]  

(25)

where \( \bar{R} = B \log (1 + \alpha (M - K)) \) and (using our model)

\[
P^{(ZF)}_{CP} = \sum_{i=0}^{3} C_i K^i + M \sum_{i=0}^{2} D_i K^i + AK \left(1 - \frac{(\tau^{(ul)} + \tau^{(dl)}) K}{U}\right) \bar{R}
\]  

(27)

Objective: Finding EE-optimal value of \((M, K, \alpha)\) when the other two are fixed.

<table>
<thead>
<tr>
<th>Coefficients {C_i}</th>
<th>Coefficients (A) and {D_i}</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_0 = P_{FIX} + P_{SYN})</td>
<td>(A = P_{COD} + P_{DEC} + P_{BT})</td>
</tr>
<tr>
<td>(C_1 = P_{UE})</td>
<td>(D_0 = P_{BS})</td>
</tr>
<tr>
<td>(C_2 = \frac{4B\tau^{(dl)}}{UL_{UE}})</td>
<td>(D_1 = \frac{B}{L_{BS}} (2 + \frac{1}{U}))</td>
</tr>
<tr>
<td>(C_3 = \frac{B}{3UL_{BS}})</td>
<td>(D_2 = \frac{B}{UL_{BS}} (3 - 2\tau^{(dl)}))</td>
</tr>
</tbody>
</table>
Theorem 1

For given values of $\bar{\alpha} = \alpha K$ and $\bar{\beta} = M/K$, the number of UEs that maximize the EE metric is

$$K^* = \max_{\ell} \left[ K^{(o)}_{\ell} \right]$$

where the quantities $\{K^{(o)}_{\ell}\}$ denote the real positive roots of the quartic equation

$$K^4 - \frac{2U}{\tau(ul) + \tau(dl)} K^3 - \mu_1 K^2 - 2\mu_0 K + \frac{U\mu_0}{\tau(ul) + \tau(dl)} = 0$$

where $\mu_1 = \frac{U}{\tau(ul) + \tau(dl)}(C_2 + \bar{\beta}D_1) + C_1 + \bar{\beta}D_0$ and $\mu_0 = \frac{C_0 + \frac{B\sigma^2 S\times \bar{\alpha}}{\eta}}{C_3 + \bar{\beta}D_2}$.

Observations on $K^*$:
- Decreases with $\{P_{UE}, P_{BS}\}$
- Increases with $\{P_{FIX}, P_{SYN}\}$ and coverage area
- Unaffected by $\{P_{COD}, P_{DEC}, P_{BT}\}$
Theorem 2

For given values of $K$ and $\alpha$, the number of BS antennas maximizing the EE metric can be computed as $M^* = \lceil M^{(o)} \rceil$ with

$$M^{(o)} = e^{\frac{\alpha \left( \frac{B \sigma^2 S}{\eta} \alpha + C' \right)}{\alpha \mathcal{D}' e + \alpha K - 1}} + 1$$

with

$$C' = \sum_{i=0}^{3} C_i K^i$$

and

$$\mathcal{D}' = \sum_{i=0}^{2} D_i K^i.$$  

(31)

Corollary 3

When $\alpha$ grows large, we have

$$M^* \sim \frac{\alpha}{\ln(\alpha)}$$

(32)

which is an almost linear scaling law.
EE optimization
Optimal RF Power (1)

Theorem 4

For given values of $K$ and $M$, the EE-optimal $\alpha \geq 0$ can be computed as

$$\alpha^* = \frac{W \left( \eta \frac{(M-K)(\mathcal{C}'+MD')}{\sigma^2 S} - \frac{1}{e} \right) + 1}{M-K} - 1$$

with $\mathcal{C'} > 0$ and $\mathcal{D'} > 0$.

Observations on $\alpha^*$:

- Increases with $\{P_{BS}, P_{FIX}, P_{SYN}, P_{UE}\}$ and coverage area
- Unaffected by $\{P_{COD}, P_{DEC}, P_{BT}\}$
Corollary 5

The optimal $\alpha$ is approximately given by

$$\alpha^* \sim \frac{M}{\ln(M)}$$

(34)

when $M$ grows large.

If $M$ becomes large, then

- $\alpha^*/M$ the RF power emitted per BS antenna (and per UE if we let $K$ scale linearly with $M$) decays as $1/\ln(M)$ – RF amplifiers can be gradually simplified with $M$.
- Much slower than the scaling laws $1/M$ and $1/\sqrt{M}$ observed in [7] and [8].

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EE optimization
Joint sequential optimization

Ultimate goal: Joint Global Optimum
- Too complex – only for off-line cell planning

Alternating Optimization Algorithm
- Assume that an initial set \((K, M, \alpha)\) is given;
- Update the number of UEs \(K\) (and implicitly \(M\) and \(\alpha\)) according to Theorem 1;
- Replace \(M\) with the optimal value from Theorem 2;
- Optimize the RF power through \(\alpha\) by using Theorem 4;
- Repeat 2) – 5) until convergence is achieved.

Convergence: A local optimum is achieved for any initial set \((K, M, \alpha)\)
PART III

Numerical results

Matlab code available for download\textsuperscript{7}

\textsuperscript{7}https://github.com/emilbjornson/is-massive-MIMO-the-answer
Numerical results

ZF processing

- $M = 165 \gg K = 104$ Massive MIMO!
- $\alpha = 0.8747$, SE = 5.7644 bit/s/Hz (per UE)
**Numerical results**

**MMSE processing**

- $M = 145 \gg K = 95$ **Massive MIMO!**
- Same EE of ZF
**Numerical results**

MRT/MRC processing

- $M = 81 \approx K = 77$ Massive number of BS antennas but not Massive MIMO!
- Lower EE compared to ZF and MMSE
Numerical results

MRT/MRC processing in our previous work [9][8]

- Single-user transmission was optimal for MRT
- Different power consumption model
- As compared to [9], we have increased $P_{BT}$ (based on [10]) and made $P_{C/D}$ proportional to the rates instead of $K$.

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Numerical results
ZF processing with imperfect CSI

- $M = 185 \gg K = 110$ **Still Massive MIMO!**
- But lower EE with respect to perfect CSI
Numerical results
Average RF power vs. $M$

- RF power of 100 mW/antenna with ZF and MMSE
- RF power of 23 mW/antenna with MRT
- Much smaller than for macro BSs (40 W/antenna [11])

EE-optimal solution can be deployed with low-power UE-like RF amplifiers!
Numerical results
Area Throughput vs. $M$

- 3-fold improvement in EE for ZF and MMSE vs. MRT/MRC.
- 8-fold improvement in area throughput for ZF and MMSE vs. MRT/MRC

Massive MIMO with proper interference-suppressing precoding (ZF or MMSE) can achieve great EE and unprecedented area throughput.
Extension to multi-cell

Symmetric scenario

<table>
<thead>
<tr>
<th>Cluster 1</th>
<th>Cluster 2</th>
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<th>Cluster 2</th>
<th>Cluster 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster 3</td>
<td>Cluster 4</td>
<td>Cluster 3</td>
<td>Cluster 4</td>
<td>Cluster 3</td>
</tr>
<tr>
<td>Cluster 1</td>
<td>Cluster 2</td>
<td>Cell under study (Cluster 1)</td>
<td>Cluster 2</td>
<td>Cluster 1</td>
</tr>
<tr>
<td>Cluster 3</td>
<td>Cluster 4</td>
<td>Cluster 3</td>
<td>Cluster 4</td>
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<tr>
<td>Cluster 1</td>
<td>Cluster 2</td>
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<td>Cluster 1</td>
</tr>
</tbody>
</table>

Typical cell:

$M$ antennas at BS

$K$ uniformly distributed UEs

500 meters
Numerical results
ZF in the symmetric multi-cell case

- Optimal EE value is smaller
- Mainly due to inter-cell interference
- $M = 123 \gg K = 40$ Massive MIMO is still the EE-optimal architecture.
Conclusions
Conclusions and outlook

How should a multi-user MIMO system be designed to maximize energy efficiency?

- Need: Reasonable throughput model
- Need: Reasonable power consumption model

Is Massive MIMO The Answer?

- YES! Deploying $M = 100/200$ with ZF or MMSE a relatively large $K$ is EE-optimal using today’s circuit technology.
- RF power decreases with $M$: Low-power UE-like equipment can be used at the BS

Things change fast!

- Code available for download (to enable simple testing of other circuit power coefficients)
- Circuit power coefficients will decrease over time
- Higher EE with fewer UEs, fewer BS antennas, less RF power, but more advanced processing.
References


