

Revealing Utilization at Internet Interconnection Points

Nick Feamster
Princeton University

Abstract

Recent Internet interconnection disputes have sparked an increased interest in developing methods for gathering and collecting data about utilization at interconnection points. One mechanism, developed by DeepField Networks, allows Internet service providers (ISPs) to gather and aggregate utilization information using network flow statistics, standardized in the Internet Engineering Task Force as IPFIX. This report (1) provides an overview of the method that DeepField Networks is using to measure the utilization of various interconnection links between content providers and ISPs or links over which traffic between content and ISPs flow; and (2) surveys the findings from five months of Internet utilization data provided by seven participating ISPs—Bright House Networks, Comcast, Cox, Mediacom, Midco, Suddenlink, and Time Warner Cable—whose access networks represent about 50% of all U.S. broadband subscribers.

We first discuss the problem of interconnection and utilization at interconnection points. We then discuss the basic operation of the measurement capabilities, including the collection and aggregation of traffic flow statistics (i.e., IPFIX records), providing an assessment of the scenarios where these aggregate measurements can yield accurate conclusions, as well as caveats associated with their collection. We assess the capabilities of flow statistics for measuring utilization, and we discuss the capabilities and limitations of the approach the aggregation techniques that the ISPs use both in providing data to us, and that we apply before making the data public.

The dataset includes about 97% of the paid peering, settlement-free peering, and ISP-paid transit links of each of the participating ISPs. Initial analysis of the data—which comprises more than 1,000 link groups, representing the diverse and substitutable available routes—suggests that many interconnects have significant spare capacity, that this spare capacity exists both across ISPs in each region and in aggregate for any individual ISP, and that the aggregate utilization across interconnects is roughly 50% during peak periods.

1 Introduction

As traffic demands increase due to the rise of large asymmetric traffic flows such as video streaming, interconnection disputes are frequent, and they are becoming increasingly visible and public. The nature, causes, and location of Internet congestion has spawned contentious debate over the past two years. End users have become increasingly invested in this topic as well, although they have sometimes conflated the issues of Internet

congestion with other concerns about the prioritization of Internet traffic.

Discussion about interconnection can and should be better informed by accurate, up-to-date information about where capacity bottlenecks exist. Unfortunately, until now, data about traffic utilization at Internet interconnection points has been hard to come by, due to confidentiality and business constraints. This opacity has led users, policymakers, and researchers to resort to techniques that attempt to isolate congestion using end-to-end probes [3, 6, 12], which nonetheless still leave significant uncertainty about where congestion may be occurring.

One of the biggest barriers to furthering this debate is the lack of clear data on this problem. As the Internet pioneer David Clark recently said, “An issue that has come up recently is whether interconnection links are congested. The parties who connect certainly know what’s going on, but that data is generally not disclosed. The state of those links matters to a lot of people ... and there have been some misunderstandings around congestion and interconnection links” [5].

To help shed light on this important issue, ISPs have provided unprecedented data around the state of interconnection links. This data yields some information concerning the utilization of network ports that face each network’s “peers” (i.e., the networks that each ISP connects to directly). This data aims to illuminate the utilization properties of each network’s externally facing switch ports and ascertain whether each collection of ports between a given ISP and its respective neighboring network is uncongested. Although this data cannot, by itself, tell the complete story about the location of congestion along end-to-end Internet paths, it can tell us a lot about where congestion is not occurring.

Each participating ISP has provided information about its interconnection to other ISPs in each region, as well as the capacity of each interconnect. The data that participating ISPs provide account for about 97% of links from all participating ISPs in any given month; the only links that are missing from the dataset are those where the measurement infrastructure has not yet been deployed. This information offers sufficient information to ascertain the capacity of each interconnect between an ISP and neighboring networks. Given this information, we can compare this provisioned capacity against traffic statistics for traffic that traverses each of these network ports and compare the measured utilization to the provisioned capacity to achieve an estimate of utilization. The ability to perform this analysis depends on the ability to collect ac-

curate, utilization measurements. Section 3 discusses the collection method.

Ideally, the information we would be able to see the utilization and capacity for each individual port, for every ISP—in such a scenario, comparing utilization to provisioned capacity would be straightforward. Of course, the practical realities are more complicated: even the *existence* of an individual interconnection is typically considered proprietary, not to mention the business agreement surrounding that interconnection, as well as the capacity and utilization of the interconnection. As a result, the data that the ISPs provide aggregates sampled flow statistics across link groups in each region, providing a high-level picture of capacity and utilization per region and ISP, as well as how this utilization fluctuates over time. The traffic flow statistics, based on IPFIX [4] and collected by DeepField Networks [7] represents utilization information that is collected at the interconnection points, thus providing a more direct indication of the utilization information at interconnection points.

The data does have some limitations that make it inappropriate for answering certain questions about utilization. First, it is sampled, which makes it difficult to answer certain types of questions about flow size distributions, characteristics of small flows, and utilization by application. Second, to preserve proprietary information, the data is aggregated and anonymized, preventing conclusions about utilization at specific interconnection points. Yet, the data illuminates interconnection capacity and utilization at many levels. Throughout this report, we are careful to highlight conclusions that we can and cannot make with the data that the participating ISPs have provided. (Based on feedback from other experts, we have also iterated on the data that the ISPs have agreed to release, resulting in a careful balancing act between preserving proprietary information and revealing information about utilization at interconnection points that can inform ongoing debates. Subsequent sections of this report provide additional detail on the method used to collect and report this data, as well as what we can and cannot conclude from the data that the ISPs have agreed to provide.

The rest of this paper is organized as follows. Section 2 describes related work and analysis techniques. Section 3 describes the measurement techniques and data, as well as the effects of various phenomena such as sampling on the accuracy of the collected data. Section 4 discusses where the measurements from this study can (and cannot) be applied. Section 5 describes the findings from a preliminary analysis of the data collected as part of the project. Section 6 concludes with a summary and suggestions for possible next steps.

2 Related Data and Analysis Techniques

In this section, we briefly outline existing attempts to measure both end-to-end performance of Internet paths and infer congestion along these paths (and at interconnects) using these datasets. All of these techniques and approaches involve inference based on measurements from end hosts, as opposed to direct measurements of utilization at the intercon-

nect. As a result, public data about utilization and capacity at the interconnects—which this project provides for the first time—fills a significant gap concerning our visibility into the current state of utilization at interconnects.

2.1 Measurements from End-Hosts

A common approach to performing Internet performance measurements is to actively send test traffic along end-to-end Internet paths and observe the performance characteristics of those paths. For example, one might perform test uploads or downloads from an end-user device (laptop, phone, home gateway device) and measure the time to transfer a certain number of bytes. Similarly, it is possible to measure end-to-end latency or packet loss along these end-to-end paths, as well as to measure how these characteristics may vary in response to additional load on the network.

Measurement Lab. The Measurement Lab [12] operates global server infrastructure for conducting throughput measurements from various endpoints, using pre-approved measurement tools. Measurement Lab (MLab) limits the tools that can perform throughput measurements against their servers due to the fact that server bandwidth is a limited resource. One of the tools that has permission to measure against this infrastructure is BISmark [1, 14], which we describe in more detail below. Other tools for measuring mobile performance (e.g., MobiPerf) exist. The tool that perhaps offers the most comprehensive data from the project is the Network Diagnostic Tool (NDT), which we also describe in more detail below.

Network Diagnostic Tool (NDT). The network diagnostic tool (NDT) [3] performs throughput tests; users run NDT from end-hosts, which measure throughput to a corresponding server. One version of the tool runs as a Java applet from a web browser. Measurement Lab runs a version of the Java applet from its website that measures throughput to the collection of deployed Measurement Lab servers around the world, using geolocation to map the client to a nearby NDT server for the purposes of the throughput test (the accuracy of a TCP throughput test depends on measuring throughput to a nearby server, since TCP throughput is inversely proportional to round-trip latency). NDT also forms the basis of well-known measurement efforts, such as the Internet Health Test. Unfortunately, MLab’s NDT test setup is known to be inaccurate due to its use of only a single thread to measure TCP throughput, which our previous work shows can significantly underestimate the throughput of the link [14]. Additionally, NDT provides no mechanism for locating a throughput bottleneck along an end-to-end path.

BISmark. The Broadband Internet Service Benchmark (BISmark) [1, 14] project runs custom throughput, latency, and packet loss measurements from home routers that run OpenWrt. The project has been collecting performance data from home networks since 2011; at its peak, the project was collecting data from about 400 home networks in more than 30 countries. Currently, about 70 home routers are actively reporting

measurements. The project was the first research effort to explore the means of measuring access-network throughput and latency of a broadband access networks access link using direct measurements. All of the data is publicly available, both through a web portal, and via direct download in XML format. The BISmark measurement techniques perform end-to-end measurements against deployed servers and do not attempt to draw inferences or conclusions about congestion at interconnect. The BISmark project produced the first published research paper that documented interconnection congestion at many interconnects that occurred in March 2014; because the measurements were end-to-end, they manifested as pronounced increases in latency along specific end-to-end paths between home Internet subscribers and the M-Lab servers. Subsequent work, which we describe in the next section, has followed up on this effort in more detail.

FCC Measuring Broadband America Reports. The FCC’s Measuring Broadband America project [11] produces periodic reports using similar measurements as the BISmark project, albeit with a much larger deployment. Their reports are less frequent (typically once per year), as opposed to BISmark’s “real time” visualizations of throughput, latency, and packet loss. The techniques are similar (some of them, such as the throughput test and the Web performance test, were co-designed), as are the servers against which the home network gateways perform measurements (i.e., both perform throughput measurements against the Measurement Lab servers). Similarly, the project does not provide any mechanism for directly measuring congestion at interconnection points; the only performance measurements that the devices can perform are end-to-end performance measurements.

2.2 Measuring Interconnect Performance

Because the above tools can only measure from end-host vantage points, they do not provide direct information about utilization or congestion at interconnection points. Because congestion manifests as an increase in latency, the measurement techniques that we have discussed above can often detect congestion along an Internet path. Yet, detecting congestion at a particular interconnection point is difficult to do with these types of measurements. We discuss various other methods to indirectly infer or directly measure congestion at an interconnection point below.

2.2.1 Indirect: Tomography & Round-Trip Latency

A general measurement approach sometimes referred to as *network tomography* attempts to use a combination of performance measurements along different end-to-end Internet paths to infer specific links where congestion or failures may be occurring [6]. The intuition is quite simple: Given “simultaneous” measurements of two end-to-end Internet paths that may share one or more links, if one end-to-end path experiences symptoms of congestion (i.e., an increase in latency) whereas a second end-to-end path does not, then we can infer that the congestion must be occurring on the portion of the second path that is not common with the first path.

One can generalize this to N end-to-end paths; the hope is there is some set of end-to-end paths in the measurement infrastructure such that each link could be isolated.

Unfortunately, it is difficult to obtain a comprehensive set of vantage points in practice because most end-to-end paths will share more than one interconnection point or link in common. For example, in an M-Lab report released in 2014 [13], many of the end-to-end paths between NDT vantage points and the M-Lab servers could (and likely do) share multiple end-to-end links along the path—not only the interconnection point (where the report implies congestion is taking place) but also other links along the path (e.g., links within transit providers). The second scenario is a distinct possibility that previous reports have outlined in detail [8], and it would be naïve to suggest that these measurements conclusively pinpoint congestion at interconnection points. Worse yet, providers can (and have) gamed these active measurement techniques by prioritizing probe traffic [10].

Another approach, proposed by CAIDA [2], is to use traceroutes to discover an end-to-end path and subsequently send latency probes to either side of an interconnect. While this approach is more direct than network tomography, the approach entails significant shortcomings, which are outlined in detail in CAIDA’s own report. Among the limitations are the difficulty in accurately identifying points of interconnection points along and end-to-end traceroute, as well as the fact that increases in latency might be occurring along reverse paths, as opposed to the forward path that the probes are attempting to measure.

2.2.2 Direct: Packet Capture and SNMP

An alternative method for directly gathering information about the traffic that passes through a network is via packet traces. Packet traces capture what is effectively a recording of every packet that traverses a particular interface. When packet trace collection is configured, an administrator may capture the complete packets, the first bytes of each packet, or simply the “headers” or metadata for each packet. Packet capture provides complete timing information about the arrival of individual packets and the header information on individual packets (including the TCP window size), and can as such be used to compute or infer properties of traffic flows including jitter, packet loss, and instantaneous throughput.

It would be beneficial to have better information about latency and packet loss to assess the congestion status of a particular flow, as well as what might be causing poor user quality of experience, but these types of conclusions typically require gathering packet-level statistics. Methods such as deep-packet inspection are typically not practical at large, high-throughput interconnection points; these methods tend to be costly to deploy, and they produce more data than can be reasonably backhauled to a data-center for post hoc analysis. Additionally, typically gathering fine-grained, packet-level information is not tenable at high packet rates, so gathering traffic flow statistics must often suffice. Traffic flow statistics are quite a bit more coarse, because they only provide infor-

mation about the number of bytes and packets transferred over the duration of the flow record. Accordingly, although these types of methods may be appropriate for certain types of analysis pertaining to quality of experience, security, or other network management tasks, the question of utilization of interconnects is best answered today with flow-level statistics (e.g., IPFIX) or SNMP counters. Traffic flow statistics can represent traffic statistics on a per-flow basis as opposed to SNMP byte counts, which only represent total interface utilization counts. SNMP statistics are thus more coarse for many purposes, because they do not represent the utilization of specific flows and are polled at relatively infrequent intervals.

AT&T/DirectTV Merger Analysis. The Cooperative Association for Internet Data Analysis (CAIDA) [2] is participating in an ongoing consultation with the Federal Communications Commission (FCC) concerning the performance metrics that should be reported in conjunction with the merger between AT&T and DirectTV, to ensure that the network is offering suitable performance to all traffic flows [9]. Reporting on performance at interconnection points is a condition of the merger. The FCC appointed CAIDA as an independent measurement expert (IME) to recommend a set of metrics that should be included in these reports on interconnection performance; the recommendations suggest including metrics such as packet loss, latency, and jitter of flows at the interconnection point, as proxies for congestion. It is unclear at this time what information, if anything, will be publicly reported.

In contrast, this study only reports on utilization, but these measurements are made public. Although these recommendations suggest that utilization need not be a proxy for congestion (indeed, it may be possible to engineer an interconnect to run at 95% capacity or higher), it is also worth noting that *none* of these metrics tell the complete story. Similarly, packet loss may increase as a result of active queue management or traffic shaping, as opposed to congestion. Similarly, latency or jitter are only indirect proxies for congestion.

3 Measurement and Data

We now describe the data that each ISP provides concerning the utilization of each network port, and how this data is sampled and aggregated.

Sampling and aggregation can affect the accuracy of the resulting measurements, and we discuss the effects of sampling and aggregation later in this section. In addition to discussing the methods that the ISPs use, we also describe alternative approaches to measuring network utilization and the advantages and drawbacks of each method.

3.1 Traffic Flow Statistics and Utilization

A common method for gathering statistics about the utilization of a network—and the method that this project uses—is to gather what are often referred to as “flow statistics”; the most common version of flow statistics is likely the IPFIX protocol (often instantiated in Cisco products as “NetFlow”) [4].

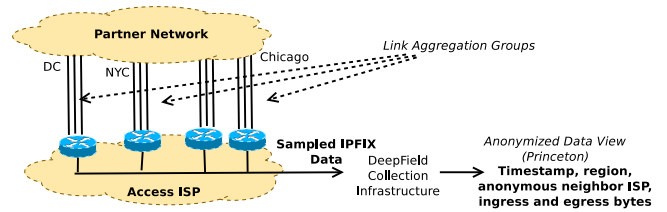


Figure 1: Data collection infrastructure and approach.

Many other vendors have conformed to a similar standard when exporting records about traffic flows.

A IPFIX record contains metadata about the flow, including the number of bytes transferred, the number of packets in the flow, the start and end times for the flow, and the network interface associated with the flow. Accordingly, the statistics in a flow record can give useful information about the average utilization over a period of time in terms of either bytes or packets. For example, if the flow record has a duration of ten seconds and reports that 1 gigabyte of traffic was transferred during that ten seconds, then the average utilization over that ten-second period would be 800 megabits per second (eight gigabits per ten seconds). The flow statistics can also be used to compute average packet rates, in terms of packets per second, in a similar manner.

The traffic in this dataset covers interconnection points for access ISPs that account for about 50% of the broadband subscribers in the United States. Figure 1 shows how data is collected from each interconnection point between an access ISP and neighboring partner network. Each participating access ISP may connect to a partner network in multiple geographic regions. The access ISP collects IPFIX data at each interface that interconnects with a neighboring partner network. The traffic statistics that each ISP reports are based on IPFIX records that are exported at least as frequently as every 60 seconds and subsequently aggregated across a link group; to protect the confidentiality of information pertaining to usage on specific interconnects, the data is aggregated into a single link group per geographic region. (Section 3.2 describes this approach in more detail, and how it affects the conclusions we can draw.) The statistics represent an aggregate that is computed based on the sum of peak five-minute intervals in each hour, for each neighbor ISP, circuit group pair.

The dataset contains about 97% of links from all participating ISPs in any given month; the only links that are missing from the data set are links that are not configured in DeepField’s measurement system. All interconnections between participating ISPs and neighboring partner networks are private (i.e., none of the interconnections in this study involve public IXP switch fabrics). Each row in the dataset that CITP receives includes the following statistics:

- Timestamp (representing a five-minute interval)
- Region (representing an aggregated link group)
- Anonymized partner network
- Access ISP

- Total ingress bytes
- Total egress bytes
- Capacity

Because flows do not begin and end on discrete five-minute intervals, each five-minute timestamp represents the sum of utilization of active traffic flows that were active during that interval. Suppose that, at a given time, a set of flows are active. Then, the total ingress bytes for that five-minute interval for a single flow would be the average bitrate for that flow over its total duration, multiplied by the amount of time that the flow was active during the given five minute interval. The total utilization for the link aggregation group is the sum of all such statistics, for any flows that were active during that five-minute interval.

3.2 Aggregation and Load Balancing

When measuring the contribution of a traffic flow to a link's utilization, it is also important to ensure that flows are not double counted. An ISP's ports may be configured as a link aggregation group (we are aware of this configuration for at least one ISP in the study). In this ISP's case, the router balances outbound traffic flows across the links; a single flow always goes across a single link. The allocation of outbound traffic flows to links is based on a hashing algorithm on the router; given enough traffic flows, this type of load balancing typically works well enough to balance load evenly across the available links in any given aggregation group.

We are cognizant of only the outbound load balance mechanisms for all of the ISPs that contribute data; we are unaware of the traffic load balance practices of partner networks that do not participate in the study, but, for the purposes of assessing inbound traffic loads across links in an aggregation group, it is likely reasonable to assume that these ISPs also use typical load balancing practices for outbound traffic (and, hence, we can assume a relatively uniform load balance of inbound traffic flows for a link aggregation group).

In networks where there exist only a small number of flows, such as in commercial VPNs, it is possible that utilization across links might become unbalanced, but on links carrying consumer traffic, such as those in this study, it would be highly unusual for traffic to be unevenly balanced across links, due to the nature of the router hashing function, which is designed to randomly assign these flows to available links. Thus, although traffic statistics are reported in aggregate across an aggregation group, it is highly unlikely that we would encounter a situation where average traffic flow statistics would report low congestion, but some links in the aggregation group would be congested while others would be underutilized.

3.3 Sampling

IPFIX records must be sampled, meaning that the statistics in any given record are based not on all of the packets in that flow, but rather a random sample of the packets in that flow. In this project, ISPs report statistics that are based on sampled IPFIX records. Typically, IPFIX sampling can take one of

two forms: *random* and *deterministic*. If the sampling factor is N , then random sampling will incorporate the statistics for any given packet with probability $1/N$; on the other hand, deterministic sampling will incorporate the statistics based on every N th packet deterministically.

The effects of sampling on overall traffic volume estimation bears some discussion. Certainly, when trying to estimate certain characteristics, such as the number of small flows that cross an interface, or the overall distribution of flow-sizes, aggressive sampling can distort measurement accuracy. On the other hand, estimating overall utilization is possible in general—flows may be missed entirely, but on average, some fraction of the small flows will be captured. Attempts to normalize the flow sizes for small flows will result in inaccurate estimates of the flow sizes of these small flows, but the estimates for overall traffic volume should remain reasonably accurate. For example, suppose that a link creates flow statistics based on a packet-sampling rate of $1/1,000$. In the extreme case, suppose that each flow is a single packet. Then, on average, the statistics will reflect one in every thousand flows, and attempts to normalize these statistics would result in an estimate of one flow of 1,000 packets. Clearly, the flow-size estimates are incorrect, but the total utilization is accurate, on average.

The observation that sampled IPFIX records are sufficient for aggregate capacity utilization holds empirically, as well. We compared the SNMP byte counters to sampled IPFIX records with a $1/8,000$ sampling rate across 250 interconnect links for one of the largest participating ISPs in the study for a single day. The mean and median of the ratio between both metrics were both around 0.98, with a standard deviation of 0.095. As ISPs increase their sampling rates, the accuracy of IPFIX relative to SNMP should improve further.

In conclusion, the average of sampled utilization across port groups may underestimate utilization, and averaging across port groups may not be able to characterize the distribution of utilization (and congestion) across the group (e.g., some ports may be congested while others remain uncongested). Yet, we can certainly use this data to determine with confidence whether there exist uncongested ports in a region between a pair of networks.

Sampling rates in this study. Most of the Internet service providers in the study report traffic flow statistics based on a sampling rate of $1/1,000$, meaning that statistics are collected based on a sampling of every thousandth packet, on average; all of the ISPs who are contributing data implement a sampling rate of at least $1/8,000$. Some of the ISPs in the study use deterministic sampling and others use random sampling; given that the goal is to estimate capacity on links where much of the traffic flows that contribute to congestion are large, long-running video streams—which have fairly large packet and byte counts—neither the sampling rate nor the mode of sampling should affect the accuracy in estimating the overall utilization.

3.4 Configuration and Topology

Each participating Internet service provider (ISP) provides the following information from configuration data, and from SNMP polling:

- *Interconnection.* For each of an ISP's peers, the ISP's router configuration data provides information about which interface maps to each neighboring autonomous system (AS), as well as the policies associated with each connection, such as Border Gateway Protocol configuration options (e.g., local preference, and AS path prepending). The router configuration also provides information such as the mapping of individual network interface names to the AS that the interface corresponds to. In this study, the next-hop AS was determined from BGP routing information gathered from the interconnection router.
- *Provisioning.* In addition to the mappings between interfaces and ASes that the configuration provides, SNMP polling data yields information about the interface capacity that is provisioned on each link.

DeepField has the ability to collect this data from all routers in the network—including those that peer directly with neighboring autonomous systems (ASes) and those that are internal to the network. For the purposes of this study, data from the border routers alone suffices, as we are not concerned with internal utilization but rather only with utilization that may occur at the edge of the network.

3.5 Public Use of Data

Although the ISPs make the above data available to us, much of it is bound by non-disclosure agreements, due to the proprietary nature of interconnections. As mentioned, both the existence and nature of any particular interconnection is considered proprietary, as are the decisions about where any particular ISP has a point of presence and where any ISP tends to route different types of traffic. These details reflect both business strategy (e.g., provisioning), business relationships, the source and destination of traffic demands, and decisions about network management and operations.

Due to the sensitive nature of much of this information, the public dataset reports utilization that is aggregated by region and across at least three participating ISPs. The publicly released visualizations and underlying data include statistics about link aggregation groups, as we describe below. The public dataset reports the following aggregate utilization statistics:

- For each ISP, across all interconnect links to all neighbor networks.
- For each region, across all ISPs
- Across all interconnects and all regions.
- Across all links, both per-link and weighted by overall aggregate capacity.

The public visualizations and underlying data, which we plan to update monthly, reveal the following aggregate statistics and information:

- Peak utilization at an interconnect, relative to total capacity, aggregated across ISPs in that region.
- The fraction of interconnects that experience a percentage maximum utilization, for the 95th percentile of five-minute intervals.
- Utilization by region over time, for all regions with at least three operators.

This level of aggregation does not make it possible to assess the overall utilization of a particular ISP's connections to a neighboring ISP, and analysis of the public data cannot show that there are no highly utilized links. Demonstrating this result would require analysis of much more fine-grained data. Nonetheless, the public aggregate statistics do provide evidence that each participating ISP and region has spare capacity at respective interconnection points, as we discuss in more detail in the coming sections.

4 Limitations

In this section, we briefly discuss the applicability of the measurement techniques for various purposes. We survey the types of conclusions can and cannot be drawn from sampled and aggregated IPFIX measurements.

4.1 Limitations of Flow Statistics

Traffic flow statistics are commonly used to estimate link utilization for purposes of capacity estimation and planning, and for traffic engineering purposes. Large transit provider networks commonly deploy IPFIX across all of the routers in their networks to determine whether certain links are overutilized. As previously discussed, even sampled IPFIX records can be useful for determining *aggregate* link utilization. Nonetheless, sampled IPFIX records have certain limitations that make them inappropriate for certain types of analysis. While these additional features would undoubtedly shed more light on both congestion and application performance, the currently deployed technologies do not permit these types of analyses at the interconnection points. The rest of the section discusses various measurements that are not possible with the existing measurement approach.

Analysis of small flows. Due to the sampling rates of the measurements, performing any analysis that is specific to small flows or on the distribution of flows may not be possible. As previously discussed, this affects our ability to analyze statistics such as flow-size distribution but should not have any affect on our ability to estimate utilization.

Timing, loss, or quality of experience. Traffic flow statistics also do not capture timing effects or accurate statistics about packet loss, jitter, and so forth. Due to the lack of detailed information that aggregate traffic flow statistics provide, inferring properties that directly relate to user quality

of experience will be difficult with the existing dataset, given only aggregate volumes.

Information about specific applications. Additionally, assessing the performance of any given application will be difficult with the given dataset, since the traffic flow statistics do not have any application-specific identifiers or other information that would help associate the traffic with a particular end-user application. Traffic flow statistics are gathered on flows, which correspond to source and destination IP address and port, as well as protocol type. Yet, this information alone does not provide enough information to infer the application type of a flow, since applications often share the same destination port (in particular, many applications, including streaming video and the web, use destination port 80). Associating performance with a particular application will require more precise statistics, including possibly information from the application layer or associated domain name system (DNS) lookup information.

Statistics on short timescales. The traffic statistics represent aggregates across a group of links and across time (typically the duration of a particular flow). As a result, the statistics cannot capture fluctuations that may occur on short timescales; for example, a traffic flow may send a high volume of traffic over a relatively short interval and low volume for the remainder of the flow duration. Utilization may spike on short timescales, and such spikes would not be reflected in aggregate traffic flow statistics, since one can really only compute an average utilization over the duration of time that the flow record reflects. Because the aggregate statistics reflect only average utilization across the duration of a flow, the statistics will reflect these short-term fluctuations.

4.2 Limitations Due to Aggregation

Even in the private dataset, statistics are reported in aggregate link groups. In this case, any fluctuations that occur on only a single link may not be reflected in the aggregate statistics. We previously described assumptions about traffic load balance that suggest that drawing conclusions based on average utilization per link is reasonable. Additionally, short-term periods of high utilization across the entire link group may not be evident in the data, because utilization is reported on five-minute averages.

In the public dataset, it is possible to assess the overall utilization in some region across all ISPs and partner networks, but not for any individual interconnection point in a region. Similarly, it is possible to see the aggregate utilization for any of the participating ISPs, but not for a specific region or neighbor ISP. As a result, the aggregates make it difficult to drill down into the utilization between any pair of networks, either as a whole or for any particular region. As a result, it is not possible to conclude that no interconnection links experience high utilization. Because the public data shows utilization across each ISP, we can conclude that each ISP has spare capacity—although we cannot conclude that it has spare capacity in each region or on any individual port.

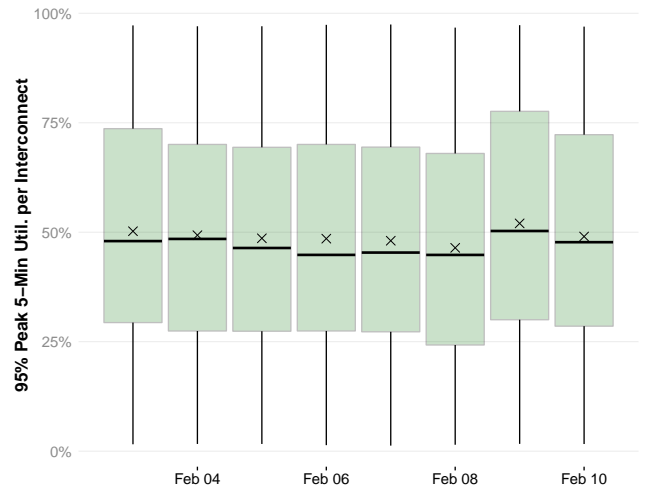


Figure 2: Utilization of each interconnect group over one week in February 2016, normalized by capacity of the interconnects.

To mitigate concerns that result from this level of aggregation, the public dataset also includes 95th percentile peak utilizations for all links in the dataset, which demonstrates that most of the links in the dataset as a whole experience low utilization, and that much of the aggregate capacity remains under-utilized even at peak. We also show the aggregate utilization for all ISPs in each region, which allows us to demonstrate that each region has spare capacity; because this statistic is aggregated across ISP, we cannot conclude that a particular ISP has spare capacity in a region—especially to a specific neighbor. Yet, our ability to show spare capacity in aggregate increases confidence that this capacity exists, since most ISPs have significant spare capacity at peak utilization, and most links in the dataset have spare capacity at peak, as well.

5 Utilization at Interconnection Points

In this section, we present preliminary analysis of the utilization measurements from the interconnect groups from the participating ISPs. We survey the capacity and utilization of each interconnect group both overall and by region. Over the past five months, aggregate interconnect capacity has been roughly 50% utilized at peak, and has grown consistently by about 3% monthly, or about 14% over the five-month period. In the rest of this section, we explore the utilization characteristics of these links.

5.1 Aggregate Utilization

Figure 2 shows the interconnect utilization over time, for a one-week period in February 2016 across all regions. Each data point in the timeseries shows a box plot illustrating the distribution of utilization across interconnect points. The median utilization across interconnects is consistently below 50%, even at peak times, and many of the links have significantly less utilization. Less than 4% of the link aggregation groups exceed 95% utilization in any five-minute interval,

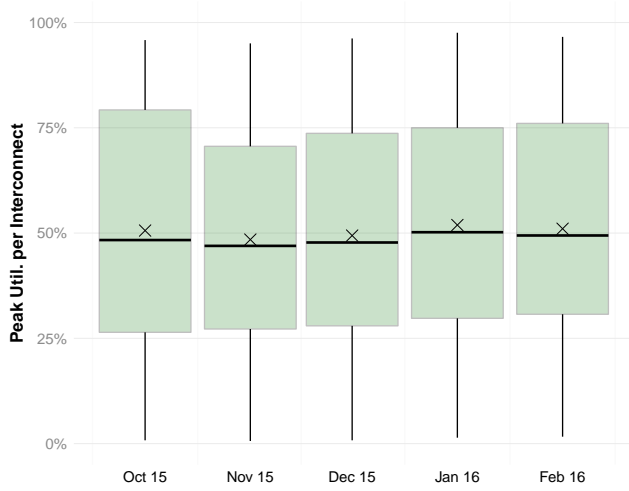
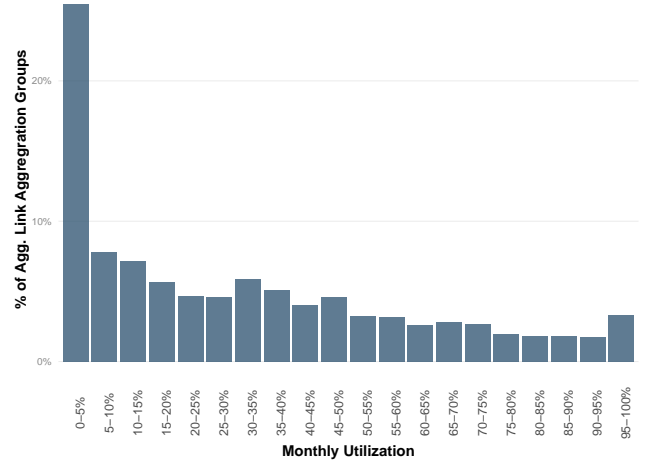


Figure 3: Per-month utilization of all participating interconnects.



(a) Weighted by links.

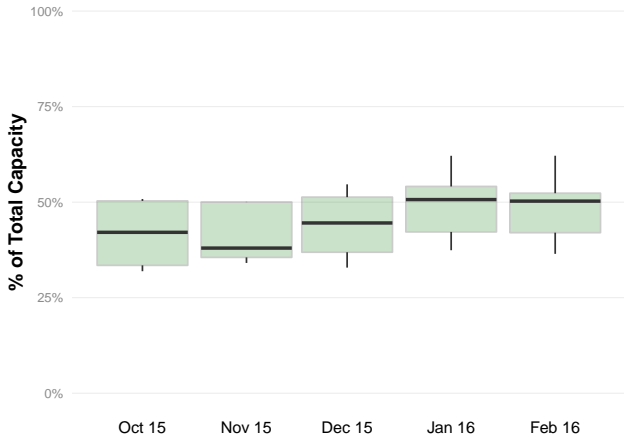
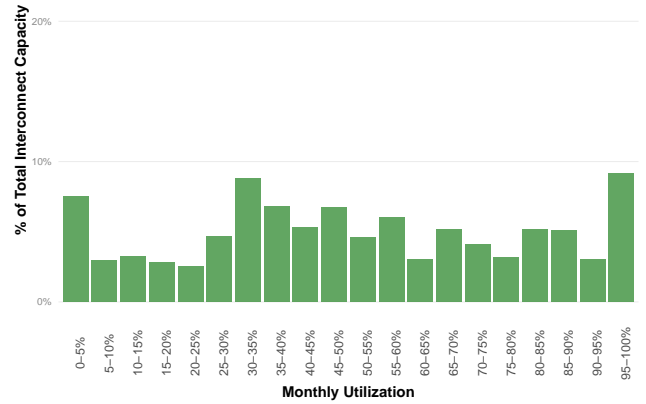


Figure 4: Distribution of 95th percentile peak ingress utilization across all ISPs, with all ISPs equally weighted.



(b) Weighted by capacity.

and the vast majority of the link aggregation groups see much less utilization, even at peak times. In the next section, we explore these trends for individual regions.

Recall that, due to aggregation, we cannot determine whether a utilization of, say, 75% indicates that there are no links in the aggregation group running at full utilization. What we *can* conclude, however, is that there *exist* links in the aggregation group with sufficient spare capacity, and thus that the sender of traffic has the ability to send traffic flows over links at the interconnect that have spare capacity, even as other links may have high utilization.

Figure 3 shows the distribution of interconnect capacity by peak utilization over all five-minute intervals across link aggregation groups for each month, for all aggregation groups. The box plot shows the inter-quartile ranges, the horizontal line shows the median utilization, and the whiskers show the 5th and 95th percentiles.

Figure 5: The fraction of interconnect capacity, weighted by the number of links and the amount of total capacity, respectively, whose 95th percentile utilization in a month experienced a particular utilization level. The figure shows statistics for February 2016.

5.2 Utilization by ISPs and Links

Figure 4 shows the distribution of 95th percentile peak ingress utilization across all ISPs, normalized by capacity. The median ISP in the group of seven ISPs experienced a 95th percentile peak ingress utilization that was less typically around 50% of the available capacity. This plot shows that each ISP has significant spare capacity across its set of links and regions. This figure does *not* indicate whether a particular ISP is experiencing congestion in a particular region, to a particular partner network, or across a set of links.

Unfortunately, we cannot show utilization for specific links or neighbor ISPs, because the existence of a particular business relationship or even the existence of a specific link in a region may reveal proprietary information. We can, however, explore the utilization across the aggregate of all links, which

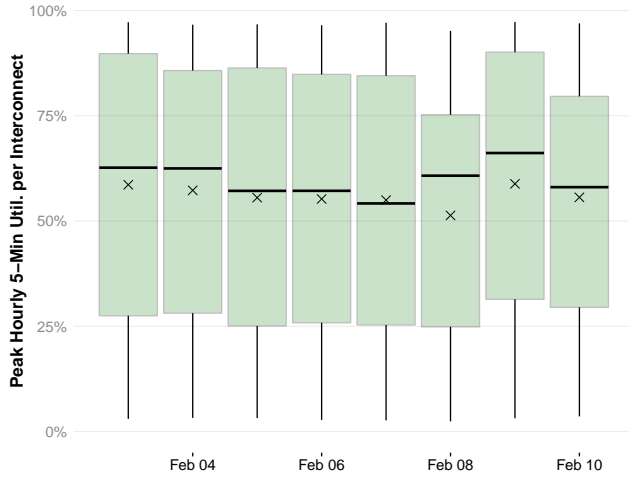
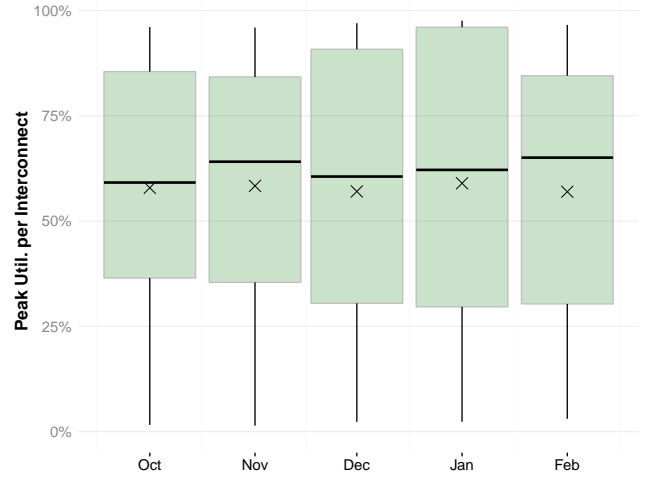


Figure 6: Utilization of each interconnect group over one week in February 2016 across interconnects in Chicago, IL, normalized by capacity of the interconnects.

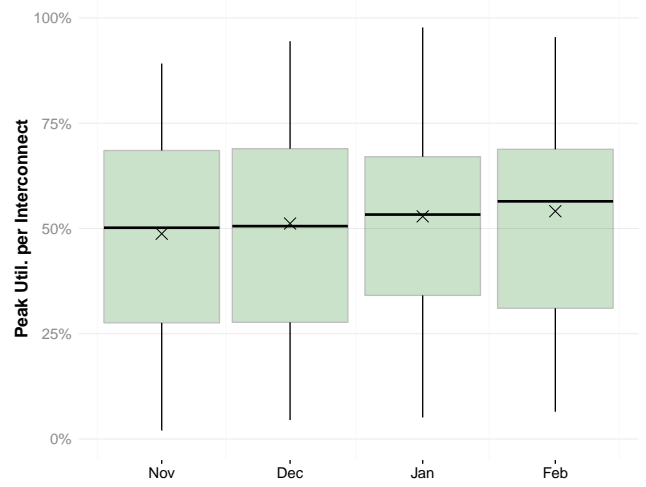
also shows the existence spare capacity. Specifically, we can show how the characterization of peak utilization across *all* links, weighted both by links and by overall capacity, as shown in Figure 5. Figure 5a shows the distribution of 95th percentile peak monthly utilization across all links, for all participating ISPs. This figure shows that more than 25% of all links are significantly underutilized, and that less than 10% of all links experience a 95th percentile peak utilization that exceeds 90%.

In Figure 5a all links are weighted equally, which does not reveal whether there exists significant excess *capacity*, only whether there exist links that have spare capacity. Exploring utilization where the set of links is weighted by their capacity reveals more information. Figure 5b shows the same distribution, where links are weighted by overall capacity. The figure shows that links that account for about 10% of overall interconnect capacity experienced a 95th percentile peak utilization that exceeded 95%. Most of the capacity experienced significantly less utilization.

Together, these plots present a picture of the existence of spare utilization across many of the interconnects that also account for much of the capacity at interconnects. Certain answers remain obscured, such as whether a particular partner network is experiencing persistent congestion, or whether particular types of connections (e.g., paid peering) are experiencing more or less congestion. Yet, the figures above do reveal a general picture of (1) all ISPs having spare capacity in aggregate across interconnects; (2) most interconnect capacity in aggregate showing spare capacity at peak. Both of these conclusions reveal significantly more than we have known to date; as this project matures and we receive further feedback, we hope to make additional views of the data available that also respect the private and proprietary information of each ISP.



(a) Chicago.



(b) San Jose.

Figure 7: Per-month utilization of participating interconnects in two example regions.

5.3 Utilization by Region

We also explored how utilization evolves over time in individual regions, to determine whether utilization patterns at interconnects in specific regions agreed with the overall general trends that we observed in Figure 2. Figure 6 shows how utilization evolves over time across interconnects in Chicago; the trends in this specific region are similar to the overall trends. The trends are similar in other cities with busy interconnects; interconnects in Atlanta show similar distributions.

Washington, New York, Dallas, and Los Angeles exhibit similar utilization trends, although utilization exceeded 90% less frequently than it did in Chicago and Atlanta, the two busiest regions. Figure 7 shows the distribution of interconnect capacity across link aggregation groups over all five-minute intervals. Figure 7a shows this distribution for a busier Interconnect (Chicago); Figure 7b shows the same distribution for San Jose. Interconnections in San Jose tend to have lower

median utilizations across link groups, although the highest loaded link groups at peak time also follow similar trends as those that we observed in Chicago.

6 Conclusion and Next Steps

Public discourse surrounding interconnection and congestion begs the need for better visibility into congestion at interconnection points between ISPs and content providers. Furthermore, the increasing frequency of peering disputes begs the need for better information about congestion in general, and specifically about traffic utilization at interconnection. Unfortunately, the methods that exist for inferring these statistics from the edge using active probes are inconclusive—cannot accurately pinpoint congestion at interconnection, and in many cases they cannot disambiguate congestion that occurs on a forward path from congestion that occurs on a reverse path.

Ultimately, stronger conclusions require more direct measurements of utilization at the interconnection points themselves. The public data collected from ISP interconnection points makes it possible to establish that spare capacity exists at interconnection points in the aggregate, and that congestion that is observable at the edge may ultimately reflect the inefficient use of existing capacity. Until now, all of this information has been protected by non-disclosure agreements between ISPs. Yet, more informed debate requires better data. This paper presents a next step in that direction, based on data from interconnection points from seven major Internet service providers.

Our preliminary analysis tells a different story than previous direct measurement approaches have suggested. Specifically, evidence suggests that, capacity continues to be provisioned to meet growing demand and that spare capacity does exist at interconnection points, even though specific links may be experiencing high utilization. We do not speculate on the reasons behind these usage patterns, which ultimately derive from content (“edge”) providers’ decisions about where to direct traffic, but the patterns appear to show clear trends: there exists spare capacity at the interconnection points.

The need to assess metrics that directly affect user experience, such as application quality or the quality of user experience, will ultimately require a much richer dataset than that which is currently available. For example, more work is needed to understand how the utilization of a link ultimately affects a customer’s quality of experience for a given application. It may be possible, for example, that high utilization does not adversely affect customer quality of experience. Future work may include assessing the correlation between these network-level traffic statistics and the corresponding quality of experience for different types of applications.

Acknowledgments

We thank Steve Bauer, Jennifer Rexford, and Walter Willinger for their feedback on this paper. This work was made possible with support from CableLabs.

References

- [1] BISMark: Broadband Internet Service Benchmark. <http://projectbismark.net/>. (Cited on page 2.)
- [2] Cooperative Association for Internet Data Analysis (CAIDA). <https://www.caida.org/>. (Cited on pages 3 and 4.)
- [3] R. Carlson. Network Diagnostic Tool. <http://e2epi.internet2.edu/ndt/>. (Cited on pages 1 and 2.)
- [4] B. Claise, B. Trammell, and P. Aitken. *Specification of the IP Flow Information Export (IPFIX) Protocol for the Exchange of Flow Information*. Internet Engineering Task Force, Sept. 2013. <https://datatracker.ietf.org/doc/rfc7011/>. (Cited on pages 2 and 4.)
- [5] D. Clark. Keynote: Internet measurement. <https://youtu.be/2GE8qSh0oJ4?t=6m53s>, Feb. 2016. Comments on interconnection congestion start at 6:53. (Cited on page 1.)
- [6] M. J. Coates and R. D. Nowak. Network tomography for internal delay estimation. In *Acoustics, Speech, and Signal Processing, 2001. Proceedings (ICASSP'01). 2001 IEEE International Conference on*, volume 6, pages 3409–3412. IEEE, 2001. (Cited on pages 1 and 3.)
- [7] DeepField Networks. <https://www.deepfield.com/>. (Cited on page 2.)
- [8] N. Feamster. Where is Internet Congestion Occurring?, Apr. 2015. <https://freedom-to-tinker.com/blog/feamster/where-is-internet-congestion-occurring/>. (Cited on page 3.)
- [9] M. Jeffreys. Compliance filing 14-90. Technical report, Federal Communications Commission, Dec. 2015. <http://apps.fcc.gov/ecfs/document/view?id=60001396715>. (Cited on page 4.)
- [10] H. Kilmer. M-Labs data and Cogent DSCP markings, Nov. 2014. <https://goo.gl/9m8Kk5>. (Cited on page 3.)
- [11] Measuring Broadband America. <https://www.fcc.gov/general/measuring-broadband-america>. Federal Communications Commission. (Cited on page 3.)
- [12] Measurement Lab. <http://measurementlab.net>. (Cited on pages 1 and 2.)
- [13] ISP Interconnection and its Impact on Consumer Internet Performance. Technical report, Measurement Lab, Oct. 2014. http://www.measurementlab.net/static/observatory/M-Lab_Interconnection_Study_US.pdf. (Cited on page 3.)
- [14] S. Sundaresan, W. de Donato, N. Feamster, R. Teixeira, S. Crawford, and A. Pescapè. Broadband internet performance: A view from the gateway. Toronto, Ontario, Canada, Aug. 2011. (Cited on page 2.)