Energy Minimization in Load Coupled Heterogeneous Networks

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A joint work with C. K. Ho (I²R), D. Yuan, and L. Lei (Linköping University, Sweden)
Two Primary Technical Challenges for 5G Network

1000X increase in capacity

1000x reduction in energy consumption
Candidate Technologies

- Small cells and network densification
- Massive MIMO
- mmWave
- Spectrum aggregation
- Large-scale distributed antenna systems
- Cloud RAN
- Non-orthogonal multiple access (NOMA)
- WiFi offloading
- …
Candidate Technologies

• **Small cells and network densification**
• Massive MIMO
• mmWave
• Spectrum aggregation
• Large-scale distributed antenna systems
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• **WiFi offloading**
• …
Our Model: A Heterogeneous Network with 2-Tier Cellular Network + WiFi

- Macro-cell eNB
- Small-cell eNB
- WiFi AP
- Users
Our Model: A Heterogeneous Network with 2-Tier Cellular Network + WiFi

• **Load** $x_i$
  - measures the fractional usage of resource in cell $i$
  - In LTE systems, it can be interpreted as the expected fraction of the time-frequency resources scheduled to deliver data.

• **Demand** $d_j$
  - Individual user’s rate requirement
  - May be fulfilled by the cellular, or WiFi, or both networks

Load-coupled network
Load Coupled Networks

- Frequency reuse couples the neighbouring cells in load and interference

- A load-coupled interference model [Siomina2009]

\[
\text{SINR}_{ij}(x) = \frac{p_i g_{ij} x_j}{\sum_{k \in N \setminus \{i\}} p_k g_{kj} x_k + \sigma^2}
\]

- To satisfy rate demand \( d \), a non-linear load/power coupling equation (NLCE/NLPE) can be established:

\[
x = f(x; d, p) \iff p = h(p; x, r)
\]

- Inter-cell interference, \( x_k \) being the load of cell \( k \)

- Small cell and macro-cell are load-coupled through the above model

- WiFi network is load-coupled within itself

Data Offloading in Load Coupled Networks – Utility Maximization

\[
\max_{\tilde{d}, \tilde{d}'} \sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{J}_i} k_{ij} U(\tilde{d}_i) + k'_{\pi(i,j)} U(\tilde{d}'_{\alpha(i,j)})
\]

s.t. \( \tilde{d} \in \mathcal{F} \triangleq \{\tilde{d} > 0 : r(\Lambda(\tilde{d})) < 1\} \)

\( \tilde{d}' \in \mathcal{F}' \triangleq \{\tilde{d}' > 0 : r(\Lambda'(\tilde{d}')) < 1\} \)

\( \tilde{d}_i + \tilde{d}_{\alpha(i,j)} < D_{ij}, \forall j \in \mathcal{J}_i, i \in \mathcal{N} \)

\( \Lambda(\hat{d}) \geq 0 \) be the \( n \)-by-\( n \) real matrix with the \((i, k)\)th
element

\[
\lambda_{i k} = \begin{cases} 
0, & \text{if } i = k; \\
\sum_{j \in \mathcal{J}_i} g_{k,j} d_{i,j} / g_{i,j}, & \text{if } i \neq k
\end{cases}
\]

for \( 1 \leq i \leq n \) and \( 1 \leq k \leq n \).

- Two utility functions:
  - LOG: \( U(d) = \log(d) \),
  - DLOG: \( U(d) = \log(\log(1 + d)) \)

- Theorem: For LOG and DLOG utility functions, the problem is convex. Hence standard convex optimization techniques apply.
Data Offloading in Load Coupled Networks – Energy Minimization

\[
\min_{p>0,r>0} \sum_{i=1}^{n} x_i p_i \\
\text{s.t. } x = f(x; p; r), \quad 0 < x \leq 1 \\
r \geq d_{\text{min}}.
\]

• A load is implementable if the corresponding power exists.

• Theorem: If full load \( x = 1 \) is implementable, then the optimal solutions are \( r^* = d_{\text{min}} \), and \( p^* \) is such that \( x^* = 1 \). Otherwise, no solution exists.

• Thus \( 1 = f(1; d_{\text{min}}, p^*) \).

Data Offloading in Load Coupled Networks – Energy Minimization: Simulation Scenario

• Based on publicly available data provided by the European MOMENTUM project

• Channel-gain data derived from a path-loss model and calibrated with real measurements of signal strength in the network of a sub-area of Alexanderplatz in the city of Berlin

• Path-loss model takes into account the terrain and environment, pre-optimized antenna configuration (height, azimuth, mechanical tilt, electrical tilt)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Service area size</td>
<td>7500 × 7500 m²</td>
</tr>
<tr>
<td>Pixel resolution</td>
<td>50 × 50 m²</td>
</tr>
<tr>
<td>Number of sites</td>
<td>50</td>
</tr>
<tr>
<td>Number of cells</td>
<td>148</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>22500</td>
</tr>
<tr>
<td>Number of users</td>
<td>1480</td>
</tr>
<tr>
<td>Thermal noise spectral density</td>
<td>-145.1 dBm/Hz</td>
</tr>
<tr>
<td>Total bandwidth per cell</td>
<td>4.5 MHz</td>
</tr>
<tr>
<td>Bandwidth per resource unit</td>
<td>180 kHz</td>
</tr>
<tr>
<td>Tolerance $\epsilon$ in IAP</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Initial power vector $p$ in IAP</td>
<td>1 W</td>
</tr>
</tbody>
</table>
Sum Transmission energy vs user's rate demand
Data Offloading in Load Coupled Networks – Energy Minimization: Numerical Results II

Sum transmission energy vs cell load
Summary and Discussions

• Introduced a load coupling model which takes into account the inherent coupling relation among the cells

• Considered two problems based on the load coupling model in a heterogeneous network
  – Problem 1: utility maximization for data offloading
    • demand offloading more important than power allocation
    • problem convexity depends on how utility function emphasizes fairness
  – Problem 2: energy minimization
    • full load is optimal
    • optimal power can be obtained via an iterative method

• Energy minimization problem needs to be further looked into with basestation on-off and non-ideal power amplifier effects
Thank you!

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