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Abstract

Providing end-to-end (ETE) guarantees and quality-of-service to a diverse class of applications on the Internet has become the Holy Grail for networking researchers. As the growth of the Internet continues, service providers are facing interesting challenges that include: network design, engineering, pricing structures and business models that maximize profit. In this paper, we first present taxonomy of approaches to solving the ETE QOS problem. Most of these approaches are technical mechanisms that have been developed by various standardization bodies. However, we point out that there is clear evidence that suggests using socio-economic approaches to solve this problem. We describe a novel bandwidth broker approach that integrates game theory, utility theory and pricing mechanisms to come up with heuristics. This is on-going research but we describe our current work to date using these new ideas.

Keywords: End-to-end, Internet QOS, bandwidth broker, IntServ, DiffServ, game theory

Introduction

A recent study released by the U.S. Department of Commerce (2002) suggests that the Internet is rapidly growing across all demographic groups and geographic regions. The rate of growth of Internet use in the United States is currently two million new Internet users per month. More than half of the nation is now online. In September 2001, 143 million Americans (about 54 percent of the population) were using the Internet – an increase of 26 million in 13 months. In September 2001, 174 million people (or 66 percent of the population) in the United States used computers (U.S. Department of Commerce 2002).

This growth of Internet use can be good as well as bad news for Internet Service Providers (ISPs). On one hand, this data tells them that there is demand for services which will likely generate additional revenues. On the other hand, this huge surge in traffic causes them to refocus on engineering their networks in order to provide a satisfactory level of service. It turns out that the current best-effort service provided by IP networks and the flat-pricing structure (monthly fee for unlimited usage) are conflicting characteristics for a network to provide any Quality-of-Service (QoS).

The Internet architecture and design philosophy is simple yet robust. It has a simple core network (routers that forward IP datagrams) and smart end-points (clients and servers that run intelligent applications). One can create a new application (e.g., Napster) and suddenly thousands of end-users begin to use the application to transfer data. This scalability is the basis for the ubiquitous successes of the Internet.

Current market conditions however are causing a rethinking in the design of the Internet Architecture (Blumenthal and Clark 2001). First, there are a number of real-time applications (Voice over IP, Videoconferencing) that require strict guarantees in delay and are more susceptible to delay jitter[1] than plain data. Second, ISPs are beginning to deploy different levels of service since clearly "one class fits all" does not work anymore on the Internet. Their deployment of new architectures (e.g., Diffserv and Inteserv) approved by the IETF is causing a fundamental paradigm shift. Thirdly, while ISPs would love to create a class based pricing structure, there is ample evidence which shows that users hate usage-based or per-packet pricing (Camp and Gideon 2001). They tend to prefer flat fees with unlimited usage. All these restrictions make an interesting challenge: How to provide end-to-end (ETE) QoS?

[1]Jitter refers to the gaps between packet arrivals. Variable jitter causes applications to stretch beyond reasonable performance.

Researchers from the technical community have provided several solutions to QoS such as IntServ (Braden et al. 1994), DiffServ (Blake et al. 1998), RSVP (Braden et al. 1997), and MPLS (Rosen et al. 2001). All of these methods mainly deal with the technical solutions for classifying traffic and managing congestions. But from deployment and trial experiences, it is quite clear that there are frustrations and difficulties to implement these QoS techniques (Teitelbaum 2001). Besides, there is also evidence that point towards a combination of economic and social approaches to solving the congestion problem on the Internet (Shenker 1994).

Currently, the network service supply and demand are unbalanced or not in the optimal equilibrium. Some network providers have over provisioned their networks in order to guarantee bandwidth availability but this is often an expensive solution. With the recent downturn in economy, telecommunication carriers and providers are looking towards upgrading their network with new packet technology so that new services can be provided. Since providing Internet access has become a commodity business, their niche (or rather survival) depends of providing differentiated services. But the current plethora of possible architectures causes increased frustrations for engineers who want to deploy such QoS enabled networks. Unfortunately there are no available guidelines and neither are there test trials which give data about performance. A major QoS initiative undertook by folks at Internet-2 declares:

> "*Today, nearly four years later, use of new resource intensive applications and bandwidth demand have not grown as quickly as expected and there has been no need for a QoS safety belt. The reasons for this are complex and not fully understood. One set of factors that is fairly well understood, however, has come to be known as the "end-to-end" performance problem* (Teitelbaum 2001)".

In this paper, we explore the issues and complexity involved in providing end-to-end QoS. In Section 2, we begin by describing the problem of ETE QoS. In Section 3, we provide a survey of literature on work done to date in ETE QoS and develop Taxonomy of approaches that are currently available. In section 4, we discuss a novel approach to creating a bandwidth broker solution for ETE QoS. In this technique, we formulate the problem from a game theoretic view where we use utility and pricing theories to develop Bandwidth Broker actions. While this is on-going research, we conclude in Section 5 with future work about the need for such novel techniques.

The End-to-End QoS Problem

Quality of Service (QoS) is defined as "the ability to deliver the required services from the source to the destination[s]" (Ferguson and Huston 1998). By differentiating the traffic and services of the network, one can provide the required QoS (Stardust 1999; Bouch and Sasse 1999).

QoS is measured by the delay, jitter, and loss. However, they are not reliable and very difficult to measure precisely (Albrecht et al. 2000). ETE QoS can be divided into three parts: customer premise QoS, access network QoS, and core internetwork QoS (Fineberg 2002). QoS is defined by the bilateral contract or agreement (SLA: Service Level Agreements) between two inter-connected parties. Perhaps the biggest challenge facing QoS practitioners and designers is to come up with a scheme so that IP packets receive end-to-end QoS support. The difficulty with this is the fact that the packets traverse several network domains, which are managed by different service providers and may be using different mechanisms (see Fig. 1). Hence end-to-end QoS on the Internet becomes a chain of links issue where your chain is only as strong as your weakest link. One of the critical problems in QoS research is the lack of common definition for functionalities, delivery methods, and implementation (Ferguson and Huston 1998).

Supply versus Demand of QoS

The recent "Internet bubble" led to increased capital spending by carriers and service providers who laid down fiber optic cables in their networks preparing to meet the huge demand for Internet services. Advances in optical networking (wavelength division multiplexing) helped fuel this dramatic push for exponentially higher link speeds while per-bit bandwidth cost went down at an equally dramatic pace. Many service providers over provisioned their networks.

As the economy went south, the first casualties were the service providers who suddenly lost customers. These customers were the dot com corporations who were going out of business. Web hosting and data center business models plummeted. As service providers stopped further network build out, carriers, CLECs (Competitive Local Exchange Carriers) and OEM (Original Equipment Manufacturer) vendors all started taking the hit. The reasons for these failures are manifolds but one particular reason, that severely impacts the OEM vendors, is the drying up of the "invested" capital that these manufacturers enjoyed. Most service providers went into an over build situation without a solid revenue stream. As a result, we are currently seeing unprecedented bankruptcies, scaled back operations and staff, businesses closing down and the remaining ones developing new business models.

As the dust settles from the current economic situation for telecom vendors, one clear theme is emerging. Service differentiation will gain in importance as a weapon against the threat of competition. And ways to differentiate will depend upon two primary things: i) creating a converged network with QoS-enabled, and ii) developing innovative pricing plans. A provider will have to better utilize its resources, provide more than best-effort service to its customer's application and make money in the process. The challenges are formidable.

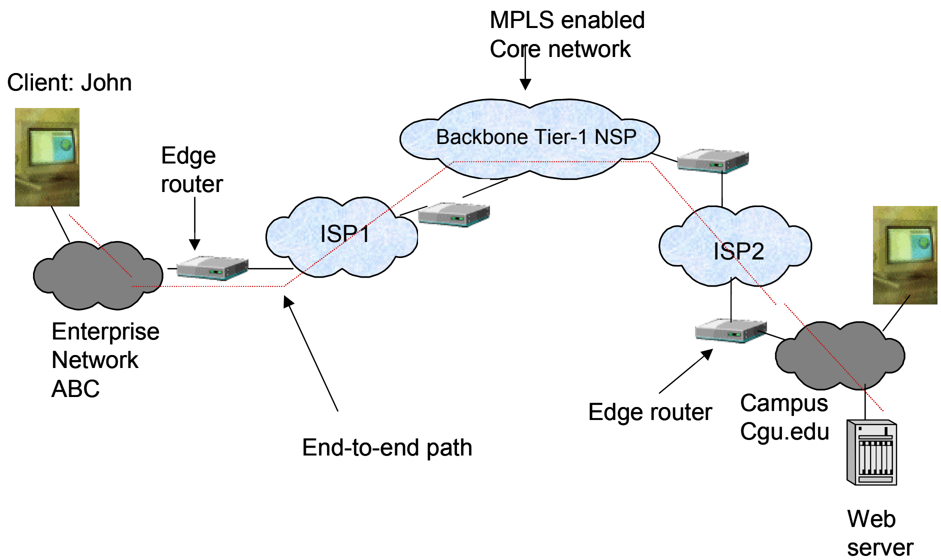

Figure 1. The End-to-End Path IP Packets Take to Traverse the Internet from Client to Server

Survey of Literature on ETE QoS

When communication networks become congested, the quality of service becomes worse. Traditional approach for the network congestion is either expanding the network capacity or reducing the network demand by various traffic engineering techniques such as queuing, routing, shaping, and policing (Sabata et al. 1997; Terzis et al. 1999; Xiao and Ni 1999). Over-provisioning or expanding the capacity is a convenient way because the network demands has been growing exponentially and the cost of the fiber network has been steadily decreasing. However, the over-provisioning is a time consuming and uneconomical solution and it doesn't prevent the temporal demand fluctuation or the network failure.

Current Internet can't support the ETE QoS properly since the Internet Protocol version 4 (IPv4) doesn't have mechanisms to assure the end-to-end reliability of the communication and control of the data flows. IPv4 was designed for the addressing and fragmentation of data. While IPv4 has the Type of Service (TOS) bits in its header, the TOS were not used and IPv4 provides only 'best-effort' service that delivers the data as soon as possible without any assurance and control mechanism.

Two broad approaches have been proposed to provide ETE QoS requirements. First approach is connection oriented, in which packets traverse a virtual circuit over the IP network from source to destination. Each data packet has its own identification and flow over the virtual circuit. The second approach is connectionless in which each individual packet is marked and forwarded through the network. Each network node provides different services such as queuing and routing to this packet according to the markings.

Taxonomy of Approaches in ETE QoS

Integrated Service (IntServ) is designed for the ETE QoS based on the resource reservation and connection oriented mechanism (Braden et al. 1994). By using Resource ReSerVation Protocol (RSVP), IntServ reserves the network resources such as bandwidth and buffer of each intermediate router from the source to the destination (Braden et al. 1997). To provide the requested service, each intermediate router should keep the information about the traffics and available network resources. Since IntServ reserves the resources and has a virtual circuit, it can provide guaranteed service over the heterogeneous networks. Each traffic flow has its own routes and allocated resources to use at anytime. IntServ is known for the difficulty of the implementation and lack of scalability. When the traffic volume increases the intermediate routers can't keep up its database for the incoming network resource reservation requests. RSVP is a stateful protocol. All of the intermediate routers should be the IntServ enabled to deliver the guaranteed service. Otherwise the ETE QoS can't be guaranteed.

Differentiate Service (DiffServ) can improve the scalability compared to the IntServ model for the ETE QoS (Blake et al. 1998). Since it uses the relative priority marking mechanism and connectionless transmission, it is known as the most flexible and scalable architecture. The ingress router marks the incoming packet differently based on the application requirements. Each intermediate router uses its own Per-Hop-Behavior (PHB) criteria and serves the packet differently. DiffServ is scalable but it has limited ability to provide the guaranteed service since there is no connection between the sender and the receiver.

Bandwidth Broker (BB) is a resource manager, which controls the network resource allocation according to the bilateral Service Level Agreement (SLA) between service requester and the BB (Teitelbaum and Chimento 2000; Sreekantan and Rao 1999; Khalil and Braun 2000). The service request comes from customer sites and other BB. The signals go to the BB and it checks the resource availability and other demands to make the allocation decision. By performing admission control and resource allocation, BB can deliver the ETE QoS requests.

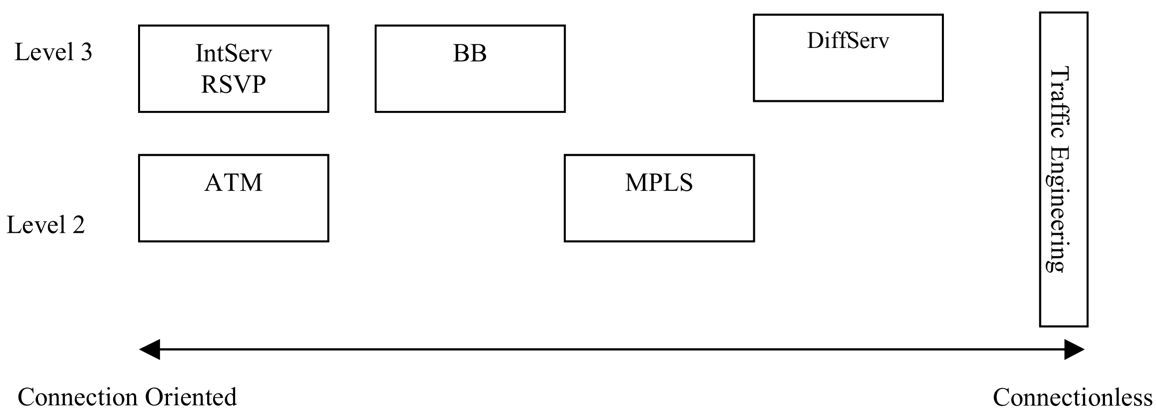

Figure 2. Various Major Approaches to Solving QoS in Networks

Many traffic-engineering techniques such as queuing and routing algorithms are also used for ETE QoS (Xiao and Ni 1999). However these techniques use local information and optimize the local traffic transmission. There is little assurance for the ETE QoS.

IPv6 is proposed as an extension of the current IPv4 and it defines the priority codes and several extension mechanisms (Deering and Hinden 1995). While IPv6 has flow labels, it does not have any specific ETE QoS mechanisms (Weiser 2001).

Table 1 shows the comparison of the various approaches to the ETE QoS. According to the table, currently all of the approaches are focused on the technical solutions, not economic or social solution.

Novel Bandwidth Broker Solutions

Some recent research suggests the growing popularity of using bandwidth brokers in QoS-enabled networks. Each QoS domain is represented by an "Oracle" that responds to admissions requests for network resources. Such oracles have become colloquially known as "bandwidth brokers (BB)" (Teitelbaum and Chimento 2000).

The BB model works as follows: For a network domain, a BB may receive a resource allocation request (RAR) message from either a customer element that the domain controls or manages and from a peer (adjacent) bandwidth broker. Obviously there is a need to standardize the inter-domain bandwidth broker signaling messages.

Table 1. Taxonomy of QoS Approaches

Mechanism	Resource Reservation	Relative Priority Marking	Virtual Circuit	Label Switching	Resource Allocation Management	Economic and Social	Reference
IntServ/RSVP	*		*				(Braden et al. 1994), (Braden et al. 1997)
DiffServ		*					(Blake et al. 1998)
Bndwidth Broker	*				*		(Teitelbaum and Chimento 2000), (Sreekantan and Rao 1999), (Khalil and Braun 2000)
ATM			*		*		(ATM Forum 1999), (Cole et al. 1996), (Armitage et al. 1999)
MPLS				*			(Rosen et al. 2001), (Zielke 2001)
IPv6		*					(Deering and Hinden 1995), (Weiser 2001)
Traditional	Overprovision						(Teitelbaum 2001)
Traffic Engineering					*		(Xiao and Ni 1999)

The BB responds to such request with a confirmation of service or denial of service. If the flow is admitted, then this may result in certain alterations such as router configurations at the inter-domain borders or within the domain along with some possible reservations of resources (bandwidth, buffers etc).

The basic input to BB oracle is defined via a Service Level Agreement and Service Level Specifications. The service is specified in terms of the space-time coordinates of the flow, the kind of service (and possibly other parameters) and any other relevant characteristics of the input. If the network domain has implemented diff-serv standard, then SLA would include PHBs to be applied, traffic conditioners, policers, markers, shapers, and any other applicable policies. SLAs are changed by human parties and BBs do not involve themselves in SLA negotiations.

Current BB implementations are often limited to simple parameter passing and simple resource reservations. In the next section, we discuss a novel approach.

Bandwidth Brokers: Integrating Game Theory, Utility Functions and Pricing Mechanisms

Consider an ISP that currently serves *n* customers (e.g., small and medium businesses) as shown in Fig. 3.

The goal of network design (Shenker 1994) is to maximize the sum of the utility of the user applications. Thus, the total utility function of the network V is given by $V = \sum_i U_i(s_i)$ where *i* is the number[2] of applications flows [$1 \le i \le n$]

Here,

U_i = utility function that maps the service delivered by the network into the performance of application flow i
s_i = measures of service (bandwidth, delay, jitter, loss)

[2] For simplicity, consider one flow per customer site.

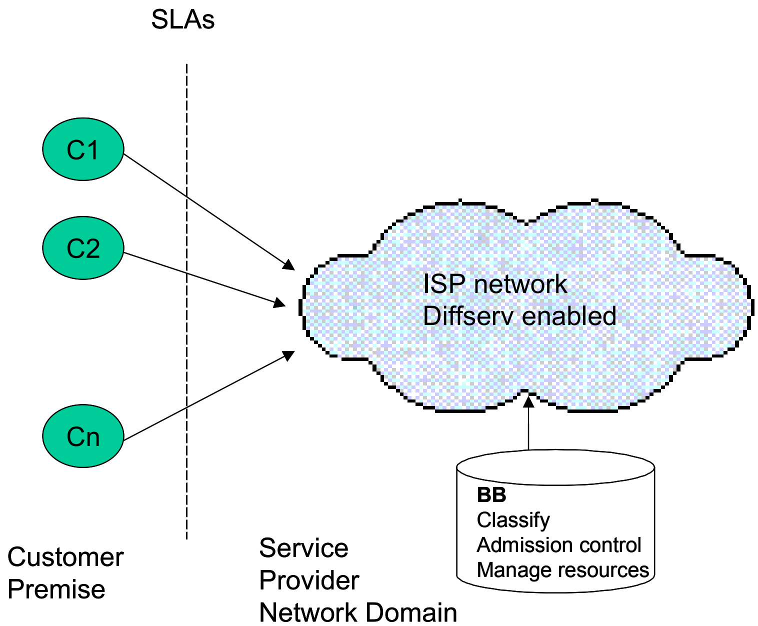

Figure 3. "N" Clients and One ISP with QOS and BB in Place

In this paper, we argue that the above is not the only goal of a service provider. The ISP has three goals which often conflict with each other:

(1) Design a network so that there is high utilization
(2) Provide a reasonable $U_i(s_i)$ for *i*th flows
(3) Maximize the revenue generated by deploying a suitable pricing model.

When you consider such a system with diverse goal requirements, it often helps to look at the system from a game theoretic viewpoint. In a game, we are concerned with a group of players, each maximizing his/her pay-off. Each player has to consider possible reactions of other players. Players do not know the moves of his opponent with certainty. Players have to come up with a strategy that helps him decide with some sort of rational justification. Any strategy he chooses is expected to maximize his payoff.

The challenge for the service provider then is to come up with the *Nash equilibrium* (Myerson 1991). It is defined as a strategy in an extensive form of a game with perfect information, where given the strategies of other players, a player cannot be better off by choosing another strategy.

Conclusions

At this time, we are designing a number of different heuristics that the BB would use based on the formulation we have proposed. These heuristics would aim for fair resource allocation while at the same time provide maximum profit to service provider and yet achieve maximum value (or benefit) to applications from the customers. Simulation models are being built to test the performance of such heuristics.

The next step would be to have an end-to-end path across several domains each running a BB that utilizes our heuristics for decision making. Multiple domains will surely introduce several new challenges. But we hope to test the performance through simulation models.

In this paper, we have proposed a novel way of thinking about network design. The taxonomy also helps to put ETE QoS in perspective. The bandwidth broker concept utilizing our proposed formulation can provide useful tools for ETE QoS on the future Internet.

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