Efficient Algorithms for Resource Allocation in Heterogeneous OFDMA Networks

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Resource Allocation in Multiuser OFDMA

Downlink OFDMA Assumptions:

- $M$ Users
- $K$ Subcarriers
- CSIT
- Discrete Adaptive Modulation Scheme

Resource Allocation in Heterogeneous OFDMA Networks

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Resource Allocation: Subcarriers, Power and Bit-loading
Heterogeneous Network Users

**Heterogeneity**: Based on QoS requirement

- **Best-Effort (BE) Users**
  - Traditional internet users w/o QoS requirement.
  - Traffic demand → elastic, Data requirement → not fixed.
  - Can utilize even the minimum amount of bandwidth provided to them.

- **High-Priority (HP) Users**
  - Demand a level of QoS
  - Traffic demand → inelastic
  - QoS Metric → Bandwidth(Data Rate), BER etc.
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  - Traffic demand \(\rightarrow\) inelastic
  - QoS Metric \(\rightarrow\) Bandwidth(Data Rate), BER etc.
Assumes either BE user network or HP user network

- Rate Adaptive (RA) Scheme
  - [Rhee, Cioffi 00], [Inhyoyoung, Lee et.al. 01], [Zukang, Andrews 05], [Song, Li 05]-I,II etc.
  - Allocate resources among BE users in a fair manner.

- Margin Adaptive (MA) Scheme
  - [Cheong, Cheng, Lataief, Murch 99], [Pietrzyk, Janssen et.al. 02], [Ergen, Coleri, Varaiya 03], [Svedman, Wilson, Cimini, Ottersten 07] etc.
  - QoS aware resource allocation among HP users.
Existing Works

Assumes either BE user network or HP user network

► Rate Adaptive (RA) Scheme
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  [Ergen, Coleri, Varaiya 03], [Svedman, Wilson, Cimini, Ottersten 07] etc.
  ► QoS aware resource allocation among HP users.
Resource allocation framework for heterogeneous network

Observation:

- **Figure:** (a) HP Utility Function (b) BE Utility Function

- **Nature of users**
  - HP users with **hard** QoS requirement
  - BE users with flexible rate requirement
  
  are inherently different.

- **Should not use same type of utility function to represent both.**
Resource allocation framework for heterogeneous network

Observation:

![Utility vs. Data Rate Graphs]

*Figure: (a) HP Utility Function  (b) BE Utility Function*

- **Nature of users**
  - HP users with **hard** QoS requirement
  - BE users with flexible rate requirement

  are inherently different.

- Should not use same type of **utility function** to represent both.

**Need:** A new framework for heterogeneous network scenario.
Resource allocation framework for heterogeneous network

Assumptions:

- Priority: HP users first, then BE users
- Pricing: HP users will pay more

Two Step Approach for Heterogeneous Network:

- Satisfy QoS requirement of HP users (as many as possible)
  - Admission Control
  - Resource Allocation
- Remaining resources: Distribute among BE users fairly.
Resource allocation framework for heterogeneous network

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Clustering: Grouping of adjacent subcarriers.

Figure: (a) Subcarrier Allocation (b) Cluster Allocation
Clustering: Why?

- Adjacent subcarriers are correlated → similar SNR values.
- Reduction in feedback information.
- Reduction in the number of variables in allocation algorithms.
- Practical; Consistent with 802.16e (e.g., 2048 subcarriers divided into 32 subchannels).
Cluster Allocation Subproblem (CASP)

\[
\begin{align*}
\text{maximize} & \quad \sum_{i \in \{\text{BE Users}\}} V_{BE}(R_i) \\
\text{subject to:} & \\
\quad & R_i \geq Q_i, \quad i \in \{\text{HP Users}\} \\
\quad & R_i = \sum_{l=1}^{L} c_{i,l} z_{i,l}, \quad i \in \{\text{Users}\}, \quad l \in \{\text{Clusters}\} \\
\quad & \sum_{i=1}^{M} z_{i,l} = 1, \quad z_{i,l} \in [0,1]
\end{align*}
\]

- \(V_{BE}(\cdot)\) BE user utility function
- \(Q_i\) QoS demand of \(i\)-th HP user
- \(c_{i,l}\) Capacity of \(l\)-th cluster on user-\(i\)

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Resource Allocation in Heterogeneous OFDMA Networks
Utility Function

Utility Function: User Satisfaction with supplied Data Rate.

- maximize $\sum_{i \in \text{BE Users}} V_{BE}(R_i) \iff$ Fair resource allocation
- BE user psychology: User satisfaction $\uparrow$ with supplied rate, reaches saturation.
- Traditional approach: log utility function.
- Piecewise linear function can also be used.
Solution of CASP using Linear Programming (LP)

- Piecewise linear utility function: Converts CASP into LP

![Graph showing the conversion of CASP to LP using piecewise linear utility function](image)
CASP Algorithm II : Partial Dual Decomposition Method

- **Objective**:
  - Break a bigger problem into smaller subproblem → achieve scalability.
  - Solve each smaller subproblem in parallel/sequential manner.

- **Used in Network Utility Maximization** problem [Kelly 97], [Chinag, Low, Calderbank, Doyle 07], [Palomar 07] etc.

- **Take a partial Lagrangian wrt. the complicating constraint** \( \sum_{i=1}^{M} z_{i,l} \) as

\[
\mathcal{L}(R_i, z_{i,l}, v_l) = \sum_{i \in \mathcal{B}} \left[ -V_{BE}(R_i) + \sum_{l=1}^{L} v_l z_{i,l} \right] + \sum_{i \in \mathcal{H}} \left[ \sum_{l=1}^{L} v_l z_{i,l} \right] - \sum_{l=1}^{L} v_l
\]

- **Partial dual function**: \( \inf_{R_i,z_{i,l}} \mathcal{L}(R_i, z_{i,l}, v_l) \) is

\[
g(v_l) = \sum_{i \in \mathcal{B}} \left[ \inf_{R_i,z_{i,l}} \left\{ -V_{BE}(R_i) + \sum_{l=1}^{L} v_l z_{i,l} \right\} \right] + \sum_{i \in \mathcal{H}} \left[ \inf_{z_{i,l}} \left\{ \sum_{l=1}^{L} v_l z_{i,l} \right\} \right] - \sum_{l=1}^{L} v_l
\]
CASP Algorithm II: Partial Dual Decomposition Method

BE User Subproblem: \( i \in \{\text{BE Users}\} \)

\[
\begin{align*}
\text{minimize} & \quad - V_{\text{BE}}(R_i) + \sum_{l=1}^{L} v_l z_{i,l} \\
\text{subject to:} & \\
R_i &= \sum_{l=1}^{L} c_i[l] z_{i,l} \\
z_{i,l} &\in [0, 1] \quad l = 1, \ldots, L
\end{align*}
\]

HP User Subproblem: \( i \in \{\text{HP Users}\} \)

\[
\begin{align*}
\{\tilde{z}_{i,l}\} &\triangleq \arg\min_{z_{i,l}} \sum_{l=1}^{L} v_l z_{i,l} \\
\text{subject to:} & \\
\sum_{l=1}^{L} c_i[l] z_{i,l} &\geq R_i \\
z_{i,l} &\in [0, 1] \quad l = 1, \ldots, L
\end{align*}
\]
CASP Algorithm II : Partial Dual Decomposition Method

BE User Subproblem : \( i \in \{ \text{BE Users} \} \)

\[
\begin{align*}
\text{minimize} \quad & -V_{BE}(R_i) + \sum_{l=1}^{L} v_l \, z_{i,l} \\
\text{subject to:} \quad & R_i = \sum_{l=1}^{L} c_{i[l]} \, z_{i,l} \\
& z_{i,l} \in [0, 1] \quad l = 1, \ldots, L
\end{align*}
\]

HP User Subproblem : \( i \in \{ \text{HP Users} \} \)

\[
\begin{align*}
\{\bar{z}_{i,l}\} = \arg \min_{z_{i,l}} \sum_{l=1}^{L} v_l \, z_{i,l} \\
\text{subject to:} \quad & \sum_{l=1}^{L} c_{i[l]} \, z_{i,l} \geq R_i \\
& z_{i,l} \in [0, 1] \quad l = 1, \ldots, L
\end{align*}
\]

Dual Problem :

\[
\begin{align*}
\text{maximize} \quad & g(v_l) \\
= \quad & \text{maximize} \left[ \sum_{i \in B} \left\{ -V_{BE}(\bar{R}_i) + \sum_{l=1}^{L} v_l \, \bar{z}_{i,l} \right\} + \sum_{i \in H} \left\{ \sum_{l=1}^{L} v_l \, \bar{z}_{i,l} \right\} - \sum_{l=1}^{L} v_l \right]
\end{align*}
\]
Partial Dual Decomposition

- Solution of the Dual Problem: Subgradient Method
- Iteration Update: $v_l(t+1) = v_l(t) + \alpha(t) \left( \sum_{i=1}^{M} \tilde{z}_{i, l} - 1 \right)$ for $l = 1, \ldots, L$

Diagram:

1. Initialize / Update Dual Variables
2. BE User Subproblem
3. HP User Subproblem
4. Projection of Variables
5. Duality Gap $< \varepsilon$
6. Optimal Solution
Power Allocation Subproblem (PASP)

\[
\text{maximize} \quad \sum_{i \in B} V_{BE}(R_i)
\]

subject to:

- HP constraints set: \ldots
- BE constraints set: \ldots
- Total Power constraint: \[
\left[ \sum_{i \in H} \sum_{k=1}^{K} p_{i,k} x_{i,k} \right] + \left[ \sum_{i \in B} \sum_{k=1}^{K} p_{i,k} x_{i,k} \right] \leq P_{total}
\]
Power Allocation Subproblem (PASP)

\[
\begin{align*}
\text{maximize} & \quad \sum_{i \in B} V_{BE}(R_i) \\
\text{subject to:} & \\
\text{HP constraints set:} & \cdots \\
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\end{align*}
\]

**HP PASP:**

\[
\begin{align*}
\text{minimize} & \quad t_{HP} \\
\text{subject to:} & \\
\text{HP Constraints set:} & \cdots \\
\sum_{i \in H} \sum_{k=1}^{K} p_{i,k} x_{i,k} & \leq t_{HP} \\
t_{HP} & \leq P_{total}
\end{align*}
\]

**BE PASP:**

\[
\begin{align*}
\text{maximize} & \quad \sum_{i \in B} V_{BE}(R_i) \\
\text{subject to:} & \\
\text{BE constraints set:} & \cdots \\
\sum_{i \in B} \sum_{k=1}^{K} p_{i,k} x_{i,k} & \leq P_{total} - t_{HP}
\end{align*}
\]
Power Allocation Subproblem (PASP) : Intuition

- **HP PASP**: Use minimum power to satisfy the QoS demand of all HP users.
- **BE PASP**: Allocate remaining powers among BE users to maximize total utility.
Power Allocation Subproblem (PASP) : Algorithm

**HP PASP:** Use modified successive bit allocation algorithm to determine $p_{i_{\text{min}}}$ for all HP users.

**BE PASP:** Already solved in literature [Song, Li 05] - II etc.

**Successive Bit Allocation Algorithm:**

- Assign bits and corresponding power successively.
- At each assignment, subcarrier that requires least additional power to employ next higher modulation level is selected.
- **Modified stopping criteria:** assignment ends when QoS requirement is fulfilled.
Success Rate: % of total HP users’ QoS satisfied
Average utility of BE users

10 users, 512 subcarrier OFDMA: Success Rate

![Graph showing the success rate (%) vs. SNR (dB) for different admission control methods.]

- **CASP-II** (heuristic admission control)
- **CASP-I** (heuristic admission control)
- **CASP-I** (exhaustive admission control)
- **PASP**

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Resource Allocation in Heterogeneous OFDMA Networks
10 users, 512 subcarrier OFDMA : Average Utility

![Graph showing Average BE User Utility vs SNR (dB) for different allocation subproblems.

- CASP − II (heuristic admission control)
- CASP − I (heuristic admission control)
- CASP − I (exhaustive admission control)
- PASP

Success Rate : % of total HP users’ QoS satisfied
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Resource Allocation in Heterogeneous OFDMA Networks
Clustering Effect on a 512 subcarrier OFDMA Network Performance

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Resource Allocation in Heterogeneous OFDMA Networks
Joint Admission Control and Resource Allocation

Admission Control: Controls HP user admission into the network.

- Traditionally, considered separately from resource allocation.
- Admission control depends on
  - Available network resource
  - User channel condition
- Heterogeneous Network: Joint Admission Control and Resource Allocation

PASP admission control: two step approach

- Determine $p_{i\text{min}}$ for all HP users
- Allocate power to a subset of HP users $\mathcal{N}$ such that $|\mathcal{N}|$ is maximized and $\sum_{i \in \mathcal{N}} p_{i\text{min}} \leq P_{\text{total}}$
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Admission Control in CASP

Removal of min cardinality IIS (Irreducible Infeasible Set) set cover from the QoS constraints set.

▶ NP-hard problem
▶ Elastic variables $e_i$ in LP
▶ Minimize $\sum_{i \in \mathcal{H}} e_i$

Resource Allocation in Heterogeneous OFDMA Networks
Admission Control : Simulation Result

Figure: Joint Admission Control and Resource Allocation.
Conclusion

- A new framework: heterogeneous network
  - Clustering based LP
  - Dual Decomposition

- Joint admission control and resource allocation.
  - Elastic LP
Thank You