Power-Aware Cognitive Packet Networks

Erol Gelenbe
Dennis Gabor Chair

Ricardo Lent
Research Fellow

Department of Electrical and Electronic Engineering
Imperial College London, UK

IST 054 - Rome - April 2005
# Power-Aware Cognitive Packet Networks

**1. REPORT DATE**
DEC 2006

**2. REPORT TYPE**
N/A

**3. DATES COVERED**
-

**4. TITLE AND SUBTITLE**
Power-Aware Cognitive Packet Networks

**5. AUTHOR(S)**

**6. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
Department of Electrical and Electronic Engineering
Imperial College
London Exhibition Road
London SW7 2AZ
UK

**7. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSOR/MONITOR’S ACRONYM(S)**

**10. SPONSOR/MONITOR’S REPORT NUMBER(S)**

**12. DISTRIBUTION/AVAILABILITY STATEMENT**
Approved for public release, distribution unlimited

**13. SUPPLEMENTARY NOTES**
See also ADM202750. RTO-MP-IST-054, Military Communications (Les communications militaires), The original document contains color images.

**14. ABSTRACT**

**15. SUBJECT TERMS**

**16. SECURITY CLASSIFICATION OF:**
<table>
<thead>
<tr>
<th>a. REPORT</th>
<th>b. ABSTRACT</th>
<th>c. THIS PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>unclassified</td>
<td>unclassified</td>
<td>unclassified</td>
</tr>
</tbody>
</table>

**17. LIMITATION OF ABSTRACT**
UU

**18. NUMBER OF PAGES**
32

**19a. NAME OF RESPONSIBLE PERSON**

---

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18
Motivation

- Mobile nodes have limited energy
- In ad hoc routing, nodes rely on other nodes to deliver their messages
- Routing algorithms unaware of energy in nodes may shorten network lifetime
- Objective: Identify paths which intelligently distribute energy consumption
Cognitive Packet Networks

- Distributed algorithms that implements self-adaptation that searches QoS on demand
- Data flows are characterized by a QoS goal (one or more metrics)
- Packets can acquire network status (experience) as they move and this information can be exploited in future decision makings
- Different data flows can collaborate by sharing information
Information Collection and Storage

- Smart packets search for routes, dumb packets transport payload, both of which accumulate experience.
- Acknowledgements distribute experience.
- Information is stored in nodes along paths (mailboxes and RNNs).

<table>
<thead>
<tr>
<th>Header</th>
<th>Cognitive Map</th>
<th>Payload</th>
</tr>
</thead>
</table>

Routing Decisions

- At each hop, smart packets use a random neural network (RNN) with as many neurons as possible decisions (neighbors)
- The most excited neuron in steady-state gives the best decision for the packet
CNP in Ad Hoc Networks

- Neighboring information is acquired by listening to channel transmissions.
- Each packet reception updates a time-to-live value for the sending neighbor.
- Expired entries are removed.
- Smart packets may use broadcasts instead of unicast decisions (RNN/RL):
  - When not sufficient information is available at a node to construct a valid RNN (for example, when the node just entered the network).
  - With a small probability to avoid trapping the algorithm in local minima.
Random Neural Networks (RNN)

\[ \lambda^+(i) = \sum_j q_j w_{ji}^+ + \Lambda_i \]

\[ \lambda^-(i) = \sum_j q_j w_{ji}^- + \lambda_i \]

\[ q_i = \frac{\lambda^+(i)}{r(i) + \lambda^-(i)} ; 1 \leq i \leq N \]
Reinforcement Learning in RNN

- Measured performance (with respect to a particular routing goal) is used to adjust the weights of the RNN

- Example of routing goal:
  - $G = 1/D$; $D = \text{delay}$
Power-Aware Routing Goal

\[ G_{id} = P_p(n_i, n_d)D(n_i, n_d) + [1 - P_p(n_i, n_d)](T_o + G_i) \]

\[ P_p(n_i, n_d) = \prod_{j=i}^{d-1} P_n(n_{i+1})P_l(n_i, n_{i+1}) \]

\[ P_n(n_i) = \frac{B_i}{B_m} \]

Gid = goal at node i to destination d

Pp = path availability, To = time penalty, Bi = battery level

Pn, Pl = Probability of being available of nodes and links
Simulation

- NS-2
- 50 nodes divided into 2 populations:
  - 10 nodes (full battery charge = 2 hours operation)
  - 40 nodes (1/8 of full battery charge = 15 min)
- Area: 1500 x 500 m
- Assume random starting locations and random waypoint mobility at 2 m/s with no pause
- Traffic: 5 concurrent connections between nodes of the first population
- Smart packets sent at a ratio of 0.01
Number of nodes with no residual energy over time
Packets Delivered to Destination

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
Total DP and SP Transmitted

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
Total DP and SP Received

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
Summary

- CPN offers “best effort” QoS routing with smart packets both for wireline and wireless networks.
- A focused information collection mechanism allows smart packets make decisions towards the desired QoS target.
- Decisions can be tailored to enable energy-awareness, which in combination with delay gives balance between fast routes and an intelligent distribution of energy consumption in the network.
Power-Aware Cognitive Packet Networks

Erol Gelenbe
Dennis Gabor Chair

Ricardo Lent
Research Fellow

Department of Electrical and Electronic Engineering
Imperial College London, UK

IST 054 - Rome - April 2005
Motivation

- Mobile nodes have limited energy
- In ad hoc routing, nodes rely on other nodes to deliver their messages
- Routing algorithms unaware of energy in nodes may shorten network lifetime
- Objective: Identify paths which intelligently distribute energy consumption
Cognitive Packet Networks

- Distributed algorithms that implement self-adaptation that searches QoS on demand
- Data flows are characterized by a QoS goal (one or more metrics)
- Packets can acquire network status (experience) as they move and this information can be exploited in future decision makings
- Different data flows can collaborate by sharing information
Information Collection and Storage

- Smart packets search for routes, dumb packets transport payload, both of which accumulate experience.
- Acknowledgements distribute experience.
- Information is stored in nodes along paths (mailboxes and RNNs).

| Header | Cognitive Map | Payload |
Routing Decisions

- At each hop, smart packets use a random neural network (RNN) with as many neurons as possible decisions (neighbors)
- The most excited neuron in steady-state gives the best decision for the packet
CPN in Ad Hoc Networks

- Neighboring information is acquired by listening to channel transmissions.
- Each packet reception updates a time-to-live value for the sending neighbor.
- Expired entries are removed.
- Smart packets may use broadcasts instead of unicast decisions (RNN/RL):
  - When not sufficient information is available at a node to construct a valid RNN (for example, when the node just entered the network).
  - With a small probability to avoid trapping the algorithm in local minima.
Random Neural Networks (RNN)

\[ \lambda^+(i) = \sum_j q_j w^+_{ji} + \Lambda_i \]

\[ \lambda^-(i) = \sum_j q_j w^-_{ji} + \lambda_i \]

\[ q_i = \frac{\lambda^+(i)}{r(i) + \lambda^-(i)} \quad ; 1 \leq i \leq N \]
Reinforcement Learning in RNN

- Measured performance (with respect to a particular routing goal) is used to adjust the weights of the RNN.

- Example of routing goal:
  
  - $G = 1/D$ ; $D = \text{delay}$
Power-Aware Routing Goal

\[ G_{id} = P_p(n_i, n_d)D(n_i, n_d) + [1 - P_p(n_i, n_d)](T_o + G_i) \]

\[ P_p(n_i, n_d) = \prod_{j=i}^{d-1} P_n(n_{i+1})P_l(n_i, n_{i+1}) \]

\[ P_n(n_i) = \frac{B_i}{B_m} \]

G\(_{id}\) = goal at node \(i\) to destination \(d\)
P\(_p\) = path availability, \(T_o\) = time penalty, \(B_i\) = battery level
\(P_n, P_l\) = Probability of being available of nodes and links
Simulation

- NS-2
- 50 nodes divided into 2 populations:
  - 10 nodes (full battery charge = 2 hours operation)
  - 40 nodes (1/8 of full battery charge = 15 min)
- Area: 1500 x 500 m
- Assume random starting locations and random waypoint mobility at 2 m/s with no pause
- Traffic: 5 concurrent connections between nodes of the first population
- Smart packets sent at a ratio of 0.01
Number of nodes with no residual energy over time
Packets Delivered to Destination

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
Total DP and SP Transmitted

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
Total DP and SP Received

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
Summary

- CPN offers “best effort” QoS routing with smart packets both for wireline and wireless networks.
- A focused information collection mechanism allows smart packets to make decisions towards the desired QoS target.
- Decisions can be tailored to enable energy-awareness, which in combination with delay gives balance between fast routes and an intelligent distribution of energy consumption in the network.
Power-Aware Cognitive Packet Networks

Erol Gelenbe and Ricardo Lent
Department of Electrical and Electronic Engineering
Imperial College London
Exhibition Road
London SW7 2AZ
UK

This paper was received as a PowerPoint presentation without supporting text.