The Growing Complexity of Internet Interconnection

Peyman FARATIN, David CLARK, Steven BAUER, William LEHR
Massachusetts Institute of Technology, Cambridge MA, USA

Patrick GILMORE, Arthur BERGER
Akamai Technologies, Cambridge MA, USA

Abstract: End-to-End (E2E) packet delivery in the Internet is achieved through a system of interconnections between heterogeneous entities called Autonomous Systems (ASes). The initial pattern of AS interconnection in the Internet was relatively simple, involving mainly ISPs with a balanced mixture of inbound and outbound traffic. Changing market conditions and industrial organization of the Internet have jointly forced interconnections and associated contracts to become significantly more diverse and complex. The diversity of interconnection contracts is significant because efficient allocation of costs and revenues across the Internet value chain impacts the profitability of the industry. Not surprisingly, the challenges of recovering the fixed and usage-sensitive costs of network transport give rise to more complex settlements mechanisms than the simple bifurcated (transit and peering) model described in many earlier analyses of Internet interconnection (see BESEN *et al*., 2001; GREENSTEIN, 2005; or LAFFONT *et al*., 2003). In the following, we provide insight into recent operational developments, explaining why interconnection in the Internet has become more complex, the nature of interconnection bargaining processes, the implications for cost/revenue allocation and hence interconnection incentives, and what this means for public policy. This paper offers an abbreviated version of the original paper (see FARATIN *et al*., 2007b).
Key words: internet interconnection, economics, public policy, routing, peering.

The Internet was designed so that different providers could operate different parts of the network. Today, the Internet is built up out of regions, or Autonomous Systems (ASes) that include commercial Internet Service Providers (ISPs), corporations and other enterprise providers, universities, government agencies, and (more recently) content providers and other specialized service providers. This design results in a network of networks that, like any distributed supply-chain, requires competitors to cooperate to deliver a coherent end-to-end service. In today's Internet this state of "coopetition" takes the form of rich interconnection among ASes such that networks carry each other's traffic to reach final destinations.

In the beginning, the pattern of AS interconnection somewhat resembled a simple hierarchy, with campuses and other geographically local networks connecting to regional networks, and the regional network connecting (in the U.S.) to a single government-subsidized NSF backbone. The pattern of interconnections that emerged in the commercial Internet in the mid-1990s is relatively more complex, comprised of many networks connected among themselves and to multiple interconnected backbones (so-called "Tier 1" providers, as we will define below), governed by market-based contracts that are negotiated on a bilateral basis. This evolution was enabled by infrastructure innovation toward higher capacity switching and transmission links and new routing protocols.

The pattern of interconnection may be viewed conceptually as the result of a complex, dynamic bargaining game between pairs of ASes. The outcome of this bargaining game is important because the choice of interconnections determines not only reachability but also performance features such as the scope of routing capabilities (e.g., how many diverse routes are available and the quality or congestion experienced along those routes). However, these bargaining games are fraught with potential breakdowns due to either transaction costs and/or to agency/opportunism problems. For instance, it is often unclear who should pay whom for interconnection on the Internet. It is not possible to deduce the direction of "value flow" by looking at the direction of packet flow.

Given the simultaneous benefits of interconnections, two simple standardized types of bilateral contracts for AS interconnection emerged in the early commercialization of the Internet: *peering* and *transit*. A *peering* agreement (also called "Bill and Keep" or "Sender Keeps All") is where two networks provide access *only* to each other's customers for no financial settlements. In contrast, *transit* is where one network provides reachability to the *entire* Internet in return for a monetary settlement. The recursive combination of these standardized bilateral peering and transit contracts created the complex web of interconnections wherein networks become resellers of transport and peer with one another in what has been a mutually beneficial and hence largely stable manner.

Previous academic work on the incentives of network operators to interconnect has focused either on direct externality effects (NEUCHTERLEIN & WEISER, 2005) or agency models (MILGROM, MITCHELL & SRINAGESH, 2000). In contrast, this paper focuses on the emerging interconnection bargaining practices involving heterogeneous ASes.

The goal of this paper is to provide insight into this rich and complex operating environment, to suggest some of the ways that interconnection is changing and will continue to change, and to trace the implications for future Internet architecture, industry structure, and public policy. [1]

We will focus on a single Internet service, namely content (web) delivery: first, because content accounts for a large portion of today's Internet traffic and second, because interconnection and settlement mechanisms and strategies are being increasingly influenced by the emergence of large sources of web content and very large aggregators of residential broadband customers -- the DSL and cable ISPs, each with asymmetric patterns of traffic (almost all traffic is outbound from the server and inbound to the consumer). These large networks are substantial-enough players that their interests are changing Internet interconnection bargaining processes and giving rise to greater reliance on more complex contracting variants such as paid-peering and partial transit. [2] We will also show how a system limited to bilateral transfers fails to send relevant price signals that can be used to internalize potential *indirect* externalities across complementary distinct markets, leading to closure of viable markets. This market failure is partially responsible for the entry by third-party application layer content distribution networks, and other overlay models of content delivery.

■ Settlement-free peering and transit introduced

The entities that are interconnected are referred to as Autonomous Systems (ASes). As of October 2008, there were over 29,000 in use (ASN, 2008). Most ASes are ISPs, but they also include enterprises, governmental or educational institutions, and increasingly large content providers with mostly outbound traffic such as Google, Yahoo, and YouTube as well as overlay content distribution networks such as Akamai and Limelight (CLARK

[1] This paper is an abbreviated version of an earlier version (see FARATIN *et al*, 2007b).

[2] We owe Scott Marcus for pointing out that partial transit and paid peering contracts are not new in the Internet, but have been in use for over a decade. What is new is the trend toward increased reliance on such contracts.

et al, 2005). An autonomous system is also sometimes referred to as a routing domain. ASes manage pools of IP addresses. For each AS, the "cone of prefixes" refers to addresses that terminate either in that AS or on other ASes that it has sold transit to (which recursively includes any addresses of customers of those ASes, and so on).

Transit

ASes may interconnect with each other in several ways. For example, an ISP A may enter into an interconnection agreement with an ISP X wherein ISP A pays ISP X to tell the rest of the Internet about "where" A is (which is called "announcing its prefixes") and ISP X agrees to send and receive traffic between A and the rest of the Internet. This form of agreement is called full *transit,* and is equivalent to saying that "A is a customer of X".

X either has access to all global Internet addresses or else in turn purchases access from another AS that has more extensive access. Each AS will have been allocated one or more address prefixes for its use, but if it provides transit service to another ISP, it must also take responsibility for announcing the prefixes of its customers. This relationship is recursive. A small AS A could purchase transit service from a medium sized AS M, which in turn could purchase transit service from X.

If A purchases transit service from X, then A can have a very simple forwarding table. It needs only two classes of AS-level entries: its own prefixes and "everywhere else". For its own prefixes, it will use its intra-AS routing protocols to forward the packet internal to the AS. For "everywhere else", it just sends the packet to X. This sort of forwarding entry is called a "default route". When A purchases transit from X, X must make sure that all the ISPs know that X is the path to the prefixes of A, but A need not concern itself with where all the other prefixes are. It just sends the traffic to X.

Any AS can choose to purchase transit from more than one provider. They might do this, for example, to obtain more diverse and resilient access to the Internet (called *multi-homing*). When an AS does this, its addresses become part of the prefix cone of all of their transit providers.

Generally, full transit pricing is subject to substantial volume discounts. To get an idea of what levels of transit pricing look like (while recognizing that the variation in what ISPs pay varies widely across agreements and around the globe), the table below summarizes data gathered from a sample of 42 ASes in 2006: [3]

Table 1 - NANOG 2006 Transit Survey

Survey Sample Size	42
Average Monthly Price	$25/Mbps
Maximum Price	$95/Mbps
Minimum Price	$10/Mbps
Average Commit Levels	1440 Mbps

Transit contracts are enforceable and the customer usually receives a service level agreement (SLA) to ensure appropriate quality of service and reliability. This will include commitments to repair and restore service after failures, as well as performance commitments under normal operation.

Settlement free peering

Another common form of Internet interconnection agreement is *peering*. In a peering agreement, X and Y interconnect, but only for the purpose of providing a path between their two cones of prefixes. In the original model of peering, called *settlement free peering*, there was no payment between X and Y for this arrangement.

The so-called Tier 1 ISPs are the set of ASes that do not purchase transit from any other AS, and thus must peer with every other Tier 1 ISP. The Tier 1 ISPs collectively form a complete mesh of peering arrangements. Tier 1 ISPs are large, with global scope. They do not peer at only one physical location, but at a number of points around the globe. Since a Tier 1 AS does not purchase transit, it cannot take advantage of a default route. Together, the Tier 1 ISPs define the "Global Routing Table" (GRT), which lists every single prefix on the Internet, the different available paths to that prefix, and other information that lets the AS make forwarding choices based on the available paths.

All Tier 1 ISPs must peer with each other, but the use of peering is not restricted to Tier 1 ASes. Any two ISPs can choose to peer with each other, by mutual agreement. Two small ASes that discover that they have a lot of traffic for each other might decide to create a direct peering connection rather than sending the traffic up to their transit providers, which would not

3 This data was collected by B. Norton in 2006 from 42 surveyed ASes at the 36th Peering Birds of a Feather at North American Network Operator's Group (NANOG) (see NORTON, 2006).

only increase the load and thus (often) the cost of their transit service, but also lead to packet delivery performance degradation because of longer latencies caused by longer paths.

Because peering is cost saving it exhibits a number of *ex-ante* (see NORTON, 2003) and *ex-post* opportunism/agency problems (see MILGROM, MITCHELL & SRINAGESH, 2000). Therefore peering agreements often have a number of requirements, including:

- *Geographic Diversity:* Many networks require potential peering partners to set up links in multiple, geographically diverse locations.
- *Traffic Volume:* If A requests settlement free peering from Z, Z will measure its traffic to/from A. If the volume is small, Z will deny the request. The traffic volume requirement in each network's peering policy is usually based on the size of the network.
- *Traffic Ratio:* In settlement free peering relationships with very large networks, there is frequently a requirement to keep traffic "in ratio". The traffic going from A to Z is measured, and the traffic going from Z to A is measured. If the two numbers are not close enough, peering will be denied. For very large networks, the traffic ratio requirement is usually 2:1, and sometimes 1.5:1.
- *Consistent Announcements:* Most networks require peers to maintain consistent Border Gateway Protocol ("BGP") announcements across all peering links. This simply means that the BGP announcements should be identical, modulo irrelevant location-specific details, on every BGP session between the two networks. [4]
- *Marketing considerations:* Many ISPs will refuse to peer with an ISP that is a customer or a potential customer, as we discuss below.

Over time, as interconnection has become more strategic, peering requirements have become more complex, formal, and detailed.

[4] Consistent announcements allow a peer to hot potato traffic, inconsistent announcements force a peer to cold potato traffic. Assume A and B peer, and A only announces west coast prefixes on west coast peering points, and the same for east coast. If B has a packet in New York for A, B must carry the packet to the west coast where B sees the prefix announced. If B is announcing consistently to A, A can pass the return packets to B on the west coast. This shifts costs from A to B.

History of internet interconnection

Historically, the major distinction among different ISPs was their size. Size could be measured in a number of ways, including: geographic scope, total rates of traffic across the boundaries, or the number of attached customers. Although ISPs differed in size and coverage area, most were approximately similar with respect to the types of services they offered and (size aside) with respect to their incentives to interconnect. These relatively symmetric incentives to interconnect were important in shaping the environment in which interconnection agreements evolved in the early days of the commercial Internet.

The idea of symmetry among ISPs of similar size emerged as follows. In the backbone, the presumption of symmetric costs among approximately symmetrically sized "peers" meant that when network A delivered a packet received from network B to customers in its cone of prefixes, it was reasonable to believe that the costs of that delivery were approximately similar to the costs incurred by network B when it delivered a packet received from network A to customers in its cone of prefixes. If the costs are similar, the traffic is balanced and by some estimate the networks host equal numbers of users, then it could be argued that the benefit of interconnection was similar to both parties. Second, since the costs of constructing and operating a data network are mostly traffic insensitive (and associated with maintaining the network's peak load capacity), the incremental costs of delivery were presumed to be relatively small. In conjunction with the first point, this implies that total network costs could be reduced if usage-sensitive metering were largely dispensed with, resulting in settlement free (revenue neutral) peering among similar sized backbone providers.

In contrast, the assumption of symmetric delivery costs seems less applicable when a large network exchanges traffic with a small network. In an uncongested state, a typical packet that originates on a network with smaller geographic scope and ends up on the larger network might be expected to impose higher delivery costs on the larger network (which must typically carry the packet a greater distance). A larger network would presumably have more customers, and this might be seen as giving the larger network more value because of the larger positive network externalities associated with being part of their networks. Taken together, these effects may have contributed to the perception that size contributed to a network's bargaining position. [5] In any case, smaller networks tended to negotiate transit agreements with one or more larger providers under which the smaller networks agreed to pay the larger providers to deliver their traffic.

In this earlier world of peering (among networks of the same size) and transit (between large and small networks), although ASes might differ with respect to size, in other respects, they were remarkably similar and symmetric in their overall incentives and view of the interconnection problem.

■ The erosion of homogeneity

Over time and with the growth of Internet traffic, the idea that ISPs of a certain size were more or less the same has eroded. We have seen the emergence of "eyeball" heavy broadband access networks such as Verizon, AT&T or Comcast, on the one hand, and "content" heavy networks such as Abovenet or Cogent (that host a lot of content servers) and large content-providers such as Google and Yahoo. These networks have asymmetric traffic flows. Users on eyeball networks send small requests to content servers on content networks, while the servers on a content network send large replies. The "eyeball" customers want the content since that is part of the reason they pay for broadband service; the content networks need the eyeballs because that is what they sell to advertisers and the "eye balls" are the end-users who may subscribe directly to pay-to-view content. Thus, there are demand complementarities across distinct end-host markets (content providers and consumers) who are customers of ASes. Such markets also exhibit strong *indirect* externalities, where consumption by one side of the market increases as the consumption of the other market grows. The question of who should pay whom to recover the costs of supporting that interconnection is ambiguous in this asymmetric world.

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5 The relative strength of the bargaining position of ISPs, even in the early days, was ambiguous with respect to size. While the positive network externalities associated with joining a large network are larger in aggregate, there were many backbone providers and the incremental benefits of larger size decrease with size. In section 4 we discuss the apparent shift in the bargaining positions over time.

We observe in practice that most content-heavy networks are more open in their peering policies than are most eyeball-heavy networks. We can speculate on a number of reasons for this difference:

- As opposed to early access networks where switching costs for consumers were insignificant (because they could call any local modem bank ISP), modern broadband consumers may feel that switching costs are relatively higher, assuming they even have a choice of providers. Therefore eyeball networks may perceive that they have some increased bargaining power because they "own" the eyeballs.

- Eyeball networks believe that the "natural" direction of value flow is toward them, rather than away from them. The growth of Internet advertising suggests that content-providers place high value on reaching end-users on eyeball networks.

- The last-mile networks of the broadband eyeball networks are more capital intensive, often involving "lumpy" investments, than are the long-haul and backbone networks of content-providers.[6] Consequently, the cost recovery challenge of the last-mile networks is greater (although as noted earlier, it is not clear that their incremental costs for delivery are higher).

For these sorts of reasons, we observe that even small eyeball-heavy networks might sometimes refuse to peer with a much larger content-heavy network, and this has fueled the move toward more complex forms of interconnection contracts.

Paid peering

Paid Peering, sometimes called "Settlement Based Peering," is identical to settlement free peering in terms of how prefixes are announced and traffic is forwarded. What differs is that the traffic is no longer exchanged without payment. If an eyeball provider is not prepared to offer settlement-free peering to a content provider, then the traditional interconnection agreements offer few options, none of which is a good solution. These include:

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[6] The distinction is analogous to the lower capital intensity of long distance telephone service relative to local telephone service. The fact that the long distance network shared the local access network was used to help justify long distance services subsidizing local telephone services to help recover the fixed costs (non-traffic sensitive) of last-mile infrastructure.

- If the eyeball network has a very strong bargaining position, it might try to force the content provider to purchase transit service from the eyeball network. However, apart from cost, the content provider may not need access to all of the Internet, but only to the cone of prefixes that belong to the eyeball network.

- Both the eyeball network and the content network can purchase transit from third parties, in which case both are worse off, and the third parties are the only beneficiaries.

- If the eyeball network already peers with some third network, the content network can negotiate a transit arrangement with that third network. Again, in this case, only the third network is better off.

Paid peering may offer an alternative that leaves both parties better off than any of the above options. Paid peering can be either paying for all bits flowing over the interconnect, or just a negotiated rate for the traffic over the agreed ratio.

In fact, settlement free peering arose as a defensible approximation only in the context of assumed symmetry in value flow. If the difference in actual value were small, bargaining costs would swamp the benefits of negotiating a price. However, once the assumption of symmetric value starts to break down, the binary world of transit and settlement free peering will break down.

Partial transit

The second new type of interconnection agreement that is growing in importance is *Partial Transit*. Under partial transit, a network Z sells access to and/or from a *subset* of the Internet prefixes to another network A or Z which sells transit with some service restriction. For instance, Z may sell A only the ability to send traffic to part of the Internet, but not receive traffic. (In other words, A can behave like a content network but not like an eyeball network.) The reverse may also hold – A may be allowed to receive traffic but not send traffic. In this relationship, A will pay Z, but the price for partial transit will usually be less than half the cost of a comparable amount of full transit.

Partial transit agreements are a response to two competing commercial pressures. For example, providers with significant amounts of asymmetric in-bound traffic have a strong incentive to sell the outbound capacity on links for which the set-up costs have already been committed. Partial transit can also be used strategically to help a network balance peering ratios to allow them to stay in conformance with their peering agreements.

Networks also frequently sell access only to valuable peering relationships. If M and N peer, then M might consider selling partial transit to A but only to get to N. In this way, the partial transit agreement operates as a form of arbitrage that expands the range of networks that may participate (even if only indirectly) in peering agreements with large providers.

Summary

Taken together, the expansion of paid peering and partial transit interconnection agreements represent a filling in of the contract space. Instead of a choice of two (relatively) standardized agreements that neatly mapped to networks based on their relative size (i.e., similar sized networks might peer, but large networks charged small networks for transit), the world is moving towards a continuum of contract types. The drivers for this include the growing heterogeneity and sheer size of the Internet, as well as the bifurcation of the large networks by symmetry type as well as by size. The expansion of contract types may be viewed as a rational expansion in choice to accommodate the greater diversity of needs. This is consistent with market competition forcing participants to innovate towards more efficient cost-saving contracts. Viewed in this light, these new contracts may be interpreted as an efficiency-enhancing outcome. Paid peering allows providers who otherwise would fail to negotiate peering to better accomplish their interconnection objectives. And, partial transit represents a way to make transit more like peering, allowing flexibility in the scope of termination commitments in return for greater flexibility in payment terms as well as the benefits of enforceable contracts.

The welfare effects of these emerging contracts are nonetheless ambiguous. Presumptively, under the assumption of efficient bargaining, the fact that the parties mutually agree to adopt these new contracting forms in preference to simpler forms suggests that the movement to these contracts ought to be welfare enhancing. On the other hand, if bargaining is imperfect then the movement to these types of contracts may increase bargaining complexity and costs, which in turn might pose a threat of increased bargaining failures.

■ Further complexity of settlement-free bargaining strategies

In the following subsections, we describe some real-world negotiation strategies employed by ASes seeking to establish and maintain settlement-free peering in today's more complex and heterogeneous world. [7]

Refusal to peer

Uncertainties over how to allocate (shared or standalone) costs, especially across multiple ASes (when multi-homed) involving different contracts, may raise the risks of peering bargaining failures. Many large networks (and some small networks) will not accept peering requests from smaller networks, even if there are likely to be cost or performance benefits for the larger network. Some of the reasons that networks may cite for refusing to peer include the following:

- *Do not peer with current (or potential) customers:* Almost no network will peer with its own customers, because doing so means lost revenue. This also means networks will not request transit from existing peers for fear of losing their peering.

- *Do not peer with existing peer's customers:* Stability of interconnections are important. For large networks that already have robust peering, many peering requests come from customers of existing peers. Providers often turn down these requests. First, while stealing transit customers from one another based on price or performance is normal business practice, in a networked economy stealing a revenue generating customer by agreeing to a non-revenue generating relationship is unstable because the peer may in turn "poach" the network's downstream customers asking for peering in a tit-for-tat exercise. Second, agreeing to such peering requests will move traffic off the original peering link, onto a direct link with customer. This will change traffic ratios and volumes with the original peer, perhaps putting the larger peering relationship in danger.

- *Inflexibility, or adherence to peering policy:* When large networks create a peering policy, they may strictly conform to it, to avoid the risk of

[7] This paper is based, in part, on the real-world experience of some of its authors and the stories they have gathered. Citations to actual interconnection agreements are not possible since these are typically regarded as confidential and proprietary information.

being sued. The threat of lawsuits is valid, and possible concern about anti-trust scrutiny may apply to a few large networks. However, it is difficult, perhaps even impossible, to write in advance a policy that is detailed and complex enough to cover all the issues that may arise, so formal policies often preclude mutually beneficial negotiations.

- *Cost sharing:* A provider will often not peer with anyone who has not demonstrated equal investment in infrastructure, resources, etc. The logic behind this includes: ensuring the peer has the ability to carry the traffic; ensuring the peer is capable of troubleshooting problems; and ensuring the peer has the same investment in the quality of traffic. Obviously there are possible mutually beneficial situations where the costs are not equal, which this policy would preclude.

- *Perception:* In the real world of bargaining, some motivations are purely subjective. Network engineers almost always have a large amount of pride in their creation. They feel the networks they created are large, important, and significant on a global scale. A peering request from a network they feel is much smaller or less important may seem to diminish their own importance. Peering with the smaller network might diminish their network in the eyes of their colleagues.

Creating incentives to peer

Networks who would like to peer are frequently turned down for a variety of reasons, including those in the previous section. The long-term benefits of peering (e.g., cost savings, performance enhancements, and scalability) drive many networks to take unintuitive or even harmful (in the short term) steps in order to induce potential partners to peer. Some of these strategies include:

- *Force traffic over (expensive) transit:* Because of the reasons mentioned above, providers will frequently turn down peering requests from networks who are customers of existing peers. An obvious response for that customer, if they can control the routing of their traffic, is to cause their traffic to/from the prospective peer to route over the peer's transit connection to raise the peer's transit costs in order to induce it to peer. This response only works when the peer in question is not a Tier 1 network, since Tier 1 networks have no transit. This response is a game of "chicken", since it may raise the cost for both parties.

• *Lower performance:* If a provider refuses to peer, a network may direct traffic to a smaller link, or not upgrade an existing one. If the link reaches capacity, it will precipitate congestion, which means packet loss, high latency, and performance degradation. Similarly, the network may direct traffic through trans-oceanic lines (e.g. From London to Paris through New York), which increases latency and lowers throughput. Again, the basic idea is to raise the costs until the prospective peer agrees. And, as before, this strategy can raise both agents' costs.

• *Move traffic away:* Most large networks do not have the majority of traffic sourced from or terminated on their own AS, but on the prefixes of their transit customers. Customer prefixes are often not single-homed, and hence there is more than one path to the customer. Say Network A asks to peer with Network Z, and Z denies the request. A may find some large customer of Z, C, to which A is sending a large amount of traffic through Z. It may be possible for A to find a second path to C. This other path may involve directly peering with the C, finding another transit path, or peering with a second transit provider of C. A special case of this strategy is called "doughnut peering". This is where a provider will intentionally seek out and peer with all of a network's downstream customers or their second transit provider, removing the incentive to peer with the network itself, and potentially harming Z through loss of revenue.

• *Cross geographic boundaries:* Although most large networks will not peer with small or medium sized networks, a smaller network which makes a large investment, such as crossing an ocean to meet the larger network, may get an exemption to the Peering Policy of the larger network.

• *Interesting prefixes:* If a network has something on its network that is interesting for the potential peer, this can shift the bargaining. For example, a network with a Root Name Server will increase its chance of peering.

Strategies to remain in compliance with policy

ISPs also employ multiple strategies in order to sustain settlement-free peering agreements. These include:

• *Traffic engineering:* The term "traffic engineering" refers to the collection of management decisions an ISP makes, including the local configuration of the way the Internet routing protocol (BGP) works, to allocate traffic to the different paths they control. Traffic engineering techniques can be used to keep peering traffic ratios within balance by, for instance, directing traffic over transit which could have been served through peering.

- *Buy additional services:* Most network providers do not supply just full transit but instead have a whole portfolio of products for sale. A non-complying partner may purchase some of these additional services as a way to preserve a peering relationship.

- *Incentives to customers:* Some networks will offer incentives (low price or even free transit) to customers who will help correct a policy violation. It is common for large content networks to charge different prices to "eyeball" and "content" end-customers.

- *Threat of disconnection:* If the only path to a network is over the peering links (i.e. neither network purchases full transit), then shutting down peering will cause disconnection between the two networks. This gives a very large incentive to continue peering.

■ Bilateral negotiations, market-failure and entry of CDNs

As we attempted to demonstrate above, the Internet is a network of networks and provisioning end-to-end service involves many multiparty negotiation challenges. However, various entities in the Internet have learnt how to coordinate, albeit more inefficiently, using and designing various standardized bilateral contracts so as to ensure a "best-effort" service. The scalability and stability of end-to-end interconnections in the Internet has been dependent on the stability of this underlying bargaining mechanism that implements only a restricted set of transfers.

However, the collective price paid for the limitations inherent in building an end-to-end Internet from a collection of bilateral bargains has been the lack of services (QoS, multicast) that might arguably benefit all, because values can be better internalized. Failure to internalize realizable demand is best demonstrated with the entry and growth of Content Distribution Networks (CDNs). As noted earlier, large content providers, and at times content consumers, may be presumed to have a high willingness to pay for better than best-effort packet transport services, However, incumbent ISPs have consistently failed to coordinate and service this end-to-end demand. This market failure helped provide entry incentives for third party CDNs (see CLARK *et al*, 2005, or HOFFMAN & BEAUMONT, 2005) who invest in caching technologies, hosting content closer to the "eyeballs" thereby reducing transit costs. As we have argued elsewhere CDNs in effect transform the single principal (the end-host content provider) multiple agent (packet transport ASes) coordination problem into a single-principal (the content provider), single agent (the CDN) who in turn becomes the single principal interacting with multiple agents (packet transport ASes). A CDN as a principal internalizes the (provisioning, monitoring and enforcing) transaction costs of bargaining with the transport ASes, but benefits from strong economies of scope and scale. [8]

■ Conclusions and future work

The Internet is a network of networks, comprised of entities called Autonomous Systems (ASes) that are semi-autonomous administrative domains managed, in many cases, by commercial entities known as ISPs. How these ASes are interconnected influences how traffic is routed across the Internet, the reachability of content, and the services that can be supported. In addition to helping to determine the physical routing of packets, the business agreements by which ASes are interconnected also serve to route value transfers between and among ASes.

Historically, there were two dominant types of interconnection agreements: settlement-free peering and transit. Interconnection can be roughly described by a hierarchical model in which smaller ISPs purchased transit from large ISPs and the largest ISPs exchanged traffic at multilateral (public) or, more commonly, bilateral (private) peering points. Smaller ISPs, if they saw mutual benefit, could also arrange peering agreements. Under the assumption of approximately symmetric traffic and costs, it made sense for similar ISPs to exchange traffic without any monetary payments. Using only these two types of standardized agreements, the Internet was able to scale and grow substantially in geographic scope, traffic volume, and capabilities.

The fact that the Internet has been able to scale as a network of competing yet cooperating networks, resulting in a relatively stable and robust set of interconnections, is perhaps remarkable. Of particular note is that this has happened in a mostly un-regulated market – in rather dramatic contrast to the legacy of regulation that has characterized interconnection in

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[8] See FARATIN & WILKENING (2006) and FARATIN (2007a) for further discussion.

the PSTN. With the growing commercial importance of the Internet, including its role as a replacement for the PSTN, it is inevitable that various parties will question whether the contracts and mechanisms that have sustained interconnection in the Internet to date will be sufficient to sustain stable interconnection in the future.

The goal of this paper is to provide a richer view of what real-world Internet interconnection looks like, relying in part on contributions from industry practitioners with deep knowledge of what negotiating interconnection looks like on the ground. With the growth of the Internet the diversity of ASes has expanded and the presumption of symmetry has eroded. New types of providers such as content-heavy ISPs such as Abovenet and Cogent and large content providers like Google, Yahoo, and YouTube are interacting with ever-larger eye-ball heavy ISPs like Comcast and Verizon. New types of players like Akamai and Limelight are providing overlay services. These changes lead to traffic patterns that are highly asymmetric, as traffic flows from content to eyeball, and also lead to changing perceptions regarding the symmetry of value flows. In response to this growth and resultant changes in the Internet industry landscape, the range of interconnection contracts have expanded to include greater reliance on paid peering and partial transit, reflecting a filling in of the contracting space.

What this implies for the future of Internet Interconnection is unclear. There is little evidence, aside from a few highly visible events such as de-peering actions, that the range of negotiated contracts, whether discriminatory or not, has harmed the overall connectivity of the Internet. Most users seldom encounter an event where a failure to negotiate an interconnection agreement (as opposed to a failure of a link or a router) keeps them from reaching some part of the network. If there is a failure today, it will be found not in a lack of reachability, but in the failure of certain sorts of providers and services to emerge in the market, potentially due in part to the lack of appropriate mechanisms to manage value flows. Further, as the CDN example demonstrated, under some circumstances such failures may be alleviated by third party entrants with incentives to internalize potential value-flows from indirect externalities. The discovery of additional hypothetical failures would require more work than we have been able to undertake. However, it is worth considering the possibility that different sorts of value flows (e.g. from the advertiser toward the consumer) might help to increase the penetration of consumer uptake of broadband by reducing the cost of broadband access. Advertising subsidizes the media industry, so it is not intrinsically inappropriate to ask whether such an outcome could also happen in the Internet.

We also have a cautionary conclusion: if one should be motivated (for whatever reason) to contemplate some regulatory rule to manage interconnection, the design of such a rule will be both complex and informationally demanding. Partial transit and paid peering may be seen as efficiency-enhancing responses to changing market conditions. While there may be opportunities for abuse by providers with excessive bargaining power, the complexity of what is in place today, and what seems to be working today, would argue that the best way to address any potential concern would be to focus on the sources of bargaining power and identify anti-competitive opportunism, rather than to impose *ex ante* restrictions on the range of bilateral contracts.

Other actions, both by industry and academia, could be contemplated. For example, it is clear that the commonly understood, "old-fashioned" model of peering and transit reduced bargaining costs, which is efficiency enhancing. If it were possible to bring a "best practice" or "common practice" in interconnection out from the non-disclosure agreement and into the light, this might also help reduce bargaining costs, but in a more flexible way than might be achieved via regulatory constraints. An industry forum that tried to discuss this openly (and which was given a clear mandate for how to behave so as to avoid anti-trust concerns) might offer a substantial contribution to efficient operation of this asymmetric world, and might mitigate the sorts of fears that have prompted calls for more direct regulation. Neutral development of cost models and hypothetical value flow might inform such a forum. Lack of real data and available cost models hinder any academic contribution to the efficiency of this process.

For the future, the growth of multimedia traffic, including delay-intolerant applications such as voice-over-IP (VoIP), will imply a growing need for differentiated quality of service (QoS) to accommodate the requirements of different types of traffic. The lack of QoS support in the legacy "best efforts" Internet has quite possibly hindered the emergence of some applications that demand enhanced services, and the ability to cache content enabled innovation in content distribution and facilitated the rise of Content Distribution Networks. We can speculate that there may be new sorts of applications that cannot be supported using CDNs or built by exploiting application-level interconnection with other kinds of networks such as the PSTN. In order for such applications to emerge, the community of ASes will need to coordinate and provision better end-to-end services. Tier 1 ASes have begun to implement interprovider QoS over peering links to support VoIP. Interconnections are also emerging for interprovider VPNs, developments that may signal the need for more efficient coordination and contracting mechanisms by ASes, perhaps as packet-transport continues to become a commodity market.

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