Anomalies in Optimal Rate-control and Scheduling Protocols for Cognitive Radio Networks

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Introduction

Cognitive Radio Networks are promising
- Large spectrum can meet growing capacity demands
- WiFi, Mesh, Sensor Networks based on CRNs

But, large spectrum $\neq$ large capacity to end-applications
- Primary user activities
- Resource allocation among secondary nodes

Paper focus: How do we design and realize efficient protocols?
How do we design and realize efficient protocols?

Two broad categories:

- **Heuristic protocols**: Fast design cycle, low-complexity
- **Theoretical models**: Systematically formulate, derive insights

Well-known theoretical methodology: Generalized Network Utility Maximization (GNUM)

- Formulate optimal network models
- Derive optimal protocols, network layers
- Demonstrated in real-systems (e.g. FAST-TCP)
Contribution

Varieties of GNUM formulations have been studied in CRN
- Power-control, Scheduling, etc
- Joint optimization of source-rate, routing and scheduling

Paper focus:
- Can we realize Joint source-rate, routing and scheduling in systems?
- What are the anomalies when translating theory into systems?

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Joint Source-rate, routing and scheduling

Deriving optimal protocols in GNU: A three step recipe

- Formulate the primal optimization problem
- Decompose into sub-problems
  - Structure of sub-problems → Functions carried out at physical entities
- Identify message-passing between physical entities
Joint Source-rate, routing and scheduling

Deriving optimal protocols in GNUM: A three step recipe

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Primal Problem

1. Maximize application utilities (e.g., throughput, fairness, . . .) such that

$$\text{Maximize } \sum_{k \in K} U(r_k)$$
$$\text{s.t. }$$

$$x^k_a \leq \sum_{b : (a,b) \in L} \sum_{c \in C} f^k_{ab,c}$$
$$- \sum_{b : (b,a) \in L} \sum_{c \in C} f^k_{ba,c}$$

$$f \in \Pi$$

$$\sum_{k \in K} t^k_{i,c} + P_{i,c} \leq 1$$

2. Packets are routed from src to dest

3. Schedule for links are feasible (an NP-hard problem)

4. Don’t schedule when primary is on

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Maximize \[ \sum_{k \in K} U(r_k) \]

s.t.

\[ \sum_{a \in A} \chi_a^k \leq \sum_{b : (a,b) \in L} \sum_{c \in C} f_{ab,c}^k - \sum_{b : (b,a) \in L} \sum_{c \in C} f_{ba,c}^k \]

\[ f \in \Pi \]

\[ \sum_{k \in K} t_{i,c}^k + P_{i,c} \leq 1 \]
Dual decomposition

Use standard Lagrangian Dual Decomposition method.

Two subproblems

1. **Source-rate maximization problem**
   \[
   D_1(q) = \max_{r \geq 0} \sum_{k \in \mathcal{K}} U(r_k) - \sum_{k \in \mathcal{K}} r_k q^k_{src(k)}
   \]
   - Completely distributed

2. **Joint routing and scheduling problem**
   \[
   D_2(q) = \max_{f \geq 0} \sum_{(a,b) \in \mathcal{L}} \sum_{c \in \mathcal{C}} f^k_{ab,c} \max_{k \in \mathcal{K}} (q^k_a - q^k_b)
   \]
   - Weight for a flow = *Congestion price differential* at link end-points
   - Needs message passing at each time-slot
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Use standard Lagrangian Dual Decomposition method.

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Optimal algorithms

At each time-slot

1. Each node updates *congestion-prices*
2. Source node locally solves the Source-rate problem.
3. Centralized scheduler computes schedule
   - Each link computes congestion price differential for each connection.
   - Sender and receiver will transmit Primary Usage Map
   - Scheduler computes optimal flow for each link, and disseminates
System issues in GNU
Example scenario

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Example scenario

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Closer look at scheduling

Scheduling works on the basis of back-pressure

Scheduler balances queue-length differences
- Links with larger price differential are given priority

System issue 1: What happens at inactive links of a connection?
- *Spurious pressure* at inactive links is necessary to push packets through actual link

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Spurious pressure points

Example scenario
Choice of time-slot

Scheduling happens in microseconds or milliseconds

Message passing overhead too high

Practical solutions:
- Exchange messages at coarse time-granularity (say, 1 sec)
- Reuse schedules

System issue 2: Bursty schedules
  Links are turned on and off for long times
Bursty schedules

Prohibitively large delays, unfairness, large buffer spaces

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Conclusions and future work

- Extended Joint Source-rate, routing and scheduling GNU Model for CRNs
- Analyzed system issues and impact of back-pressure based GNU Model models
  - *Spurious pressure points* induce packet losses
  - *Bursty schedules* result in large delays, buffer-spaces and unfairness
  - *Link-pruning* can help in designing fast-schedulers

Future work:
- Evaluation in simulation and SDRs

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Thank you.

For further information, please contact:
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Problem 1:

Compute list of all links that can be scheduled
- Maximal Independent Set (MIS) problem on multi-channel conflict graph of CRN

Each MIS $M_i$: (link, channel) pair

Problem 2:

Schedule each MIS
- Total time for all MIS $\leq 1$
- Time for a (link, channel) should respect MIS membership

System issue 1: Computing MIS is NP hard
- Number of MISs grow exponentially if number of edges, channels grow

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