Policy challenges in mapping Internet interdomain congestion

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Abstract

Interconnection links connecting access providers to their peers, transit providers and major content providers are a potential point of discriminatory treatment and impairment of user experience. In the U.S., the FCC has asserted regulatory authority over those links, although they have acknowledged they lack sufficient expertise to develop appropriate regulations thus far. Without a basis of knowledge that relates measurement to justified inferences about actual impairment, different actors can put forward opportunistic interpretations of data to support their points of view.

We introduce a topology-aware model of interconnection, to add clarity to a recent proliferation of data and claims, and to elucidate our own beliefs about how to measure interconnection links of access providers, and how policymakers should interpret the results. We use six case studies that span data sets offered by access providers, edge providers, academic researchers, and one mandated by the FCC. This last example reflects our recent experience as the Independent Measurement Experts that worked with the FCC and AT&T in establishing a measurement methodology for reporting on the state of AT&T's interconnection links. These case studies show how our conceptual model can guide a critical analysis of what is or should be measured and reported, and how to soundly interpret these measurements. We conclude with insights gained in the process of defining the AT&T/DirecTV methodology and in the process of defining and applying our conceptual model.

Contents

1 Introduction

The best publicly available data about the global interconnection system that carries most of the world's communications traffic is incomplete and of unknown accuracy. There is no map of physical link locations, capacity, utilization, or interconnection arrangements. Recent public policy challenges have triggered the need for more transparency into the state of Internet interconnection. In particular, as a result of U.S. telecommunications policy over the last twenty years, the Internet industry structure has evolved toward a state where carriage (infrastructure) networks increasingly own content, and monetize transmission of that content on their networks, creating naturally misaligned incentives regarding interconnection with other content providers. Specifically, as stated in the FCC's 2015 Open Internet Order [1] *"broadband Internet access providers have the ability to use terms of interconnection to disadvantage edge providers and that consumers' ability to respond to unjust or unreasonable broadband provider practices are limited by switching costs."*

Although regulators have gained some experience measuring broadband Internet access link bandwidths [2, 3, 4], and accommodated extensive debate to inform rule-making on what constitutes reasonable network management of these links [5, 1], they (at least in the U.S.) have no experience with measurement of Internet interconnections nor in analyzing its role in user quality of experience. And yet, links connecting access providers to their peers, transit providers and major content providers are a potential point of discriminatory treatment and impairment of user experience. In the U.S., the FCC has asserted regulatory authority over those links, although they have acknowledged they lack sufficient expertise to develop appropriate regulations thus far.[1] Without a basis of knowledge that relates measurement to justified inferences about actual impairment, different actors can put forward opportunistic interpretations of data to support their points of view. The recent proliferation of performance-related data and claims leaves policymakers, researchers, and the general public with the tremendous of challenge of interpreting it all.

In this context, the FCC has turned toward the research community for help with two measurement challenges: measurement of interconnection links; and measurement of overall quality of experience for users accessing specific services. The FCC has expressed interest in augmenting its Measuring Broadband America (MBA) program with both types of measurements, and is evaluating measurement methodologies for users accessing specific services. Unfortunately, this sort of measurement has not been a high priority for the academic research community, nor its funding agencies. There is no known way for a third party to remotely measure directly basic parameters of an interconnection link, e.g., capacity and utilization, and commercial concerns regarding sharing data or access to instrumentation generally prevent researchers from being able to validate measurements or methods. Thus, like the FCC, the research community cannot bring to this discussion much experience with this sort of measurement. Absent a regulatory requirement for mandatory sharing of such data, the research community is not in a position to offer concrete advice to regulators. But researchers can bring objectivity, insights into how to think about the problem, and suggestions for how to start gathering data to inform regulatory trajectories.

In this paper we take up this challenge, in four parts. First we provide background on the range of methods of harmful discrimination against interconnecting parties (§2) and the complexity of trying to measure it (§3). We then introduce a new topology-aware model (§4) that captures

[1] *Quoting from the 2016 ruling, "As a result, the Commission concluded that it could regulate interconnection arrangements under Title II as a component of broadband service. It refrained, however, from applying the General Conduct Rule or any of the bright-line rules to interconnection arrangements because, given that it lack[ed] [a] background in practices addressing Internet traffic exchange, it would be premature to adopt prescriptive rules to address any problems that have arisen or may arise. Rather, it explained that interconnection disputes would be evaluated on a case-by-case basis under sections 201, 202, and 208 of the Communications Act."* [6, pg 52, citations omitted].

some of this complexity by recognizing hierarchical structure in interconnection architectures. We explain in general terms how the model enables interpretation of measurement of different aggregation granularities (§5), i.e., how pervasive congestion is across a set of possible paths between a given content source and destination pair: is evidence of congestion observed only on a single link, or an aggregate set of links, in a single metropolitan region, or more broadly? We do not intend this model to be predictive, i.e., to allow forecasting of congestion or any other network dynamics, but rather as a *conceptual model*, to add clarity to a recent proliferation of data and claims, and to elucidate our own conclusions about how to define and measure interconnection-related performance problems, and the complexity of interpretation induced by different choices.

To concretely demonstrate the utility of our conceptual model, we apply it to the examination of six measurement projects (§6) that different stakeholders have propounded to illuminate their view of the landscape of interconnection performance. These projects span data sets offered by access providers, edge providers, academic researchers, and mandated by the FCC. In the final case study, we share some of our experience as the Independent Measurement Expert (IME) that worked with the FCC and AT&T in establishing a measurement methodology for reporting on the state of AT&T's interconnection links. Finally, we offer some conclusions, implications, and recommendations for researchers and policymakers. The key contributions of this paper are:

1. We construct a topology-aware model of interconnection that distinguishes itself from existing models by capturing nested aggregations of links between access providers and their interconnecting parties.

2. We discuss the tradeoffs and limitations of examining data at different aggregation granularities, and how to use them to evaluate the relative significance of performance impairment.

3. We demonstrate the utility of our conceptual model by applying it to six case studies, which show how it can guide informed decisions regarding interpreting, or mandating, measurements intended to reveal harmful (impairment-inducing) congestion at interconnection links.

2 Approaches to interconnection discrimination, and policy responses

Network operators could impose several potentially harmful forms of discrimination in the context of interconnection; we descrive five sorts of discrimination in this section. First, *differential treatment of packets* could occur at interconnection links. With today's typical Internet usage, content generally flows *toward* the access provider, in which case discrimination across the link would have to occur not on the access provider's router but on the upstream router operated by interconnecting party. Once traffic is on the access provider's side of the interconnection link, from a regulatory perspective it would count as discrimination within the access ISP, subject to existing regulation about reasonable network management.[2]

A second form of discrimination uses *routing policy*: an access provider could engineer its network so traffic from different interconnecting parties traverses different links within the access ISP. Underprovisioned links afflict only the interconnecting parties using such links, and any resulting impairment of their traffic requires no selective treatment of packets within any router. However,

[2]An episode of traffic differentiation outside the access provider occurred in 2014 when Cogent, a transit provider for Netflix among others, began to mark packets using the IP Type of Service (ToS) bits to classify their customers' traffic into *wholesale* and *retail* categories, and prioritized traffic belonging to retail customers [7, see quote embedded in group discussion]. In this case, an upstream (i.e., not broadband access) provider materially altered the the performance of broadband users' traffic by employing traffic differentiation techniques.

an interconnecting party can detect this sort of congestion, and has a strong incentive (especially if it is paying for interconnection) to do so and complain when it occurs.

A third and non-technical approach is *price discrimination* across direct interconnection. Content from different directly connected content providers travels across different physical links, and the contracts for those links reflect terms that each pair of interconnecting parties may craft separately, perhaps with different costs for equal capacity. Since these agreements are almost always covered by non-disclosure agreements, there is no way for a given content provider (or a third party observer) to tell whether two content providers seeking direct interconnection are receiving equivalent treatment. Since agreements may include complex business terms, including commitments to rates of capacity expansion over time or restrictions on routing, it might be difficult to compare treatments of different interconnecting parties, even if one could see the contracts.

Fourth, another non-technical approach to discrimination is for an access provider to *limit the number of interconnections* with one content provider more than another. Fewer points of connection might disadvantage the content provider, increasing latency for traffic that flowed longer distances across the access ISP. But this approach would also increase transit costs internal to the access ISP, so it is often in the best interest of both parties to interconnect at many points.

Finally, and the approach that has been the subject of media and policy attention in recent years, a provider could simply *fail to upgrade capacity* of an interconnection when evidence of congestion manifests. Thus far, the highest profile dispute about interconnection between access and content providers involved Netflix and some of its transit providers claiming that access providers were exercising this form of discrimination. When Netflix started delivering content streamed over the Internet in 2007, it first used its own servers in five locations in the US. As traffic grew, Netflix began enlisting third-party CDNs such as Akamai and Limelight in 2008. In 2012, Netflix began moving away from third-party CDNs to using transit providers, and simultaneously started installing its own content servers (Netflix OpenConnect) across the Internet to interconnect directly with major access ISPs [8]. Sometimes these negotiations for direct interconnection became contentious, with Netflix arguing that these arrangement were similar to traditional peering connections and should be settlement-free, while major access ISPs asserted that they were commercial arrangements that required payment [9, 10, 11, 12]. Before successfully negotiating direct interconnection to access ISPs, Netflix used its existing connections (where it was a customer) to its Tier 1 transit providers to transmit traffic to Netflix customers on access ISPs. Those links lacked sufficient capacity to keep up with the growth in Netflix traffic, leading to massive congestion on the Tier 1 interconnection links, which impaired both Netflix traffic and any other traffic unfortunate enough to be passing over the same interconnections [13]. In the U.S., the FCC had until this point avoided intervening in negotiation of commercial terms between large Internet players, but in this case the FCC pressured the parties to resolve these conflicts quickly, to relieve ongoing impairments. In other countries, these disputes ended up in court: in France the competition court ruled with respect to a Tier 1 provider (Cogent) delivering large volumes of content into France Telecom (FT) that FT had the right to demand payment from Cogent [14].

The consumer complaints and media coverage about these interconnection disputes brought attention to the power of access providers to impose terms for interconnection, and on the important role that interconnection plays in the stability and function of the Internet. In the 2015 Open Internet Order, the FCC pivoted from their 2010 position to exclude interconnection from their purview, and explicitly asserted that their authority extends to the regulation of interconnection with access providers [1, para 295].[3] They have not yet imposed any overall regulations on Inter-

[3] As the 2015 order notes [1, para 294] *In the 2010 Open Internet Order, the Commission applied its open Internet rules "only as far as the limits of a broadband provider's control over the transmission of data to or from its broadband customers," and*

net interconnection, but they have imposed regulatory requirements as conditions on two large mergers involving access providers.

The first such merger agreement was between AT&T and DirectTV in 2015. Responding to specific concerns in the merger review process that interconnection links could be a locus of unreasonable discrimination, the final agreement imposed a requirement on AT&T to report to the FCC the contractual terms of their interconnections with major peering and paid peering parters, as well as performance parameters of these interconnections (§6.6).[4] Similar concerns arose during the 2016 Time-Warner/Charter merger, but instead of imposing measurement requirements, they imposed interconnection traffic volume reporting requirements, as well as constraints on the business relationships that the combined entity could negotiate with interconnecting parties.[5]

3 The complexity of interconnection measurement

Measurement of Internet interconnection performance is technically complex, for many reasons identified in the networking literature [13]. In this work we focus on three reasons with current policy implications. First, understanding performance of an interconnection link requires measuring several parameters, e.g., utilization, loss rates and variation in latency. Operators that control interconnection links could measure such parameters for those links, although accurate assessment of these parameters may require cooperation of the operator at the other end of the link (§6.6), and we are not aware of any commercial operators voluntarily cooperating to do so. Second, modern interconnection practices render it potentially necessary to measure multiple links, sometimes in different cities, in an integrated manner to assess overall performance degradation. Third, neither regulators nor researchers clearly understand how to relate variation in measured performance to impairment of the user's quality of experience (§5.3).[6]

The relationship between congestion and impairment is complex. Understanding a little about the dynamics of the predominant Internet transport protocol, TCP, provides some insight into the complexity. When excess traffic arrives at the ingress to a link, a queue of packets forms, and the holding time of the packets in this queue adds to the delay across the link. This variation, usually

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excluded the exchange of traffic between networks from the scope of the rules. In the 2014 Open Internet NPRM, the Commission tentatively concluded that it should maintain this approach, but explicitly sought comment on suggestions that the Commission should expand the scope of the open Internet rules to cover issues related to Internet traffic exchange. (See also footnote 1.)

[4]The FCC is using this occasion as an opportunity to educate itself and to gain experience about what sort of data should actually be gathered, and how to interpret it.

[5]The Time-Warner/Charter merger agreement includes the following reporting requirement [15, Appendix B.I]:

> *Information for each Interconnect Exchange Point, which shall include, as of the date that is the last day of the calendar quarter preceding the Report:*
>
> 1. *Each Interconnection Party interconnected with the Company at that Interconnect Exchange Point;*
> 2. *For each Interconnection Party, the aggregate link capacity between the Company and each Interconnection Party at that Interconnect Exchange Point;*
> 3. *For each Interconnection Party, traffic exchange, in each direction, as measured by the 95th percentile method;*
> 4. *For each port through which traffic is exchanged with an Interconnection Party, the percentage time within the reporting period that the port was over 75% capacity in the dominant direction.*

The agreement also requires the new entity to provide settlement-free peering for 7 years, although it lays out a complex set of obligations on the parties in order to obtain these settlement-free arrangements, including the number of peering locations, rates of growth in traffic, and restrictions on routing and delivery of non-customer traffic. We revisit this issue in §4.2.

[6]*Quality of experience*, or QoE, refers to a subjective characterization by users of their level of satisfaction using a particular application at a given moment. This term contrasts with Quality of Service (QoS) metrics such as throughput.

called *jitter*, is a signal of potential congestion, and may impair latency-sensitive applications such as real-time communications and multi-player games. If the queue becomes full and excess traffic continues to arrive, the router will drop some arriving traffic. Dropped packets can impair service, but routers drop packets for other reasons, and applications on the sending end will typically detect and retransmit dropped packets. More significantly, TCP (which most Internet applications use as a transport protocol) treats a lost packet as a signal of congestion and reduces the sending rate. Dropped packets are thus a necessary part of the transport control mechanism that regulates the sending rate of traffic sources to match the capacity of the link. Reductions in throughput can be a severe impairment to applications such as streaming content, but of almost no concern to a delay-tolerant application such as email. In general, while dropped packets at the ingress to a link may signal congestion, there is no way to measure the link to determine how much excess traffic an endpoint could send if the link had more capacity, since the content sources control the sending rate, not the link ingress.

In addition to normal TCP congestion control behavior, applications may use even more sophisticated ways to adapt to an indication of a congested link. Large CDNs or content networks typically interconnect to broadband access networks at multiple points, and can engineer server placement and routing policy to avoid congested links. Alternatively, content providers may adapt to a signal of congestion along a path to a recipient by degrading the content encoding to fit into a lower data rate, e.g, from HD to SD video encoding. This adaptation is impossible to detect with active measurement.[7] These factors prevent the use of measurements of individual links to prove impairment of the user experience.

4 Topology-aware hierarchical model of rich interconnection

Researchers have explored increasingly refined economic models of Internet interconnection, including modeling paid peering [16, 17, 18, 19], game-theoretic justifications of settlement-free peering [20, 21], the business effects of transit versus peering relationships [22, 23], transit pricing and provisioning of service tiers [24, 25, 26, 27], simple pricing schemes that approximate complex revenue-maximizing pricing [28], network formation models [29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39], and more generally the evolution of the Internet from a game theoretic perspective [40, 41]. We offer a new conceptual model of interconnection (illustrated in Figure 1 and 2), which captures hierarchical aggregations of links between an access provider and their interconnecting parties. These nested aggregation levels are implicit in many measurements and often not explained in published assertions and data sets. We use this model to explicate two other important factors in understanding interconnection as it relates to performance impairments. First, interconnecting parties may take direct or indirect paths to reach access providers; indirect paths go through at least one peer or transit provider before reaching the access provider. Second, either party could impose performance bottlenecks on the other at some other location than the interconnection link itself, detection of which would require measurements of the overall path, or at least the right path segments. We first define the five levels of aggregation, then differentiate among direct paths, indirect paths, and potential paths between interconnecting parties, and finally explain the complementary roles of end-to-end and link performance measurements.

[7]One could use passive monitoring at the right link to collect evidence of adaptive coding, or try to directly assesses the impairment of the quality of experience assuming a user can distinguish encoding qualities.

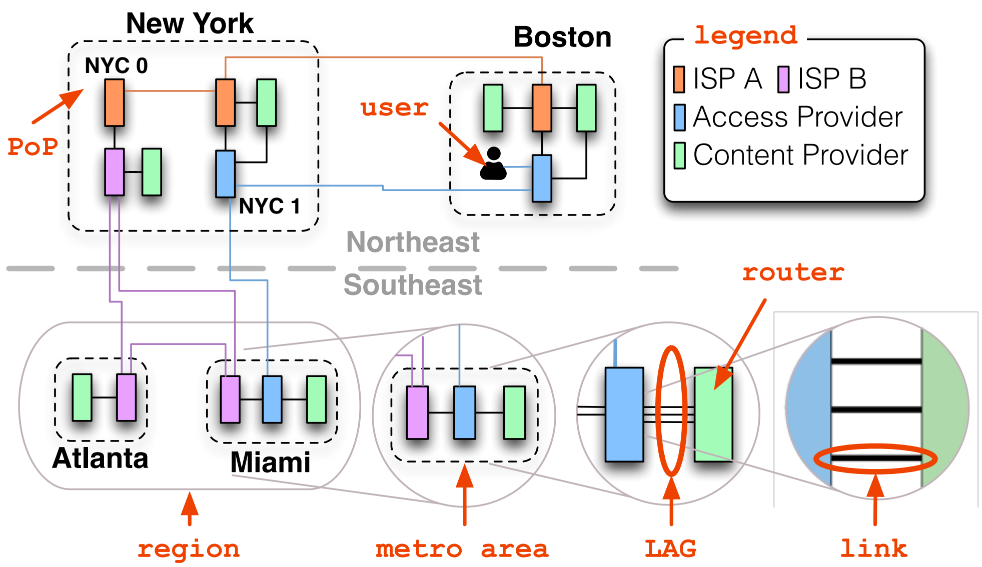

Figure 1: Hierarchical aggregations of links between access provider and interconnecting parties.

4.1 Levels of aggregation in interconnection relationships

Figure 1 illustrates the five aggregation granularities of our model:

1. **Individual link**: connection between two physical ports, either directly connected or through a switch. Individual links today are often one (1GB) or ten (10GB) gigabit connections.

2. **Link aggregation group (LAG)**: combination of physical ports into a more reliable and higher bandwidth connection between two parties, with a single router balancing traffic load across all links in a LAG. A LAG is is often the lowest aggregation that network operators consider, as traffic management functionality on modern routers and switches renders a LAG group essentially indistinguishable from a single link of aggregate capacity. More important from a measurement perspective, aggregate performance of the LAG is generally representative of performance over the individual links in the group [42]. In 2016, LAGs of large providers often consist of multiple 10GB links. Multi-chassis LAGs implement node-level redundancy over a single logical link level connection between two points.

3. **Metro area group**: aggregate of all link and LAG interconnections between two parties in a metro area. In contrast to individual links in a LAG, different LAGs connecting two parties in a metro area can have different traffic characteristics. Traffic is often not load-balanced equally across all interconnections in a metro area, so summary statistics about a metro area may not be representative of performance of all individual interconnections that compose the metro area group. Traffic flow across metro areas reflects routing policy as well as application and service considerations such as which cache serves a particular request. A LAG is part of a metro area if one end of the link exists in that metro area.[8]

4. **Region group**: aggregate of all LAGs in multiple metro areas with geographic proximity between two parties, e.g., Boston and NYC in a Northeast region. This granularity matters because interconnection LAGs in one metro area can potentially substitute for those in a

[8]Normally, both ends of large-volume interconnection LAGs are in one location.

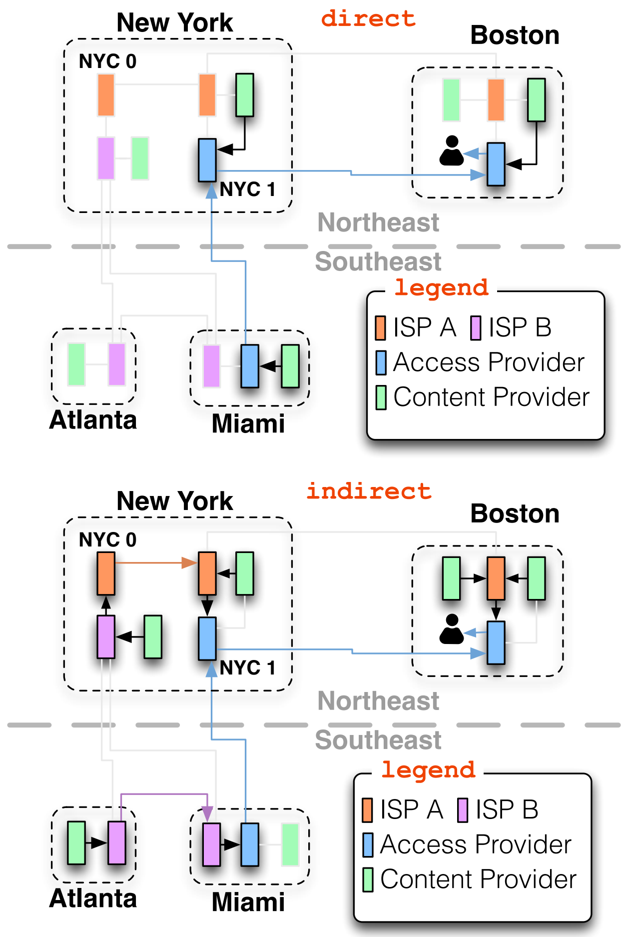

Figure 2: Direct and indirect paths between interconnecting parties (§4.2)

nearby metro area For example, if LAGs in Boston are filled to capacity but available capacity exists in NYC, it may not be necessary to augment interconnection capacity in Boston. However, a path from the alternative metro area increases latency, and an increased hop count increases the potential that a problem will occur between user and server. The notion of *substitutability* is essential to reasoning about aggregation from a measurement perspective (§5.1).

5. **Provider-wide**: aggregate of all direct LAGs between two parties. This includes LAGs in potentially diverse geographic locations e.g. Boston, Chicago and San Diego.

4.2 Direct, indirect, and potential connections

In addition to capturing structure in the set of interconnection *links* between two organizations, our model recognizes structure in the set of *paths* between two organizations. Interconnecting parties often have both direct and indirect paths to each other. Figure 2(top) depicts a party directly connecting to an access provider, but (bottom) with alternative indirect paths through other networks to that access provider. These alternative paths might be through a transit network that connects to both the content and access providers, or through a CDN like Akamai. The diverse set of paths connecting two parties may have different performance and economic characteristics. Although end users do not care about what path traffic takes unless it impacts their perceived performance, it can make a huge economic difference to the interconnecting parties.

In addition to direct and indirect paths utilized between two networks, other *potential* indirect paths may exist – paths that are potentially available from a business and routing perspective, but not actively used by default. A nuance of defining this superset of potential paths is knowing what action is necessary to make a path available for use, e.g., is it available on reasonable terms? In general a third party has no way of either identifying or measuring the set of potential paths.[9]

5 Applying the conceptual model to performance measurements

We apply our model to performance and impairment measurements at different aggregation granularities, which illustrates how each granularity reveals some characteristics of interconnection between two networks while obscuring others. We first consider what performance measures are relevant to assessing the quality of a link. We then discuss what performance measurements reveal at various granularities: LAG, metro, region or overall. We then consider additional measurements that can contribute to a more complete picture of performance: measures along a path segment that include several links (including end-to-end measurements), and higher-level measurements related to QoE. The background in this section will prepare us to use the model to critically examine six concrete case studies in §6, to gain insight into what each approach can and cannot say about interconnection.

5.1 Measurements of link utilization

We begin with a caveat that applies to all aggregation granularities. Measurement of *link utilization* is a common way for an operator to assess link (or LAG) behavior, but interpreting utilization measurements is not always straightforward. In the past, when ISPs typically interconnected with a single LAG and there were few options for alternative routes, a single LAG showing persistent plateaus of essentially full utilization (such as illustrated in Figure 3(a)) implied congestion: unserved demand between the two interconnecting parties, and impairment of flows crossing the LAG. Since Internet traffic typically shows a diurnal variation, a plateau suggested that the LAG was fully utilized well before (and after) its peak demand, and was thus underprovisioned, losing some packets, delaying others, and reducing throughput of flows. In other words, measurements from a single LAG served as strong evidence of significant impairment.

Today's sophisticated traffic engineering and interconnection practices prevent this conclusion without additional information, particularly in the case of aggregates between a content provider and an access provider. Business terms, loads on servers, and internal LAG capacities may induce an operator to fully load one LAG before starting to load another LAG beyond a certain level. Thus, if multiple LAGs in an aggregate (for example, a metro area) connect two providers, assessing congestion in that area requires consideration of all of them. If the edge provider can control

[9] Notably, in the Time Warner/Charter merger, the order's restriction on settlement-free peering obligations specifically takes into account the existence of indirect paths: *"In the event that the Interconnection Party begins conveying data to or from New Charter that was previously conveyed to or from New Charter by a third party, the parties shall account for this additional data transfer as the Interconnection Party's own for the purposes of measuring growth rates during subsequent measuring periods. The parties shall not count in the growth rate any portion of that incremental traffic that was previously being delivered to New Charter by third parties."* Furthermore, the interconnecting party cannot use the settlement-free interconnection to deliver traffic unless the source of the traffic is a *customer*, and the agreement explicitly excludes the option of a customer that purchased a path only to Charter. [15, para 456, Appendix B.III].

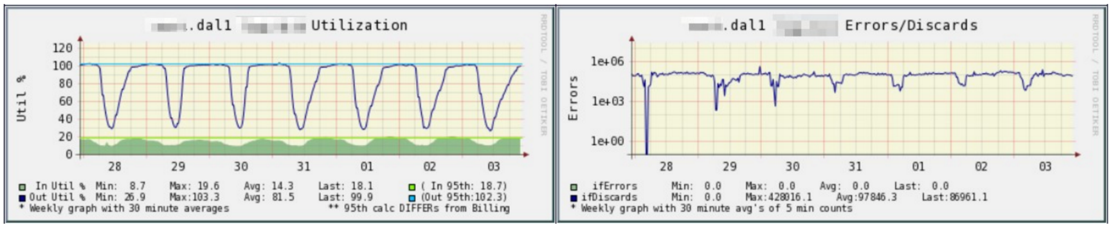

Figure 3: Utilization (left) and loss (right) plots for a Level3 100Gbps interconnect with an unnamed broadband access provider in Dallas for one week ending April 3 2014. The significant loss confirms that the high utilization plotted for the same interval induced impairment for consumers of traffic over this link [43].

content source selection, one cannot verify congestion without additional measurement, such as the packet loss ("discards") plotted on the right of Figure 3. The loss rate indicated is around a 1K packets/sec. Conservatively assuming packets lost are maximum sized 1500-byte packets this loss rate exceeds 1% for the 100 Gbps LAGs.[10]

1. **Link and LAG data.** Since the point of a LAG is for a router to manage a set of links as a single logical link, examining a LAG in aggregate will generally suffice for regulatory purposes. A failure of the link sharing mechanism is important to the interconnecting parties involved, but not more generally.

2. **Metro level data.** If multiple interconnection LAGs exist in a metro area, then the primary appropriate scope of analysis will be the metro area, so long as the LAGs are *substitutable*, i.e., have comparable performance characteristics. Determining substitutability may itself require measurement. Obtaining a full picture of a metro area may require looking at aggregated as well as individual LAG statistics. Measurements of only a subset of metro area links connecting two providers may mislead inferences about interconnection conditions.

3. **Regional data.** Similar to a metro area, a regional aggregate may be a useful level of measurement aggregation, but the region may comprise smaller aggregates (metro areas or isolated LAGs), and looking *only* at a region in the aggregate is sensible only if its components are *substitutable*. As a region gets larger, this presumption of substitutability is less plausible.[11] Whether the motivation for defining regional boundaries is technical, geographic, or regulatory scope, each presents tradeoffs. A technical justification for region size likely depends upon the nature of the traffic flows. i.e., what performance parameters flows require for acceptable QoE, with implications for substitutability of links. For highly latency-sensitive gaming content, a region of substitutable links would be smaller than for less latency-sensitive entertainment traffic, due to speed of light limitations on transmission speed. State-level aggregates have the benefit of corresponding to the jurisdiction of state level regulators. For regulators, region-wide persistent impairments probably merit regulatory interest. But fully loaded LAGs in one metro area in a region where other metro areas have unloaded LAGS to the same party may merit less concern, depending on substitutability of the LAGs. Unfortunately, regulators currently have no way to measure LAG substitutability.

[10]What is an acceptable loss rate at interconnection links is an important question, but not one we discuss here.

[11]If the elements that make up a region are *not* substitutable, one might question the utility of that region definition.

4. **Provider wide-data.** This level of aggregation considers all direct links between a provider and a single other partner network. Level3 posted the plots in Figure 3 in a 2014 essay that also claimed that similar patterns on most interconnect points between two ISPs had persisted for over a year [43]. In the context of our model, Level3 aggregated this measurement over a single LAG, but asserted that all other LAGS to the same interconnection partner were behaving similarly. A regulator would probably want to confirm that claim with data from other individual LAGS. Impairments might manifest as persistent problems across all paths connecting two networks or as patterns of path-specific periodic impairment. While the aggregate of "all direct interconnection LAGs" is easy to define it can be hard to measure for parties other than the two directly connecting networks, due to the challenge of discovering all LAGs in the set.

5.2 Measurements of path segments

Our model provides a structured way to describe and interpret interconnection measurements. To this point we have considered measures of an interconnection link or aggregate. However, sources of impairment between networks may not manifest as congestion on the interconnection link itself, but at some other bottleneck in the path. Measurement across a longer path segment, up to and including end-to-end measurements from sender to receiver, may be essential to assessing performance between two networks.

Measurement of a partial path segment (i.e., including several links) may be helpful in localizing impairment or excluding certain segments as a source of impairment, but it may not be possible to position test probes so as to measure the right partial path segments. More commonly reported are end-to-end measurements that record overall performance of a transfer, such as achieved throughput. How these reported results aggregate individual end-to-end measurements is crucial to making sound inferences from them.

The edge content provider is well-positioned to record end-to-end performance measures such as throughput of an individual flow transfer, but has flexibility in how to aggregate these measures for reporting purposes, both with respect to the source and the destination. A content provider would not normally report transfer speeds to a single destination, but to a set of destinations that correspond to one of our aggregates: a metro area, a region or overall for an access provider. They can also choose to report all transfers *from* a single content source (not typical), or for all sources in a region, or from all sources belonging to the content provider. An aggregated report of end-to-end throughput from any content source into a metro or region of an access ISP may or may not include both direct and indirect paths. The mix of traffic flowing on the direct and indirect paths may vary over time, likely a function of how much capacity is available on direct paths. Direct and indirect paths may have different performance characteristics, and aggregating them together may give an overall result that is not indicative of either class of path. Using our previous terminology, aggregated end-to-end measures may lump together paths that are not *substitutable*, and thus obscure important information about specific paths.

If the path segment is the entire end-to-end path, then another interpretation challenge is that it may reflect impairments in the user home or problems in the edge provider network or services, both of which vary over time, rather than anything related to the interconnection.

Finally, these measurements of actual user performance can only measure actively used paths. Access providers have argued that an analysis should consider both paths that edge providers are using to send traffic as well as alternative (potential) paths, since edge providers may choose not to avail themselves of all available paths. On the other hand, some unused alternative paths may not be practical for business or topology reasons, which third parties cannot determine on their own. Under these circumstances, regulators are justifiably skeptical of expansive claims that all interconnection links of an access provider represent an appropriate scope of analysis.

An alternative to end-to-end measurement by the content provider is measurement from the client end that attempts to estimate end-to-end performance. As an example, in late 2013, the FCC began to expand the range of measurements in their Measuring Broadband America program, to better understand the implications of end-to-end measurement. They are exploring how to test the performance of video services like YouTube and Netflix [44]. This effort expanded from a preliminary pilot phase in 2014 [45] to a wider roll out throughout 2015 [46], but is still remarkably tentative. The FCC notes that [47]: "the video streaming tests developed by SamKnows and the FCC in collaboration with content providers like Netflix, YouTube and Hulu are not intended to compare the performance of the carriers, but rather to develop a methodology study." To date, the FCC has released no results from this study, in part due to concerns from stakeholders about the accuracy of the methodology and results.[12] In July 2016, the FCC announced a new CDN test to measure the download throughput of small objects hosted on the following CDNs: Apple, Akamai, Microsoft, Google, Cloudflare, and Amazon. They have not released any results from this test either [49], due to similar concerns. The slow pace and lack of resolution in this project is an indication of both the difficulty of sound measurement and its contentious context. The research community cannot contribute to the design of these experiments, nor participate in the discussion about the interpretation of the data, due to concerns about control over disclosure of early results. Researchers also do not have access to any suitable experimental platform to carry out similar experiments at a suitable scale, nor any assurance that content providers would cooperate in validating measurement methods.

5.3 Relating performance measures to QoE

A second issue with performance measurements is how to relate them to the higher-level question of whether the observed measures actually relate to any degradation of the user experience. In relating measures of quality of service (measurable performance metrics) to quality of experience, operators and researchers tend to make intuitive assumptions. If an aggregate, e.g., a metro area, shows persistent congestion for many hours a day, users are likely experiencing negative consequences. In other cases, the argument is harder to make. Imagine that a content provider reports that over a 24-hour period, overall traffic into a metro area shows periods where the throughput of individual flows drops by 5%. First, the congestion is not necessarily causing this drop; users could be downloading different sorts of content, or using different devices, which changes the mix of of content coding.

However, if the drop is due to congestion, would users perceive a drop in QoE? The answer is application-specific. Applications such as real time communication (VoIP, teleconferencing) and multi-player games are sensitive to jitter. Streaming content (audio and video) applications are less affected by jitter, since they buffer some content at the receiver to smooth out variation in arrival time, but a reduction in bandwidth may require the source to reduce the encoding quality, which often affects QoE. Jitter or reduced throughput (unless severe) have less effect on interactive

[12] Quoting from the cable lobbying organization's letter to the FCC: " *With regard to the Netflix streaming tests in particular, the ISP Representatives questioned whether the proposed testing would accurately measure the performance that a consumer actually experiences in streaming a Netflix video. We expressed our concern that the testing of Netflix streaming currently under way uses synthetic 25MB binary files instead of actual video files that are delivered to Netflix customers. The ISP Representatives stressed that the testing should replicate the real-life consumer experience of streaming a video, and that therefore the testing should randomly access actual video files from the same servers that deliver videos to Netflix customers. The ISP Representatives also stressed the importance of requiring that participating streaming services sign a Code of Conduct to ensure that there is no gaming of the testing process, similar to the Code of Conduct that all of the participants in the fixed-line MBA Collaborative signed [48].*

applications like web browsing, and negligibly affects background traffic Although considerable research literature exists in the space of QoE [50], it is not easy to translate these results into operational criteria for asserting impairment. This sort of work has not been thus far of high priority to the research community, nor to its funding agencies. In the U.S., the FCC has recognized the need for this sort of basic research, and has co-sponsored (with the NSF) a workshop on QoE, one goal of which was to explore the relationship between observed operational measures of network performance and impairments to QoE.[13]

5.4 Using this model to inform regulatory attention

One of our goals in developing this model is to frame an objective discussion of what measurements at different aggregates might mean in the context of potential discrimination at interconnection points. Consistent with a long history of telephony regulation, one might hypothesize that the more people affected by an impairment, the sooner it will merit regulatory attention, other factors held constant. So for example, persistently observed performance problems at the metro level might warrant regulatory attention, while observations of impairments at few links or LAG are more likely brief operational problems of less regulatory interest. Similarly, regional-level impairments would more quickly warrant regulatory attention than one metro area. Of course, an impairment in a single metro area that persists briefly but during a popular event might be of great interest to a regulator. So the regulator faces a tradeoff: between fine-grained reporting that will burden not only the network operator but the regulator who must process the data, and coarser-grained data (e.g., the provider-wide level) that is much easier to manage but may fail to observe a material event. When receiving third-party data in support of some argument, the regulator must carefully consider whether its level of presented aggregation (over time and in space) is potentially masking material events. Aggregation may also mask underutilized capacity or paths. One aspect of the disputes between content providers and access ISPs over interconnection capacity centers on whether the content provider is using all possible interconnection links (including reasonably available potential links). A network operator could aggregate data in ways that suggest either conclusion. We turn next to some concrete case studies that hopefully demonstrate how our model can help guide appropriate conclusions.

6 Applying the model to specific measurement data sets

We consider six case studies that span data sets offered by seven U.S. broadband access providers [52], edge providers Google [53] and Netflix [54], ourselves as academic researchers [13, 55], and ourselves as the independent measurement expert for the AT&T/DirecTV merger [56]. Each example covers large content and service providers interconnecting with large access providers in many different locations. We chose these examples to show how our model and approach above can facilitate understanding of what is being measured, and how to soundly interpret it. The first three projects focus on end-to-end path measurement data: Google's Video Quality report; Netflix's ISP Speed Index; and Measurement Lab's interconnection study. The second three projects focus on specific interconnection link measurements: CAIDA/MIT's interconnection measurement project; Princeton's CITP interconnection measurement project; and the measurements we proposed for the AT&T/DirecTV merger conditions.

[13] The report of the first FCC/NSF workshop is available at [51]. A second workshop is planned for early 2017.

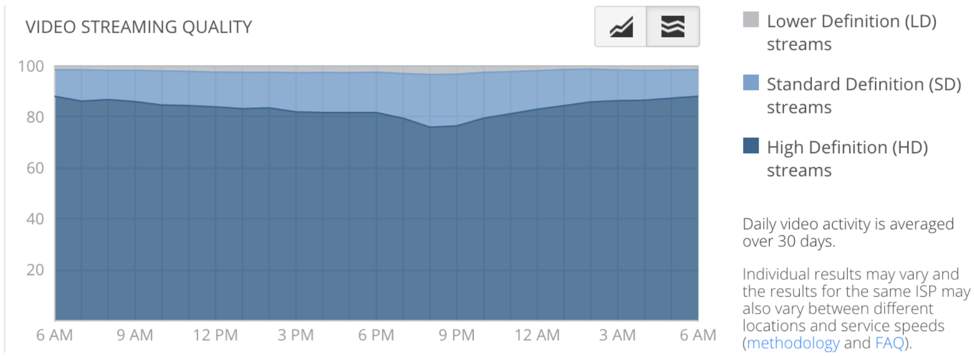

Figure 4: Google video quality reports summarize video performance at the metro or state level, in this case for ATT U-verse in Bardstown, KY (13 August 2016).

6.1 Google Video Quality Reports

Google's Video Quality Report [53] includes data derived from end-to-end measures, aggregated per ISP per city, of throughput of YouTube streams. This data set includes, for each YouTube video request: timestamp, access network, estimated geographical region (e.g. country, metro), total bytes transferred to the client, time at which receiver acknowledges receipt of all bytes [57]. This chosen aggregation granularity for reporting removes visibility into what paths the flows are using to reach their destination. Internally Google knows in detail how they route traffic to the users for any given measurement, e.g., whether it crossed a direct interconnection link with the broadband access provider or via an indirect path through a third party. Unlike Google's *peering.google.com* peering portal which provides capacity and traffic volume statistics on direct interconnection links with its peers, our understanding from discussion with Google is that these Video Quality reports aggregate measures over both direct and indirect paths. Exactly how they aggregate these measures is not clear. Figure 4 illustrates a video streaming quality report for a cable provider in Bardstown, KY, reporting the fractions of time Google is sending the video at high definition and standard definition. A reduced fraction of high definition flows, particularly during peak hours, and when other comparable providers and comparable regions do not experience a drop, is evidence of a potential impairment.

These published statistics allow one to examine data at a metro, regional (which Google defines by state in the U.S.), and entire provider level of aggregation in the U.S. For instance, one can look at the performance of Comcast in a given city, such as Boston, across an entire state, Massachusetts, or across the whole U.S. The web interface facilitates comparisons between broadband providers at these three granularities, which provides evidence that Google is capable of delivering high definition video content to users in some networks even if impairments are evident in others.

Another limitation of this data, and all end-to-end performance measurement, is its inability to localize the source of any impairment to the access provider itself. The measurements also capture, but do not distinguish, impairments in the home network, which may manifest more often as access speeds increase [58]. On the other hand, large and geographically distributed end-to-end measures of similar users across multiple ISPs mitigates this concern. Examining diurnal patterns can also establish some baseline of impairments, although some portion of the variation detected during peak hours are also likely due to changes in user behavior, for example a larger mix of devices accessing content.

In summary, this data set should capture impairments at the metro, regional (state-based) or

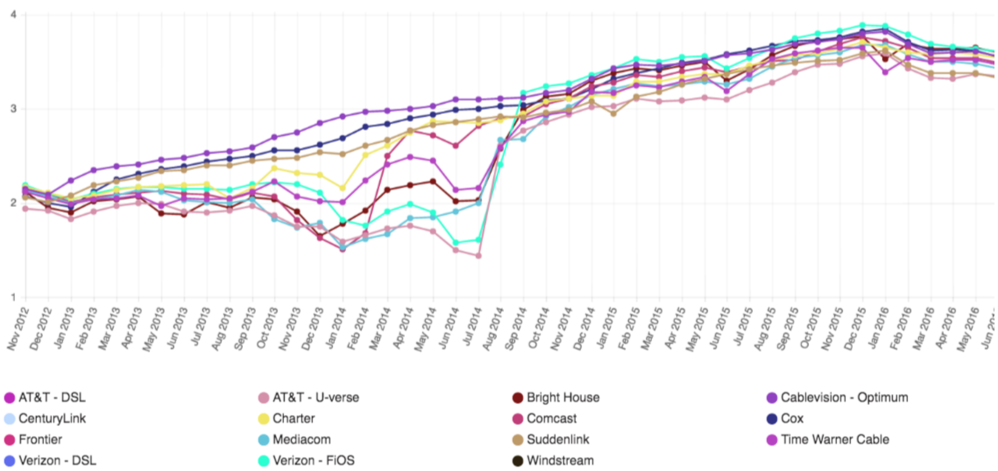

Figure 5: *Netflix ISP speed index is an aggregate summary of performance across all possible paths by which Netflix serves traffic to a given access provider's customers (both direct and indirect paths across all regions and metro areas.)*

provider-wide level of aggregation, but may also imply that a broadband provider is responsible for an impairment that is not under their control.

6.2 Netflix ISP Speed Index

Netflix reports per-ISP values of their *speed index*, an aggregate summary of end-to-end download speed across all paths from Netflix servers to a given access provider's customers (Figure 5). This plot shows significant improvement of this metric for many ISPs in late summer 2014 which appears to be the result of resolution of noticeable earlier performance degradation to customers of those ISPs. In our model, this data aggregation includes content served directly from Netflix caches in access provider networks, direct interconnections, as well as indirect paths. Why is Netflix aggregating statistics at this overall provider-wide granularity, rather than metro or regional levels of aggregation as Google does? One plausible explanation is that Netflix is balancing the desire to establish a public record of access provider performance with concerns that they do not want to discourage adoption of their services by suggesting certain regions have performance problems. This public provider-wide aggregate prevents inferences about regional interconnection issues. Also, the end-to-end measures here suffer the same risks of the Google's video quality report, in terms of potentially masking issues happening other places in the network.

6.3 Measurement Lab

Google's Measurement Lab (M-lab) operates a set of servers against which clients can measure throughput, traffic shaping, and traffic differentiation. NDT is a popular test hosted on the M-lab infrastructure that clients use to measure achievable throughput of their Internet connection. When a client initiates the test, the M-lab backend directs the client to an available server geographically near the client. The client and server then conduct throughput tests in both directions. A report from M-lab [59] used this end-to-end measurement data, i.e., the achieved throughput in NDT tests from a server hosted in a certain AS (say S) to clients in an access AS (say A), to infer performance degradations on the path from S to A. The methodology looked for significant differences between peak and off-peak throughput for a server-client AS pair to infer peak-hour congestion on paths from that server to the client AS. The report went a step further, attributing observed performance degradation between S and A to the interconnection between S and A in the region of the server S, e.g., the interconnection between Cogent and Comcast in LA.

We can use our model to critically consider three assumptions underlying this inference method. First, similar to the previous two case studies, this method assumes that congestion is more likely to exist at the interconnection points between networks rather than within a network. Second, also an unspoken assumption of the previous two case studies, that the server and client AS directly connect, thus any observed interconnection congestion exists on that direct link. It is possible an individual test could execute over an indirect path, in which case reported measurements reflect a combination of *direct* and *indirect* paths between server and client ASes. Third, the method assumes that M-lab's server selection algorithm works well enough that clients in a certain metro region are directed to servers in that same region, and the NDT test thus reflects performance from S to A in that metro region. The M-lab report did not examine performance at a finer or coarser granularity than metro region, i.e., at the LAG level. M-lab publishes all NDT test data, along with path data in the form of traceroutes from servers to clients. This data could enable performance evaluation of specific LAGs, although we have found that due to the way the NDT tests sample individual LAGs, only a small set of LAGs admit statistically significant inferences. One could also aggregate the data to a provider-level view by aggregating all tests from servers in an AS S to clients in an AS A. One concern with such aggregation is that some metro regions may be under or over-represented based on deployment of server-side infrastructure.

6.4 CAIDA / MIT Study

The CAIDA/MIT project is developing methods to detect interconnection links and evidence of persistent congestion on these links, e.g., recurring patterns of increased latency. The interconnection discovery phase uses vantage points (VPs) inside a network to perform an extensive active topology discovery process that infers all interconnections of that network visible from each vantage point. By widely distributing many active probes in an access network, we believe that we can find essentially all points of interconnection with other connecting parties. We also developed the *time-series latency probing* (TSLP) method [13, 55], a method to infer congestion at these discovered interdomain interconnections. The VPs send probes toward the near and far end of each discovered interdomain link to obtain two time series of latencies. The presence of diurnal patterns in latency to the far end of the link but not to the near end of the link signals evidence of congestion at the interconnection. The method generates raw measurements on each interconnection LAG discovered from the VP, and we can examine the resulting latency data (using heuristic geolocation) at the metro, region, or provider level. The TSLP method does not measure the utilization or capacity of LAGs; it uses active measurement to reveal only whether individual LAGs show latency-based evidence of congestion. For example, we could use TSLP data to infer that "all LAGs connecting providers A and B in a certain region appear congested", or that "4 out of 5 LAGs connecting providers A and B in a certain region appear congested". The main challenge in aggregation based on geography is accurately geolocating interconnection links to specific cities or metro regions, which is known to be less accurate for core router infrastructure than edge devices [60]. A further challenge is that a VP inside an access network may not observe interconnection LAGs in geographically distant regions, depending on the nature of routing between the access network and its interconnection partner. A full provider-level view from an access provider to an

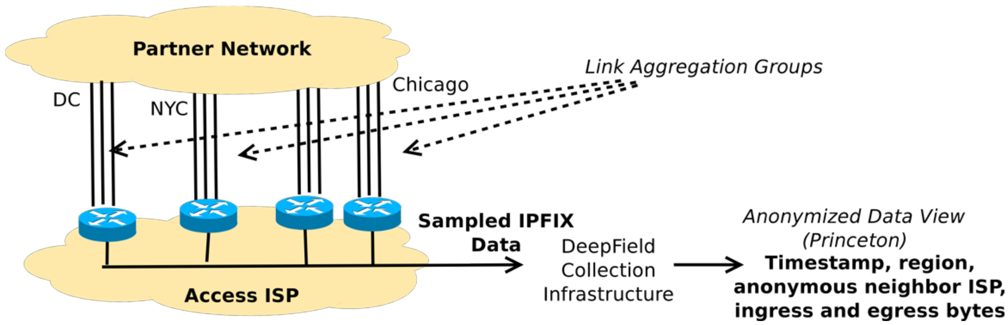

Figure 6: Center for Information Technology Policy's Interconnection Measurement Project architecture (borrowed from [61])

interconnection partner may require a dense deployment of VPs inside the access network.[14]

6.5 Princeton's CITP Interconnection Measurement Project

Seven broadband access providers, which service over half of U.S. broadband subscribers, cooperated to provide Princeton's Center for Information Technology Policy with aggregated utilization data for interconnection links of broadband providers. It contains data on nearly all of the paid peering, settlement-free peering, and ISP-paid transit links of Bright House Networks, Comcast, Cox, Mediacom, Midco, Suddenlink, and Time Warner Cable. Each broadband ISP submitted the following data for each five-minute interval (See Figure 6): timestamp; region (which maps to *metro* in our model) representing an aggregated link group; anonymized interconnecting party; total ingress bytes; total egress bytes; and capacity of the aggregated link group.[15] We try to map these terms to our model of interconnection, but note that although the data *collection* granularity maps to terms in our model (if we consider each metro area its own region), the *reporting* granularity does not match any aggregation granularity in our model.

First, Feamster [61] states that "to protect the confidentiality of information pertaining to usage on specific interconnects, the data is aggregated into a single link group per geographic region." In other words, the broadband providers are aggregating capacity and utilization data to a metro level before sharing it with CITP. In an apparent defense of this aggregation, Feamster notes that "we can assume a relatively uniform load balance of inbound traffic flows for a link aggregation group." [61] But content providers do not necessarily balance load equally across multiple LAGs in a metro area. From the data CITP shares publicly [52], it is unclear whether many of the link aggregation groups in the CITP data set have multiple constituent LAGs. If they do, this assumption is not valid.

More problematic is that although each broadband provider anonymized the partner network for each data point they shared, they also required NDAs that further limited the analysis and reporting to even more heavily aggregated forms of this data. In particular, the participating ISPs required aggregation of capacity and utilization levels either *across all regions* or *across multiple broadband networks* to anonymize any given interconnecting party. Feamster acknowledges that such aggregation does not enable understanding of impairments between any pair of networks:

[14]We found 45 distinct interconnection LAGs (router-level links) from a major broadband access provider into Level 3, the largest of the Tier 1 providers. Because different points are announced in different regions of that access network, it took 19 observation points to find all of those interconnection points.

[15]Additional details on data collection in [61].

> 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. [61, p.7]

We use the terminology of our model to explain how this excerpt is unnecessarily misleading. First, the intentionally chosen aggregates do not just make it "difficult" to drill down into issues between any pair of networks – they make it impossible; as Feamster has previously clarified, obfuscating that information was a requirement of the NDAs between the access and content providers. Furthermore, the conclusion that each ISP has spare capacity refers to that ISP's connections with *all* of its interconnecting parties, which is not a meaningful aggregation granularity, since e.g., Netflix cannot use Google's links. Indeed, we note that the most interesting observation in the public data that CITP posted [52][16] is that a non-negligible number of interconnection links experience nearly 100% utilization!

Feamster proceeds to aggregate the utilization of interconnect groups for *all* interconnections from *all access ISPs* to *all interconnecting parties* across *all* regions, as if they were substitutable, to conclude that even if there are heavily congested individual LAGs (which he cannot disclose), there is some LAG somewhere in the highly aggregated data set that has spare capacity that a partner could be using but is choosing not to use. He draws similar conclusions from aggregating and presenting utilization statistics *per region* but *across all ISPs*. The problem with such broad aggregations, across all regions *or* across all interconnecting parties in a region, is that the reported capacity could include links that are unlikely to be available to all interconnecting content providers. (Again, Netflix links are probably not a substitute for delivering Google content.) We consider these aggregation granularities to hide exactly the information a regulator needs to see to assess performance problems with interconnection between parties.

He again acknowledges the limits of these aggregation:

> " 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." [61, p.9]

but concludes that the reported granularities:

> 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..

Unfortunately, we do not believe these measurements reveal anything new that can address any disagreements related to Internet interconnection that have appeared in the research literature, media coverage, or FCC filings.

[16] This page provides an anonymized view of each aggregated LAG: http://interconnection.citp.princeton.edu/project/views-by-interconnect/

6.6 Measuring the interconnection links of AT&T

During the AT&T/DirecTV merger proceedings, publicly filed objections from edge providers and their representatives focused on interconnection as a locus of harmful discrimination, and strongly advised the FCC impose conditions related to interconnections on any approved merger. In response to these concerns, the merger order imposed a requirement for AT&T to provide to the FCC the business terms for all their significant interconnecting parties, and to report key performance metrics of those interconnections, for a duration of four years beyond the merger approval date. This information will educate the FCC about the character of interconnection, and whether the contracts suggested unreasonable discrimination among AT&T's interconnecting parties. Since objectors focused only on interconnection as a point of possible discriminatory behavior, the merger order limited the scope of measurement to interconnection links, and no other part of the path from senders to receivers.

To define exactly how AT&T would gather and report these measurements, the FCC merger agreement called for the joint appointment of an Independent Measurement Expert (IME). AT&T and the FCC selected the four authors of this paper to serve as this IME. The full report of our methodology, and our supporting filing with additional justification for some of our choices, are available as FCC filings and on CAIDA's web site [56, 62]. The FCC specified a range of required measurements [17]; here we examine how those measurements fit within our conceptual model.

Capacity and utilization. Consistent with the reasoning we presented in §5, we required that AT&T report on LAGs, and as well metro and provider-wide aggregations, but not on individual links. To account for factors that might make this data ambiguous, including possible use of the link to carry non-Internet traffic, e.g., carrier VoIP, IPTV transport, or other such specialized (or "non-BIAS") traffic. we required that AT&T disclose to the FCC if any such sharing is taking place.

[17] In full, the merger agreement placed the following requirements on the IME [63, Appendix B.V.2.c.iv], and required the specification of the following measurements:

> *...the Company, in consultation with the Independent Measurement Expert, will submit for approval by the Commission's Office of General Counsel, in consultation with the Wireline Competition Bureau and the Chief Technologist, a report describing the Independent Measurement Expert's proposed methodology for the measurement of the performance metrics described herein. Such report shall also be submitted to the Independent Compliance Officer. The proposed methodology should, at a minimum, address the following criteria:*
>
> 1. *Identification of Internet Interconnection Points, including the identity of the interconnecting parties and the location and capacity of each interconnection point;*
> 2. *Identification of a disclosure exemption threshold for a de minimis volume of traffic exchanged between the Company and interconnecting parties;*
> 3. *A definition of "Latency," which shall include the disclosure of the probability distribution;*
> 4. *A definition of "Packet Loss";*
> 5. *Time of measurements, which shall, at a minimum, include an identified window within peak usage periods;*
> 6. *For any performance metric contingent upon an interconnecting party's participation in the selected measurement methodology, a process for waiving the disclosure of that metric at points of interconnection where the interconnecting party declines to participate;*
> 7. *Frequency and duration of measurements;*
> 8. *Any devices used for measurement;*
> 9. *End points of measurements;*
> 10. *Placement of any devices; and*
> 11. *Frequency of disclosures.*

We emphasized that it may be necessary to seek the cooperation of the interconnecting party to fully characterize how the interconnecting party is managing different sorts of traffic [62].

Packet Loss rate. Since utilization data alone cannot confirm the presence of congestion (§5.1), the FCC required the reporting of packet losses and variation in latency (jitter), presumptively an indication of packet queues due to congestion. We recommended several way of measuring packet loss. The first is to use the network management capability on the routers at the endpoints of the LAG. Routers track how many packets they drop at the ingress to a link.[18] But the FCC's regulatory concern was primarily with traffic flowing *into* AT&T, which means that the packet loss of interest occurs on the other end of the link, on the router belonging to the interconnecting party. In the context of these merger conditions, the FCC could compel AT&T to report, but the IME could only *ask* that the interconnecting party provide this information, and those parties have legitimate reasons for reluctance to cooperate with this request. Most obviously, if the link is congested in the incoming direction, the interconnecting party may not want to reveal it. Additionally, the router may drop packets that are malformed, classified as malicious (e.g., part of a DDoS attack), mis-routed, etc. A dropped packet does not necessarily mean congestion, and if the link is only occasionally congested, other causes of drops may distort the overall measure. Given these factors, the IME required that AT&T use a second approach to measure losses (and latency, as discussed below) on the interconnecting links, which is to send a probe packet across the link with the goal of triggering a response packet. The final methodology required using both approaches to the extent possible, which provides a means to determine whether the two yield similar answers, and (if not) the circumstances under which the two differ, e.g., [64].

Latency and jitter. In addition to loss rates, the FCC required (that the IME specify a method for) AT&T to report on variation of latency across the LAG. While some commercial routers support a measurement of queue length, operators do not generally use it, and the IME had no way to calibrate it. So the final methodology recommended two approaches to active measurement, both of which depend on measuring the time between the sending of the probe and the return of the reply, which estimates the round-trip latency. Variation in this measurement is evidence of jitter. Limitations of the canonical probing protocol (ICMP) [56] motivated the requirement for another more accurate protocol (TWAMP [65]) for interconnecting parties willing to cooperate to support it. TWAMP tries to remove the uncertainty associated with a simple ICMP probe by a using a more complex set of timings. While TWAMP may be more accurate, it is not widely deployed in the Internet, and the operational and research community has little experience with validating the accuracy of TWAMP probes. The interconnecting party would have to install a TWAMP responder at the far end of the link, which there is no way to mandate in the context of the merger order. All the IME (and AT&T) could do is *ask* the interconnecting party if they will install and activate a TWAMP responder. The fallback is the less accurate ICMP probing.

Applying our model to aggregating the AT&T measurements. Because measurement at different aggregations reveals different behavior, we required AT&T to report utilization at three aggregations: individual LAGs, metro, and overall for each interconnecting party. The IME required reporting on individual LAGs so that the FCC can detect an imbalance among LAGs in an aggregation, which might have implications for substitutability of those LAGs. The requirement for reporting at three levels of aggregation was first to allow for the possibility that measurements

[18] These loss counters may be incomplete, i.e., reporting only drops the router properly records.

at one level may suggest a problem with data aggregated at another level. But more fundamentally, the goal is to learn what these levels of aggregation reveal, given that they are based on the same underlying LAG-level data. Defining a region raised enough ambiguities that we omitted that level of our hierarchy. Aiming for a fine-grained view of the variation of demand, the methodology required that AT&T gather raw data in 5-minute intervals, and plot key parameters (across all three aggregations) as well as summary statistics. We did not require that AT&T report either loss or jitter at higher levels of aggregation, since we know of no way to aggregate these values in a way that yields meaningful results. This challenge is a future research question.

7 Summary and Policy Recommendations

We have used our conceptual model to position a number of current data gathering efforts, and to frame our justification for the measurements we required AT&T to report to the FCC. Our goal is not to recommend a specific set of measurements, but to assist policymakers in making informed decisions regarding how to interpret measurements intended to reveal significant performance impairments. Here we summarize lessons learned in the process of defining the AT&T/DirecTV methodology and in the process of defining the model we offer in this paper.

Measurement is political, and often adversarial. If parties are in a dispute, they may favor measurement that reflects well on them and poorly on another disputant. Measurements that reveal the location of an impairment may be in the best interest of one party but not the other. ISPs are only likely to share data that will reflect well on them.

Measuring individual interconnection points does not tell a complete story. Content providers have control over how they source content into an access provider network such as AT&T (including potentially over indirect links), and so a coherent view requires examination of the larger aggregates in our model, possibly including traffic flow over indirect paths, to see if available capacity can meet demand. A challenge of obtaining a more expansive view is that a third party may not be able to ascertain which transit links might be available to content providers as indirect paths. Unanonymized network-level traffic flow data is required to confirm that a transit connection really is being used by a given content provider.

Reporting for a given pair of interconnecting parties at two of aggregation granularities – metro and region – are generally useful in determining whether material impairments are occurring that might warrant regulatory attention. But a caveat applies. Specifically, if data from finer aggregation granularities does not lend credibility to the claim that the contained elements are substitutable, looking *only* at an aggregate may mask exactly what one is trying to use the data to ascertain. Particularly with respect to content providers, who may connect to an access provider with many LAGs in a metro area (and connect in many metro areas), the metro level of aggregation is useful, assuming substitutability of component links. The largest levels of aggregation (such as all links between two providers) is rarely a useful scope of regulatory analysis. It is unlikely that links in such a large scope will be substitutable, due to variation in the lower level elements that compose the aggregate.

Path measurements provide a useful and complementary view of performance across multiple ISPs. But caveats apply here too. Absence of impairments in a single interconnection link does not imply absence of impairments in the end to end path. Obtaining a reasonably complete picture will require consideration of both link and path (or path segment) measurements. The end-to-end measurements from Netflix and Google (§6.1 and 6.2) provide another measure of whether overall capacity is meeting demand, and whether there is actual variation in throughput. End-to-end measurement will reveal behavior that most directly maps to possible impairment, but it does not reveal where impairment is arising, nor indicate if there is any actual degradation in user-percived QoE. Mapping such data to QoE impairment requires agreement on application-specific thresholds for impairment, an open resarch question.

An accurate picture of packet loss and latency across interconnection links requires cooperation of interconnecting parties with counterincentives to cooperate. Content providers, in particular, navigate a complex set of issues surrounding interconnection, starting with commercial contracts. Using our AT&T case as an example, content providers are customers of AT&T, not peers. Further, the FCC compelled AT&T to reveal under a protective order the contracts the interconnecting parties signed with AT&T. If a direct interconnection link is apparently congested, it does not necessarily mean AT&T is preventing the interconnecting party from obtaining wanted capacity. An alternative explanation is that the interconnecting party has, for economic reasons, chosen not to purchase additional capacity. Content providers may have many paths to deliver their content, but if their interconnection links become congested, it might not reflect well on them, especially if they had recently lodged complaints about their ability to interconnect, and the FCC now had the terms of their interconnection agreement in hand. These vested interests may motivate a preference for reporting larger aggregates (metro or provider-wide, including indirect links) and reporting measures that are not scoped to interconnection links specifically, but to longer path segments, or end-to-end.

Each stakeholder brings a unique contribution to the overall picture of interconnection conditions. The research community has not devised third-party measurement tools to remotely measure the capacity or utilization of an interconnection link. But neither do the ISPs have full visibility into behavior. An ISP observing a link may measure utilization and congestion but it cannot easily measure how the senders have chosen to deal with this congestion: how much they have slowed their sending, whether they have changed the encoding of the traffic. Third-party observers (or providers of higher-level applications and content) may be better positioned than operators to measure the overall QoE of an activity by end-to-end measurement, but they are not well-positioned to assess substitutability of LAGs. An ISP can only see part of the path, and may have excellent visibility into that part, but cannot see all of it. An end-to-end measurement has imperfect visibility into the path but can detect if there is an overall problem.

The FCC should pursue wider visibility of what is learned in the face of protective orders. It is important for the larger community to learn about the utility and effectiveness of these various measurement methods. However, the measurement methodology defined by the IME is public, the gathered data is not. The merger order requires that AT&T share data with the FCC under a protective order, and with the IME itself only in the beginning of the reporting process, for the purpose of resolving flaws in the measurement methods.[19] Some operational issues that triggered the reporting requirement, such as overloaded LAGs, may not arise during the limited period in

[19]From the contract [http://www.caida.org/funding/att-interconnection/]:

(c) CAIDA and AT&T jointly will review the first report that AT&T must submit to the FCC on Internet interconnection performance metrics resulting from the Methodology (the "Metrics Report").

which the IME is reviewing the measurement method and resulting reporting. Validation of a method to detect an issue is not possible until and unless the condition of interest arises.

Furthermore, while the data shared with the FCC will inform regulatory policies and the FCC's understanding of access network interconnection links, some sanitized public view of this data might dispel many concerns about the health of the interconnection ecosystem. The merger agreement contained a high-level acknowledgment of the goal of public release of the data in some form.[20] Because of the structure of the merger agreement, only the FCC is in a position to make this happen. We urge that this effort be undertaken.

One potentially productive role for the academic research community is as a partner to the regulator, which is only possible if the regulator can facilitate access to data for validation and deployment of measurement infrastructure in support of policy needs. Sustained funding and support for such infrastructure is an on-going challenge, and no country (to our knowledge) has stable sources of government funding specifically for measurement infrastructure to enable Internet research by independent third parties, nor to fund objective analysis of data obtained from such infrastructure. Lacking such a capability, the regulators must assume that actors will choose to gather and report numbers in a form that represents the interest of those actors.

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(i) *AT&T acknowledges and understands that in order for CAIDA to fulfill its obligations as part of this review process, including to assert confidence as to the validity of the Methodology, CAIDA must have reasonable access to certain underlying data necessary to validate the Methodology. Any method for measurement must be tested and evaluated in practice, and CAIDA must be materially involved in this activity.*

(ii) *If either CAIDA or AT&T believes that there is an issue with the performance metrics contained in the first Metrics Report, CAIDA will (A) propose reasonable adjustments to the Methodology to resolve the issues(s) that are satisfactory to the FCC, and (B) consult with AT&T on AT&T's explanation of the issue(s) and the proposed adjustments to the Methodology to the FCC and the ICO. CAIDA and AT&T will repeat this process until there has been a Metrics Report that CAIDA believes contains appropriate performance metrics.*

(d) If, after CAIDA's repeated, good faith attempts to propose reasonable adjustments to the Methodology to resolve issue(s), the FCC fails to approve the proposed Methodology, CAIDA reserves the right to terminate this Agreement upon prior written notice to AT&T and the FCC and indicating the reasons therewith. If such termination occurs: (1) This agreement shall terminate and CAIDA shall no longer have the right to access and use the Protected Information (as described in 5(b)), (2) CAIDA is relieved of any obligation or penalty under this Agreement; and (3) AT&T shall reimburse CAIDA for all services performed and reimbursable expenses incurred up to that point of termination.

[20] From the merger order:

This condition will enable the monitoring of the combined entity's future interconnection agreement's terms to determine whether the combined entity is using such agreements to deny or impede access to its networks in ways that limit competition from third-party online video content providers. In addition, this condition requires the combined entity to work with an independent measurement expert to report certain Internet interconnection performance metrics, and to the extent possible, make such metrics publicly available. [63, Page 148]

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