Medium Access Control via Contention-Based Distributed Power Control

Themistoklis Charalambous
Automatic Control Lab
KTH

Ioannis Krikidis
ECE
University of Cyprus

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Outline of the talk

• Medium Access Control (MAC)
• Motivation
• Network and channel models
• Related work
• The CB-DCPC algorithm
  ▸ Description of the algorithm
  ▸ The back off protocol
• Performance evaluation
• Conclusions
Medium Access Control (MAC)

MAC: Part of the Data Link Layer
- **Purpose:** to manage access to the shared wireless medium. Responsible for resolving conflicts among different nodes for channel access.
- **Nodes:** decide when to access the channel, avoiding collisions and efficiently utilizing the bandwidth.

Classification of MAC protocols:

- **Contestion Based**
  - Random Access
  - Reservation/Collision resolution
- **Contention Free**
  - i.e. Transmission Scheduling (e.g., Token based, FDMA, CDMA, TDMA)
Motivation

• *Contention control*: distributed strategy to access and share the wireless channel.

• Study contention/interaction among wireless nodes.

• Design contention-based Medium Access Control algorithms using power control.

• Stabilize the network around a steady-state with reduced overhead communication, and with
  ▶ *fairness*
  ▶ *service differentiation*
  ▶ *efficiency*
Network model

- Planar network
- Half duplex transceivers, hence unidirectional links
- Omnidirectional antennae
Channel models

Graph-based models:
- Ideal model or Unit Disk Graph (UDG)
- Protocol model

Limitations:
- Define a set of interference edges (interference: binary and a local measure)
- Interference for far away nodes is not considered (substantial from several nodes)

Fading channel models:
- Geometrical Physical model
- Abstract Physical model

Limitations of the geometrical Physical model:
- Path loss between nodes constrained by their Euclidean coordinates
- Simplifying assumptions: isotropic users with no obstructions
We consider the *abstract* Physical Model where receivers experience *interference*:

\[ I_i = \sum_{j \neq i, j \in T} g_{ji}p_j + \nu \]

where
- \( g_{ij} \) is the channel gain on the link between transmitter \( i \) and receiver \( j \)
- \( p_i \) is the power level chosen by transmitter
- \( \nu \) is the variance of thermal noise at the receiver

The link quality is measured by the Signal-to-Interference-and-Noise-Ratio (SINR), given by

\[ \Gamma_i = \frac{g_{ii}p_i}{\sum_{j \neq i, j \in T} g_{ji}p_j + \nu} . \]

A transmission is successful (error free), if the SINR at the receiver is greater than the capture ratio, \( \gamma_i \):

\[ \frac{g_{ii}p_i}{\sum_{j \neq i, j \in T} g_{ji}p_j + \nu} \geq \gamma_i . \]
Feasibility of a network

The transmission condition can be written as

\[ p_i \geq \gamma_i \left( \sum_{j \neq i, j \in T} \frac{g_{ji}}{g_{ii}} p_j + \frac{\nu}{g_{ii}} \right) \]

In matrix form, for a network consisting of \( n \) communication pairs, \( \mathbf{p} \geq \Gamma G \mathbf{p} + \eta \)

where

\[ \Gamma = \text{diag}(\gamma_i) \]
\[ \mathbf{p} = \begin{pmatrix} p_1 & p_2 & \ldots & p_n \end{pmatrix}^T \]
\[ G_{ij} = \begin{cases} 0 & \text{if } i = j, \\ \frac{g_{ji}}{g_{ii}} & \text{if } i \neq j. \end{cases} \]
\[ \eta_i = \frac{\gamma_i \nu}{g_{ii}} \]

Let \( C = \Gamma G \), then \( (I - C) \mathbf{p} \geq \eta \). From Perron-Frobenius theorem, the following are equivalent statements:

1. There exists a vector \( \mathbf{p}^* \geq 0 \) (i.e. \( p_i > 0 \) for all \( i \)) such that \( (I - C) \mathbf{p} \geq \eta \).
2. \( (1 - C)^{-1} \) exists and is positive component-wise.
3. \( \rho(C) < 1 \).
Feasibility of a network

\[ g_{11} \quad g_{12} \quad g_{22} \]

\[ g_{21} \]

\[ S_1 \quad S_2 \quad R_1 \quad R_2 \]

\[ C_1 \quad C_2 \quad K, L \quad M \]

\[ g_{11} \quad g_{12} \quad g_{22} \]

\[ g_{21} \]

\[ S_1 \quad S_2 \quad R_1 \quad R_2 \]

\[ C_1 \quad C_2 \quad K, L \quad M \]

\[ g_{11} \quad g_{12} \quad g_{22} \]

\[ g_{21} \]

\[ S_1 \quad S_2 \quad R_1 \quad R_2 \]

\[ C_1 \quad C_2 \quad K, L \quad M \]
Related work

DCPC (no admission)

Characteristics:
- Constrained power control.
- If $p_{\text{updated}}>p_{\text{max}}$, then $p=p_{\text{max}}$.

Disadvantages:
- Aggravation of interference.
- System degradation with pairs.

If we try to minimize interference by setting $p=0$ if $p_{\text{updated}}>p_{\text{max}}$, then we may obtain oscillatory responses.

DPC/ALP

Characteristics:
- Enhanced SINR ($\delta \gamma_i, \delta>1$)
- Voluntary Drop-Out (VDO)
- Forced Drop-Out (FDO)

Disadvantages:
- Communication overhead.
- Monopoly of the channel by “weak” pairs.

If communication pair 3 ($S_3 \rightarrow R_3$) enters the network, then only pair 5 can potentially enter the network simultaneously.
The CB-DCPC algorithm

Back-off Time: $BT \sim E(\mu)$, $\mu = \mu_0 2^{-b}$

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**Initializations:**
- $p = p(0)$;
- Clock 1: $K_1 = 0$;
- Clock 2: $K_2 = 0$;
- Counter: $b = 0$;

---

- **START**

- **Initialization:**
  - $p = p(0)$;
  - Clock 1: $K_1 = 0$;
  - Clock 2: $K_2 = 0$;
  - Counter: $b = 0$;

---

- **p = 0**
  - **Yes**
  - **K_1 < BT**
    - **Yes**
      - $K_1 = K_1 + 1$;
    - **No**
      - **K_2 < ST**
        - **Yes**
          - Update $p$;
        - **No**
          - **$\Gamma/\gamma > \delta$**
            - **Yes**
              - $b = 0$;
            - **No**
              - $p = p(0)$;

---

- **p = 0;**
- Clock 1: $K_1 = 0$;
- Clock 2: $K_2 = 0$;
- Counter: $b = b + 1$;
- Back-off time: $BT$
On the stability of the CB-DCPC algorithm

So far...

- No theoretical justification of stability and performance of random multi-access protocols (e.g. ALOHA, IEEE 802.11), due to coupling between wireless nodes.
- They make use of the assumption are mutually independent (decoupling).
- Proved to be exact for a wide range of back off algorithms as the number of nodes grows.
- Also assume that all the nodes are synchronized and time is slotted.

In this work...

- Lifted all the assumptions (decoupling, synchronization, time slotted).
- Consider saturated nodes (no queues).
- We don’t consider stability issues: coupling between nodes is complex and it is difficult to model and analyze.
- Instead evaluate the performance for various networks.
Examples

Parameters evaluated:

- throughput of the network over time;
- average share of the network each communication pair acquires;
- average number of users in the network during simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired SINR ($\gamma_i$)</td>
<td>3</td>
</tr>
<tr>
<td>Proportionality constant ($k_i$)</td>
<td>0.25</td>
</tr>
<tr>
<td>Threshold ($\delta$)</td>
<td>0.95</td>
</tr>
<tr>
<td>Settling Time ($ST$)</td>
<td>30s</td>
</tr>
<tr>
<td>Initial expected Back off Time ($\mu_0^{-1}$)</td>
<td>200s</td>
</tr>
<tr>
<td>Noise ($\nu$)</td>
<td>0.04 W</td>
</tr>
</tbody>
</table>

Power and noise are measured in Watts, data rate in bits/s.
Example 1: Small-sized network [$\rho(C)<1$]
Example 2: Small-sized network $[\rho(C)>1]$

DCPC:

CB-DCPC:
Example 3: Medium-sized network \[\rho(C)=7.8>1\]

Average number of pairs connected: **1.8374** - better than algorithms that claim collision when two wireless nodes transmit simultaneously.

<table>
<thead>
<tr>
<th>Pair</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Proportion of time (%)</strong></td>
<td>0.287</td>
<td>0.138</td>
<td>0.131</td>
<td>0.327</td>
<td>0.232</td>
<td>0.218</td>
<td>0.054</td>
</tr>
</tbody>
</table>

Proportion of time each communication pair manages to meet the QoS requirement.
## Throughput for various networks

<table>
<thead>
<tr>
<th>Network Label</th>
<th>Number of Pairs</th>
<th>Average number of pairs</th>
<th>Maximum number of simultaneous transmissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>1.8374</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>1.3755</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>1.6219</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>1.9772</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>14</td>
<td>2.2036</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>14</td>
<td>2.3919</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>18</td>
<td>2.7558</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>19</td>
<td>2.8702</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>21</td>
<td>3.1780</td>
<td>7</td>
</tr>
<tr>
<td>10</td>
<td>28</td>
<td>3.7746</td>
<td>8</td>
</tr>
<tr>
<td>11</td>
<td>33</td>
<td>3.7744</td>
<td>9</td>
</tr>
</tbody>
</table>
Conclusions:

☐ CB-DCPC does not claim to improve the overall throughput - allows all nodes to participate in the network.

☑️ However, it improves fairness - allows nodes with high interference to attempt for a connection.

☐ No power dissipation with respect to total throughput

☑️ but minimizes power of individuals with respect to the share obtained in the wireless channel.

☐ Disadvantage: No link protection

☑️ but overhead communication for admission is eliminated, thus reducing the noise in the channel.
Thank you!