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2016 Survey of Internet Carrier Interconnection Agreements

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Introduction

The Internet, or network of networks, consists of 7,557 Internet Service Provider (ISP) or carrier networks, which are interconnected in a sparse mesh.[1] Each of the interconnecting links takes one of two forms: transit or peering. Transit agreements are commercial contracts in which, typically, a customer pays a service provider for access to the Internet; these agreements are most prevalent at the edges of the Internet, where the topology consists primarily of singly connected “leaf” networks that are principally concerned with the delivery of their own traffic. Transit agreements have been widely studied and are not the subject of this report. Peering agreements – the value-creation engine of the Internet – are the carrier interconnection agreements that allow carriers to exchange traffic bound for one another’s customers; they are most common in the core of the Internet, where the topology consists of densely interconnected networks that are principally concerned with the carriage of traffic on behalf of the networks which are their customers. This report examines and quantifies a few of the characteristics of the Internet peering agreements between those carriers.

The Survey

Packet Clearing House first conducted this survey in 2011 as input to the OECD’s 2013 Internet regulatory recommendations.[2] Over the past five years, the 2011 survey has been downloaded more than 500,000 times and cited in hundreds of research and policy papers. At the time, we promised to repeat the survey every five years in order to build time-series data about the global state of Internet interconnection. We have made every attempt to keep numbers directly comparable between the 2011 report and this one, while adding new analyses that we expect to repeat in comparable form in 2021.

In preparing this report, we analyzed 1,935,822 Internet carrier interconnection agreements. We collected our data by voluntary survey, distributed globally through the regional Network Operators Groups and Regional Internet Registries in September 2016. For each agreement, in addition to the identities of the carriers party to the agreement, we asked the following four questions:

- Is the agreement formalized in a written document, or is it a “handshake” agreement?
- Does the agreement have symmetric terms, or do the parties exchange different things?
- What is the country of governing law of the agreement?
- Is IPv6 traffic being exchanged between the parties?

Of all characterized agreements, 955,510 (49.35% of the total) comprised 477,755 matching pairs in which both parties to the same agreement responded to our survey, and in 98.71% of those cases both parties’ answers to each of the questions were in agreement. We believe that, among other things, this indicates that respondents understood the questions clearly and were able to answer unambiguously and accurately. We note that the rate of agreeing responses decreased slightly from 99.52% five years ago, and we attribute that to the addition of the IPv6 question. The more questions we ask, the more opportunities exist for disagreement between each pair of answers.

In addition to the survey, we conducted unstructured follow-up interviews with 35 of the responding networks, to garner additional detail and comments on observed trends.

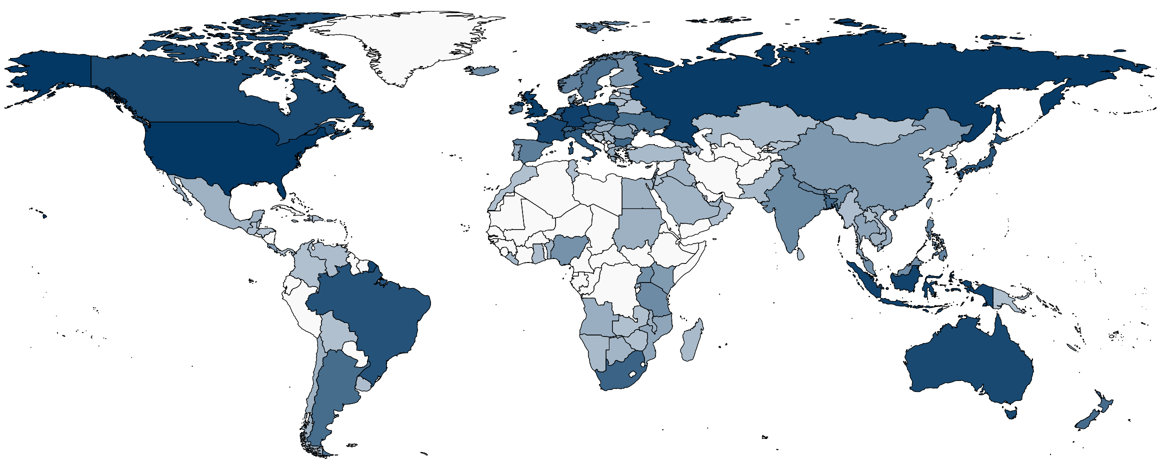

Figure 1: Geographic distribution of the networks represented in the dataset. Darker shading indicates a larger absolute number of networks represented in the dataset,.

The responses we received represented 10,794 different networks, incorporated in 148 countries, including all 35 OECD member countries and 21 of the 48 UN Least Developed Countries. That latter number is of particular note since it represents a threefold increase from the seven LDCs represented in the 2011 dataset. The increase was principally among African LDCs, nine of which had 100% response rates. Figure 1 shows the geographic distribution of the absolute quantity of responses per country; it is not normalized by number of carriers within each country, so although the darkest countries had the largest number of respondents, they often did not have the largest proportion of respondents relative to the number of carriers incorporated in those countries.

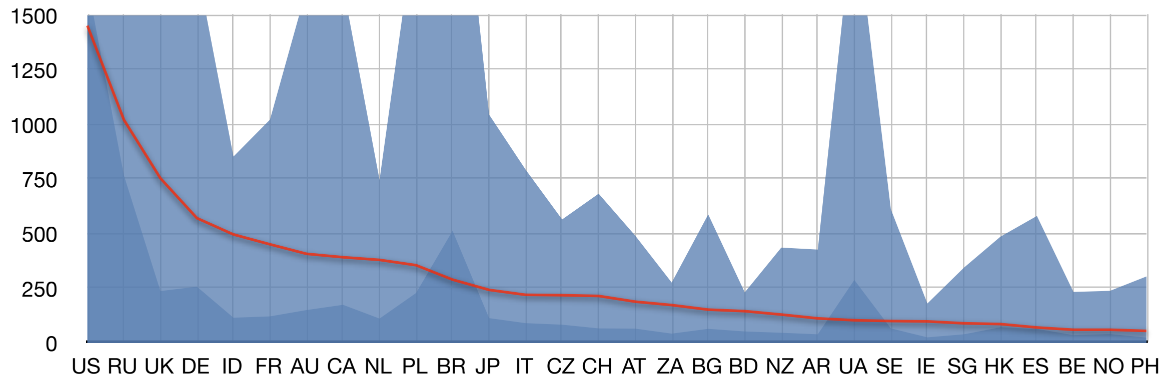

Figure 2: Top thirty countries of incorporation of the represented networks (X-axis), where the red line indicates the number of networks represented in the dataset, the darker blue area indicates the number of transit network present in each country, and the lighter blue area indicates the total number of networks including non-transit networks (Y-axis).

As in 2011, the largest number of networks represented in the dataset were incorporated in the United States (1,454, up from 466 in 2011), followed by Russia (1,022, up from 337), the United Kingdom (755, up from 239), and Germany (572, up from 209), and their order in our rankings did not change relative to five years ago. In 2011, the fifth-most represented country was Brazil, with 165 networks; this year Brazil fell to eleventh place, with 290 networks, and fifth place was taken by Indonesia, with 497 networks. As in 2011, a little less than half of the countries (42%) were represented by three or fewer networks. The darker blue area in Figure 2 indicates our best estimation of the total number of transit networks incorporated in each country, the lighter blue area shows the total number of networks, and the red line indicates the number of networks represented in the responses to our survey. In most countries, all or a significant majority of the transit networks are represented in our data. The countries of significant size but with particularly low coverage were India (50 responses covering 15% of transit networks), Romania (28 responses covering 13% of transit networks), and Thailand (21 responses covering 13% of transit networks).

Informal Agreements

Of the total analyzed agreements, 1,347 (0.07%) were formalized in written contracts. This is down from 0.49% in 2011. The remaining 1,934,166 (99.93%) were “handshake” agreements in which the parties agreed to informal or commonly understood terms without creating a written document. The common understanding is that only routes to customer networks are exchanged, that BGP version 4 is used to communicate those routes, and that each network will exercise a reasonable duty of care in cooperating to prevent abusive or criminal misuse of the network.[3] These numerous informal agreements are arrived at by the “peering coordinators” or carrier-interconnection negotiation staff of the networks, often at self-organized regional or global “peering forums” that take place many times each year.[4] Several of the respondents who participated in follow-up interviews noted that they expected the portion of written contracts to continue to decline over time because, in many cases, existing written contracts were expiring as their defined terms passed or their original signatories were subsumed, and although the relationships continued to grow on an informal basis, the written contracts related to them were not being renewed.

Symmetric Terms

Of the agreements we analyzed, 1,935,111 (99.98%) had symmetric terms, in which each party gave and received the same conditions as the other. Only 403 (0.02%) had asymmetric terms, in which the parties gave and received conditions with specifically defined differences, and these exceptions were down from 0.27% in 2011. Typical examples of asymmetric agreements are ones in which one of the parties compensates the other for routes that it would not otherwise receive (sometimes called "paid peering" or "on-net routes"),[5] or in which one party is required to meet terms or requirements imposed by the other ("minimum peering requirements"), often concerning volume of traffic or number or geographic distribution of interconnection locations (see the section "Market-Dominant Incumbents" below).[6] In the prevailing symmetric relationship, the parties to the agreement simply exchange customer routes with each other, without settlements or other requirements.[7]

IPv6 Routing

Of the agreements we analyzed, only 74,886 (3.88%) reported the exchange of IPv6 traffic, whereas 1,854,411 (96.12%) were not. We were unhappily surprised to see so few respondents routing IPv6. In five years, we hope to see significant progress there, and that seems possible given the combination of IPv4 address exhaustion and the rate at which major content providers are beginning to support IPv6 and mobile operators are migrating their customers to IPv6.

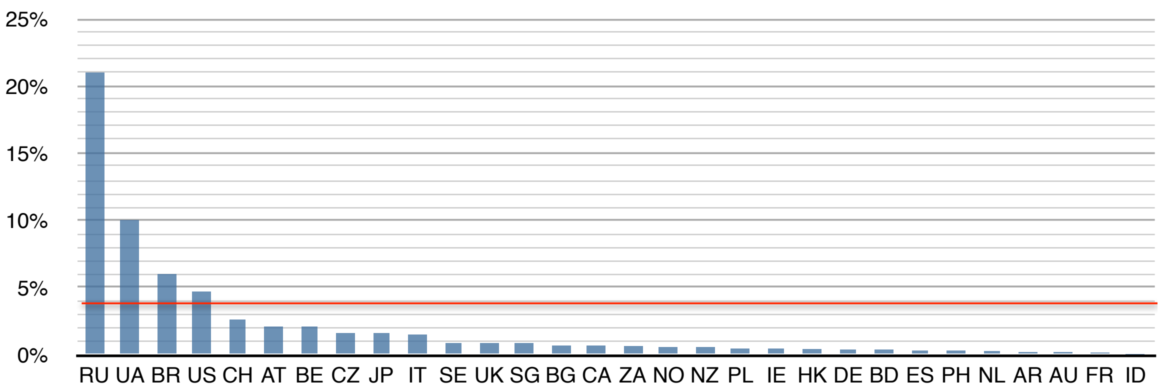

Figure 3: Top thirty countries of incorporation of the represented networks (X-axis), by percentage of networks reporting routing of IPv6 traffic (Y-axis). The red line indicates global average of 3.88%.

Of the thirty most represented countries in our dataset, Russia had the highest average rate of IPv6 routing at 21%, followed by the Ukraine at 10%, Brazil at 6%, and the United States at 4.7%. Every other country in the top thirty fell below the global average of 3.88%. If we look at all countries in which at least one network reported its IPv6 routing status, 44 of 144 countries (31%) fell above the global average, and 100 (69%) fell below the global average.

If we look at individual responding networks rather than aggregating by country, we find a huge discrepancy between IPv6 support in large and small networks; all of the dozen largest respondents were routing IPv6; they were, on average, advertising more than 100 IPv6 prefixes each and supported IPv6 with nearly 70% of their peers. By contrast, if we look at the bottom half of the respondents, 92.5% of them had no IPv6 peers or prefixes at all, they averaged 0.44 IPv6 prefixes, and they supported IPv6 routing with 0.15% of their peers.

Although very few Internet Exchange Points (IXPs) report IPv6 bandwidth production numbers independently of their totals, the rates of IPv6 support in interconnection agreements appear to track IPv6 bandwidth production rates, as we expected. Of the Moscow IX's bandwidth production, 17.5% is IPv6, as compared to 21% of Russian peering agreements; 4.75% of the Seattle IX's bandwidth production is IPv6, as compared with 4.7% of American peering agreements; and 2.1% of the Amsterdam IX's bandwidth production is IPv6, as compared with 0.2% of Dutch peering agreements. Assisting IXPs in reporting IPv6 production statistics is the subject of ongoing PCH work, so we anticipate making this correlation more definitively in our 2021 survey.[8]

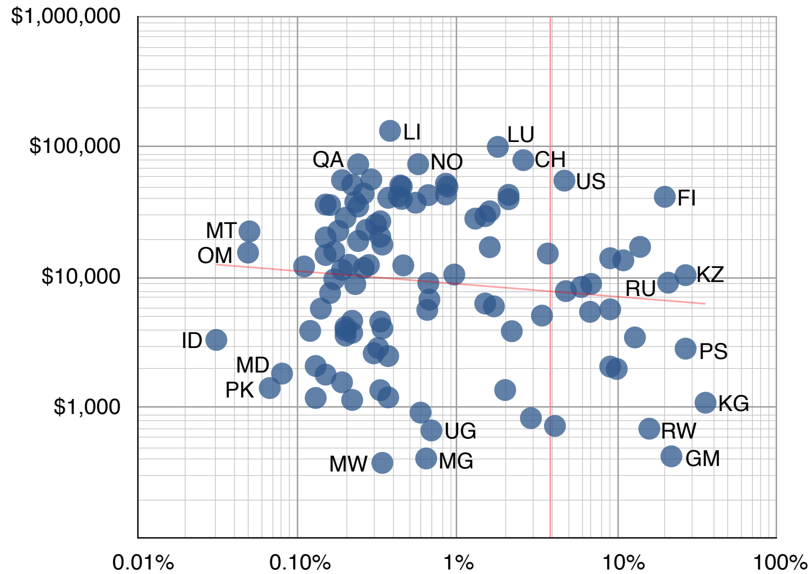

Figure 4: Percentage of responding networks routing IPv6 traffic within each country (X-axis, log scale) by GDPPP of those countries (Y-axis, log scale). The vertical red line indicates the global average of 3.88%, and the sloping red line is an essentially meaningless best-fit trend for the observed data points.

Most measures of Internet infrastructure development track relatively closely with other indicators of industrial and economic development, but we did not discover any clear correlation between density of IPv6 support and any other obvious measures. Figure 4, for example, shows that there is no discernible correlation between gross domestic product per capita (GDPPP, often a good proxy for state of Internet technical development) and IPv6 routing among respondents. Generally, the geographic cluster of Russia, the Ukraine, Finland, Belarus, and the three Baltic states stood out as both having significant IPv6 support of 10% or better and being of statistically significant size.

Governing Law

In only a tiny number of cases were interconnection agreements reported to utilize a country of governing law that was not also the country of incorporation of one of the two carriers party to the agreement. Typically these were agreements predating mergers or acquisitions that resulted in a new country of incorporation of the new parent organization. The only significant exceptions were several agreements with Chinese networks that utilized the law of the Hong Kong Special Autonomous Region rather than mainland Chinese law; because we used ISO3166 country-codes for tracking countries of incorporation and governing law, we tracked Hong Kong and China with separate codes, HK and CN. In our 2011 survey there were no cases in which the parties chose a country of governing law that was not one of their own then-current countries of incorporation. The 2016 survey's Chinese examples notwithstanding, this is still an extremely uncommon practice, amounting to less than one thousandth of one percent of cases. Contrast this with other areas of commerce in which countries tailor regulatory or legislative environments to attract business, as, for example, the registration of much maritime shipping in Panama or banks in Switzerland.

Clear governance preferences were expressed in the data, with the distribution of countries of governing law being sparser than the distribution of countries of incorporation and operation. In other words, some countries' governing law was preferred to a different degree than their frequency as a country of incorporation would suggest.

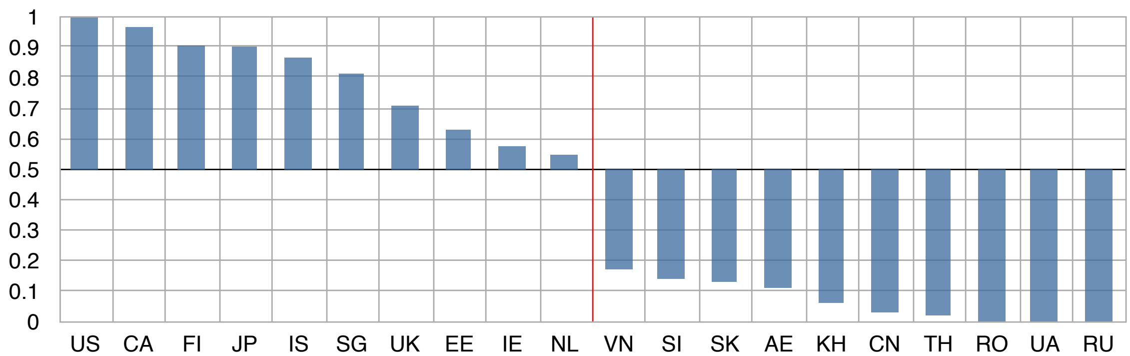

Figure 5: Probability of selection as a country of governing law (Y-axis) of the ten most likely and ten least likely countries (X-axis). The red line in the center represents the many intermediate countries that are not shown.

When we compare the frequency of appearance as a country of incorporation to the frequency of selection as a country of governing law (Figure 5), in nearly every interconnection agreement in which one of the two parties is incorporated in the United States or Canada, that country is selected as the country of governing law. At the opposite end of the spectrum, there were no agreements in the dataset in which Russia, the Ukraine, or Romania was selected to supply governing law for an agreement with a country outside this group of three, even though 588 Russian, 60 Ukrainian, and 16 Romanian networks are represented in the dataset. In each case of a Russian, Romanian, or Ukrainian network agreeing to interconnect with a foreign network, the parties elected to use the other country's governing law.

National Interconnection Partners

Looking solely at the frequencies with which pairs of countries of incorporation appear within the dataset, it is possible to chart the relative number of connections between any country and all others. By way of example we chart the most frequent interconnection partners of the four countries most represented in our dataset – the United States, Russia, the United Kingdom, and Germany (Figures 6 –10).

Typically, larger countries have a large proportion of domestic interconnection and a large number of international interconnection partners, each of which accounts for a small portion of the total. The United States (Figure 6) is relatively typical, although it interconnects internationally more than other countries of similar size.

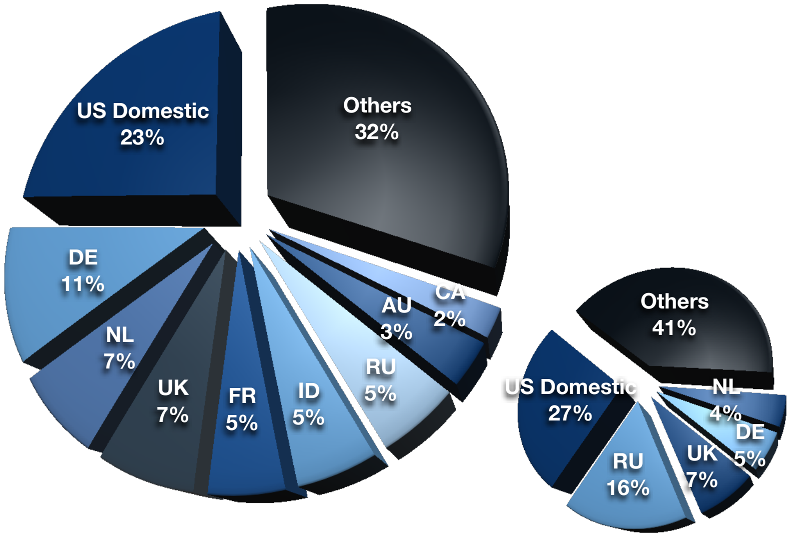

Figure 6: Nationalities of U.S. networks' interconnection partners, IPv4 (large graph) and IPv6 (small graph)

As seen in Figure 7, Russia's 182,424 domestic IPv4 interconnections and 72,104 domestic IPv6 interconnections dwarf those of the other three countries examined in detail here; in terms of domestic-to-international connection ratio, Russia looks more like number five Indonesia. It has more than twice as many domestic IPv4 interconnections as the United States, and more than twenty-five times as many domestic IPv6 interconnections. This success is due primarily to Russia's numerous large IXPs, each of which has a multilateral peering agreement (MLPA) with a high rate of participation. Russia is also second only to the United States in number of international interconnections.

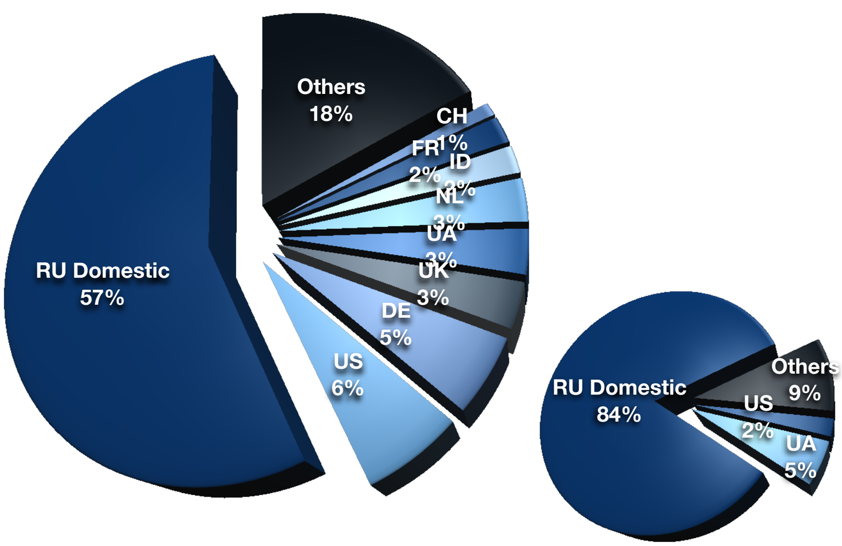

Figure 7: Nationalities of Russian networks' interconnection partners, IPv4 (large graph) and IPv6 (small graph)

In 2011 we observed a relatively small share of domestic interconnection agreements within Russia, which we attributed to a selection bias in the dataset rather than to actual conditions on the ground; this year, with a much richer response from Russian networks, we believe we are seeing a much more accurate picture of the Russian domestic interconnection situation.

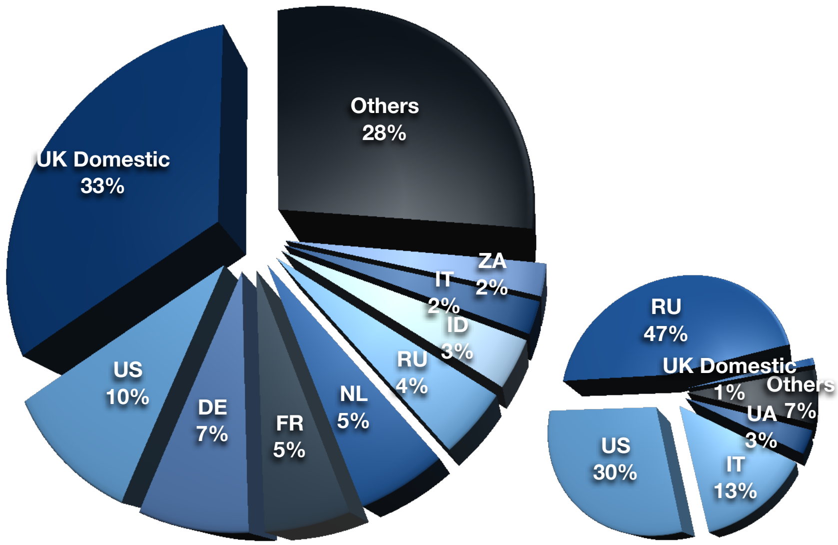

Figure 8: Nationalities of U.K. networks' interconnection partners, IPv4 (large graph) and IPv6 (small graph)

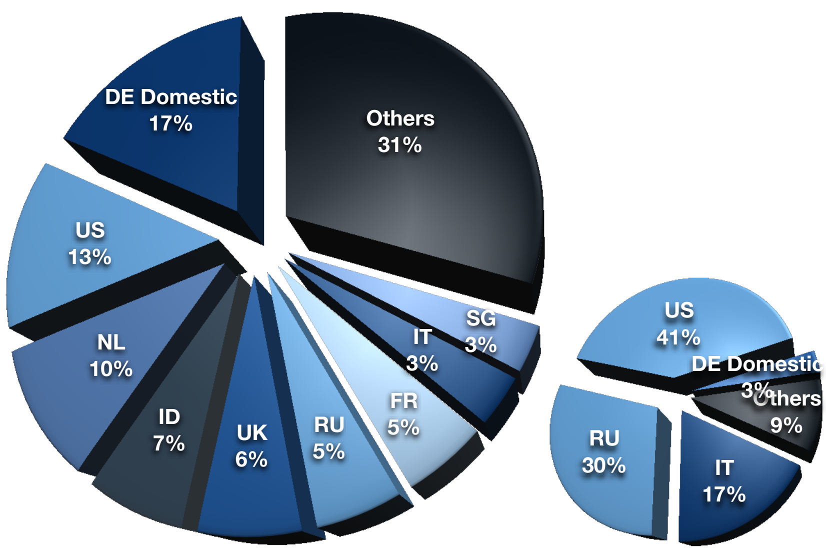

Figure 9: Nationalities of German networks' interconnection partners, IPv4 (large graph) and IPv6 (small graph)

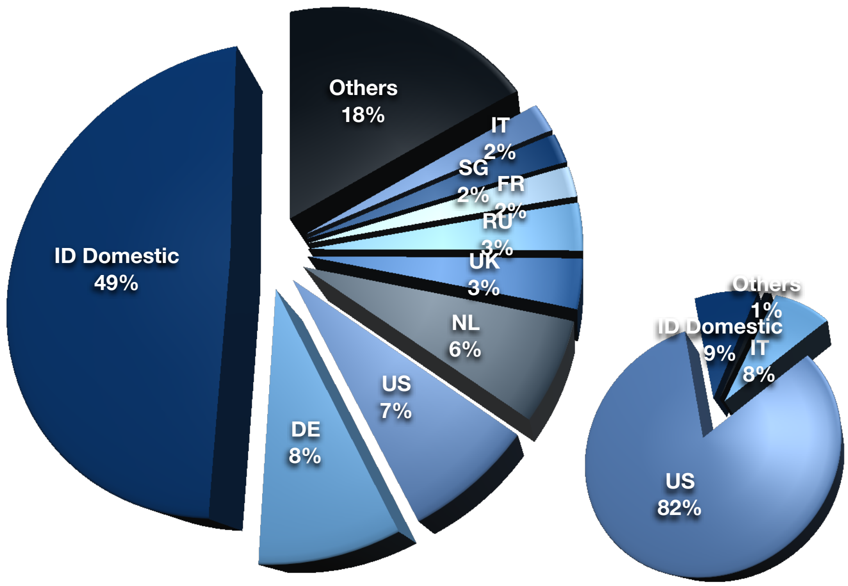

Figure 10: Nationalities of Indonesian networks' interconnection partners. IPv4 (large graph) and IPv6 (small graph)

As one would expect, linguistic cohorts, geographically proximal neighbors, and frequent commercial trading partners tend to be favored in these pairings.

The ratio between domestic interconnection agreements and international agreements varies considerably from country to country. It's tempting to seek a simplistic explanation for these differences, but they reflect a complex interplay between amount of domestic bandwidth production, amount of domestic consumption, and degree of import/export trade, among other factors. There are, however, some interesting trends that can be picked out by eye from Figure 11.

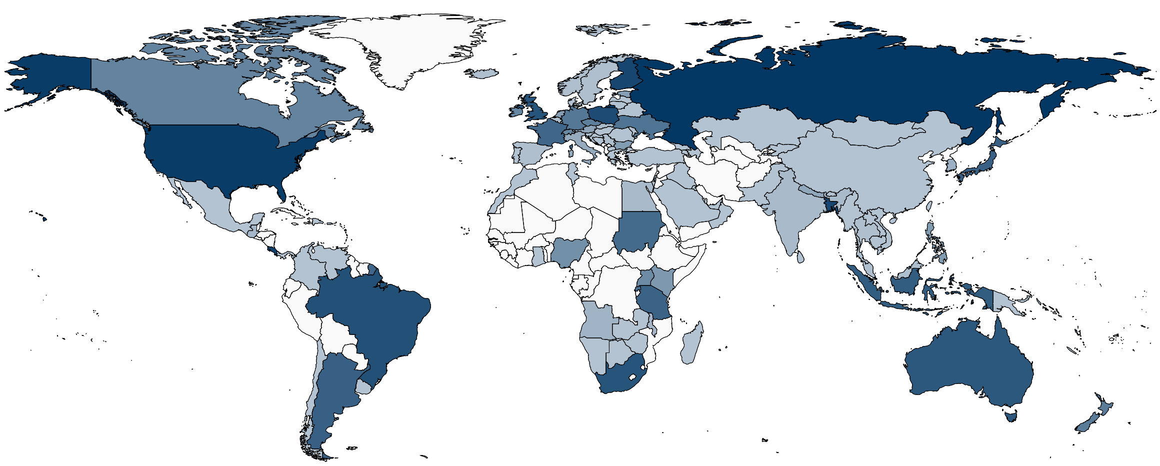

Figure 11: Ratio of domestic interconnection to international interconnection. Darker shades indicate higher ratios. White means we have insufficient data to code the country.

Countries that have both large domestic bandwidth production and large domestic consumption tend to be internally well connected, in order to transport that bandwidth between users. Thus in Figure 11 the United States, Russia, Brazil, Indonesia, Australia, Argentina, Finland, Poland, and South Africa show up relatively dark, not because they have little external connectivity but because they have much more internal connectivity. Some small countries with well-developed

IXPs but very small populations or economies also fare well: Bangladesh, New Zealand, Sudan, and Tanzania fit this niche. By contrast, countries with little or no domestic production capacity but a population or economy to support high consumption tend to have many international connections, particularly when they neighbor a large producer. Thus Chile next door to Argentina, Uruguay sandwiched between Brazil and Argentina, Colombia next to Brazil and near the United States, Mexico bordering the United States, Namibia and Madagascar near South Africa, Morocco and Egypt just across the Mediterranean from Europe, the entire Persian Gulf heavily dependent upon European production, and much of Southeast Asia dependent upon its more industrialized neighbors to the northeast.

Degree of Interconnection

Many of the networks represented have small numbers of interconnection partners. 35% have ten or fewer interconnection agreements. The good news is that this figure is down from 62% five years ago. At the other end of the spectrum, the dozen largest networks range between 2,200 and 4,500 peers, up from a range of 700 to 2,400 peers five years ago. So not only has the number of ISPs increased nearly fourfold in the past five years, the average number of reported interconnections per network has increased from an average of 77 and median of 5 in 2011 to an average of 292 and median of 81 today. This demonstrates a dramatic improvement in the density of interconnection in the sparse mesh of the Internet, which translates to more direct and efficient paths between endpoints. The vast majority of this improvement can be attributed to the continued growth of multilateral peering agreements.

Multilateral Peering

Multilateral peering, the exchange of customer routes within groups of more than two parties, has long been characterized as a practice principally engaged in by smaller networks. It has been commonly assumed that large networks decline to participate in multilateral peering agreements (MLPAs), and that multilateral agreements are therefore outside of the mainstream of peering practice. Although the method by which we collected our survey data does not allow us to compare absolute quantities of bilateral agreements to multilateral agreements, the majority of the AS-pairs we observed were instantiated in multilateral agreements, and many of those agreements were very large.

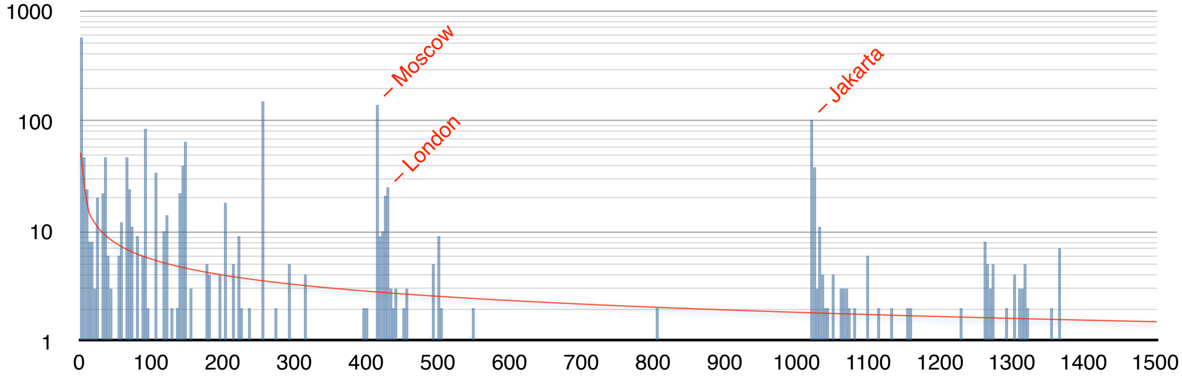

Figure 12: Distribution of number of networks (Y-axis, log scale) with each quantity of interconnection partners (X-axis, linear scale). The 112 largest networks with more than 1,500 interconnection partners are not shown.

As in 2011, a number of “spikes” are visible in the distribution graph (Figure 12), with major ones appearing clustered after the values 418, 452, and 1,021. These are the effect of large MLPAs,, specifically those associated with the Moscow, London, and Jakarta IXPs. Shorter-peaked clusters are typically the effect of common combinations of MLPAs. For instance, there are ISPs that participate in the MLPAs of both major London Internet exchanges, LINX and LoNAP, which together yield a total of 574 peers.

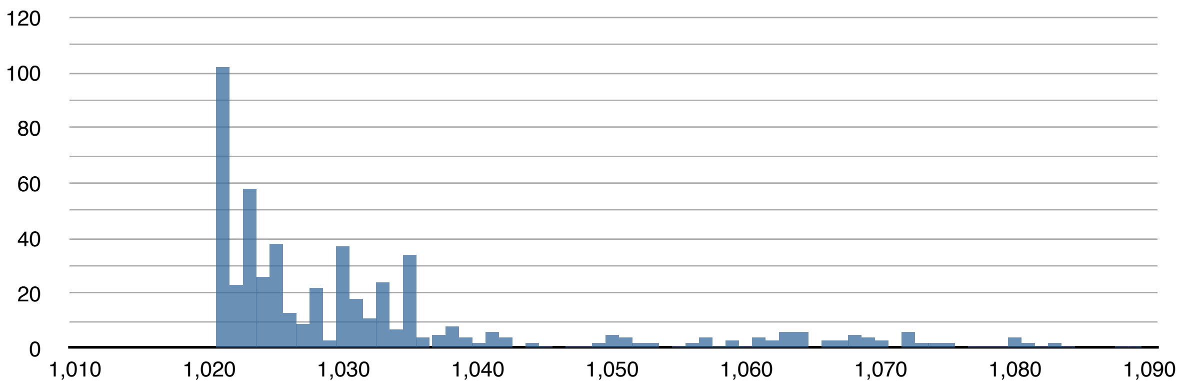

Figure 13: Expanded view of the number of networks with each quantity of interconnection partners (Y-axis, linear scale) in the range 1,010 –1,090 (X-axis, linear scale) from Figure 12, detailing Jakarta’s Matrix-IX MLPA.

In each case, a large number of networks all peer with each other, creating a spike at that value, which trails off as a function of the portion of those networks that also have other interconnection agreements outside of that MLPA. The volume of the tail to the right of the spike’s peak is thus a rough indicator of the maturity of the participants of the MLPA, though it does not speak to the age of the MLPA itself. Generally speaking, MLPAs are identifiable in Figure 12 as spikes that have a Y-axis value similar to the volume under their curve. In Figure 13, the peak at the left side is at 1,021 on the X-axis and 102 on the Y-axis, and the volume under the appreciable curve is 572,561. Since $1{,}021^2$ is 1,042,441, we can deduce that we are seeing slightly more than 50% of the participants of Jakarta’s Matrix-IX MLPA between the range 1,021 and 1,089, while the others form a “long tail” scattered throughout the range above 1,089. Without more complicated analysis, we cannot distinguish the specific portion, because the larger participants of other smaller MLPAs that exist further to the left on the X-axis are themselves scattered throughout this range, contributing to it in a small but unknown degree.

It is important to remember that if two ISPs both participate in two different MLPAs they create value and enrich their connectivity, which are what matter economically. But they do not contribute a new peering agreement to our survey or a new AS-level adjacency to our statistics. So the $1{,}021^2$ adjacencies in Jakarta, the 452^2 in London, and the 418^2 in Moscow are not additive, they are overlapping to some significant degree, and those in London, Amsterdam, and Frankfurt are overlapping to a very large degree.

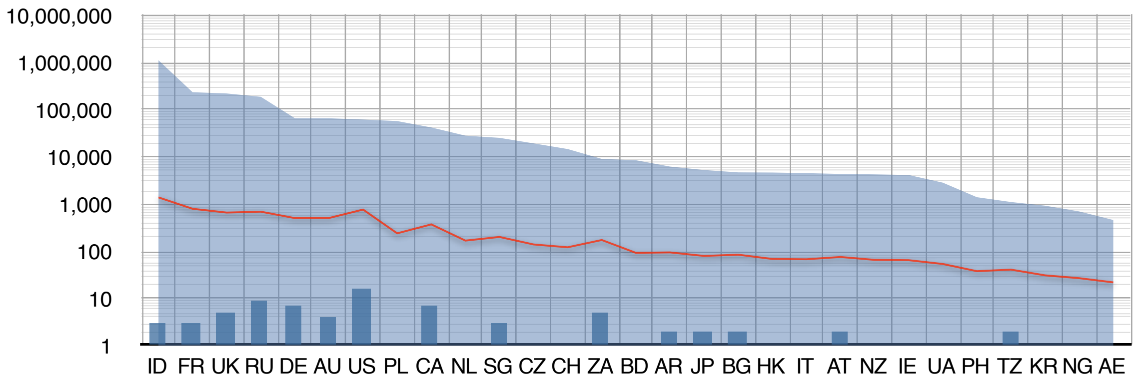

Figure 14: The thirty countries that benefit most from MLPAs (X-axis), showing number of MLPAs in the country (bars), number of networks participating in those MLPAs (red line), and the number of network adjacencies produced (blue area) on the Y-axis.

By looking more closely at the distribution of MLPAs and their users on a country-by-country basis (Figure 14), we can readily see the reason for Indonesia's rapid growth in the past five years. Indonesia has the world's largest, fifth-largest, and twenty-second-largest MLPAs, all in Jakarta, coupling the world's fourth largest population and sixteenth largest economy with more than 1,000 ISPs to create a formidable engine of economic growth. France, similarly, benefits from having the world's fourth-, seventh-, and ninth-largest MLPAs. The United States, Russia, Canada, and Germany have large numbers of MLPAs which, with continued growth, will produce good results in the future, but those MLPAs have not yet individually achieved the popularity of those in Jakarta, and the benefit of an MLPA scales as the square of its size, so size matters greatly.

Just as "donut peering" overtook "tier-1" peering in the late 1990s, multilateral peering has now overtaken bilateral peering in number of AS-adjacencies, although the jury is still out on whether there is a corresponding volume of traffic.[9] In both cases, market-dominant networks loudly derided as "peripheral" a practice that sought to render them irrelevant, but that practice slowly gained prevalence over time, becoming mainstream without ever receiving much attention. As an example, the 33 participants in the Dar es Salaam Internet Exchange MLPA represent 1,056 interparticipant adjacencies, and *each one* of those participants individually exceeds the average "tier-1" carrier in degree of interconnection. When articulated in writing, MLPAs tend to follow the same general form and terms as other peering agreements, with the sole exception of having more than two parties.[10]

Although we fully expected to see continued growth of multilateral peering, both in number of agreements and in the size of each agreement, we were surprised to find that the largest of the MLPAs had passed 1,000 participants and interested to see that a practical consequence was Indonesia's dramatic rise in many of our statistics. We suspect that the focus Russian, French, Canadian, and other IXPs are putting on MLPAs is likely to result in a further acceleration of the predominance of multilateral peering, and it may be that when we do the survey again in 2021 this will be accepted as common knowledge rather than a surprise to many people in the Internet industry.

Market-Dominant Incumbents

In any market, dominant parties may engage in practices intended to retain or strengthen their dominance or to capitalize upon it. One form of such behavior which occurs in the Internet bandwidth market is clearly visible in our statistics.

Large institutional customers of Internet bandwidth are typically “multi-homed,” meaning that they receive their Internet bandwidth from multiple suppliers and thus are not critically dependent upon any individual carrier’s network. Maintaining multi-homed routing has many advantages, but it also introduces a degree of complexity and managerial overhead that must be supported. The vast majority of Internet bandwidth customers (such as customers of “residential broadband” or mobile Internet service) are “single-homed,” meaning that at any given time each of their devices is connected to the Internet through a single carrier network, to which these customers pay subscription fees. A single carrier that becomes market-dominant by amassing a sufficient portion of these customers could attempt to extract excess rent. But extracting that rent directly from its own customers would incentivize the customers to switch carriers, which would lead to the carrier losing its dominant position. So, instead, if the dominant carrier has a sufficiently large number of single-homed customers who can be reached only through that carrier, it may take its own customers hostage as a way to extract rent from third parties, like this: The carrier’s customers are connecting to the Internet in order to communicate with third parties, some of whom also have commercial relationships of other sorts with those customers, and some of whom are served by other carriers. In either case, the dominant carrier proposes to the third parties, and their carriers, that communication with the customers will be possible, reliable, or sufficiently fast only if fees are paid by these non-customers to the carrier. These fees are usually termed “paid peering” or “on-net routes” or “partial transit,” or they’re camouflaged through the offering of an “on-net CDN.”

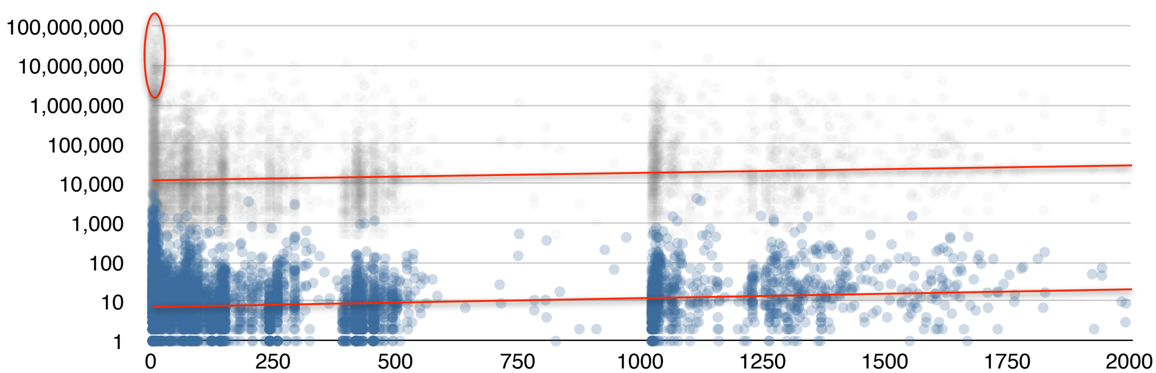

Figure 15: Number of advertised IPv4 prefixes (Y-axis, blue) and IPv4 addresses (Y-axis, gray) over number of interconnection partners (X-axis) per carrier. Red trend lines rising to the right indicate that, in the general case, as carriers get larger in terms of addresses and prefixes they also meet that consumption through creation of more interconnection. The area circled in red contains market-dominant incumbents (between 1M and 133M IPv4 addresses) that depart significantly from this trend.

A normal competitive carrier maximizes interconnection in order to produce bandwidth, because that is the product it is selling to its customers, and more bandwidth permits more and happier customers. As shown by the trend lines in Figures 15 and 16, as normal competitive carriers grow by amassing more customers, they also increase their interconnection relationships proportionately, in order to supply those customers with the bandwidth the customers are purchasing.

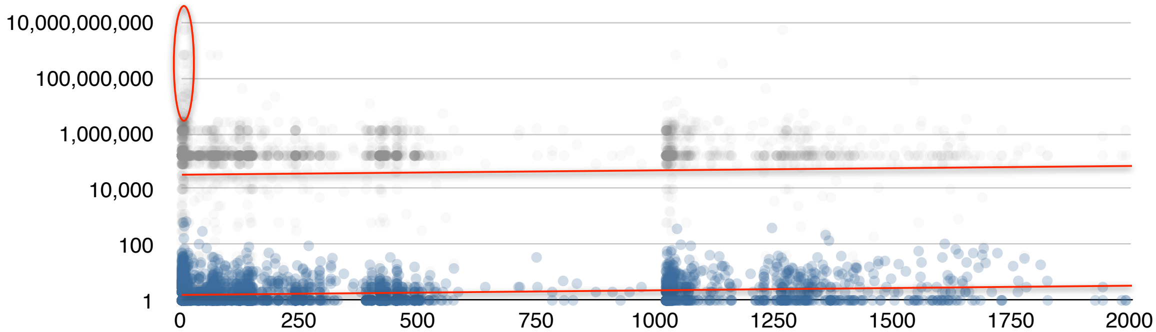

Figure 16: Number of advertised IPv6 prefixes (Y-axis, blue) and IPv6 addresses (Y-axis, gray, divided by 10^{24} for clarity) over number of interconnection partners (X-axis) per carrier. As in Figure 15, the area circled in red contains market-dominant incumbents (between 10^{32} and 10^{34} IPv6 addresses) that depart significantly from this trend.

Abusive market-dominant carriers, by contrast, create artificial scarcity by minimizing interconnection, which in turn minimizes bandwidth. Where it can be supported by lack of competition, this underinvestment in infrastructure and undersupply of bandwidth tends to yield higher profit margins while simultaneously allowing the extraction of rent from the third parties with whom the abusive carrier's customers are trying to communicate. Carriers engaging in this practice are easily spotted statistically (the circled clusters in Figures 15 and 16), since they have both very large numbers of single-homed customers and disproportionately small numbers of interconnections with other carriers. Out in the real world, they may also be visibly making offers to sell "paid peering" to third parties who have no reason to purchase bandwidth from them.

If one were to project the trend lines in Figures 15 and 16 that indicate the average correspondence between size and number of interconnection partners to the right, most of the market-dominant carriers would have many thousands of peers, if they were within mainstream ratios. By contrast, large content-distribution networks ("CDNs"), which have similar scale and degree of infrastructural investment, tend to be exemplars of mainstream trends in our data, with very broad interconnection, both in absolute numbers and in geographic diversity. The practice described here is at the heart of the "network neutrality" debate.

Further Work Necessary

Although outside the scope of the survey as currently constituted, a question we are often asked is how quantities of peering agreements relate to traffic volumes. If there are, for example, five peering agreements between ISPs in Tunisia and Algeria, and ten between ISPs in Kenya and Tanzania, is it likely that there is twice as much traffic crossing the latter? Or, does traffic disproportionately flow between carriers that have written, or asymmetric, agreements? The predominance of IPv6 routing between large networks and its scarcity between small ones certainly suggests that growth of IPv6 traffic could outstrip the growth of IPv6 peering agreements.

This paper and past and future editions may be found at https://pch.net/resources/papers/peering-survey.

[1] The 2011 paper cited the number of transit-providing networks as 5,039, a number derived from Philip Smith's *Weekly Routing Table Report* of April 15, 2011. Philip's analysis code has not yet been updated to handle 32-bit Autonomous System Numbers (ASNs), which were defined in RFC 4893 and gradually introduced into the routing table starting in 2009. As of April 2011, 32-bit ASNs were still scarce enough that they would not contribute significantly to the 5,039 figure, but in November 2016, 28.43% of all allocated ASNs are 32-bit, and more than half of Latin American ASNs are 32-bit. Accordingly, we have switched to calculating the total number of transit Autonomous Systems ourselves, using the union of University of Oregon Route-Views and PCH internal data as the source of our raw data. This ensures a uniform analytical methodology used throughout the survey for distinguishing transit from leaf networks. We calculate a 49.97% increase in transit networks from the number Philip produced five years ago, a compound annual growth rate of 8.44%, a number that is likely very slightly high on account of the 2011 failure to count the few 32-bit ASNs that would have already been present in the routing table then. By switching to an internally produced figure, we can ensure that 2021 numbers will be exactly comparable with 2016 numbers.

[2] Weller, D. and B. Woodcock,, *Internet Traffic Exchange: Market Developments and Policy Challenges*, January 2013: http://www.oecd-ilibrary.org/internet-traffic-exchange_5k918gpt130q.pdf.

[3] For a discussion of standard symmetric peering terms and conditions, read Chris Hall's http://www.highwayman.com/peering/peering_agreement.html. Although much more detailed, the London Internet Exchange's model peering agreement also encapsulates the generally accepted terms of a symmetric peering agreement: https://www.linx.net/good/bcp/peeringagreement_draftv4.html.

[4] For a global schedule of Internet governance meetings, including many peering forums, see http://internetmeetings.org. For specific examples, see the Global Peering Forum website, http://peeringforum.net, or the European Peering Forum website, http://www.peering-forum.eu.

[5] A discussion of MWEB, a South African ISP, transitioning from paid peering to normal peering can be read at http://mybroadband.co.za/news/broadband/16313-MWEB-peering-link-cuts-How-impacts-you.html. Specific solicitations of paid peering can be found on the websites of the AOL Transit Data Network, http://www.atdn.net/paid_peering.shtml; and Cox Communications, http://www.cox.com/peering/paid-peering.asp.

[6] Bill Norton discusses the barriers to entry often contained in "minimum peering requirements" in his *Study of 28 Peering Policies*: http://drpeering.net/white-papers/Peering-Policies/A-Study-of-28-Peering-Policies.html. Original documents can be found on the websites of Comcast, http://www.comcast.com/peering; Tiscali, http://www.as3257.net/peering-policy; AT&T, http://www.corp.att.com/peering; and Internet Solutions, ftp://ftp.is.co.za/tech/peering.pdf.

[7] Definitions and discussions of peering and its general terms can be found on the Packet Clearing House website, https://www.pch.net/wiki/pch:public:glossary#p; Wikipedia, http://en.wikipedia.org/wiki/Peering; and Bill Norton's website, http://drpeering.net/white-papers/Ecosystems/Internet-Peering.html.

[8] See https://pch.net/ixpdir "IPv6" column for percentage of IPv6 bandwidth produced as a portion of the total for each IXP.

[9] "Donut peering" is the practice of small and medium-size networks peering with each other aggressively in order to reduce the detrimental impact of a larger network refusing to peer with them. This results in a "donut" of densely interconnected networks surrounding a self-proclaimed "tier-1" network – the "donut hole" that is poorly interconnected with the networks around it. For a further discussion of donut peering, see the Cook Report's November 2002 *Economics of IP Network Interconnection*, http://www.cookreport.com/backissues/nov-dec2002cookrep.pdf; or Bill Woodcock's January 2003 lecture to the University of Minnesota Digital Technology Center, *Internet Topology and Economics: How Supply and Demand Influence the Changing Shape of the Global Network* http://www.pch.net/resources/papers/topology-and-economics/. "Tier-1" is the moniker some carriers in the mid-1990s gave themselves as they attempted to form a cartel, peering with each other but nominally refusing to peer with any networks outside the cartel. Their misunderstanding of Internet growth rates led them to become irrelevant, as the portion of the market held outside the cartel grew exponentially while that inside the cartel grew in linear fashion.

[10] A range of typical multilateral peering agreements can be found on the websites of the Open Peering Initiative, http://www.openpeering.nl/mlparegistry.shtml and the Indonesia Internet Exchange, http://www.iix.net.id/library/iix-peering-agreement_ind.pdf. Note that their specific terms differ little if at all from those of the bilateral agreements discussed in note 3.