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Dynamic Bandwidth Provisioning Economy of A Market-Based IP QoS Interconnection: IntServ–DiffServ

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Abstract

With the evolution of the telecommunications infrastructure and the emergence of Internet bandwidth as a commodity market, backbone ISPs will encounter a new set of questions regarding with bandwidth and QoS management for the QoS interconnection. Those questions include: How do the different QoS mechanisms affect the resource and quality allocations over the connection? How will the interconnection policy and schedule differ for different demand characteristics for different network services? What will be the quantitative method of resource allocation of QoS services when cost sharing is necessary for interconnection? How would network profitability, consumer surplus and total surplus differ for QoS interconnection with or without the existence of competitive market information such as price and price index from the bandwidth commodity market such as www.ratexchange.com? These and other important questions arise with the evolution of the Internet as both a network of QoS networks and a market for the bandwidth.

This paper proposes a market based bandwidth management model for DiffServ networks with the implementation of bandwidth brokers. We formulate the optimization problem for the optimal policy of the DiffServ network's on resource allocation. We use the price data of bandwidth commodity markets to capture the opportunity costs for the DiffServ's network services. The different opportunity costs are measured and estimated based on the results of network simulation using statistics of traffic flow measured from a current Internet backbone. By using these economic models, we numerically simulated the behavior of a backbone ISP network provider to optimize its payoff strategies for different assumptions. We test several hypotheses related to the bandwidth management of QoS interconnection based on the results of numerical simulation for different sets of market and demand assumptions. We expect that this paper will be useful to both backbone ISP network planners and the regulators concerning with the interconnection issues of the next generation Internet.

Keywords: IP QoS, IntServ, DiffServ, QoS interconnection, QoS Economics, Bandwidth Market, Bandwidth management, QoS Allocation. Internet Settlement

1 Introduction

The interconnection of the next generation Internets is hindered by various new problems that are different from the issues of conventional telephone interconnection and the best-effort Internet interconnection. Those challenging issues of the next generation Internet interconnection include hybrid QoS interconnection, service coordination, traffic engineering and QoS allocation among the heterogeneous QoS-support networks.

There is an important rationale for examining the hybrid QoS networks in this study. Most importantly, the technical motivation of hybrid QoS management in the next generation Internet is scalability. Some hybrid QoS-network architectures designed to enhance the scalability of the QoS-support networks have been proposed by the IETF (Internet Engineering Task Force) ISSLL (Integrated Services over Specific Link Layer) working group. Those hybrid network approaches include IntServ (Integrated Service)–DiffServ (Differentiated Service), IntServ–ATM (Asynchronous Transfer Mode) and other variants. Yet these approaches have not addressed the potential problems of QoS interconnection mechanisms and bandwidth management when a QoS connection traverses hybrid-QoS networks, which affects the optimal interconnection strategies of networks. In addition, different QoS network services may have different cost characteristics (opportunity costs in this study) for different levels of network performance. This study investigates how the opportunity costs of different QoS network services characterize the optimal interconnection strategies of individual network service providers.

In this paper, we present the network economic study for the dynamically provisioned QoS interconnection of IntServ–DiffServ networks. This study, especially, is concerned with the issues of opportunity costs of different DiffServ QoS classes and consequent economic effects of dynamic bandwidth management mechanisms for the DiffServ networks' network interconnection in the existence of bandwidth commodity market.

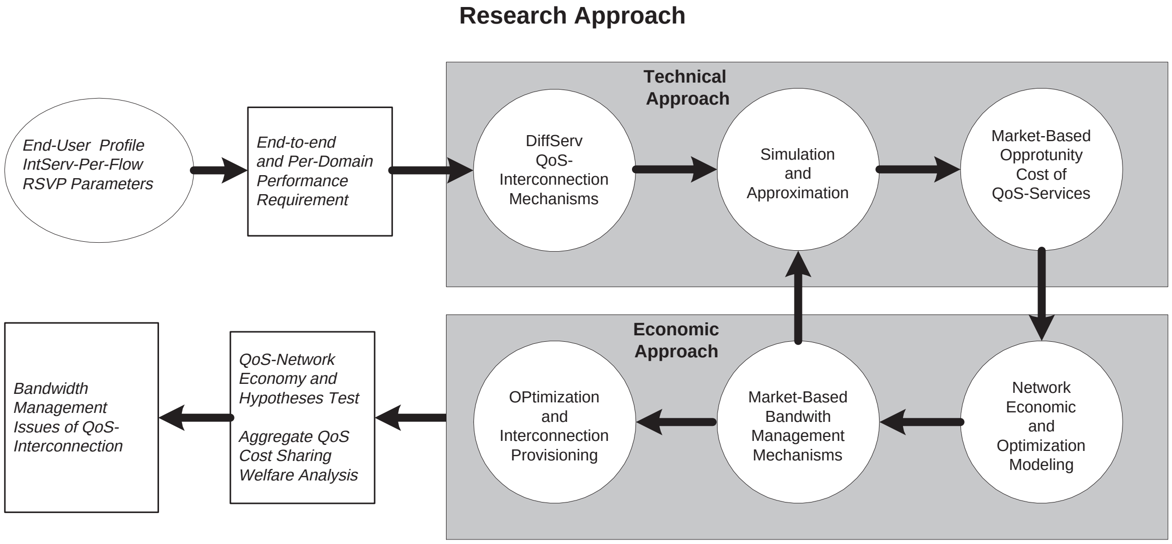

Figure 1: Technico-Economic Research Approach

Figure 1 illustrates the research approach taken in this study. Many applications will demand a variety of QoS requirements and represent those requirements in the form of the profiles of network users such as RSVP (ReSource reserVation Protocol) parameters in IntServ-DiffServ interconnection. Those QoS needs can be expressed as the end-to-end system or network domain performance (Per-Domain-Behavior performance: PDB performance) requirement and translated into the demand on the network resources such as the bandwidth for the different service classes in the DiffServ networks.

Focusing on the market-based bandwidth management of DiffServ network interconnection, we use the method of computer simulation to assess the proxy opportunity costs for the different types of network services of DiffServ for the different scenarios of market and interconnection condition. For the different technical factors of the interconnecting networks such as capacity, and various QoS requirement (worst case delay, average delay, and packet loss ratio), we perform iterative simulations to assess the opportunity costs of QoS network services with the different bandwidth market price input. The assessed opportunity costs for different DSCP classes and service levels are statistically tested to check the differences among them. Then we formulate the profit optimization problems of the DiffServ's BMP (Bandwidth Management Point) using marginal cost pricing rules for the QoS bandwidth allocation for the limited capacity interconnection.

By solving the optimization models, we numerically simulate the bandwidth management of the DiffServ network to investigate the effects on the network welfare and consumer surplus of the QoS interconnection bandwidth management. Several hypotheses are proposed and tested through this network economic analysis. The network economic analysis of interconnection includes issues of cost allocation, network welfare and the cost and benefits of market-based network resource exchange and trading mechanism. A set of results from economic analysis related to QoS interconnection conclude this paper with the further bandwidth management issues of QoS-interconnection for the next generation Internet and commodity market economy.

2 Technical Overview

In this section, we review some of the relevant technical details for the service interconnection and bandwidth management mechanisms for the hybrid IP QoS IntServ-DiffServ network interconnection. The interconnection network architecture, feature system components and operational mechanisms for the hybrid QoS interconnection are presented here.

2.1 IntServ-DiffServ Interconnection Architecture

The IntServ-DiffServ architecture we are considering in this study is the case when IntServ end-to-end service is served over DiffServ network, as was proposed in [1]. There are two main motivations of this scenario: The end-to-end service accomplishment of aggregate QoS support of DiffServ and the increased scalability of RSVP with such aggregate QoS guarantees to IntServ users.

As illustrated in Figure 2, the IntServ-DiffServ interconnection network consists of flowing major components:

- In the IntServ-DiffServ architecture proposed, both sending and receiving hosts are able to use RSVP signaling. In general, a QoS process of the host's operating system generates RSVP in response to the network and on behalf of application.
- Edge routers in IntServ are adjacent to the DiffServ network region. The edge routers can act as admission control agents for RSVP messages on the behalf of the DiffServ's bandwidth management based on the resource availability within the DiffServ network and the policy.
- Border routers in the DiffServ region reside next to the edge router of the IntServ. The main functions of those border routers are to configure the tunnel within the DiffServ network, and to police submitted traffic based on the SLS[1] and SLA[2]
- An IP-DSCP (Differentiated Service Code Point) Provisioning Tunnel encapsulates IP traffic in another IP DSCP header as it passes through the tunnel; the presence of these two IP headers is a defining characteristic of IP tunnels. The inner IP header is that of the original traffic; an outer IP header is attached and detached at tunnel endpoints. In general, intermediate network nodes between tunnel endpoints operate solely on the outer IP header, and hence DiffServ-capable intermediate nodes can only access and modify the DSCP field in the outer IP header (e.g., for an encrypted tunnel, interior nodes cannot access the inner IP header).
- A Bandwidth Management Point (BMP) makes a decision on the provisioning for the DiffServ network and performs DSCP assignment, admission control, traffic conditioning router configuration and class profiling based on the bandwidth management mechanism implemented. This agent allocates and controls the bandwidth share between different interconnecting networks and serving DSCP service classes. Therefore, the DiffServ network should be able to pass end-to-end RSVP messages and the BMP must be able to communicate, process and update the RSVP messages to support IntServ-DiffServ interconnection. This allocates and controls the bandwidth shares between interconnecting networks and different DSCP classes.

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[1] Service Level Specification (SLS) provides the technical specifications such as QoS, aggregate traffic profile and service provisioning

[2] Service Level Agreement (SLA) includes general terms and conditions with respect to the interconnection contract encompassing service availability, pricing, QoS specification and other legal and business issues.

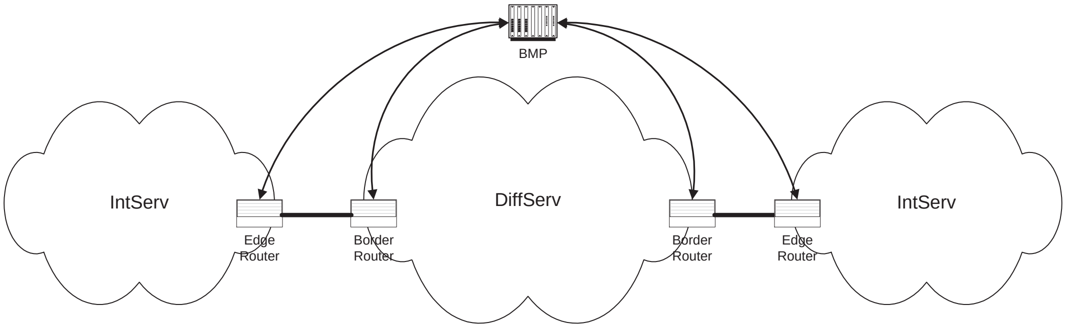

Figure 2: IntServ-DiffServ Interconnection Network Architecture

2.2 A Proposed Dynamic Bandwidth Provisioning and Management Mechanism

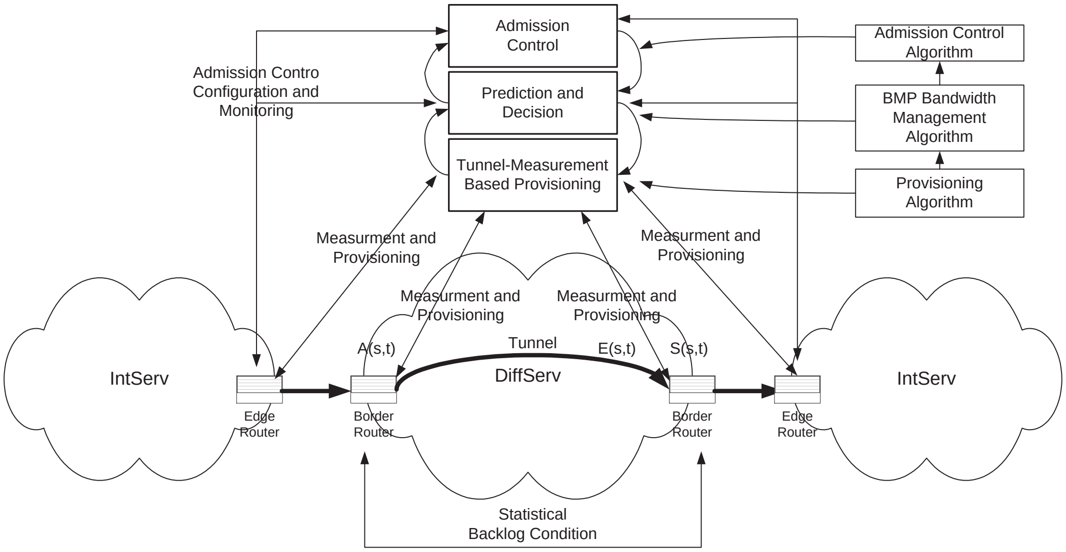

Figure 3: Measurement Based Tunnel Provisioning Mechanism

The proposed dynamic tunnel provisioning mechanism consists of algorithms of a measurement and provisioning, a bandwidth management and an admission control as illustrated in Figure 3. The measurement algorithm assesses the statistical behaviors of aggregate traffic over the connections. for prescribed intervals. Characterizing the statistical behavior of traffic demand and service capability, provisioning algorithm checks for the availability of expanding or shrinking the aggregation with an associated confidence interval to deal with the future uncertainty. Once the availability of updating the aggregation is conformed, the algorithm should consult and control with the bandwidth management and admission control algorithm.

The bandwidth management proposed in this paper uses a market based mechanism through the BMP of DiffServ domain. This market based mechanism control and manage the network resource based on the demand of network services and market value by using the economic model. This mechanism is inspired from the recent introduction of commodity market, dynamic contract for bandwidth and development dynamic policy service protocols such as COPS (Common Open Policy Service) Protocol.

In the proposed bandwidth management model, we define following key elements of the BMP architecture as illustrated in Figure 4. These are functional components and the physical network component could assume more than one functional entities:

Bandwidth Management Point (BMP), from the perspective of bandwidth management, BMP measures the current service demand and market values of the network resources. Using such measures, the BMP makes a decision or sets a policy for the admission control, network resource provisioning, SLS configuration and bandwidth marketing.

Bandwidth Measurement Base (BMB) is a MIB (Management Information Base) which collects traffic load measurements and demand statistics of the BMP domain. Management Creation Point (MCP) relates BMB with SLAs of interconnections.

Interior-BMP (I-BMP) is a processor which provide a mechanism of managing the network resources within a BMP domain. The network provisioning among different service classes and different users within a BMP domain using market information is one of key tasks of the I-BMP.

Exterior-BMP (E-BMP) is a processor which provide a mechanism of managing the interconnection SLS with other BMP domains and other interconnection points. Therefore, it is concerned with resource allocation and provisioning at the network boundary among multiple domains.

Service-Provisioning-Points (S-P-P) are the network nodes and interface where the I-BMP and E-BMP can configure with the their own management information and decision. The ingress and egress border routers of its own network or the outsourced network capacity from the commodity market could be such provisioning points.

SLS-Enforcement-Points (S-E-P) are the network nodes and interfaces that are involved in the inter-domain resource allocation (admission) based on the SLS. The I-BMP and E-BMP configure these points and have them perform the admission tasks (where SLS is enforced).

User-BMP-Interconnection-Point (UBIP) is the interconnection point where the user interconnection access networks (such as in IntServ) subscribe the aggregation network with BMP (such as in DiffServ with BMP).

Private BMP-BMP-Interconnection-Point (BBIP) is the network interconnection point where the bilateral SLS is negotiable and configurable through the inter-BMP communication.

Public BMP Interconnection Point (PBIP) is the independent interconnection peering point where a BMP domain can negotiate and configure the multilateral SLS with multiple networks through a single point.

Commodity Market Interconnection (CMI) is the interconnection achieved through the concept of a public market for network and capacity expansion such as in the commodity market of electricity. The aspects of interconnection in the CMI is virtually a list of offers from different providers with different interconnection locations. Each BMP negotiate, contract and configure its interconnection through this CMI with the information provided by MIP (Market Information Provider).

Market Information Provider (MIP) is an information manager which is concerned with bandwidth commodity market, gather the timely market data and make them available for trading and transaction. The MIP could provide value added service and information to the BMPs through the signaling to allow inter-BMP transaction and interconnection.

Market Information Interface (M-I-I) is an interface process of BMP to be connected to the MIPs and other BMPs' MII. This interface allows the BMP to signal with other market players about the market status (benchmark, availability and price) and statistics (global market trends, such as bandwidth index).

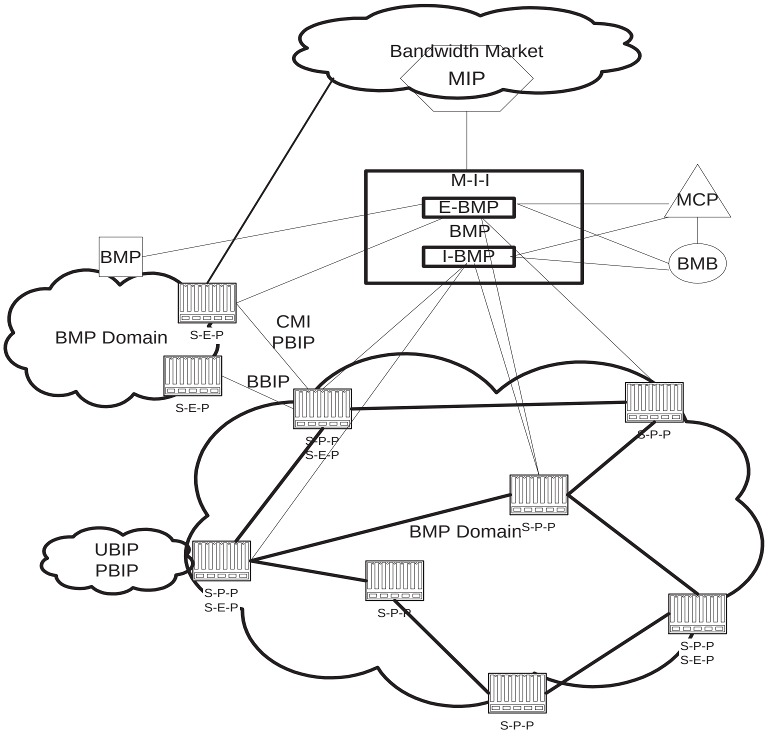

Figure 4: Market-Based BMP Domain Architecture

3 The Bandwidth Management Models and Processes

Designing the BMP operation mechanism of controlling the various network resources requires a set of processes and rules (market-based) for operational algorithm and control protocol. The operational mechanisms of BMP proposed consist of a set of following key process steps.

- Load Measurement and Demand Assessment
- Market Interface and Opportunity Cost Calculation
- Pricing and SLS Scheduling

3.1 Load Measurement and Demand Assessment

The following list includes the measurement and information that BMB will keep for the demand assessment process:

- Aggregate traffic envelope statistics over series of measurement interval for each IP-DSCP tunnel.
- Aggregate service envelope statistics over series of measurement interval for each IP-DSCP tunnel.
- Price scheduling associated with the traffic statistics for each tunnel.
- Demand elasticity for each service class (if known): Long-term statistic analysis also can provide the estimation on this.
- Peak pricing bound for each IP-DSCP tunnel contracted in the default SLS.
- Minimum and Maximum load bound for each IP-DSCP tunnel contracted in the default SLS.
- Accumulated token priority values for all the admitted traffic (IntServ flows) associated with each measurement interval for each IP-DSCP tunnel.

Using the collected information on the network usage, the BMP can characterize interconnecting networks' demand for different service classes in terms of provisioned service rates in kbps. The demand function that a BMP will use can be modeled by capturing the utility of the interconnecting networks on price through the measurement.

3.2 Market Interface and Opportunity Cost Calculation

In our mechanism, the optimization process of a BMP approximate the opportunity costs of differentiated services in the following ways. An opportunity cost in a network is the real sacrifice (internal to the ISP) of providing additional unit of a commodity (service) when a network (firm) must choose or allocate scarce goods like bandwidth for fixed capacity networks. Therefore, the opportunity cost of a resource allocation decision in the multi service network is the value of the best available service alternative. Consequently, understanding the opportunity costs for different types services that an ISP provides is important for the BMP for optimal resource allocation.

For the measured offered load and capacity of the network, the BMP will measure the different PHB classes opportunity costs in the unit of dollars per kbps per time. For any fixed capacity interconnection of a specific duration, the maximum usable bandwidth of IP-DSCP tunnel will be bounded at least by the usable bandwidth of overengineered network of the QoS requirement for that tunnel if the network only supports this type of traffic load. For example, if EF (5 msec) service can be utilized up to 30% (average) of a DS-3 interconnection using overengineering, the offered load of the same PHB still cannot exceed the upper bound even with differentiated services. The opportunity cost of the highest priority can be approximated as a function of the total capacity interconnection market commodity value divided by the IP-DSCP tunnel's achievable average utilization in kbps. Different opportunity costs of different quality achieved by different treatment of DSCP with different level can be calculated in such way when they are highest priority in the interconnection SLSs. The opportunity cost of the other priority will be also dependent on the available capacity of the interconnection. The available capacity for the certain priority can be stated as total capacity times (1 - utilization) of the higher priority PHB. Therefore, in similar way, the opportunity cost of this second priority PHB can be the function of the available interconnection capacity price (total interconnection price * available utilization for the second priority PHB) divided by the total PHB's achievable average utilization in kbps. This algorithm of the opportunity calculation means that the opportunity cost for the lowest or best effort PHBs opportunity costs will be approaching zero when the interconnection capacity is almost fully utilized by the higher PHB classes. This means the resource for the best effort traffic cannot be entirely utilized, so that a zero opportunity cost is incurred in putting it to productive use.

3.3 Edge Pricing and SLS Scheduling

The pricing of different network service class will play a key role in determining the resource allocation among different network service classes. This pricing schedule can be the control mechanism for the resource allocation (offered service selection and provisioning) among different revenue generation strategies (different PHB classes, and bandwidth sales) within the fixed capacity constrained network.

Here, we present the pricing scheduling mechanism for aggregate differentiated service based on the opportunity cost (aggregate pricing has the unit of $ per kbps per time, while flow based pricing has the unit of $ per call or flow per time). The dynamic pricing of interconnection is edge pricing [5] since the pricing is charged at the interconnection point using the proxy opportunity costs.

Figure 5 illustrates the opportunity cost based pricing mechanism for the differentiated services for the aggregate services. For each service at each interconnection point, the pricing schedule is determined for the predetermined pricing update interval for the interconnection. This pricing update interval should be selected as consistent with the provisioning and measurement interval. At the detected update period (triggered by the measurement or market price changes), the BMP recalculates the opportunity cost for each service and uses it for price scheduling. Using the appropriate bandwidth pricing and allocation optimization model depending on the SLS, the BMP finds the optimal price for each class that maximizes the BMP profit. By validating with the default SLS for the interconnection agreement, the BMP schedules the new price for the new update interval pricing at the interconnection point and configures the edge and core routers for the updated provisioning and admission control.

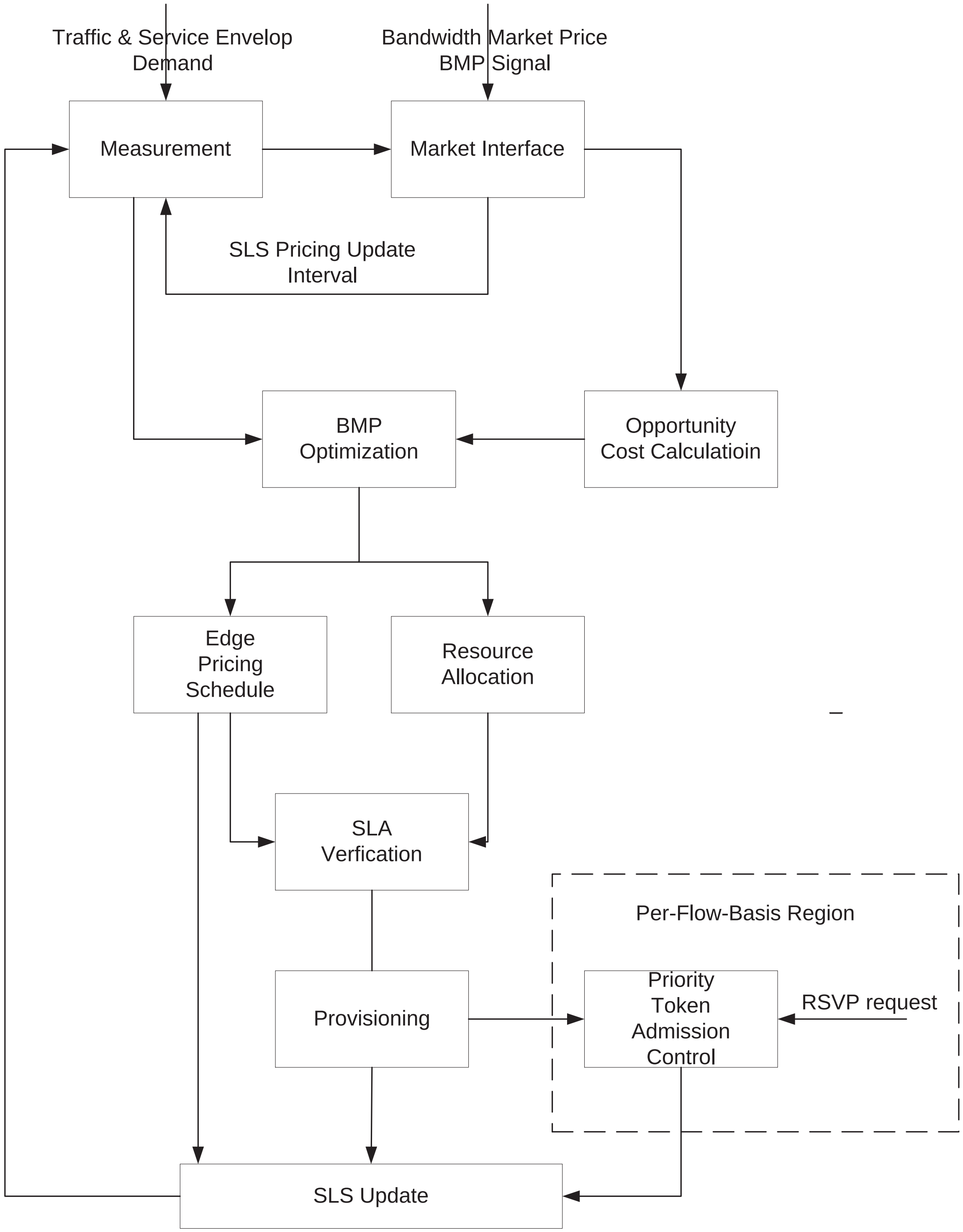

Figure 5: Opportunity Cost Based Pricing and SLS Update Mechanism

The revenue maximization pricing schedule for the individual service classes can be easily derived from the demand function analysis, however optimal profit maximization pricing for the different network service classes requires the observation of the opportunity costs of each service class. Differently valued demand and opportunity cost characteristics of different network services define different optimal pricing strategies and service selection. The optimal schedule for pricing and service classes can be determined in the aspects of network profit maximization or total surplus maximization (consumer surplus and network profit). The opportunity costs captured for different service classes and demand will define the price scheduling that maximizes network profit. From the economic theory, the fully competitive market will enforce the network's price at the level of opportunity cost which maximize the total welfare of network (consumer surplus and network profit).

Considering a network domain producing differentiated services i, we can find a pricing schedule interval selected so that a potential demand R_i at a price p_i stays fixed over the given interval. We assume that the aggregate service i perceives a benefit ν_i from the service and that ν_i is randomly distributed across the aggregate service i with a probability density function $r_i(\nu)$. If the density function is independent for each service i, then, for a given price p_i at the time interval δt, the normalized potential (expected from the measurement) demand can be expressed by

$$R_i(p) = \int_p^\infty r_i \delta\nu.$$

In the interconnection network, we assume that the service benefits are independent if the services are differentiated in term of its price and performance. For those services that can be replaced by other services (such as AF11 and AF12), we assume joint functional services. However, in the following pricing discussion, we assume the all the services i are differentiable to have a independent density function. The optimal pricing for the independently differentiated services of which the opportunity cost can be calculated can be formulated as follows:

$$\arg\max_{p_i} \quad \pi = \sum_{i=0}^{n} \int_0^T [p_i - f_i] R_i dt$$

where T is the pricing and provisioning interval, f_i is opportunity cost of service i for the fixed C interconnection interface capacity for T. This is an optimization problem of pricing over a time and we solve this optimization problem with interconnection constraint which is discussed in the next section.

3.4 Bandwidth Management Optimization Model

To represent per-settlement bandwidth management optimization problem for optimal edge pricing, consider a DiffServ network with a BMP. We consider a simple DiffServ IP network which treats each packet differently based on only two priority service set (EF and DF) in the DSCP tunnel. Then the first level optimization model for the specified example can be expressed in the following forms with the constraints:

$$\begin{aligned}
\max \quad & \int (p_{EF} - f_{EF}) R_{EF} e^{-\gamma t} v(t) + (p_{DF} - f_{DF}) R_{DF} e^{-\gamma t} v(t) dt \\
\text{s.t} \quad & f_{EF} R_{EF}, \quad f_{DF} R_{DF} \le IC_0 \\
& f_{EF} R_{EF} + f_{DF} R_{DF} \ge IC_0 \\
& f_{EF} \le p_{EF} \le p_{EF-MAX} \\
& 0 \le p_{DF} \le p_{DF-MAX} \\
& 0 \le R_{EF} \le R_{EF-MAX} \\
& 0 \le R_{DF} \le R_{DF-MAX} \\
& R_{EF} + R_{DF} \le C
\end{aligned}$$

The stated constraints imply the BMP's bandwidth management mechanisms and the network characteristics. The first constraint says that the individual opportunity costs f are limited to quantify the costs which are less than the market value of the interconnection IC_0. The second constraint represents the gain of the interconnection due to the differentiation of the service traffic since the IC_0 is the cost for best-effort interconnection data from the current market. The third and fourth constraints state that the selected price schedule p from the DiffServ interconnection is bounded with individual opportunity costs and demand price bound. The fifth and sixth constraints represent the bandwidth allowable for each service R are constraint with the demand characteristics for the interconnection shown the previous demand model. The last constraint shows the capacity limit C of the interconnection.

If the bandwidth demands are affected by the service prices, we need to consider demand functions. Suppose the following function is given.

$$R_i(p_i, t) = R_{i,max}\left[1 - \left(\frac{p_i(t)}{p_{i,max}}\right)^{\alpha_i(t)}\right]$$

This formula implies that any allowable bandwidth should be determined by the corresponding price of the service at each time. That is, a bandwidth does not directly depend on the time but on the price. This fact gives us a simplified form. The problem can be discretized. For each time t the subproblem will be an nonlinear programming problem. For each time, the current resource is independent of the resource at the previous time, and then the problem is partitioned into subproblems at each time. Such decomposition suggests a good solution method. Since at each time, the subproblem should be

$$\begin{aligned}
\max \quad & R_{i,max}[p_i - f_i]\left[1 - \left(\frac{p_i(t)}{p_{i,max}}\right)^{\alpha_i(t)}\right]\Delta t \\
\text{s.t} \quad & f_{EF,t}R_{EF,t} \leq IC_0 \\
& f_{DF,t}R_{DF,t} \leq IC_0 \\
& f_{EF,t}R_{EF,t} + f_{DF,t}R_{DF,t} \geq IC_0 \\
& R_{EF,t} + R_{DF,t} \leq C \\
& f_{EF,t} \leq p_{EF,t} \leq p_{EF-MAX,t} \\
& 0 \leq p_{DF,t} \leq p_{DF-MAX,t}
\end{aligned}$$

that is a nonlinear programming problem.

4 Model Results

This tests a set of the selected hypotheses in which the results of the hypothesis testing provide important interpretation on the QoS network interconnection economy. For testing the hypothesis, We used methods of statistical test for different hypotheses. To capture data for statistical tests, we use a method of simulation and optimization.

4.1 Simulation Model

To capture the cost implications of various QoS networks, we performed network simulation using COMNET III for the dimensioning of network for different types of capacity and QoS service requirements. We choose to simulate the networks of the five tandem node networks with different interconnection interface capacity and service demand.

We select these QoS approaches based on the most probable solutions for the backbone applications. The topology of simulation network model was selected by considering current backbone ISP networks in the United States. Since most of the internet backbone networks have average an one to two hops between Network Access Points (NAP), the five node network model is large enough to show the practical performance effects of QoS mechanisms.

We classified and differentiated above mentioned traffic models as in the PHB classes of the DiffServ service architecture. Voice traffic models are considered the delay-sensitive traffic and classified as EFx classes with different priority depending on the different delay requirement. Data traffic is modeled as AFxy classes with or without drop preference. The DiffServ network is modeled to differentiate these traffic classes based on CBQ (Class Based Queuing) with priority. The performance requirement for each PHB class is used to tune the service utilization within the network and find the optimal service utilization.

The simulation allows us to capture the idle usable capacity of the fixed network interconnection link capacity for different QoS requirements, for example, different delay variation for EF PHB of DiffServ. The captured idle capacity is used to approximate the opportunity costs ($ per kbps per hour: kbps is from the average throughput of the served load) of using resources in a fixed capacity network (constrained by fixed interconnection link capacity) for different PHB classes in the DiffServ networks for different PHB provisioning mechanisms. This allows us to see how they differ in opportunity costs among differently assigned PHB groups and understand the implication of the results for the SLAs between IntServ-DiffServ. The detail simulation model description can be found in [2, 4, 3].

4.2 Optimization Programming

Using the economic theory of pricing (profit maximization pricing), we formulated the interconnection pricing optimization problem of BMP of DiffServ network for different market assumptions. In the real implementation of bandwidth management of DiffServ networks the pricing schedule is the major decision variable that BMP will schedule for the interconnection service with other DiffServ or IntServ networks.

To operationalize and solve the BMP's optimization decision for different market and demand scenario, we used CPLEX optimization solver and Matlab optimization toolbox. Especially, we used the software for solving QP (Quadratic Programming) which is a special model for per-settlement service price control optimization of interconnection. We used the linear model of demand function for the simplicity of the analysis.

$$R_i(p_i, t) = R_{i,max}\left[1 - \frac{p_i(t)}{p_{i,max}}\right]$$

We varied $p_{i,max}$ to represent different levels of elasticity of the demand curve. We considered eight demand scenarios varying the elasticity of demand of each DiffServ service class for three types of interconnection capacity. Table A-1 summarizes the values used for different demand scenarios.

As it is shown above, two maximum price values are assigned to each service class to reflect different elasticity measures of each class. Since we considered three service classes per interconnection, the total number of demand scenario we consider is eight.

We used optimization input variables shown in Table A-2 for each demand scenarios stated above. The opportunity cost set was selected to represent the interconnection service of EF(5msec)-AF(10^{-4})-DF, EF(100msec)-AF($2*10^{-2}$)-DF, and EF(50msec)-AF(10^{-2})-DF for different hypothesis and network configuration. Using these parameters, we gathered the optimization pricing schedule and service allocation to calculated the network welfare and consumer surplus created. The network welfare can be expressed in the following form, which is sum of values created for the service provider (producer surplus) and interconnecting network (consumer surplus);

$$\sum_i^n \int_0^T (p_i - f_i) R_i dt + \sum_i^n \int_0^T \int_{p_i}^{p_{max,i}} R_i dp dt$$

The first term is the total profit and the second term is the total consumer surplus created from the differentiated service of interconnection.

We compared the network welfare values for dynamic and static pricing interconnection. Also, we compared the consumer surplus values when dynamic interconnection involves one network or two networks to satisfy the same quality services for the interconnecting network as shown in A-2.

4.3 Statistical Result Representation

Figure A-1 plots mean utilization of differentiated services gathered from the simulation. Each point in the figure represents mean of simulations on the network utilization of different network services. Each of the mean point were gathered for different interconnection capacity and service performance requirement. The statistic data summary is included in Appendix. The group of points on the left side of the figure contains mean utilization values of EF services to fulfill the given set of service requirement discussed in the previous section. The center data group and the right side group of the figure corresponding mean utilization of service to satisfy those service schedule and performance for EF and AF integrated traffic and EF, AF, and EF integrated traffic, respectively. The graphical representation of this data shows that a significant amount of variation exists depending on the service class scheduling, which motivates further analysis on the variation and difference of opportunity costs among different service class and service level.

Figure A-2 shows opportunity cost trend of EF DiffServ service class groups for different interconnection capacity and service scheduling. The opportunity costs are the monthly scaled values in $ per Kbps for different service schedules and different interconnection capacities. The interconnection capacity is in terms of kbps. The service level schedule defines different sets of service combination for interconnection. We also captured opportunity costs of other service classes (AF and DF). The opportunity costs of EF, AF and DF varied between $ 11.537 and $1.472; $4.18 and $0.536; and $2.2 and $0.288, respectively. The interconnection capacity below about DS3 (44.736 Mbps) shows higher marginal opportunity costs than the capacity above DS3 approximately. We used the six month (Dec.1998 to May. 1999) average price data of bandwidth capacity of the links between New York and L.A. from www.rateexchange.com as a proxy for the Internet interconnection price.

Figure A-3 is the plot showing profit maximization price schedule for DiffServ Services for given demand parameters in Table A-1 for the interconnections of OC3. Three points of each service pricing group represent the maximum, the mean and the minimum. Since we expected, the optimal pricing schedules for inelastic service demand are higher than the optimal pricing schedules for elastic service demand between same classes of DiffServ service. Additionally, we captured the price schedule for other interconnection capacities (DS3 and DS1). Also, the optimal pricing for lower capacity service interconnection is higher than the optimal pricing for higher capacity service interconnection for the same service among the considered three capacity group, which is expected from the opportunity cost trends data presented in Figure A-2.

Figures A-4, A-5, A-6, A-7, A-8, and A-9 summarize the mean consumer surplus and network welfare of static and dynamic interconnection pricing for different interconnection capacities and demand groups. The interconnection service schedule is of EF(5msec)-AF(10^{-4})-DF. Each capacity group is classified into two different demand groups. The demand groups are based on the closeness of the values of network welfare that the considered demand group generates. For example, Figure A-4 shows the means of higher network welfare groups and Figures A-5 shows the mean of lower network welfare groups of DS1 interconnection. One The x axis of these figures represents the varying bandwidth costs from the bandwidth market and the resulting opportunity costs. The bandwidth costs are assumed to vary 30 % more or less from the mean market price for each interconnection capacity. We have observed that the dynamic interconnection does not necessarily provide better network welfare than the static interconnection for some demand groups, which require further data analysis on this.

In Figure A-10, mean consumer surpluses of different network interconnection scenarios (one-network, two-network, two-network-adjusted) are assessed for different demand patterns. The demand patterns are defined as different combination of demand elasticity which were presented in Table A-1. The optimization parameters for these values are given in Table A-2. For each interconnection with different demand condition, we can see some difference on the mean of the consumer surpluses that different interconnection condition generates and further data analysis is required for this. Also, we gathered the consumer surplus values for other interconnection capacities in similar ways.

5 Discussion of Results

This section summarizes the major results of statistical data analyses for relevant hypothesis testing of our study and related implications.

Hypothesis: Opportunity Costs of Differentiated Service Classes

This Hypothesis is formally stated as: *H: The opportunity costs of different PHB groups (EF, AF, DF) are significantly different each other with the proposed bandwidth management of DiffServ networks.* In the F-test, the difference among the means of differentiated service classes' opportunity cost dependent variable was significant for both one-way and two-way ANOVA with capacity interaction. On the one-way ANOVA, the difference between EF service class and other service classes is only noticeable in term of mean comparison. With the interaction of capacity choice, all three groups's mean differences were noticeable. For both of the cases, therefore, the null hypothesis could be rejected.

The result of this hypothesis testing has two important implication and inference. The proposed opportunity cost for DiffServ service classes are differentiable, this could be used a proxy for the marginal costs for differentiated services. As Shenker et al. declared in the proposal of edge pricing in [5], it is practically difficult or impossible to calculate exact marginal costs and congestion costs for integrated services. Therefore, the proposed opportunity costing is for a practical proxy for marginal costs for the differentiated service interconnection edge pricing. The hypothesis supports the idea that the proxy opportunity costs can be used as basis for differentiated service pricing. Unlike the effective bandwidth based edge pricing such as [6], the proposed opportunity cost based pricing can reflect the cost effect associated with the interconnection capacity. In addition, the proposed opportunity costs can practically interwork with the price of dynamic bandwidth market. In the aspect of interconnection policy, the service utilization statistics of the network service provider might be a good indicator for costing and pricing interconnection services. Additionally, such utilization and quality metric can be good indicator for pricing the bandwidth in the bandwidth market economy.

Hypothesis: Opportunity Costs of Differentiated Service Levels within Each DiffServ Service Class

This Hypothesis is formally stated as: *H: The opportunity costs of different levels within a PHB group are significantly different each other with the proposed bandwidth management of DiffServ networks.* With one-way ANOVA test, the collected opportunity cost data provide no support for the hypothesis that the opportunity costs are significantly different among different service levels without factoring the interconnection capacity. However, by factoring the interconnection capacity, we could successfully reject the null hypothesis of different service level opportunity costs. The achievable significance level of the EF service level opportunity costs was relatively stronger than the one of the AF service level opportunity costs for the considered service levels in this study.

The implication of this hypothesis testing is the extension of the implication of Hypothesis 2. How finely the network service provider can differentiate the costs and pricing for the different service level is associated with this Hypothesis.

Hypothesis: Network Welfare of Market-Based Bandwidth Management Dynamic Interconnection

The formal statement of this hypothesis is: *H: The network welfare of the proposed bandwidth management is significantly higher than the network welfare with static interconnection.* Based on the F-test results, the dynamic interconnection pricing does not provide support for the hypothesis that the network welfare of the proposed dynamic interconnection is significantly higher than the network welfare with static interconnection. Therefore, the null hypothesis cannot be rejected. In the data analysis of the resulting statistics, there were evidences that the degradation of consumer surplus was larger than the profit increase of the service provider due to dynamic interconnection pricing.

The results of this hypothesis testing provide some indicator for the Internet interconnection policy for market based economy. For the stable and down-slope bandwidth cost economy, the market-based dynamic bandwidth interconnection may not be problematic in the policy aspects since the value created due to cost reduction at least can be shared between interconnecting networks. However, with the highly fluctuating bandwidth market economy, the market-based dynamic interconnection may require closer attention of the interconnection policy maker. Self-interest profit maximization behavior of one interconnection network can results in remarkable surplus degradation of the other interconnecting network in such market condition. There should be some safeguard and guideline to deal with such condition in the SLA of market-based dynamic interconnection. Thanks to current down-sloping bandwidth cost trends due to technical advances, economies of scale and reduce transaction costs, the market-based dynamic interconnection can still be supported in the aspects of network economics.

Hypothesis: Consumer Surplus Effect of Two-Network QoS Interconnection
This hypothesis is formally stated as *H: The consumer surplus (served network surplus) due to the proposed bandwidth management mechanism does not significantly differ depending on whether the QoS interconnection involves single or two DiffServ networks.* The F-test results indicate that the mean consumer surpluses of two-network market-based QoS interconnection can be significantly different from the one-network interconnection. We compared three different network configurations to reflect two different cases (bandwidth costs fixed, and bandwidth costs adjusted). Among the comparisons of the those configurations, the mean consumer surplus of one network was not significantly differ if the bandwidth cost was not adjusted from the bandwidth market. However, if the bandwidth cost is adjusted (half-cost in this case), we observed significant difference for all the demand pattern considered.

The results of testing this hypothesis have some market implication of the bandwidth commodity market economy. With the existence of more market signal (price) information and market products (service and interconnection) in the bandwidth economy, the dynamic pricing and provisioning interconnection mechanism will help the networks to take the best opportunity and availability of the market. This dynamic interconnection mechanism may be strongly supportable by the ISPs who do not own their own carrier networks. Further study on such market mechanics and business implication on the dynamic interconnection between backbone carriers and ISPs will be important for evaluating proposed interconnection and bandwidth mechanisms. However, it is not central to this study.

6 Conclusion and Future Research

A research is performed to develop a model for QoS interconnection and assess the network economic performance of the proposed technical model. There are two main objectives in conducting this research. The first objective is to develop a dynamic interconnection model in the QoS Internet, which can interwork with bandwidth market economy. The second is evaluating economic consequences of the proposed interconnection and bandwidth management model. We present the framework for the interconnection and bandwidth management mechanisms between IntServ and DiffServ network in which the network resource is managed based on market values and use network economic approaches to evaluate the mechanisms.

This research has covered a specific part of many important issues of QoS interconnection and its network economy. There exist many possible and interesting extensions from the major findings described in the previous section. Among those, a research problem can be formulated as a game-theoretic modeling with the interconnection negotiation strategies (SLS exchanges and updates). These mechanisms can be supported by inter-BMP communication and signaling explained in the BMP architecture in this paper. This work also can be generalized as the interconnection problem between networks with different service cost characteristics. Examples of those networks with different cost characteristics include interconnection between wireless network and packet network for integrated services; and interconnection between large scale networks and small scale networks. The game theoretic modeling can explore the interaction between different QoS networks and the quality allocation among them. In addition to the pricing for the connection, the networks might have to set the strategy for the quality of connectivity. The next generation Internet is going to be composed of different sub-networks with diverse methods of QoS-support mechanisms to optimize the performance of individual networks and addressing such interaction can be important contribution to the area of study. Evaluating stableness of the Nash equilibrium strategy among the interconnecting networks on QoS support will be an important telecommunication policy issue. In our study, we present the difference in the bandwidth opportunity costs of QoS interconnection among different service levels and different capacity. By extending the results developed from our study, we can develop the models on the interconnection networks' game strategies.

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Appendix A: Detailed Modeling Parameters

R_{max} **(kbps)**	**Service Class**	**Elastic** P_{max}	**In elastic** P_{max}
1544	Expedite Forwarding	18.404	23.074
1544	Assured Forwarding	6.106	8.366
1544	Default Forwarding	3.241	4.412
44736	Expedite Forwarding	7.702	11.537
44736	Assured Forwarding	2.753	4.183
44736	Default Forwarding	0.621	2.206
155000	Expedite Forwarding	4.210	7.702
155000	Assured Forwarding	1.225	2.753
155000	Default Forwarding	0.587	0.621

Table A-1: Demand Parameters for Different Service Class

Hypothesis	**Opportunity Costs EF-AF-DF**	**Interconnection Costs**	**Capacity** R_{max}
Dynamic vs. Stat.	11.547-4.183-2.206	4400	1544
	2.345-0.843-0.439	27800	44736
	1.978-0.738-0.401	91062	155000
one-network	8.333-3.020-1.530	4400	1544
	1.755-0.621-0.306	27800	44736
	1.567-0.569-0.289	91062	155000
two-network	8.636-3.105-1.585	4400	1544
	1.817-0.656-0.331	27800	1544
	1.674-0.610-0.326	91062	155000

Table A-2: Optimization Parameters for BMP Optimization

Appendix B: Statistical Result Figures

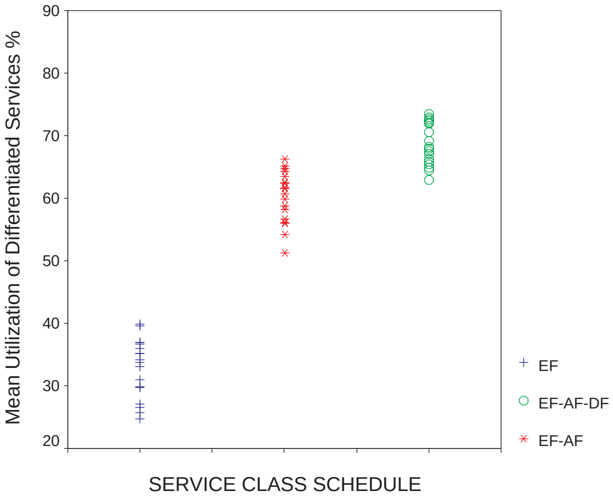

Figure A-1: Mean Service Utilization of Network of Differentiated Service Schedule

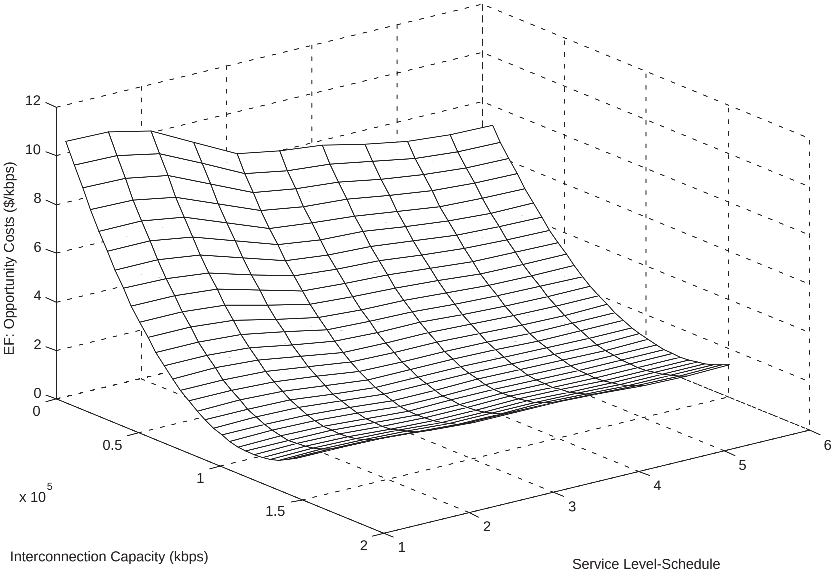

Figure A-2: Opportunity Costs of EF Service

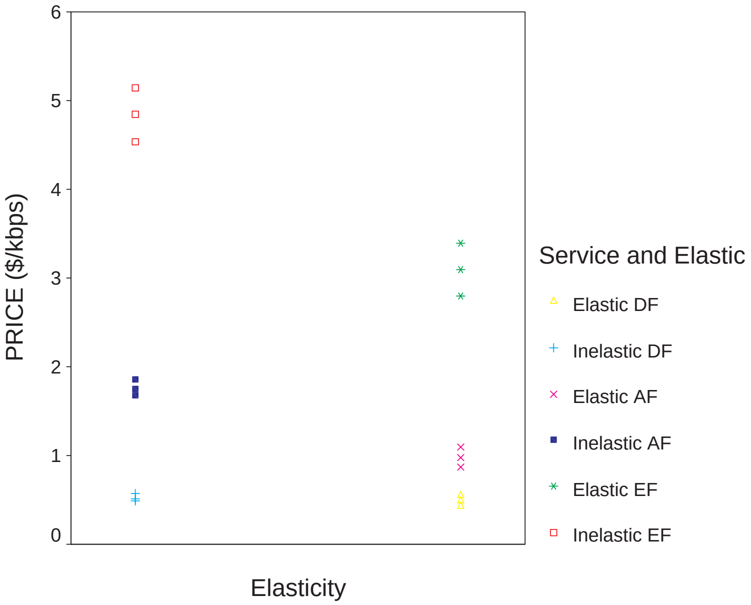

Figure A-3: Optimal DiffServ Pricing Schedules of OC3 Interconnection

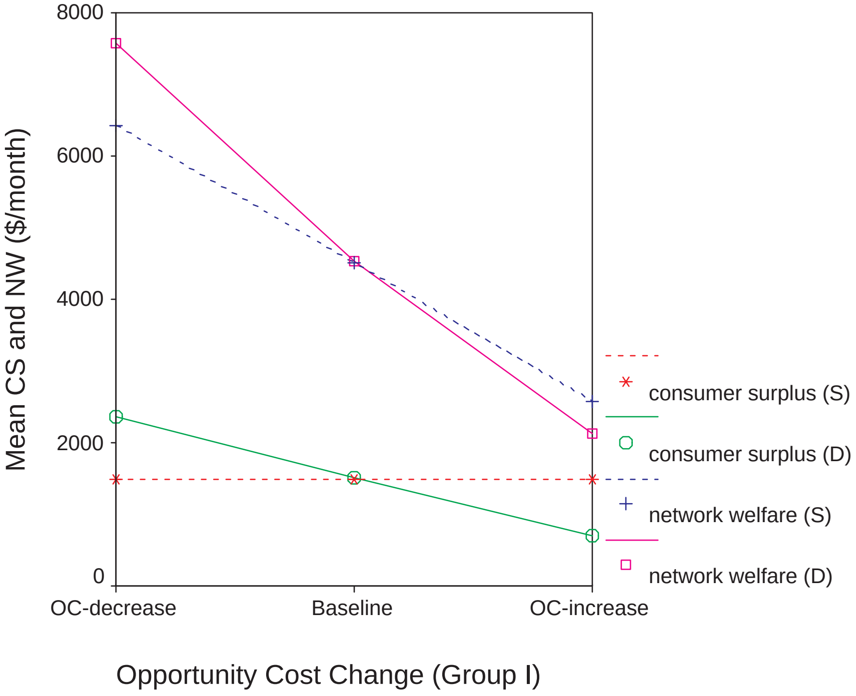

Figure A-4: Mean Network Welfare Values of Static and Dynamic Interconnection: DS1–Group1

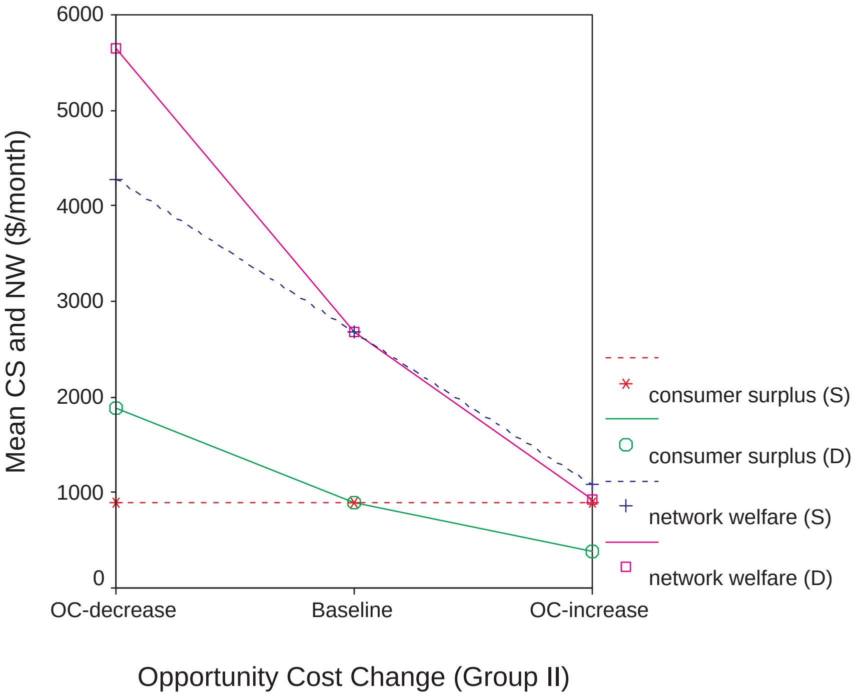

Figure A-5: Mean Network Welfare Values of Static and Dynamic Interconnection: DS1–Group2

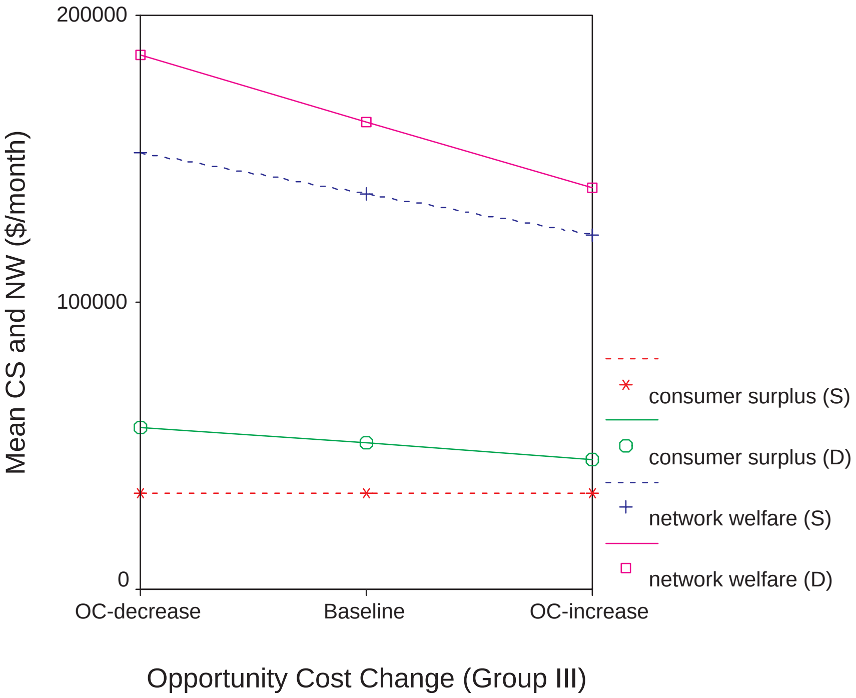

Figure A-6: Mean Network Welfare Values of Static and Dynamic Interconnection: DS3–Group3

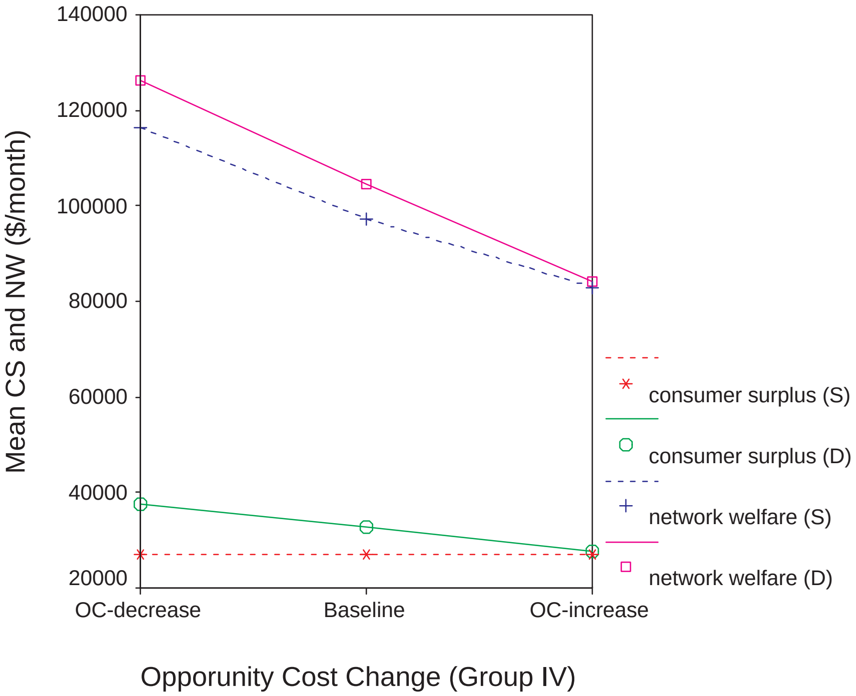

Figure A-7: Mean Network Welfare Values of Static and Dynamic Interconnection: DS3–Group4

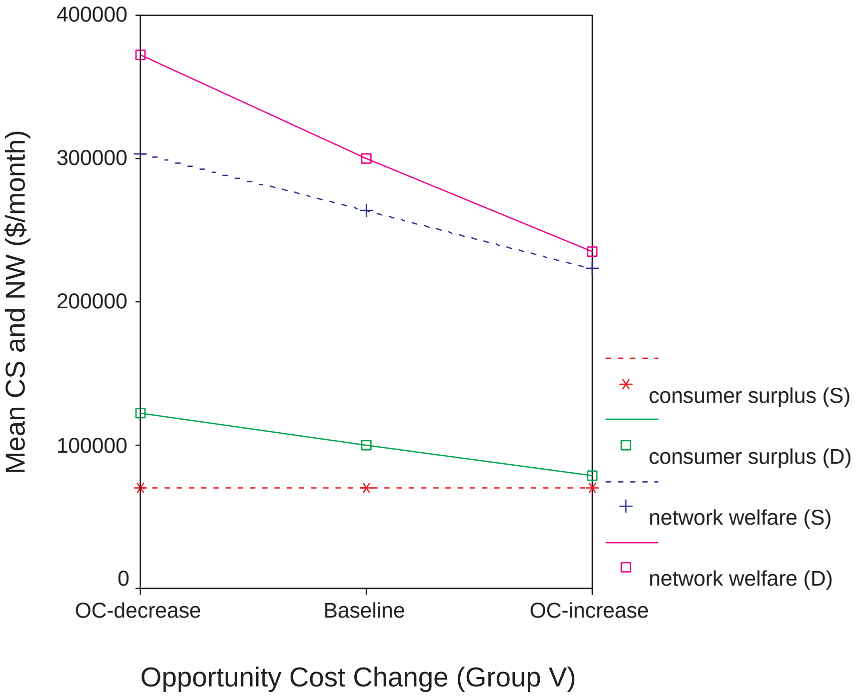

Figure A-8: Mean Network Welfare Values of Static and Dynamic Interconnection: OC3–Group5

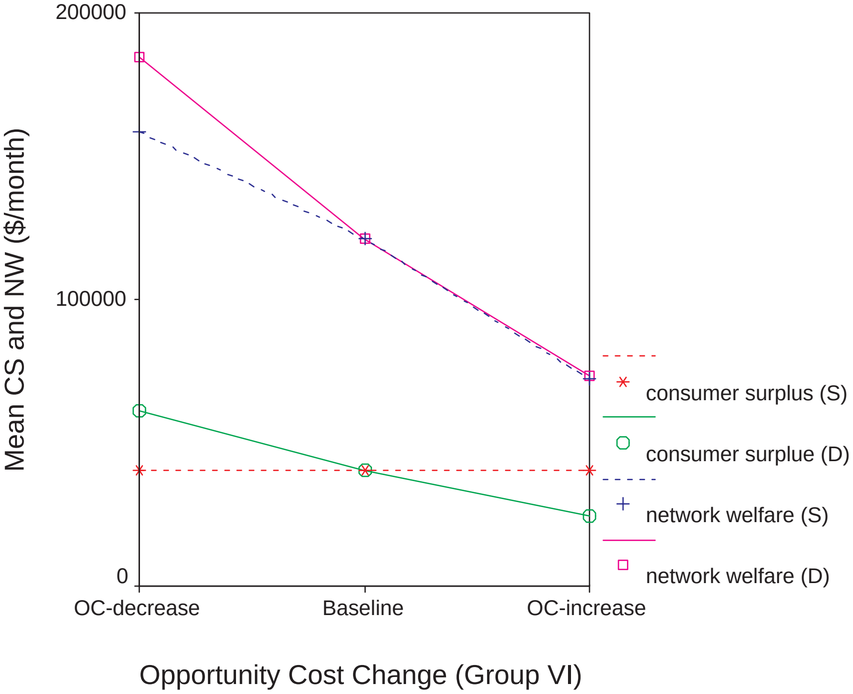

Figure A-9: Mean Network Welfare Values of Static and Dynamic Interconnection: OC3–Group6

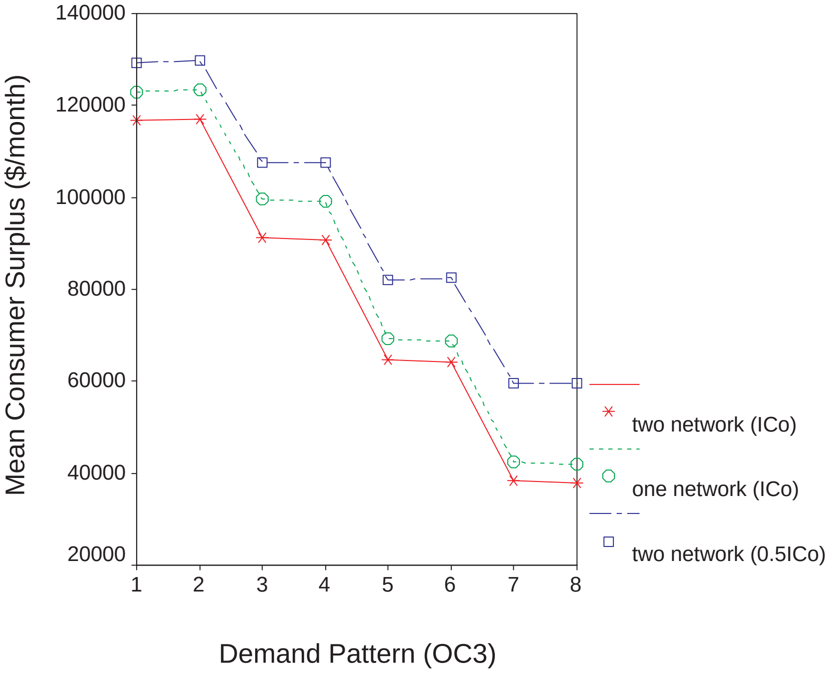

Figure A-10: Mean Consumer Surplus Values of One or Two Network Interconnection: OC3