Technical Presentation:

Radio Engineering of Relay-Based OFDMA Networks

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Joint work with Ma Maode, Marceau Coupechoux and Philippe Godlewski
Outline of Topics

1. Introduction
2. State of the Art
3. My Contribution
Why Relaying?

- IMT-Advanced demanding requirements for 4G systems [1]

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downlink peak rate (low mobility)</td>
<td>1 Gbit/sec</td>
</tr>
<tr>
<td>Downlink peak rate (high mobility)</td>
<td>100 Mbit/sec</td>
</tr>
<tr>
<td>Data rate bw any 2 points</td>
<td>100 Mbit/sec</td>
</tr>
<tr>
<td>Roaming across networks</td>
<td>Seamless</td>
</tr>
</tbody>
</table>

- Need for ubiquitous coverage and uniform data rate [2]

- BS densification too expensive [3]
Relay Nodes: Definition and Network Structure

- D&F devices [4]
- Lower costs [5]
  - Single omni-directional antenna
  - Smaller (f.ex. put on lamppost)
- Multiple access scheme: OFDMA [2]
Relaying

- Energy savings
  - MH communication: reduced power consumption
- RRM: Simultaneous/division mode of operation
- Strong interf. from eNB
  - Literature: division mode of operation

![Graph showing received power from eNB and RN](image)
Resource Partitioning: how to assign time-freq. resources

- Strong interference from eNB ⇒ AL - DL - RL time-frequency separation
  - Time relaying (case a))[6]
  - Frequency relaying (case b))[6]
  - Hybrid time/frequency relaying schemes

Variability of RP:

1. **Static RP**: RP fixed bw frames
2. **Dynamic RP**: RP changes bw frames
Static Resource Partitioning

- RP based on average network performance
  
  \[ \bar{R}_{AL} = B_{AL}E \left[ \log (1 + SINR_{AL}) \right] \]

Implementation

- RP derived by imposing constraints on frame structure (example from [7]):
  
  1. Fairness among UE
     
     \[ \frac{\bar{R}_{AL}}{N_{AL}} = \frac{\bar{R}_{DL}}{N_{DL}} \]
  
  2. Multihop feasibility

     \[ B_{AL}E \left[ \log (1 + SINR_{AL}) \right] = B_{RL}E \left[ \log (1 + SINR_{RL}) \right] \]

  3. Total available band

     \[ B_{AL} + B_{DL} + B_{RL} = B_{TOT} \]

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple RP approach</td>
<td>No optimal resources use</td>
</tr>
<tr>
<td>Cheaper network hardware</td>
<td></td>
</tr>
</tbody>
</table>
Dynamic Resource Partitioning

- Possible alternative [8]: control system approach

- Control variables: RP data
- Feedback: Ue satisfaction
- Target: maximization UE satisfaction.

\[
\tilde{Z}[t] = \frac{T - 1}{T} \tilde{Z}[t - 1] + \frac{1}{T} Z[t - 1] \]  

(1)

- Exponential average to avoid high variability of partitioning
Dynamic Resource Partitioning

- Overall system can be written as:

\[ x[t] = Ax[t - 1] + Bu[t - 1] \]  

(2)

- Solution chosen: linear quadratic-optimal controller

- Results:
  - Higher UE throughput
  - Uniform UE throughput

<table>
<thead>
<tr>
<th><strong>Pros</strong></th>
<th><strong>Cons</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptability wrt load, UE pos., etc...</td>
<td>Higher computat. compl.</td>
</tr>
<tr>
<td>Optimization of resources allocation</td>
<td>More complex hardware</td>
</tr>
</tbody>
</table>
Relay Selection and Resource Scheduling

Definitions

- Relay selection (in-cell routing) [2]: how to associate UE with serving stations
- Resource scheduling: how to assign station resources to served UE

Implementations

1. Disjoint R&S: Relay selection separated from scheduling
   - In-cell routing strategies: nearest server, best server, best SINR, ...
   - Resources scheduling: single-hop network methods (e.g. PFS [9])

2. Joint R&S: Joint relay selection and resource scheduling
   - Find best combination of UE serving nodes and resource scheduling at once
   - Implemented as maximization of a functional over all combinations (e.g. [10])
Joint RN Selection and Scheduling: Example [10]

- Queue-aware: improve fairness w/o throughput penalty
  - Highest rate subchannels to longest queues ⇒ Cell load balance, stable queue length, fairness
- Quality Functional: Demand for each subcarrier $n$, for each node $m$-UE $k$ link:
  \[ D_{n,m \rightarrow k} = R_{m,k,n}Q^m_k \]
  - $R_{m,k,n}$: Rate on subchannel $n$ for the link bw node $m$ and UE $k$
  - $Q^m_k$: UE $k$ buffer queue length at node $m$.
- **Target**: maximization of **sum demand** on all links, nodes and UE
  ⇒ Cell load balance, stable queue length, fairness
Joint Routing and Scheduling: Example [10]

- Subchannels assignment: maximization of sum demands:

\[
D_s = \max_{\rho, \gamma} \left\{ \sum_{n=1}^{N} \sum_{m=0}^{M} \sum_{k=1}^{K} \rho_{m,k,n} D_{n,m \rightarrow k} + \sum_{n=1}^{N} \sum_{m=1}^{M} \gamma_{0,m,n} D_{n,0 \rightarrow m} \right\}
\] (3)

- \( \rho_{m,k,n}, \gamma_{0,m,n} \): binary subch. assignment variables

- Maximization performed with constraints

- Queue-aware algorithm: throughput maximization
  - capacity \( \neq \) throughput (burst traffic nature)

- Maximization wrt all UE-node links, and subcarriers: high computational complexity
Disjoint vs Joint RN Selection and Scheduling

<table>
<thead>
<tr>
<th>Disjoint R&amp;S</th>
<th>Joint R&amp;S</th>
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</thead>
<tbody>
<tr>
<td><strong>Pros</strong></td>
<td><strong>Pros</strong></td>
</tr>
<tr>
<td>Simple nw management</td>
<td>Optimal performance wrt target</td>
</tr>
<tr>
<td>Low overheads</td>
<td>Performance stable in time [10]</td>
</tr>
<tr>
<td>sub-optimal solution</td>
<td>Performance stable wrt UE position [2]</td>
</tr>
<tr>
<td>⇒ performance loss</td>
<td>⇒ Ubiquitous coverage</td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td><strong>Cons</strong></td>
</tr>
<tr>
<td></td>
<td>Very high computational complexity</td>
</tr>
<tr>
<td></td>
<td>Completely centralized processing</td>
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</table>
Relaying in LTE-Advanced (3GPP)

- RN are D&F devices [11].

- Backhaul link is wireless.

- Type 1 RN: Non-transparent. Transmits the common reference signal and control information from the eNB (coverage extension). It appears as a separate cell.

- Type 2 RN: Transparent. Does not transmit reference signals and control informations. Used for achieving multipath diversity and transmission gains (capacity extension).
Resource Partitioning in LTE-Advanced

- Need for backward compatibility

- Relay Link resources obtained by configuring part of the subframes as Multicast/Broadcast Single-Frequency Network (MBSFN) subframes.

- Dynamic RP, but only partially flexible
Store-and-Forward Type 2 Uplink RN

- Used for uplink coverage enhancement (cell-edge UE)
- RN stores uplink PUSCH transmission
- Forward to eNB in case of HARQ NAK

Figure: Uplink store-and-forward RN HARQ scheme (from [12])
Simulations results: SINR spatial distribution [13]
Simulations results: $N_{RN}$ vs Desired Capacity [13]

$$N_{RN} = \alpha (E[C] - C_0)$$ (4)
Long-Term Downlink Power Optimization

Optimal solution:
- frame-by-frame and node-by-node power allocation
- joint resource and power allocation

Drawbacks:
- High complexity
- High protocol overheads

Suboptimal solution:
- Fixed eNB and RN transmit power
- Power allocation independent from scheduling
Long-Term Downlink Power Optimization

Target: maximize UE average spectral efficiency

- Assumption: UE served by node guaranteeing highest received power [14] → av. spectral efficiency depends on nodes tx power
- Assumption: eNB and RN transmit on orthogonal resources
- Assumption: SIR good channel quality metric

- Shadowing has small influence on peak spectral efficiency
  - Simplified model

- 'Brute force' Maximization long
  - Geometrical approach faster
Long-Term Downlink Power Optimization

**Strategy:** match *SIR area* of nodes with *serving area*.

- **Serving area:** circle
- **SIR area:** ?

Mathematically:

\[
\argmax_{P_{RN}} \frac{1}{A_c} \int_{A_c} \log_2(1 + SIR(z, P_{RN})) \, dz \quad (5)
\]

Equivalent problem:

\[
\argmin_{P_{RN}} \frac{1}{A_c} \int_{D_i} (C_H(z) - C(z, P_{RN})) \, dz \quad (6)
\]
**Strategy**: match *SIR area* of nodes with *serving area.*

- **Serving area**: circle
- **SIR area**: ?

![Diagram showing serving and SIR areas with power levels](image)

\[
\text{Equivalent problem:} \quad \argmin_{P_{RN}} \frac{1}{A_c} \int_{D_i} (C_H(z) - C(z, P_{RN}))dz \quad (6)
\]

\[
\argmax_{P_{RN}} \frac{1}{A_c} \int_{A_c} \log_2(1 + SIR(z, P_{RN}))dz \quad (5)
\]
**Long-Term Downlink Power Optimization**

**Strategy:** match *SIR area* of nodes with *serving area*.

- Serving area: circle
- *SIR area:* ?

\[ \pi_{i,j}(P_2) \]

\[ \pi_{i,j}(P_3) \]

\[ D_i \]

\[ P_1 < P_2 < P_3 < P_4 < P_5 < P_6 \]

\[ \text{Equivalent problem:} \]

\[ \argmax_{P_{RN}} \frac{1}{A_c} \int_{A_c} \log_2(1 + SIR(z, P_{RN})) \, dz \]  

(5)

\[ \argmin_{P_{RN}} \frac{1}{A_c} \int_{D_i} (C_H(z) - C(z, P_{RN})) \, dz \]  

(6)

\[ I \]

\[ P_3 < P_{RN}^* < P_5 \]
**Long-Term Downlink Power Optimization**

**Strategy:** match *SIR area* of nodes with *serving area*.

- Serving area: circle
- *SIR area:* ?

\[
\pi_{i,j}(P_4) \\
\gamma_{i,j} \\
\pi_{i,j}(P_3) \\
\text{RN}_j \\
\times \\
\text{C}(P_4) \\
\mathcal{D}_i
\]

\[
P_1 < P_2 < P_3 < P_4 < P_5 < P_6
\]

\[
\argmax_{P_{RN}} \frac{1}{A_c} \int_{A_c} \log_2(1 + \text{SIR}(z, P_{RN})) dz \tag{5}
\]

Equivalent problem:

\[
\argmin_{P_{RN}} \frac{1}{A_c} \int_{\mathcal{D}_i} (C_H(z) - C(z, P_{RN})) dz \tag{6}
\]
Long-Term Downlink Power Optimization

**Strategy**: match SIR area of nodes with serving area.

- Serving area: circle
- SIR area: ?

\[
\begin{align*}
\pi_{i,j}(P_5) & \quad \pi_{i,j}(P_4) \\
D_i & \\
\gamma_{i,j}
\end{align*}
\]

\[
P_1 < P_2 < P_3 < P_4 < P_5 < P_6
\]

**Equivalent problem**:  
\[
\argmin_{P_{RN}} \frac{1}{A_c} \int_{A_c} \log_2(1 + SIR(z, P_{RN})) dz 
\]

(5)
**Long-Term Downlink Power Optimization**

**Strategy:** match *SIR area* of nodes with *serving area*.

- **Serving area:** circle
- **SIR area:** 

\[
\pi_{i,j}(P_6) \\
\pi_{i,j}(P_5) \\
\mathcal{D}_i \\
\gamma_{i,j} \\
\text{RN } j \quad \text{C}(P_6) \\
\text{RN } j \quad \text{C}(P_5) \\
P_1 < P_2 < P_3 < P_4 < P_5 < P_6
\]

\[
\argmax_{P_{RN}} \frac{1}{A_c} \int_{A_c} \log_2(1 + \text{SIR}(z, P_{RN})) \, dz \quad (5)
\]

Equivalent problem:

\[
\argmin_{P_{RN}} \frac{1}{A_c} \int_{D_i} (C_H(z) - C(z, P_{RN})) \, dz \quad (6)
\]

\[
I \\
P_3 < P_{RN^*} < P_5
\]

\[
P_1, P_2, P_4, P_5, P_6
\]
Long-Term Downlink Power Optimization

How to find $P_3$ and $P_5$

- Find a set of points $\{p_{n}^{i,j}\}_{n\in[1,N_{i,j}]} \in \gamma_{i,j}$
- For each $p_{n}^{i,j} = (x_{n}^{i,j}, y_{n}^{i,j})$, we find the associated RN power $\tilde{P}_{RN}(p_{n}^{i,j})$ and store it in $\mathcal{P}(\gamma_{i})$
- We approximate $P_3 = \min \mathcal{P}(\gamma_{i})$, $P_5 = \max \mathcal{P}(\gamma_{i})$.

<table>
<thead>
<tr>
<th>$N$</th>
<th>$P_{RN}^*(f)$</th>
<th>$P_{RN}^*(2)$</th>
<th>$P_{RN}^*(b)$</th>
</tr>
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<tbody>
<tr>
<td>2</td>
<td>38.5</td>
<td>40.6</td>
<td>39.9</td>
</tr>
<tr>
<td>3</td>
<td>33.9</td>
<td>37.7</td>
<td>37.7</td>
</tr>
<tr>
<td>4</td>
<td>29.7</td>
<td>35.2</td>
<td>35.4</td>
</tr>
<tr>
<td>5</td>
<td>30.4</td>
<td>32.7</td>
<td>33.6</td>
</tr>
<tr>
<td>6</td>
<td>31.7</td>
<td>32.3</td>
<td>32.1</td>
</tr>
<tr>
<td>7</td>
<td>28.8</td>
<td>30.3</td>
<td>30.5</td>
</tr>
<tr>
<td>8</td>
<td>27.8</td>
<td>29.7</td>
<td>29.1</td>
</tr>
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<table>
<thead>
<tr>
<th>$d/D$</th>
<th>$P_{RN}^*(f)$</th>
<th>$P_{RN}^*(2)$</th>
<th>$P_{RN}^*(b)$</th>
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<tbody>
<tr>
<td>1/10</td>
<td>34.0</td>
<td>31.3</td>
<td>30.7</td>
</tr>
<tr>
<td>2/10</td>
<td>36.2</td>
<td>38.3</td>
<td>38.9</td>
</tr>
<tr>
<td>3/10</td>
<td>38.4</td>
<td>38.6</td>
<td>38.7</td>
</tr>
<tr>
<td>4/10</td>
<td>38.5</td>
<td>38.4</td>
<td>38.2</td>
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<tr>
<td>5/10</td>
<td>38.1</td>
<td>38.0</td>
<td>37.9</td>
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References II


reuse one frequency planning for two-hop cellular system with
fixed relay nodes.

"Dynamic Radio Resource Management for OFDMA-Based
Relay Enhanced Cellular Network".

Falconer Y.-Doo Kim W. Shin E. Kim.
Fairness-aware joint routing and scheduling in OFDMA-based
cellular fixed relay networks.

