ADDING ENHANCED SERVICES TO THE INTERNET

Lessons from History

k. c. claffy and David D. Clark

ABSTRACT

We revisit thirty-five years of history related to the design of Quality of Service (QoS) on the Internet, hoping to offer some clarity to current debates around service differentiation. We describe the continual failure to get QoS capabilities deployed on the public Internet, including the technical challenges of the 1980s and 1990s, the business challenges of the 1990s and 2000s, and recent regulatory challenges. In short, while the standards community developed protocols to support enhanced services (QoS), service providers have only deployed them in intranet scenarios where they can internalize costs and benefits, rather than across fiscally distinct organizational boundaries. We examine lessons learned from this failure to deploy interdomain QoS, the resulting tensions and risks, and their regulatory implications.

Keywords: network neutrality, Internet, Quality of Service, differentiated service, history

Introduction

Recent rhetoric around network neutrality might suggest that the Internet has a history of neutrality, and deviations from neutrality are a recent consequence of profit-seeking operators adapting to rapidly growing traffic demands. In this article, we draw on over thirty years of personal involvement in the design and specification of enhanced services on the Internet (also described in terms of Quality of Service [QoS]), to put the current debates into context, and dispel some confusion that swirls around service differentiation. We describe the thirty-year failure to get QoS capabilities deployed on the public Internet, including technical, economic, and regulatory barriers, and we consider implications of this failure for the future.

k. c. claffy: UCSD, CAIDA
David D. Clark: MIT, CSAIL

JOURNAL OF INFORMATION POLICY, Volume 6, 2016

We first review terminology and technical issues that shape QoS implementations, and how they can affect applications running over the Internet (section "Related Technical Concepts"). We then offer a historical perspective. The first two decades of history (sections "Early History of Enhanced Services: Technology and Operations [1980s]" and "Formalizing Support for Enhanced Services Across ISPs [1990s]") include dramatic episodes of dangerous levels of congestion on Internet backbones, proposals to augment the Internet Protocol (IP) suite to support enhanced services, and proposals of interim solutions to alleviate congestion while new protocols are being developed and deployed. Although protocols now exist to support enhanced services, nowhere on the global Internet today are these services supported across multiple Internet service providers (ISPs).

The section "Nontechnical Barriers to Enhanced Services on the Internet (2000s)" reviews the third decade of history, when it became clear that although technical mechanisms for QoS were (and are) deployed in private IP-based networks, global deployment of QoS mechanisms foundered due to coordination failures among ISPs. Although the Internet has a standards body (the Internet Engineering Task Force [IETF]) to resolve technical issues, it lacks any similar forum to discuss business issues such as how to allocate revenues among competing ISPs offering enhanced services. In the United States, ISPs feared such discussions would risk antitrust scrutiny. Thus, lacking a way to negotiate the business implications of QoS, it was considered a cost rather than a potential source of revenue. Yet, the relentless growth of a diversity of applications with widely varying performance requirements continued on the public Internet, with ISPs using relatively primitive, and not always completely benign, mechanisms for handling them.

The section "Evolving Interconnection Structure and Implications for Enhanced Services (2010s)" describes a transformation of the interconnection ecosystem that has emerged this decade, driven by performance and cost optimizations, and how this transformation is reshaping the landscape and the role of enhanced services in it. The role of Internet exchanges (IXes) as anchor points in the mesh of interconnection has enabled, as well as benefitted from, the growing role of content providers and content delivery networks (CDNs) as major sources of traffic flowing into the Internet. By some accounts, over half the traffic volume in North America now comes from just two content distributors (YouTube and Netflix). This shift constitutes the rise of a new kind of hierarchy in the ecosystem, bringing new constraints on existing players who need to manage traffic on their

networks to minimize congestion. Evidence of trouble has increased this decade, resulting in tussles among commercial players as well as between the private sector and regulatory bodies, at the expense of users suffering degraded quality of experience (QoE).

More recently, a few large ISPs have built private interconnected IP-based networks, using the IP technology but distinct from the public Internet, and able to support higher service qualities. The emergence of these private networks raises the question: are we better off driving capital investment into private interconnected (and unregulated) IP networks that can offer enhanced QoS, thus limiting the public Internet to best-effort and lower revenue services?

With an engineering perspective on this evolution, we reflect on lessons learned from three decades of experience trying to solve the "multi-provider QoS problem," the resulting tensions and risks, and their implications for the future of Internet infrastructure regulation.

First, the continued failure of QoS over the last three decades derives from political and economic (business) obstacles as well as technical obstacles. The competitive nature of the industry, and a long history of antitrust regulation (at least in the United States) conflicts with the need for competing providers to agree on protocols that require sharing operational data with each other to parameterize and verify committed service qualities.

Second, QoS technology can yield benefits as well as harms. Thus, in our view, policymaking should try to focus on regulating harms rather than mechanisms. If deployed appropriately, QoS technology can benefit latency-sensitive traffic without impairing performance of latency-insensitive traffic. But to assure consumers and regulators that deployment of QoS technology (or other traffic management mechanisms) will fall into this "no collateral harm" category, that is, not impair the QoE for users, regulators may need to require transparency about the state of congestion and provisioning on networks using such mechanisms.

Third, we emphasize the daunting technical obstacles to the use of QoE impairment as a basis for regulation. It will require research, tools and capabilities to measure, quantify, and characterize QoE, and developing metrics of service quality that better reflect our understanding of QoS and QoE for a range of applications.

Finally, shifting patterns of interconnection warrant a closer examination of the challenges and risks associated with enhanced services on the public Internet. The risk is the potential to incentivize artificial scarcity as opposed to pro-growth strategies. Network operators can respond to congestion on their networks by either increasing capacity or selling

enhanced services to those willing to pay for their applications to work well during congestion periods. The tension may be exacerbated in regions of limited competition at the (wired and wireless) access level, and a lack of transparency into whether these perverse incentives are prevailing at any given time.

The coevolution of regulatory, legal, business, and technological capabilities, all at different paces, is tightly coupled in the case of enhanced services—a quintessential interdisciplinary challenge. While, as we document, the barriers to the deployment of scalable interprovider QoS on today's Internet may be insurmountable, the issues and challenges remain. If any Internet of the future is to be the platform for the full range of useful applications, either the basic service of that Internet must be so improved that no support for differentiated services is necessary, or it will be necessary to overcome these challenges in some way. For this reason, it is worth developing a systematic understanding of the challenge of enhanced services and documenting successes and failures over the history of the Internet as carefully as possible.

Related Technical Concepts

In this section, we review terminology and concepts related to enhanced services on the Internet.

What Does "Enhanced Services" Mean?

The traditional service model of the Internet is called best effort, which means that the networks that make up the Internet try their best to deliver packets in a timely and reliable manner, but there are no specifications that define a minimal acceptable service. IP networks may lose packets, deliver them out of order or more than once, or deliver them after inexplicable delays. Some IP networks, for example wire-line ISPs in most parts of the developed world, do a pretty good job of delivering packets. Other parts of the Internet, including some wireless networks or networks in developing regions, do less well.

One layer of the IP suite is called the Transmission Control Protocol (TCP).[1] TCP runs in end nodes attached to the Internet and tries to mitigate these sources of unreliability from lower layers. Two end nodes

1. Postel, "Transmission Control Protocol, Network Working Group Request for Comments 793."

participating in a TCP connection with each other will: number packets they send, track which packets arrive, retransmit those that are lost, reorder them if necessary, and deliver the data to the receiver as it was initially sent by the sender. However, TCP cannot remedy all problems. Delays due to congestion or retransmission of lost packets cannot be reversed. Different sources of unreliability, combined with TCP's transmission algorithms, can lead to long and variable delays from the sending application to the receiving application. There is simply no guarantee of a certain amount of bandwidth from sender to receiver.

For many applications, this variation in delay and bandwidth is tolerable. If a web page loads a few seconds more slowly, or an e-mail is delayed a few seconds, the user is not really disadvantaged. But for some applications, especially real-time applications, this variation can be disruptive. An audio or video conversation that suddenly suffers seconds of delay becomes essentially unusable. Similarly, unpredictable variation in bandwidth can disrupt the viewing of video.

There are competing views on how to improve this situation. One approach is to increase our expectation of minimum "best effort" to a threshold that allows real-time applications to work. Many ISPs in the developed world advertise that their basic service is suitable for real-time multimedia applications.[2] This assertion may often be true. However, the two of us, as collaborators on opposite sides of the country, often must disable video in a Skype call to get the audio to work. Disruption of real-time applications is a reality today. Further, for the typical user, there are no tools to help understand why.

Whether parts of the Internet are working well enough today to support demanding applications, congestion, and lack of capacity are not equally easy to remedy to this level of performance in all parts of the Internet, so another view is that ISPs should provide different treatment of packets as they cross the Internet, giving preferential treatment to packets from more demanding applications, and shifting less sensitive applications to lower priority forwarding. Support for this sort of differential traffic treatment is also called enhanced services,[3] and one goal of this article is to see what lessons we can glean from the (failed) history of trying to get enhanced services deployed in the Internet.

---

2. See, for example, https://www.att.com/shop/internet.html, which states that with AT&T U-verse you can "video chat with friends and family."

3. Clark, Shenker, and Zhang, "Supporting Real-Time Applications in an Integrated Services Packet Network: Architecture and Mechanism."

Using Enhanced Services to Mitigate Congestion

The term congestion has multiple interpretations,[4] but most simply, congestion arises when the offered load exceeds the capacity at points within the network. Different networks deal with congestion differently. The traditional telephone network, a virtual circuit network, dealt with this possibility by reserving enough capacity for a call at every link along the path through the network when the call was being initiated. If there was not sufficient capacity, the call would not go through.[5] This admission control approach made sense when the network only carried one sort of traffic (phone calls). In contrast, the Internet was designed under the assumption that it would carry a wide range of traffic, from long-lived flows to short message exchanges. The designers rejected any sort of admission control: most applications (like file transfer) did not have a well-defined target service requirement, and the overhead of admission control seemed excessive for small interactions, which might be completed with few packets in the time it would take to process the admission control request. The design approach in the Internet is that applications simply sent traffic as desired. This approach, in contrast to virtual circuits, was called a datagram network. In this case, the consequence of excess offered load is that, in the short run, queues of packets form, and over the longer term, either some congestion control algorithm causes the senders to slow down or else overloaded routers run out of memory to store queued packets and thus drop some packets. In contrast to the telephone network, this best effort service of the Internet made no performance commitments, which implies potential impairment of certain applications, in particular so-called real-time applications like voice.

The idea of enhanced services is to add mechanisms to the network that differentially treat traffic in order to mitigate these impairments. There are two general approaches: use different paths through the network for the different flows, or treat the packets from different flows differently as they pass through the same router. Early designers of the

4. For a discussion of different definitions of congestion, see Bauer, Clark, and Lehr, "The Evolution of Internet Congestion."

5. The busiest day of the year for the phone system was reputed to be Mother's Day, and in past time fears of not getting through made dutiful children call home early in the day. The indication that a call was blocked due to lack of resources was a "busy signal" delivered twice as fast as normal.

Internet contemplated but never implemented the first option. The other approach—distinct treatment of distinct flows through a single router—mostly applies when a router experiences congestion. When a link leaving a router becomes overloaded, a queue of packets form; the router can implement different service qualities by scheduling packets in different ways, for example, giving packets of real time flows priority by jumping their packets to the head of the queue. If there is no congestion, there is no queue, so there are no options for rearranging the queue.[6]

As concerns over Internet congestion waxed and waned over the years, so has interest in enhanced services. Interestingly, the locus of congestion has shifted over time. In the early days of the Internet, where the transcontinental links were 50 kb/s and there were not yet effective algorithms to control overloads, congestion in the core of the Internet was commonplace. By the time dial-up residential access became common, the capacity of the core had increased, and because dial-up speeds were initially at such low rates (e.g., 9,600 b/s), the access link was often the point of overload, and the core of the network was less often congested.

At the time, there was a lot of (investment-bubble funded) fiber available to build out the core, and even the advent of broadband residential access was not enough to shift congestion to the core. Today, in many parts of the Internet, especially wire-line access providers, the internal circuits of individual ISPs are often provisioned with adequate capacity to carry the traffic from their customers, in which case the access link is the point of overload, unless the overload occurs at points of interconnection among ISPs. On the other hand, some wireless access networks show evidence of considerable congestion in the wireless access, due to limited capacity (radio and backhaul) in the base stations. This variation raises a design question: if enhanced services are added to the Internet, should the mechanisms be general enough to deal with congestion wherever it manifests, which calls for multi-provider coordination with all the complexity it implies, or customized to deal with a specific type of congestion prevalent at a particular region and time, which might be easier to implement but of diminishing (or at least inconsistent) value over time as the nature and location of congestion evolves.

---

6. Here, we ignore the particular case where packets from a specific flow are rate-limited, perhaps, as a result of a service agreement, even though there is adequate capacity.

QoS Versus QoE

The term QoS is used to describe technical measures of network performance, such as throughput, latency, jitter, and packet loss. However, users do not directly perceive these parameters. Users perceive how their applications work, and whether there is degradation in the way the application performs. The term used to describe user-perceived impairments is quality of experience (QoE). QoE is a subjective measure of quality, and assessment of QoE is application specific. Was voice quality degraded? Is the video stream experiencing rebuffering delays? Impairments to QoE derive in part from underlying QoS parameters (e.g., jitter impairs voice QoE but not e-mail) and can arise anywhere in the network.

Network engineers can measure parameters of QoS, but they cannot directly measure QoE. The application designer can attempt to estimate QoE, perhaps by a questionnaire at the end of the application session, or by observing user behavior (did the user abandon the application session in the middle). Laboratory research with human subjects can try to correlate variation in QoS with the resulting variation in QoE by subjecting subjects to controlled variation in QoS and asking them to report on their assessment of QoE. But this information informs the network engineer only indirectly. As a practical matter, the linkage between QoS and QoE is sometimes obscure; many technical quirks in the system can produce observable impairment in QoE. As well, our understanding of QoE and how to measure it is not as well developed as our understanding of the technical dimensions of QoS. So the argument that deployment of enhanced services is justified depends on a line of reasoning that is subject to argument—is the proposed differentiation actually going to mitigate the QoE impairment?

Limiting the Use of Enhanced Services via Regulation

The notion of best effort suggests that all packets receive the same treatment, which superficially implies a sense of fairness even if it actually impairs certain applications without measurably benefitting any others. Much regulatory attention has focused over the last several years on the possibility that Internet service providers (ISPs) will discriminate among traffic flows for business rather than technical reasons. The rallying cry for intervention to prohibit this sort of behavior is called "network neutrality," and the more nuanced but still ill-defined term used by regulators such as

the FCC is reasonable network management, which requires a "reasonable" technical rather than business justification.

Early History of Enhanced Services: Technology and Operations (1980s)

In this section, we review the early intentions of the Internet designers to support distinct types of service qualities in the architecture and protocol features to implement them.

Early 1980s: Initial Specification of Type-of-Service in the IP Suite

The idea of enhanced or differentiated services has been a part of the Internet's design from the beginning. The Internet Protocol (first defined by RFC 760 in 1980) had as a part of its header an eight-bit field called Type of Service (ToS).[7] Box 1 describes how the designers conceived of this ToS field at the time. This field enabled specification of service quality using five parameters, some of which were supported by some networks at the time: precedence, stream versus datagram, reliability, speed versus reliability, and speed. The specific precedence terminology mirrored then-current controls in military command and control networks, and allowed the sender to specify the importance of the message. Military message networks of the time allowed different messages to be tagged with different precedence, which influenced the order of delivery. "Flash Override" was the most urgent. At the time, it was unclear how this concept mapped to the packet level of the Internet, but the designers were encouraged to add this feature to make the network more familiar to potential military users.

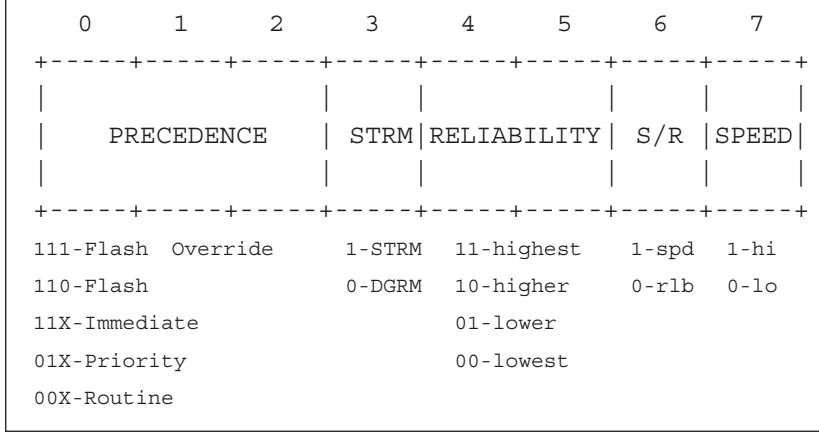
This version of the IP specification was "pre-standard," in that RFC 791 was issued a year later (1981), which is generally taken as the first official standard for the Internet Protocol. RFC 791 presented an updated definition of the ToS field (Box 2). While the designers still had no experience with implementing any ToS function, they decided to separate the bits used to code delay, throughput, and reliability requirements. They also removed the distinction between stream versus datagram models of flows, as the design philosophy had evolved to a pure datagram model. The addi-

7. Postel, "Internet Protocol, DARPA Internet Program Protocol Specification."

Box 1 Definition of Type of Service field (RFC 760)

"The Type of Service provides an indication of the abstract parameters of the quality of service desired. These parameters are to be used to guide the selection of the actual service parameters when transmitting a datagram through a particular network. Several networks offer service precedence, which somehow treats high precedence traffic as more important than other traffic. A few networks offer a Stream service, whereby one can achieve a smoother service at some cost. Typically this involves the reservation of resources within the network. Another choice involves a low-delay vs. high-reliability trade off. Typically networks invoke more complex (and delay producing) mechanisms as the need for reliability increases." (RFC 760, p. 11)

Bits 0–2: Precedence.
Bit 3: Stream or Datagram.
Bits 4–5: Reliability.
Bit 6: Speed over Reliability.
Bits 7: Speed.



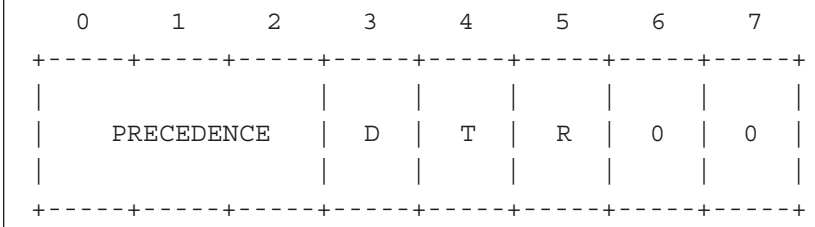
tional precedence levels reflect the realization that network control traffic was necessary to keep the network itself working, and thus of the highest importance.

At the time, there was no use of these bits to control how routers treated packets. The intention was to enable differential control of traffic on networks that made up the early Internet, for example, the ARPANET, the

Box 2 Definition of the IP TOS field as of RFC 791

The IP Type of Service has the following fields:

Bits 0–2: Precedence.
Bit 3: 0 = Normal Delay, 1 = Low Delay.
Bits 4: 0 = Normal Throughput, 1 = High Throughput.
Bits 5: 0 = Normal Relibility, 1 = High Relibility. [*sic*]
Bit 6–7: Reserved for Future Use.



Precedence values:

111—Network Control

110—Internetwork Control

101—CRITIC/ECP

100—Flash Override

011—Flash

010—Immediate

001—Priority

000—Routine

packet radio network PRNET, or the satellite network SATNET.[8] The idea was that the Internet ToS field would be used to set the network-specific ToS features of the various network technologies being used in the Internet of the time. RFC 795[9] catalogued these service mappings from IP ToS to network-specific ToS mechanisms. Although based on the then best understanding of service variation, this specification was in some respects

8. RFC760 (Postel, "Internet Protocol, DARPA Internet Program Protocol Specification"), page 27, states, "for example, the ARPANET has a priority bit, and a choice between 'standard' messages (type 0) and 'uncontrolled' messages (type 3), (the choice between single packet and multipacket messages can also be considered a service parameter). The uncontrolled messages tend to be less reliably delivered and suffer less delay."

9. Postel, "Service Mappings, Network Working Group Request for Comments 795."

a placeholder, and these fields were substantially redefined in the 1990s (section "Formalizing Support for Enhanced Services Across ISPs (1990s)").

The important point of this early specification was not exactly how the fields were defined, but the intention to support endpoint requests for a specific QoS via setting bits in the packet header. An alternative approach would have been for the router to deduce what application was sending the data (perhaps by looking at the port field in the TCP header) and map the application to a service class. Drawbacks to this approach were well understood at the time. First, not all applications used port fields in the same way, even then. Second, the port fields are in a higher-layer (transport) protocol header, which might be encrypted. The design intent was that code running on the endpoint, and reflecting the desires of the end-node for the requested service, would set the TOS fields, and the network would honor them. For some subfields, such as the precedence indicator, there was no way the router could consistently deduce the correct value, because the precedence field was conceived as differentiating messages of the same sort (e.g., e-mail) based on the sender's assessment of the importance of the content, and the necessity of rapid delivery. Only the sender could determine the importance of the message.

Mid-1980s: Reactive Use of Service Differentiation to Mitigate NSFNET Congestion

In the mid-1980s, the US National Science Foundation commissioned a national backbone network to replace the original ARPANET, which was planned for decommissioning by ARPA. The backbone links of the original network built by the NSF, called NSFNET, were 56 kb/s, and gradually became congested. In response, the NSFNET engineers deployed an emergency measure to provide certain interactive network applications, specifically remote login (telnet), preferential treatment. This is probably the first example of enhanced services (or service differentiation) being used in the Internet.

The routers that made up the early NSFNET backbone were programmed by David Mills at the University of Delaware. The hardware for each backbone router was an LSI-11, a modest computer even for those times, and the device was called, perhaps lovingly, a "Fuzzball." The Fuzzball software supported queue management schemes (primarily a priority scheduling scheme) to support multiple service classes, which allowed for prioritizing the most delay-sensitive applications of the time, remote login

(telnet). While the Fuzzball software was designed to use the TOS field to trigger service differentiation, the remote login software running on end-nodes was not setting these bits. So in perhaps the first example of routers peeking at higher-level protocol fields in the header, the Fuzzball looked at the port field to see if the protocol being used was remote login. In 1988,[10] Mills wrote: "However, many implementations lack the ability to provide meaningful values and insert them in this [TOS] field. Accordingly, the Fuzzball cheats gloriously by impugning a precedence value of one in case the field is zero and the datagram belongs to a TCP session involving the virtual-terminal TELNET protocol."[11]

Priority treatment allowed interactive users to continue working under highly congested circumstances. But because the backbone administrators did not have any way to provide an incentive not to use the highest priority, they did not publicize the priority-based treatment of traffic, and end users did not know it was possible to give high precedence to other applications. It was a short-term operational tactic, not a long-term strategy.

Late 1980s: TCP Protocol Algorithmic Support for Dampening Congestion

While the initial design of the Internet included the specification of a mechanism to signal congestion (the ICMP Source Quench, see RFC 792), there was no success in designing an effective overall mechanism to dampen congestion. The traffic prioritization described earlier only sorted through packets that were not dropped by routers, but did nothing to dampen congestion. In the late 1980s, Van Jacobson proposed a workable scheme for congestion control.[12] With refinements, this scheme is still the basis of TCP congestion control in the Internet, and immediately mitigated congestion in the overloaded core of the NSFNET backbone.

However, it did not resolve all congestion-related issues. First, it did not prevent queues from forming. The signal of congestion from the network to the originating host was a dropped packet, which only occurred (in the original version) when the queue in the router was full. Delays and variance caused by congestion were still present. Hosts that encountered a lost packet would slow down, which prevented massive overload in the core.

10. Mills, "The Fuzzball."

11. Thus, routers have been looking at parts of the packet beyond the IP header since well before 1990.

12. Jacobson, "Congestion Avoidance and Control."

However, hosts might suffer very low rates (only a few packets per second in extreme cases), inducing high variation in achieved throughput. Taming excess flows into the network was critical in preventing massive packet drops in the core, but did not remove the justification for offering enhanced services to applications that were intolerant of excess delay, jitter, and highly variable throughput.

Formalizing Support for Enhanced Services across ISPs (1990s)

In this section, we relate proposals from the 1990s to actually use existing but underutilized protocol features that supported enhanced services, and attempts to augment the IP suite with more formal and fine-grained support for real-time media services.

Proposed Short-Term Solution: Formalize Use of IP Precedence Field

NSFNET leadership recognized even over twenty years ago that software developers were building network applications that could consume as much bandwidth as network operators could provide. In particular, real-time video and voice applications did not exhibit the same stochastic burstiness characteristics and modest resource requirements of traditional applications such as file transfer and e-mail. In their view, the popularity of real-time applications "bodes ominously for an infrastructure not able to: distinguish among certain traffic types; provide more than a best-effort guarantee to datagram traffic; or upgrade in a time efficient way towards an availability of higher bandwidth (if only due to lack of accounting and billing mechanisms to enable cost recovery)."[13]

The authors predicted that in the long run the community would redesign networks and network protocols to support complex resource reservation and accounting. In the meantime, however, they proposed an interim strategy that would shield, in a limited way, the existing environment from traffic whose behavior conflicts with the nature of resource sharing, for example, high-volume continuous traffic. Specifically, they proposed a scheme for voluntarily setting and respecting priorities (precedence levels) for Internet traffic that included incentives to limit one's use of high

13. Bohn et al., "Mitigating the Coming Internet Crunch: Multiple Service Levels via Precedence."

precedence levels.[14] Application developers could set default priority levels for the IP precedence field, which users could modify based on their own criteria, for example, latency sensitivity. By default, the value is typically 0, the lowest priority. If users encountered no problems with their traffic, they would see no reason to change. Administrators of participating networks would update router software to maintain multiple queues based on the IP precedence field (well within router capabilities at that time). ISPs could selectively enable IP precedence-based queuing as they saw a need, and disable it in case of misuse.

An obvious risk of this enhanced services scheme was that users would set all their traffic to the highest priority. The third part of the proposed scheme addressed this incentive problem. The scheme included support for ISPs to set soft quotas on the total volume of traffic sent at higher (although not at lower) precedence levels. As before, there would be no quota on traffic sent at the lowest (say, lowest two) precedence levels. Quotas on higher precedence levels would be only a loose incentive, monitored after the fact. If a customer exceeded its quota, its provider could assess a penalty, such as a fee on the next bill. If a customer found that it was exceeding its quota regularly (similar to some of today's residential broadband service traffic volume quotas), it would have three choices: negotiate a higher quota, put and enforce quotas on its own customers (or internal users), or pay the assessed penalties. The proposal also clarified that quotas would be measured and enforced only at gateways between networks, and optionally. The authors imagined a variety of coexisting quota systems. They also imagined (more naively) that peer pressure and informal mechanisms (such as publishing a list of offenders) could be effective methods of enforcement. The scheme was not tied directly to billing and pricing, but over time it could establish a knowledge base from which to tie multiple service qualities more directly to monetary incentives for compliance, such as paid prioritization.

The authors acknowledged and discussed approaches to potential issues with the scheme, including incentives to discriminate against competitors' packets by placing them on lower priority queues. They recognized the social obstacles as at least as great as the technical ones, but they also saw the potential for a cultural shift as people saw massive video streams slowing down traditional transactions. Specifically, they considered it possible that transparency, for example, publishing statistics on usage and

14. Loc. cit.

congestion, could raise awareness and promote this culture shift. Yet the proposal was acutely academic in nature, and published at the height of the privatization and commercialization of the previously largely academic and government-funded NSFNET community. Nothing like this scheme was ever deployed.

Proposed Long-Term Solution: Standardizing Support for Enhanced Services

Assuming that in the long term, architectural support for enhanced services would be required on the Internet, starting in the 1990s there was a major push by the research and standards community to produce a fully defined approach to adding differentiated services to the Internet. In 1992, one of us (Clark), along with two coauthors, presented a paper[15] at SIGCOMM (the major networking conference at that time) that laid out a proposal for adding what was called Integrated Services to the Internet. They chose this term to align the language of the Internet community with the (then) language of the telephone industry, which was arguing that the failure of the Internet to provide such services would doom the Internet in the marketplace. The concept of Integrated Services suggested that the network should equally be able to support the traditional best-effort services of the Internet (of that era), as well as applications such as real-time voice, what we now call Voice over IP or VoIP. The telephone industry, which held itself to high standards with respect to voice quality (cellular had not yet entered the picture), was arguing that a single integrated network would be economically beneficial, but that the Internet could not be the basis for such a system because of the under-specified best effort delivery model.

In parallel, the telephone industry was developing its alternative to Internet packet switching, which was called cell switching; this work grew out of early work at Bell Labs starting in the early 1970s on a system called DataKit. This technology was virtual circuit rather than datagram and offered a more predictable and stable service than the best-effort service of the Internet, a service better matched to the telephone industry's conception of how to deliver digital real-time voice. In 1992, Fraser documented this alternative view of networking in the *Communications of the ACM*,[16] and the telephone industry set to work to standardize and commercialize

15. Clark, Shenker, and Zhang, "Supporting Real-Time Applications in an Integrated Services Packet Network: Architecture and Mechanism."

16. Fraser, "On the Interface between Computers and Data Communications Systems."

it, which led to the technology called Asynchronous Transfer Mode, or ATM. ATM provided a number of service classes, and thus embedded the idea of differentiated or enhanced service in its architecture.[17] The ATM forum was established in 1991,[18] and set about standardizing what the members saw as an alternative and replacement for the Internet Protocol.

The Internet community was faced with a dilemma: they could continue to argue that the single, best-effort service would prove good enough to support all the commercially relevant services that might emerge in the context of data networking, or argue for adding new functionality to the packet carriage layer of the Internet. To some, this was a mandatory step to preserve the competitive advantage of the Internet Protocols; to others it was heresy. In a 1992 talk to the IETF, Clark predicted that the emergence of real-time applications such as interactive voice, and the proposals for an alternative network architecture to meet these requirements, would be one of the major challenges the Internet community would face in the decade.[19] At a March 1993 IETF meeting, he laid out the challenge to the Internet community,[20] and in June 1994, RFC 1633 was published, drawing substantially on the earlier work.[21] The Internet community accepted the challenge of defining differentiated services for the Internet, and set up a number of working groups that produced the standards that are in use today (if not in the public Internet), which we describe next.

Standardization of Enhanced Service in the IETF

The literature we have cited describes the concept of an Integrated Services network in terms of services. The example used to justify this effort was a "low latency, low jitter" service that would meet the needs of real time voice. The technical challenge is to translate such an abstract idea into operational terms. As the IETF progressed, they considered two variants of an enhanced forwarding service: a guaranteed service and a predictive service. They intended the guaranteed service to match the service that the phone system claimed to offer: it would give a strict guarantee as to

17. The different service classes were called ATM Adaptation Layers or (AALs). There were AALs designed to carry fixed-rate traffic like voice, and variable-rate traffic like data.

18. See https://www.broadband-forum.org/about/forumhistory.php.

19. Clark, "A Cloudy Crystal Ball—Visions of the Future."

20. Clark, "An Architecture for Resource Management in Networks."

21. Clark, Shenker, and Zhang, "Supporting Real-Time Applications in an Integrated Services Packet Network: Architecture and Mechanism."

the variation in delay (jitter) for arriving packets, and thus a computable bound on the maximum end-to-end delay. In contrast, the predictive service did not provide any guarantee, and no algorithm for precomputing the bound. Rather, the application would have to measure the service in operation, estimate the bound, and adapt to it. The predictive service was conceived as giving a low bound (better than the default best-effort service), but the application did not know in advance what the bound would be. The service was called predictive because the application needed to include an estimation algorithm to predict the current delay bound. The outcome of the standards process resulted in two groups of standards, one called *IntServ*, which realized the guaranteed service, and the other *DiffServ*, which realized the predictive service.

When the IETF began to debate these services, it heard from a constituency not usually heard at IETF meetings: the designers and marketers of advanced network applications. They contended that the predictive service was too unpredictable and they would only be interested in networks that offered the guaranteed service. The guaranteed service is much harder to implement because it requires per-flow state to be set up in every router along the path, a mechanism totally at odds with the overall philosophy of the Internet. However, there was progress on this effort. The IntServ standards, which realize the guaranteed service, are specified in RFC 1633 ("Integrated Services in the Internet Architecture: an Overview").[22] The core standard (RFC 2211: "Specification of the Controlled-Load Network Element Service")[23] described a complex set of mechanisms, including a flow setup phase where the sending machine specifies key parameters of the anticipated flow, and the state setup protocol RSVP (RFC2205).[24]

There are two potential components to a standard that describes a technique for traffic differentiation: the operation of the various network components and the resulting end-to-end service. The distinction is subtle but important. A service is what would be described to a higher level in the service stack, for example an application. "Low latency/low jitter" is the description of a service. The original specification of the ToS field in the IP header describes an abstract service; the mapping of the service to the technology of different networks was relegated to a separate RFC

22. Braden, Clark, and Shenker, "Integrated Services in the Internet Architecture: An Overview."

23. Wroclawski, "Specification of the Controlled-Load Network Element Service."

24. Braden et al., "Resource ReSerVation Protocol (RSVP)—Version 1 Functional Specification."

(RFC 795). But what a router designer needs to know is what mechanisms and functions to program into that device. The end-to-end service must result from the suitable behavior of the components along the path, and the standard must specify what those components must do in sufficient precision that the end-to-end behavior is achieved. Most of the effort in defining the controlled load service was specifying what network elements should do. At the same time, the Controlled-Load RFC[25] described the resulting end-to-end service, as follows: "The end-to-end behavior provided to an application by a series of network elements providing controlled-load service tightly approximates the behavior visible to applications receiving best-effort service *under unloaded conditions* from the same series of network elements." The word "tightly," while not quantitative, was meant to suggest that deviations from the behavior that would result in an unloaded network would be so minor as to not impair the operation of the application.

The IETF standardization effort was reshaped by a pivotal thesis done at MIT by Abhey Parekh.[26] This thesis used reasonable assumptions to derive a lower bound on the jitter that would occur with any such guaranteed service, and it was a tight bound; he displayed a worst-case arrival pattern of packets that would generate an arrival delay at this bound. The bound was a function of the ratio of the capacity of the links in the network to the average speed and burstiness of the flows across the link. Capacity can be related to cost, so an informed network engineer could compute the cost to provision a network so as to achieve a reasonable bound. For traffic with any degree of variation in sending rate, the answers were not appealing. To build a network that gave an absolute worst-case guarantee would require substantial over-provisioning (cost). This realization shifted the attention of the IETF from the guaranteed service to the predictive service, which could not give a guaranteed bound, but gave a much lower bound most of the time, with much lower complexity and better bandwidth utilization.

During the course of these debates, the IETF participants became uncertain about the desirability of what they were doing. The IETF did not have a tradition of specifying or standardizing a service, although they had essentially done so (informally) for the Controlled Load standard. The

25. Wroclawski, "Specification of the Controlled-Load Network Element Service."

26. The results of this thesis are described in Parekh and Gallager, "A Generalized Processor Sharing Approach to Flow Control in Integrated Services Networks: The Single-Node Case."

IETF normally standardized mechanisms and protocols, but not services, and many felt strongly that specification of a service was out of scope for the IETF. The IETF, after a struggle to understand how such a specification might be more precise, backed off and instead decided that for the DiffServ standards, what they would standardize was the functional behavior in the router. They decided to standardize technology rather than service. To make this point clear, the IETF working groups defined a new term, "per hop behavior" or PHB, to describe what the router would do, and they redefined the ToS field in the IP header so that instead of specifying a service, as it did in the original IP specification described earlier, it now specified a particular PHB that the router should apply to the packet. The concept of per-hop behavior, or PHB, is discussed in RFC 3086.[27]

The DiffServ standards were intended to provide the predictive service described earlier and initially specified in RFC 2475 ("An Architecture for Differentiated Services").[28] The architecture provides a framework to specify different PHBs; each such specification would result in a standard. With respect to defining the resulting service, RFC 2475 gives this advice: "It is strongly recommended that an appendix be provided with each PHB specification that considers the implications of the proposed behavior on current and potential services."

The DiffServ architecture redefined the IP TOS field so that different values of the field (in the DiffServ context, called "Differentiated Services Code Points" or DSCPs) select different PHBs.[29] The most commonly used PHB today within the DiffServ architecture is called "An Expedited Forwarding PHB" described in RFC 2598,[30] which maps the PHB to a service as follows: "Note that the EF PHB only defines the behavior of a single node. The specification of behavior of a collection of nodes is outside the scope of this document." The specification of the Expedited Forwarding PHB, informally, is simple: a router offering EF service must specify an aggregate traffic rate R such that so long as the aggregate arrival rate does not exceed R, the router will forward EF packets with minimal delay.[31]

---

27. Nichols and Carpenter, "Definition of Differentiated Services per Domain Behavior and Rules for Their Specification."

28. Blake et al., "An Architecture for Differentiated Services."

29. The TOS field is not used for the IntServ scheme. Since IntServ treats each flow separately, the packets must be classified using the IP addresses and port numbers in the packet, not the TOS field.

30. Jacobson, Nichols, and Poduri, "An Expedited Forwarding PHB."

31. RFC 4594 (Babiarz, Chan, and Baker, "Configuration Guidelines for DiffServ Service Classes") defines twelve DSCP values, including the default service of best-effort forwarding.

One key difference between the IntServ and DiffServ approaches is that IntServ deals with individual flows, while DiffServ deals with aggregates of flows. Routers aggregate all packets with the same code point value and give them the same collective treatment. By working with aggregates, the design avoids any need to keep track of individual flows, which leads to great simplicity compared to the IntServ approach. However, for the DiffServ approach to result in an overall good service, some larger mechanism must ensure that the flows marked with the specific code point do not result, in aggregate, in too large a total demand. But this mechanism is outside the scope of the specification of the PHB.

This design shift from service to PHB made the participants at the IETF more comfortable, but created a serious dilemma for the overall concept of enhanced services. What applications care about is the service they are going to receive, not the technological approach used to achieve it. The decision of the IETF to standardize on PHBs and remain silent on how these PHBs were to be used to create a service meant that an ISP considering offering such a service had a lot of work to do beyond what the IETF had done. It would be necessary to define the service that the ISP is offering, and define how the end-node requests that service for a flow of packets. Further, application designers write code based on the assumption that it can be used in any part of the Internet, which meant applications needed a standard way to request a service, which each network would translate into the best technical approaches to achieve that service. However, the IETF retreated from writing any such standard, as the effort was hard, and inextricably related to business models, which many thought were out of scope for the self-defined mission of the IETF.

Limitations of the IETF Standardization Model

A reader unfamiliar with the dynamics of Internet governance might wonder why the IETF could not resolve the ambivalence about standardizing QoS in terms of services in order to set the industry on a course toward the provision of enhanced services. The answer is the political, sociological, and economic context in which the IETF came into being and evolved. The engineering and research communities who formed the IETF tended toward libertarian in political philosophy, and explicitly eschewed authority to create mandatory standards. Instead they believed technologies would become *de facto* standards based on their merit, leading to natural pervasive adoption. At the same time, nobody has the authority to tell the IETF what to standardize. In 1992, just as the QoS standards

work was starting, a committee called the Internet Advisory Board (IAB), which had some authority to set overall direction for the IETF, made the unpopular decision that the next generation of the Internet Protocol should be based on a competing proposal developed by the International Standards Organization. The IETF rejected this recommendation, and defiantly declared that the IAB was a group to which they would no longer listen.[32] As the leading source of Internet governance at that time, the IETF was proudly and perhaps excessively bottom-up in its governance approach, rejecting any attempts to offer leadership and direction from above. Indeed, advocates for QoS standardization had to convince the IETF to take up the effort based on its merits (section "Proposed Long-Term Solution: Standardizing Support for Enhanced Services").

Revealing Moments: The Greater Obstacle Is Economics, Not Technology

A personal anecdote illustrates some of the problems facing technical innovation in QoS. One of us (Clark) was trying to push for the deployment of QoS technology in the mid-1990s. He spoke to the major vendor of routers (Cisco), and an engineer from Cisco responded that they added features when they had a customer. So he went to the CTO of the (then) largest wide-area ISP and suggested that deploying QoS would be a good idea. The CTO had a simple answer: "No." His elaboration was revealing: "Why should I spend a lot of money deploying QoS so Bill Gates can make a lot of money selling Internet Telephony for Windows?" In one sentence, this comment captures one of the central economic dilemmas of the Internet. If money is spent at one layer (e.g., the facilities and packet carriage layer), and is being made at another layer (the application layer), and the open interface of the packet carriage service platform makes it hard for revenue to flow across this interface, there may be a mismatch of incentives across these layers: between the ISP and the application provider. This same CTO went on to say, more ominously: "And if I did deploy QoS, why do you think I would turn it on for anyone besides me?" Again, in one

32. This event, the so-called "Kobe decision," named for the location of the meeting where the decision was taken, is documented in Mueller, *Ruling the Root*, p. 96, and the formal IETF response is in Crocker, "The Process for Organization of Internet Standards Working Group (POISED)." Among the actions described in RFC 1396 is the transfer of any authority to approve standards from the IAB to a leadership group of the IETF, and a revised process for selecting members for the IAB.

sentence, this brought into focus all the concerns we now address under the banner of network neutrality.

Nontechnical Barriers to Enhanced Services on the Internet (2000s)

The 2000s were the decade during which operational and research attention shifted away from purely technical issues inherent in QoS, toward the economic and business/market drivers of and obstacles to deployment of QoS. It was also the decade when the issue of QoS hit public policy debates, and by the end of this decade, it was unclear which challenge was more daunting: the business coordination and incentive issues, or regulatory resistance.

Early 2000s: A Funeral Wake for QoS

The work on standardization of differentiated services resulted in many research papers on the topic, but no successful deployment on the Internet. Frustration with this failure motivated ACM SIGCOMM to host a workshop in 2003 called "Workshop on Revisiting IP QoS: Why do we care, what have we learned? (RIPQOS)." The organizers framed this workshop as a place for examination of reasons behind the failure. From the workshop summary, "Large segments of the operational community simply cannot see the point of adding QoS to networks that are humming along quite nicely as they are. A broad spectrum of people can't entirely agree on what QoS actually is."[33]

One paper presented at this workshop[34] proposed that the obstacles to wide-area deployment of QoS were the complexity of the mechanisms, the immaturity of the code, and the lack of clear motivation for deployment. The paper also notes a structural rift between network operators and the designers of protocols and QoS architectures. Protocol designers may prioritize performance and efficient use of link capacity, while operators prioritize network resilience and manageability. As such, operators are cautious regarding the difficulty and risk associated

33. Armitage, "Revisiting IP QoS: Why Do We Care, What Have We Learned? ACM SIGCOMM 2003 RIPQOS Workshop Report."

34. Bell, "Failure to Thrive: QoS and the Culture of Operational Networking."

with deployment of complex mechanisms, and may consider overprovisioning of bandwidth to be the best overall approach to stable QoS. Several participants felt that the appropriate response to contention for network bandwidth is usually not QoS support but rather creating more bandwidth, but acknowledged that it is not always possible to easily upgrade wide-area network links. Internet2 engineers (a US research and education network) observed, "Neither customers nor Internet service providers need or want hard performance guarantees. Instead, each wants tools to understand and manage risk."[35]

Bruce Davie from Cisco surprised many at the workshop when he reported that the QoS technology developed by the IETF was in use in many IP-based enterprise networks, for example, corporate intranets.[36] Although intra-domain (as opposed to inter-domain) deployment of QoS is not necessarily visible to researchers, he assured us that the technology worked, and it was delivering solid benefits to the networks that deployed it. The workshop summary[37] emphasized deep nontechnical reasons that differentiated services had not been deployed in the Internet, including complexity of coordination among multiple ISPs, and lack of an economic framework to allocate revenues across providers and management complexity. The conclusion from the organizers was: "QoS is not dead, but as an IP QoS R&D community we need to reach out and include business, systems control, and marketing expertise in our efforts to get IP QoS meaningfully deployed and used."

In the next few years, this same debate continued in the research literature. AT&T published a study in 2007 that, while it provided no traffic or cost data about AT&T's network, reported traffic and user growth estimates from elsewhere to portend an imminent bandwidth and investment problem that will require new QoS-based revenue models to solve.[38] They used modeling and simulation techniques to compare the amount of extra capacity required of a best-effort network to support the same performance requirements of a simple two-class differentiated services network, for a range of traffic scenarios. The conclusion is that a relatively small fraction of premium traffic could require considerable extra capacity to make sure

35. Teitelbaum and Shalunov, "What QoS Research Hasn't Understood about Risk."

36. Davie, "Deployment Experience with Differentiated Services."

37. Armitage, "Revisiting IP QoS: Why Do We Care, What Have We Learned? ACM SIGCOMM 2003 RIPQOS Workshop Report."

38. Houle et al., "The Evolving Internet-Traffic, Engineering, and Roles."

those traffic needs are satisfied (consistent with the results of Parekh[39]), and the revenue for that capacity would simply not exist under best-effort revenue models. Two years later, Andrew Odlyzko offered a more academic view: "To evaluate claims about need for additional revenues . . . one needs solid cost data and a dynamic model of the industry. At the moment we do not have either one."[40]

Mid-2000s: Working with Industry to Gain Insight

One benefit of the best-effort service model of the Internet is that it allows ISPs to interconnect without having to negotiate any performance parameters in order to provide that service. ISPs already have to participate in a protocol that exchanges routing information, and in doing so they of necessity reveal something about their patterns of interconnection—this revelation is considered normal. But tight specification of performance characteristics of an end-to-end service requires more complex inter-ISP protocols. Such protocols have never been proposed, let alone standardized, partly due to the considerable resistance to the inherent need for ISPs to reveal significant internal operating information in order for those protocols to work.[41] In addition, the 1990s discussions among ISPs to develop a general approach to defining and marketing cross-ISP differentiated services raised considerable anxiety related to antitrust concerns, since the conversation inherently touched on pricing and revenue sharing.

In 2006, the MIT Communications Futures Program convened a series of meetings involving ISPs (engineers) to try to work through the issues that would have to be solved to provide true multi-provider QoS. The attendees, all network engineers, were not willing to discuss the problem of pricing and revenue sharing in the context of a traditional peering relationship, because peering had traditionally been revenue neutral. Discussion of payment for enhanced QoS across peers might well trigger questioning this revenue-neutral model. The group developed an alternative business framework to sidestep this problem: the hypothetical use case

39. Parekh and Gallager, "A Generalized Processor Sharing Approach to Flow Control in Integrated Services Networks: The Single-Node Case."

40. Odlyzko, "Network Neutrality, Search Neutrality, and the Never-Ending Conflict between Efficiency and Fairness in Markets."

41. The need for exchange of information could be minimal if every ISP always fulfilled its service commitments, but any failure of a flow to receive a promised level of service requires ISPs along the path to share enough internal information to locate the source of impairment.

of provisioning an intranet for a global corporation, where no single ISP has the required service footprint to cover all outposts of the corporation. The business assumption was that one ISP would contract to provide the service, and subcontract with other regional ISPs to build a global footprint. In this scenario, the question of pricing seemed less vexing, since it was clear that the ISP with the customer contract would pay the other ISPs for service, and could thus be set aside.

The discussions, which initially focused on the technical aspects of delivering a differentiated service (a low-jitter service for VoIP), revealed a number of complex and thorny issues. The participants were skeptical that an unquantified service could successfully be brought to market. They felt that some quantitative service specification would be required, such as "jitter will be no more than 20 ms end-to-end." But then the challenge was to sort out how ISPs along a path would cooperate to achieve a quantitatively specified outcome. One answer is to allocate a static jitter budget to each ISP. If there are two ISPs in the path, each would be allowed a jitter budget of 10 ms. But one of these ISPs might be well-provisioned, and could easily avoid inducing jitter without special effort, while the other ISP might be overloaded and hard-pressed to hit the 10-ms target. If the entire 20-ms budget was allocated to the second ISP, it would be a better outcome from an optimization point of view, but in this case, the second ISP would have to disclose to the first its state of under-provision, which was unacceptable.[42]

Worse, what if the actual service provided did not meet its specification? What sort of information sharing and inter-ISP measurement would be required to assign the responsibility for the fault to one of the providers? The recurring problem in the design of cross-ISP service provision was that to ensure the service was meeting its commitment, ISPs would have to share information about their internal operation that they view as proprietary. ISPs are competitors, even as they cooperate to interconnect.

The report of this effort was released,[43] and some of the firms that participated in the discussions intended to bring the document forward into a suitable standards forum, but in retrospect it does not appear to have had much visible impact. This tension between providing a better specified

42. There is substantial literature exploring how to dynamically allocate bandwidth and buffer among multiple autonomous systems, for both IntServ and for DiffServ, to maximize sum utility, for example, Jin and Jordan, "On the Feasibility of Dynamic Congestion-Based Pricing in Differentiated Services Networks."

43. MIT Communications Futures Program, "Inter-Provider Quality of Service."

service across a multi-ISP Internet and the resistance to the sharing of operational information is an issue for other public policy challenges as well, the most acute of which today is improving the Internet's resistance to distributed denial of service (DDoS) attacks and other security vulnerabilities.

Late 2000s: QoS Becomes a Public Policy Issue

The exercises of the 2000s convinced many that the coordination problems and business-related barriers to QoS were so severe as to preclude any possible deployment in the public Internet, even though they were seen as delivering benefits in private IP networks. At the same time, fear of a dark side of QoS began to emerge. As we have described the use of QoS, and as the IETF standardized the mechanisms, the goal was to benefit applications that required enhanced service. But an ISP could also use QoS techniques to *disadvantage* certain packet flows, for example, a third-party video service competing with the carrier's own. In response to this fear, the goal (and vocabulary) of network neutrality emerged, with the objective of preventing potential harms from traffic discrimination.

Furthermore, while using QoS as a tool for performance improvement seems to require cooperation of every ISP in the path, any single ISP could use QoS technology to induce impairment of a flow crossing its network. So, from a technical perspective, the concern is certainly legitimate.

The concern is even stronger from an economic perspective, because any QoS capability has the potential to incentivize anticonsumer business behavior based on technologies that induce artificial scarcity, as opposed to pro-growth and innovation-driven strategies. This problem has been called the "dirt road future for the information super highway." Queue management (e.g., scheduling packets in a queue to give one set of packets a different service) only makes sense if there is a queue. If there is enough capacity in the network to carry all of the offered traffic, then queues do not form, and there is no queue to manage. So QoS tools only become relevant when the network is congested, and the QoS technology creates a possible perverse incentive. As traffic builds up on a network and periods of congestion start to occur, the network operator can either spend money to increase the total capacity, or instead sell enhanced services to its users to allow critical applications to continue to function well in the face of congestion. The question a rational ISP faces could be cast as whether to spend money on improving infrastructure or make money off services. This tension is exacerbated in regions where there is limited competition

at the access level (in both wired and wireless infrastructures), and a lack of transparency into whether the perverse incentives prevail. For this reason, discussions about acceptable uses of tools for traffic differentiation trigger discussions about measurement of performance, and disclosure and transparency with respect to practices and network conditions.

In the United States, we know of a few instances of the use of QoS technology to slow down one Internet flow relative to another,[44] as well as cases where ISPs have used blocking and termination of flows—extreme forms of traffic discrimination—to disadvantage certain applications. In 2005, the FCC fined Madison River, a small ISP, for blocking VoIP traffic based on its port number. In 2006, a researcher discovered that Comcast was blocking BitTorrent uploads from their customers by injecting a TCP reset packet into the data stream.[45] Comcast argued that they were enhancing performance for non-heavy users, but shortly thereafter changed their network throttling to be agnostic to the application.

In contrast, British Telecom (BT) used traffic shaping tools to limit but not block BitTorrent during peak hours, which did not trigger a UK regulatory reprimand. BT argued that this step was performance enhancing for latency- and jitter-sensitive applications such as VoIP and games.[46]

By the late 2000s, the US FCC realized it needed to ramp up its understanding of the how technical and business issues connected, in order to inform any future regulatory framing around QoS.[47] The TCP/IP architecture had become a remarkably stable platform for communications, one of the goals of its original designers, in order to facilitate innovation

---

44. Rayburn, "Cogent Now Admits They Slowed down Netflix's Traffic, Creating a Fast Lane & Slow Lane."

45. Federal Communications Commission, "In the Matters of Formal Complaint of Free Press and Public Knowledge against Comcast Corporation for Secretly Degrading Peer-to-Peer Applications; Broadband Industry Practices Petition of Free Press et al. for Declaratory Ruling That Degrading an Internet Application Violates the FCCs Internet Policy Statement and Does Not Meet an Exception for Reasonable Network Management."

46. For a detailed and thoughtful analysis of the British Telecom rate-limiting situation, see Cooper, "How Regulation and Competition Influence Discrimination in Broadband Traffic Management: A Comparative Study of Net Neutrality in the United States and the United Kingdom." It is interesting to contemplate what would have happened in the United States if Comcast had chosen to slow rather than block BitTorrent uploads, disclosed in advance that they were going to do so, and maintained that it was performance enhancing.

47. FCC Technical Advisory Workshop on Broadband Network Management, https://www.fcc.gov/events/technical-advisory-process-workshop-broadband-network-management. Some material from this section was presented at this workshop (http://www.caida.org/publications/presentations/2009/traffic historical context/).

above and below this network layer. Indeed, many aspects of networking technology below and above the Internet layer—bandwidth provisioning, data processing, and storage efficiencies—made phenomenal (Moore's Law) advancements in the first twenty years of the Internet's largely unregulated global deployment. The political economy of just about every aspect of the ecosystem experienced upheaval as the US government continued the policy it began in the mid-1990s to privatize the Internet infrastructure and governance. The result was an evolutionary shift in capital and industry structure, and associated business models, of not only core and access infrastructure providers but also the naming (Domain Name System [DNS]) provisioning and content (CDN) provisioning industry.

As it became clear that most telephone calls would eventually use IP infrastructure, the US FCC began to realize that it would have to exercise stewardship over that infrastructure, and initiated attempts (not very successfully) to learn more about its dynamics and economics.[48] During the Obama Administration's Broadband America program in 2009, the National Telecommunications and Information Administration (NTIA) constructed a set of requirements for data collection associated with $7B of "stimulus" funds allocated to broadband, the Broadband Technology Opportunities Program, or BTOP. The nature of these requirements[49] would have provided the US government with some (limited) empirical data on demand for some Internet infrastructure resources, and possibly some insight into drivers for QoS. To our knowledge, the requirements were never implemented.

The last years of that decade (2008–2009) also provided examples of how advanced countries (Japan and Canada) were handling possible harms that could arise from traffic management practices, in particular packet shaping, which is traffic discrimination against heavy users to improve

48. Another anecdote: an FCC engineer called one of us around 2006 to ask whether the research community knew how to define "outage" of a voice call over the Internet, since the FCC is required to track telephony outages, and clear metrics for doing so.

49. Awardees receiving Last Mile or Middle Mile Broadband Infrastructure grants must report, for each specific BTOP project, on the following:

(a) The terms of any interconnection agreements entered into during the reporting period;
(b) Traffic exchange relationships (e.g., peering) and terms;
(c) Broadband equipment purchases;
    Total and peak utilization of access links;
    Total and peak utilization on interconnection links to other networks;
(d) IP address utilization & IPv6 implementation;
(e) Any changes or updates to network management practices.

overall service for most users. That is, the term packet shaping is associated with a subset of QoS behaviors that degrade QoS of specific users in order to improve overall QoS, which triggers the question of how to constrain packet-shaping behavior to minimize harm to users. In May 2008, a group of Japanese ISP industry associations published an industry consensus (not legally binding) on guidelines that described circumstances in which they considered packet shaping acceptable.[50] They cited specific examples that emphasized the relationship between "secrecy of communications" (which has strong weight in Japan) and fairness in use under Japanese business law. The guidelines affirmed that packet shaping should be implemented only in exceptional circumstances to "facilitate necessary network management" or to "protect users." Such packet shaping must: (a) be in response to congestion of specific heavy users that is degrading or will likely degrade service of general users; (b) must be substantiated by objective data. For example, content examination, such as looking for copyright infringement based on payload, was not deemed reasonable because one cannot do it accurately for a single user, nor reasonably for all users. They emphasized the need for further study of the impacts of different packet shaping approaches to adapt to the increase in streaming video traffic, as well as the need for more information-sharing among players.

An international case closer to home was Canada, whose regulator (Canadian Radio-Television and Telecommunications Commission [CRTC]) published Internet traffic management best practices in October 2009. In spirit similar to those expressed by the US FCC's and Japan's ISPs, the CRTC's guidelines required transparency about ISP traffic management practices.[51] They emphasized that any packet shaping must be narrowly tailored for purpose (technically "efficient"), and minimize harm to consumers. They recognized the challenge of defining "reasonable" network management, but affirmed that targeting specific content or applications was not allowed, and that any techniques used should be based on transparent quantifiable data.

By 2010, the FCC formalized their own need for transparency with respect to network traffic management, and implemented disclosure requirements in their 2010 Report and Order.[52] As part of this order,

50. Japan Internet Providers Association (JAIPA) et al., "Guideline for Packet Shaping."

51. Canadian Radio-Television and Telecommunications Commission, "Review of the Internet Traffic Management Practices of Internet Service Providers."

52. Federal Communications Commission, "Report and Order, Preserving the Open Internet."

they also established the Open Internet Advisory Committee to facilitate evaluation of the risks and benefits associated with QoS.[53]

Evolving Interconnection Structure and Implications for Enhanced Services (2010s)

In pursuit of performance and cost optimizations in the face of demanding new services and applications, the interconnection ecosystem has been profoundly transformed in this decade. In this section, we describe several dimensions of this transformation, and implications for the theory and practice of regulation of enhanced services on the Internet.

Expansion of Network Interconnection Scale and Scope

An evolutionary shift in the pattern of interconnection in the Internet has emerged and stabilized over the last ten years: from one where ISPs typically exchanged traffic via intermediate larger transit providers (the 1990s Internet equivalent of long-distance telephone companies) to a pattern where many ISPs exchange traffic directly, over peering links. ISPs can peer with each other bilaterally via a private interconnection, or peer multilaterally, that is, with multiple ISPs, through an Internet Exchange (IX), which is a location with a central switch that can route traffic among many connected ISPs. The term peering arose in the early 1990s because interconnecting large ISPs viewed each other as equal players (peers) in the market. Traditionally, such peering was revenue neutral (settlement free), because large ISPs perceived the arrangement as of approximately equal value.

As smaller ISPs began to peer with each other, avoiding larger transit providers, (sometimes called donut peering), they sent less traffic—and thus less revenue—to the transit providers, diminishing their importance in the marketplace. Many transit providers from the 1990s disappeared into mergers or bankruptcies by the 2010s. The result has been called the flattening of the Internet topology.[54] Another market sector

53. https://www.fcc.gov/encyclopedia/open-internet-advisory-committee. This committee met several times in 2012–2013 and published a report (available at that URL), after which the committee chair stepped down and they have not met since.

54. Dhamdhere and Dovrolis, "The Internet Is Flat: Modeling the Transition from a Transit Hierarchy to a Peering Mesh."

of the interconnection ecosystem that enabled, as well as thrived on, this peering expansion was Internet exchanges (IXes), which served as anchor points in the mesh of interconnection. A third related trend was the growing role and importance of content providers and CDNs as major sources of traffic flowing into the Internet. Proliferation of IXes around the world facilitate interconnection among networks within a region, allowing traffic to flow along cheaper and lower-latency routes, which CDNs leverage to place (cache) content as close to users as practical.

We now see a new shift in the structure of ISP interconnection. This shift constitutes the rise of a new kind of hierarchy in the ecosystem, bringing fundamentally new constraints on existing players who need to manage traffic on their networks to minimize congestion. One option for large CDNs that can afford it is to install content caches adjacent to (or inside) major access networks, perhaps maintaining their own global networks to serve content to these caches. A CDN may use these caches to deliver its own content or content on behalf of its customers. When ISPs connect directly with content providers, we use the term direct interconnection to describe this mode. The economies of scale of technology of the high-bandwidth content delivery market, with its concomitant requirements for storage, bandwidth, computation and IT expertise, and legal licensing support, has led to concentration of content ownership and delivery capability among a few large content providers. By some accounts over half the traffic volume in North America now comes from just two content distributors (YouTube and Netflix). Most of this traffic flows over direct interconnection paths.

The emergence of direct interconnection has been accompanied by disputes between ISPs and content providers over the terms of interconnection. Evidence of trouble has increased dramatically in the last five years, resulting in tussles among commercial players as well as between the private sector and regulatory bodies, at the expense of users suffering degraded QoE. These disputes have to some extent masked the emergence of direct interconnection as a distinct phenomenon, in part because some content providers have referred to this mode of interconnection as another form of peering, which suggests that it should be revenue neutral, as peering between approximately similarly sized players had traditionally been (i.e., in the 1990s). Through heated debates in the press and to the regulator (at least in the United States), access ISPs have argued that interconnection between large content providing networks and access networks did not fit

the traditional paradigm of settlement-free peering, among other reasons because traffic exchange was heavily asymmetric. The apparent resolution of these disputes[55] has been that content providers and CDNs are paying for direct interconnection, and ISPs view them as customers, to whom they make service commitments.

In the context of a debate over enhanced services on the public Internet, the important aspect of this shift toward direct interconnection is that CDNs are not offering mass-market services to the public. While they are a part of the global Internet, they either serve a single firm to deliver its content (e.g., Netflix or YouTube) or they serve as a third-party delivery service to firms that market content (e.g., Akamai). For such networks, there are currently no regulatory restrictions on the use of traffic differentiation; they can operate their networks as best supports the services running over them. But equally important, with direct interconnection, there is only one ISP in the path between the source of the content and the destination—the broadband access network itself. This pattern implies that for an access ISP to offer enhanced QoS to a flow from a content provider to a user via direct interconnection, no negotiation with any other ISP is necessary. The technical issues in the MIT study (section "Mid-2000s: Working with Industry to Gain Insight"), such as how to allocate a delay budget or isolate service impairments across several ISPs, do not arise. It is likely not a coincidence that business relationships (and associated interconnection) have evolved to enable technology to mitigate the inability to support truly interprovider QoS.

However, at least this year in the United States, the obstacle to enhanced QoS in this specific circumstance would be regulatory, because the FCC has ruled out the possibility for the content provider, as a customer of the access ISP, to pay for any service enhancement to the end user.[56] The FCC termed this *paid priority*, and concluded that it violates the neutrality that the ISPs are expected to provide, both with respect to end users and content providers (what the FCC calls edge providers). The FCC has stated[57] that service differentiation is more likely to be acceptable if it is application agnostic, or if it is under the control of the user,

55. The details of these negotiations and resulting agreements are under nondisclosure agreements determined by the interconnecting companies.

56. Federal Communications Commission, "In the Matter of Protecting and Promoting the Open Internet: Report and Order on Remand, Declaratory Ruling, and Order."

57. Ibid., paragraph 221.

thus presumptively not harming the user or his data flow. Unfortunately, as described in the section "Standardization of Enhanced Service in the IETF," there is currently no framework within which a user (or application code acting on the user's behalf) could take steps to invoke or control the use of service discrimination.[58]

Even without QoS technology, the use of direct interconnection itself implies a form of traffic differentiation to enhance the performance of the applications being served over that interconnection. This differentiation is not related to how packets are scheduled at a point of congestion, but the number and location of interconnection points, and the algorithm used to select the source for a particular piece of content. By adding more points of interconnection, and by picking a source close to the destination, the content provider can reduce latency, both improving end-to-end performance and bandwidth efficiency of the access ISP. Cooperation between the ISP and the content provider can potentially lead to more efficient and higher quality delivery of the service. The fact that one provider of content may negotiate more points of direct interconnection compared to their competitor has raised the issue of whether, through pricing, an access ISP can cause harms to bear on one CDN relative to another. An access ISP might offer direct interconnection at a given point to different CDNs at a different price (price discrimination), or offer more points of interconnection to different CDNs. However, this sort of discrimination has thus far been outside the scrutiny of regulators, because it seems a pure business practice, with no technical component such as packet scheduling.

Emergence of Private IP-Based Platforms to Support Enhanced Services

The traditional discourse on network neutrality (and specifically the FCC's Open Internet principles) approaches the question of regulating QoS (or not) primarily by considering constraints on the Internet offering itself. But as the world converges on the Internet Protocols as a universal method to implement networks, these protocols are being used to deliver far more than just access to the public Internet. Recently, a few large ISPs have built private interconnected IP-based networks, using the IP technology but

58. This issue sheds light on another reason why QoS tools have been successfully deployed within private IP networks and private regions of the Internet: a private network operator is free to use classification rules to assign QoS service classes to specific services and applications using inspection of the packets, thus imposing its own policy constraints on its traffic.

distinct from the public Internet. The resulting IP-based multi-provider networks are currently being used to carry what is called "carrier-grade Voice over IP." Voice over IP, or VoIP, when provided by the carriers (in particular the mobile carriers), is carried using IP packets, but not over the public Internet. An alternative interconnection architecture has been developed to allow these networks to be connected for the purpose of carrying VoIP among providers.[59] These private networks are build using the same physical infrastructure as the public Internet, but use different addresses and separate capacity allocations.

These private IP networks will allow ISPs operating them to develop new business models, support enhanced services, and vertically integrate infrastructure and applications. We recently used multisided platforms (MSP) theory to explore the range of options ISPs have to offer and interconnect enhanced services in today's IP-based ecosystem.[60] In particular, we identified the single and multi-firm IP platforms as alternative delivery options for consumer-facing services.

Such networks are a natural industry response to the need for stable network infrastructure, but they present a serious challenge to the theory and practice of regulation, particularly vivid in the now quite muddled debate over enhanced services on the Internet. First, this shift leaves the public Internet as a place for activities of lower importance and lower profitability, and perhaps starved for capital investment. Second, the new networks constitute a shadow activity, serving a role previously served by a regulated sector that is not currently regulated. Without regulation, these activities may carry substantial systemic risk, amplified in this case by gaps across different bodies of law, which hinder policymakers' ability to respond to problems.

For example, a platform operator (broadband provider) may allocate a share of the IP platform as an alternate, logically separate, multi-firm service platform, which is IP based but not interconnected with the public Internet. On that share, the platform operator may allow third-party complementors to offer consumer-facing services, perhaps with desirable qualities compared to the public Internet: it may have better performance;

59. The interconnection architecture, called IP Exchange or IPX, was developed by the GSMA (see http://www.gsma.com), and provides for service-specific interconnection, with per-service payment. See, for example, http://www.gsma.com/newsroom/wp-content/uploads/2013/05/IR.34-v9.1.pdf.

60. claffy and Clark, "Platform Models for Sustainable Internet Regulation."

a curated library of available applications like the Apple app store; more security; or be billed in ways that are not available over the Internet. For the context of this article, we suggest that these platforms may provide superior QoE, either through the use of QoS technology, or capacity engineering combined with limits on traffic allowed onto the platform. (If the ISP limits the platform to specific applications, it is easier to provide congestion-free provisioning than it is for the Internet, where the user can send any sort of traffic desired.)

The emergence of these alternative platforms signals an important point: ISPs would not position services on these alternative platforms unless the result was new revenue opportunities. These platforms, in one way or another, must reflect an opportunity for a facilities-owning service provider to offer services using their own facilities in ways that give them a competitive advantage over competing over-the-top services on the Internet. Under these circumstances, policymaking must consider the side effects of constraining the Internet service relative to what is allowed on a different platform serving the same participants.

Similarly, we must consider the implications of QoE impairments on the public Internet for edge-provider innovation: does lack of service differentiation inhibit development of classes of applications, because the application designers cannot achieve an acceptable QoE? Real harms might arise from an access provider's ability to negotiate direct interconnection on its private IP platform with arbitrary levels of QoS. One harmful trajectory is that innovative edge providers who need special QoE, and can afford it will migrate away from the global Internet onto alternative specialized service platforms, eroding the centrality of the global Internet as the universal platform for innovation. The future might be an all-IP world, but with parallel IP platforms competing both for end user and edge-provider access. Inherent harms of such a fragmented world include inconsistent access to end users, and constant concerns about discriminatory treatment.

Any theory of regulation that tries to limit activities of the platform owner must consider the full range of consequences. Banning discriminatory traffic treatment on the Internet may prevent certain harms, but may also prevent the public Internet from competing with alternative private IP platforms with superior QoE, an undesirable outcome. To limit this harm, regulators might try to control what uses a facilities owner makes of their infrastructure—what service they can offer aside from Internet. One approach would be to specify unacceptable uses of an interconnected

IP platform.[61] Alternatively, they might try to specify what uses are acceptable. The European Union has taken a much more aggressive approach in this area,[62]requiring that there must be objective evidence that any enhanced QoS for such a service is necessary, and that the deployment of services other than Internet over the facilities of a provider not deprive the Internet service of adequate capacity.

A structured focus on potential harms and benefits of specific discrimination and pricing behavior of ISPs can help frame a debate about how to maintain the Internet as a vigorous platform that can compete with alternative private platforms. Specifically, allowing ISPs to sell QoS enhancements that lead to improved QoE on the public Internet may reduce the drive to offer specialized services, preserving the Internet as the unified service platform. It is worth exploring possibilities to accommodate such enhancements using monitoring to detect potential collateral impairments.

---

61. In the 2010 Open Internet order, the FCC took this approach. That order stated that the FCC's limits on discriminatory traffic treatment shall apply to the Internet and to any service platform that is: "*providing a functional equivalent of the service described in the previous sentence [retail Internet access], or that is used to evade the protections set forth in this Part*." (Federal Communications Commission, "Report and Order, Preserving the Open Internet," §44). They elaborate (ibid., §47, footnotes omitted):

> *A key factor in determining whether a service is used to evade the scope of the rules is whether the service is used as a substitute for broadband Internet access service. For example, an Internet access service that provides access to a substantial subset of Internet endpoints based on end users preference to avoid certain content, applications, or services; Internet access services that allow some uses of the Internet (such as access to the World Wide Web) but not others (such as e-mail); or a "Best of the Web" Internet access service that provides access to 100 top websites could not be used to evade the open Internet rules applicable to "broadband Internet access service." Moreover, a broadband provider may not evade these rules simply by blocking end users' access to some Internet endpoints. Broadband Internet access service likely does not include services offering connectivity to one or a small number of Internet endpoints for a particular device, e.g., connectivity bundled with e-readers, heart monitors, or energy consumption sensors, to the extent the service relates to the functionality of the device. Nor does broadband Internet access service include virtual private network services, content delivery network services, multichannel video programming services, hosting or data storage services, or Internet backbone services (if those services are separate from broadband Internet access service). These services typically are not mass market services and/or do not provide the capability to transmit data to and receive data from all or substantially all Internet endpoints.*

The complexity of this paragraph hints at the definitional difficulty with regulating the allowable uses of an interconnected IP platform.

62. European Parliament and Council, "Regulation 2015/2120, Laying down Measures Concerning Open Internet Access."

Advancing Our Empirical Understanding of Performance Impairments

There has been research on the technical aspects of QoE: how it relates to aspects of underlying service quality. More central to this article is the policy question—what is driving observed QoE impairments today: is the underlying cause technical issues that are hard to mitigate or decisions about level of investment and exploiting deliberate scarcity? Unless tools to enhance QoS (and thus QoE) are a response to actual technical issues, they may be nothing but a way for infrastructure owners to maximize return on their capital investment.

Today, traffic from users is capped by an access link with a fixed peak speed, which is often the limiting factor for throughput, that is, by design this segment path will congest first. For some access technologies, for example, DSL, these limits on throughput are fundamental. When the capacity of the access link to the Internet is the limiting factor in performance, interaction among different traffic flows for a single user across that link can lead to impairments of QoE. Today, a phenomenon called bufferbloat[63] can induce excess latency and jitter on access links. Some ISPs are moving to a new generation of access technology that uses service differentiation techniques to mitigate these problems. For example, the cable industry has proposed a new generation of their DOCSIS standard (DOCSIS 3.1), which will provide isolation among classes of flows for a single Internet user so congestion from one class of flows would not trigger impairment in another user flow such as over-the-top VoIP, for example, Skype.[64] This transition will require upgrading cable modems and other equipment of the cable provider. Some access providers use a crude form of this isolation today (separate queues feeding into separate capacity allocations) to separate Internet traffic from specialized services.

Thus far, using QoS tools in this context has not triggered regulatory concerns. There is a strong argument that traffic differentiation in this context will improve QoE. But there is a lurking regulatory dilemma. On the one hand, allowing QoS enhancement for the Internet service to the user can make the QoE of Internet services more competitive relative to other services offered over that link (those "private IP platform" services discussed in the section "Emergence of Private IP-Based Platforms to Support Enhanced Services"). On the other hand, perhaps the right goal for regulation should

63. Lang, "Bufferbloat."

64. Isolating traffic into different queues does not automatically prevent the harms from buffferbloat. Devices must properly manage their queues, which can include proper queue sizing and regulation of traffic admitted into the low-jitter queue.

be to encourage investment in higher-capacity Internet access, which would remove some of the impairments without the need for QoS, and improve the users' ability to run a wider range of services with good QoE. Allowing the use of traffic differentiation for Internet services over the access link could incentivize ISPs to build business models based on (and extract revenues from) scarcity rather than invest to reduce the need for QoS.

One approach to regulation of differentiated services is to link its use to a strong requirement for disclosure and justification. Since any traffic management mechanism, including QoS, can be used in ways that either benefit the user or cause harms, we have advocated explicit attention to possible harms from traffic management approaches, their causes, and means to prevent them.[65] One approach is to require ISPs to publish an analysis of harms and benefits of their proposed traffic management techniques, which explains why the benefits outweigh the harms. This approach has many challenges, depending on the detail required of the ISP: ensuring such analyses are sufficiently detailed to allow independent, third-party evaluation; obtaining such evaluations; adapting to changing reasonable expectations about QoE over time; and capturing specific as well as more general societal harms, such as the effects of under-investment in capacity. However, ISPs are required to disclose network management practices today, and a less demanding explanation may be useful in the marketplace.[66]

---

65. Clark, Bauer, and claffy, "Approaches to Transparency Aimed at Minimizing Harm and Maximizing Investment."

66. As a justification for a particular management practice in their network, AT&T offers the following discussion of its harms and benefits, targeted to consumers (https://www.att.com/gen/public-affairs?pid=20879):

> *With the ever increasing growth in smart phone and tablet usage on our networks, and the growing prevalence of video downloads, AT&T has deployed a reasonable network management video optimization technique in our mobile data network. That technique delivers recorded video to the user's device in a "just in time" fashion ("Buffer Tuning"). Buffer Tuning only applies to internet browser traffic (HTTP, port 80) for recorded video downloads, regardless of the source (including AT&T branded or 3rd party content), and does not affect real-time streaming video. Without Buffer Tuning, video content may be completely delivered to the device and charged against the user's data plan regardless of whether it is viewed. With Buffer Tuning, a sufficient amount of video is delivered to the device so that the user can start viewing the video, and the remainder of the video is delivered just in time to the device as needed for uninterrupted viewing. This optimizes the user's data plan consumption. Additionally, this frees up network resources for all users. Buffer Tuning does not alter video content and should not directly introduce any adverse impact to the viewing experience.*

A more fundamental problem is that while impaired QoE is a meaningful indicator of harm, tools to measure and analyze QoE today are primitive. Using QoE as a basis for regulation will require research, tools and capabilities to measure, quantify, and characterize QoE, and developing metrics of service quality that better reflect our understanding of QoS and QoE for a range of applications. Indeed, there are motivations for measurement, disclosure and transparency that arise for reasons unrelated to differentiated services. Persistently congested links are an indicator that users with traffic flowing over those links may not achieve their desired service quality, and this circumstance should attract regulatory attention. Although it does not exist today, we can imagine a scenario where ISPs provide enough transparency about the state of congestion and provisioning on their networks to assure both consumers and regulators that deployment of some proposed traffic management mechanism falls into this "no collateral harm" category. One option is a policy that triggers when persistent congestion is detected on major paths in the Internet, to compel access to information from ISPs relevant to the cause of the congestion. This option would require tackling the daunting challenges of defining congestion as well as defining how to detect and report it and who is responsible for doing so.

An interesting question is whether, by provision of enough capacity in the Internet, we could eliminate congestion (and thus the impairments caused by congestion) everywhere, or whether congestion would shift to the least recently upgraded part of the infrastructure (see the section "Using Enhanced Services to Mitigate Congestion"). Recently, firms in Japan have invested to support gigabit access services, and are subsequently seeing congestion move from access networks to the backbone networks.[67] The cited RFC states: "Since fiber to the home (FTTH) has rapidly spread all over Japan, bottlenecks in IP networks have been shifting from access networks to backbone networks and equipment, such as bandwidth between ISPs and capacity in IXs." As long as users are mixing a broad range of services, it is hard to imagine eliminating congestion altogether. Today's computers can easily exchange data among themselves at over a Gb/s. If users were offered truly unlimited service, so that they could consider streaming constant data at these speeds, Internet traffic loads might rise by orders of magnitude.

67. Kamei et al., "The P2P Network Experiment Council's Activities and Experiments with Application-Layer Traffic Optimization (ALTO) in Japan."

Lessons Learned

> In such situations of moderate scarcity, however, not all people can have whatever means of communications they want. The means are rationed. The system of rationing may or may not be equitable or just. There are an infinity of ways to partition a scarce resource—egalitarian . . . meritocratic . . . [recognizing] privilege . . . cultural values . . . [rewarding] skill and motivation, as that which allows communications institutions to earn profits that depend on their efficiency. (Ithiel de Sola Pool, *Technologies of Freedom*, p. 240)

It has been understood since the earliest days of networking that there will be situations in which there is not enough capacity to serve all users and all uses. Many parts of the Internet are well-provisioned, and usually provide quite adequate service, even for applications like VoIP, without any use of enhanced services. In other places, this presumption does not hold, including some mobile networks, residential access links, and interconnection points between ISPs. Some level of congestion is inevitable over time, and ISPs must find effective and efficient ways to handle it. The public policy dilemma is how to balance respect for the judgment of network operators in managing service qualities on their own networks with respect for consumers who do not have the capability to measure performance, nor in some cases the ability to switch to a different provider if their provider underperforms.

With an engineering perspective on this evolution, we reflect on lessons learned over the last three decades, and their implications for the future of policy. First, as with cybersecurity, obstacles to enhanced services on the Internet today are multidimensional with interrelated root causes that span politics, economics (business), and technology. We learned from the 1990s that ISPs lack a venue, such as a standards body or a neutral convener, in which to develop clear rules on how to define and negotiate cross-ISP services. The competitive nature of the industry conflicts with the need for providers to agree on protocols that fundamentally require sharing operational data with each other to parameterize and verify committed service qualities. Furthermore, some ISPs in the 2006 MIT inter-provider QoS discussions (section "Mid-2000s: Working with Industry to Gain Insight") felt that forcing conversations about value flow and settlements would threaten the entrenched norm of revenue-neutral peering for

best-effort service. The relative prevalence of paid-peering arrangements today (although all bilateral and under Non-Disclosure Agreements [NDAs]) may mitigate this resistance, that is, revenue-neutral peering can no longer be assumed.

Thus, there might be several services that could be defined and marketed using tools standardized by the IETF, but there has been no effective forum to support discussion of the necessary business coordination practices to bring enhanced services to market. Similarly, the reaction of the IETF to the standardization of differentiated service, and in particular their resistance to discussing a service specification, has created a hole in the path from research to deployment. What an ISP wants to offer, and what an application designer needs to understand, is a service specification, not the behavior of a router (the PHBs). The IETF limits itself to standardizing equipment behavior, not ISP behavior, perhaps because IETF participation is dominated by equipment suppliers to ISPs, not ISPs themselves.

Second, QoS technology can yield benefits as well as harms, thus in our view policymaking should focus on regulating harms rather than mechanisms. If deployed appropriately, QoS technology can benefit latency-sensitive traffic without impairing performance of latency-insensitive traffic. But to assure consumers and regulators that deployment of QoS technology (or other traffic management mechanisms) will fall into this "no collateral harm" category, that is, not impair the QoE for users, regulators may need to require transparency about the state of congestion and provisioning on networks using such mechanisms.

Third, in the meantime, we have little empirical understanding of QoE because business obstacles to enhancing end-to-end QoE have in turn constrained strategic investment in measurement capability. Using the concept of QoE impairment as a basis for regulation will require (at least) research, tools and capabilities to measure, quantify, and characterize QoE, and developing metrics of service quality that better reflect our understanding of QoS and QoE for a range of applications.

Finally, the unregulated use of IP technology to build and interconnect private network platforms as alternatives to the public Internet, and direct interconnection between content providers and access ISPs to avoid congestion on the public Internet, are both natural reactions to the demand for high service qualities and demanding workloads, but may have the perhaps unintended consequence of drawing capital investment away from the public Internet. When considering policies that try to limit the use of

QoS to prevent harm to consumers, we must also take into consideration the possibility of collateral harm from the policy itself: incenting innovation to move to alternate platforms.

If, in the context of the public Internet, a generalized approach to delivering QoS is too hard to define and bring to market, more specific approaches to mitigating impairments are likely to prevail (section "Advancing Our Empirical Understanding of Performance Impairments"). We see service differentiation used in specific situations today in the public Internet, most obviously to manage Internet traffic over cellular networks. Cellular operators insist they need tools for service differentiation to enhance service quality.[68] Lacking a way to give the user some control of (and ability to pay for) service quality, cellular operators will render their own allocation of service classes to different applications, which will trigger regulatory concern and possible response. Resolution of these tensions will probably be the next chapter in the Internet QoS saga.

The coevolution of regulatory, legal, business, and technological capabilities, all at different paces, is tightly coupled in the case of enhanced services—a quintessential interdisciplinary challenge. While barriers to the deployment of scalable interprovider QoS on today's Internet may be insurmountable, the issues and challenges remain. If any Internet of the future is to be the platform for a full range of useful applications, either the basic transport service must be so improved that no support for differentiated services is necessary, or it will be necessary to overcome these challenges. For this reason, it is worth developing a systematic understanding of the challenge of enhanced services, starting with cataloging their successes and failures over the history of the Internet as carefully as possible.

ACKNOWLEDGMENTS

Research at UCSD was supported by NSF award CNS-414177. Research at MIT was supported by NSF award CNS-141390. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

We appreciate the comments of the anonymous reviewers.

68. See, for example, AT&T, "Comments of AT&T Services, Inc."

BIBLIOGRAPHY

Armitage, Grenville J. "Revisiting IP QoS: Why Do We Care, What Have We Learned? ACM SIG-COMM 2003 RIPQOS Workshop Report." *SIGCOMM Computer Communication Review* 33, no. 5 (2003). doi:10.1145/963985.963995.

AT&T. "Comments of AT&T Services, Inc." *Filing before the FCC*. July 2014. Accessed August 11, 2016. http://apps.fcc.gov/ecfs/document/view?id=7521679206.

Babiarz, Jozef, Kwok Chan, and Fred Baker. "Configuration Guidelines for DiffServ Service Classes." 2006. Accessed August 11, 2016. http://www.ietf.org/rfc/rfc4594.txt.

Bauer, Steven, David Clark, and William Lehr. "The Evolution of Internet Congestion." In *Proceedings of the 37th Research Conference on Communication, Information and Internet Policy (TPRC)*, 2009.

Bell, Gregory. "Failure to Thrive: QoS and the Culture of Operational Networking." In *Proceedings of the ACM SIGCOMM Workshop on Revisiting IP QoS: What Have We Learned, Why Do We Care?* RIPQoS '03, 2003. doi:10.1145/944592.944595.

Blake, Steven, David Black, Mark Carlson, Elwyn Davies, Zheng Wang, and Walter Weiss. "An Architecture for Differentiated Services." 1998. Accessed August 11, 2016. http://www.ietf.org/rfc/rfc2475.txt.

Bohn, Roger, Hans-Werner Braun, kimberly claffy, and Stephen Wolff. "Mitigating the Coming Internet Crunch: Multiple Service Levels via Precedence." *Journal of High Speed Networks* 3, no. 4 (November 1994): 335–49. Accessed August 11, 2016. http://www.caida.org/publications/papers/1994/mcic/.

Braden, Robert, David Clark, and Scott Shenker. "Integrated Services in the Internet Architecture: An Overview." 1994. Accessed August 11, 2016. http://www.ietf.org/rfc/rfc1633.txt.

Braden, Robert, Lixia Zhang, Steve Berson, Shai Herzog, and Sugih Jamin. "Resource ReSerVation Protocol (RSVP)—Version 1 Functional Specification," RFC 2205. 1997. Accessed August 11, 2016. http://www.ietf.org/rfc/rfc1633.txt.

Canadian Radio-Television and Telecommunications Commission. "Review of the Internet Traffic Management Practices of Internet Service Providers." 2009. Accessed August 11, 2016. http://www.crtc.gc.ca/eng/archive/2009/2009-657.htm.

claffy, kimberly, and David Clark. "Platform Models for Sustainable Internet Regulation." *Journal of Information Policy* 4 (September 2014): 463–88.

Clark, David. "A Cloudy Crystal Ball—Visions of the Future." July 1992. Accessed August 11, 2016. http://groups.csail.mit.edu/ana/People/DDC/future_ietf_92.pdf.

———. "An Architecture for Resource Management in Networks." In *Proceedings of the 26th IETF*, 619–23. March 1993. Accessed August 11, 2016. https://www.ietf.org/proceedings/26.pdf.

Clark, David, Stephen Bauer, and kimberly claffy. "Approaches to Transparency Aimed at Minimizing Harm and Maximizing Investment." In *Federal Communications Commission (FCC) Commission Documents*. September 2014. Accessed August 11, 2016. http://www.caida.org/publications/papers/2014/approaches_to_transparency_aimed/.

Clark, David, Scott Shenker, and Lixia Zhang. "Supporting Real-Time Applications in an Integrated Services Packet Network: Architecture and Mechanism." In *Proceedings of SIGCOMM 1992*, August 1992.

Cooper, Alissa. "How Regulation and Competition Influence Discrimination in Broadband Traffic Management: A Comparative Study of Net Neutrality in the United States and the United Kingdom." PhD diss., Oxford University, 2013. Accessed August 11, 2016. https://www.alissacooper.com/files/Thesis.pdf.

Crocker, Stephen. "The Process for Organization of Internet Standards Working Group (POISED)," RFC 1396. January 1993. Accessed August 11, 2016. http://www.ietf.org/rfc/rfc1396.txt.

Davie, Bruce. "Deployment Experience with Differentiated Services." In *Proceedings of the ACM SIGCOMM Workshop on Revisiting IP QoS: What Have We Learned, Why Do We Care?* RIPQoS '03. 2003, doi:10.1145/944592.944598.

Dhamdhere, Amogh, and Constantine Dovrolis. "The Internet Is Flat: Modeling the Transition from a Transit Hierarchy to a Peering Mesh." In *Proceedings of ACM CoNEXT*. 2010.

European Parliament and Council. "Regulation 2015/2120, Laying down Measures Concerning Open Internet Access. . . ." November 25, 2015. Accessed August 11, 2016. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32015R2120.

Federal Communications Commission. "In the Matters of Formal Complaint of Free Press and Public Knowledge Against Comcast Corporation for Secretly Degrading Peer-to-Peer Applications; Broadband Industry Practices Petition of Free Press et al. for Declaratory Ruling That Degrading an Internet Application Violates the FCC's Internet Policy Statement and Does Not Meet an Exception for Reasonable Network Management." FCC 08-183. August 2008. Accessed August 11, 2016. https://apps.fcc.gov/edocs_public/attachmatch/FCC-08-183A1.pdf.

———. "In the Matter of Protecting and Promoting the Open Internet: Report and Order on Remand, Declaratory Ruling, and Order, GN Docket No. 14-28." March 2015. Accessed August 11, 2016. https://apps.fcc.gov/edocs_public/attachmatch/FCC-15-24A1.pdf.

———. "Report and Order, Preserving the Open Internet." FCC10-201. 2010.

Fraser, Anthony G. "On the Interface between Computers and Data Communications Systems." *Communications of the ACM* 15, no. 7 (1972), doi:10.1145/361454.361471.

Houle, Joseph D., K. K. Ramakrishnan, Rita Sadhvani, Murat Yuksel, and Shiv Kalyanaraman. "The Evolving Internet-Traffic, Engineering, and Roles." In *Proceedings of the Telecommunications Policy Research Conference*, 2007.

Jacobson, Van. "Congestion Avoidance and Control." *SIGCOMM Computer Communication Review* 18, no. 4 (August 1988), ISSN:0146-4833; doi:10.1145/52325.52356.

Jacobson, Van, Kathleen Nichols, and Kedarnath Poduri. "An Expedited Forwarding PHB," RFC 2598. 1999. Accessed August 11, 2016. https://tools.ietf.org/html/rfc2598.

Japan Internet Providers Association (JAIPA), Telecommunications Carriers Association (TCA), Telecom Services Association (TELESA), and Japan Cable and Telecommunications Association (JCTA). "Guideline for Packet Shaping." 2008. Accessed August 11, 2016. http://www.jaipa.or.jp/other/bandwidth/guidelines_e.pdf.

Jin, Nan, and Scott Jordan. "On the Feasibility of Dynamic Congestion-Based Pricing in Differentiated Services Networks." *IEEE/ACM Transactions on Networking* 16, no. 5 (October 2008), ISSN:1063-6692; doi:10.1109/TNET.2007.908163.

Kamei, Satoshi, Tsuyoshi Momose, Takeshi Inoue, and Tomohiro Nishatani. "The P2P Network Experiment Council's Activities and Experiments with Application-Layer Traffic Optimization (ALTO) in Japan." 2013. Accessed August 11, 2016. http://www.ietf.org/rfc/rfc6875.txt.

Lang, Jean-Philippe. "Bufferbloat." 2014. Accessed August 11, 2016. http://www.bufferbloat.net.

Mills, David L. "The Fuzzball." In *Proceedings of the ACM SIGCOMM 88 Symposium*, 115–22. August 1988.

MIT Communications Futures Program. "Inter-Provider Quality of Service." November 2006. Accessed August 11, 2016. http://cfp.mit.edu/docs/interprovider-qos-nov2006.pdf.

Mueller, Milton. *Ruling the Root.* Cambridge: MIT Press, 2002.

Nichols, Kathleen and Brian Carpenter. "Definition of Differentiated Services per Domain Behavior and Rules for Their Specification," RFC 3086 2001. Accessed August 11, 2016. https://tools.ietf.org/html/rfc3086.

Odlyzko, Andrew. "Network Neutrality, Search Neutrality, and the Never-Ending Conflict between Efficiency and Fairness in Markets." *Review of Network Economics* 8, no. 1 (March 2009). Accessed August 11, 2016. http://www.dtc.umn.edu/~odlyzko/doc/rne81.pdf.

Parekh, Abhay K., and Robert G. Gallager. "A Generalized Processor Sharing Approach to Flow Control in Integrated Services Networks: The Single-Node Case." *IEEE/ACM Transactions Networking* 1, no. 3 (June 1993). doi:10.1109/90.234856.

Pool, Ithiel de Sola. *Technologies of Freedom*. Cambridge, MA: Belknap Press, 1984.

Postel, Jonathan. "Internet Protocol, DARPA Internet Program Protocol Specification," RFC760. Information Sciences Institute, January 1980. Accessed August 11, 2016. http://www.ietf.org/rfc/rfc760.txt.

———. "Transmission Control Protocol, Network Working Group Request for Comments 793." Information Sciences Institute, 1981. Accessed August 11, 2016. http://www.ietf.org/rfc/rfc793.txt.

———. "Service Mappings, Network Working Group Request for Comments 795." 1981. Accessed August 11, 2016. http://www.ietf.org/rfc/rfc795.txt.

Rayburn, Dan. "Cogent Now Admits They Slowed down Netflix's Traffic, Creating a Fast Lane & Slow Lane." 2014. Accessed August 11, 2016. http://blog.streamingmedia.com/2014/11/cogent-now-admits-slowed-netflixs-traffic-creating-fast-lane-slow-lane.html.

Teitelbaum, Benjamin and Stanislav Shalunov. "What QoS Research Hasn't Understood about Risk." *ACM SIGCOMM 2003 Workshop: Rest in Peace QoS*, 2003.

Wroclawski, John. "Specification of the Controlled-Load Network Element Service." Information Sciences Institute. September 1997. Accessed August 11, 2016. http://www.ietf.org/rfc/rfc2211.txt.