Algorithmic Approaches and Challenges in QoS Routing

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Outline

- Introduction:
  - Motivation
  - QoSR fundamentals
  - Models

- Basic Model
  - Provisioning of QoS in Unicast
  - Restoration of QoS in Unicast
  - Provisioning of QoS in Multicast

- Extended Model
  - Unicast
  - Multicast
  - Coping with uncertainty

- Coupled Model

- Conclusion
Motivation

- Networks grow in size
- Emergence of new applications
  - e.g., voice over IP, multimedia streaming
- Requirements
  - Provision of QoS guarantees:
    - “bottleneck” - e.g., bandwidth
    - “additive” - e.g., delay and jitter
  - Resilience to failures
  - Network mechanisms must be scalable
QoS Provision

- Traffic Models
- Scheduling disciplines
- QoS routing
- Call admission control
- And more..
QoSR Mechanisms

- Provisioning
  - Routing – identifying a suitable topology (paths, trees)
  - Resource Allocation – securing the required resources
- Restoration – establishing a restoration topology, i.e., a set of restoration paths/trees, each protecting part of the primary path/tree
QoSR Challenges

- Coping with intractability
- Coping with scalability
- Coping with uncertainty
- Integrating with other QoS-enabling building blocks
- Implementation issues:
  - Integrating with existing routing protocols
  - Distributed schemes
- … And all for multicast too
Methods

- Coping with intractability by:
  - Heuristics
    - [Kompella et al., 93; Zhu et al., 95; Ma et al., 97; De Neve and Van Mieghem, 98; Sriram et al., 98; Korkmaz & Krunz, 99; Juttner et al., 01]
  - Identifying circumstances and conditions in which it is solvable
    - [Guerin & Orda, 96; Ma & Steenkiste, 97; Kuipers & Van Mieghem, 03]
  - Approximations with proven performance guarantees
    - [Lorenz & Orda, 98; Goel et al., 01; Ergun, Sinha & Zhang, 00; Korkmaz et al., 00; Lorenz et al., 00; Raz & Shavitt, 00; Orda & Sprintson, 02; Siachalou & Georgiadis, 02; Bejerano et al., 03; Biton & Orda, 04]
Improved scalability by way of:

- Better (more scalable) algorithms
- Exploiting hierarchical structure of the topology and employing aggregation
  - [Lee, 95; Orda, 99; Van Mieghem, 99; Korkmaz & Krunz, 00; Orda & Sprintson, 00; Awerbuch & Shavitt, 01; Lui et al., 04]
- Employing a precomputation approach:
  - Reduce the time required for (e.g.) computing a path by performing computations in advance
  - [Le Boudec & Przygienda, 95; Shaikh et al., 98; Orda & Sprintson, 00]
Precomputation

The main loop of a network element

Idea: Reduce the time required to identify a solution by precomputing solutions for each possible delay value.
For concreteness..

- We shall focus on:
  - A single, additive QoS constraint.
  - Solutions that provide
    - proven worst-case performance
    - within polynomial worst-case complexity
    - in general topologies.
  - Centralized schemes.
  - At most a single network failure.
Models

- **Basic model**
  - A link can provide a certain QoS guarantee at a certain “cost”

- **Extended model**
  - A link can provide several QoS guarantees at different “costs”
  - Per-link cost function that assigns a cost to each QoS value
  - Special case: uncertainty

  (“cost” = estimation of amount of resources needed to provide the required QoS)

- **“Coupled” model (routing with scheduling)**
  - Given the schedulers’ bounds, traffic profile and session’s QoS requirements, consider the actual consumption of resources, and make the route choice accordingly.
### Problems considered

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Provisioning</th>
<th>Restoration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basic Model</strong></td>
<td>![Checkmark]</td>
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</table>
Problems considered (cont.)

<table>
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<tr>
<th>Coupled Model (Unicast, Provisioning)</th>
<th>Deterministic traffic (Burstiness-Constrained)</th>
<th>Stochastic traffic (Exp.-Bounded-Burstiness)</th>
</tr>
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<tr>
<td>WFQ</td>
<td>[✓]</td>
<td>[✓]</td>
</tr>
<tr>
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Basic Model

- Directed Graph $G(V,E)$
  - For each link $l \in E$
    - $d_l$ - the delay of link $l$
    - $c_l$ - the cost of link $l$

- Path $(P)$ Sequence of distinct nodes $v_0, v_1, \ldots, v_n$

\[
C(P) = \sum_{l \in P} c_l, \quad D(P) = \sum_{l \in P} d_l
\]
Provisioning of QoS paths

- Find a minimum cost path between s and t that satisfies QoS constraint D
- Can be efficiently solved for bottleneck constraints
- For additive constraints, the problem is NP-hard
  - Approximation schemes [Hassin, 92; Lorenz & Raz, 01]
  - \( \varepsilon \)-approximate solutions
    \( O(|E| \cdot |V| \cdot (1/\varepsilon + \log \log |V|)) \)
Provisioning of QoS paths: Precomputation

Problem:

For each QoS constraint $D \geq 1$, find a minimum cost path whose delay is at most $D$

[Orda & Sprintson, 2000]:

- $\varepsilon$-Approximate solutions
- Complexity $O(1/\varepsilon \cdot |E| \cdot |V| \cdot \log C)$
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Coupled Model

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Global vs. local restoration

- Global restoration – a pair of disjoint paths
  - Both must satisfy the delay constraint
  - Simpler: implemented only at the source
  - But not always possible (or best choice)
  - [Taft et al., 99; Kodialam & Lakshman, 00; Guo et al., 03; Orda & Sprinston, ’04]

- Local restoration – a primary path and a set of “bridges”
  - [Bejerano et al., 03]
Local Restoration: problem formulation

- **Problem RT**
  - Given a delay constraint $D$ and a QoS path $P$, $D(P) \leq D$, find a minimum cost restoration topology $R = \{B_1, B_2, \ldots, B_k\}$

- **Problem P+RT**
  - Given a delay constraint $D$, find a QoS path $P$ and a corresponding restoration topology $R$, such that their total cost is minimum

- **The problems are NP-hard**

- **[Bejerano, Breitbart, Orda, Rastogi & Sprintson, 03]**:
  - Polynomial solutions, with proven guarantees
Global Restoration: Problem formulation

- Given:
  - A directed graph $G$, source node $s \in G$, destination node $t \in G$, delay requirement $D$

- Find two link-disjoint paths $P_1$ and $P_2$ such that:
  - $D(P_1) = D$ and $D(P_2) = D$
  - The total cost $C(P_1) + C(P_2)$ is minimum

- The problem is NP-hard

- [Orda & Sprintson, 2004]:
  - Polynomial solution, with proven guarantees
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Provisioning of QoS Trees

Example: find a tree that satisfies delay constraint D=6
Provisioning of QoS trees

Find a minimum cost tree $T$ that connects source $s$ to each terminal $t_j \in X$ and satisfies the delay constraint $D$

Related problems:
- Directed Steiner Tree (DST)
  - Special case with no QoS constraints
  - Extensively investigated for undirected networks
  - Directed Networks: Algorithm by [Charikar et al., 99]
- Restricted Shortest Path (RST)
  - Special case for unicast
Provisioning of QoS trees

- Problem has attracted a large body of research
  - Most studies proposed heuristic solutions
    - often based on restrictive assumptions, e.g. symmetry of link delays
  - Provable solutions available only for special cases
    - E.g., identical link delays
    - Or incur large violation of QoS constraint,
      - e.g., an \(O(\log N, \log N)\) solution
  - No solution of provable performance has been established for general networks and no violation of QoS constraints.
<table>
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<tr>
<th>Delay violation</th>
<th>Approximation ratio</th>
<th>Complexity</th>
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<tr>
<td>1+ε</td>
<td>$(1+\varepsilon)(i-1)K^{1/i}$</td>
<td>$O\left(\left(\frac{N \cdot i}{\varepsilon}\right)^{i-1}K^{2i-1}\right)$</td>
</tr>
<tr>
<td>none</td>
<td>$(1+\varepsilon)(i-1)K^{1/i}$</td>
<td>$O\left(\left(\log\log N + \log\frac{1}{\varepsilon}\right)\left(\frac{N}{\varepsilon}\right)^{i-1}K^{3i-2}\right)$</td>
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More generally: A scheme that

- Translates any approximation scheme for the unconstrained directed version
- into an approximation scheme for the constrained directed version, with about identical (epsilon-close) performance guarantees.
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The Problem

How to provide the required QoS with a minimal cost?

- Cost per delay is given by Service Level Agreements (SLAs)
- Less delay for more cost
The QoS Partition Problem

Given:
- Route (multicast tree)
- End-to-end delay requirements for all users.
- Link cost functions \( \{c_i(d)\}_{i \in E} \)

Find:
- Delay requirement for each link
- Satisfy E2E requirements
- with minimal cost
The QoS Routing Problem

Given:
- Network graph
- End2End delay requirement
- Link cost functions \( \{c_i(d)\}_{i \in E} \)

Find:
- Minimum cost route
  - Cost of optimal QoS partition
Given:
- Path (multicast tree)
- End-to-end delay requirement \( \hat{d} \)
- Link cost functions \( \{c_i(d)\}_{i \in E} \)

**Find:**
- Minimum cost tree
- Cost of optimal QoS partition
The Cost

Each “link” offers different SLAs

Cost function:

\[ c_l(d) \]
The Cost Function (cont.)

- Simplest form: \((\text{delay}, \text{cost})\) pair
- In many cases discrete
- Is always decreasing
- In many cases convex
Results

- Problem is NP-hard
  - Routing: Even for a scalar \((delay, cost)\) pair on every link (Restricted Shortest Path)
- Convex cost functions [Lorenz & Orda 98,99]
- Discrete cost functions [Raz & Shavitt, 00]
- General cost functions:
  - [Ergun, Sinha and Zhang, 00]: unicast.
  - [Lorenz, Orda, Raz and Shavitt, 00]: lower complexity + multicast.
  - [Orda & Sprintson, 02]: lower complexity + precomputation.
  - [Lorenz, Orda & Raz, 03]: any-to-any multicast.
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“QoS-based routing can determine a path, from among possibly many choices, that has a good chance of accommodating the QoS (requirements) of a given flow.”

-- IETF QoSR WG

“good chance” = there is uncertainty

• [Guerin & Orda, 97; Lorenz & Orda, 98; Korkmaz & Krunz, 03; Masip-Bruin et al., 04]
Origins of Uncertainty

- Network dynamics
  - Outdated parameters
- Aggregation in large networks
  - Inherent loss of information
- Hidden information
  - Private network internals
- Approximate calculations
  - Parameters reflect averages or worst-case behavior
QoS Routing under Uncertainty

- \( f_l(d_l) = \text{Prob}\{\text{delay in link } l < d_l\} \)
- End-to-end delay requirement is usually decomposed into link requirements
  - \( D \rightarrow \{d_1, d_2, ..., d_{|p|}\} \) such that \( \sum_i d_i = D \)
- Problem: find path \( p \) and delay partition such that probability of not exceeding \( D \) is maximum.
- \( \text{Prob}\{\text{success}\} = f_1(d_1) \cdot f_2(d_2) \cdot ... \cdot f_{|p|}(d_{|p|}) \)
- Can be expressed in cost terms:
  - \( c_l(d) = -\log f_l(d), c_p(D) = \sum_l c(d_l) \)
- Special case of the extended model
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Coupling Routing with Scheduling

- Scheduling discipline: provides end-to-end Performance bounds
- E.g., for WFQ:

\[ D(p) \leq \frac{\sigma + n(p) \cdot L}{r(p)} + \sum_{l \in p} d_l \]

- For a given session and path, how much resources are needed?
- For a given network:
  - On which path(s) can the session be routed?
  - Which is the best path (e.g., min. rate consumption)?
Coupling Routing with Scheduling (cont.)

- **Common QoSR approach:**
  - Choose a route that:
    - *Seems* to have enough resources for supporting the session’s QoS.
    - Consumes network resources relatively efficiently.
  - *Afterwards*, see how much resources are really needed on the chosen path.

- **Alternative approach:**
  - *Consider* the actual consumption of resources for the given (1) schedulers’ bounds, (2) traffic profile and (3) session’s QoS requirements, and
  - choose a route that
    - *has* enough resources for supporting the session’s QoS,
    - *minimizes* the actual consumption of network resources.
Coupling Routing with Scheduling (cont.)

- E.g., for WFQ:
  - Minimum required rate for a session \((s,L)\) on a path \(p\):
    
    \[
    r = \frac{\sigma + n(p) \cdot L}{D - \sum_{l \in p} d_l}
    \]

- “Min. rate” algorithm: \(O(M^2N)\)
- Approximations with lower complexity
- Other variants, e.g., “relative rate”, “load balancing”, etc.
- Experiments: blocking probability reduced considerably (~factor of >2)
Related work:

WFQ:
- Deterministic traffic (bounded burstiness)
  - [Guerin & Orda, 96; Ma & Steenkiste 97; Orda, 99]
- Stochastic (Exp. Bounded Burstiness)
  - [Biton & Orda, 04]

EDF:
- Deterministic traffic
  - [Ferrari & Verma, 90; Chou & Shin, 95; Firoiu et al., 98; Shin et al., 00; Ayad et al., 01]
- Stochastic traffic
  - [Biton & Orda, 04]
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Implementation issues

- Integration with existing routing protocols
- Distributed schemes
- And more..

Out of the scope of this talk.
QoS routing is a highly complex problem

Efficient, scalable & provable approximation schemes can be employed

Its solution is invaluable for the technological and economical success of communication networks.
Algorithmic Approaches and Challenges in QoS Routing

Questions and Comments are welcomed:
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The End