Edge-to-Edge Bailout Forward Contracts for Single-Domain Internet Services

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***Abstract*—Despite the huge success of the Internet in providing basic communication services, the Internet architecture needs to be upgraded so as to provide end-to-end QoS services to its customers. Currently, a user or an enterprise that needs end-to-end bandwidth guarantees between two arbitrary points in the Internet for a short period of time has no way of expressing its needs. To allow these much needed basic QoS services, we propose a single-domain edge-to-edge (g2g) dynamic capacity contracting mechanism, where a network customer can enter into a bandwidth contract on a g2g path at a future time, at a predetermined price. For practical and economic viability, such forward contracts must involve a bailout option to account for bandwidth becoming unavailable at service delivery time, and must be priced appropriately to enable ISPs manage *risks* in their contracting and investments. Our design allows ISPs to advertise point-to-point different prices for each of their g2g paths instead of the current point-to-anywhere prices, allowing for better end-to-end paths, temporal flexibility and efficiency of bandwidth usage. We compute the *risk-neutral prices* for these g2g *bailout forward contracts* (BFCs), taking into account correlations between different contracts due to correlated demand patterns and overlapping paths. We implement this multiple g2g BFC framework on a realistic network model with Rocketfuel topologies, and evaluate our contract switching mechanism in terms of key network performance metrics like fraction of bailouts, revenue earned by the provider, and adaptability to link failures.**

I. Introduction

The Internet is a commercial environment embodying multiple service providers competing with each other. Provisioning inter-domain end-to-end (e2e) quality-of-service (QoS), thus, strictly depends on the viability and flexibility of single-domain edge-to-edge (g2g) contracting capabilities. Current single-domain contracts (or SLAs) are typically *point-to-anywhere* settlements happening in a peer-to-peer or customer-provider ISP relationships. This point-to-anywhere nature of SLAs carry all the way to the end users, and thus the current Internet services are packaged in a typically flat-rate and point-to-anywhere deals without any specific QoS guarantees, except the access bandwidth guarantees. Though such best-effort point-to-anywhere contracting has the convenience of making the customer not worry about per-destination prices (i.e., different prices for the traffic destined to different locations instead of a single price for all possible destinations), the tradeoffs are (i) lack of e2e QoS and (ii) the lost opportunity for discovering potentially better value flow paths both economically (e.g., cheaper) and technically (e.g., higher capacity).

Another key characteristic missing in the current SLAs is the economic flexibility to manage risks involved in the settlement. For example, the time-scale of SLAs is too long (e.g., months to years) and there is typically no way of bailing out of an SLA if the ISP finds a better deal. Further, SLAs are closed at the present time (or very near future such as days/weeks) and an ISP typically cannot easily close deals for its future investments to reduce risks involved in its investment. It is a pressing need to have such economic instruments for enabling the ISPs to *manage risks* in their investments.

We consider an Internet architecture that allows flexible, finer grained, dynamic contracting over multiple providers. We propose a new family of single-domain contracting based on edge-to-edge (g2g) dynamic capacity contracting [1] involving forward contracts with bailout options, also called *g2g bailout forward contracts* (BFCs). Our design allows ISPs to advertise point-to-point different prices for each of their g2g paths instead of the current point-to-anywhere prices. Such g2g contracts enable composition of end-to-end higher quality paths given that inter-domain relationships are made over such g2g contracting [2]. Breaking the point-to-anywhere contracts into point-to-point g2g contracts allows more tussle points [3] (between multiple network service providers and content providers) into the system and thus opens the door for discovering better end-to-end paths [4]. This phenomenon is also illustrated in Figure 1, where end-to-end QoS paths can be composed by concatenating single-domain g2g contracts.

A forward contract for a g2g path, as the name suggests, offers a service on that g2g path which will be delivered at a future time, but at a predetermined price, called the forward price. We modify the contract with a bailout clause, thus creating a bailout forward contract (BFC), that allows the provider to bailout from offering the service at the future time should the available capacity on the g2g path not suffice to support the service at the future time. Offering such g2g BFCs on all the chosen g2g paths in a domain provides a mechanism for efficient use of bandwidth and creates temporal tussle points for network management. Multiple g2g BFCs between multiple network service providers can create mechanisms for temporal flexibility and efficiency for end-to-end bandwidth usage.

The rest of the paper is organized as follows: We first detail our contributions and cover related literature in the rest of this section. In Section II, we formally define bailout forward

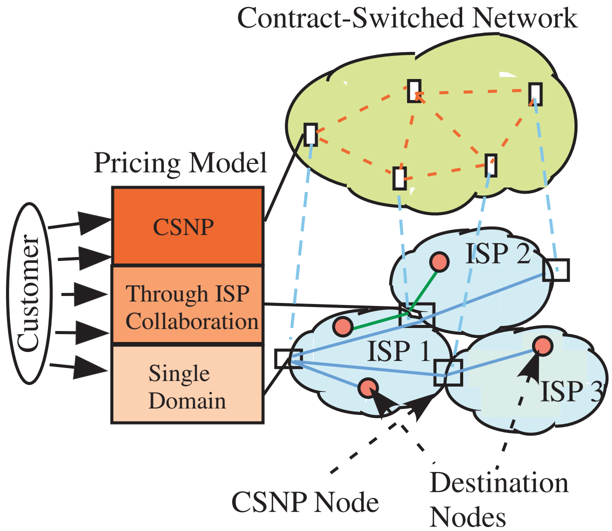

Fig. 1. Major components of an inter-network leveraging edge-to-edge (g2g) contracts. An overlay network provider (called Contract-Switched Network Provider (CSNP)) can concatenated several g2g single-domain contracts to compose an end-to-end path. Distributed end-to-end path composition is also possible with appropriate updates to inter-domain protocols [2].

contracts (BFCs). Section III details our proposed method of composing edge-to-edge prices for multiple BFCs for an ISP domain. We then present BFC performance results for ISP topologies with link failures in Section IV. We summarize our work in Section V.

A. Contributions

In this article, we first define the bailout forward contract for a single g2g path, and then extend this definition to create a formulation for BFCs on multiple g2g paths. The BFCs defined on multiple g2g paths incorporate and respond to how bandwidth available on one path can influence that on others based on an intensity of overlap defined for each path pair. We implement this multiple g2g BFC framework on a realistic network model with Rocketfuel topologies. We analyze the framework with respect to two major aspects of its properties. First, we evaluate the impact of base network characteristics on the forward price structure for the set of multiple g2g paths. Given the bailout terms, one important metric is what fraction of BFCs bailout and which specific g2g path BFCs bail out. Second, if network characteristics change due to link failures, how does the multiple g2g BFCs respond, i.e, what is the increase in the fraction of BFCs bailing out and BFCs for which specific g2g paths bailout.

B. Related Work

Traditionally network QoS involved the study of different queueing, scheduling and buffer management mechanisms to provide bandwidth and delay guarantees to flows at a statistically multiplexed resource [5]. Several QoS mechanisms have been adopted within single ISP domains, while inter-domain QoS deployment has not become reality. Arguably the reasons for this include the highly fragmented nature of the ISP market and the glut in core optical capacity due to overinvestment and technological progress of the late 1990s. BGP routing convergence and routing instability issues [6] also contribute to inter-domain performance uncertainties. Recent QoS research (e.g., [7], [8]) clearly identified a lack of inter-domain business models and financial settlement methods (i.e. monetary flows to compensate for QoS traffic flows), and a need for flexible risk management mechanisms (including insurance, money-back-guarantees).

Our work also relates to the Internet pricing research, which has focused on pricing for a single link or for traffic within a single provider's domain [9], [10]. Several flavors of pricing schemes have been debated ranging from flat rate, time-of-the-day, usage-based pricing, to dynamic pricing, and congestion-sensitive pricing [9], [1], [11]. The consensus is that price elasticity of **individual consumers** is low, and that whatever be the pricing mechanism, it has to be simple, efficient and scalable [12], [13]. This simplicity requirement does not translate as is to customers in our context, since customers in our contract-switching paradigm are mainly business enterprises, ISPs, content-providers, Service Overlay Networks (SONs), and other network service providers.

In most dynamic pricing schemes, the duration of contract is very short (in milliseconds). Designing and delivering spot and derivative contracts on such time scales is in general quite difficult [14]. In [15], the authors propose a two-component spot pricing framework for intra-domain expected bandwidth contracts with a loss based QoS guarantee. Auction-based pricing models are studied for bandwidth pricing, including combinatorial auctions, progressive second price auction, and simultaneous Dutch auctions [16], [17], [18], [19], [20]. Game theoretic analysis of competitive behavior between ISPs, as well as interaction between users and ISPs from a pricing standpoint is also analyzed [21]. Related QoS issues have been considered [22], [23]. Consideration of forward contacts, and the use of risk-neutrality ideas in the pricing of contracts, are some of the key aspects in which our work differs with previous work.

II. Bailout Forward Contracts (BFCs)

In general, one can define a contract as an embedding of three major flexibilities in addition to the contracting entities (i.e., buyer and seller): (i) *performance component*, (ii) *financial component*, and (iii) *time component*. The performance component of a contract can include QoS metrics such as delay or packet loss to be achieved. The financial component of contract will include various fields to aid entities in making financial decisions related to value and risk tradeoffs involved in engaging in the contract. The basic fields can be various prices, e.g., spot, forward, and usage-based. It is possible to design interesting financial component fields identifying financial security and viability of the contract, e.g., whether or not the contract is insured or has money-back guarantees. The time component can include operational time-stamps and be useful for both technical decisions by network protocols and economic decisions by the contracting entities. Example time component fields are the duration the contract will expire in, and the time left for the insured term when the money-back guarantee will expire. Notice that all these three components operate over an aggregation of several packets instead of a single packet. Given the potential scalability issues, this is the right granularity for embedding economic tools into the network protocols instead of finer granularity at the packet level, e.g., per-packet pricing.

In this section, we first formally define a forward contract and a bailout forward contract, and then present a mathematical formalization for determining the price of a bailout forward contract. A bailout forward is useful for a provider since it eliminates the risk of demand for bandwidth in the future without imposing a binding obligation to meet the contract if the network cannot support it. A customer of a bailout forward contract locks in the bandwidth required in future, but obtains the bandwidth at a discount. The discount is provided since the customer shares the risk of the scenario that if the network is congested at the future time, the contracted bandwidth may not be delivered due to the bailout clause. The customer may choose not to purchase a forward, but in that case runs the risk of not being able to obtain the necessary bandwidth at the future time due to congestion or price reasons. Therefore, constructing and offering bailout forwards is beneficial for both providers and customers.

A. A Forward Contract

A forward contract is an obligation for delivering a (well-defined) commodity (or service) at a future time at a pre-determined price - known as the 'Forward Price'. Other specifications of the contract are Quality Specification and Duration (start time - T_i, and end time - T_e, for the delivery of a timed service).

B. A Bailout Forward Contract (BFC)

In the case of a capacitated resource underlying a forward contract, restrictions may be necessary on what can be guaranteed for delivery in future. A key factor that defines the capacity of the resource is used to define the restriction. A bailout clause added to the forward contract releases the provider from the obligation of delivering the service if the bailout clause is activated, i.e. the key factor defining the capacity rises to a level making delivery of the service infeasible. A set up is essential for the two contracting parties to transparently observe the activation of the bailout clause in order for the commoditization of the forward contract and elimination of moral hazard issues. The forward price associated with a bailout forward contract takes into account the fact that in certain scenarios the contract will cease to be obligatory.

C. Risk Segmentation

Creation and pricing of a bailout forward contract on a capacitated resource allows for risk segmentation and management of future uncertainties in demand and supply of the resource. Contracts are written on future excess capacity at a certain price, the forward price, thus guaranteeing utilization of this capacity; however if the capacity is unavailable at the future time, the bailout clause allows a bailout. Therefore, it hedges the precise segment of risk. The price of the bailout forward reflects this.

D. Formalization for Pricing a BFC

For pricing a bailout forward, we first need to define the price of spot contracts on which the forward is defined. The spot prices reflect present utilization of the network and price the contract using a nonlinear pricing kernel to promote utilization and cost recovery. The risks underlying the spot contract prices are key determinants for formulating the pricing framework for the bailout forward contract. Appropriate modeling abstractions are necessary.

We make an edge-to-edge (g2g) "contract" abstraction of the network, where this contract is defined unidirectionally from an ingress edge point to an egress edge point instead of the traditional point-to-anywhere contracting scheme of the Internet. We model the time-dependent demand for the spot contract, μ_t (in Mbps), and the available capacity on this g2g path, A_t (also in Mbps), where $\mu_t < A_t$ by virtue of admissions control. Price of the spot contract is obtained as a non-linear transformation, $S_t = P(\mu_t, A_t)$ (in \$/Mbps/s). A predictive model for A_t is used as the bailout factor to define the bailout condition and price the BFCs on this contrac abstraction of the network. Therefore, the forward price, F_t, is a function of the spot contract price, predicted future available capacity, and parameters that define the bailout term.

We model the time-dependent demand for the spot contract as follows,

$$d\mu_t = \gamma(m - \mu_t)dt + b_1 \mu_t dW_t^1, \tag{1}$$

and the available capacity on the g2g path as,

$$dA_t = \beta(\overline{A} - A_t)dt + b_2 A_t dW_t^2, \tag{2}$$

where the two Wiener processes are taken to be uncorrelated. The m in the above equation is the long-run mean for demanded bandwidth and $\overline{A}$ is the long-run mean for available bandwidth.

A specific choice of demand profile results in the spot price to be the following function of μ_t and A_t,

$$S_t = P(\frac{\mu_t}{A_t}) = \int_0^{\mu_t/A_t} p^*(q)dq, \tag{3}$$

where $p^*(q)$ is the optimal price schedule in the nonlinear pricing methodology, obtained as,

$$p^*(\frac{\mu_t}{A_t}) = \frac{c + (1 - \frac{\mu_t}{A_t}) \times \alpha}{1 + \alpha}. \tag{4}$$

Parameters c (in \$/Mbps/s) and α are the marginal cost and the Ramsey number, respectively. We apply Ito's formula to describe the change in the spot price due to change in demand

and available capacity.

$$
\begin{aligned}
dS_t &= \\
&= \frac{c+\alpha(1-\frac{\mu_t}{A_t})}{1+\alpha} d(\frac{\mu_t}{A_t}), \\
&= \frac{c+\alpha(1-\frac{\mu_t}{A_t})}{1+\alpha} [(\frac{\gamma(m-\mu_t)}{A_t} + \frac{\beta(\overline{A}-A_t)\mu_t}{A_t^2} \\
&- \frac{\mu_t}{A_t^3})dt + \frac{b_1\mu_t}{A_t} dW_t^1 - \frac{b_2\mu_t}{A_t} dW_t^2].
\end{aligned}
\tag{5}
$$

If $f(S_t, t; T)$ is the price of a bailout forward at some time t, maturing at a future time, T, then the standard derivative pricing derivation for any derivative defined on the spot contract, S_t, gives that $f(S_t, t)$ should satisfy the following partial differential equation.

$$
\frac{\partial f}{\partial t} + \frac{1}{2} p^2(\frac{\mu_t}{A_t})(b_1^2 \frac{\mu_t^2}{A_t^2} + b_2^2 A_t^2) \frac{\partial^2 f}{\partial S^2} + \frac{\partial f}{\partial S_t} r S_t - r f = 0, \tag{6}
$$

along with the end condition,

$$
f(S_T, T) = (S_T - F)\mathbf{I}_{\{A_T > Th\}}, \tag{7}
$$

where T is the time of delivery of service in future, F is the forward price, and $\mathbf{I}$ is the indicator function for no bailout defined in terms of a threshold level, Th. The r in the partial differential equation is the short-term, risk-free interest rate. The derivation entails that a risk-free trading strategy is designed combining the spot and forward (derivative) contract, which in an arbitrage-free world should match a risk-free asset, resulting in the above equation and end-condition that the forward price should satisfy [31]. The solution of the above equation is obtained as [31], follows,

$$
f(S_0, 0) = E[e^{-rT}(S_T - F)\mathbf{I}_{\{A_T > Th\}}]. \tag{8}
$$

Since initially there are no payments, only the forward price is determined, we obtain the forward price, F, by equating the above equation to zero and solving for F.

$$
F = \frac{1}{P(A_T > Th)} E[S_T \mathbf{I}_{\{A_T > Th\}}], \tag{9}
$$

where S_t in the risk-neutral world evolves by the process,

$$
dS_t = r S_t dt + p(\frac{\mu_t}{A_t}) \frac{b_1 \mu_t}{A_t} dW_t^1 - p(\frac{\mu_t}{A_t}) \frac{b_2 \mu_t}{A_t} dW_t^2]. \tag{10}
$$

Had there been no bailout clause in the bailout forward, which would be the regular forward contract, the end condition would be,

$$
f_{regular}(S_0, 0) = E[e^{-rT}(S_T - F_{regular})], \tag{11}
$$

and again, since there are no payments initially, the forward price simplifies to,

$$
F_{regular} = e^{rT} S_0, \tag{12}
$$

noting that $e^{-rT} S_T$ is a Martingale in the risk-neutral world.

Therefore, in the regular forward contract, the customer pays full price and gets the service versus in BFC, the customer pays a discounted price and gets the service so long as the provider does not become overcommitted (determined by the indicator function in the formula) at the time of delivery. Otherwise, the customer does not get the service and does not have to pay.

To test the definition and pricing framework of the Bailout Forwards, we first need to expand it to multiple g2g paths in a domain, and then our next task is to test it in a realistic network topology setting.

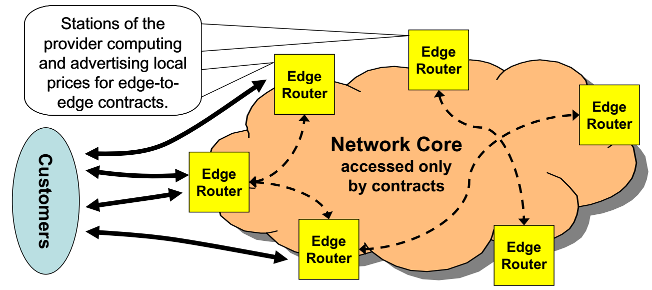

Fig. 2. Dynamic Capacity Contracting (DCC) framework.

III. Single-domain Architecture with Multiple Edge-to-Edge BFCs

Composition of better end-to-end paths requires flexibilities in single-domain contracting capabilities. In our design, we consider point-to-point edge-to-edge (g2g) contracting capabilities with unidirectional prices, which pose the question of "How should an ISP price its g2g contracts?". Though similar questions were asked in the literature [24], [1] for simple contracts, BFCs require new pricing methodologies. Availability of such flexible g2g contracting provides the necessary building blocks for composing end-to-end QoS paths if inter-domain contracting is performed at sufficiently small time-scales. This distributed contracting architecture gives more flexibilities to users as well, e.g., users can potentially choose various next-hop intermediate ISPs between two peering points that are involved in users' end-to-end paths [4].

A. Single-domain Architecture with Edge-to-Edge Contracts

We consider an ISP's domain as an abstraction of multiple g2g contracts involving buyer's traffic flowing from an ingress point to an egress point, i.e., from one edge to another. Our design abstracts the point-to-point QoS services provided by each ISP as a set of "overlay contracts" each being defined between peering points, i.e., ingress/egress points. Previous work showed that this kind of "edge-to-edge" dynamic contracting can be done in a distributed manner with low costs [1]. Figure 2 illustrates the big picture of such a distributed framework. Customers can only access the network core by making contracts with the provider stations placed at the edge points. A key capability is that an ISP can advertise different prices for each edge-to-edge contract it offers, where locally computed prices can be advertised with information received from other stations. Therefore, we abstract the point-to-point QoS services provided by each ISP as a set of "overlay contracts" each being defined between peering points, i.e., ingress/egress points.

Thus, for an ISP with N edge points, there can potentially be $N(N-1)$ advertisable g2g contracts. ISPs would in practice choose to have only a portion of their network capacity available for market, which means only a subset of these $N(N-1)$ g2g contracts will be advertised by the owner ISP. ISPs will have to find a balance on being able to advertise more contracts and manage the additional overhead due to these contracts, which we will look at next.

B. Multiple Edge-to-Edge BFC Definition and Management

We extend the forward contract definition and pricing framework to test the definition and its implications in a realistic network topology setting. The key question to examine is as follows.

To capture a realistic network topology, we will need to generalize from a single g2g contract abstraction of the network to a set of g2g contracts. For this, appropriate formalization will be necessary, along with information to support the formalization. A "multiple contracts" abstraction will be created, where the available capacity of each g2g contract is modeled, along with a pair-wise interaction of available capacities of g2g contracts to denote the intensity of overlap between the contracts. Definition and pricing of the bailout forward contract terms will be implemented for each contract. However, the multiple contracts abstraction will require the ISP's network topology information, where interactions between the g2g paths are known. Thus, an intensity of overlap will help determine how much g2g capacity is available for a g2g contract C^i, given the existing committed contracts crossing (i.e., overlapping) C^i's g2g path.

1) Multiple g2g BFCs: In a multiple contracts abstraction of the network, the time-dependent demand for spot contract on each g2g path is modeled by, μ_t^i, and the available capacity on each g2g path is modeled by, A_t^i. As described in the previous section, the price of the spot contract is a non-linear transformation, $S_t^i = f(\mu_t^i, A_t^i)$ (in \$/Mbps/s). An intensity of overlap, ρ_t^{ij}, models the correlation between the contracts and a predictive model for A_t^i as the bailout factor are used to define and price the bailout forward contracts on each g2g path of the network.

Following the mathematical formalization developed for the single g2g path, the time-dependent demand for spot contracts on each g2g path is defined as,

$$d\mu_t^i = \gamma^i(m^i - \mu_t^i)dt + b_1^i \mu_t^i dW_t^{1i}, \tag{13}$$

and the available capacity on the g2g path as,

$$dA_t^i = \beta^i(\overline{A}^i - A_t^i)dt + b_2^i A_t^i dW_t^{2i}, \tag{14}$$

where the two set of Wiener processes $W^{1\cdot}$ and $W^{2\cdot}$ are taken to be uncorrelated. The intensity of overlap describing the correlation between available capacity on each g2g path is captured by correlation between the driving Wiener processes as,

$$dW^{2i} dW^{2j} = \rho^{ij} dt, \tag{15}$$

where ρ^{ij} is the **intensity of overlap** describing the shared resources between path i and path j. As before, the m^i is the long-run mean for demanded bandwidth on i^{th} g2g path and $\overline{A}^i$ is the long-run mean for available bandwidth on the path.

Maintaining the same choice of demand profile for each g2g path gives the spot price to be the following function of μ_t^i and A_t^i,

$$S_t^i = P(\frac{\mu_t^i}{A_t^i}) = \int_0^{\mu_t^i/A_t^i} p^*(q)dq, \tag{16}$$

where $p^*(q)$ is the optimal price schedule in the nonlinear pricing methodology as before. Applying rest of the derivation as in the single g2g path case, the price of a bailout forward, $f^i(S_t^i, t; T^i)$, at some time t, maturing at a future time, T^i, satisfies the following partial differential equation.

$$\frac{\partial f^i}{\partial t} + \frac{1}{2}p^2(\frac{\mu_t^i}{A_t^i})((b_1^i)^2(\frac{\mu_t^i}{A_t^i})^2 + (b_2^i)^2(A_t^i)^2)\frac{\partial^2 f^i}{\partial S^2} + \frac{\partial f^i}{\partial S_t^i} r S_t^i - r f^i = 0, \tag{17}$$

along with the end condition,

$$f(S_T^i, T^i) = (S_T^i - F^i)\mathbf{I}_{\{A_T^i > Th^i\}}, \tag{18}$$

where T^i is the time of delivery of service in future for the i^{th} g2g path, F^i is the corresponding forward price, and $\mathbf{I}$, as before, is the indicator function for no bailout defined in terms of a threshold level, Th^i. The solution of the above equation is obtained as follows,

$$f(S_0^i, 0) = E[e^{-rT}(S_T^i - F^i)\mathbf{I}_{\{A_T^i > Th^i\}}]. \tag{19}$$

We obtain the forward price, F^i, for each g2g path by equating the above equation to zero and solving for F^i.

$$F = \frac{1}{P(A_T^i > Th^i)} E[S_T^i \mathbf{I}_{\{A_T^i > Th^i\}}], \tag{20}$$

where S_t^i evolves in the risk-neutral world. Therefore, as opposed to the single g2g path case, when contracts are defined on multiple g2g paths, the forward price of a g2g path is modified by the extent that evolution characteristic of A_t^i is affected by variability in the available capacity in other g2g paths, dictated by the intensity of overlap between paths.

2) Intensity of Overlap - ρ^{ij}: To evaluate the risk involved in advertising a particular g2g contract, knowledge of the interactions among crossing flows within the underlying network is crucial. As shown in the previous subsection, we develop our multiple g2g BFC terms based on the assumption that an intensity of overlap, ρ^{ij}, abstractly models the correlation between flows i and j. High correlation means that flows i and j are tightly coupled and share more of the network resources on their paths. In other words, an increase in flow i's traffic will adversely affect the available g2g capacity for flow j and vice versa.

We construct the correlation information among the g2g contracts as a square matrix of overlapping links. Each entry of ρ^{ij} reflects the overall effect of flow i on flow j which is the result of the contention that takes place on common links that two flows overlap on their e2e paths. Contention becomes severe if a race condition exists between flows for limited bandwidth on a link. We model this contention as being dominated by the *severity of contention* at the bottleneck link on the g2g path. Thus, we pick the severity of contention on the most utilized common link as the indicator of the correlation between the two overlapping flows. In our calculation, we also reflect the utilization level of bottleneck link as an indicator of severity of race condition among the flows.

Also, we consider the *asymmetric* characteristic of the overlaps arising due to the amount of individual traffic which are not necessarily equal. So, the effect of flow i on flow j, is not necessarily equal to the effect of flow j on flow i. In that sense, the effect of flow i on j is proportional to the ratio of traffic that flow i generates to the overall traffic generated by this flow pair.

Thus, we model the correlation between flows i and j as:

$$\rho^{ij} = U_{link} \times \left(\frac{\tau_i}{\tau_i + \tau_j} \right)$$

where τ_k is the portion of bandwidth that flow k can have according to max-min fair share among all flows passing through the common bottleneck link, and U_{link} is the utilization of the bottleneck link. To calculate τ_k for flow k, first we calculate bandwidth distribution over every single link using e2e demand for flow k (i.e., μ_t^k) and the available link capacities (i.e., $C_{N\times N}$). More specifically, on the common bottleneck link, we distribute the available capacity to all passing flows according to max-min fair share. Then, we distributed the excess capacity evenly across all the flows until no excess capacity is left on the link. This strategy makes τ_k being the minimum capacity allocated to flow k over all links it passes through.

IV. Performance Evaluation

Our performance study attempts to reveal answers to the following questions:

- *Robustness of g2g BFCs:* What is the probability that a g2g BFC will break due to a link/node failure in the ISP's network?
- *Efficiency of Network QoS:* There is a tradeoff between the risk undertaken to provide a better service (e.g., longer contracts with larger capacity promise) and the loss of monetary benefit due to bailouts. In comparison to simple contracting, what are the additional expected revenues, profits, or losses of the ISP due to BFCs?

A. Network Model

In our experimental setup, we first devise a realistic network model with Rocketfuel's ISP topologies [25], shortest-path intra-domain routing, and a gravity-based traffic matrix estimation. We assume that the QoS metric of BFCs is the g2g capacity. We focus on developing our network model to reflect a typical ISP's backbone network. Crucial components of a network model include (i) a realistic *topology* (i.e., adjacency matrix, link weights, link propagation delays, link capacities) and (ii) a realistic *traffic matrix*. We first calculate a routing matrix R for the ISP network from the link weight information. With a realistic traffic matrix T, we can then calculate the traffic load pertaining to individual links by taking the product of T and R. We use this realistic network model to identify a demand (i.e., μ) and supply (i.e., A) model, which we use to develop multiple g2g BFCs.

1) Methodology: For a network with N nodes, L links, and $F = N(N-1)$ flows, let $T_{N\times N}$ be the traffic matrix. If there exists a positive flow from ith node to jth node, then $T_{i\times j}$ is the traffic rate in Mb/s from ith node to jth node; if not, then $T_{i\times j}$ is 0. Let $\lambda_{F\times 1}$ be the traffic vector, which is the vectorized version of $T_{N\times N}$ such that $\lambda_{(i-1)N+j} = T_{i\times j}$ where $i, j = 1..N$. Let $R_{F\times L}$ be the routing matrix, where $R_{i\times j}$ is 1 if the ith flow traverses the jth link. If not, $R_{F\times L}$ is 0. The network model requires the following inputs:

- *The traffic matrix:* $T_{N\times N}$
- *Topology information:* Adjacency matrix $Adj_{N\times N}$, link weight matrix $W_{N\times N}$, link propagation delay matrix $S_{N\times N}$, link capacity matrix $C_{N\times N}$

Our network model takes the following steps to calculate a baseline where all the g2g traffic can be served feasibly:

- *Step 1:* Construct the *routing matrix* $R_{F\times L}$ based on shortest path first (Dijkstra's) algorithm using the topology information $Adj_{N\times N}$ and $W_{N\times N}$.
- *Step 2:* Form the *traffic vector* $\lambda_{F\times 1}$ from $T_{N\times N}$.
- *Step 3:* Calculate the *traffic load on each link* by performing the matrix operation $Q = R^T\lambda$, where $Q_{L\times 1}$ is the link load vector (in Mb/s).
- *Step 4:* Check the *feasibility* of the traffic load and routing. If any link's capacity is less than the load on to that link, then we fix the infeasibility by increasing the capacity of that link.

2) Topology: To obtain some of the topology information, we used the Rocketfuel [25] data repository which provides router-level topology data for six ISPs: Abovenet, Ebone, Exodus, Sprintlink, Telstra, and Tiscali. Specifically, it provides Adj, W, and S for the six ISPs, but an estimation of C is not provided. Table I shows a summary of the topology information for the six Rocketfuel topologies. We updated the original Rocketfuel topologies such that all nodes within a PoP (assuming that a city is a PoP) are connected with each other by adding links to construct at least a ring among routers in the same PoP.

3) BFS-Based Link Capacity Estimation: In order to assign estimated capacity values for individual links of the Rocketfuel's topologies, we use a technique based on the Breadth-First Search (BFS) algorithm. We, first, select the maximum-degree router in the topology as the center node for BFS to start from. After running BFS from the max-degree router, each router is assigned a *BFS distance* value with respect to the center node. The center node's distance value is 0.

Given these BFS distances, we apply a very simple strategy to assign link capacities: Let the BFS distances for routers i and j be d_i and d_j respectively. For the links (i, j) and (j, i) between the routers i and j, the estimated capacity $C_{i,j} = C_{j,i} = \kappa[\max(d_i, d_j)]$ where κ is a decreasing vector

TABLE I
ROCKETFUEL-BASED ROUTER-LEVEL ISP TOPOLOGIES.

ISP	# of Routers	# of Links	Degree (avg/max)	BFS Distance (avg/max)	Degree Threshold	BFS Distance Threshold	# of Edge Routers	Max. # of g2g Contracts
Abovenet	141	922	6.6/20	2.3/4	9	3	108	11,556
Exodus	79	352	4.5/12	3.0/5	6	4	60	3,540

of conventional link capacities. In this paper, we used: $\kappa[1] = 40Gb/s$, $\kappa[2] = 10Gb/s$, $\kappa[3] = 2.5Gb/s$, $\kappa[4] = 620Mb/s$, $\kappa[5] = 155Mb/s$, $\kappa[6] = 45Mb/s$, and $\kappa[7] = 10Mb/s$. So, for example, a link between the center router and a router with BFS distance 5 will be assigned 155Mb/s as its estimated link capacity. Similarly, a link between routers with distances 1 and 3 will be assigned with a capacity estimation of 2.5Gb/s. The intuition behind this BFS-based method is that an ISP's network would have higher capacity and higher degree links towards center of its topology. This intuition is well-supported by the recent study [26] showing that router technology has been clearly producing higher degree-capacity combinations at core routers in comparison to the edge routers.

4) Traffic Model: A crucial piece in modeling an ISP network is the workload model, i.e., a traffic matrix. In addition to being realistic in size, each traffic flow in the network model must reflect the traffic from edge router to another edge router. Thus, there are two important steps in constructing a reasonable traffic matrix. First, we identify the edge routers from the Rocketfuel topologies by picking the routers with smaller degree or longer distance from the center of the topology. To do so, for each of the Rocketfuel topologies, we identified *Degree Threshold* and *BFS Distance Threshold* values so that the number of edge routers corresponds to 75-80% of the nodes in the topology.

Second, we use gravity models [27], [28] to construct a feasible traffic matrix composed of edge-to-edge (g2g) flows. The essence of the gravity model is that the traffic between two routers should be proportional to the product of the populations of the two cities where the routers are located. We used CIESIN [29] dataset to calculate the city populations. We construct an initial traffic matrix based on the gravity model using populations of the cities, and then adjust the BFS-bases link capacity estimations (see Section IV-A3) so that traffic load on individual links are feasible. This method of generating traffic matrices based on gravity models yields a power-law behavior in the flow rates as was studied earlier [30], [27]. We assume that this final traffic matrix reflects the state of the network in a steady state condition. During the simulation, we base our work on this initial condition and analyze the transitions from this initial state of the network.

B. Model Analysis

We implement our model analysis on two of the Rocketfuel topologies, the Exodus and the Abovenet. Since the results obtained for the properties of the BFCs in the two topologies are similar, we focus on presenting detailed results for the former. In the Rocketfuel's Exodus topology, we used data for a total of 372 g2g paths to calibrate the mathematical model for developing the definition and pricing of BFCs. It is possible

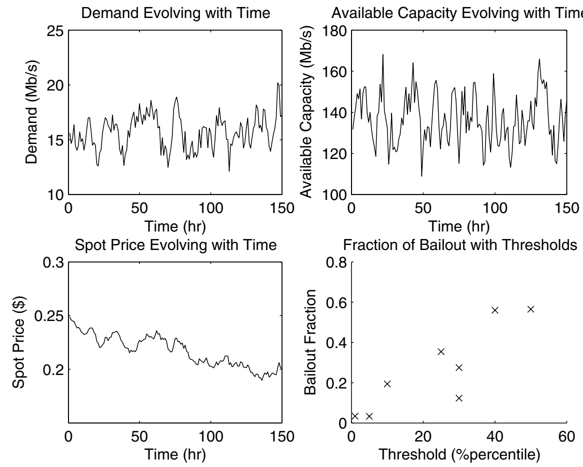

Fig. 3. (i) One sample demand evolution for the next 5 days; (ii) Available capacity evolution for next 5 days; (iii) Price of spot contract; (iv) Probability of bailout as function of Threshold.

Link	Forward Prices	$E[S_T]$	Prob$\{S_T>F\}$	Prob$\{A_T<Th\}$
1	0.20609	0.20305	0.502	0.09
2	0.27162	0.24982	0.449	0.065
3	0.21293	0.21213	0.486	0.079
4	0.25039	0.24825	0.477	0.094
5	0.22177	0.21211	0.465	0.093

Th = 15%

Fig. 4. Sample BFC prices for five g2g paths.

to apply the price analysis to a much larger set of g2g paths, however we select a relatively smaller set of paths for ease of presentation. For these paths, we use summary statistics for available capacity, A_t^i, and demanded bandwidth, μ_t^i, such as means and standard deviations, to calibrate the models (Eqns. 13 and 14). Some sample paths from calibrated models are shown in Figure 3. The intensity of overlap estimates of ρ^{ij} are used to capture the linkage in available capacity of various g2g paths.

We begin our model based analysis of the BFC framework from analyzing single g2g paths. For a single g2g path, we display sample paths for the evolution of available capacity, the bandwidth demand and the price of the spot contracts in panels (i)-(iii) of Figure 3. Based on a calibrated model for demand, available capacity and spot prices given by the derivation of Section II, we determine the price of BFCs for a range of choice of the thresholds defining the bailout. For simplicity, all BFCs mature 5 days in the future and are defined for the same threshold for bailout. The probability of bailout, plotted in panel (iv) of Figure 3, shows an increasing trend with an increasing threshold level, as expected. The thresholds are defined in terms of a low percentile of the distribution of available capacity.

We report the price of the BFC for a sample of 5 g2g paths in Figure 4, determined within the single g2g framework of

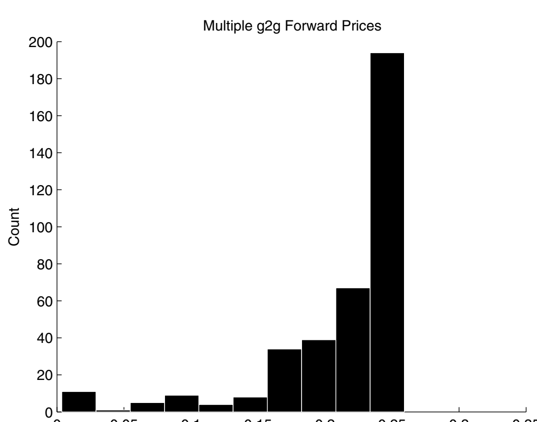

Fig. 5. Histogram for Forward prices across the 372 g2g paths

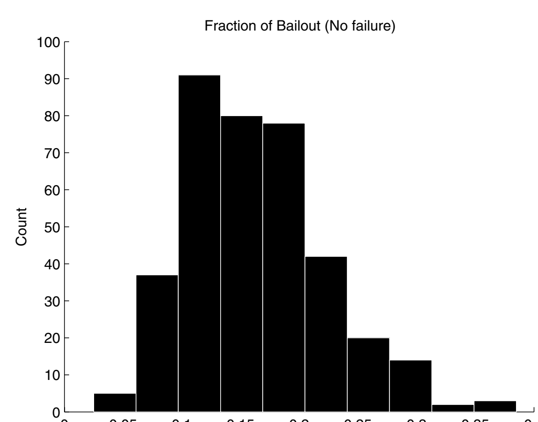

Fig. 6. Histogram of fraction of g2g paths bailing out in 1000 runs of simulation

Section II. The BFC delivers service 5 days in the future with the threshold for bailout set at 15^{th} percentile of the available capacity. The objective in this display is to indicate how the forward prices compare with the spot contract prices. On average the forward prices remain slightly above the spot price at maturity, however the risk in future spot prices entails that the forward prices will be below future spot prices by a probability exceeding 45% (see the 4th column in Figure 4). We also indicate for these 5 g2g paths, the probability of BFCs to bailout in the last column. For these paths, the probability of bailout is well-bounded by 10%.

We next implement the multiple g2g path framework for BFC pricing of Section III to analyze the effect of the interaction between the paths that is captured in terms of the intensity of overlap, ρ^{ij}. The forward price of a set of 372 paths is determined and plotted in a histogram in Figure 5. As the histogram suggests, although there is variability in the forward prices across the set of paths, many of the paths pick a forward price in a similar range, in this case approximately around 0.25. This suggests that a distinct forward price for each of the thousands of g2g paths in a topology may be an overkill, and hence, directs us to a much desired simplicity in the forward pricing structure.

Bailout characteristics are the next important feature to study to evaluate the BFC framework. We plot the fraction of 372 g2g paths bailing out in 1000 runs of simulation in a histogram in Figure 6. The mean fraction of g2g paths bailing out from this histogram is 0.16403, or 16.4%. To highlight which specific paths bail out in these simulation runs, we also plot the number of times each link bails out in the 1000 runs of simulation in Figure 7. There are a few paths that clearly stand out in bailing out most frequently, marking the 'skyline', while most of the paths cluster in the bottom. Another important measure of performance is how much revenue is lost when the BFC on a g2g path bails out. This is shown also by each g2g link in Figure 8. Clearly, the pattern of clusters here will be similar to Figure 7, however the height of the bars is a function of the forward price of each g2g path and how frequently it bailed out in the runs of simulation.

Finally, we conduct a robustness analysis of the BFC

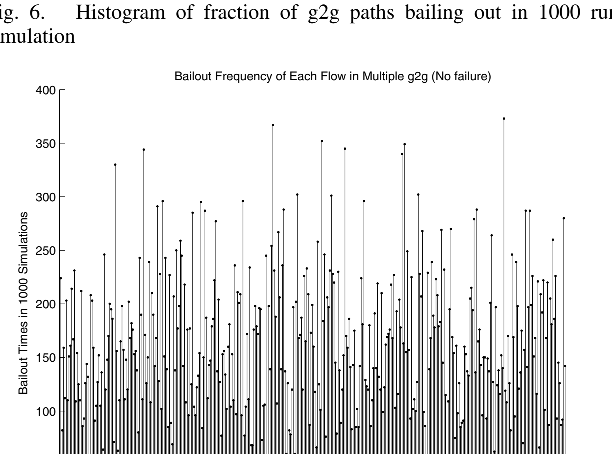

Fig. 7. Display of number of times each of the 372 g2g paths fail in the 1000 runs of simulation

framework to test how the contracts, determined based on a base network characteristic scenario, perform should the network suffer various modes of failure. We consider three failure modes created by failing specific high load links for this analysis. The failures change the network characteristics in the model by changing the intensities of overlap, means and standard deviations of available capacity. We recalibrate the mathematical models of Section III and evaluate the BFC

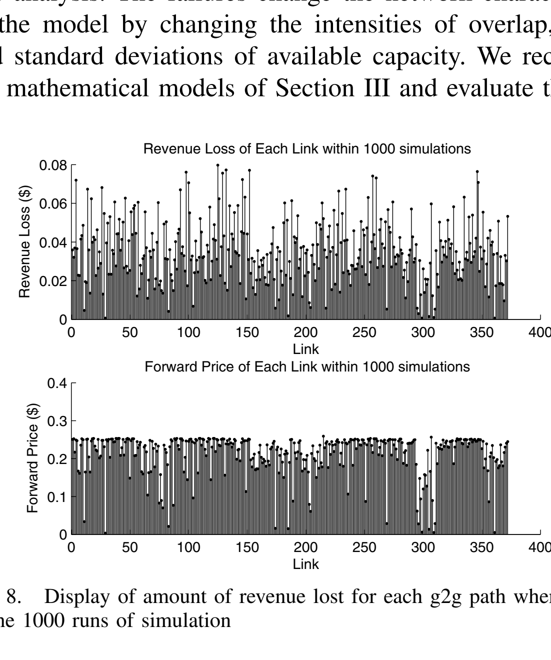

Fig. 8. Display of amount of revenue lost for each g2g path when it failed in the 1000 runs of simulation

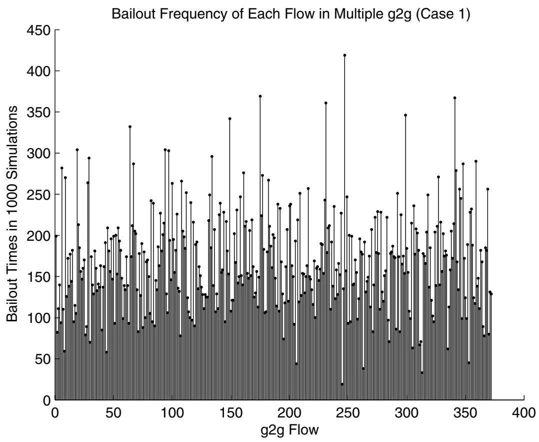

Fig. 9. Display of bailout of BFCs on 372 g2g paths under Failure mode 1.

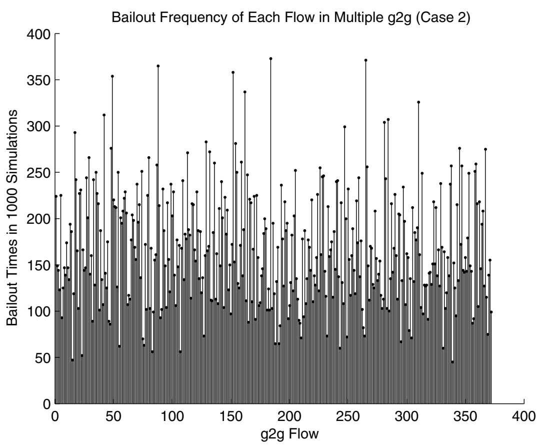

Fig. 10. Display of bailout of BFCs on 372 g2g paths under Failure mode 2.

bailout behavior. Figures 9- 11 show the number of times each of the 372 BFCs bail out in the 1000 runs of simulation within each failure mode. The height of the 'skyline' described by the most frequently bailing out g2g paths is comparable, however, the clustering at the base appears slightly intensified in cases 1-3. Figure 12 summarizes the comparison of loss in revenue and fraction of paths bailing out in the four scenarios - the base case and the three failure modes. There is only a small increase in the fraction of paths bailing out in the failure modes, as well as only a small reduction in revenue from the base case. This is supporting evidence for the robustness of the BFC framework.

C. Network Analysis

In the previous subsection we showed how our multiple g2g BFC definitions can perform when traffic demand and g2g available capacity processes may change. We studied the performance under three different failure modes, each corresponding to a major link failure in the Exodus topology.

In this subsection, to test the viability of our BFC definitions, we evaluate the performance of our BFCs when a failure occurs in the underlying network, i.e., Exodus. Specifically, we take the baseline BFC definition and identify the fraction of g2g BFCs getting invalidated (i.e., to be bailed out) due to a link failure in the underlying network topology. Notice that this analysis *conservatively* assumes no a priori knowledge of the failure scenarios.

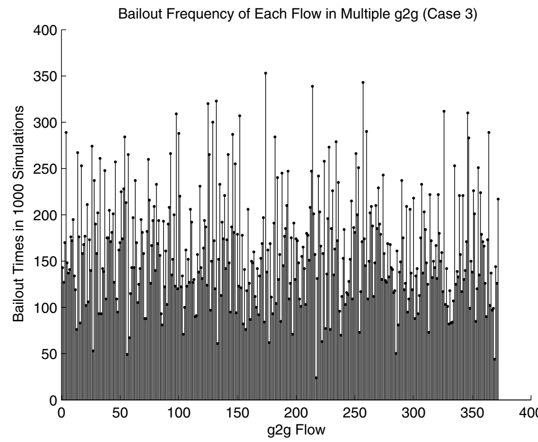

Fig. 11. Display of bailout of BFCs on 372 g2g paths under Failure mode 3

Case	Expected Total Revenue	Mean Bailout Fraction
Artificial No Bailout or Failure Case	**95.7464**	0
Base Case Bailout Scenario	80.43655	0.16403
Bailouts in Failure Mode 1	78.98833	0.16505355
Bailouts in Failure Mode 2	81.34074	0.163980954
Bailouts in Failure Mode 3	80.98213	0.16676308

Fig. 12. Comparison of revenue loss and fraction of BFCs bailing out due to link failures.

To perform the analysis we take down each link of the Exodus topology one by one. After each link failure, we determine the effective g2g capacity each BFC will be able to get based on max-min fair share (and equal share with the excess capacity). We then compare this effective g2g capacity with the bailout capacity thresholds identified for each g2g BFC (based on the formulation in Section III-B).

Figure 13 shows the distribution of the fraction of bailed out BFCs after a link failure in the Exodus network. The distribution roughly follows a similar pattern observed in Figure 6 which was obtained under a dynamic demand-capacity pattern. Our experimental evaluation in Figure 13 clearly shows that our abstraction of intensity of overlap can be practically used to ease the process of pricing multiple g2g BFCs. This is also evident from the average bailout fraction being close to the one we obtained from the model analysis, i.e., 16.4%. Another key

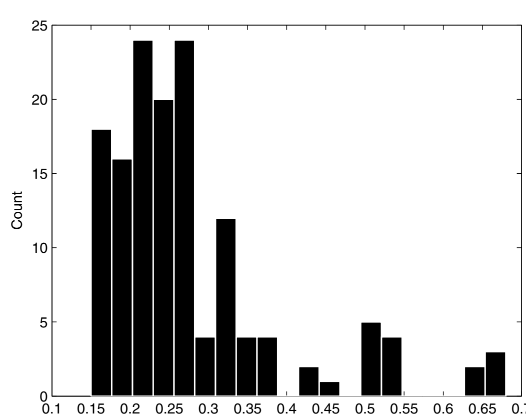

Fig. 13. Histogram of the fraction of g2g paths bailing out after a link failure in Exodus network. The average fraction of bailed out BFCs is 27.6%.

observation here is that our multiple g2g BFC definitions are robust and can survive even in a predominantly hub-and-spoke network topology such as Exodus.

The reason why our network analysis results in an approximately 11% higher bailout rate is due to the fact that the intensity of overlap abstraction does leave out some of the realistic situations for the sake of easing the multiple g2g BFC pricing computations. One reasonable strategy to follow can be to define BFC terms with more conservative values than the ones obtained based on intensity of overlap approximations.

V. Summary

In this paper, we propose a single-domain edge-to-edge (g2g) dynamic capacity forward contracting mechanism with bailout options. In this contracting mechanism, a network service provider can enter into forward bandwidth contracts with its customers, while reserving the right to bail out (for a pre-determined penalty) in case capacity becomes unavailable at service delivery time. We show how the risk-neutral contract prices can be derived for a domain with multiple g2g contracts, which may have correlated demand processes and capacity variations, potentially due to overlapping paths. The proposed risk-neutral contract pricing mechanism allows the ISPs to appropriately manage risks in offering and managing these contracts.

In the proposed architecture, providers can advertise different prices for different g2g paths, thereby providing significantly increased flexibility over the current point-to-anywhere prices. Experiments on a Rocketfuel-based realistic topology shows that our g2g bailout contracting mechanism is quite robust to individual link failures in terms of the bailout fraction and revenue lost. Future work includes a more thorough evaluation of our g2g bailout forward contracting over a larger set of ISP topologies, and extending the concepts to inter-domain for establishment of end-to-end QoS contracts.

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