Energy-Efficient, Large-scale Distributed-Antenna Systems (L-DAS)

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2 May 2014
1 Introduction
   - Green Wireless Communications
   - Efficiency
   - Spectral Efficiency & Energy Efficiency Tradeoff

2 Large-scale Distributed-Antenna Systems (L-DAS)
   - EE of L-DAS
   - EE Maximization Problem
   - Proposed Algorithms
   - Performance Evaluation

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- Green Wireless Communications
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2 Large-scale Distributed-Antenna Systems (L-DAS)
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- EE Maximization Problem
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3 Conclusion
Green Wireless Communications

- Green
  - Reduce energy consumption
  - Reduce CO₂ emission

world-wide energy consumption
Green Information & Communications Technology (ICT)

- ICT is the 5\textsuperscript{th} largest industry in power consumption [1]
- ICT infrastructure consumes 3\% of the world-wide energy consumption [1]
- ICT emits around 2\% of the world-wide CO\textsubscript{2} [1]
Green Wireless Communications

Wireless access communication networks consume significant amount of energy to overcome fading and interferences [2, 3, 4].
The energy is mostly consumed at the **transmitter**, e.g., base station (BS) in cellular networks [4]
Green Wireless Communications

50–80% of transmitter’s power is consumed at **power amplifier (PA)** [5-9]
References

[1] [Fettweis and Zimmermann, 2008]
[2] [Baliga et al., 2011]
[3] [Joung and Sun, 2012]
[4] [Vereecken et al., 2011]
[5] [Gruber et al., 2009]
[6] [Bogucka and Conti, 2011]
[7] [Joung et al., 2012]
[8] [Joung et al., 2013]
[9] [Joung et al., 2014b]
What’s Efficiency

Efficiency: has widely varying meanings in different disciplines

- “refers to the use of resources so as to maximize the production of goods and services” – *economics*
- “the ratio of the work done or energy developed by a machine, engine, etc., to the energy supplied to it” – *dictionary*
- “describes the extent to which time, effort or cost is well used for the intended task or purpose” – *wikipedia*

Efficiency in general

\[ \eta \triangleq \frac{\text{valuable resource produced}}{\text{valuable resource consumed}} \]

Efficiency in communications?
What’s Efficiency

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Efficiency in general

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Efficiency in *communications?*
Spectral & Energy Efficiencies (SE&EE)

- Valuable resource produced in comm.: \textit{bits}
- Valuable resource consumed in comm.: \textit{frequency, space, time, power, etc.}

SE and EE

- \textbf{SE, b/s/Hz}: number of reliably decoded bits per channel use.
- \textbf{EE, b/s/W = b/J}: number of reliably decoded bits per energy.
Spectral & Energy Efficiencies (SE&EE)

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\textbf{SE and EE}

- \textit{SE, b/s/Hz}: number of reliably decoded bits per channel use.
- \textit{EE, b/s/W = b/J}: number of reliably decoded bits per energy.
Ideal SE-EE Tradeoff

- \( \text{SE} = \log_2(1 + \frac{P_{\text{out}}}{\sigma^2}) \): Gaussian signalling, perfectly linear PA [Shannon, 1949]
- \( \text{EE} = \frac{\Omega \cdot \text{SE}}{P_c} \): ideal power consumption model [Verdú, 2002, Chen et al., 2011]

\[ P_c = P_{\text{PA}} = P_{\text{out}} \]

[\( P_{\text{out}} \): transmit power; \( \sigma^2 \): noise power; \( \Omega \): total bandwidth]
Ideal SE-EE Tradeoff

\[
SE = \log_2(1 + \frac{P_{out}}{\sigma^2}) \quad \text{Gaussian signalling, perfectly linear PA} \quad [\text{Shannon, 1949}]
\]

\[
EE = \frac{\Omega \cdot SE}{P_c} \quad \text{ideal power consumption model} \quad [\text{Verdú, 2002, Chen et al., 2011}]
\]

- $P_c = P_{PA} = P_{out}$

- $SE = \log_2(1 + \frac{P_{out}}{\sigma^2})$
- $EE = \frac{\Omega \cdot SE}{P_c}$

[$P_{out}$: transmit power; $\sigma^2$: noise power; $\Omega$: total bandwidth]
What is a practical SE-EE tradeoff?

- Practical power consumption model
- PA nonlinearity
- PA efficiency < 100%

Practical SE-EE Tradeoff

\[ P_c \gg P_{PA} \gg P_{out} \]
Practical SE-EE Tradeoff

What is a practical SE-EE tradeoff?

- Practical power consumption model
- PA nonlinearity
- PA efficiency < 100%

$P_c \gg P_{PA} \gg P_{out}$
Practical SE-EE Tradeoff

- Quasiconcave and narrow (bad) tradeoff
  [Chen et al., 2011, Héliot et al., 2012, Onireti et al., 2012, Joung et al., 2012, Joung et al., 2014b].
Energy Efficient Technologies

- 50–80% of transmitter’s power is consumed at power amplifier (PA)
Energy Efficient Technologies

Device-Level Approach
Transmitter architecture
PA package structures

world-wide energy consumption
3% ICT energy consumption
wireless networks
transmitter

50%-80% power amplifier
Energy Efficient Technologies

- **Device-Level Approach**
  - Transmitter architecture
  - PA package structures

- **System-Level Approach**
  - Transceiver signal processing
  - IBO/PAPR/DPD/…

-world-wide energy consumption
- 3% ICT energy consumption
- Wireless networks
Energy Efficient Technologies

Device-Level Approach
- Transmitter architecture
- PA package structures

System-Level Approach
- Transceiver signal processing
  - IBO/PAPR/DPD/…

Network-Level Approach
- Network processing
  - SC/HetNet/CZ/CoMP/CoNap/DTX/…

3% ICT energy consumption

World-wide energy consumption

50%-80% power amplifier
## EE Techniques [Joung et al., 2014a]

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Motivation

To achieve high SE and EE

- For high SE
  - MU-MIMO: LTE-A beyond Re-7
  - Distributed systems: e.g., coordinated multi-point operation (CoMP), LTE-A Re-11
  - Massive (large) MIMO: recent trend

- For high EE
  - Power control: efficient-power transmission
To achieve high SE and EE

- **For high SE**
  - ✓ MU-MIMO: LTE-A beyond Re-7
  - ✓ Distributed systems: e.g., coordinated multi-point operation (CoMP), LTE-A Re-11
  - ✓ Massive (large) MIMO: recent trend

- **For high EE**
  - ✓ Power control: efficient-power transmission
To achieve high SE and EE

- **For high SE**
  - ✓ **MU-MIMO**: LTE-A beyond Re-7
  - ✓ **Distributed systems**: e.g., coordinated multi-point operation (CoMP), LTE-A Re-11
  - ✓ **Massive (large) MIMO**: recent trend

- **For high EE**
  - ✓ **Power control**: efficient-power transmission
Objectives & Contribution

- Study an L-DAS
- Provide a practical power consumption model
- Formulate an EE maximization problem
- Resolve issue on huge signaling, complexity requirement:
  - Distributed antenna (DA) selection method
  - SINR-threshold-based DA-clustering method
  - MU-MIMO precoding method
  - Optimal and heuristic power control methods
- Verify the EE merit of L-DAS
Energy-Efficient Large-scale DAS (L-DAS)

L-DAS and Signal Model

\[ y = H (S \circ W) \sqrt{P} x + n \]

- \( y \): Received signal vector
- \( H \): Channel matrix
- \( S \): Signal matrix
- \( W \): Matrix completion
- \( P \): Power
- \( x \): Transmitted signal vector
- \( n \): Noise vector

**User Equipments (UEs)**
**Distributed Antennas (DAs)**

*km* *km*
L-DAS and Signal Model

\[ y = H(S \circ W) \sqrt{P} x + n \]
L-DAS and Signal Model

\[ y = H (S \circ W) \sqrt{P} x + n \]

- \( U \) user equipments (UEs)
- \( M \) distributed antennas (DAs)

km

km

BBU

Jingon Joung

Energy-Efficient Large-scale DAS (L-DAS)
L-DAS and Signal Model

\[ y = H \left( S \circ W \right) \sqrt{P} x + n \]

- \( U \) user equipments (UEs)
- \( M \) distributed antennas (DAs)
- BBU
- km

km
Energy Efficiency (EE) of L-DAS

\[
\text{EE} (S, W, P) \triangleq \frac{\text{System throughput per unit time}}{\text{Total power consumption}}
\]

- System throughput:
  \[
  R(S, W, P) = \sum_{u \in U} \Omega \log_2 (1 + \text{SINR}_u(S, W, P))
  \]
  \[
  \text{SINR}_u(S, W, P) = \frac{|h^r_u(s_c^u \circ w^c_u)|^2 p_{uu}}{\sum_{u' = 1, u' \neq u} |h^r_u(s_c^u \circ w^c_{u'})|^2 p_{u'u'} + \sigma^2}
  \]

- Total power consumption:
  \[
  C(S, W, P) = f(S, W, P) + g(S, W)
  \]
  \[
  f(\cdot): \text{TPD (transmit power dependent) term}
  \]
  \[
  g(\cdot): \text{TPI (transmit power independent) term}
  \]
Energy Efficiency (EE) of L-DAS

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  R(S, W, P) = \sum_{u \in \mathcal{U}} \Omega \log_2 \left(1 + \text{SINR}_u(S, W, P)\right)
  \]
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  \text{SINR}_u(S, W, P) = \frac{|h_r^u(s^c_u \circ w^c_u)|^2 p_{uu}}{\sum_{u'=1, u' \neq u} |h_r^u(s^c_{u'} \circ w^c_{u'})|^2 p_{u'u'} + \sigma^2}
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- **Total power consumption:**
  \[
  C(S, W, P) = f(S, W, P) + g(S, W)
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  f(\cdot): \text{TPD (transmit power dependent) term}
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  \]
Cont.

**baseband module**

ASIC, FPGA, DSP

Examples:
- digital up converter
- digital predistorter
- scrambling
- CRC check
- conv. encoder
- interleaver
- modulation
- IFFT
- CP insertion
- parallel-to-serial

**mth RF module at BBU**

- eRF module
  - Examples:
    - D/A converter
    - filters
    - synthesizer

- oRF module
  - Examples:
    - E/O converter
    - laser
    - driver
    - modulator

**mth distributed antenna (DA) port**

- fiber

- \(P_{cc1,m}^{(TPI)}\)
- \(P_{cc2,m}^{(TPI)}\)

**baseband unit (BBU)**

- \(P_{fix}^{(TPI)}\)
- \(P_{sp1}, P_{sp2}, P_{sig}^{(TPI)}\)

**mth Ant.**

**Mth Ant.**

**TPD term**

\[
f(S, W, P) = \sum_{m \in M} \frac{c}{\eta_m} \left[(S \circ W)P(S \circ W)^H\right]_{mm}
\]

✓ eRF (electric RF)
✓ oRF (optical RF)
TPI term

\[ g(S, W) = g_{rf}(S) + g_{bb}(W) + g_{net}(M) + P_{fix} \]

- \[ g_{rf}(S) = \sum_{m \in M} \left( P_{cc1,m} + P_{cc2,m} \sum_{u \in U} R_u \right) \max_u s_{mu} \]
- \[ g_{bb}(W) = \Omega P_{sp1} \left[ \dim(W) \right]^{\beta+1} + \Omega P_{sp2} \]
- \[ g_{net}(M) = M\Omega P_{sig} \]
- \[ P_{cc1}: \text{eRF} \]
- \[ P_{cc2}: \text{per unit-bit-and-second of oRF} \]
- \[ R_u: \text{target rate of user } u \]
- \[ \beta \geq 0: \text{implies overhead power consumption of MU processing compared to SU-MIMO} \]
- \[ P_{fix}: \text{fixed power consumption (e.g., pow supply, AC/DC, DC/DC, and cooling system)} \]
\[
\text{EE} (S, W, P) = \\
\sum_{u \in \mathcal{U}} \Omega \log_2 \left( 1 + \frac{|h_u^r (s_u^c \circ w_u^c)|^2 p_{uu}}{\sum_{u' = 1, u' \neq u} |h_u^r (s_{u'}^c \circ w_{u'}^c)|^2 p_{u'u'} + \sigma^2} \right) \\
\sum_{m \in \mathcal{M}} \frac{c}{\eta_m} \left[ (S \circ W) P (S \circ W)^H \right]_{mm} \\
+ \sum_{m \in \mathcal{M}} \left( P_{cc1,m} + P_{cc2,m} \sum_{u \in \mathcal{U}} R_u \right) \max_u s_{mu} \\
+ \Omega P_{sp1} \left[ \text{dim}(W) \right]^{\beta + 1} + \Omega P_{sp2} \\
+ M \Omega P_{\text{sig}}
\]
Original Problem Formulation

\[ \text{Objective: } \text{max } \{ S, W, P \} \]

\[ \text{subject to: } \left[ (S \circ W)P(S \circ W)^H \right]_{mm} \leq P_m, \ \forall m \in \mathcal{M}, \]

\[ R_u(S, W, P) \geq R_u, \ \forall u \in \mathcal{U}, \]

\[ p_{u_1u_2} = 0, \ \forall u_1 \neq u_2 \in \mathcal{U}, \]

\[ s_{mu} \in \{0, 1\}, \ \forall m \in \mathcal{M}, \forall u \in \mathcal{U}, \]

- **objectives function:** EE
- **per-ant pow constraints** with max-output pow \( P_m \)
- **per-user rate constraints** with a target rate \( R_u \)
- **diagonal structure of** \( P \)
- **DA selection**
Original Problem Formulation

**P_0**: original problem

\[
\begin{align*}
\text{max} & \quad \text{EE} (S, W, P) \\
\text{s.t.} & \quad [(S \circ W) P (S \circ W)^H]_{mm} \leq P_m, \quad \forall m \in M, \\
& \quad R_u(S, W, P) \geq R_u, \quad \forall u \in U, \\
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\]

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$P_0$: original problem

$$\max \{S, W, P\} \quad \text{EE} (S, W, P)$$

s.t. $$(S \circ W) P (S \circ W)^H \leq P_m, \forall m \in M,$$

$$R_u (S, W, P) \geq R_u, \forall u \in U,$$

$$p_{u_1 u_2} = 0, \forall u_1 \neq u_2 \in U,$$

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- objective function: EE
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\begin{align*}
\text{max}_{\{S,W,P\}} & \quad \text{EE} (S, W, P) \\
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\begin{align*}
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\text{s.t.} & \quad [(S \circ W) P (S \circ W)^H]_{mm} \leq P_m, \ \forall m \in \mathcal{M}, \\
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- **objective function**: EE
- **per-ant pow** constraints with max-output pow $P_m$
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Problem Decomposition

Issues to solve the original problem $P_o$:

- Non-convex objective function
- Integer variables $\{s_{mu}\}$ in the constraints
- Signaling overhead
- Computational complexity

Suboptimal decomposition approach

Step 1: DA selection: $S$

Step 2: DA clustering

Step 3: Cluster-based optimization (cluster index $\ell$)
Problem Decomposition

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**Step 3:** Cluster-based optimization (cluster index $\ell$)
  - Step 3-1: Precoding, $W_\ell$
  - Step 3-2: Power allocation, $P_\ell$
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Step 1: DA selection: $S$

Step 2: DA clustering

Step 3: Cluster-based optimization (cluster index $\ell$)
  - Step 3-1: Precoding, $W_\ell$
  - Step 3-2: Power allocation, $P_\ell$
Problem Decomposition

- **Issues to solve the original problem** $P_o$:
  - ✓ Non-convex objective function
  - ✓ Integer variables $\{s_{mu}\}$ in the constraints
  - ✓ Signaling overhead
  - ✓ Computational complexity

Suboptimal decomposition approach

**Step 1:** DA selection: $S$

**Step 2:** DA clustering

**Step 3:** Cluster-based optimization (cluster index $\ell$)
  - Step 3-1: Precoding, $W_\ell$
  - Step 3-2: Power allocation, $P_\ell$
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  ✓ Non-convex objective function
  ✓ Integer variables $\{s_{mu}\}$ in the constraints
  ✓ Signaling overhead
  ✓ Computational complexity

Suboptimal decomposition approach

Step 1: DA selection: $S$
Step 2: DA clustering
Step 3: Cluster-based optimization (cluster index $\ell$)
  Step 3-1: Precoding, $W_\ell$
  Step 3-2: Power allocation, $P_\ell$
Step 1: DA Selection

- 20 UEs
- non-activated DA: $M = 400$
- activated DA: $M_u = 1$

- Channel-gain-based greedy AS: RSSI
- Min-dis-based greedy AS: localization info.
Step 2: Selected-DA Clustering

- **SINR-threshold** $\gamma$ based clustering
- If UE $u''$’s *distance* from cluster $\ell$ is shorter than $\gamma$, UE $u'$ is included to the cluster $\ell$ as follows:

  $$\mathcal{U}_\ell = \mathcal{U}_\ell \cup \{u'\}, \text{ if } D(\mathcal{U}_\ell, u') \leq \gamma$$

  ✓ Distance metric between two clusters

  $$D(\mathcal{U}_\ell, \mathcal{U}_{\ell'}) \triangleq \min_{u \in \mathcal{U}_\ell, u' \in \mathcal{U}_{\ell'}} d(u, u').$$

  $$d(u, u') \triangleq \min \left\{ \frac{\sum_{m \in \mathcal{M}_u} |h_{um}|^2 P_m}{\sigma^2 + \sum_{m' \in \mathcal{M}_{u'}} |h_{um'}|^2 P_{m'}}, \frac{\sum_{m' \in \mathcal{M}_{u'}} |h_{u'm'}|^2 P_{m'}}{\sigma^2 + \sum_{m \in \mathcal{M}_u} |h_{u'm}|^2 P_m} \right\}$$
Cont.

(a) $\gamma = 25 \text{ dB}, \ L = 11$

- $\gamma \uparrow \implies \text{cluster size} \uparrow, \ \text{number of clusters} \downarrow, \ \text{inter-cluster interference} \downarrow$

(b) $\gamma = 32 \text{ dB}, \ L = 6$

- $\gamma \downarrow \implies \text{cluster size} \downarrow, \ \text{number of clusters} \uparrow, \ \text{inter-cluster interference} \uparrow$
Cont.

(a) $\gamma = 25 \text{ dB, } L = 11$

- SINR between users in different clusters $> \gamma$
  $\implies$ cluster-based optimization

(b) $\gamma = 32 \text{ dB, } L = 6$

- SINR between users within a cluster $\leq \gamma$
  $\implies$ MU-MIMO precoding
cluster with a single UE

cluster with four UEs

(a) $\gamma = 25\,\text{dB}$, $L = 11$

(b) $\gamma = 32\,\text{dB}$, $L = 6$

- SINR between users in different clusters $> \gamma \implies$ cluster-based optimization
- SINR between users within a cluster $\leq \gamma \implies$ MU-MIMO precoding
Step 3: Cluster-based Optimization

Problem

\( P_\ell: \) cluster-\( \ell \) problem for given \( S^*_\ell, \ell \in \mathcal{L} \)

\[
\begin{align*}
\max_{\{W_\ell, P_\ell\}} & \quad \text{EE} \left( S^*_\ell, W_\ell, P_\ell \right) \\
\text{s.t.} & \quad \left[ (S^*_\ell \circ W_\ell) P_\ell (S^*_\ell \circ W_\ell)^H \right]_{mm} \leq P_m, \forall m \in \mathcal{M}_\ell, \\
& \quad R_u(S^*_\ell, W_\ell, P_\ell) \geq R_u, \forall u \in \mathcal{U}_\ell, \\
& \quad p_{u_1u_2} = 0, \forall u_1 \neq u_2 \in \mathcal{U}_\ell.
\end{align*}
\]

- Maximization of EE upper bound
- Computational complexity reduction
- CSI and signaling overhead reduction:
  e.g., \( 8000 \Rightarrow 48 \) and \( 160 \) in (a) and (b)
Step 3: Cluster-based Optimization Problem

\[ P_\ell: \text{cluster-\(\ell\) problem for given } S_\ell^*, \ell \in \mathcal{L} \]

\[
\begin{align*}
\max_{\{W_\ell, P_\ell\}} & \quad \text{EE} (S_\ell^*, W_\ell, P_\ell) \\
\text{s.t.} & \quad \left[(S_\ell^* \circ W_\ell) P_\ell (S_\ell^* \circ W_\ell)^H\right]_{mm} \leq P_m, \forall m \in \mathcal{M}_\ell, \\
& \quad R_u(S_\ell^*, W_\ell, P_\ell) \geq R_u, \forall u \in \mathcal{U}_\ell, \\
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\end{align*}
\]

- Maximization of EE upper bound
- Computational complexity reduction
- CSI and signaling overhead reduction:
  - e.g., 8000 \(\Rightarrow\) 48 and 160 in (a) and (b)
Problem Decomposition

\( P_{\ell,1} \): Precoding matrix \( W_\ell^* \) for fixed \( S_\ell^* \) and \( P'_{\ell} \)

\[
\max_{\{W_\ell, P_\ell\}} \quad \text{EE} (W_\ell, P'_\ell)
\]

s.t.
\[
\begin{align*}
\left[ (S_\ell^* \circ W_\ell^*) P_\ell (S_\ell^* \circ W_\ell^*)^H \right]_{mm} & \leq P_m, \forall m \in \mathcal{M}_\ell \\
R_u(S_\ell^*, W_\ell^*, P_\ell) & \geq R_u, \forall u \in \mathcal{U}_\ell \\
p_{u_1 u_2} & = 0, \forall u_1 \neq u_2 \in \mathcal{U}_\ell
\end{align*}
\]
Problem Decomposition

\( P_{\ell,2} \): Power control matrix \( P_{\ell}^* \) for fixed \( S_{\ell}^* \) and \( W_{\ell}^* \)

\[
\begin{align*}
\max_{\{W_{\ell}, P_{\ell}\}} & \quad \text{EE} (W_{\ell}^*, P_{\ell}) \\
\text{s.t.} & \quad \left[ (S_{\ell}^* \circ W_{\ell}^*) P_{\ell} (S_{\ell}^* \circ W_{\ell}^*)^H \right]_{mm} \leq P_m, \forall m \in M_{\ell} \\
& \quad R_u (S_{\ell}^*, W_{\ell}^*, P_{\ell}) \geq R_u, \forall u \in U_{\ell} \\
& \quad p_{u_1u_2} = 0, \forall u_1 \neq u_2 \in U_{\ell}
\end{align*}
\]
**ZF-MU-MIMO Precoding Design**

\[ P_{\ell,1}: \text{Precoding matrix } W_\ell^* \text{ for fixed } S_\ell^* \text{ and } P'_\ell \]

\[
W_\ell^* = \max_{W_\ell} \text{EE}(S_\ell^*, W_\ell, P'_\ell)
\]

\[(a) \quad \min_{W_\ell} C(S_\ell^*, W_\ell, P'_\ell) \equiv \min_{W_\ell} \frac{1}{c} \sum_{m \in M_\ell} \eta_m \left[ (S_\ell^* \circ W_\ell) P'_\ell (S_\ell^* \circ W_\ell)^H \right]_{mm}
\]

\[(b) \quad \min_{W_\ell} \sum_{m \in M_\ell} \left[ (S_\ell^* \circ W_\ell) P'_\ell (S_\ell^* \circ W_\ell)^H \right]_{mm}
\]

(a) rate does not depend on \( W_\ell \) due to a ZF property

(b) \( W_\ell \) affects only on TPD term for given \( S_\ell^* \) and \( P'_\ell \)

(c) equal capability of PA is preferred for high EE [Joung and Sun, 2013], \( c/\eta_m \) is assumed to be a constant
$P_{\ell,1}$: Precoding matrix $W_\ell^*$ for fixed $S_\ell^*$ and $P'_\ell$

\[
W_\ell^* = \min_{W_\ell} \sum_{m \in M_\ell} \left[ (S_\ell^* \circ W_\ell) P'_\ell (S_\ell^* \circ W_\ell)^H \right]_{mm}
\]

\[
= \min_{W_\ell} \left\| S_\ell^d W_\ell \sqrt{P'_\ell} \right\|_F^2
\]

1. $S_\ell^d = \text{diag}(s_{\ell,c}^*, \ell) \in \mathbb{R}^{M \times M}$
2. $s_{\ell,c}^* = \sum_{u \in U_\ell} s_{u}^{c,*}$

ZF-MU-MIMO precoding matrix as

\[
W_\ell = (H_\ell S_\ell^d)^\dagger + \text{null}(H_\ell S_\ell^d) A_\ell
\]

1. $H_\ell \in \mathbb{C}^{U_\ell \times M}$: a channel matrix of cluster $\ell$ that consists of row vectors $h_u^r$, $u \in U_\ell$
2. $A_\ell \in \mathbb{C}^{U_\ell \times U_\ell}$ is a $U_\ell$-dimensional arbitrary matrix.
\[ P_{\ell,1}: \text{Precoding matrix } W_\ell^* \text{ for fixed } S_\ell^* \text{ and } P'_\ell \]

\[ W_\ell^* = \min_{W_\ell} \sum_{m \in M_\ell} [(S_\ell^* \circ W_\ell) P'_\ell (S_\ell^* \circ W_\ell)^H]_{mm} \]

\[ = \min_{W_\ell} \| S_\ell^d W_\ell \sqrt{P}'_\ell \|^2_F \]

\[ \checkmark \quad S_\ell^d = \text{diag}(s_\ell^{c,*}) \in \mathbb{R}^{M \times M} \]

\[ \checkmark \quad s_\ell^{c,*} = \sum_{u \in U_\ell} s_\ell^{c,u} \]

**ZF-MU-MIMO precoding matrix as**

\[ W_\ell^* = (H_\ell S_\ell^d)^\dagger \]

\[ \checkmark \quad H_\ell \in \mathbb{C}^{U_\ell \times M}: \text{a channel matrix of cluster } \ell \text{ that consists of row vectors } h_u^r, u \in U_\ell \]

\[ \checkmark \quad A_\ell \in \mathbb{C}^{U_\ell \times U_\ell} \text{ is a } U_\ell\text{-dimensional arbitrary matrix.} \]
### Power Control

**P\(_{\ell,2}\): Power control matrix \(P^*_\ell\) for fixed \(S^*_\ell\) and \(W^*_\ell\)**

\[
P^*_\ell = \max_{P_\ell} \text{EE}(S^*_\ell, W^*_\ell, P_\ell)
\]

**Subject to:** 
\[
\left[(S^d_\ell W^*_\ell)P_\ell (S^d_\ell W^*_\ell)^H\right]_{mm} \leq P_m, \forall m \in M_\ell
\]

\[
R_u(P_\ell) \geq R_u, \forall u \in U_\ell
\]

\[
p_{u_1 u_2} = 0, \forall u_1 \neq u_2 \in U_\ell.
\]

\[
\sum_{u \in U_\ell} R_u(P_\ell) \geq \xi C(S^*_\ell, W^*_\ell, P_\ell)
\]

- Using an additional variable \(\xi\)
- **Convex feasibility problem**
- **Bisection search** to find the optimal \(\xi\)
Power Control

$P_{\ell,2}$: Power control matrix $P_{\ell}^*$ for fixed $S_{\ell}^*$ and $W_{\ell}^*$

\[
P_{\ell}^* = \max_{P_{\ell}} \xi
\]

subject to

\[
\left[ (S_{\ell}^d W_{\ell}^*) P_{\ell} (S_{\ell}^d W_{\ell}^*)^H \right]_{mm} \leq P_m, \forall m \in \mathcal{M}_{\ell}
\]

\[R_u(P_{\ell}) \geq R_u, \forall u \in \mathcal{U}_{\ell}\]

\[p_{u_1 u_2} = 0, \forall u_1 \neq u_2 \in \mathcal{U}_{\ell}.
\]

\[
\sum_{u \in \mathcal{U}_{\ell}} R_u(P_{\ell}) \geq \xi C(S_{\ell}^*, W_{\ell}^*, P_{\ell})
\]

- Using an additional variable $\xi$
- Convex feasibility problem
- Bisection search to find the optimal $\xi$
Cont.: Heuristic Method

- Minimum required power to satisfy $R_u$ with ZF-MU-MIMO precoding

$$\tilde{p}_{u,\ell} = \sigma^2 \left( 2 \frac{R_u}{\Omega} - 1 \right)$$

- $\overline{p}_{u,\ell}$ is a ratio based on minimum required power for target rate [Joung and Sun, 2013] s.t.

$$\overline{p}_{u,\ell} = \frac{\tilde{p}_{u,\ell}}{\sum_{k \in \mathcal{U}_\ell} \tilde{p}_{k,\ell}}, \ \forall u \in \mathcal{U}_\ell$$

- $p_{u,\ell} = \alpha_\ell \overline{p}_{u,\ell}$

- $\alpha_\ell$: common power scaling factor for power limit of PAs and target rate of UEs in cluster $\ell$

- Maximize EE lower bound
Cont.: Heuristic Method

\[ P'_{\ell,2} : \alpha^*_\ell = \arg \max_{\alpha_\ell} \zeta(\alpha_\ell), \text{ s.t. } \alpha_{LB,\ell} \leq \alpha_\ell \leq \alpha_{UB,\ell} \]

\[ \checkmark \quad \zeta(\alpha_\ell) = \frac{\Omega U_\ell \log_2(1+c_{1,\ell}\alpha_\ell)}{c_{2,\ell}\alpha_\ell+c_{3,\ell}} : \text{concave function} \]

\[ \checkmark \quad c_{1,\ell} \triangleq \min_u \{ \overline{p}_{u,\ell} \} \sigma^{-2} \]

\[ \checkmark \quad c_{2,\ell} \triangleq c \sum_{m \in M_\ell} \eta_m^{-1} \left[ S_{d}^d W_\ell^* \overline{P}_\ell (S_{d}^d W_\ell^* H) H \right]_{mm} \]

\[ \checkmark \quad c_{3,\ell} = \sum_{m \in M_\ell} (P_{cc1,m} + P_{cc2,m} \sum_{u \in U_\ell} R_u) \max_{u \in U_\ell} s_{mu} + \Omega P_{sp1} [\dim(W_\ell)]^{\beta+1} + M_\ell \Omega P_{sig} + \Omega P_{sp2}/L + P_{fix}/L \]

\[ \checkmark \quad \alpha_{LB,\ell} = \sigma^2 \left( 2 \frac{R_u}{\Omega} - 1 \right) / \overline{p}_{u,\ell} \text{ from QoS constraint} \]

\[ \checkmark \quad \alpha_{UB,\ell} = \min_{m \in M_\ell} \left( P_m / \left[ S_{d}^d W_\ell^* \overline{P}_\ell (S_{d}^d W_\ell^* H) H \right]_{mm} \right) \text{ from power constraint} \]
Closed form solution:

\[ \alpha_o = \frac{1}{c_1} \left( \exp \left( 1 + W \left( \frac{1}{\exp(1)} + \frac{c_1 c_3}{c_2 \exp(1)} \right) \right) - 1 \right) \]

\[ \alpha^* = [\alpha_o]^{\alpha_{UB}}_{\alpha_{LB}} \]

\[ P^*_{heuristic} = \alpha^* \overline{P} \]
Algorithm 1: Clustering threshold $\gamma$ adaptation

1. Initial setup: $\gamma, \delta > 0$, stop = 0, $q = 0$, $M_u$, and $Q_C \geq 0$.
2. compute $EE_p$ with $\gamma$: $M_u$ Adaptation Algorithm 2.
3. compute $EE_c$ with $\gamma = \gamma + \delta$: $M_u$ Adaptation Algorithm 2.
4. if $EE_c > EE_p$ then
5. $EE_p = EE_c$ and $\xi = 1$.
6. else
7. compute $EE_c$ with $\gamma = \gamma - 2\delta$: $M_u$ Adaptation Algorithm 2.
8. if $EE_c > EE_p$ then $EE_p = EE_c$ and $\xi = -1$.
9. else stop = 1 end if
10. end if
11. while stop = 0 & $q < Q_C$ do
12. compute $EE_c$ with $\gamma = \gamma + \xi\delta$: $M_u$ Adaptation Algorithm 2.
13. if $EE_c > EE_p$ then $EE_p = EE_c$.
14. else stop = 1 end if
15. $q = q + 1$
16. end while
Algorithm 2: $M_u$ adaptation algorithm for AS

1. Initial setup: $M_u = 1, \forall u \in U, q = 0, \gamma$, and $Q_{AS} \geq 0$.
2. **while** feasibility = 0 & $q < Q_{AS}$ **do**
3. DA Selection Algorithm 3.
4. DA Clustering Algorithm 4 with a threshold $\gamma$.
5. feasibility = 1
6. **for** cluster $\ell = 1, \ldots, L$ **do**
7. precoding: $W_\ell = (H_\ell S_\ell^d)^\dagger$.
8. power control: Bisection Search Algorithm 5 or $P^\text{heuristic} = \alpha^*$.
9. **if** power control is infeasible & $\sum_{u \in U} M_u < M$

10. **then** add one additional DA to UE $u \in U_\ell$ who has the weakest channel gain, i.e., $M_u = M_u + 1$ where $u \in U_\ell$ s.t., $u = \arg\min_{u \in U_\ell} |h_{um}|$.
11. feasibility = 0 **end if**
12. **end for**
13. $q = q + 1$
14. **end while**
Algorithm 3 : CGB/MDB-Greedy DA selection algorithm

1. Initial setup: $U = \{1, \ldots, U\}$, $M = \{1, \ldots, M\}$, $s_{mn} = 0, \forall m \in M, \forall u \in U, \mathcal{M}_u = \emptyset, \forall u \in U$, and given $M_u$'s.

2. While $U \neq \emptyset$ do
3. Find $\{m^*, u^*\} = \operatorname{arg\ max}_{m \in M, u \in U} |h_{um}|$ for CGB, $\operatorname{min}_{d_{um}}$ for MDB
4. Set $s_{m^* u^*} = 1$, $M = M \setminus m^*$ and $\mathcal{M}_{u^*} = \mathcal{M} \cup m^*$
5. If $|\mathcal{M}_{u^*}| = M_{u^*}$ then
6. $U = U \setminus u^*$
7. End if
8. End while
Algorithm 4: DA clustering algorithm

1. Initial setup: distance $d_0 = 0$, clusters $\mathcal{U}_\ell = \{\ell\}$ where $\ell \in \mathcal{L} = \{1, \ldots, U\}$, and given $\gamma$.
2. while $d_0 < \gamma$ do
3. find the distance of most closest pair of clusters $\mathcal{U}_\ell$ and $\mathcal{U}_{\ell'}$, i.e., $d_0 = \min_{\ell, \ell' \in \mathcal{L}, \ell \neq \ell'} D(\mathcal{U}_\ell, \mathcal{U}_{\ell'})$.
4. if $d_0 < \gamma$ then
5. merge clusters as $\mathcal{U}_\ell = \mathcal{U}_\ell \cup \mathcal{U}_{\ell'}$.
6. update $\mathcal{L}$.
7. end if
8. end while
Algorithm 5: Bisection search algorithm: Per-cluster optimal power control for MU

1. setup: \( \xi_{LB} = 0 \), \( \xi_{UB} \approx \infty \), and a tolerance value, \( \delta > 0 \)
2. while \( \xi_{UB} - \xi_{LB} > \delta \) do
3. \( \xi \leftarrow (\xi_{UB} - \xi_{LB})/2 \)
4. Solve convex feasibility problem and find (update) \( P^*_\ell \).
5. if infeasible then \( \xi_{UB} \leftarrow \xi \)
6. else \( \xi_{LB} \leftarrow \xi \) end if
7. end while
8. \( P_{optimal, \ell} = P^*_\ell \)
## Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell model two square grid cells</td>
<td>(1km²)</td>
</tr>
<tr>
<td>Number of DAs/CAs</td>
<td>25 ≤ M ≤ 900</td>
</tr>
<tr>
<td>Intra-antenna distance (IAD)</td>
<td>from 33 m to 200m</td>
</tr>
<tr>
<td>Number of UEs</td>
<td>2 ≤ U ≤ 20</td>
</tr>
<tr>
<td>UE distribution Uniform (10⁴—realization)</td>
<td></td>
</tr>
<tr>
<td>Path loss exponent</td>
<td>μ = 3.76</td>
</tr>
<tr>
<td>Small scale fading</td>
<td>h_{um} \sim \mathcal{CN}(0, 1)</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>Ω = 10MHz</td>
</tr>
<tr>
<td>Target rate</td>
<td>R_u = 10Mb</td>
</tr>
<tr>
<td>Maximum Tx power</td>
<td>P_m = 17dBm</td>
</tr>
<tr>
<td>AWGN standard deviation</td>
<td>σ² = −174dBm/Hz</td>
</tr>
<tr>
<td>Power loss coefficient</td>
<td>c = 2.63</td>
</tr>
<tr>
<td>eRF circuit pow.cons.</td>
<td>P_{cc1,m} = 5.7W</td>
</tr>
<tr>
<td>oRF circuit pow.cons.</td>
<td>P_{cc2,m} = 0.5/0pW/bit/s</td>
</tr>
<tr>
<td>Fixed pow.cons.</td>
<td>P_{fix} = 34 W</td>
</tr>
<tr>
<td>Signal processing pow.cons.</td>
<td>P_{sp1} = 0.94 \times 1/1.1µW/Hz</td>
</tr>
<tr>
<td>Signal processing pow.cons.</td>
<td>P_{sp2} = 0.54 \times 1/1.1µW/Hz</td>
</tr>
<tr>
<td>Signaling pow.cons./antenna</td>
<td>5 ≤ P_{sig} ≤ 500nW/Hz</td>
</tr>
<tr>
<td>preprocessing pow.cons. ratio</td>
<td>0 ≤ β ≤ 2</td>
</tr>
<tr>
<td>PA efficiency</td>
<td>η_m = 0.08/0.6</td>
</tr>
<tr>
<td>Clustering threshold</td>
<td>−∞ ≤ γ ≤ ∞dB</td>
</tr>
</tbody>
</table>
Simulation Visualization

(outage: cell boundary)

Jingon Joung
Energy-Efficient Large-scale DAS (L-DAS)
\[ M = 400, \ U = 20, \ P_{\text{sig}} = 50\text{nW/Hz} \]
$M = 400$, $\beta = 0.5$, $P_{\text{sig}} = 50\text{nW/Hz}$

**Graph:**
- **x-axis:** Number of UEs, $U$
- **y-axis:** Average energy efficiency $\text{Mb/J}$

Lines and markers indicate different scenarios:
- **Optimal pow ctrl with adaptation**
- **Heuristic pow ctrl with adaptation**
- **L-CAS with $\beta = 0.5$**

Legend:
- $\gamma = \infty \text{dB}$ (full MU, single cluster)
- $\gamma = 22 \text{dB}$
- $\gamma = -\infty \text{dB}$ (full SU, $U$ clusters)
$U = 20, \beta = 0.5, \gamma = 22\,\text{dB}$

![Graph showing average energy efficiency vs. number of transmit DAs, $M$, with different power control methods and signal powers.]

- **Optimal power control**
- **Heuristic power control**

- $P_{\text{sig}} = 5\,\text{nW/Hz}$
- $P_{\text{sig}} = 50\,\text{nW/Hz}$
- $P_{\text{sig}} = 500\,\text{nW/Hz}$

L-CAS with $P_{\text{sig}} = 5\,\text{nW/Hz}$
1. Introduction
   - Green Wireless Communications
   - Efficiency
   - Spectral Efficiency & Energy Efficiency Tradeoff

2. Large-scale Distributed-Antenna Systems (L-DAS)
   - EE of L-DAS
   - EE Maximization Problem
   - Proposed Algorithms
   - Performance Evaluation

3. Conclusion
Summary

- EE-aware large-scale distributed antenna system
- EE-aware strategies including
  - ✓ Distributed antenna (DA) selection methods
  - ✓ DA clustering method
  - ✓ ZF-based MU-MIMO precoding
  - ✓ Power control methods
- Further Work regarding Deployment, Implementation, and Operation of L-DAS
  - ✓ cell planning
  - ✓ regular/irregular deployment of DAs
  - ✓ synchronization for large cluster
  - ✓ robustness against CSI error
  - ✓ infrastructure cost for wired optical fronthaul
  - ✓ capital expenditure and operational expenditure
Summary

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- EE-aware strategies including
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  - DA clustering method
  - ZF-based MU-MIMO precoding
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  - Regular/irregular deployment of DAs
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  - Robustness against CSI error
  - Infrastructure cost for wired optical fronthaul
  - Capital expenditure and operational expenditure
Thank You

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Energy efficient power control for distributed transmitters with ZF-based multiuser MIMO precoding.

On the energy efficiency-spectral efficiency trade-off in the uplink of CoMP system.


Figure 1: 3. Amplitude-to-amplitude (AM/AM) distortion characteristics.
Figure 1: 3. Amplitude-to-amplitude (AM/AM) distortion characteristics.

Distortion: memoryless baseband PA models
Figure 2: 4. Maximum output power (at the linear region) versus $P_{DC}$. 

\[ \eta_{PAE} < 100\% \]