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An Empirical Evaluation of Wide-Area Internet Bottlenecks

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Abstract

Conventional wisdom has been that the performance limitations in the current Internet lie at the edges of the network – *i.e* last mile connectivity to users, or access links of stub ASes. As these links are upgraded, however, it is important to consider where new bottlenecks and hot-spots are likely to arise. In this paper, we address this question through an investigation of *non-access* bottlenecks. These are links within carrier ISPs or between neighboring carriers that could *potentially* constrain the bandwidth available to long-lived TCP flows. Through an extensive measurement study, we discover, classify, and characterize bottleneck links in terms of their location, latency, and available capacity.

We find that nearly half of the Internet paths explored have a non-access bottleneck with available capacity less than 50 Mbps, many of which limit the performance of well-connected nodes on the Internet today. Surprisingly, the bottlenecks identified are roughly equally split between intra-ISP links and peering links between ISPs. Also, we find that low-latency links, both intra-ISP and peering, have a significant likelihood of constraining available bandwidth.

Finally, we discuss the implications of our findings on related issues such as choosing an access provider and optimizing routes through the network. We believe that these results could be valuable in guiding the design of future network services, such as overlay routing, in terms of which links or paths to avoid (and how to avoid them) in order to improve performance.

1 Introduction

A common belief about the Internet is that poor network performance arises primarily from constraints at the edges of the network. These narrow-band access links (e.g., dial-up, DSL, etc.) limit the ability of applications to tap into the plentiful bandwidth and negligible queuing available in the interior of the network. As access technology evolves, enterprises and end-users, given enough resources, can increase the capacity of their Internet connections by upgrading their access links. The positive impact on overall performance may be insignificant, however, if other parts of the network subsequently become new performance bottlenecks. Ultimately, upgrades at the edges of the network may simply shift existing bottlenecks and hot-spots to other parts of the Internet. In this study, we consider the likely location and characteristics of future bottleneck links in the Internet. Such information could prove very useful in the context of choosing intermediate hops in overlay routing services [1, 27] or interdomain traffic engineering, and also to customers considering their connectivity options.

Our objective is to investigate the characteristics of links within or between carrier ISP networks that could *potentially* constrain the bandwidth available to long-lived TCP flows, called *non-access* bottleneck links. Using a large set of network measurements, we seek to discover and classify such links according to their location in the Internet hierarchy and their estimated available capacity. By focusing on interior links, we try to avoid access links near the source and destination (*i.e.*, first-mile and last-mile hops), as these are usually obvious bottlenecks in the current Internet. This paper makes two primary contributions: 1) a methodology for measuring bottlenecks links and 2) a classification of existing Internet bottleneck links.

Methodology for measuring non-access Internet bottleneck links: Our main challenge in characterizing Internet bottlenecks is to measure paths that are representative of typical routes in the Internet, while avoiding biases due to a narrow view of the network from few probe sites, or probes which themselves are poorly connected. Our results are based on measurements from 26 geographically diverse probe sites located primarily in the U.S., each with very high speed access to the Internet. We measure paths from these sites to a carefully chosen set of destinations, including paths to all Tier-1 ISPs, as well as paths to a fraction of Tier-2, Tier-3, and Tier-4 ISPs, resulting in 2028 paths in total. In addition, we identify and measure 466 paths passing through public Internet exchange points in order to explore the common perception that public exchanges are a major source of congestion in the Internet.

A second challenge lies in actually measuring the bottleneck link and reporting its available bandwidth and location. Due to the need for administrative privileges, or control at both ends of the path, we were unable to leverage any of the existing tools to measure the available bandwidth. Hence, we developed a tool, *BFind*, which measures available capacity using a bandwidth probing technique motivated by TCP's behavior, and operates in a single-ended mode without requiring superuser access.

Classification of bottleneck links: We apply our measurement methodology to empirically determine the locations, estimated available bandwidth, and delay of non-access bottleneck links. In classifying these links, we draw extensively on recent work on characterizing AS relationships [29, 8]. Our results show that nearly half of the paths we measured have a non-access bottleneck link with available capacity less than 50 Mbps. Moreover, the percentage of observed paths with bottlenecks grows as we consider paths to lower-tier destinations. Surprisingly, the bottlenecks identified are roughly equally split between intra-ISP links and peering links between ISPs. Also, we find that low-latency links, both within and between ISPs have a significant probability of constraining available bandwidth. Of the paths through public exchanges that had a bottleneck link, the constrained link appeared at the exchange point itself in nearly half the cases.

Our work complements and extends the large body of work on measuring and characterizing the Internet. In particular, several recent efforts have focused on end-to-end Internet path properties, as these can have a significant impact on application performance and transport protocol efficiency. For example, recent wide-area measurement studies focus on performance metrics like delay, loss, and bandwidth [21, 33], packet reordering [15], routing anomalies [22, 11, 28], and path stability [16]. In addition, a number of measurement algorithms and tools have been developed to measure the capacity or available bandwidth of a path (see [13] for examples). Our focus is on identifying and characterizing potential bottleneck links through the measurement of a wide variety of Internet paths.

We believe that our observations provide valuable insights into the location and nature of performance bottlenecks in the Internet, and in some cases, address common impressions about constraints in the network. In addition, we hope that our work could prove instrumental in improving the performance of future network protocols and services in terms of which bottlenecks to avoid (and how to avoid them).

In the next section we describe our measurement methodology with additional details on our choice of paths and the design and validation of BFind. Section 3 presents our observations of non-access bottlenecks, and Section 4 offers some discussion about the implications of our findings. In Section 5 we briefly review related work in end-to-end Internet path characterization and measurement tools. Finally, Section 6 summarizes the paper.

2 Measurement Methodology

The Internet today is composed of an interconnected collection of Autonomous Systems (ASes). These ASes can be roughly categorized as carrier ASes (e.g. ISPs and transit providers) and stub ASes (end-customer domains). Our goal is to measure the characteristics of potential performance bottlenecks that end-nodes encounter that are not within their own control. To perform this measurement we need to address the following issues:

- **Sources**: A careful choice of sources from which to measure paths is important to ensure they do not encounter bottlenecks in their own access networks. They should also provide a diverse view of the network, both in terms of geographic distribution and ISP connectivity.
- **Paths**: Given a set of sources, the next question is how to choose target destinations in order to measure non-access bottlenecks in typical Internet paths.
- **Tools**: Once a suitable path is identified we require a tool that can detect the location and characteristic of the bottleneck, if one exists.
- **Metrics**: Finally, we need an appropriate set of metrics to categorize and characterize bottlenecks in a way that allows us to compare their features.

In this section, we describe our approach to each of these issues in turn.

2.1 Choosing a Set of Traffic Sources

The stub ASes in the Internet are varied in type, size and connectivity to their carrier networks. Larger stubs, such as large universities and commercial organizations, are often multi-homed and have very high speed links to all of their providers. Other stubs, such as small businesses, usually have at most a single provider with a much slower connection.

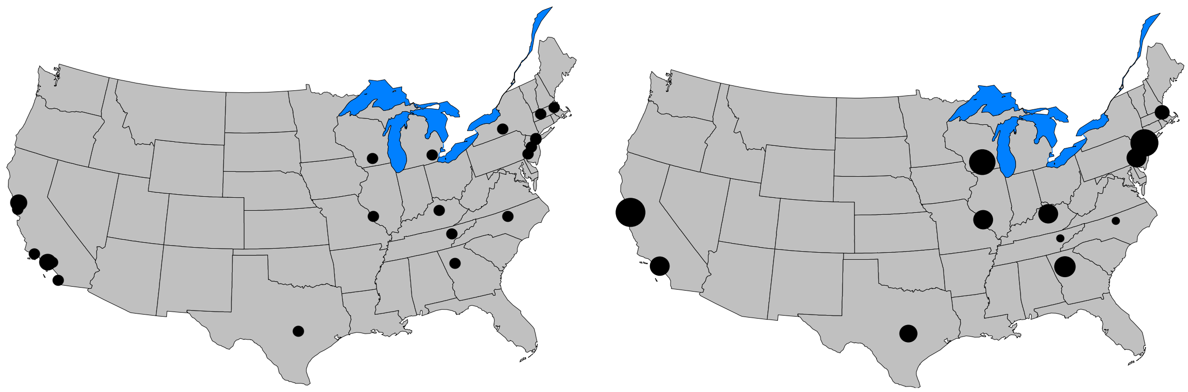
At the core of our measurements are traffic flows between a set of sources, which are under our control, and a set of random, but carefully chosen destinations. Unfortunately, it proves to be extremely difficult to use such measurements when the source network or its connection to a carrier network is itself a bottleneck. Therefore, we choose to explore bottleneck characteristics by measuring paths from well-connected end-points, i.e. stub ASes with very high speed access to their upstream providers. Large commercial and academic organizations, mentioned above, are example of such end-points.

In addition to the connectivity of the stub ASes, we consider a number of other factors when choosing the set of sources. First, it is important to pick a geographically diverse set of sources to get a wider view of the bottlenecks. Second, our measurements should not be biased by any particular carrier AS. Therefore, we must ensure that the chosen stub ASes use a wide variety of ISPs. Ensuring these two properties is critical since a narrow or biased view of the network (either geographic or in terms of ISPs) might result in repeated measurement of a small set of bottlenecks links (due to the properties of Internet routing, e.g. BGP policies and *hot-potato routing*).

We use hosts participating in the PlanetLab project [24], which provides access to a large collection of Internet nodes that meet our requirements. PlanetLab is a Internet-wide testbed of multiple high-end machines located at geographically diverse locations. Most of the machines currently available are located in large academic institutions and research centers in the U.S. and Europe. As a result, most of these machines have very high speed access to the Internet.

Initially, we chose one machine from each of the PlanetLab sites as the initial candidate for our experiments. While it is generally true that the academic institutions and research labs hosting PlanetLab machines are well-connected to their upstream providers, we found that the machines themselves are often on low-speed local area networks. Out of the 38 PlanetLab sites operational at the outset of our experiments, we identified 12 that had this drawback. In order to ensure that we can reliably measure non-access bottlenecks, we did not use these 12 machines in our experiments.

The unique upstream providers and geographic location of the remaining 26 PlanetLab sites are shown in Table 1 and Figure 1(a) respectively. We use the hierarchical classification of ASes into four *tiers*, defined in [29], to categorized the upstream ISPs of the different PlanetLab sites. As described in [29], ASes in tier-1 of the hierarchy, for example AT&T and Sprint, are large ASes that do not have any upstream providers. Most ASes in tier-1 have peering arrangements with each other. Lower in the hierarchy, tier-2 ASes, including Savvis, Time Warner Telecom and several large national carriers, have peering agreements with a number of ASes in tier-



(a) Sources

(b) Destinations (mapped to the closest source)

Figure 1: **Locations of PlanetLab sources (a) and destinations (b):** Each destination location is identified by the PlanetLab source with minimum delay to the destination. Three of our sources and seven destinations are located in Europe (not shown above). The size of the dots is proportional to the number of sites mapped to the same location.

	tier-1	*tier-2*	tier-3	tier-4
Total #unique connections	11	11	15	5
Avg. #connections per PlanetLab source	0.92	0.69	0.81	0.10

Table 1: **First-hop connectivity of the PlanetLab sites:** We show the number of unique ASes in each tier attached to the PlanetLab sites. We also show the average number of PlanetLab sources connected to ASes in a particular tier.

1. ASes in tier-2 also have peering relationships with each other, however, they do not generally peer with any other ASes. ASes in tier-3, such as Southwestern Bell and Turkish Telecomm, are small regional providers that have a few customer ASes and peer with a few other similar small providers. Finally, the ASes in tier-4, for example rockynet.com, have very few customers and typically no peering relationships at all.

2.2 Choosing a Set of Destinations

We have two objectives in choosing paths to measure from our sources. First, we want to choose a set of network paths that are representative of typical paths taken by Internet traffic. Second, we wish to explore the common impression that public network exchanges, or NAPs (network access points), are a significant bottleneck in the network. Our choice of network paths to measure is equivalent to choosing a set of destinations in the wide-area as targets for our testing tools. Below, we describe the rationale and techniques for choosing test destinations to achieve each of our two objectives.

2.2.1 Typical Paths

Most traffic in the Internet flows *between* stub networks. One way to measure typical paths would have been to select a large number of stub networks as destinations. However, the number of such destinations needed to characterize properties of representative paths would make the measurements impractical. Instead, we use key features of the routing structure of the Internet to help choose a smaller set of destinations for our tests.

Traffic originated by a stub network subsequently traverses multiple intermediate autonomous systems before reaching the destination stub network. Following the definitions of AS hierarchy presented in [29] (and summarized earlier), flows originated by typical stub source networks usually enter a tier-4 or a higher tier ISP. Beyond this, the flow might cross a sequence of multiple links between ISPs and their higher-tier upstream carriers (*uphill path*). At the end of this sequence, the flow might cross a single peering link between two peer ISPs after which it might traverse a *downhill path* of ASes in progressively lower tiers to the final destination, which is also usually a stub. This form of routing, arising out of BGP policies, is referred to as *valley-free* routing. We refer to the portion of the path taken by a flow that excludes links within the stub network at either end of the path, and the access links of either of the stub networks, as the *transit path*.

Clearly, non-access bottlenecks lie in the transit path to the destination stub network. Specifically, the bottleneck for any flow could lie either (1) *within* any one of the ISPs in the uphill or the downhill portion of the transit path or (2) *between* any two distinct ISPs in either portion of the transit path. Therefore, we believe that measuring the paths between our sources and a wide variety of different ISPs would provide a representative view of the bottlenecks that these sources encounter.

	tier-1	*tier-2*	*tier-3*	*tier-4*
Number tested	20	18	25	15
Total in the Internet	20	129	897	971
Percentage tested	100	14	3	1.5

Table 2: **Composition of the destination set:** The number of target ISPs chosen in each tier of the AS hierarchy.

Due to the large number of ISPs, it is impractical to measure the paths between our sources and all such carrier networks. However, the *reachability* provided by these carrier ASes arises directly from their position in the hierarchy. Therefore, it is more likely that a typical path will pass through one or two tier-1 ISPs than to have a lower tier ISP. Hence, we test paths between our sources and *all* tier-1 ASes. To make our measurements practical, we only test the paths between our sources and a fraction of the tier-2 ISPs. We measure an even smaller fraction of all tier-3 and tier-4 providers. The number of ISPs we chose in each tier is presented in Table 2.

In addition to choosing a target AS, we need to choose a target IP address within the AS for our tests. For any AS we choose, say `<isp>`, we pick a router that is a few (2-4) IP hops away from the machine `www.<isp>.com` (or `.net` as the case maybe). We confirm this router to be *inside* the AS by manually inspecting the DNS name of the router where available. Most ISPs name their routers according to their function in the network, *e.g.* edge (chi-edge-08.inet.qwest.net) or backbone (sl-bb12-nyc-9-0.sprintlink.net), routers. The function of the router can also be inferred from the names of routers adjacent to it. In addition, we double check using the IP addresses of the carrier's routers along the path to `www.<isp>.com` (typically there is a change in the subnet address close to the web server). We measure the path between each of the sources and the above IP addresses. The geographic location of the destinations is shown in Figure 1(b). Each destination's location is identified by that of the traffic source with the least delay to it.

2.2.2 Public Exchanges

The carrier ASes in the Internet peer with each other at a number of locations throughout the world. These peering arrangements can be roughly categorized as public exchanges, or NAPs, (e.g., the original 4 NSF exchanges) or private peering (between a pair of ISPs). One of the motivations for the deployment of private peering has been to avoid the perceived congestion of public exchanges. As part of our measurements, we explore whether this perception is accurate. Therefore, we need a set of destinations to test paths through these exchanges.

We first pick a set of well-known NAPs. The NAPs we selected are Worldcom MAE-East, MAE-West, MAE-Central, SBC/Ameritech AADS and PAIX in Palo Alto. For each of these NAPs, we first gather a list of low-tier (*i.e.*, low in the hierarchy) customers attached to the NAP. The customers are typically listed at the corresponding Web sites of the exchanges. As in each of the above cases, we use the hierarchy information from [29] to determine if a customer is small. Since these customers are low tier, there is a reasonable likelihood that a path to these customers from any source passes through the corresponding NAP. We then find a small set of addresses from the address block of each of these customers that are reachable via traceroute. We use the complete BGP table dump from the Oregon route server [31, 3] to obtain the address space information for these customers.

Next, we use a large set of public traceroute servers (153 traceroute sources from 71 providers) [30], and trace the paths from these servers to the addresses identified above. We script the process of finding working servers and automating access to these servers. For each NAP, we select all paths which appear to go through the NAP. For this purpose, we use the router DNS names as the determining factor. Specifically, we look for the name of the NAP to appear in the DNS name of any router in the path. From the selected paths, we pick out the routers one-hop away (both a predecessor and a successor) from the router identified to be at the NAP and collect their IP addresses. This gives us a collection of IP addresses for routers next to the routers located at a NAP. However, it is not sufficient to simply use the IP addresses as destinations to measure NAPs as the path taken might not traverse the NAPs.

To ensure that routes traverse the NAP, we run traceroutes from each of our PlanetLab sources to *each* of the predecessor and successor IP addresses identified above. For each PlanetLab source, we collect the subset of these IP addresses whose traceroute indicates a path through the corresponding NAP. The resulting collection of IP addresses is used as a destination set for the PlanetLab source.

2.3 Bottleneck Identification Tool - *BFind*

Next, we need a tool that we can run at the chosen sources that will measure the bottleneck link along the selected paths. We define the *bottleneck* as the link in the path where the available bandwidth (*i.e.*, left-over capacity) to a TCP flow is the minimum. Notice that a particular link being a bottleneck does not necessarily imply that the link is heavily utilized or congested. In addition, we would like the tool to report the available bandwidth, latency and location (i.e. IP addresses of endpoints) of the bottleneck along a path. In this section, we describe the design and operation of our bottleneck identification tool – *BFind*.

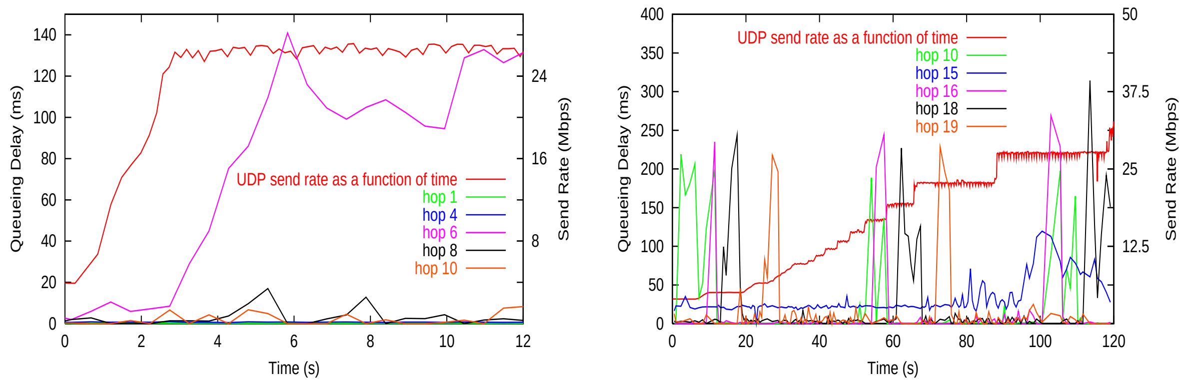
2.3.1 BFind Design

BFind's design is motivated by TCP's property of gradually filling up the available capacity based on feedback from the network. First, BFind obtains the propagation delay of each hop to the destination. For each hop along the path, the minimum of the (non-negative) measured delays along the hop is used as an estimate for the propagation delay on the hop [1]. The minimum is taken over delay samples from 5 traceroutes.

After this step, BFind starts a process that sends UDP traffic at a low sending rate (2 Mbps) to the destination. A trace process also starts running in parallel with the UDP process. The trace process repeatedly runs traceroutes to the destination. The hop-by-hop delays obtained by each of these traceroutes are combined with the raw propagation delay information (computed initially) to obtain rough estimates of the queue lengths on the path. The trace process concludes that the queue on a particular hop is *potentially* increasing if across 3 consecutive measurements, the queuing delay on the hop is at least as large as the maximum of 5ms and 20% of the raw propagation delay on the hop. This information, computed for each hop by the trace process, is constantly accessible to the UDP process. The UDP process uses this information (at the completion of each traceroute) to adjust its sending rate as described below.

If the feedback from the trace process indicates that there is no increase in the queues along any hop, the UDP process increases its rate by 200 Kbps (the rate change occurs once per feedback event, *i.e.*, per traceroute). Essentially, BFind emulates the increase behavior of TCP, albeit more aggressively, while probing for available bandwidth. If on the other hand, the trace process reports that the delay seems to increase on any hop(s), BFind flags the hop as being a potential bottleneck. The traceroutes continue monitoring the queues in parallel. In addition, the UDP process keeps the sending

[1] If the difference in the delay to two consecutive routers along a path is negative, then the delay for the corresponding hop is assumed to be zero



(a) (b)

Figure 2: **The operation of BFind:** In (a), BFind identifies hop 6 as the bottleneck. In (b), BFind identifies hop 15 as the bottleneck, although this could potentially be a false positive.

rate steady at the current value until one of the following things happen:

1. The hop continues to be flagged by BFind over *consecutive* measurements by the trace process and a threshold number (15) of such observations are made for the hop.
2. The hop has been flagged a threshold number of times in total (50).
3. BFind has run for a pre-defined maximum amount of total time (180 seconds).
4. The trace process reports that there is no queue build-up on *any* hop implying that the increasing queues were only a transient occurrence.

In the first two cases, BFind quits and identifies the hop responsible for the tool quitting as being the bottleneck. In the third case, BFind quits without providing any reliable conclusion about bottlenecks along the path. In the fourth case, BFind continues to increase its sending rate at a steady pace in search of the bottleneck.

In addition, if the trace process observes that the queues on the first 1-3 hops from the source are building, it quits immediately, to avoid flooding the local network (The first 3 hops almost always encompass all links along the path that belong to the source stub network). Also, we limit the maximum send rate of BFind to 50Mbps to make sure that we do not use too much of the local area network capacity at the PlanetLab sites. Therefore, we only identify bottlenecks with less than 50Mbps of available capacity. If BFind quits due to these exceptional conditions, it does not report any bottlenecks.

By its very nature, BFind not only identifies the bottleneck link in a path, but also estimates the available capacity at the bottleneck equal to the send rate just before the tool quit (upon identifying the bottleneck reliably). In addition, BFind also outputs the queuing delay across the hop identified as the bottleneck (averaged over all samples that caused the hop to be flagged). For paths on which no bottlenecks have been identified, BFind outputs a lower bound on the available capacity.

Notice that in several respects, the operation of BFind is similar to TCP Vegas's [4] rate-based congestion control. However, our sending rate modification is different than Vegas for two reasons. First, we actually wanted to ensure that the bottleneck link experiences a reasonable amount of queuing in order to come to a definitive conclusion. Therefore, BFind needs to be more aggressive than Vegas. Second, the feedback loop of the trace process is much slower than Vegas. As a result, BFind lacks tight transmit control to use Vegas' more gradual increase/decrease behavior.

One obvious drawback with this design is that BFind is a relatively heavy-weight tool that sends a large amount of data. This makes it difficult to find a large number of sites willing to host such experiments. BFind is not suitable for continuous monitoring of available bandwidth, but rather for very short duration measurements. In addition, since BFind may induce losses at the bottleneck, other congestion controlled traffic may react and slow down. This may cause the queuing delays to vanish and BFind to possibly ramp up its transmission speed. This will cause BFind to predict higher than the capacity really available to TCP. As a result, the available bandwidth reported by BFind is likely to be higher than the throughput that would be achieved by a TCP flow on the same path. Effectively, BFind reports something between the TCP fair share rate on the path and the raw capacity of the path.

2.3.2 *BFind Operation: An Example*

Figure 2 shows examples of the operation of BFind. In Figure 2(a), BFind is run between `planet1.scs.cs.nyu.edu` (NYU) and `r1-srp5-0.cst.hcvlny.cv.net` (Cable Vision Corp, AS6128, tier-3). As BFind ramps up its transmission rate, the delay of hop 6 (link between `at-bb4-nyc-0-0-0-OC3.appliedtheory.net` and `jfk3-core5-s3-7.atlas.algx.net`) begins to increase. BFind freezes its sending rate as the delay on this hop increases persistently. Finally, BFind identifies this hop as bottleneck with about 26Mbps of available capacity. This link also had a raw latency of under 0.5ms. The maximum queuing delay observed on this bottleneck link was about 140ms.

Figure 2(b) presents a potential false-positive. Running between `planetlab1.lcs.mit.edu` (MIT) and `Amsterdam1.ripe.net` (RIPE, tier-2), BFind observes the delays on various hops along the path increasing on a short time-scale causing BFind to freeze its UDP send rate quite often. The delay on hop

15 increases reasonably steadily starting at around 80 secs. This steady increase causes BFind to conclude that hop 15 was the bottleneck. However, it is possible that, similar to the other hops, this congestion was transient too, as indicated by a dip in the delay on hop 15 after 100secs.

Figure 3 shows the cumulative distribution function of the average queuing delay output by BFind for the bottleneck hops identified in our measurements. As the graph shows, the average queuing delay is smaller than 10ms only about 10% of the time. This shows that the decision of the trace process to flag a certain hop as being a bottleneck is not very sensitive to the corresponding thresholds (*i.e.* 5ms and 20%).

However, as Figure 2(b) shows, we cannot entirely rule out the possibility of false-positives in our analysis. But we do believe that our choices of the set thresholds for BFind, chosen empirically after experimenting with various combinations while looking for minimal error in estimation, would keep the overall number of false positives reasonably low. Notice that false negatives might occur in BFind only when the path being explored was very free of congestion during the run, while being persistently overloaded at other times. Given that BFind runs for at least 30secs, and sometimes up to 150secs, we think that false negatives are unlikely.

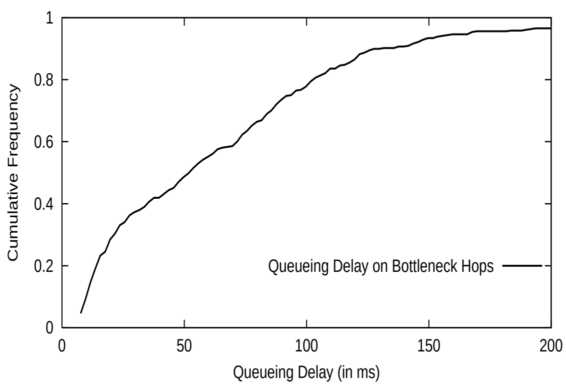


Figure 3: **BFind's sensitivity to thresholds:** A CDF of the average queuing delay of the bottleneck hops identified by BFind. The queuing delay, as reported by traceroute, is sampled whenever BFind flags the hop.

2.3.3 BFind Validation

In this section we present the results from a limited set of experiments to evaluate the available bandwidth estimation and the bottleneck location estimation accuracies of BFind. To validate the available bandwidth estimate produced by BFind, we compare it against Pathload [13], a widely-used available bandwidth measurement tool. Pathload estimates the range of available bandwidth on the path between two given nodes. Since measurements are taken at either end of the path, control is necessary at both end-hosts.

To validate the bottleneck location estimation of BFind, we compare it with Pipechar [20], which operates similarly to tools like pathchar [12] and pchar [18]. Pipechar outputs the path characteristics from a given node to any arbitrary node in the Internet. For each hop on the path, Pipechar computes the raw capacity of the link, as well as an estimate of the available bandwidth and link utilization. We consider the hop identified as having the least available bandwidth to be the bottleneck link output by Pipechar and compare it with the link identified by BFind. We also compare the available bandwidth estimates output by BFind and Pipechar.

For these experiments, we perform transfers from a machine located at a commercial data center in Chicago, IL to a large collection of destinations. Some of these destinations are nodes in the PlanetLab infrastructure and hence we have control over both ends of the path when probing these destinations. The other destinations are randomly picked from the set of 68 addresses we probe (summarized in Table 2). In probing the path to the latter destinations, we do not have control over the destination end of the path. In total, we probe 30 destinations.

A small sample of the results of our tests are presented in Table 3. These samples are chosen to represent the three coarse grained classes of the bandwidth available on the paths we probe – high (>40Mbps, the first two destinations), low (<10Mbps, the next three destinations) and moderate (the last destination) [2]. From these results, it is apparent that the output of BFind is reasonably consistent with the outputs of Pathload and Pipechar – both in terms of available bandwidth as well as the location of the bottleneck link. We observe similar consistency in the outputs across all the other destinations we probe.

2.4 Metrics of Interest

Based on the results of BFind, we report the bandwidth and latency of the bottlenecks we discover. In addition to these obvious metrics of interest, we post-process the tool's output to report on the ownership and location of Internet bottlenecks. Such a categorization helps identify what parts of the Internet may constrain high-bandwidth flows and what parts to avoid in the search for good performance. We describe this categorization in greater detail below.

In our analysis, we first classify bottlenecks according to *ownership*. According to this high level classification, bottlenecks can be described as either those within carrier ISPs, which we further classify by the tier of the owning ISP, or those between carrier ISPs, which we further classify according to the tiers of the ISPs at each end of the bottleneck. In order to characterize each link in our measurements according to these categories, we use a variety of available utilities. We identify the AS owning the endpoint of any particular link using the whois servers from RADB [25] and RIPE [26] routing registries. In addition, we use the results of [29] to categorize these ASes into tiers.

Our second classification is based on the latency of the bottleneck links. We classify bottlenecks according to three different levels of latency – low latency ($<$ 5ms), medium latency (between 5 and 15ms) and high latency ($>$ 15ms). Within each level, we identify bottlenecks that are within ISPs and those that are between carrier ISPs.

For paths to the NAPs, we classify the path into three categories – those that do not have a bottleneck (as reported by BFind), those that have a bottleneck at the NAP, and those that have a bottleneck

[2] About 20 of the destinations we probed had a very high available bandwidth. Of the remaining, 9 had very low available bandwidth. The remaining destination had moderate available bandwidth.

Destination Node	Path length	Pathload Report	Pipechar Report	BFind Report
CMU-PL	14	58.1 - 107.2Mbps	82.4Mbps	>39.1Mbps
Princeton-PL	12	91.3 - 96.8Mbps	94.5Mbps	>20.5Mbps
KU-PL	15	8.23 - 8.87Mbps	5.21Mbps (hop 12)	9.88Mbps (hop 12)
XYZ	14	4.17 - 5.21Mbps	4.32Mbps (hop 11)	8.34Mbps (hop 11)
www.fnsi.net	11	N/A	8.2Mbps (hop 10)	8.43Mbps (hop 10)
www.i1.net	11	N/A	19.21Mbps (hop 7)	32.91Mbps (hop 8)

Table 3: **BFind validation results:** Statistics for the comparison between BFind, Pathload and Pipechar. The first three machines belong to the PlanetLab infrastructure. The fourth machine, XYZ, is located at our site and is attached via AT&T. The source is a host located in a Chicago area data center. In all cases, whenever a bottleneck was found by any tool, the corresponding hop number is shown in parentheses. Note that since BFind limits its maximum sending rate it cannot identify bottlenecks with a higher available capacity as shown by the probes to the first two destinations. In this case, BFind was further constrained to a maximum of 40Mbps at the data center. In the second case, the 180secs maximum execution time was insufficient for BFind to probe beyond 20Mbps.

elsewhere. In all cases, we are only interested in non-access bottlenecks.

For each category in the classification scheme described above, we present a cumulative distribution function of the available capacity of the bottlenecks of the particular category.

2.5 A Subjective Critique

Below we briefly describe some possible shortcomings of our approach.

To approximate the measurement of "typical" paths, we choose what we believe to be a representative set of network paths. While the set of paths is not exhaustive, we believe that they are diverse in their location and choice in network connectivity. However, as the sources for our measurements are dominated by PlanetLab's academic hosts, there may be some hidden biases in their connectivity. For example, they may all have Internet2 connections which are uncommon elsewhere. This particular bias does not affect our measurements since our destinations are not academic sites (and hence the paths do not pass over Internet2). However, our test nodes are relatively USA-centric (only 3 international sources and 7 destinations) and may not measure international network connectivity well.

Routing could also have a significant impact on our measurements. If routes change frequently, it becomes difficult for the BFind tool to saturate a path and detect a bottleneck. Similarly, if an AS uses multipath routing, BFind's UDP probe traffic and its traceroutes may take different paths through the network. As a result, BFind may not detect any queuing delays nor, hence, any bottleneck despite saturating the network with traffic. If either of these situations occurred, traceroutes along the tested path would likely reveal multiple possible routes. However, despite the high frequency of the traceroutes during a BFind test, we did not observe either of these routing problems occurring frequently.

The processing time taken by routers to generate traceroute ICMP responses can impact our measurement of queuing delay and, therefore, bottlenecks in the network. Many researchers have noted that ICMP error processing, typically done in the router "slow" processing path, takes much longer than packet forwarding. In addition, some routers pace their ICMP processing in order to avoid being overwhelmed. Either of these could cause the delays reported by traceroute to be artificially inflated. However, recent work [9] has shown that slow path/fast path differences should not affect traffic measurement tools in practice since the typically observed ICMP processing delays are on the order of 1-2 ms, well within the timescales we need for accurate bottleneck detection.

Finally, address allocation may also skew our results. We rely on using the address reported by routers in their response to traceroute probes to determine their ownership. However, in some peering arrangements, a router owned by an ISP is allocated an address from the peer ISP's address space to make configuration convenient. In such situations, our link classification may erroneously identify the incorrect link (by one hop) as a the peering link between the ISPs. However, we believe that the common use of point-to-point links in private peering situations and separate address allocations used in public exchanges (these both eliminate the above problem) reduce the occurrence of this problem significantly.

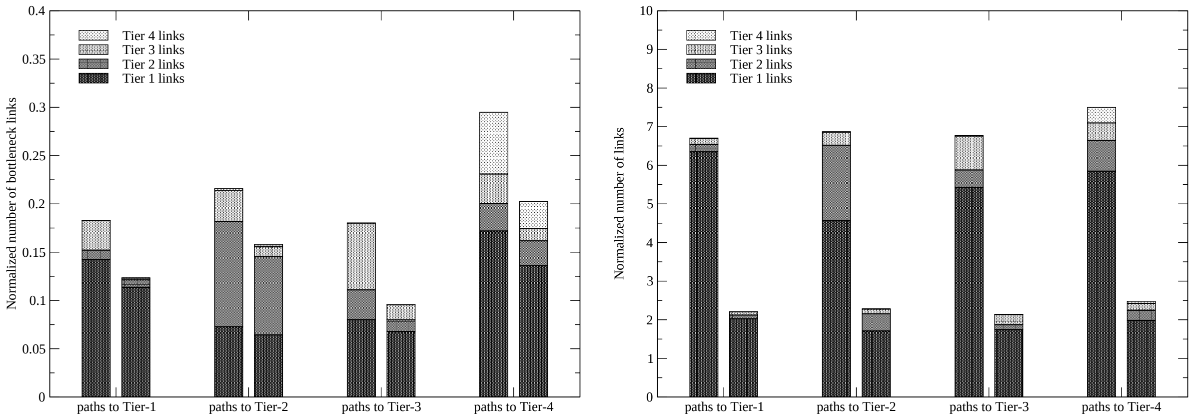
3 Results

Over a period of 5 weekdays, we ran our BFind tool between our chosen source and destination sites. The experiments were conducted between 9am and 5pm EST on weekdays. These tests identified a large number (889) of non-access bottleneck links along many (2028) paths. As described in Section 2, our post-processing tools categorize these network links and bottlenecks in a variety of ways. In this section, we describe the properties of these paths and bottleneck in these different categories.

3.1 Path Properties

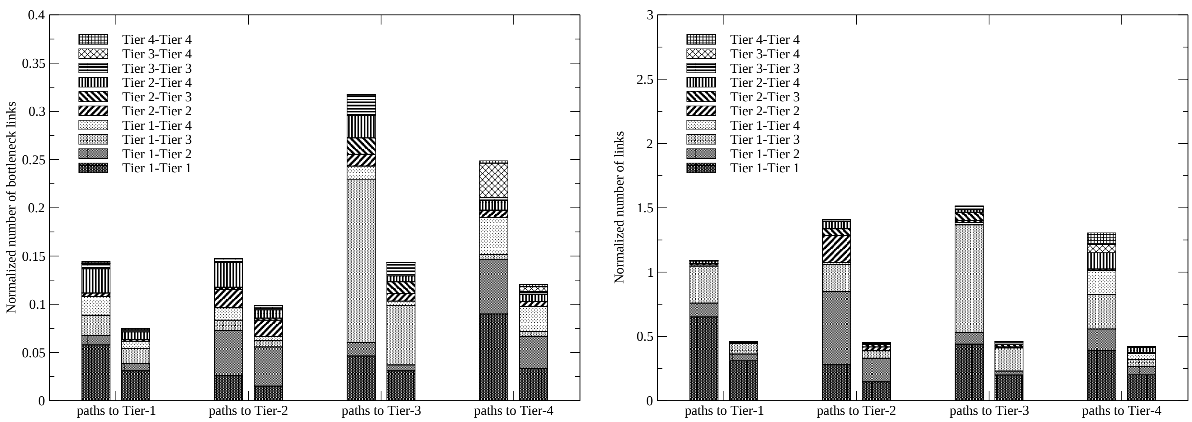
As described in Section 2, our results are based on observations made on paths between the PlanetLab sites and ISPs at different tiers in the Internet hierarchy. Before describing the results on bottleneck links, it is useful to consider some important overall characteristics of these paths.

The graphs in Figures 4(b) and 5(b) summarize some of the overall features of paths from PlanetLab sites, classified by paths to ISPs of a particular tier. On the y-axis, we plot the normalized number of links, *i.e.*, the total number of links encountered of each type divided by the total number of paths in each class. Each path class has a pair of bars. The left bars in the graphs show the overall average properties of the paths. The right bars in the graphs show the average number of *unique* links that each path class adds to our



(a) intra-ISP bottlenecks (b) All intra-ISP links

Figure 4: **Relative prevalence of intra-ISP bottlenecks**: The left graph shows the average number of bottlenecks of each kind appearing inside carrier ISPs classified according to paths to different tier destinations. The graph on the right shows the possible bias in the previous graph by showing the actual number of links (bottleneck or not) of each kind appearing in all the paths we considered.



(a) Bottlenecks at peering links (b) All peering links

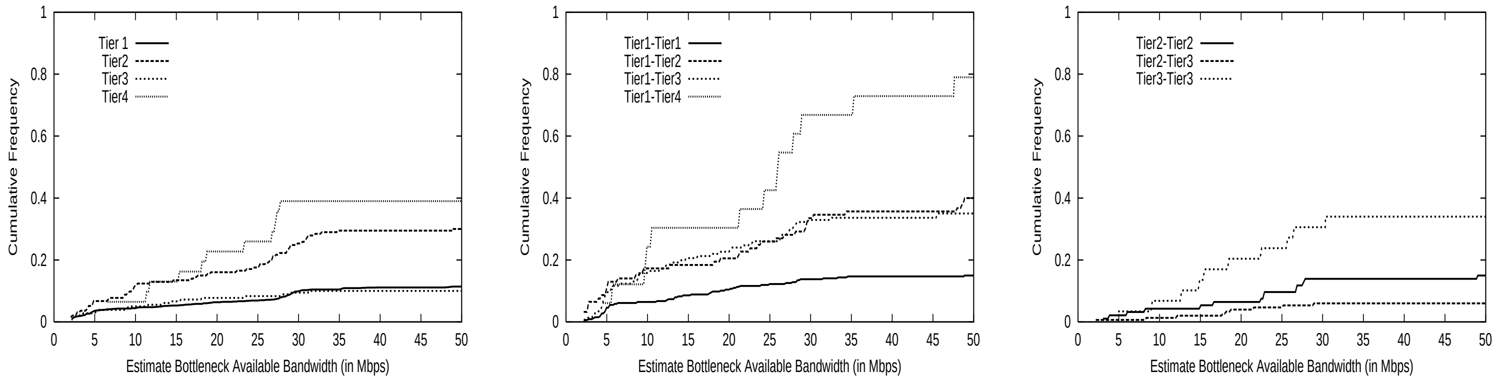
Figure 5: **Relative prevalence of peering bottlenecks**: Graph (a) shows the average number of bottlenecks of each kind appearing between ISPs, classified according to the type of path. Graph (b) shows the possible bias in (a) showing the actual number of links (bottleneck or not) of each kind appearing in all the paths we considered.

measurements. This number is significantly less, by a factor of 2 or 3, than the actual link counts. This is because links near the sources and destinations are probed by many paths (and are counted repeatedly). Such links can bias our measurements since they may appear as bottlenecks for many paths. Therefore, we also present information about unique links instead of describing only average path properties.

Note that Figure 4 shows intra-ISP links while Figure 5 shows peering links. Characteristics of the entire paths are evident by examining the two together. For example, Figure 4(b) shows that the average path between a PlanetLab site and one of the tier-2 destinations traversed about 4.5 links inside tier-1 ISPs, 2.0 tier-2 ISP links, and 0.5 tier-3 links. Figure 5(b), which illustrates the location of the peering links, shows that these same paths also traversed about 0.25 tier-1 to tier-1 peering links, 0.75 tier-1 to tier-2 links, 0.2 tier-1 to tier-3 links, 0.2 tier-2 to tier-2 links, and a small number of other peering links. The total average path length of paths to tier-2 ISPs, then, is the sum of these two bars, i.e. $7 + 1.4 = 8.4$ hops. Similar bars for tier-1, tier-3 and tier-4 destinations show the breakdown for those paths. One clear trend is that the total path length for lower tier destinations is longer. The tier-1 average length is 7.8 hops, tier-2 is 8.3, tier-3 is 8.3 and tier-4 is 8.8. Another important feature is the number of different link types that make up typical paths in each class. As expected from the definition of the tiers, we see a much greater diversity (*i.e.*, hops from different tiers) in the paths to lower tier destinations. For example, paths to tier-4 destinations contain a significant proportion of all types of peering and intra-ISP links.

3.2 Locations of Bottlenecks Links

Figures 4(a) and 5(a) describe the different types of bottleneck links found on paths to different tier destinations. Recall that BFind identifies either one, or zero, bottleneck links on each path. The left bars in the graphs show the probability that the identified bottleneck link



(a) intra-ISP (b) Tier-1 peering (c) Lower tier peering

Figure 6: **Available capacity at bottleneck links**: Graph (a) corresponds to bottlenecks within ISPs. Graphs (b) and (c) show the distribution of available capacity for bottlenecks in peering links involving Tier1 ISPs, and those in peering links not involving Tier1 ISPs, respectively. We do not show the distributions for bottleneck links between tiers 2 and 4 and those between tiers 3 and 4 since they were very small in number.

is of a particular type, based on our observations. For example, from Figure 4(a), we see that the bottleneck links on paths to tier-2 networks consist of links inside tier-1 ISPs 7% of the time, tier-2 links 11% of the time, and tier 3 links 3% of the time (bottlenecks within tier-4 ISPs appear only in 0.2% of the cases). From Figure 5(a), we see that various types of peering links account for bottlenecks in tier-2 paths nearly 15% of the time, with tier-1 to tier-2 links appearing as the most likely among all types of peering bottleneck links. These two graphs together indicate that approximately 36% of tier-2 paths we measured had a bottleneck that we were able to identify. The other 64% appear to have bottlenecks with an available capacity greater than 50Mbps.

From the left bars in Figure 4(a), it first appears that lower-tier intra-ISP links are path bottlenecks in much greater proportion than their appearance in the paths in Figure 4(b). Note, however, that the right bars in Figure 4(a) show the number of unique bottlenecks links that we observed. Considering the left and right bars for paths to tier-1 destinations, for example, we notice that there is a significant difference in the proportion of tier-3 bottleneck links. Upon further examination, we discovered that some of the PlanetLab sites were connected to the Internet via a tier-3 ISP. A few of these ISPs were bottlenecks for many of the paths leaving the associated PlanetLab site. However, even discounting this bias by looking only at the right bars, we see that lower-tier intra-ISP links seem to be bottlenecks more frequently than we would expect based on the appearance of these links in the paths. For example, tier-2 links make up 31% of the bottlenecks we found to tier-2 destinations but only about 16% of the links in these paths.

A similar examination of Figure 5(a) reveals several interesting details about the properties of bottlenecks at peering links. Some trends that are clear from this graph include:

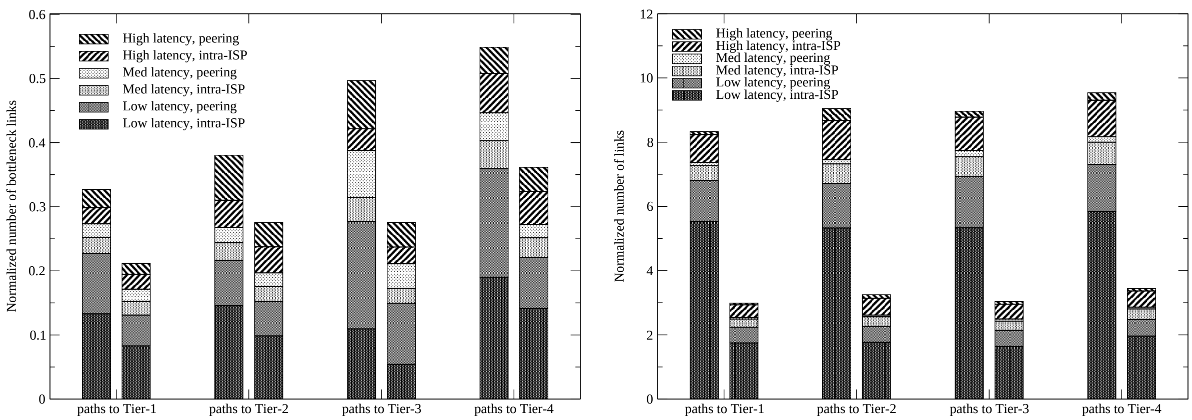
- Tier-1 to tier-1 peering links are bottlenecks less frequently than might be expected, given their proportion in the overall path length shown in Figure 5(b).
- Peering links to or from tier-2 and tier-3 networks are bottlenecks slightly more frequently than expected.
- Peering links with tier-4 ISPs are bottlenecks much more frequently than expected. Consider, for example, the proportion of tier-2 to tier-4 peering bottlenecks in paths to destinations in tiers 1–3, compared with the proportion of these links in the corresponding overall path length in Figure 5(b).

Looking at Figures 4(a) and 5(a) together, we can observe some additional properties of bottleneck links. For example, total path lengths are around 8–9 hops (adding the heigts of the bars in Figures 4(b) and 5(b)), of which only 1–1.5 hops are links between different ISPs. However, bottlenecks for these paths seem to be equally split between intra-ISP links and peering links (comparing the overall height of the bars in Figures 4(a) and 5(a)). This suggests that if there is a bottleneck link on a path, it is equally likely to be either in the interior of an ISP or between ISPs. Given that the number of peering links traversed is much smaller, however, the likelihood that the bottleneck is actually at one of the peering links is higher. But the fact that the bottleneck on any path is equally likely to lie either inside an ISP or between ISPs is surprising.

Another important trend is that the percentage of paths with an identified bottleneck link grows as we consider paths to lower-tier destinations. About 32.5% of the paths to tier-1 destinations have bottlenecks. For paths to tiers 2, 3, and 4, the percentages are 36%, 50%, and 54%, respectively. Note that while paths to tier-3 appear to have fewer intra-ISP bottlenecks than paths to tier-2, this may be because the peering links traversed on tier-3 paths introduce a greater constraint on available bandwidth.

3.3 Bandwidth Characterization of Bottleneck Links

In the previous section, we described the location and relative prevalence of observed bottleneck links, without detailing the nature of these bottlenecks. Here, we analyze the available bandwidth at these bottlenecks, as identified using BFind.



(a) Bottleneck Links (b) All Links

Figure 7: **Relative prevalence of bottlenecks of various latencies**: Graph (a) shows the average number of bottlenecks of the three classes of latencies further classified into those occuring between ISPs and those occuring inside ISPs. Graph (b) shows the actual number of links (bottleneck or not) of each kind appearing in all the paths we considered.

The graphs in Figure 6 illustrate the distribution of available bandwidth of bottleneck links observed in different parts of the network. Each graph has several curves, corresponding to different types of intra-ISP and peering links. Note that the CDFs do not go to 100% because many of the paths we traversed had more than 50 Mbps of available bandwidth. Recall that BFind is limited to measuring bottlenecks of at most 50 Mbps due to first hop network limitations. Hence we did not explore the nature of the bandwidth distribution above 50 Mbps.

Figure 6(a) shows the bottleneck speeds we observed on intra-ISP links. The tier-1 and tier-3 ISP links appear to have a clear advantage in terms of bottleneck bandwidth over tier-2 ISP bottlenecks. The fact that the tier-3 bottlenecks we identified offer higher available capacity than tier-2 bottlenecks was a surprising result. Links in tier-4 ISPs, on the other hand, exhibit the most limited available bandwidth distribution as expected.

In Figures 6(b) and (c) we consider the distribution of bottleneck bandwidth on peering links. Tier-1 to tier-1 peering links are the least constrained, indicating that links between the largest network providers are much better provisioned when compared with links between lower-tier networks. Again, we find the surprising result that tier-2 and tier-3 links exhibit very similar characteristics, in their peering links to tier-1 networks (Figure 6(b)). Also, peering links between tier-2 and tier-3 are not significantly different than tier-2 to tier-2 links (Figure 6(b)). We do see, however, that bottleneck peering links involving networks low in the hierarchy provide significantly less available capacity, as expected. This is clearly illustrated in the bandwidth distributions for tier-1 to tier-4, and tier-3 to tier-3 links.

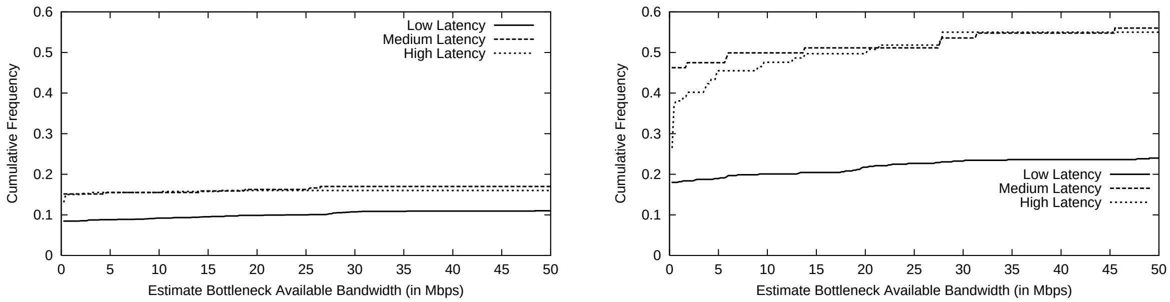
3.4 Latency Characterization of Bottleneck Links

In this section, we analyze the latency characteristics of bottlenecks, with particular interest in exploring the correlation between high-latency links and their relative likelihood of being bottlenecks. Figure 7 is similar to Figures 4 and 5, except that rather than classifying links on each type of path by their location, we separate them into latency classes (and whether they are peering or intra-ISP links). Low latency links have a measured latency, ℓ, of $\ell < 5$ ms, as determined by the minimum observed round-trip time. Medium latency and high latency links have minimum round trip times of $5 \leq \ell \leq 15$ and $\ell \geq 15$ ms, respectively. Though this is clearly a rough classification, we chose these classes to correspond to links at a PoP, links connecting smaller cities to larger PoPs, and long-haul links.

Figure 7(b) shows the overall latency characteristics of the paths. For example, paths to tier-2 destinations have an average of 5.3 low-latency intra-ISP, 1.4 low latency peering, 0.6 medium latency intra-ISP, 0.1 medium latency peering, 1.2 high latency intra-ISP, and 0.4 high latency peering links. In general, all path types have a high proportion of low-latency hops (both intra-ISP and peering) and high-latency intra-ISP hops. The latter is indicative of a single long-haul link on average in most of the paths we measured. While high latency peering links would seem unlikely, they do occur in practice. For example, one of the PlanetLab sites uses an ISP that does not have a PoP within its city. As a result, the link between the site and its ISP, which is characterized as a peering link, has a latency that exceeds 15ms.

In Figure 7(a) we illustrate the prevalence of bottlenecks according to their latency. We can observe that high-latency peering links are much more likely to be bottlenecks than their appearance in the paths would indicate. In observed paths to tier-2 destinations, for example, these links are 18.5% of all bottlenecks, yet they account for only 4% of the links. This suggests that whenever a high-latency peering link is encountered in a path, it is very likely to be a bottleneck. High latency intra-ISP links, on the other hand, are not overly likely to be bottlenecks (*e.g.*, 11% of bottlenecks, and 13.5% of overall hops on paths to tier-2).

In general, Figure 7 suggests that peering links have a higher likelihood of being bottlenecks, consistent with our earlier results. This holds for low, medium, and high-latency peering links. For example, very few paths have any medium latency peering links, yet they



(a) Intra-ISP

(b) Peering

Figure 8: **Available capacity at bottleneck links**: Graph (a) corresponds to bottlenecks within ISPs. Graph (b) corresponds to bottleneck links between ISPs.

(a) Relative Prevelance

#Paths to exchange points	466
#Paths with non-access bottlenecks	170
#Bottlenecks at exchange point	70

(b) Available bandwidth distribution

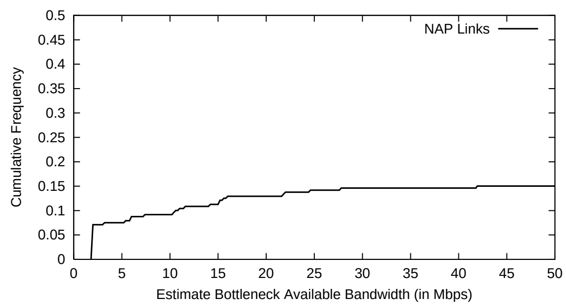


Figure 9: **Bottlenecks in paths to exchange points:** Table (a) on the left shows the relative prevalence of bottleneck links at the exchange points. Figure (b) shows the distribution of the available capacity for bottleneck links at the exchange points.

account for a significant proportion of bottlenecks in all types of paths. Also, low-latency peering links on paths to the lower tiers (*i.e.*, tier-3 and tier-4) have a particularly high likelihood of being bottlenecks, when compared to paths to tier-1 and tier-2 destinations. Recall from Figures 6(b) and (c) that these lower-tier peering bottlenecks also have much less available bandwidth.

We also examine the available bandwidth distribution of bottleneck links, when categorized according to latency. Figures 8(a) and (b) show the cumulative distribution of available bandwidth at core and peering bottlenecks, respectively. These graphs are constructed similarly to Figure 6, except that each curve represents a latency class, rather than a location.

In general, these curves reinforce the observations based on Figure 7. In particular, we see that the available bandwidth at intra-ISP bottlenecks is higher than at peering bottlenecks for all latency classes. We can also see clearly that more than half of the high and medium latency peering links encountered were bottlenecks, and that their available bandwidth was much more constrained when compared to the other link classes (*i.e.*, intra-ISP and low latency peering).

3.5 Bottlenecks at Public Exchange Points

As mentioned in Section 2, one of our goals was to explore the common perception that public exchanges are usually network choke points, to be avoided whenever possible. Using the procedure outlined in Section 2.2.2, we identified a large number of paths passing through public exchanges, and applied BFind to identify any bottlenecks along these paths.

As indicated in Figure 9(a), we tested 466 paths through public exchange points. Of the measured paths, 170 (36.5%) had a bottleneck link. Of these, only 70 bottlenecks (15% overall) were at the exchange point. This is in contrast to the expectation that many exchange point bottlenecks would be identified on such paths. It is interesting to consider, however, that the probability that the bottleneck link is located at the exchange is about 41% ($= 70/170$). In contrast, Figures 4(a) and 5(a) do not show any other type of link (intra-ISP or peering) responsible for a larger percentage of bottlenecks.[3] This observation suggests that if there is a bottleneck on a path through a public exchange point, it is likely to be at the exchange itself nearly half of the time.

4 Discussion

Our study, while to some degree confirms conventional wisdom about the location of Internet bottlenecks, yields a number of interesting and unexpected findings about the characteristics of these links. For example, we find a substantial number of bottleneck links *within* carrier ISPs. In addition, we also observed that low latency links, whether within ISPs or between them, can also constrain available bandwidth with a small, yet, significant probability.

[3]However, in Figure 5(a), bottlenecks between tiers 1 and 3 in paths to tier-3 destinations are comparable to bottlenecks at exchange points in this respect.

Furthermore, our observations can provide some guidance when considering other related issues such as choosing an access provider, optimizing routes through the network, or analyzing performance implications of bottlenecks in practice. In this section we discuss some of these issues in the context of our empirical findings.

Providers and Provisioning

Our measurements show that there is a clear performance advantage to using a tier-1 provider. Our results also show that small regional providers, exemplified by the tier-4 ASes in our study, have relatively low-speed connectivity to their upstream carrier, irrespective of the upstream carrier's size. In addition, their networks often exhibit bottlenecks (as we define them). This may be considered a reflection of the impact of economics on network provisioning if we assume that carriers lower in the AS hierarchy are less inclined to overprovision their networks if their typical customer traffic volume does not thus far require it. As a result, there is a clear disadvantage to using a tier-4 provider for high-speed connectivity. However, the tradeoffs between tier-2 and tier-3 networks are much less clear.

We found that paths to tier-3 destinations had a larger percentage of bottleneck links than tier-2 paths. Despite this, we also observed that tier-2 and tier-3 bottlenecks show similar characteristics in terms of available capacity, with tier-3 bottlenecks (both intra-AS and peering links) performing slightly better in some cases. This might be explained if we conjecture that tier-2 ASes, by virtue of their higher degree of reachability, carry a larger volume of traffic relative to their capacity, when compared with tier-3 ASes. Extending this hypothesis, we might conclude that if a stub network desires reasonably wide connectivity, then choosing a tier-3 provider might be a beneficial choice, both economically and in terms of performance, assuming that connectivity to tier-3 providers is less expensive.

Network Under-utilization

More than 50% of the paths we probed seemed to have an available capacity close to 40-50 Mbps or maybe more. This is true across most non-access links irrespective of their type. We hypothesize from this that large portions of the network are potentially under-utilized on *average*. This confirms what many large ISPs report about the utilization of their backbone networks. However, the fact that this holds even for providers of smaller size (*e.g.* tier-3) as well as for most peering links and even links at NAPs, seems surprising.

This observation about under-utilization, coupled with our results about the existence of potential hot-spots with low available bandwidth, opens the following key question – Is it possible to avoid these bottlenecks by leveraging existing routing protocols? While there has been considerable work on load-sensitive routing of traffic within an AS, little is known about how to extend this across ASes. We plan to explore this path in the future.

Route Optimization

It is sometimes suggested that a large proportion of the peering links between large carrier ISPs (tier-1) could emerge as bottlenecks, due to the lack of economic incentive to provision these links and the large volume of traffic carried over them. However, our measurements seem to suggest otherwise. We believe that this could imply that either the peering links are in fact quite well provisioned, or that a smaller portion of the entire Internet traffic traverses these links than what might be expected intuitively.

While it is difficult to discern the exact cause for this lack of bottlenecks, it may have important implications for the design of systems or choice of routes. For example, it may be unlikely that purchasing bandwidth from two different tier-1 ISPs is significantly better from a performance perspective than buying twice as much bandwidth from a single tier-1 ISP.[4] In fact, it might be more economical to purchase from one ISP. Similarly, a shorter route to a destination that passed through a tier-1 to tier-1 peering link might be better than a longer route that stays within a single, lower-tier provider.

5 Related Work

Several earlier research efforts have shared our high-level goal of measuring and characterizing wide-area network performance. This past work can be roughly divided into two areas: 1) measurement studies of the Internet, and 2) novel algorithms and tools for measuring Internet properties. In this section we review several recent representative efforts from each of these categories.

5.1 Measurement Studies

Typically studies to characterize performance in the Internet have taken two forms: 1) some, such as [21, 33, 19, 28], use active probing to evaluate the end-to-end properties of Internet paths and, 2) other studies, such as [2, 32] have used passive monitoring or packet traces of Internet flows to observe their performance in the Internet.

In [21] multiple TCP bulk transfers between pairs of measurement end-points are monitored to show evidence of significant packet reordering, correlated packet losses, and frequent delay variations on small scales. The paper also describes the distribution of bottleneck capacities observed in the transfers. The study in [28] used latency and loss measurements between network end-points to compare the quality of direct and indirect paths between nodes. The authors note that the performance gains come from avoiding congestion and using shorter latency paths. Using active measurements in the NIMI [23] infrastructure, the authors of [33] study the steadiness of Internet paths in terms of delay, loss, and throughput. For each notion of constancy, they observed that all three properties were steady on at least a minutes timescale. Finally, a recent study of delay and jitter across several large backbone providers aimed to classify paths according to their suitability for latency-sensitive applications [19]. The authors found that most paths exhibited very little delay variation, but very few consistently experienced no loss. In comparison with these efforts, our work has a few key differences. First, rather than exploring true end-to-end paths, our measurement paths are intended to probe the non-access part of the Internet, *i.e.*, the part responsible for carrying data between end networks. Second, we measure *which* part of the network may limit the performance of end-to-end paths.

In [2], the authors study packet-level traces to and from a very large collection of end-hosts, and observe a a wide degree of performance variation, as characterized by the observed TCP throughput. With a similar set of goals, [32] analyzes packet traces to understand the

[4] Of course, it might be useful for reliability purposes.

Non-access bottlenecks are equally likely to be links within ISPs or peering links between ISPs	
The likelihood of a bottleneck increases on paths to lower tier ISPs	
Interior and peering bottlenecks in tier-2 and tier-3 ISPs exhibit very similar available capacity	
Internal links in lower tier ISPs appear as bottlenecks with greater frequency than their overall presence in typical paths	
Bottlenecks appeared in only 15% of the paths traversing public exchanges, but when a bottlenck is found on such paths, the likelihood of it being at the exchange is more than 40%	
All paths have a high proportion of low-latency links (interior and peering) and roughly one high-latency interior link	

Table 4: **Summary of key observations**

distribution of Internet flow rates and the causes thereof. The authors find that network congestion and TCP receiver window limitations often constrain the observed throughput. In this paper, our aim is not to characterize what performance end-hosts *typically* achieve and what constrains the typical performance. Instead, we focus on *well-connected* and unconstrained end-points (*e.g.,* no receiver window limitations) and comment on how ISP connectivity constrains the performance seen by such end-points.

5.2 Measurement Tools

The development of algorithms and tools to estimate the bandwidth characteristics of Internet paths continues to be an active research area (see [6] for a more complete list). Tools like *bprobe* [5], Nettimer [17], and PBM [21] use packet-pair like mechanisms to measure the *raw bottleneck capacity* along a path. Other tools like *clink* [7], *pathchar* [12], *pchar* [18], and *pipechar* [10], characterize hop-by-hop delay, raw capacity, and loss properties of Internet paths by observing the transmission behavior of different sized packets. Finally, a different set of tools, well-represented by *pathload* [14], focus on the *available capacity* on a path. Unfortunately, these latter tools require control over both the end-points of the measurement.

In this paper we develop a mechanism that measures the available capacity on the path between a controlled end-host and an arbitrary host in the Internet. In addition, we identify the portion of the network responsible for the bottleneck. Our tool uses an admittedly heavyweight approach in the amount of bandwidth it consumes, however, and we hope to address this shortcoming in the future.

6 Summary

This goal of this paper was to explore the following fundamental issue: if end networks upgrade their access speeds, which portions of the rest of the Internet are likely to become hot-spots? To answer this question, we performed a large set of diverse measurements of typical paths traversed in the Internet. We identified non-access bottlenecks along these paths and studied their key characteristics such as location and prevalence (links within ISPs vs. between ISPs), latency (long-haul vs. local), and available capacity. Table 4 summarizes some of our key observations.

The results from our measurements mostly support conventional wisdom by quantifying the key characteristics of non-access bottlenecks. However, some of our key conclusions show trends in the prevalence of non-access bottlenecks that are unexpected. For example, our measurements show that the bottleneck on any path is roughly equally likely to be either a peering link or a link inside an ISP. We also quantify the likelihood that paths through public exchange points have bottlenecks appearing in the exchange.

In addition, our measurements quantify the relative performance benefits offered by ISPs belonging to different tiers in the AS hierarchy. Interestingly, we find that there is no significant difference between ISPs in tiers 2 and 3 in this respect. As expected, we find that tier-1 ISPs offer the best performance and tier-4 ISPs contain the most bottlenecks.

In summary, we believe that our work provides key insights into how the future network should evolve on two fronts. Firstly, our results can be used by ISPs to help them evaluate their providers and peers. Secondly, the observations from our work can also prove helpful to stub networks in picking suitable upstream providers.

Acknowledgment

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