Design and Benefit Analysis of Edge-to-Edge Bailout Forward Contracts for Single-Domain Internet Services

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About FIND (Future Internet Design) Program
- A major new long-term initiative of the NSF NeTS research program.
- Engages a research community to consider what the requirements should be for a global network of 15 years from now if we could design it from scratch.
- It solicits research across the broad area of network architecture, principles, and mechanism design, aimed at answering questions as:
  - How can we design a network that is fundamentally more secure and available than today’s Internet? How would we conceive the security problem if we could start from scratch?
  - How might such functions as information dissemination, location or identity management best fit into a new network architecture?
  - What will be the long-term impact of new technologies such as advanced wireless and optics?
  - How will economics and technology interact to shape the overall design of a future network?
  - How do we design a network that preserves a free and open society?

Implied Challenges
- Current architectural problems:
  - Users cannot express value choices at sufficient granularity – only at access level
  - Providers do not have economic knobs to manage risks involved in:
    - investing innovative QoS technologies and
    - business relationships with other providers

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- Inter-domain struggles…
  - When crossing domains, all bets are off..

- End-to-end reliability or performance-criticality requires:
  - assurance of single-domain performance, i.e., “contract’s
  - efficient concatenation of single-domain contracts

- Inter-domain routing needs to be aware of economic semantics
  - contract routing + risk management

- We address translation of these struggles to architectural problems

A Contract-Switched Network Core
- Contracts: a practical way to manage “value flows”
- Technologies to Support QoS
- Economic considerations for service definition and delivery:
  - Scalability, Efficiency and Fairness
  - Contract timescales
  - Cost recovery
  - Pricing the risk in QoS guarantees
  - Single-domain and end-to-end contracts
The Contract-Switching Paradigm (CSP)

- Utilize overlay contract links between edge nodes (peering points) at domain boundaries
  - To indicate wider range of service choices.
- Contracts are the building block
- Contracts include performance, financial and time duration specification

Network Core

Stations of the provider computing and advertising local prices for edge-to-edge contracts.

Customers

Baseline Case 1 (BC1)

- Contracts at each edge are point-to-anywhere spot contracts
- Flat (linear) pricing scheme
- Demand profile $N(p,q)$ – Number or fraction of customers who purchase $q$-th unit of product at $p$. We choose a demand profile:
  $$N(p,q) = 1 - p - q$$
- The linear spot price for point-to-anywhere at node $i$ is:
  $$p^*_i = \frac{M_i}{A_i}$$
  $M$ is the aggregate flow through node $i$ and $A$ is the available capacity at node $i$
- $p^*$ is the optimal marginal price obtained from price optimization for cost recovery for the above demand profile

Baseline Case 2 (BC2)

- Price of the spot contract is a non-linear transformation of time-dependent demand and available capacity.
  $$S_i^t = P\left(\frac{\mu_i^t}{A_i^t}\right) = \int_0^1 p^*(q) dq$$
  $$p^*(q)$$ is the optimal nonlinear price schedule obtained from price optimization for cost recovery (demand profile from BC1)
  $$\mu_i^t, A_i^t$$ are the demand and available capacity modeled by two Ito processes
  $$p^*(q) - \mu^t = \frac{c + (1\frac{q^2}{2} + \frac{q^3}{3})\rho}{1 + \rho}$$
  Ito's formula describes the change in the spot price due to changes in demand and/or available capacity.

Increasingly Complex Contracting Scenarios

- Baseline Case 1:
  - point-to-anywhere
  - linear price schedule designed for cost recovery
  - responsive to demand
- Baseline Case 2:
  - point-to-point
  - nonlinear price schedule designed for cost recovery
  - responsive to demand profile
- Bailout Forward Contract Case:
  - point-to-point, nonlinear price schedule
  - bailout forward for dynamic temporal composing of bandwidth services and risk management

Defining the Contracts in the CSP

- Time Duration for Contracts
  - Atomic
  - Short
  - Medium
  - Long
- Financial Component – Price discovery
  - Pricing in medium and long timescale
  - Pricing for bandwidth and allowing contracts to be composed dynamically in time
  - Pricing for cost recovery and risk management
- Financial Component – Complexity trade-off
  - Introduce measured sophistication justifying the economic benefit
  - Evaluate 3 scenarios of increased complexity.
Bailout Forward Contract (BFC) Case

- Bail-out Forwards Contracts on advertiseable spot contracts
  - between peering/edge points i and j of an ISP
  - flexibility of advertising different forward prices for edge-to-edge (peering) intra-domain paths
  - forwards contracts with provision for Bail-out conditioned on network congestion
  - spot and forwards concatenated to create long-term contracts
  - use to realize revenue stability and guaranteed network utilization
  - tool for demand prediction and network upgrades

Pricing of Bailout Forward Contract (BFC)

- Based on option pricing derivation, the price of the bailout forward satisfies:
  \[
  \frac{\partial^2 F}{\partial S_i^2} + \frac{1}{2} \rho_i^2 \frac{\partial^2 S_i}{\partial S_i^2} + (\lambda_i - r_i) \frac{\partial F}{\partial S_i} - \frac{\partial F}{\partial S_i} = 0
  \]
- With the end condition:
  \[
  f(S_i^t, T) = (S_i^t - F) I_{\{A_i' > Th\}}
  \]
- The solution is obtained as:
  \[
  F = \frac{1}{P(A_i' > Th)} E[S_i^T I_{\{A_i' > Th\}}]
  \]

Implementation Setup

- Network topologies
  - Two of the Rocketfuel ISP topologies with different network characteristics:
    - Abovenet - well-engineered, stable
    - Exodus - hub-and-spoke
  - Experimental Specification
    - Inputs: A, M, μ, \(\rho\) (Get for the two topologies), Th(15% percentile), time duration(7 days)
    - Simulate each process and determine prices for a 7 day period
    - Use 1000 replications of simulation

Implementation Setup

- Realistic Simulation requires
  - Realistic ISP Topology
  - Adjacency Matrix (Given by Rocketfuel Data)
  - Link Delays & Weights (Given by Rocketfuel Data)
  - Link Capacities (we model)
  - Edge and Backbone Router Classification (we model)
  - Routing Matrix (Path calculated by Shortest Path Algorithms, as the OSPF and BGP protocols do for real world)
  - Realistic Traffic Model
  - Traffic Demand (we model)

Implementation Setup

- How to assign link capacity?
  - Distance from network center (BFS)
  - Connectivity Degree
    - Assign higher capacity to links between routers with low distance and high connectivity

Implementation Setup

- Assign higher capacity to links between routers with low distance and high connectivity

Sources:
- 1) Abovenet Topology Map
- 2) CIESIN Population Data

Gravity Model

- Traffic Flow Size and Demand Proportional to Pop. of City 1 X Pop. of City 2
- Power Law
  - Associate Regional Populations with Edge Routers and model demand size according to that

Sources:
- 1) Abovenet Topology Map
- 2) CIESIN Population Data
Implementation Setup

San Francisco – London
Seattle – London
Chicago – Paris

All flowing through common links between NY and London, what will be the consequence of that?

Intensity of Overlap \( \rho \)
- Models the severity of competition impact from edge \( i \) on edge \( j \) for available bandwidth capacity of link
- Indicator of congestion risk
- \( U_{\text{link}} \) is the highest utilization value among common links on g2g path
- \( \tau \) is the minimum of bandwidth share that flow \( k \) can get over links on the g2g path according to min-max fair share.

Revenue Comparison between BC1 and BC2

- 7 Day Total Revenue Histograms for BC 1 and BC 2
- Total revenue is much more favorable for BC2
- At the cost of additional complexity

Revenue Comparison between BC1, BC2, and Reduced BC2

Introducing the BFC (with reduced complexity)

- Reduced BFC:
  - obtained by similar principle as Reduced BC2,
  - with links grouped by similar forward prices
- 7 Day Total Revenue comparison for BC 1, Reduced BC 2, and Reduced BFC with demand conversion rate (CR) at 40%
- Reduced BFC significantly dominates BC1, but slightly inferior to Reduced BC 2
Revenue Comparison of Reduced BFC with varying demand conversion

- The provider is trading-off the mean revenue for the variability or risk in the revenue.

Revenue Comparison of Reduced BFC with varying CR

- 95% CI on Mean Revenue vs. Standard Deviation of Revenue for Reduced BFC with different demand conversion rates
- The provider gives up mean return for reduction in the risk, depending on her risk-aversion

Take away from the Economic Benefit Analysis

- Nonlinear, point-to-point pricing of contracts significantly improves revenue over linearly priced point-to-anywhere contracts.
- Grouping of links along with nonlinear pricing retains the benefits over linear pricing, with considerable reduction in computational complexity.
- Bail-out Forward contracts, with controlled complexity, give:
  - nice tradeoff between risk and return
  - flexibility of prediction of future demand
  - possibility of concatenation for longer duration service

How often do BFC Bail-out? - Robustness of g2g BFC

- Use Rocketfuel’s ISP topology - Exodus.
- Histogram of fraction of BFCs bailing out
  - Under normal network conditions

How often do BFCs bail out in network failures?

- Three failure modes created by failing specific high load links for this analysis.
- The failures change the network characteristics in the model by changing
  - intensities of overlap between links,
  - means of available capacity, and
  - standard deviations of available bandwidth.
Revenue Impact of BFC, with and w/o failure

<table>
<thead>
<tr>
<th>Case</th>
<th>Expected Total Revenue</th>
<th>Mean Bailout Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artificial No Bailout or Failure Case</td>
<td>95.7454</td>
<td>0</td>
</tr>
<tr>
<td>Base Case Bailout Scenario</td>
<td>80.4055</td>
<td>0.16403</td>
</tr>
<tr>
<td>Bailouts in Failure Mode 1</td>
<td>78.98833</td>
<td>0.15059355</td>
</tr>
<tr>
<td>Bailouts in Failure Mode 2</td>
<td>81.34074</td>
<td>0.16986064</td>
</tr>
<tr>
<td>Bailouts in Failure Mode 3</td>
<td>80.86213</td>
<td>0.16057308</td>
</tr>
</tbody>
</table>

- There is a small increase in the fraction of paths bailing out in the failure modes
- There is a small reduction in revenue in the failure modes

Network Analysis

- Conservative Assumption
  - Although for real world more failures occur at edge routers, we fail every link in our network, including high capacity backbone links one by one.
  - As link fails, shortest path calculations and routing matrix change accordingly
  - Traffic previously passing over failed links shifts to other links following updated routes
  - According to the changed link loads and capacity figures, even under this conservative failure scenario 73% of BFCs still achieve their promise, on average
  - These results underline the robustness of the BFC model

- This is more conservative since we are considering all links failing

Summary

- Nonlinear, point-to-point pricing of contracts significantly improves revenue over linearly priced point-to-anywhere contracts.
- Grouping of links along with nonlinear pricing retains the benefits over linear pricing, with considerable reduction in computational complexity.
- Bail-out Forward contracts, with controlled complexity, give:
  - nice tradeoff between risk and return
  - flexibility of prediction of future demand
  - possibility of concatenation for longer duration service
- Experimentations shows that the g2g BFC mechanism is robust to link failures, both in terms of the bailing out behavior and revenue lost.