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2021 Survey of Internet Carrier Interconnection Agreements

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Introduction

The Internet, or network of networks, consists of 10,200 Internet service provider (ISP) or carrier networks, 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 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 each other’s customers; they are most common in the core of the Internet, where the topology consists of densely-connected networks that are principally concerned with the carriage of traffic on behalf of their customers’ networks. 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 and repeated the survey in 2016.[2] Over the past decade, the previous editions of the survey have been downloaded more than 1.5 million times and cited in many hundreds of research and policy papers. When we began performing the survey, we committed to repeat it 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 each edition of the report while adding new analyses where warranted.

In preparing this report, we analyzed the characteristics of 15,105,101 Internet carrier interconnection agreements. We collected our data by voluntary survey, distributed globally through the regional Network Operators Groups, Regional Internet Registries, and direct email contact in November 2021.

For each agreement, in addition to the identities of the interconnecting networks, we asked the following four questions, unchanged from the 2016 edition of the survey:

- Are the terms of the interconnection formalized in a written bilateral agreement?
- Does the agreement have symmetric terms?
- What is the country of governing law of the agreement?
- Is IPv6 traffic being exchanged between the parties?

Of the characterized agreements 6,542,240 (43.31% of the total) comprised 3,271,120 matching pairs, in which both parties to the same agreement responded to our survey, and in 99.43% 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. This compares with agreement rates of 98.71% five years ago and 99.52% ten years ago, indicating a generally consistent level of agreement between corresponding responses over time.

In addition to the survey, we conducted unstructured follow-up interviews with a representative sample of twenty-eight of the responding networks, to garner additional detail and observations about trends.

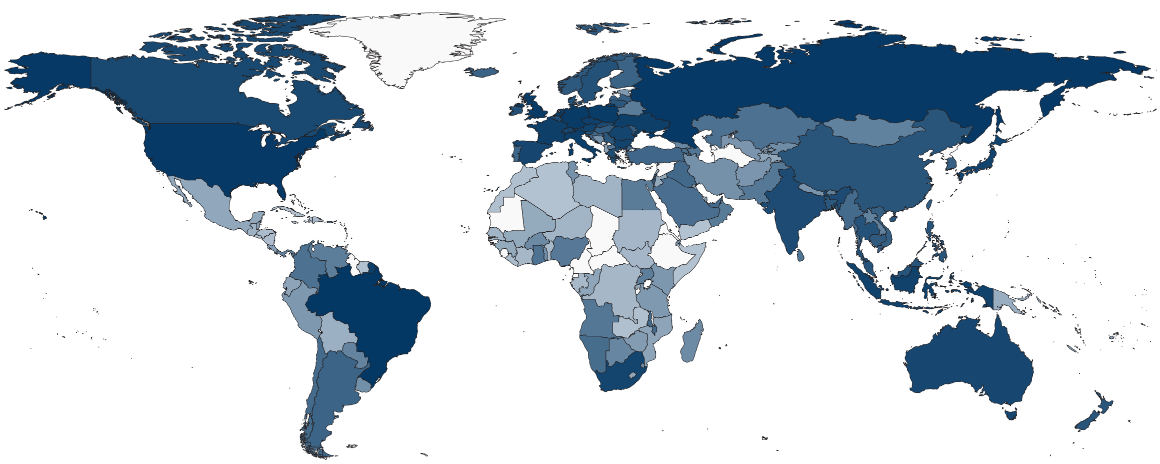

Figure 1: Geographic distribution of the networks represented in the dataset, color density by absolute number

Because of the data-collection methodology, this survey and its 2011 and 2016 predecessors include bilateral as well as multilateral peering sessions; sessions instantiated over private cross-connects as well as over public switch fabrics; agreements that may be covered by nondisclosure agreements as well as those which are fully acknowledged by both parties; sessions over which IP routes and traffic are exchanged as well as those few that never appear in a traceroute. The responses represent the vast majority of transit networks, and many leaf networks as well. Our outreach methodology, solicitation of survey responses via Network Operators Groups, tends to favor large network operators over small ones: large networks tend to appear as counterparts to reporting parties more frequently and large networks tend to have more staff time and policy inclination to respond. For those three reasons, the survey has a small bias toward higher representation among large network operators than among small ones.

The responses we received represent 17,192 different networks, incorporated in 192 countries, including all thirty-eight OECD member countries and thirty-five of the forty-six UN Least Developed Countries (up from twenty-one in 2016 and seven in 2011). 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 the trend of number of responses correlates roughly with the degree of development of, and competition within, the Internet industry in each country. Although the darkest-shaded countries have the largest number of respondents, they often do not have the largest proportion of respondents relative to the number of carriers incorporated in those countries. In Figure 2, the number of responses is normalized by the number of networks operating in each country, thereby indicating the ratio of respondents to total; in the United States, for instance, 57% of networks are represented in the dataset, whereas in China, 53% are present, and in the United Kingdom 86% are present. In both chloropleths, the color density is allocated by percentile for clarity.

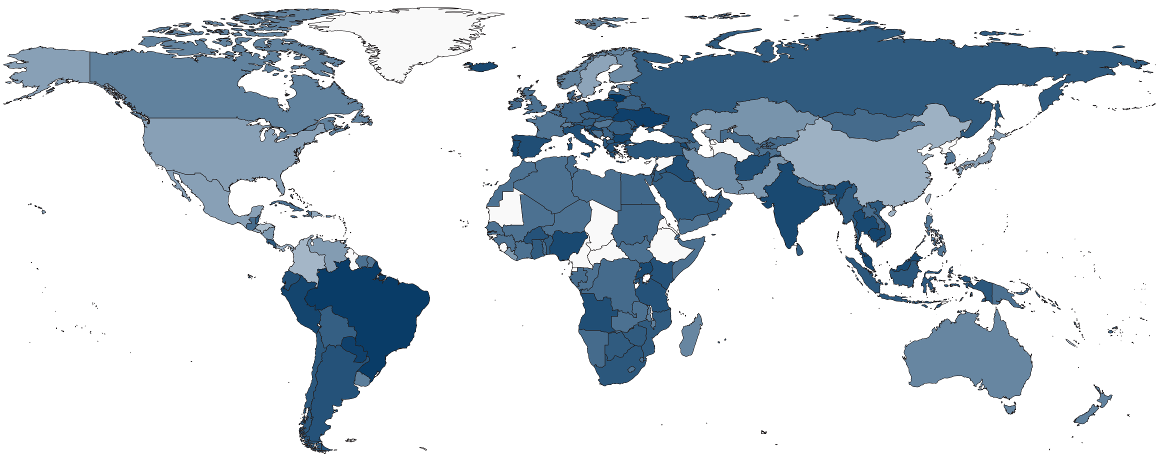

Figure 2: Geographic distribution of the networks represented in the dataset, color density by percentage

In nearly all countries, a significant and relatively uniform majority of the the networks are represented in our data; the average is 89.20% and the median is 95.91%. The five most populous countries from which we received no responses are Ethiopia (117M population), Cameroon (38M), North Korea (25M), Syria (18M), and Chad (16M).

In the 2021 edition of our survey, the five countries with the largest number of networks represented in the dataset are the United States (3,813), Brazil (1,440), Russia (881), the United Kingdom (636), and Germany (618). Of those, Brazil has reentered the top five (it was #5 in our 2011 survey) and the other four have maintained their relative rank order; Indonesia (#5 in our 2016 survey) dropped to seventh place this year. Showing relatively continuous improvement globally, 37% of countries were represented by three or fewer networks, down from 42% in 2016 and 47% in 2011.

Of the networks represented in the responses to our survey, 10,028 were present in PeeringDB, and of those most were categorized by self-reported network type. Access networks hold the largest share, at 51% (4,128); 25% (2,056) were backbone networks; and 14% (1,167) were content networks. The remainder are enterprise networks (6%), research and education (4%), and government, community, and other network types together amounting to less than 1%.

Informal Agreements

Of the total analyzed agreements, 326 (0.002%) are formalized in written bilateral agreements, representing a continuing decrease from 0.07% in 2016 and 0.49% in 2011. The remaining 15,104,775 (99.998%) are "handshake" agreements in which the parties agreed to informal or commonly understood terms without creating an individual written agreement. 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] This huge number of informal agreements are arrived at by the networks' "peering coordinators" or carrier-interconnection negotiation staff, often at self-organized regional or global "peering forums" that take place many times each year.[4] Mirroring the 2016 follow-up interviews, most respondents attributed the continuing decline in written agreements to attrition: in most cases, existing written contracts were expiring as their defined terms passed or their original signatories were subsumed, and although the relationships continued to grow any written contracts related to them were allowed to expire without renewal.

Symmetric Terms

Of the agreements we analyzed, 15,105,044 (99.9996%) have symmetric terms, in which each party gives and receives the same conditions as the other. Only 57 (0.0004%) have asymmetric terms, in which the parties give and receive conditions with specifically defined differences. The number of these exceptions has continued to trend downward, from 0.02% in 2016 and 0.27% in 2011, as the commonly understood terms of agreement continue to become more prevalent. 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 there is a nonreciprocal requirement on one party 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.[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, 3,222,452 (21.33%) are exchanging IPv6 traffic between the parties, and 11,882,649 (78.67%) are not. This is a substantial improvement from 2016, when only 3.88% of network pairs were exchanging IPv6 traffic, and reflects the "IPv4 runout" or depletion of new IPv4 addresses, which have become largely unavailable from the Regional Internet Registries since 2016.[8]

The transition to IPv6 is unevenly distributed. Twenty-nine countries reported 100% IPv6 routing. They were mostly small countries, with a combined population of 224M (2.8% of global population) and only 58 networks. But if we lower the "threshold of success" to 94%, Brazil, Uruguay, and Paraguay join the group and the population served doubles to 449M, or 5.7% of the global population, and 1,525 networks. Generally, small countries with low rates of competition have seen more complete transitions to IPv6 over the past five years, since they have smaller numbers of network operators and less access to legacy IPv4 addresses.

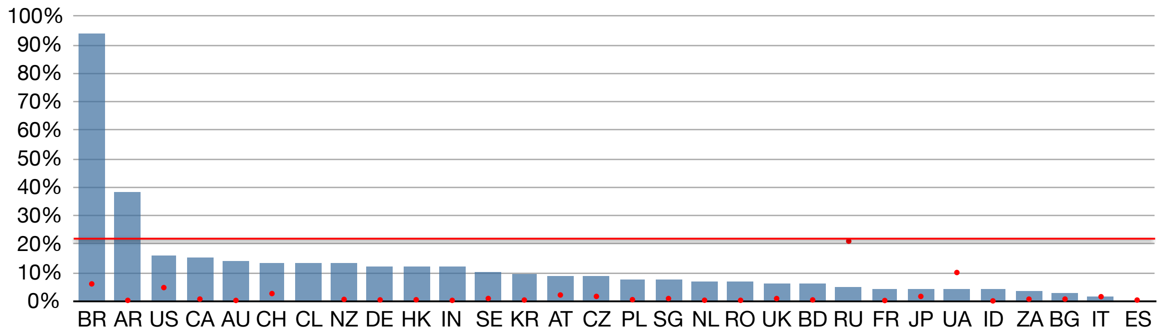

Figure 3: Top thirty countries of incorporation of the represented networks (X-axis), by percentage of networks reporting routing of IPv6 traffic (Y-axis). The horizontal red line indicates global average of 21.33%, and 2016 values for the same countries are indicated by red dots for reference.

Of the thirty most represented countries in our dataset, Brazil has the highest average rate of IPv6-enabled interconnection at 94%, followed by Argentina at 38%. Every other country in the top thirty falls below the global average of 21.33%. The shape of the graph is very similar to the 2016 graph, but with Brazil and Argentina replacing Russia and the Ukraine in the top two positions. Notably, Russia and the Ukraine are also the only two countries in the top thirty that exhibit negative growth over the past five years.

If we consider all countries in which at least one network reported its IPv6 interconnection status, 56 of 192 countries (29%) fall above the global average and 136 (71%) fall below. Though the average has risen dramatically over the past four years, these percentages are essentially unchanged from 2016's 31%–69% split, confirming that the distribution of IPv6 deployment remains unevenly distributed.

If we look at individual represented networks rather than aggregating by country, we find a huge discrepancy between IPv6 support in large and small networks; 294 of the 300 largest networks by peer count are routing IPv6 with their peers; they advertise an average of 560 and a median of 78 IPv6 prefixes each. By contrast, if we look at the bottom half of the represented networks by peer count, 76.2% (down from 92.5% five years ago) of them have no IPv6 peers or prefixes at all and they average 28 IPv6 prefixes (up from only 0.44 five years ago) and of course a median of 0.

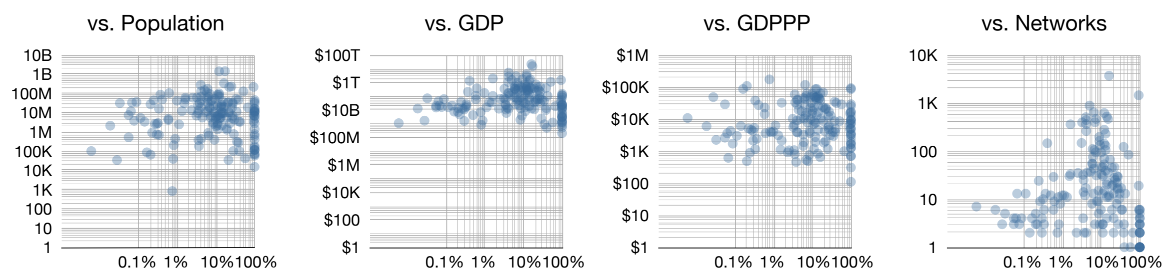

Figure 4: Comparison of percentage of responding networks that are routing IPv6 traffic within each country (X-axis, log scale) versus population, GDP, GDPPP, and number of networks for each country (Y-axis, log scale).

Most measures of Internet infrastructural development track relatively closely with other indicators of industrial and economic development but, as in the 2016 edition of our survey, IPv6 deployment does not correlate discernibly with population, GDP, or GDPPP. The fewer the number of networks operating in a country, however, the higher the percentage of IPv6 deployment; this reflects the fact that large networks have deployed IPv6 much earlier than small networks. When there are fewer networks operating in a country, they tend to be larger. So, although this correlation is clear, it produces no actionable insight beyond the evergreen truism that we need better outreach to, and education of, small network operators on this issue.

Governing Law

Clear preferences are expressed in the data for jurisdiction governing interconnection agreements, 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 is preferred to a greater degree than their frequency as a country of incorporation would suggest, whereas others are preferred for governing law less frequently than they appear as a country of incorporation. If no preferences were exhibited and governing law were always decided with the flip of a coin, all countries would have a probability of 0.5 of being selected for each pairing. In fact, we see a wide distribution of probability of selection, with the United States at one end of the spectrum and Russia at the other. Generally, there is a loose correlation between Corruption Perception Index (CPI) scores and probability of selection as a country of governing law, though other factors, notably centrality to the Internet's physical topology and the first-mover advantage of countries that connected to the Internet early, also seem to influence the probability of selection.

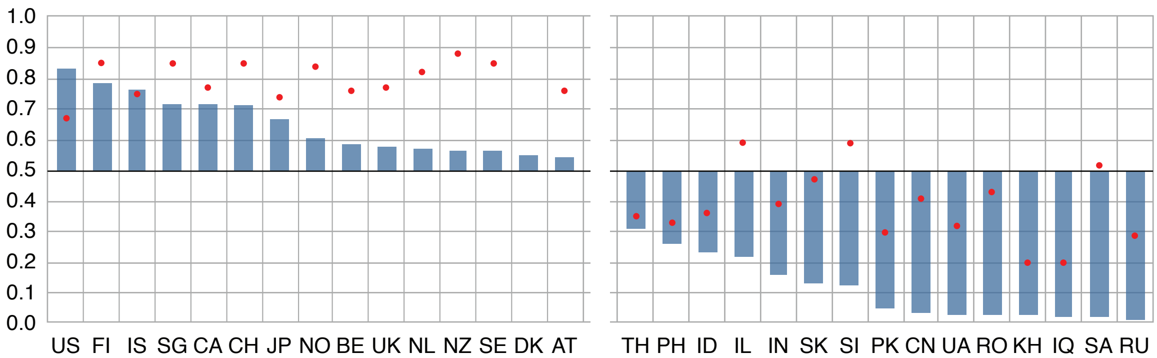

Figure 5: Probability of selection as a country of governing law (Y-axis), of the fifteen most-likely and fifteen least-likely countries (X-axis). The Corruption Perception Index of each country is indicated by a red dot for reference. The 162 countries not included in this graph are near 0.5 probability or are not sufficiently represented in the dataset to allow strong conclusions.

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), the United States continues to be strongly preferred as the legal venue of choice for arbitrating peering disputes (as in 2016 and 2011), whereas Canada, which was in second place in 2016 and 2011, has dropped back four places, overtaken by Finland, Iceland, and Singapore. At the opposite end of the spectrum, there are no agreements in the dataset in which Russia was selected to supply governing law for an agreement with a foreign party. Each time a Russian network interconnected with a foreign network, the parties elected to use the other country's governing law. Ukraine and Romania, which were previously on par with Russia, have improved marginally, and Saudi Arabia, Iraq, and Cambodia have surpassed them in degree of de-preference.

Follow-up surveys attributed the disproportionate preference for the United States principally to its historic centrality in the Internet's topology (yielding a first-mover advantage, since the networks expanding out of the United States have typically been in a later stage of growth and hence larger than those they meet in other countries, and thus more likely to dictate terms). Some respondents also cited their perception of the United States as a jurisdiction friendly, perhaps sometimes too friendly, to Internet businesses.

Conversely, the low preferences for Saudi Arabia, Romania, China, Slovenia, and Israel relative to their CPI scores were more difficult to explain. Respondents cited a perception of Romania and

China as havens of unprosecuted cybercrime, and each of these countries is, relatively speaking, in the position of a leaf node relative to the topology of global transport networks.

As in prior editions of the survey, the number of responses indicating a country of governing law that is neither of the countries of incorporation of the two parties is insignificant, amounting to only 123 cases (0.0008%). Most such cases are the result of agreements that predate mergers or acquisitions which resulted in a new country of incorporation of the new parent organization. The only significant exception is that several agreements with Chinese networks utilize the law of the Hong Kong Special Autonomous Region rather than mainland Chinese law. 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, and in 2016 there were 597 (0.03%). This is thus an extremely uncommon practice in Internet interconnection, although it is prevalent in some other fields, such as maritime shipping concentrated in Panama or banks in Switzerland.

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 each of the five countries that are most frequently represented in our dataset – the United States, Brazil, 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. The United States has far more Internet exchange points (IXPs), 120, than any other single country in the world, ahead of second-place Brazil (44), which has in the past five years overtaken now-third-place Russia (35), though the United States trails Europe (taken as a whole) in both total number and density. The high degree of US–Brazil IPv6 interconnection can be attributed principally to US networks' participation in the São Paulo route servers, and secondarily to Brazilian networks' participation in US IXPs, particularly Miami.

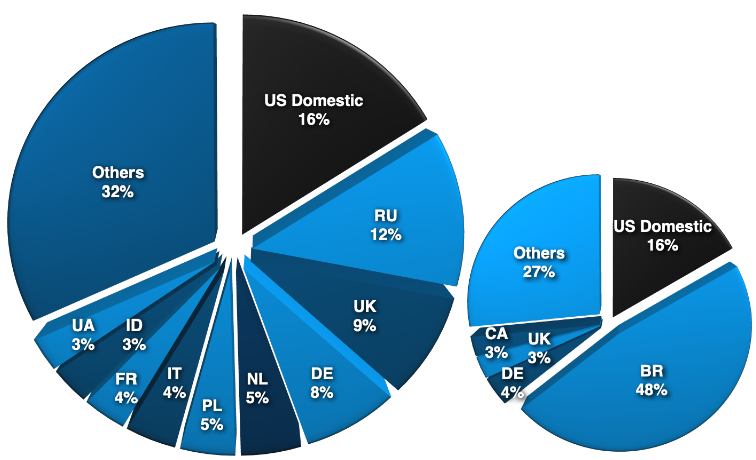

Figure 6: Nationalities of U.S. networks' interconnection partners, IPv4 (large graph) and IPv6 (small graph)

Brazil, seen in Figure 7, has radically dissimilar degrees of IPv4 and IPv6 domestic interconnection. This can be accounted for by two factors: the high degree of domestic support for IPv6 can be attributed to the prevalence of route servers domestically, which are generally configured to fully support IPv6 routing; and the fact the Brazil has a National Internet Registry, NIC.BR, which has been diligent in getting its constituents to take IPv6 allocations and put them into use. The low percentage of domestic IPv4 peering is a consequence of the huge amount of international participation in the São Paulo exchange, which is by far the largest in the world. Producing more than 20 terabits of bandwidth for 2,400 participating networks, it is more than twice as large as either the second or third-largest exchanges, in Jakarta and Frankfurt, respectively.

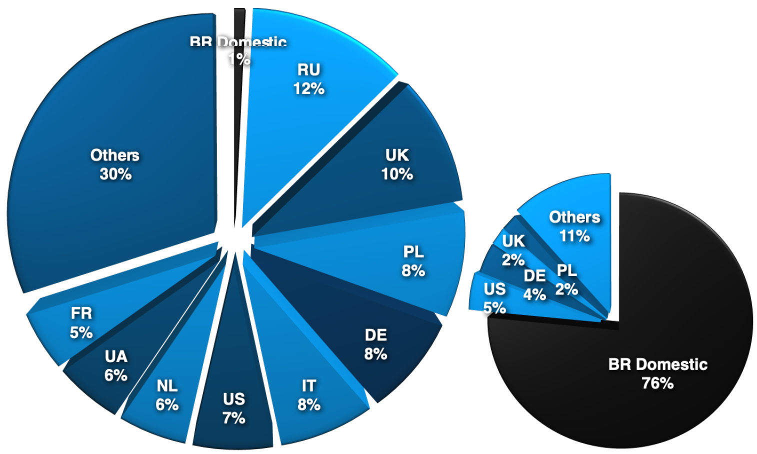

Figure 7: Nationalities of Brazilian networks' interconnection partners, IPv4 (large graph) and IPv6 (small graph)

As seen in Figure 8, Russia's substantial domestic interconnections and broad distribution of international interconnections are indicative of a relatively healthy market, characterized by numerous competitive medium-sized networks and a multiplicity of Internet exchange points, most of which possess multi-lateral peering agreements (MLPAs) with high rates of participation. In 2011 and 2016, Russia was second to the United States in total number of international interconnections, and as of 2021 it exceeds the US in number of international IPv4 interconnections, though its previously-strong IPv6 growth has slackened considerably.

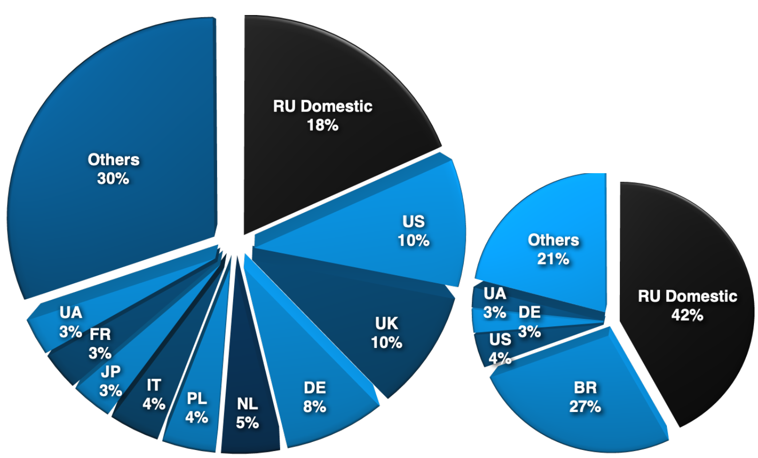

Figure 8: Nationalities of Russian networks' interconnection partners, IPv4 (large graph) and IPv6 (small graph)

The United Kingdom, seen in Figure 9, has changed relatively little in its Internet trading partners, relative to 2016 and 2011, aside from IPv6 interconnections which reflect its share of Brazil's dramatic growth. This slow rate of change reflects a relatively static number of IXPs, domestic network operators, and international participation in British exchanges. At 15 exchanges, the United Kingdom is on par with Indonesia, while lagging behind its Western European neighbors France (18) and Germany (27).

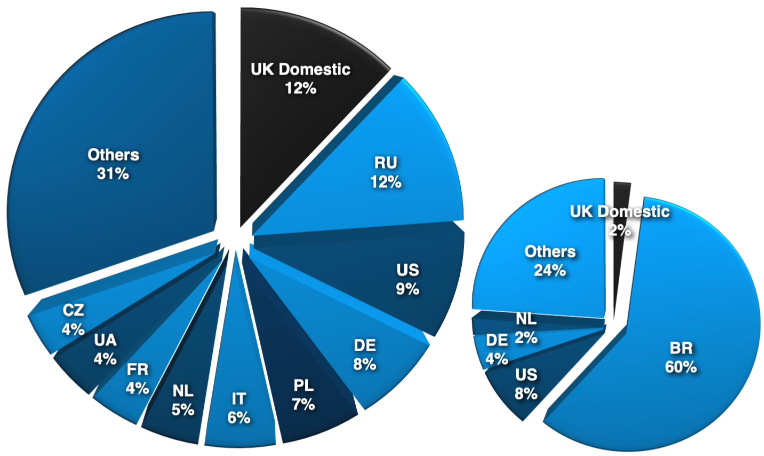

Figure 9: Nationalities of U.K. networks' interconnection partners, IPv4 (large graph) and IPv6 (small graph)

Germany, seen in Figure 10, like the United Kingdom, has a mix of Internet trading partners that has remained relatively static, with the exception of Brazil on the IPv6 side. Within that relatively stable mix, however, the growth in absolute numbers has been strong, particularly in IPv6 interconnections. Germany's central location and relatively unconstrained infrastructure continue to attract new international networks, and allow dense interconnection within its exchanges.

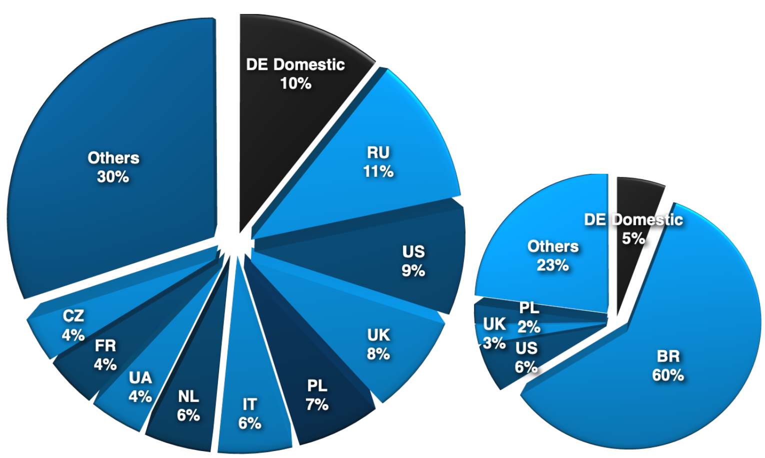

Figure 10: Nationalities of German networks' interconnection partners, IPv4 (large graph) and IPv6 (small graph)

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

In the pie charts above, IPv4 and IPv6 country distributions are displayed at a common size for readability. If we scale them relative to the absolute number of international connections, an interesting picture appears, particularly in their growth relative to 2016:

Figure 11: Size-proportional representation of IPv4 and IPv6 interconnection for top five countries, 2021 vs. 2016

In Figure 11, for each country, the upper-left circle represents international IPv4 interconnections, and the lower-right one international IPv6 interconnections; the darker circles at the center show the numbers from the 2016 survey for comparison. The number of international interconnections terminating in each of these countries has grown substantially over the past five years, but Russia, which was notable in 2016 for then having the largest number of IPv6 interconnections, has lost that lead, and Brazil's explosive growth has been even more dramatic in IPv6 than in IPv4, leading it to be not only the country with the largest number of international IPv6 interconnections, but also the first country with more international IPv6 connections than IPv4.

It is also possible to examine the ratio between domestic interconnection agreements and international agreements for each country. This represents a complex interplay among amount of domestic bandwidth production, amount of domestic consumption, and degree of import/export trade. In 2016, we visualized this in a chloropleth in which strongly domestically interconnected countries were dark-shaded, strongly internationally connected countries were light, and countries that had achieved a balance were indicated by intermediate tones. This visualization proved confusing, so we have revised the visualization for 2021 and now display ratios of either extreme as light, with darker shades representing ratios of domestic to international interconnection closer to 50/50. Accordingly, in Figure 12, the darkest countries are those in which networks have nearly equal numbers of domestic and international interconnections.

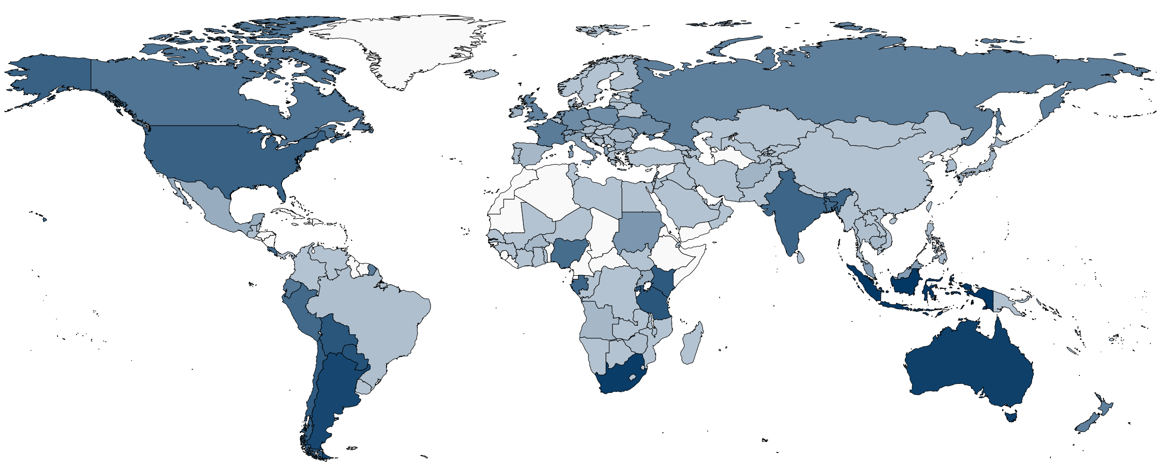

Figure 12: Ratio of domestic interconnection to international interconnection. Darker indicates more balanced, lighter indicates less balanced

Countries with otherwise healthy markets that are not represented in the darkest shades are generally unbalanced for one or more of several reasons, including geographic proximity to many neighbors (Europe), historically high degree of centrality to Internet routing (United States), or high degree of MLPA route-server utilization (Brazil). In none of these cases does the imbalance indicate an unhealthy market state.

Degree of Interconnection

Growth in the number of interconnections per network continues apace, yielding an Internet that is ever more densely interconnected over time. New market entrants continue to form, so there are still many networks just beginning peering; 6.6% have just one peer (compared to 16% in 2016 and 8.1% in 2011), and 41% have ten or fewer (compared to 35% in 2016 and 62% in 2011).

At the other end of the spectrum, the dozen largest networks have between 7,290 and 15,417 peers, more than doubling in size from five years ago and a five-fold increase relative to 2011.

The average number of reported interconnections per network is now 877, up from 292 in 2016 and 77 in 2011, and the median number of interconnections is now 92, up from 81 in 2016 and 5 in 2011. This continued increase in the average density of interconnection means that the Internet is continuing to develop both more direct optimum paths and a greater diversity of alternate paths between any source and destination.

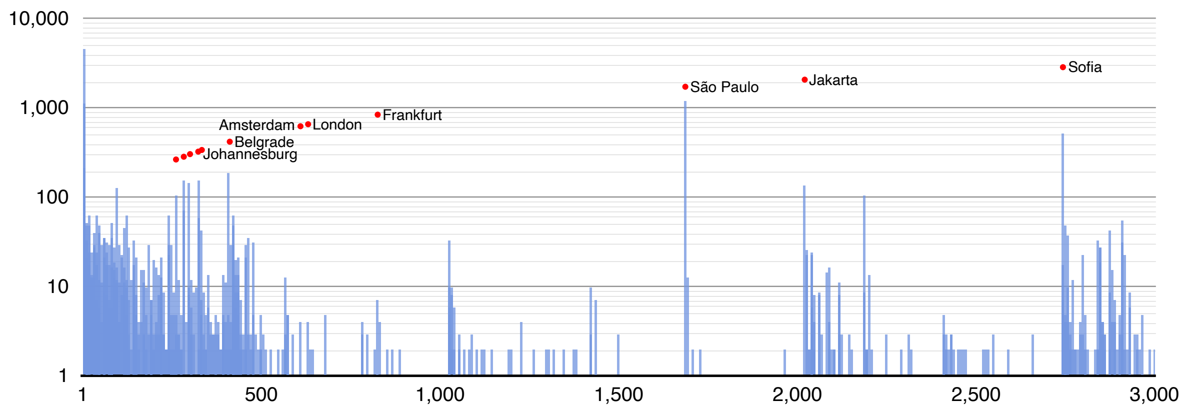

Figure 13: Distribution of number of networks (Y-axis, log scale) with each quantity of interconnection partners (X-axis, linear scale). The 1,519 largest networks with more than 3,000 interconnection partners are not displayed. Red dots indicate major multilateral peering agreements.

In Figure 13, we show the distribution of number of networks with each quantity of interconnection partners, truncating the chart at 3,000 interconnection partners at the right-hand side. Of the responding networks, 1,519 have more than 3,000 interconnection partners, and are thus not displayed, and five exceed 8,000 partners. Each of the large vertical spikes represents a major multilateral peering group, sharing a common route server.

Multilateral Peering

Multilateral peering, the exchange of customer routes within groups of more than two parties, is the source of the majority of the peering adjacencies in the Internet. Each new network entering a preexisting multilateral peering group (typically by connecting to a route server at an IXP) gains peering adjacencies with each of the preexisting peers in the group; moreover, each of the preexisting peers also gains one new adjacency. This is a classic example of the value of the network effect: each additional participant in the network both gains value and brings additional value to each preexisting participant; therefore the value to both the next party to join and the collectivity is even higher, further accelerating growth.

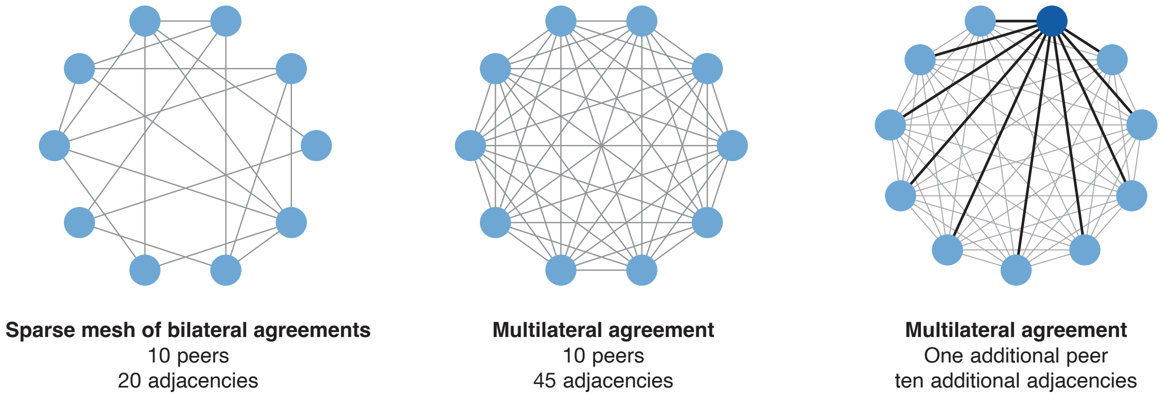

Figure 14: Network effect in growth of multilateral peering.

The beneficial consequences of multilateral peering at large exchanges can be dramatic. The connection of just one additional peer to the Sofia route server, for instance, creates nearly 4,200 new peering adjacencies, more than exist in total in most countries.

As in prior iterations of this survey, a number of "spikes" are visible in the distribution graph (Figure 13). These are the effect of large multilateral peering agreements (MLPAs). Shorter-peaked clusters are typically the effect of common combinations of route servers. For instance, there are ISPs that peer in both major London Internet exchanges, LINX (627 peers) and LoNAP (192 peers), which together produce a smaller spike at their sum, 819.

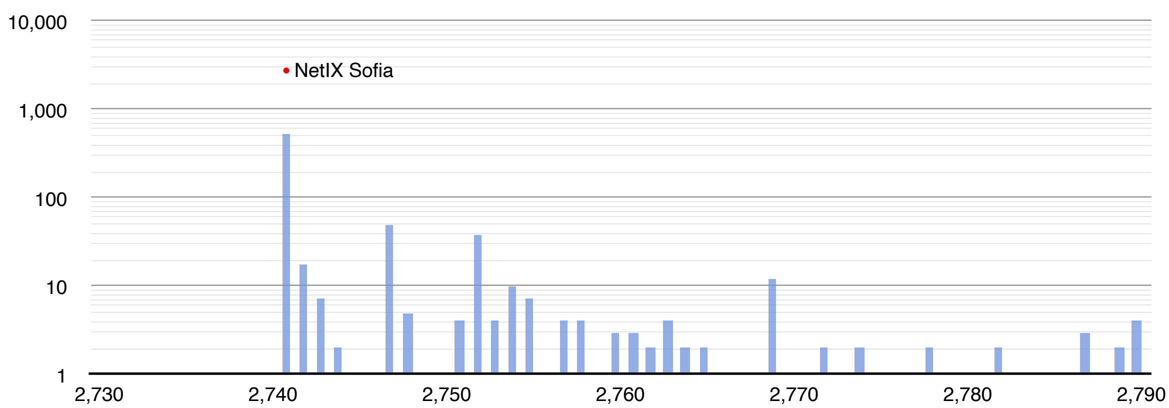

Figure 15: Expanded view of the number of networks with each quantity of interconnection partners (Y-axis, linear scale) in the range 2,730 - 2,790 (X-axis, linear scale) from Figure 13, detailing the NetIX MLPA.

In each case, there exist a large number of networks that 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 that MLPA. The volume of the tail to the right of the spike's peak is a rough indicator of the maturity of the MLPA, since MLPAs that have existed longer or are in more mature markets typically include more members who have had more time to also form bilateral agreements outside the MLPA. Generally speaking, MLPAs are identifiable in Figure 13 as spikes that have a Y-axis value similar to the volume under their curve, though that curve typically has a very long tail, which becomes indistinguishable as it mixes with other peer groups to its right on the X-axis. In Figure 15, the peak at the left side is at 2,741 on the X-axis and 512 on the Y-axis, and the volume under the curve is 7,521,306. The product of (Nx(N-1))/2 for all of the values visible in just this portion of the graph is 133,017, so this readily-apparent portion of the distribution accounts for less than 2% of the networks participating in the NetIX MLPA. In other words, 98% of them have more than fifty additional peers gained elsewhere and are represented elsewhere in the graph, to the right of 2,790 on the X-axis. Without more complicated analysis, we cannot distinguish them, because the larger participants of other smaller MLPAs that exist farther to the left on the X-axis are themselves scattered throughout this range, and contribute to it in a small but unknown degree.

When discussing MLPAs and the interconnections they facilitate, 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 are not represented as a new peering agreement in our survey or a new Autonomous System–level adjacency in our statistics. So NetIX's 7.5M adjacencies, the 4.2M in Jakarta, and the 166K in Johannesburg are not additive but overlapping to some degree, and those in the closely proximate IXPs of London, Amsterdam, and Frankfurt are overlapping to a very large degree.

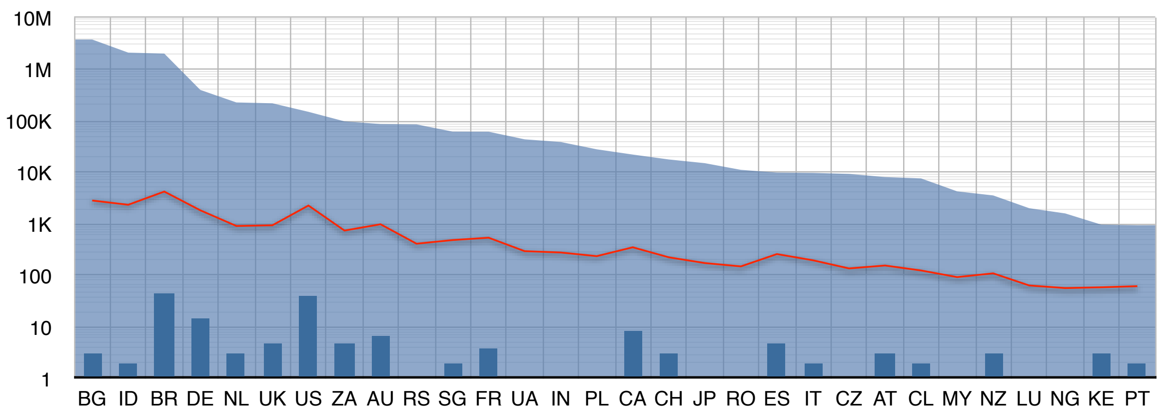

Figure 16: The thirty countries that benefit most from route-servers (X-axis) showing number of route-servers in the country (bars), number of networks participating in those route-servers (red line) and the number of network adjacencies produced (blue area) on the Y-axis.

In Figure 16 we compare the number of adjacencies, MLPA peers, and MLPAs in each of the thirty countries that most benefit from them. Indonesia has nearly doubled in number of adjacencies from 1.1M in 2016 to 2.1M in 2021, while falling to second place behind Bulgaria, which has moved from eighteenth place to first place by dint of hosting NetIX Sofia, presently the world's largest MLPA, with nearly 3.8M adjacencies on a distributed switching fabric. Likewise, Brazil, now in third place, but not in the top thirty in 2016, has 44 MLPAs, more than any other country, and more than 2M adjacencies, just 4% behind Indonesia (though achieved using 22 times as many MLPAs). Germany has moved from fifth place to fourth through steady growth. The United States remains constant in seventh place, while doubling in absolute terms from 72K to 149K adjacencies, and growing to second place in the number of MLPAs in effect, at 39. As was apparent in 2016 as well, the size of individual MLPAs matters much more than the quantity, since the number of adjacencies grows proportionately to the square of the number of participants but only linearly with the number of MLPAs.

Just as "donut peering" overtook "tier-1" peering in the late 1990s, multilateral peering has clearly overtaken bilateral peering in number of Autonomous System adjacencies, although our survey does not asses whether there is a correspondingly proportionate volume of traffic.[9] 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]

Market-Dominant Incumbents

In any market, dominant parties may engage in abusive practices intended to retain or strengthen their dominance, or to capitalize on it. One form of such abusive behavior, which we refer to as “hostage taking,” occurs in the Internet bandwidth market and is clearly visible in our statistics.

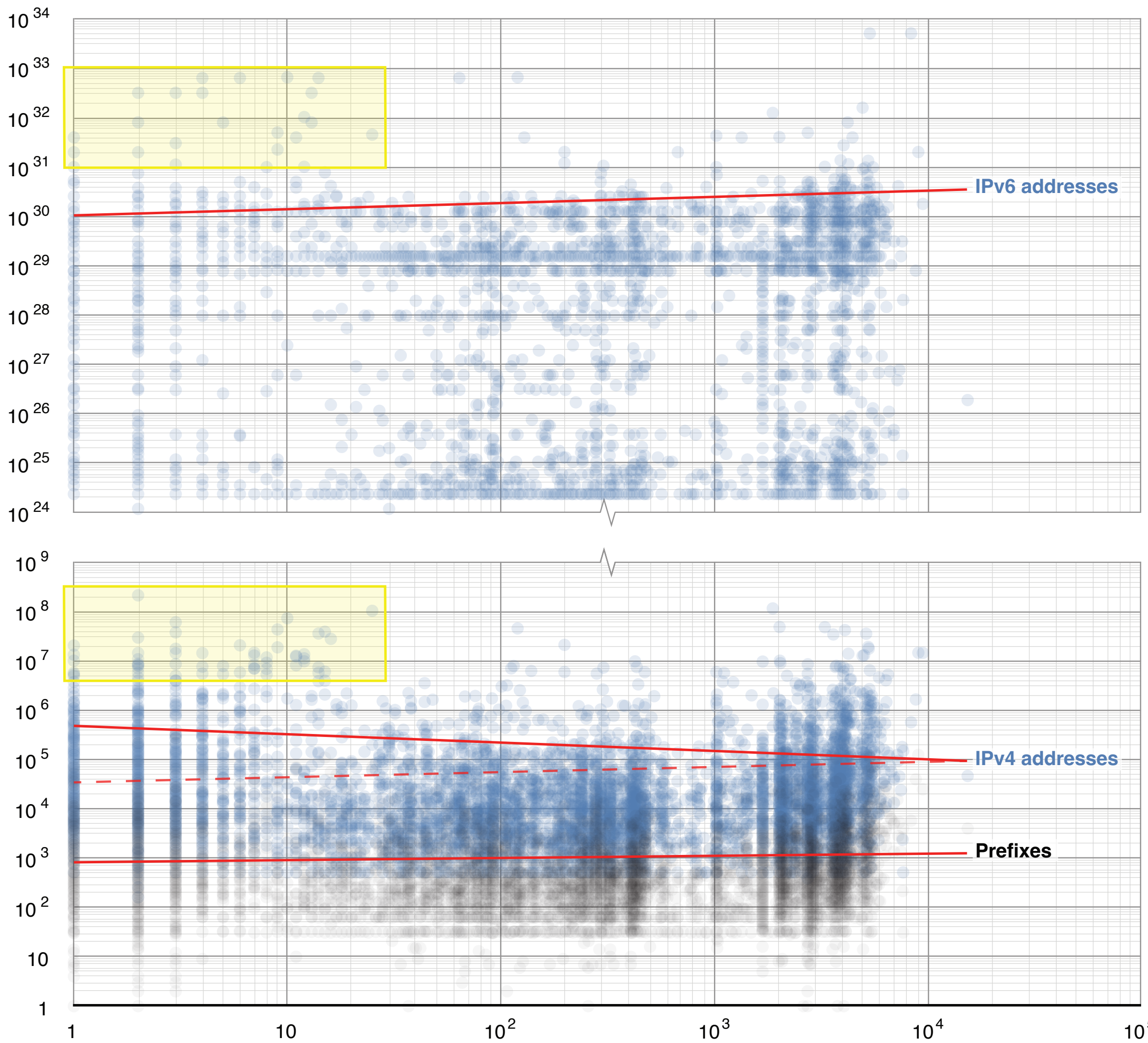

Figure 17: Number of advertised IPv4 and IPv6 addresses (Y-axis, blue) and prefixes (Y-axis, gray) over number of interconnection partners (X-axis) per carrier. The area highlighted in yellow contains market-dominant incumbents.

Large institutional customers of Internet bandwidth are typically “multi-homed,” meaning that they receive their Internet bandwidth from multiple suppliers, and are not critically dependent on any individual carrier’s network. Maintaining multi-homed routing has many advantages, but it also imposes costs in the form of complexity and managerial overhead. Thus 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; these customers pay subscription fees for the service they receive. If a single carrier becomes market-dominant by amassing a sufficient portion of these customers, the carrier may become greedy and attempt to extract excess rent from its monopoly over the connection to each of these customers. Extracting excess rent directly from its own customers would, however, incentivize the customers to switch carriers, which would lead to the original 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, they may take their own customers hostage in order to extract rent from third parties, typically ones that also serve those customers in some other role, such as content publishing, or have some interest in their welfare. The dominant carrier proposes to the third parties, and their carriers, that communication with the hostage customers will be possible, reliable, or sufficiently fast only if fees are paid by these non-customers to the abusive carrier. These fees are sometimes euphemistically referred to as “paid peering” or “on-net routes” or “partial transit.”

Non-abusive competitive carriers maximize interconnection in order to gain access to more bandwidth, since that is the product they are selling to their customers, and more bandwidth permits more, and more satisfied, customers. As shown by the trend-lines in Figure 17, as normal competitive carriers grow by amassing more customers, they also increase their interconnection relationships proportionately, in order to supply the bandwidth their customers are purchasing.

Abusive carriers, by contrast, create artificial scarcity by minimizing interconnection, which in turn minimizes bandwidth. Where it can be supported by lack of competition, this under-investment in infrastructure and under-supply of bandwidth tends to yield higher profit margins, while allowing the extraction of rent from the third parties with whom the abusive carrier’s “hostage” customers are trying to communicate. These “hostage takers” are easily spotted statistically (the yellow-highlighted clusters in Figure 17), since they distinguish themselves from the norm by having both very large numbers of single-homed customers and disproportionately small numbers of interconnections with other carriers. 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 Figure 17, which 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 broad interconnection, both in absolute numbers and in geographic diversity. The dashed trend line, produced when one excludes market-dominant incumbents, shows the correspondence one would expect, between increasing numbers of customers and increasing degree of interconnection to satisfy those customers’ bandwidth demands.

Unexpected Results

In the course of analyzing the survey results, we encountered 343 respondents to the survey and peers of respondents of the survey, that were participating in the global routing table using unallocated Autonomous System Numbers.[11] Autonomous Systems Numbers (ASNs), are normally allocated uniquely to network operators by the Regional Internet Registries in order to identify each network in the global Internet routing table unambiguously. Of these, fourteen are in ASN blocks delegated by the Internet Assigned Numbers Authority (IANA) to the American Registry for Internet Numbers (ARIN), and 329 are in undelegated IANA space.

Of the fourteen delegated to ARIN, one had been voluntarily returned to ARIN in February 2021 but was still in use, and thirteen had been revoked for non-payment of fees between January 2018 and the present but were still in use. Of those that had been revoked, ARIN reported that five were in process of being reinstated.

Of the 329 in undelegated IANA space, 282 are 8-bit ASNs, thirteen are RFC5398-reserved for documentation and sample code, 268 RFC6996-reserved for private use, and one RFC7300-reserved. The other forty-seven are 16-bit ASNs: seven reserved by IANA policy, fourteen unallocated, and twenty-six RFC6996-reserved for private use.

Of the unallocated ASNs, 206 are originating IPv4 address space, with a median of 512 addresses and an average of 6,275; the largest of them advertises 171,776 IPv4 addresses. We presume that many of these constitute unintentional leakage of private use-reserved ASNs to the public Internet. Interestingly, however, at the time of our observation none of the reserved Autonomous Systems were advertising RFC1918-reserved IP addresses.[12]

Further Work Necessary

It is our intention to continue performing this survey on a five-year recurring interval. As the time-series data accumulates, we will begin to include trend graphs. In future iterations of the survey, we will begin to address the question of IPv6-only networks, which may by then have begun to come into existence.

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

[1] Our 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. As of 2016, Smith's analysis code had 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 by November 2016, 28.43% of all allocated ASNs were 32-bit, and more than half of Latin American ASNs were 32-bit. Accordingly, in 2016, we performed our own assessment, using different origin datasets, and produced a number of 18,115 transit networks in November, 2016. This compares with Smith's 6,570 (32-bit only) counted in the same month. We have since determined that our November 2016 count was also flawed, for which we apologize. For November, 2021, Philip's counts average approximately 10,200, and this concurs with our own observations.

[2] Woodcock, Bill and Weller, Dennis, *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 *Standard Peering Contract*, archived at https://web.archive.org/web/20190902231647/http://www.highwayman.com/peering/peering_agreement.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.edu.

[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; Cox Communications, http://www.cox.com/peering/paid-peering.asp; and Verizon Business, http://www22.verizon.com/wholesale/productguide/partnerportprogram.

[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 the associated general terms can be found on the Packet Clearing House website and Wikipedia, http://en.wikipedia.org/wiki/Peering.

[8] For discussion of IPv4 address depletion, see Wikipedia: https://en.wikipedia.org/wiki/IPv4_address_exhaustion#Exhaustion_dates_and_impact, at the IANA: https://www.iana.org/assignments/ipv4-address-space/ipv4-address-space.xhtml, and from Geoff Huston: https://www.potaroo.net/tools/ipv4/.

[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" which 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 at 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 PIPE Networks https://www.pipenetworks.com/docs/mlpa.pdf; the Tampere Regional Exchange http://www.trex.fi/service/mlpa.html; and the Indonesia Internet Exchange https://iix.net.id/wp-content/uploads/2021/08/iix-peering-agreement21.pdf. Note that their specific terms differ little if at all from those of the bilateral agreements discussed in note 3. When network operators refrain from participating in multilateral agreements, they typically cite dissatisfaction with the ability to select peering partners individually, which in turn weakens Internet industry self-regulation mechanisms by making it more difficult to exclude bad actors. Here, for example, is the policy of AARnet, the Australian national research and education network, rejecting multilateral peering: https://www.aarnet.edu.au/uploads/resources/AARNet_National_Peering_Policy.pdf.

[11] An "Autonomous System" is a uniquely-identified Internet network. Autonomous System Numbers are the numeric identifiers assigned by the Regional Internet Registries (RIRs) and used within the Internet routing system to define a specific bounded network that has its own uniquely defined routing policies. An AS-pair is a pair of networks that interconnect with each other.

[12] Philip Smith has also independently noted the existence of these unallocated ASNs and is now producing daily reports on the phenomenon, available at https://thyme.apnic.net/.combined/data-badAS.