Resource Allocation in Energy-constrained Cooperative Wireless Networks

Lin Dai
City University of Hong Kong
Outline

• Resource Allocation in Wireless Networks
  – Tradeoff between Fairness and Throughput

• Fairness and Throughput in Energy-constrained Cooperative Networks

• Optimal Resource Allocation in Energy-constrained Cooperative Networks
Wireless Network

• **Medium** - electromagnetic wave
  - fading channel
  - shared spectrum

• **Terminal** - cellphone, PDA, laptop, ...
  - portable
  - not so “smart”

• Increasing demand for a large variety of services
  - Voice, data, video, …

• Limited resources
  - Bandwidth, power, processing capability…
Optimal Resource Allocation

Maximize

$$\sum_{k=1}^{K} T_k (\cdot)$$

Subject to

$$S_k (\cdot) < q_k, \quad k = 1, \ldots, K$$

**Single User**
- Power allocation
- Antenna selection
- Subcarrier allocation
- ……

**K-User**
- Throughput maximization vs. Fairness
  - Effort fairness:
    - Fairness in allocating the resources
  - Outcome fairness:
    - Fairness in utilizing the resources
Example: Opportunistic Transmission

- Allocate different time slots to different users.
- Objective: Maximize \( \sum_{k=1}^{K} T_k(\cdot) \)

- Total throughput can be maximized by always serving the user with the strongest channel.
- The more users, the higher throughput.

Multiuser Diversity
Opportunistic Transmission with Fairness Constraint

- Help the “poor” -- a disadvantaged user is scheduled when its instantaneous channel quality is high relative to its own average channel condition.

\[
\text{Maximize } \sum_{k=1}^{K} \log(T_k(\cdot))
\]
Tradeoff between Throughput and Fairness

Opportunistic Transmission without Fairness Constraint

Opportunistic Transmission with Fairness Constraint

There is always a tradeoff between fairness and throughput.
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Cooperative Networks

- Diversity gain: \( p_e \sim SNR^{-L} \)

- How to achieve diversity gain in wireless ad-hoc networks?

Node cooperation: more relay nodes, higher cooperative diversity gain.
Multiuser Cooperative Protocol

- Some node may have more chances to be relays.

Unfair!

Refuse to cooperate

Run out of energy soon
Fairness and Throughput in Energy-constrained Cooperative Networks

- **Effort fairness**: equal lifetime
  - \( k_1 \leq k_2 \) at any time slot \( t \)
  - More nodes: higher cooperative diversity gain
  - higher multiuser diversity gain

**Improved fairness may lead to throughput gains in energy-constrained cooperative networks.**
Network Model

• A wireless ad-hoc network with $K$ nodes
• Each node with an energy constraint of $E$

- Opportunistic transmission
Full Cooperative Protocol

- “Popular” nodes have more chances of acting as relays.
- They will run out of energy much faster than others.

Unfair
How to Improve Fairness?

- Power Reward – adopted by each node to evaluate the power contributed to and by other nodes.

\[
W_k \rightarrow W_k + P_j^k
\]

\[
W_k \rightarrow W_k - \Psi_k
\]

\[
\Psi_k = \sum_{j \in R_k} P_j^k
\]

- Resources required by each node should be no more than what it contributes to other nodes.

Power reward increases when node \( k \) acts as a relay.
Power reward decreases when node \( k \) employs other nodes as relays.
Fair Cooperative Protocol

• For each pair \((k, D(k))\), compare \(W_k\) and the sum relay power \(\Psi_k = \sum_{j\in R_k} P_j\)
  - If \(W_k \geq \Psi_k\), use relays for cooperation
  - Else, no cooperation.
  - Compute the possible throughput.

• Compare the throughput of all the pairs and select the maximal one.

• Update the power reward.

With a power reward:
• Nodes cannot continuously employ relays;
• Nodes will not continuously act as a relay.
Fairness Indicator

- Fairness Indicator: \( \zeta = \frac{T_{\text{min}}}{T_{\text{max}}} \)

- Equal lifetime: \( \zeta = 1 \)

- Let \( \zeta_d \) denote the fairness indicator of direct transmission
  \( \zeta_f \) full cooperative protocol
  \( \zeta_a \) fair cooperative protocol

- \( \zeta_d \leq \zeta_f \leq K^{v-1}, \quad 0 < v < 1 \)

- \( \zeta_a \to \frac{E[M_k]}{K}, \quad \text{as } K \to \infty \)
### Performance Comparison I: Fairness Indicator

<table>
<thead>
<tr>
<th>$K$</th>
<th>20</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct transmission $\xi_d$</td>
<td>0.2</td>
<td>0.11</td>
<td>0.08</td>
<td>0.06</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>Full Cooperation $\xi_f$</td>
<td>0.16</td>
<td>0.14</td>
<td>0.07</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Fair Cooperation $\xi_a$</td>
<td>0.31</td>
<td>0.34</td>
<td>0.35</td>
<td>0.41</td>
<td>0.48</td>
<td>0.48</td>
</tr>
</tbody>
</table>

$E[M_k]/K = 0.5$

<table>
<thead>
<tr>
<th>$E[M_k]/K$</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fair Cooperation $\xi_a$</td>
<td>0.32</td>
<td>0.45</td>
<td>0.48</td>
<td>0.66</td>
<td>0.87</td>
</tr>
</tbody>
</table>

$K = 250$

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Performance Comparison II: Lifetime

- Direct Transmission
- Full Cooperative Protocol
- FAP
- FAP-S
- FAP-R
- Fair Cooperative Protocol

Graph showing the number of nodes over time slots for different transmission protocols.
Aggregate Throughput

- Theorem 3 [Dai’09]: The aggregate throughput of an energy-constrained cooperative ad-hoc network with opportunistic transmission is given by

\[ C = \mu_1 \int_0^{T_{\text{max}}} \log_2 a(t) dt + \int_0^{T_{\text{max}}} \log_2 b(t) dt + \xi T_{\text{max}} + \left( \log_2 K - 1 \right) T_{\text{max}} + \nu T_{\text{max}} \]

- \( a(t) \): proportion of nodes competing for the channel
- \( b(t) \): proportion of nodes acting as relays in the relay region
- \( \mu_1 \ll 1 \)

- Full cooperation: \( C_f \approx \xi_f T_{\text{max}} + \left( \log_2 K - 1 \right) T_{\text{max}} + \nu T_{\text{max}} \)
- Fair cooperation: \( C_a \approx \xi_a T_{\text{max}} + \left( \log_2 K - 1 \right) T_{\text{max}} + \nu T_{\text{max}} \)

\( C_a > C_f \) because \( \xi_a > \xi_f \)
Performance Comparison III: Aggregate Throughput

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Optimal Resource Allocation

• **Resources:** energy & time slots

• **Objective**
  - Maximizing the total throughput
  - Fairness: equal lifetime & energy fairness

• **How to allocate?**
  - Energy allocation
  - Time-slots allocation
Energy Fairness

\(E^i_j\) denotes the energy that node \(j\) consumed in transmitting/relaying signals of node \(i\).

\[
\sum \begin{bmatrix}
E_1^1 & E_1^2 & \cdots & E_1^K \\
E_2^1 & E_2^2 & \cdots & E_2^K \\
\vdots & \vdots & \ddots & \vdots \\
E_K^1 & E_K^2 & \cdots & E_K^K 
\end{bmatrix}
\]

the total energy consumed by node 1:

\[e_1^C = \sum_{j=1}^{K} E_1^j\]

\[
\sum \begin{bmatrix}
E_1^1 & E_1^2 & \cdots & E_1^K \\
E_2^1 & E_2^2 & \cdots & E_2^K \\
\vdots & \vdots & \ddots & \vdots \\
E_K^1 & E_K^2 & \cdots & E_K^K 
\end{bmatrix}
\]

the total energy allocated to node 1:

\[e_1^A = \sum_{j=1}^{K} E_j^1\]

✓ Energy fairness:

\[e_i^A = e_i^C = E_{\text{total}} \Rightarrow \sum_{j=1}^{K} E_i^j = \sum_{j=1}^{K} E_j^i \]

\(i = 1, ..., K\)

Contribute more, gain more
Example: Two-node Cooperation

\[ \begin{bmatrix} E_1^1 & E_2^2 \\ E_2^1 & E_2^2 \end{bmatrix} \]

- Energy fairness requires:
  \[ E_1^1 + E_2^1 = E_2^2 + E_2^2 \]
  \[ E_1^1 + E_1^2 = E_2^1 + E_2^2 \]

- Suppose \(|h_1| > |h_2|\).
  \[ E_2^1 > E_2^2 \]

How to guarantee energy fairness?
To Cooperate or Not to Cooperate?

Node 1:
- State 1: Node 2 helps node 1;
- State 2: Node 1 transmits alone.

Node 2:
- Node 1 always helps node 2.
Multi-state Cooperation

• Define a cooperation Matrix $A$ with $a_{ij} = \frac{E_j^i}{e_j^A}$ ☞ $e_i^C = \sum_{j=1}^{K} E_j^i = \sum_{j=1}^{K} a_{ij} e_j^A$

$$
\begin{bmatrix}
e_1^C \\
e_2^C \\
\vdots \\
e_K^C
\end{bmatrix} = 
\begin{bmatrix}
a_{11} & a_{12} & \cdots & a_{1K} \\
a_{21} & a_{22} & \cdots & a_{2K} \\
\vdots & \vdots & \ddots & \vdots \\
a_{K1} & a_{K2} & \cdots & a_{KK}
\end{bmatrix} \cdot 
\begin{bmatrix}
e_1^A \\
e_2^A \\
\vdots \\
e_K^A
\end{bmatrix}
$$

$A$ should be a doubly-stochastic matrix!

• Divide cooperation into multiple states;
• At cooperation state $n=1,\ldots, N$, choose a relay set such that $A(n)$ is a doubly-stochastic matrix.

\[
\begin{align*}
\sum_{n=1}^{N} e_1^C(n) &= \sum_{n=1}^{N} A(n)e_1^A(n) = E_{total}\mathbf{1} \\
\sum_{n=1}^{N} e_1^A(n) &= E_{total}\mathbf{1}
\end{align*}
\]
Multi-state Cooperation

![Diagram showing multi-state cooperation with nodes 1, 2, 3, and 4 connected to a destination. Nodes are in states 1, 2, or 3, transitioning to different sets of states.]
Performance Comparison I: Aggregate Throughput

Nodes 2 and 3 run out of energy.
## Performance Comparison II: Fairness Performance

<table>
<thead>
<tr>
<th>Compared to Direct Transmission</th>
<th>Node 1</th>
<th>Node 2</th>
<th>Node 3</th>
<th>Node 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Increase in lifetime</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full</td>
<td>104%</td>
<td>-36%</td>
<td>-26%</td>
<td>74%</td>
</tr>
<tr>
<td>Multi-state</td>
<td>104%</td>
<td>104%</td>
<td>104%</td>
<td>104%</td>
</tr>
<tr>
<td><strong>Increase in throughput</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full</td>
<td>144%</td>
<td>-38%</td>
<td>-22%</td>
<td>90%</td>
</tr>
<tr>
<td>Multi-state</td>
<td>87%</td>
<td>55%</td>
<td>67%</td>
<td>76%</td>
</tr>
</tbody>
</table>

Open Issues

• Distributed implementation
  – Power reward + distributed access

• Generalization to multi-hop cooperative networks
  – Optimal framework
  – Routing and access protocol design
Thank you!

Any Questions?