

Growing Pains: Bandwidth on the Internet

Briefing Paper

Executive Summary

The Internet is about sharing. It is successful because it makes all Internet resources available to all users simultaneously. This resource sharing ability is central to the Internet's utility and success. It enables the interconnection of diverse applications over heterogeneous networking media running at diverse speeds. It allows for growth without central control. Everybody shares in the control of the network. When you place a phone call you are connected with the person at the number you dialed: when you are on the Internet, you are connected with everybody else on the Internet, all of the time.

The Internet is continuously evolving. Some of the more profound recent changes have been caused by the impact of broadband access networks. In the last decade, the number of broadband subscribers worldwide has grown over one hundred times. Widespread broadband deployment has led to tremendous innovation in Internet applications and huge increases in the average amount of bandwidth consumed per user. The effects of these changes are now being felt around the globe.

Stimulated by a recent panel event organized by the Internet Society, we present the results of several recent studies, which, when combined represent the most detailed and comprehensive picture of the contemporary Internet available today. These studies show a consensus emerging about the gross amount of bandwidth being used on the Internet, and the growth trends. The panel event hosted discussion of the impacts of growth and application innovation on Internet service providers, and some of the actions that the technical community is taking to address these 'growing pains'.

We draw a number of conclusions from the data and the discussion:

- The growth of Internet bandwidth globally is not about to cause global problems. International and intercarrier links are not, in general, unable to cope with the demands of growing bandwidth consumption.
- While gross Internet capacity is meeting demand today, new capacity will be required in the long term.
- Adding more capacity to address access network constraints may or may not resolve network congestion issues, and should be considered in light of the relative cost of alternative solutions.



- Increasingly expensive and complicated network-specific bandwidth management techniques do not address the problems arising from broadband deployment.
- Solutions emerging today are a better fit to the Internet architecture than complex bandwidth management functions in the network; and are cheaper to deploy as well.
- It is not sufficient to solve a problem for one network; we need global solutions for a global network.

In this report, we wish to highlight the new mechanisms that are being developed and deployed now to address the ‘growing pains’ arising from broadband deployment. These mechanisms enable applications to automatically ‘get out of the way’ when more sensitive applications need attention from the network. They provide a relatively inexpensive, flexible and scalable alternative to deploying more complex network gateways to broadband subscribers.

We also observe that a real and growing issue for many broadband network operators occurs when there is a mismatch between the subscribers causing congestion on a bottleneck link and the subscribers experiencing degraded connectivity as a result. In these situations network operators have to react. Volume caps and bandwidth shaping are a few of the more coarse responses that network operators implement to address this issue. We would like to highlight the more elegant and flexible responses that are now emerging, both in deployment and in the research and standardization community. Solutions that are applicable across multiple networks, and that work ‘with the grain’ of the Internet architecture, are always preferable.

Finally, while we observe that the interests of ISPs, users, and content providers are not always well aligned, we need more data to better understand and identify the real issues requiring intervention. We also acknowledge that accurate measurements are hard to make. The studies referenced in this report are a valuable addition to the evidence base upon which we can build progress and, ultimately, a better network.

Introduction

It is a truism that the Internet has grown tremendously since its inception, both in the scale of the physical internetwork that underpins it and the scope of activity that it supports. The invention and widespread dissemination of Internet technology marks an inflection point in human civilization arguably as great as that wrought by Johannes Gutenberg. Unsurprisingly, given this sudden, striking, and profound change, doom-laden predictions for the future of the Internet have never been hard to find. In addition to concerns about the impact on human social norms and the implications for economic activity, there have been regular forecasts of impending catastrophe based on fears that the technology itself is simply unable to support the huge growth curve it has experienced and is experiencing.

In this report we present a compilation and a distillation of several strands of research and analysis intended to shed light on the ways in which the Internet is growing. Our focus is on issues related to the bandwidth on the Internet as well as on areas where this growth is yielding new mechanisms and giving rise to new challenges for the community to address. The Internet Society helped stimulate some of this debate by hosting a panel discussion in late 2009, adjacent to the Internet Engineering Task Force (IETF) meeting in Hiroshima, which exposed some of the realities of bandwidth growth, operator responses to a changing landscape and new, relevant standardization work taking place in the IETF (details of the event, slides, audio and a transcript are all available from the ISOC Web site at <http://isoc.org/bandwidth/>). The purpose of that event and this report is the same: To make the issues raised by the increased demand for Internet bandwidth accessible to a wider audience—‘pulling the message out of engineering and talking to the “real world”,’ as moderator Leslie Daigle, chief Internet technology officer at the Internet Society, put it in her introductory remarks to the panel.

Bandwidth, Defined

The term bandwidth refers to the amount of information that can be passed through a communications channel in a given amount of time; that is, the capacity of the channel. It is often expressed in bits per second, or alternatively bytes per second, leading to lots of confusion. Bandwidth figures are used to express the capacity of a network link or interface (e.g., a 100Mbps Ethernet interface) or the rate of information transfer (e.g. a file downloading at 3.2KB/s).



Internet is sharing

Internet protocols have their origin in the desire to share computers in diverse locations. The early designers were simply extending the paradigm of shared resources from the computer operating system to the computer network. Leonard Kleinrock is widely credited with demonstrating the theoretical feasibility of packet-switched communications and the first wide-area Internet link was established and successfully tested on 29 October 1969 between the University of California, Los Angeles (UCLA), and the Stanford Research Institute (SRI). By packetizing data (dividing an information flow into discrete, relatively small units called packets), it is possible to make much more efficient use of networks. Computer networks in particular lend themselves to this form of networking. Flexibility, efficiency and dramatically reduced costs are the features of the packetized, shared network that became the Internet (see Figure 1).

This resource-sharing ability is central to notions of the Internet's utility and success. It enables the interconnection of diverse applications over heterogeneous networking media running at diverse speeds. It allows for growth without central control. Everybody shares in the control of the network. When you place a phone call you are connected to the person at the number you dialed; when you are on the Internet, you are connected to *everybody else* on the Internet, *all of the time*.

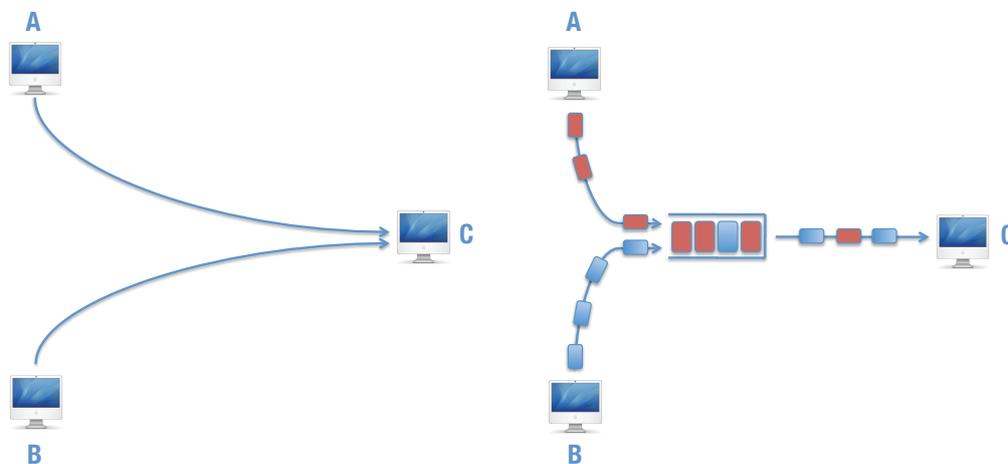


Figure 1. Packet switching is more efficient. The left-hand side of the diagram shows that two circuits are required to allow both A and B to communicate with C simultaneously. The right-hand side, in contrast, shows it is possible to connect both A and B to C, even though C only has a single connection. This works because A and B are typically not sending data to C simultaneously, and when they are it is possible to queue their communications in the network.

Of course sharing creates the potential for demand to outstrip supply and necessitates the imposition of a sharing mechanism. For the Internet, this mechanism is congestion control.

The bandwidth landscape

Before discussing congestion control, however, it's useful to review the available data to understand just how much bandwidth we're talking about sharing, and how that 'bandwidth landscape' has been evolving. Several recent studies have attempted to characterize the volume of data exchanged over the Internet and the rate at which that volume is growing. There appears to be some rough consensus emerging that the annual growth rate for global Internet bandwidth lies somewhere between 40 percent and 50 percent (see Table 1).

The Minnesota Internet Traffic Studies (MINTS) project uses a large set of publicly available data sources and concludes that current (year-end 2009) annual Internet traffic growth rates are in the region of 40–50 percent, and apparently slowing.¹ They report traffic volume per month of between 7.5 and 12 exabytes. Cisco Systems recently released their Visual Networking Index forecast, which shows global IP traffic of 11 exabytes per month, growing at a compound annual growth rate of 40 percent between 2008 and 2013.² Kenjiro Cho and his colleagues have studied the Japanese Internet using aggregated data from many local ISPs and they report seeing around 40 percent growth per annum since 2005 for peak traffic rates at domestic Internet exchange points (see Figure 2).³ Finally, Arbor Networks, Merit Networks, and the University of Michigan have undertaken a detailed study of Internet traffic, potentially observing up to a third of all the Internet traffic in the world, and they observe annual growth rates of about 45 percent and traffic volume of 9 exabytes per month.⁴ It is worth noting that these studies represent some of the most detailed and comprehensive analyses undertaken to date (see Annex III, page 17, for more details of the ATLAS study results).

Study Name	Traffic Volume (exabytes/month)	Annual Growth Rate
MINTS	7.5–12	40–50%
Cisco VNI	11	40%
Cho et al.	0.7 (Japanese domestic)	40%
ATLAS	9	45%

Table 1. A number of recent, very detailed studies have shown some rough consensus regarding traffic volumes and growth rates on the global Internet

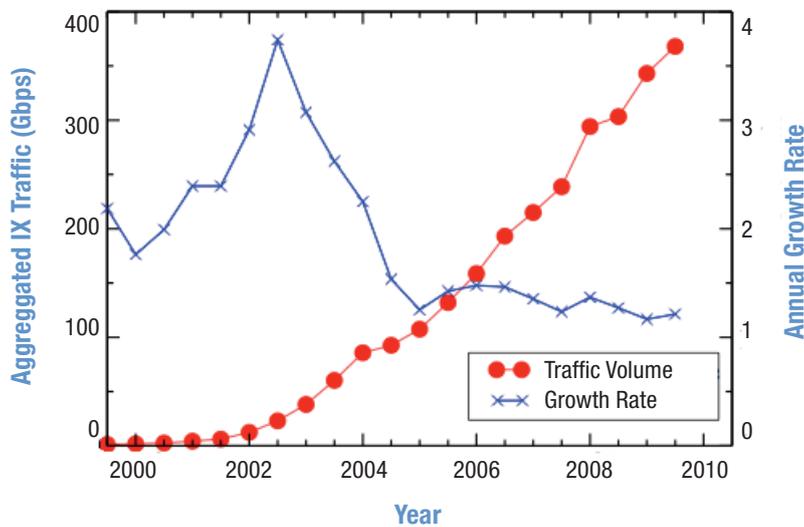


Figure 2. Traffic volume and growth rate at major Japanese IXPs

What about capacity?

TeleGeography's analysis of long-haul networks and the undersea cable market indicates gross capacity increasing at approximately 50 percent per annum, so at the macro level, the data suggests that supply is keeping pace with demand. Of course, these figures mask wide regional variations in supply, demand, and pricing for Internet bandwidth. Widespread fibre deployment during the dot-com boom years to 2001 has resulted in suppressed prices for capacity over the intervening period, but we are soon going to enter a new phase where additional, expensive capacity will need to be built to keep pace with growing demand for international bandwidth.⁵

The profound impact of broadband

According to ITU data, total worldwide broadband subscribers have grown in number by two orders of decimal magnitude in the period 1999–2009, from around 4 million to over 500 million now. This huge growth, coupled with the novel, data-intensive applications that broadband deployment has enabled, is fuelling demand for Internet bandwidth in all regions of the globe. Prior to broadband deployment, the limited bandwidth of most Internet access links acted to suppress user demand. Services that are now the dominant consumers of bandwidth were simply not viable at pre-broadband access network data rates. The huge growth of mass-market broadband since 2000 has created a, 'seismic shift in the nature of the congestion problem'.⁶ So while there appears to be no major problem with growing Internet bandwidth at macro scales, broadband has created an environment where more applications are competing for access network bandwidth, and consequently there are now growing problems arising from congestion at the network edge. Higher access speeds make it possible for individual end-users to have a significant impact on the network.

“I’m very glad that this discussion has picked up over the last few years with the rise of broadband. We need mechanisms to handle the [new broadband] speeds safely.”

—Lars Eggert, IETF Internet Area Director, and Principal Scientist
Nokia Research Center

Japan is an interesting case study in this regard as there are very high levels of fibre-to-the-home access network deployments in that country offering residential users affordable Internet services at speeds of 100Mbps. The Japanese experience indicates the likely outcome of providing increased broadband capacity, which some argue is a solution to congestion problems. According to Cho’s study, the modal user download volume has increased from 32MB/day in 2005 to 114MB/day in 2009, while modal upload volume has also increased from 3.5MB/day in 2005 to 6MB/day in 2009 (see Annex II, page 15, for more details of Dr. Cho’s research). This growth in the pres-

ence of increased capacity is one indication that simply adding capacity may not be a sufficient response to the growing pains being experienced as the bandwidth landscape on the Internet evolves. Conversely, however, it is not enough to insist that over-provisioning isn’t a long-term solution; it may, in fact, be enough of a solution, and sufficiently cheaper when compared with more complex alternatives, to make it the right choice for the time being. It is essential to bear the relative costs of different approaches in mind when considering this question.⁷

Sharing a global resource

While we can view the Internet as a global network and a shared resource, one of the reasons for its success is the fact that it is composed of multiple, independently administered, autonomous networks. There are, therefore, different levels, or regions of the network, at which the issues created by growing bandwidth consumption and application innovation are felt.

Congestion collapse

When more packets are sent than can be handled by intermediate routers, the intermediate routers discard many packets, expecting the end points of the network to retransmit the information. However, early TCP implementations had very bad retransmission behavior. When this packet loss occurred, the end points sent extra packets that repeated the information lost; doubling the data rate sent, exactly the opposite of what should be done during congestion. This pushed the entire network into a ‘congestion collapse’ where most packets were lost and the resultant throughput was negligible.^{8,9}



Bandwidth between networks

At the macro level, bandwidth pressures at the international and intercarrier level would cause regional problems. As described earlier, this does not appear to be on the horizon because gross traffic growth is not going to exceed the anticipated growth in global network capacity anytime soon. While the Internet did experience episodes of ‘congestion collapse’ more than 20 years ago, the mechanisms implemented at that time to address the problem have largely stood the test of time. Despite this, rumours of imminent network meltdown are never far away.

Bandwidth in the home

At the edge of the network we typically have a single domestic subscriber and their broadband link. Due to the nature of the congestion control mechanism used to share resources on the Internet (see Annex I, page 14), the rate at which data can be downloaded is partially a function of the rate at which receipt of that downloaded data is acknowledged. Acknowledging receipt of downloaded data requires sending packets on the broadband uplink into the network, and if that is saturated with traffic from other applications (e.g., P2P file-sharing) the performance of the downlink will be negatively impacted, even though it is typically a ‘fatter’ pipe.

Applications that saturate uplink capacity are also a problem for subscribers who wish to simultaneously use real-time conversational applications like Voice-over-IP (VoIP). While these real-time applications do not typically consume large amounts of bandwidth, they require regular service from the network. If the local network gateway is kept busy dealing with high bandwidth uploads, the performance of real-time conversational applications will be degraded, possibly to the point of failure.

It is argued by some that it is necessary for network operators to intervene, such as by prioritizing or blocking certain types of traffic, in order to give their subscribers a better experience when they use multiple applications with diverse requirements simultaneously.¹⁰ Fortunately, this is not the case. It would be extremely expensive for network operators to intervene in this way and doing so would inevitably result in higher costs for all. Such expensive, complicated, and rigid approaches to delivering a multiservice network do not address the problems arising from broadband deployment.

It is in the end-users’ self-interest to properly classify and ‘tune’ their applications. The majority of end-users will not have the interest or expertise to do this for themselves, but they are incented to use applications that employ more intelligent transport protocols, which automatically ‘get out of the way’ of other delay and jitter-sensitive applications. Given that only the end-user knows what applications they are running and how they want them to behave, it is unlikely that the network operator could do a better job of making these choices than the end-users themselves.

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Novel congestion-control algorithms are being standardized and deployed that provide application developers with the tools they need to ensure their bandwidth-intensive applications will do what users would want, without requiring the end-user to change any settings or know any details about the underlying technology. It is desirable that such 'automatic' solutions to this piece of the bandwidth puzzle are found and widely adopted because the alternative is to deploy substantially more complex (and expensive) network gateways to address the problem.

Bandwidth close to the edge

The area of most pressing concern for ISPs is the backhaul network that is shared between multiple subscribers within a single network operator's domain. While it is only of concern to an individual end-user that their simultaneous use of a file-sharing application is negatively impacting the quality of their VoIP calls, it is of legitimate concern to the network operator if one or more end-users are able to negatively impact the experience of their network 'neighbours'.

Multiple subscriber links are multiplexed, or joined together, onto a single backhaul link by routers and these devices use packet queues and packet discards to deal with congestion. Because the congestion control, or sharing, mechanism used by the Internet treats discrete data flows fairly, but knows nothing about end-users, it is possible for substantially unfair usage patterns to arise (see Figure 3).

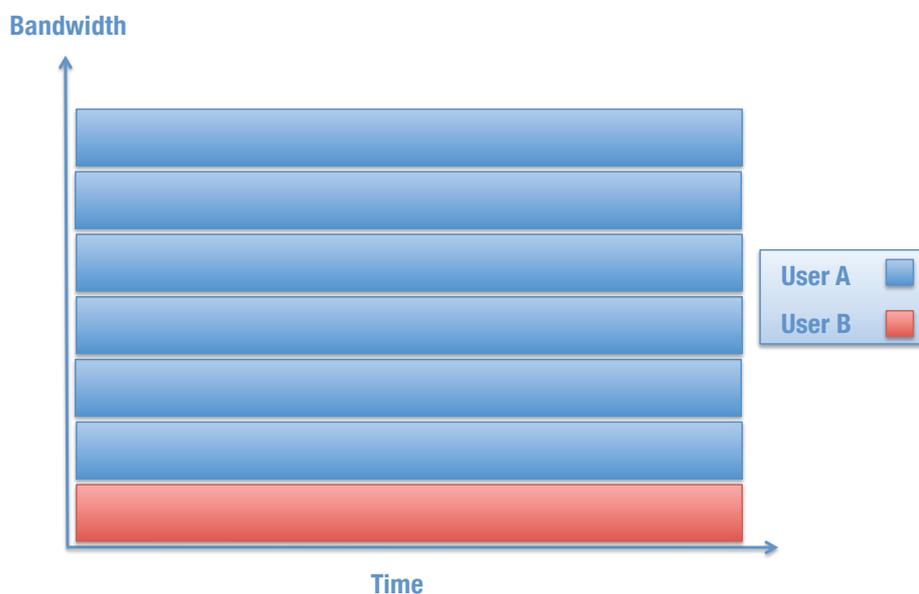


Figure 3. Starting multiple flows allows individual users to gain a greater share of the available bandwidth. By starting six flows, User A obtains six times as much bandwidth as User B.

This observation is not new. Van Jacobson, inventor of the congestion-control mechanisms that prevented congestion collapse on the early Internet, noted at the time that, "While



algorithms at the transport endpoints can ensure the network capacity isn't exceeded, they cannot ensure fair sharing of that capacity. Only in gateways, at the convergence of flows, is there enough information to control sharing and fair allocation. Thus, we view the gateway 'congestion detection' algorithm as the next big step."¹¹ In other words, because user applications can create multiple flows, and because it isn't possible for an end-user to know the impact of those flows on a bottleneck link shared with other users, it is increasingly necessary for network operators to intervene.

This intervention is necessary because, while subscribers are incented to use more sophisticated congestion control mechanisms (or at least applications and operating systems, that provide them), it is not mandatory for them to do so. At the present time it is necessary for the operator to police usage of congested links.

Such policing takes place today in the form of volume caps (limiting bandwidth consumption within a given service interval, such as 10GB/month), traffic shaping (restricting overall bandwidth rate during the busy-hour, or after some temporal consumption limit has been reached), and application throttling (restricting bandwidth for specific applications). These mechanisms provide network operators with coarse tools to address the issues created by congested backhaul links. Limiting bandwidth consumption by protocol, application, or time period can only ever be a proxy for the true marginal cost of networking, which is congestion volume (an individual user's contribution to congestion).

A more fine-grained solution is the one recently adopted by Comcast, a cable operator based in the United States, that allows bandwidth-intensive applications to consume resources as normal in the absence of competing flows, and is protocol-agnostic (meaning it does not discriminate between different applications—all are treated equally). For Comcast, the goal of their congestion-management practice is to ensure consistent performance of Internet applications even in the presence of heavy background traffic, such as from peer-to-peer file sharing. They aim to be both protocol and application 'agnostic' and compatible with current Internet standards, and their approach is based upon the DiffServ architecture, which was developed in the IETF.¹²

“it's about making sure that while we're executing a reasonable upgrade schedule, that when flash-crowds happen, or some new streaming application appears that chews up bandwidth, that we can handle all those services gracefully.”

Rich Woundy, Senior Vice President
Comcast

The Comcast congestion-management scheme utilizes two different Quality of Service (QoS) levels for best-effort traffic over the cable network: Priority Best Effort (PBE), which is the default QoS level, and Best Effort (BE). When traffic levels on a particular port exceed a set threshold, that port enters a 'near-congestion'

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state. Customers determined to be contributing disproportionately to the total traffic volume of a port in the near-congestion state will have their traffic marked as BE for a short duration. This marking only impacts the traffic of users marked BE when congestion is actually present, otherwise PBE and BE traffic are treated identically. In the presence of congestion, traffic marked BE will experience additional latency (on the order of a few microseconds) as it is queued while PBE traffic takes priority. Less than 1 percent of Comcast's customer base is currently impacted by this congestion-management scheme.

The architectural principles of the Internet mean that, in general, the responsibility is split between the applications and the network. The network is required to provide 'neutral' information about path conditions in a timely manner, while applications and transport protocols choose how to act on that information. But the 'smart edge, dumb core' paradigm only gets you so far and there is a valid role for the network as exemplified by the Comcast experience. ISPs like BT and Comcast are also collaborating with the IETF standards body on new mechanisms that could form part of future solutions for end-to-end bandwidth management (see Annex IV, page 18, for more details of relevant IETF activities). One such new mechanism is called congestion exposure. This is a potentially even more fine-grained, flexible, and protocol-agnostic solution that is now under development. Such a solution is particularly attractive because it is working 'with the grain' of the Internet architecture by putting the 'intelligence' at the end hosts whilst simultaneously providing a global solution to local problems, and allowing for individual network operators to act as they see fit, given a new level of information about the network (see Figure 4, also IETF Journal Vol. 5 Issue 3 contains an article describing congestion exposure in more detail: <http://ietfjournal.isoc.org/>).

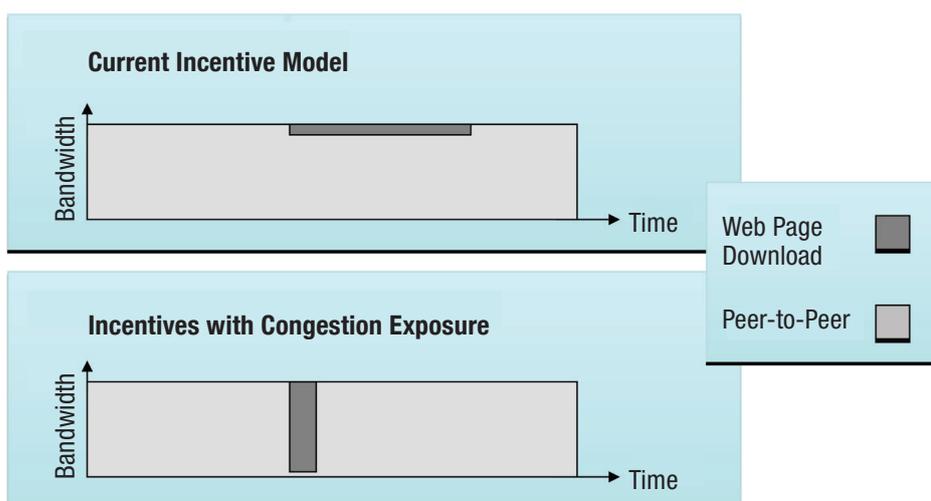


Figure 4. Congestion exposure has the potential to allow short-lived flows (e.g., Web page downloads) to go much faster without significant negative impacts on long-lived flows (e.g., peer-to-peer file sharing).



Conclusion

The Internet and broadband technology are continuing to evolve rapidly, and neither shows any signs of maturing. It is, therefore, very important to be careful when drawing strong conclusions from the way things are done today. We have presented a number of recent research results, which provide a new level of insight into how the Internet, and the bandwidth landscape in particular, are evolving. More data would be welcome. We have shown that the impact of widespread broadband adoption and the nature of the Internet's congestion control mechanisms are causing some quite specific issues for network operators today.

It would certainly be a mistake to conclude from recent developments in access network bandwidth management that ISPs want to stop investing. Traffic spikes and access network bandwidth inequities require operator intervention today, but this needs to be followed up with capacity upgrades—doing one without the other will result in the gradual erosion of service quality. However, increasingly sophisticated and expensive bandwidth management in the network is not a desirable long-term trend. The scalability and flexibility that are the hallmarks of the Internet architecture can only be maintained by adopting bandwidth management solutions that work 'with the grain' of that architecture, either by operating on the end-hosts themselves, rather than in the network, or by providing global and flexible tools for network operators and others to use in a variety of ways without prejudging incentives or outcomes. The IETF, in concert with the wider technical community, is developing and deploying such solutions today.

Annex I

Transmission Control Protocol (TCP)

Congestion control on the Internet is handled by TCP. The algorithm employed has at least a couple of features that are important to keep in mind when discussing the broader issues of bandwidth on the Internet.

TCP is self-clocking: receivers send acknowledgements immediately and senders only send when an acknowledgement for previous transmissions has been received. The consequence of this is that TCP maximizes utilization of the bottleneck link and fills the buffer at the bottleneck link. As a side effect, TCP maximizes delay. While this works well for applications that are not delay-sensitive, it harms interactive applications that share the same bottleneck. VoIP and games are particularly affected, but even Web browsing may become problematic.

The need for a receiver to continuously acknowledge receipt of data in order to receive more data from the sender means that a congested uplink can cause reduced downlink performance due to the difficulty of sending acknowledgements. Asymmetric access networks exacerbate this problem by making it easier for hosts to saturate their narrow uplink bandwidth.

Finally, TCP congestion control operates per-flow. Where flows share the same bottleneck link there is no notion of controlling the number of flows per user or by any other metric.

Guido Appenzeller and Nick McKeown have produced some very nice animations of TCP in operation, which can help with understanding some of these concepts. They are available here: <http://guido.appenzeller.net/animations/>.



Annex II

Broadband landscape in Japan

http://www.isoc.org/isoc/conferences/bwpanel/docs/20091111_bandwidth_cho.pdf

Dr. Kenjiro Cho, a senior researcher at Internet Initiative Japan, and colleagues have recent research results, which are based on data collected from six ISPs in Japan starting in 2004 and covering 42 percent of Japanese Internet traffic. As of June 2009, there were 30.9 million broadband subscribers in Japan and the market is relatively mature, increasing by only 3 percent of households in 2008, to include 63 percent of Japanese homes. While growth of cable deployments remains steady, the great majority of households enjoy fibre-to-the-home (FTTH) connections and existing DSL customers are shifting to FTTH in large numbers. In the Japanese market, 100Mbps bidirectional connectivity via FTTH costs USD 40 per month. The relatively high access bandwidth in the Japanese market leads to higher skew in the distribution of per-user bandwidth consumption statistics—there is more variability in bandwidth consumption profiles per user.

ISPs are starting to see the value in sharing traffic-growth data as a way to help others better understand their concerns. Of course, ISPs make internal measurements, but measurement methodologies and policies will typically differ from one ISP to the next. By aggregating standardized and anonymized measurements, ISPs can help third parties come to understand the pressures, concerns, and motivations that are shaping their perspective.

Understanding traffic growth on the Internet is critically important, as it is one of the key factors driving investment decisions in new technologies and infrastructure. The balance between supply and demand is crucial. Dr. Cho observes modest growth of about 40 percent per annum since 2005 based on traffic peaks at major Japanese Internet exchanges. For residential traffic, growth rates are similar—around 30 percent per annum. As network capacity is observed to grow at approximately 50 percent per annum according to various sources, there does not appear to be a problem catering for Internet traffic growth, at least at the macro scale.

Dr. Cho also observes shifts in residential user behaviour in the period 2005–2009. In 2005, the ratio of inbound to outbound traffic was almost 1:1, suggesting that file sharing was a widespread use of the network at that time. In 2009, the outbound traffic (download from a user perspective) is noticeably greater, suggesting a shift from peer-to-peer file sharing to streamed content services. Increases in the mode of download volumes over the period are greater (nearly 4x—from 32MB to 114MB per day) than increases in upload volumes (less than 2x—from 3.5MB to 6MB per day), while average download volumes are now 1GB per day per user.



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A scatterplot of in/out volumes per user in 2009 indicates that, while there are two clusters (client-type users, and peer-type 'heavy hitters'), there is no clear boundary between the two groups. This is an important point to bear in mind when considering the effectiveness of coarse-grained bandwidth management techniques deployed by some ISPs today. Most users make some use of both client-server and peer-to-peer style applications.



Annex III

Hyper-giants, port 80 and a flatter Internet

http://www.isoc.org/isoc/conferences/bwpanel/docs/20091111_bandwidth_mcpherson.pdf

The ATLAS Internet Observatory is collaborative research from Arbor Networks, the University of Michigan, and Merit Network. The observatory utilizes a commercial probe infrastructure that is deployed at more than 110 participating ISPs and content providers to monitor traffic-flow data across hundreds of routers. Believed to be the largest Internet monitoring infrastructure in the world, the results represent the first global traffic engineering study of Internet evolution.

Major findings from the ATLAS project are, first, the consolidation of content around so-called ‘hyper giants’ — the 30 companies that now account for 30 percent of all Internet traffic. Content is migrating from the enterprise or network edge to large content aggregators. Consolidation of large Internet properties has progressed to the point where now only 150 Autonomous Systems (ASNs) contribute 50 percent of all observed traffic.

Second, applications are consolidating around TCP port 80 as the Web browser is increasingly the application front end for diverse content types, such as e-mail and video. For application developers, TCP port 80 works more deterministically due to the presence of middleboxes in the network that filter or otherwise interfere with traffic using different transports and alternative ports.

Third, evolution of the Internet core and economic innovation means that the majority of traffic is now peered directly between consumers and content. Declining transit prices have not prevented this disintermediation from taking place on a large scale. High-value content owners are starting to experiment with a paid-peering model and dispensing with transit altogether, meaning that if your ISP doesn’t ‘pay to play’, then you won’t be able to view that content at all (although this phenomenon is difficult to quantify due to the inevitable commercial secrecy surrounding such deals). Disintermediation of the historical ‘tier-1’ networks means a flatter Internet with much higher interconnection density.

Annex IV

Relevant Internet Engineering Task Force (IETF) Activities

http://www.isoc.org/isoc/conferences/bwpanel/docs/20091111_bandwidth_eggert.pdf

The IETF toolbox includes TCP and TCP-friendly congestion control that allows hosts to determine their transmission rate according to path conditions based upon observed round-trip time and packet loss. Extensions and optimizations include Explicit Congestion Notification (ECN) and Active Queue Management (AQM). These mechanisms were developed at a time when Internet core speeds were much lower than they are today, and the IETF is now revisiting the question of whether similar mechanisms are required in the access network.

A new IETF working group (Low Extra Delay Background Transport: ledbat) is standardizing a congestion-control algorithm to allow hosts to transmit bulk data without substantially affecting the delay seen by other users and applications.

Another new working group (Multipath TCP: mptcp) is endeavouring to extend TCP to allow one connection to transmit data along multiple paths between the same two end systems. This effectively pools the capacity and reliability of multiple paths into a single resource and enables traffic to quickly move away from congested paths.

The Application Layer Traffic Optimization (alto) working group is focused on improving peer-to-peer application performance, whilst simultaneously aligning P2P traffic better with ISP constraints. Providing P2P applications with network, topology, and other information should enable them to make better-than-random peer selection, thereby improving performance for the application and alignment with ISP preferences.

As mentioned previously, Congestion Exposure (conex) is targeted at exposing the expected congestion along an Internet path. This would be a new capability and could allow even greater freedom over how capacity is shared than we have today. This capability could be used for a variety of purposes, e.g. congestion policing, accountability, service level agreements, or traffic engineering.

There are already many tools to share Internet capacity fairly, effectively, and efficiently. The IETF is designing new and better tools where needed. A lot could be gained by more consistently and appropriately using the tools we have.



Acknowledgements

This work was made possible by the generous contributions of the panellists who presented at 'Internet Bandwidth Growth: Dealing with Reality', an ISOC panel event held in Hiroshima, Japan, on November 10th, 2009. In alphabetical order, they are Kenjiro Cho, Lars Eggert, Danny McPherson, and Richard Woundy. Leslie Daigle of the Internet Society was moderator.

Endnotes

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Galerie Jean-Malbuisson 15
CH-1204 Geneva
Switzerland

Tel: +41 22 807 1444
Fax: +41 22 807 1445
<http://InternetSociety.org>

1775 Wiehle Avenue
Suite 201
Reston, VA 20190, U.S.A.

Tel: +1 703 439 2120
Fax: +1 703 326 9881
info@InternetSociety.org