Masterarbeit

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Measuring and Quantifying Consolidation Trends in the Internet Core

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Measuring and Quantifying Consolidation Trends in the Internet Core

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Kurzzusammenfassung

Im Internet spielen Tranistnetzwerke und Internetknotenpunkte (IXPs) eine elementare Rolle in der Weiterleitung und dem Austausch von Netzwerkverkehr. Die Relevanz von IXPs steigt stetig, jedoch schmälert dies nur unwesentlich die Position der Tranistnetzwerke, welche als Verbindungsglied der geografisch getrennten Teile des Internets auftreten. Aufbauend auf der Arbeit von Labovitz et al. aus dem Jahr 2010, in der eine Veränderung von einem stark hierarchisch aufgebauten AS Graph, zu einem durch Content-Provider und IXPs geprägten AS Graph aufgezeigt wird, fokusieren wir uns auf die Zeitspanne zwischen 2010 und 2020. Wir zeigen, dass sich diese Prägung verstärkt und die geografisch Trennung des Internets abnimmt. Die Veränderungen des AS Graphs werden mittels Clusteringalgorithmen und Zentralitäts-Metriken ermittelt. Zusätzlich wird bestimmt, welche Netzwerke, Organisationen und IXPs zu welchem Zeitpunkt Konsolidierungstrends zeigen. Sichtbar wird beispielsweise, dass die Tier 1 Netzwerke und ihre Position im Internet nur sehr geringen Schwankungen unterliegen und große Inhaltanbieter wie Akamai, Cloudflare und Google an mehr als 20% aller IXPs weltweit vertreten sind.

Zusätzlich zu den Strukturanalysen wird das IXP Ökosystem im Hinblick auf Kosten, Mitgliedschaft, Betreiber und geografische Unterschiede betrachtet. Es wird sichtbar, dass Europa eine besondere Stellung einnimmt. Europa hat den stärkste IXP Wachstum und ist der Kontinent mit den meisten IXPs und dem höchsten IXP-Netzwerkverkehrsdurchsatz.

Darüber hinaus wird ein kurzer Überblick über die Entwicklung der ökonomischen Aspekte des Internets im Hinblick auf die Ressourcenverteilung gegeben.

Jasper Eumann

Title of Thesis

Measuring and Quantifying Consolidation Trends
in the Internet Core

Keywords

Internet measurement, Internet eXchange Points, BGP, PeeringDB, Tier 1 networks

Abstract

On the Internet, transit networks and Internet exchange points (IXPs) play a fundamental role in the routing and exchange of network traffic. The relevance of IXPs is steadily increasing. This only marginally diminishes the position of the transit networks, which act as a link between geographically separate parts of the Internet.

Based on the work of Labovitz et al. from 2010, which shows a change from a mostly hierarchical AS graph to a AS graph characterized by content providers and IXPs, we focus on the time span between 2010 and 2020. We show that this characteristic is increasing while the geographical separation of the Internet is decreasing. Changes in the AS graph are examined using clustering algorithms and centrality metrics. In addition, we identify which networks, organizations and IXPs show consolidation trends at what time. For instance, we show that the Tier 1 networks and their position on the Internet are only subject to very small fluctuations, and that large content providers such as Akamai, Cloudflare and Google are represented at more than 20% of all IXPs worldwide.

In addition to structural analyses, the IXP ecosystem is considered in terms of costs, membership, IXP operators and geographical differences. It becomes apparent that Europe has a special position. Europe shows the strongest IXP growth and has most IXPs in the highest IXP traffic throughput.

Furthermore, an overview of the development of the economic aspects of the Internet in terms of resource allocation is given.

Contents

List of Figures **vii**

List of Tables **xi**

1 Introduction **1**

2 Evolution of the IXP Ecosystem **3**

2.1 Publicly Available IXP Datasets 4
2.1.1 PeeringDB 5
2.1.2 Packet Clearing House 6
2.1.3 IXPDB 7
2.1.4 Hurricane Electric 8
2.2 Relevance of IXPs 10
2.3 Evolution of Public Peering 12
2.4 Organizational Structure of IXPs 15
2.5 IXP Peering Costs 17
2.6 Dimensions of IXPs in Size and Throughput 21
2.6.1 IXP Size by Member Count 21
2.6.2 IXP Throughput 23
2.7 Points of Presence of IXPs and Their Members 29
2.8 Transit and PoP Provider Neutrality of IXPs 33
2.9 Variety of IXP Providers and Members 34
2.9.1 Fraction of IXP Member Types 34
2.9.2 AS Presence at IXPs 41
2.9.3 Variety of IXP Operator Organizations 44
2.10 Estimated Impact of IXP Outages 46
2.10.1 DE-CIX Frankfurt 48
2.10.2 AMS-IX 50
2.10.3 LINX LON1 51

2.10.4 Interim Summary 53
2.11 Interim Conclusion 54

3 Evolution of Peering Relationships **55**
3.1 Evolution of the C2P and P2P Ratio 55
3.2 Evolution of AS Relationships 56

4 Evolution of the Internet Structure **60**
4.1 Hierarchical Block Structure of AS Relationships 62
4.2 Number of AS Relationships Distribution 68
4.3 Centrality of the Internet Structure 72
4.4 Spectral Analyzes of the Adjacency Matrix 86
4.5 Interim Conclusions 91

5 Economic Aspects of the Internet **93**
5.1 WHOIS Dataset 93
5.2 Evolution of the Economic Aspects 94

6 Conclusion **100**

Bibliography **102**

A IXP Dataset Record Details **107**
A.1 PeeringDB 107
A.2 PCH 108
A.3 IXPDB 108
A.4 HE 108

B Results of Manual Analysis **109**

C ASes which are only present at one European IXP **112**
C.1 DE-CIX 112
C.2 AMS-IX 117
C.3 LINX LON1 121

Selbstständigkeitserklärung **125**

List of Figures

1.1 Beauty of the internet displayed as a minimal spanning tree of the AS graph in 2020. The clusters are formed by customers of major transit ASes 1

2.1 IXP distribution by continent (PeeringDB) 5
2.2 IXP distribution by status (PCH) 6
2.3 IXP distribution by continent (PCH) 7
2.4 IXP distribution by continent (IXPDB) 8
2.5 IXP distribution by continent (HE) 9
2.6 IXP data distribution by data quality (HE) 9
2.7 Number of IXPs per continent (PeeringDB) 10
2.8 Traceroutes performed from the HAW network (02.2020) 11
2.9 Share of all IXP members per continent participating in public peering per continent (PeeringDB) 13
2.10 Evolution of the share of all IXP members per continent participating in public peering per continent (PeeringDB) 14
2.11 Distribution of organization types of IXPs per continent (PCH) 16
2.12 Share of IXPs with publicly available price information of the top five IXPs by member size per continent 18
2.13 Average 10G link cost at IXPs per continent (Data by Snijders et al.) . . . 19
2.14 Breakdown of IXP monthly cost of 10G link for Europe and North America (Data by Snijders et al.) 20
2.15 Average IXP size by member count per continent (PeeringDB) 21
2.16 The historical evolution of the average IXP size by member count per continent 22
2.17 Link speed distribution per continent (PeeringDB) 24
2.18 Estimated average maximum throughput of IXPs per continent based on link speed information (PeeringDB) 25

2.19 Evolution of the estimated average maximum throughput of IXPs per continent based on link speed information (PeeringDB) 26
2.20 IXP throughput per continent (PCH) 28
2.21 Average number of PoPs per IXP and continent (PeeringDB) 30
2.22 Evolution of the average number of PoPs per IXP and continent 31
2.23 Number of IXPs in the top five by member count per continent offering remote peering 32
2.24 Number of IXPs in the top five by member count per continent which are transit and PoP provider neutral 33
2.25 Distribution of types of IXP members per continent (PeeringDB) 36
2.26 Evolution of the distribution of IXP member types in Europe (PeeringDB) 37
2.27 Evolution of the distribution of IXP member types in North America (PeeringDB) 38
2.28 Evolution of the distribution of IXP member types in Asia (PeeringDB) . 38
2.29 Evolution of the distribution of IXP member types in South America (PeeringDB) 39
2.30 Evolution of the distribution of IXP member types in Africa (PeeringDB) 40
2.31 Evolution of the distribution of IXP member types in Oceania (PeeringDB) 40
2.32 Cumulative top 10 IXP operators since 2010 (PeeringDB) 45
2.33 PoPs of DE-CIX Frankfurt members ranked by number of IXPs and facilities where the member is present 48
2.34 Distribution of the IXP outage dimensions of ASes that only peer in Europe at DE-CIX Frankfurt 49
2.35 PoPs of AMS-IX members ranked by number of IXPs and facilities where the member is present 50
2.36 Distribution of the IXP outage dimensions of ASes that only peer in Europe at the AMS-IX 51
2.37 PoPs of LINX LON1 members ranked by number of IXPs and facilities where the member is present 52
2.38 Distribution of the IXP outage dimensions of ASes that only peer in Europe at the LINX LON1 53

3.1 Evolution of customer-to-provider (C2P) and peer-to-peer (P2P) relationships 55
3.2 Cumulative top five ASes by number of customer since 1998 57
3.3 Cumulative top five ASes by number of providers since 1998 58

3.4 Cumulative top five ASes by number of P2P relationships since 1998 . . . 59

4.1 Hierarchical block structure [46] of the Internet routing structure of the last two decades . . . 60
4.2 Number of ASes and relationships of the Internet structure since 2000 . . . 61
4.3 Hierarchical block structures [46] of the C2P relationships of the last decade (CAIDA AS relationship data) . . . 63
4.4 Hierarchical block structures of the P2P relationships of the last decade (CAIDA AS relationship data) . . . 65
4.5 Hierarchical block structures of the Internet routing structure of the last decade (CAIDA AS relationship data) . . . 66
4.6 Out average node degree of C2P relationships (Number of providers) . . . 68
4.7 In average node degree of C2P relationships (Number of customers) . . . 69
4.8 Total average node degree of C2P relationships . . . 69
4.9 Node degree of P2P relationships . . . 70
4.10 Out average node degree of all relationships . . . 71
4.11 In average node degree of all relationships . . . 71
4.12 Total average node degree of all relationships . . . 72
4.13 C2P relationships . . . 73
4.14 C2P relationships (Only ISPs) . . . 74
4.15 Cumulative top five ASes by pagerank values of C2P relationships . . . 75
4.16 P2P relationships . . . 76
4.17 P2P relationships (Only ISPs) . . . 76
4.18 Cumulative top five ASes by pagerank values of P2P relationships . . . 77
4.19 All relationships . . . 78
4.20 All relationships (Only ISPs) . . . 78
4.21 Cumulative top five ASes by pagerank values of all relationships . . . 79
4.22 C2P relationships . . . 80
4.23 C2P relationships (Only ISPs) . . . 80
4.24 Cumulative top five ASes by betweenness values of C2P relationships . . . 81
4.25 P2P relationships . . . 82
4.26 P2P relationships (Only ISPs) . . . 82
4.27 Cumulative top five ASes by betweenness values of P2P relationships . . . 83
4.28 All relationships . . . 84
4.29 All relationships (Only ISPs) . . . 85
4.30 Cumulative top five ASes by betweenness values of all relationships . . . 85

4.31 Graph with fewer interconnections and globally important nodes 87
4.32 Graph with fewer interconnections and regional important nodes 87
4.33 Graph with high interconnections 88
4.34 Adjacency matrix spectrum of C2P relationships 89
4.35 Adjacency matrix spectrum of P2P relationships 90
4.36 Adjacency matrix spectrum of all relationships 91

5.1 Evolution of the distribution of ASNs among handles 94
5.2 Evolution of the distribution of IPv4 space among handles 95
5.3 Evolution of the distribution of IPv6 space among handles 96

List of Tables

2.1 Top IXPs per continent selected by throughput (PCH and PeeringDB dated 06.2020) 29
2.2 Member type colors 41
2.3 Top 10 ASes in Europe 41
2.4 Top 10 ASes in North America 41
2.5 Top 10 ASes in Asia 42
2.6 Top 10 ASes in South America 42
2.7 Top 10 ASes in China 43
2.8 Top 10 ASes in Africa 43
2.9 Top 10 ASes in Oceania 43
2.10 Top 10 ASes over all continents 44

4.1 Hierarchical block structure properties (C2P relationships) 64
4.2 Hierarchical block structure properties (P2P relationships) 67
4.3 Hierarchical block structure properties (All relationships) 67

5.1 Internet resource distribution per continent in 2013 97
5.2 Internet resource distribution per continent in 2020 97
5.3 Top five handles by number of ASNs in 2013 98
5.4 Top five handles by number of IPv4 prefixes in 2013 98
5.5 Top five handles by number of IPv6 prefixes in 2013 99

A.1 Data object description (PeeringDB) 107
A.2 Data object description (PCH) 108
A.3 Data object description (IXPDB) 108
A.4 Data object description (HE) 108

B.2 Europe top five IXPs overview 109
B.3 North America top five IXPs overview 109

B.4 Asia top five IXPs overview 110
B.5 South America top five IXPs overview 110
B.6 Africa top five IXPs overview 110
B.7 Oceania top five IXPs overview 111

1 Introduction

The Internet has continuously evolved since it started out as the ARPANET in the early 1980s [32]. While originally formed out of research networks, the founding of the World Wide Web (WWW) in 1989 [5] drove the commercialization of the technology which had a large impact on the composition of the Internet [27]. The backbone of the early Internet was created by Merit[1], IBM[2] and MCI[3], which all have commercial interests [25].

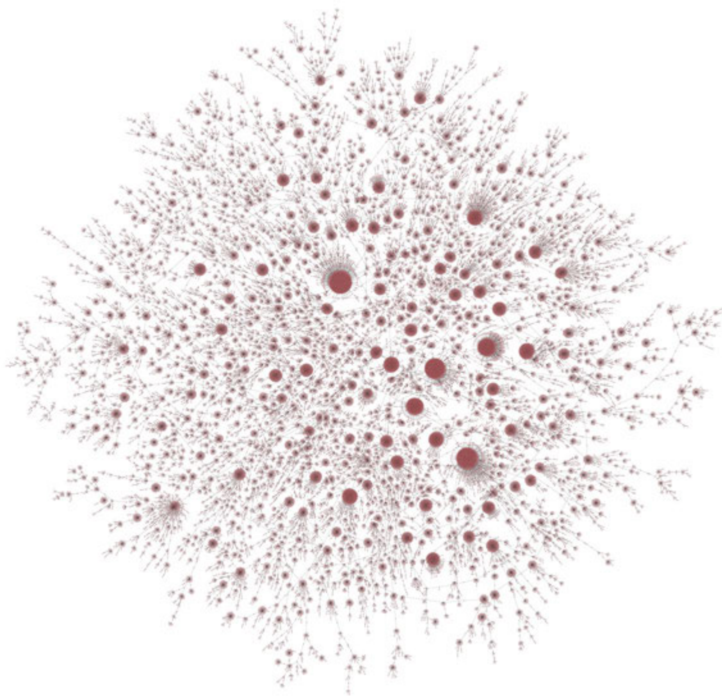


Figure 1.1: Beauty of the internet displayed as a minimal spanning tree of the AS graph in 2020. The clusters are formed by customers of major transit ASes

[1] `https://www.merit.edu/about/history/` (2020.08)
[2] `https://www.ibm.com/ibm/history/ibm100/us/en/icons/internetrise/` (2020.08)
[3] `https://en.wikipedia.org/wiki/MCI_Communications` (2020.08)

To this day the Internet sees continuous growth. Now, in 2020 fiber optic cables span the world[4] and the top five most valuable companies generate their revenue exclusively, directly or indirectly, via the Internet[5]. The networks that make up the Internet are called autonomous systems (ASes). The ASes exchange routing information (control plane) between each other and exchange traffic (data plane) following the control plane.

Based on the work of Labovitz et al. [30] from 2010, which shows a change from a mostly hierarchical AS graph [20] to a AS graph characterized by content providers and IXPs, we focus on the time span between 2010 and 2020 with the following three questions: *(i)* Can we observe consolidation trends in ASes, organizations and IXPs, *(ii)* what is the composition of the IXP ecosystem and how it has changed in the last ten years, *(iii)* are there structural changes in the AS graph and what do these changes consist of.

The complexity of the Internet are shown in Figure 1.1 as a minimum spanning tree of the AS graph. Figure 1.1 shows that correlations and properties are not directly visible in such a complex structure as the AS graphs. Changes in the graph and the evolution of the IXP ecosystem are examined using clustering algorithms and centrality metrics as well as various datasets, such as PeeringDB[6] and the CAIDA AS relationships dataset [10].

We find that the Tier 1 networks and their position on the Internet are only subject to very small fluctuations, and that large content providers such as Akamai, Cloudflare and Google are represented at more than 20% of all IXPs worldwide. It becomes apparent that Europe has a special position. As example, Europe shows the strongest IXP growth and has most IXPs in the highest IXP traffic throughput.

This thesis is organized as follows. The relevance of IXPs and their evolution over time are studied in Chapter 2. We explore which ASes are important and how the hierarchical structure of the AS graph has evolved over the years in Chapter 3 and Chapter 4. The distribution of economic aspects of the Internet is studied in Chapter 5. Finally, a conclusion is given in Chapter 6.

[4] `https://live.infrapedia.com/app` (08.2020)
[5] `https://www.forbes.com/the-worlds-most-valuable-brands/#3cd0edc6119c` (08.2020)
[6] `https://peeringdb.com` (08.2020)

2 Evolution of the IXP Ecosystem

The evolution of the role and function of Internet eXchange Points (IXPs), taking into account possible locational differences and the question of consolidation is the main research topic of this thesis. William B. Norton, the author of “The Internet Peering Playbook: Connecting to the Core of the Internet” notes that European and US IXPs tend to differ in their: **organizational structure**, **scale**, **pricing colocation**, **neutrality** and **cooperation** [44], among others. As an entry point we use these characteristics in addition to the question of consolidation trends in the Internet structure.

The Internet eXchange Federation (IX-F) defines an IXP as follows: “An Internet Exchange Point (IXP) is a network facility that enables the interconnection of more than two independent Autonomous Systems, primarily for the purpose of facilitating the exchange of Internet traffic.”[1] This definition describes the main functionality of an IXP and it will be our guideline for our understanding of an IXP.

The historical role of an IXP is to interconnect ASes to keep traffic local and avoid the need for a transit AS [42]. An IXP offers core network infrastructure at layer 2 (L2) to interconnect its participants (ASes). There are two main types of peering: private and public peering. Peering means that the participants share routing information via the Border Gateway Protocol (BGP) and exchange traffic with each other. In case of public peering an AS peers with all other ASes which take part in public peering. The ASes share their own and their customers traffic with all other public peering participants according to individual routing configurations.

To reduce the number of BGP sessions the IXP usually operates a Route Server (RS). Participants hold BGP sessions with the RS and the RS does BGP best path selection [48]. Alternatively peering ASes hold BGP sessions with all participants individually, which does not scale [48]. The control plane information of public peering traverse the IXP infrastructure and are visible to all participants via the RS. The data plane is forwarded

[1] `http://www.ix-f.net/.ixp-definition.html`(03.2020)

through the IXP switching fabric. Private peering hides the control plane because the ASes peer directly instead of using the RS. To save costs when peering privately, the IXP switching fabric is often avoided in favor of a direct connection between participants.

The main customers of IXPs are Internet Service Providers (ISPs), hosting or service providers and Content Delivery Networks (CDNs) [1]. These network types profit most from the IXP concept to deliver traffic locally and avoid transit traffic. Content providers handle massive amounts of traffic with the goal to deliver their content with low latency directly to consumers. These are usually end-customers who obtain their Internet access via an eyball ISP. This is reflected in the observation that in 2019, 12.8% of global Internet traffic was caused by HTTP media streaming such as Youtube and Netflix [49].

By delivering traffic locally and keeping short distances, theoretically the hop counts are reduced and short round-trip time (RTT) are ensured. Ahmad et al. [2] showed that there is no significant difference in number of hops between routes crossing an IXP and routes who do not. However, the RTT is shorter on routes that traverse an IXP. Apparently only the reduction of the RTT by peering at IXPs is confirmed.

Large IXPs often show different characteristics than smaller ones, even on the same continent or in the same country. We take this into account by ranking IXPs in our figures by size. Ager et al. [1] show that this characterization applies to large European IXPs, that they have very similar characteristics regardless of their geographical location. The size of an IXP has two dimensions, the number of members and the traffic throughput. Since throughput information is not available for all IXPs we use the number of members as the default IXP size for our survey.

2.1 Publicly Available IXP Datasets

We examine various aspects of IXPs based on publicly available datasets. We collected additional information manually when necessary. The following datasets were examined for our investigations from the point of view of accessibility, structure and availability.

PeeringDB[2], *Packet Clearing House (PCH)*[3], *IXPDB*[4] and *Hurricane Electric (HE)*[5].

[2]`https://www.peeringdb.com/`(02.2020)
[3]`https://www.pch.net/ixp/dir`(02.2020)
[4]`https://ixpdb.euro-ix.net/en/`(02.2020)
[5]`https://bgp.he.net/report/exchanges`(02.2020)

The completeness and quality of all datasets differs per source and region of interest and is examined in detail from Klöti et al. [28] The datasets do not contain the same information. We select from our dataset selection the one that contains the information required for the current observation.

2.1.1 PeeringDB

"PeeringDB, a nonprofit member-based organization, facilitates the exchanges of user maintained interconnection related information primarily for Peering Coordinators and Internet Exchange, Facility, and Network Operators."[6] The organization offers a database with the same name. This database contains datasets from over 738 IXPs, 17955 networks, 3552 facilities and additional meta-information (02.2020).

PeeringDB is a commonly-used source for IXP data [28] and most of the important IXPs like DE-CIX, AMS-IX and LINX-LON1 are sponsors of the PeeringDB organization[7]. The data contains peering information from all around the world which are relatively up-to-date and all large IXPs are included. An updated flag is available to evaluate the quality for a specific record. The distribution by continent are shown in Figure 2.1. In 2013, 99% of the information contained was correct and 93% of the top-100 ASes from ASRank [9] were present in the dataset [37]. We assume that the quality of the data is sufficient for our analysis. Therefore, we use the PeeringDB dataset as our main data source.

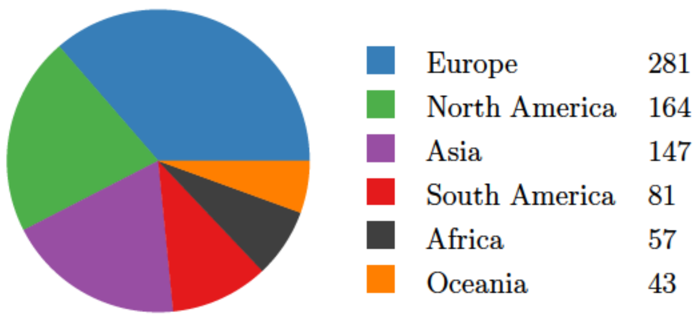


Figure 2.1: IXP distribution by continent (PeeringDB)

[6] https://docs.peeringdb.com/gov/#peeringdb-governance(02.2020)
[7] https://www.peeringdb.com/sponsors(05.2020)

At the time of writing the dataset is publicly available in its entirety and can be accessed via a RESTfull API[8] and an interactive web frontend. It consists of detailed information of ASes, IXPs, facilities and the provider organizations. A detailed overview can be found in Appendix A.1.

CAIDA creates daily snapshots of the PeeringDB since 2010 [11]. These snapshots are not uniform and not all values are available for the full time period. We used these snapshots for our historical analyses because the quality is good enough and no alternative data source was available. For our analysis we use only one day per month to reduce the data for the computation.

2.1.2 Packet Clearing House

"Packet Clearing House (PCH) is the international organization responsible for providing operational support and security to critical Internet infrastructure, including Internet exchange points and the core of the domain name system."[9]

The PCH offers a dataset with 1027 IXPs and their member ASes. In contrast to the PeeringDB dataset it includes historical IXPs and IXPs under construction (02.2020). The 1027 IXPs are divided into the status definitions shown in Figure 2.2.

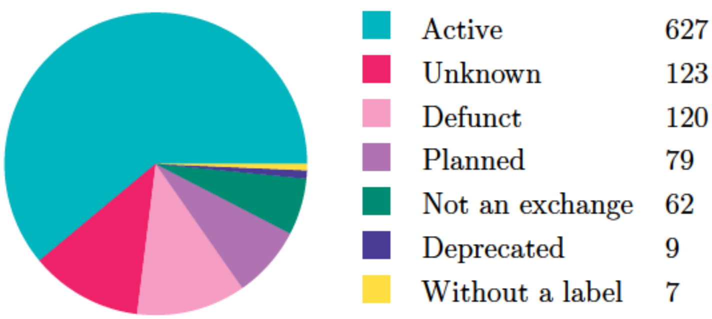


Figure 2.2: IXP distribution by status (PCH)

[8] https://www.peeringdb.com/apidocs/ (02.2020)
[9] https://www.pch.net/ (02.2020)

Figure 2.3 shows the IXP distribution by continent. The dataset contains mostly European IXPs but many North Americans and Asians are represented as well. Oceanic IXPs are not included.

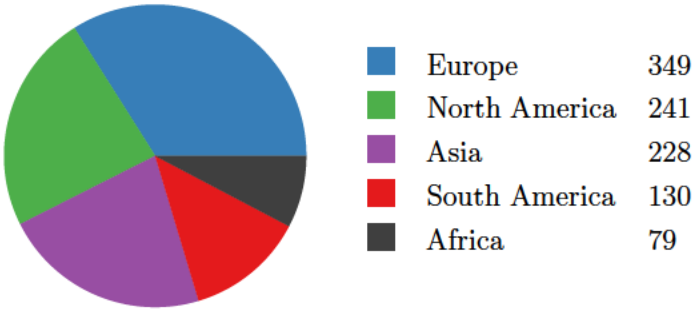


Figure 2.3: IXP distribution by continent (PCH)

Just like the PeeringDB, the dataset can be accessed via an interactive web frontend or via a RESTfull API[10]. It consists of detailed information of ASes, IXPs, facilities and information about their organizations. Some information like the organization type are only available via the web frontend. A detailed overview can be found in Appendix A.2.

2.1.3 IXPDB

"The IXP Database (IXPDB) aims to be an authoritative, comprehensive, public source of data related to IXPs. It collects data directly from IXPs through a recurring automated process. It also integrates data from third-party sources in order to provide a comprehensive and corroborated view of the global interconnection landscape. The combined data can be viewed, analyzed, and exported through this web-based interface and an API."[11]

The IXPDB dataset covers 584 IXPs and 14063 ASes (02.2020). Figure 2.4 shows the IXP distribution by continent. The dataset contains mostly European IXPs but also many Asians and North Americans are represented as well.

[10] `https://www.pch.net/ixp/data`(02.2020)
[11] `https://ixpdb.euro-ix.net/en/`(02.2020)

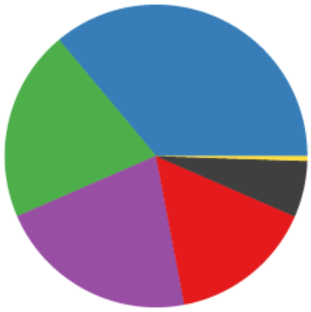


Figure 2.4: IXP distribution by continent (IXPDB)

The dataset can be accessed via an interactive web frontend and a RESTfull API [12]. Just like the previous datasets it consists of detailed information on ASes, IXPs, facilities and information about their organizations. A detailed overview can be found in Appendix A.3.

The dataset is currently the most incomplete one out of our dataset selection. A lot of fields are empty and might have empty IXP detail views. The participants can push and update their information via an API which means that the quality of the data may depend on the reputation of the database[13]. At the time of writing, 225 out of 584 IXPs update their information automatically via this API[14] (02.2020).

2.1.4 Hurricane Electric

“Hurricane Electric (HE) operates its own global IPv4 and IPv6 network and is considered the largest IPv6 backbone in the world as measured by number of networks connected. Within its global network, Hurricane Electric is connected to over 200 major exchange points and exchanges traffic directly with more than 7,500 different networks”[15].

HE offers information in addition to the IXP data, such as BGP peering graphs. Their dataset contains 663 IXPs with information about their member ASes and peering net-

[12] https://api.ixpdb.net/(02.2020)
[13] https://docs.ixpmanager.org/features/ixf-export/(02.2020)
[14] https://ixpdb.euro-ix.net/en/ixpdb/ixps/?reverse=&sort=name&q=&api=on (02.2020)
[15] https://www.he.net/about_us.html(02.2020)

works (02.2020). The information is not as detailed as in the other data sources. A detailed overview can be found in Appendix A.3.

Figure 2.5 shows the IXP fraction by continent. The dataset contains mostly European IXPs but many IXPs located in North America and Asia.

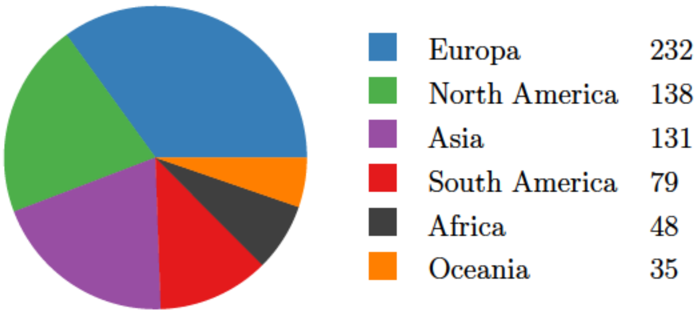


Figure 2.5: IXP distribution by continent (HE)

Figure 2.6 shows the quality of the dataset (02.2020). This shows the health of a data feed for a specific IXP. The data of 364 IXPs might not be up to date and the data of 90 IXPs is incomplete.

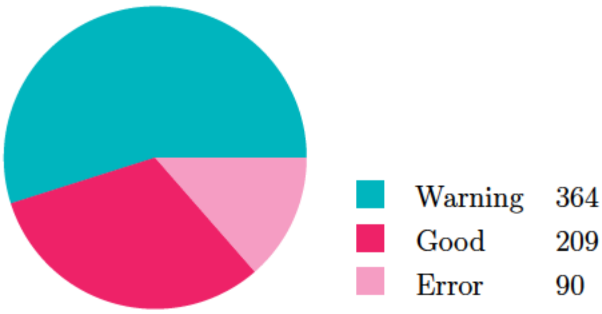


Figure 2.6: IXP data distribution by data quality (HE)

The dataset can only be publicly accessed via an interactive Web frontend. The missing accessibility via an API makes automatic processing unnecessarily difficult compared to the other data providers.

2.2 Relevance of IXPs

The impact and relevance of IXPs is difficult to identify and has been a topic of research over the last decade. Figure 2.7 shows the number of IXPs per continent since 2010. The number of IXPs grows at a relatively constant rate until 2016. From 2016 on, only the number of IXPs in Europe continues to grow of about a constant rate. South America had its peak in 2016. Europe has by far the most IXPs over the entire period. North America constantly has about 100 IXPs less. The number of IXP per continent may not be complete, but show the growth of IXPs. However, the fact that the number of IXPs is increasing does not show their importance.

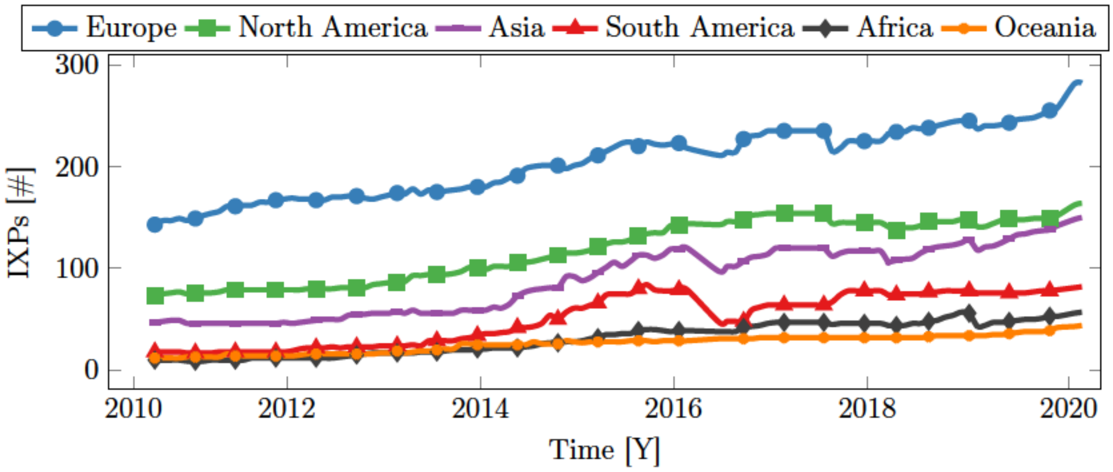


Figure 2.7: Number of IXPs per continent (PeeringDB)

Chatzis et al. showed in 2013 that IXPs are more than "add-ons to an Internet dominated by large Tier-1 ISPS and large content providers/distributors" [14]. Lv et al. conclude that the impact of IXPs on the Internet is increasing [39]. In 2019 Böttger et al. investigated the impact of IXPs on path lengths and how IXPs reduce the need for a transit AS [6]. They showed that IXPs shorten the path lengths decisively, but the transit dependency of ASes still exist. Simultaneously, they observed that the central and large ASes steadily moved away from public peering on IXPs, while the less central and smaller ASes exhibit the opposite behavior.

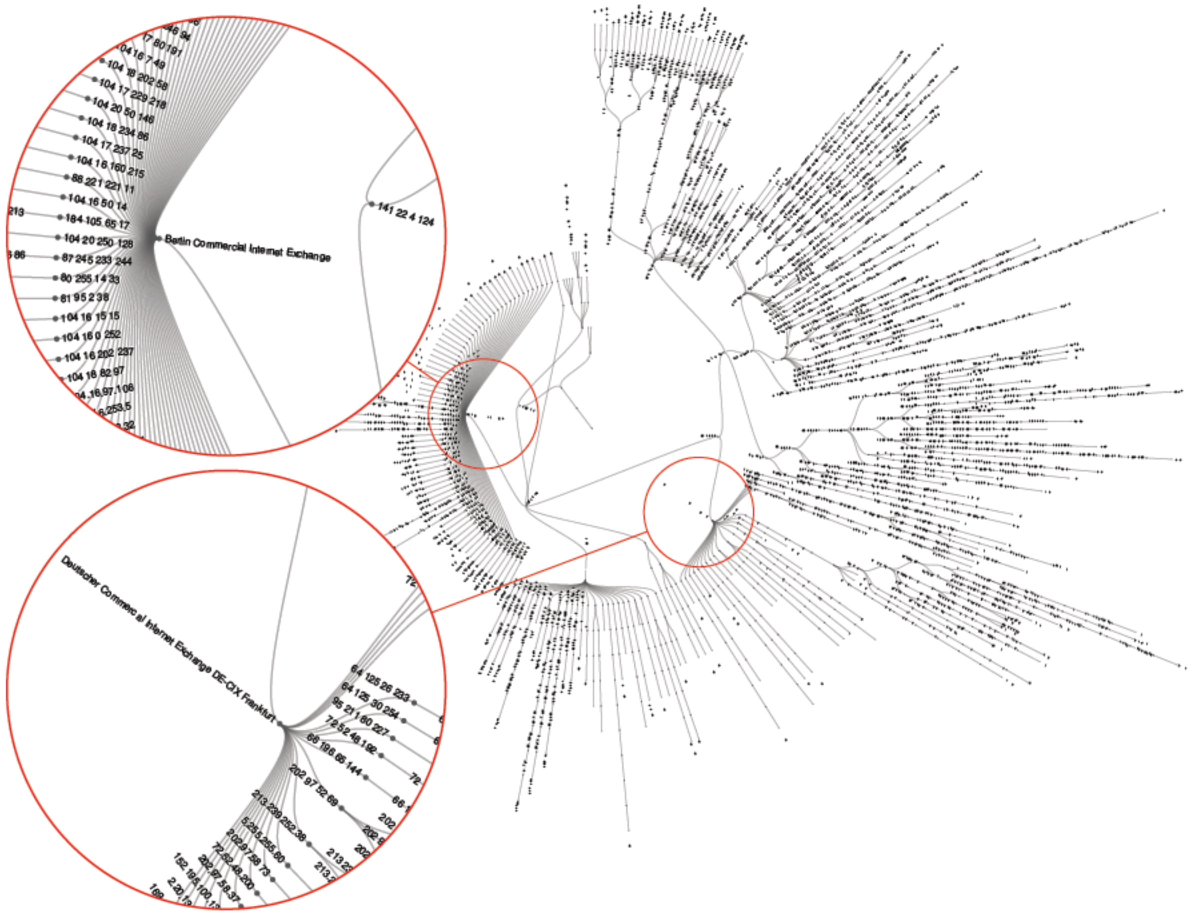


Figure 2.8: Traceroutes performed from the HAW network (02.2020)

IXPs impact end-to-end Internet routes: Böttger et al. analyze traceroutes from iPlane and CAIDA Ark to examine how IXPs impact end-to-end Internet routes. In 2016, approximately 20% of routes traversed IXPs. We obtained a similar number in a small non-representative measurement. We conducted traceroutes of five measuring points to the first 1000 websites of the Majestic Million[16] list over a period of four months. Our results were in the same range.

Figure 2.8 shows the aggregated traceroutes performed form the network of HAW Hamburg (AS680). Aggregated means that if a node is reachable via different routes, this node exists several times, but routes continue from only one of these nodes. The other routes simply end. The BCIX and DE-CIX, through which the traffic mostly flows, are highlighted. From HAW, more than 35% of the traceroutes traverse an IXP. Our small measurement shows that the visibility of IXPs in end-to-end routes differs strongly from vantage point to vantage point. In contrast to HAW, traceroutes from a server hosted by Contabo[17] (AS51167) in Germany only traverse an IXP in 10% of the cases. The number of routes passing through an IXP is perhaps a better measure of the relevance of the IXP than their quantity, since it is independent of the growth of the rest of the Internet.

All in all, it can be said that the relevance of IXPs is difficult to determine. But it seems to be increasing for small businesses and the importance of Tier-1 networks is not diminished.

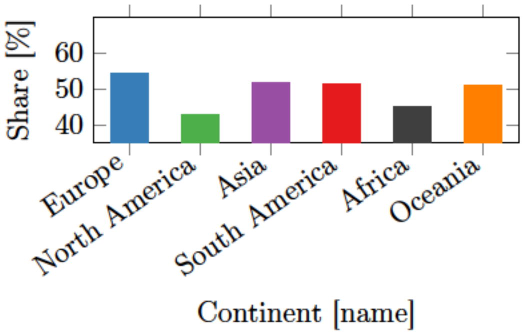
2.3 Evolution of Public Peering

Public peering is one of the main features and benefits of IXPs for most of their members. It reduces transit traffic and small ASes can exchange traffic with large ones at relatively low cost [43].

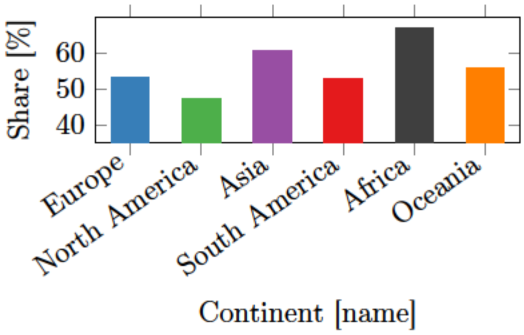
Figure 2.9 shows the fraction of public peering among all IXP members per continent. The fraction over all IXPs is shown in Figure 2.9a. More than 50% of all European IXP members hold BGP sessions with the route server (RS). In North America, the share is 40%. This difference is not as significant for the top five IXPs by members count displayed in Figure 2.9b. Combined with Figure 2.9c it shows that the peering characteristics differ strongly between the of the top five and rank 6 to 30 IXPs by member count. In Asia and Africa, the fraction is more than 10% higher for the top five and more than 10% lower for Europe. Supposedly, the peering characteristics in Europe and North America seem to change with the IXP size. The larger the IXP is, the smaller gets the share

[16] `https://majestic.com/reports/majestic-million` (02.2020)
[17] `https://contabo.de/` (02.2020)

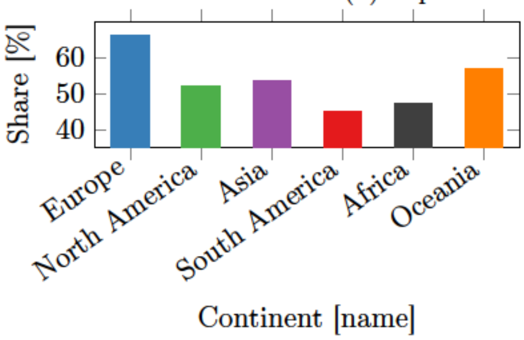
of members that participate in public peering. Africa, Asia and South America show exactly the opposite picture. This is probably related to the internet age in the region and the related composition of the member types of the IXPs [17]. We study this topic in Section 2.9.



(a) All IXPs



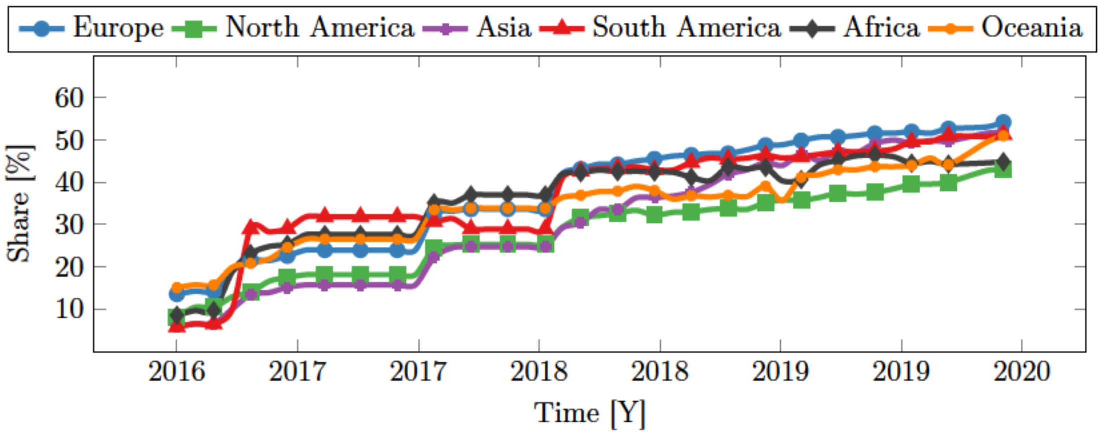
(b) Top five IXPs by members size



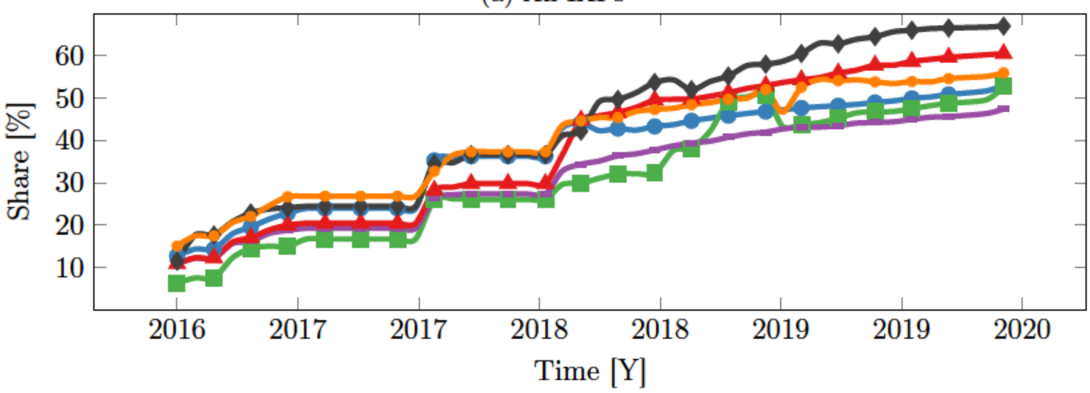
(c) Rank 6 to 30 IXPs by members size

Figure 2.9: Share of all IXP members per continent participating in public peering per continent (PeeringDB)

According to [44] a massive amount of traffic flows to European IXPs, which will be routed via public peering relationships. We cannot see the real traffic flows (data plane), but we can see how many ASes are participating in public peering (control plane). More than 50% in Europe in contrast to 40% in the North America is a clear difference but of the same magnitude. Note that the fraction of public peering is only a loose indicator for public peering traffic, because it reflects the control plane and not traffic flows. The volume of the traffic differs strongly between participants. A regional AS like a hosting provider forwards a small fraction of the traffic of a hypergiant like Google. If a hypergiant participates in the public peering, this would compensate for the proportion of small ASes that do not participate. The peering policies of hyper giants are different. Google[18], Alibaba[19], Netflix[20] generally participate in public peering. In contrast, Facebook[21], Amazon[22] do not. Future research is needed to determine the actual amount of traffic via public peering. The fraction of public peering differs not only between Europe and North America. Europe has the highest public peering share across all IXPs of all continents. Note that South America and Asia have a large fraction of public peering as well. The differences seem to be maybe culturally related [44] and determined by the age of the Internet in the specific region [17].



(a) All IXPs



(b) Top five IXPs by member size

Figure 2.10: Evolution of the share of all IXP members per continent participating in public peering per continent (PeeringDB)

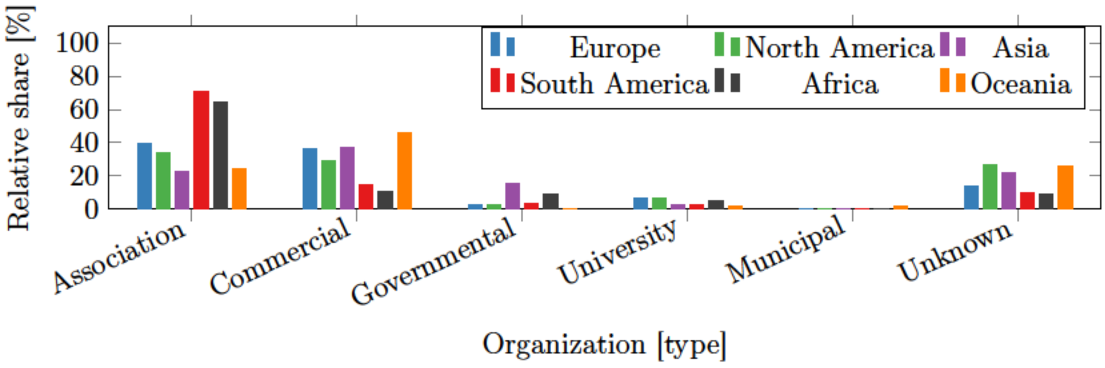
[18]`https://peering.google.com/#/options/peering` (08.2020)
[19]`https://peering.alibaba-inc.com/` (08.2020)
[20]`https://openconnect.netflix.com/en/peering/#guidelines` (08.2020)
[21]`https://www.facebook.com/peering/` (08.2020)
[22]`https://www.peeringdb.com/net/1418` (08.2020)

The evolution of public peering: The evolution of public peering since 2016 is shown in Figure 2.10. Across all continents the share of public peering among IXP members grows continually. North America has mostly the lowest public peering share over the entire period. Europe and South America have the highest shares with more than 50% in 2020. The distribution for the top five IXPs per continent presents a different picture. With more than 60% in 2020, Africa has by far the highest share of public peering and Europe and South America are in fourth and fifth place with about 50%. The gab between North America shrinks 2018, the share closes up to each other. This confirms the assumption that IXPs with similar larger resemble each other and suggests that the older the Internet in a region, the smaller the differences become. The unexpected increases in the proportion of public peering, such as in 2017, are due to on the update of the records of one or more large IXPs during the same time period.

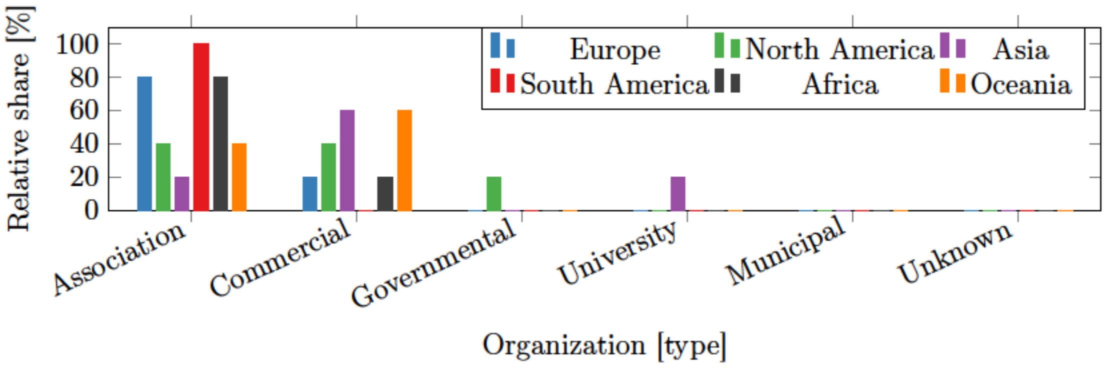
2.4 Organizational Structure of IXPs

The organizational structure of IXPs can generally be divided into a member-oriented, a profit-oriented, a research-oriented or a governmental structure. The organization type can give an indication of the orientation of the IXP.

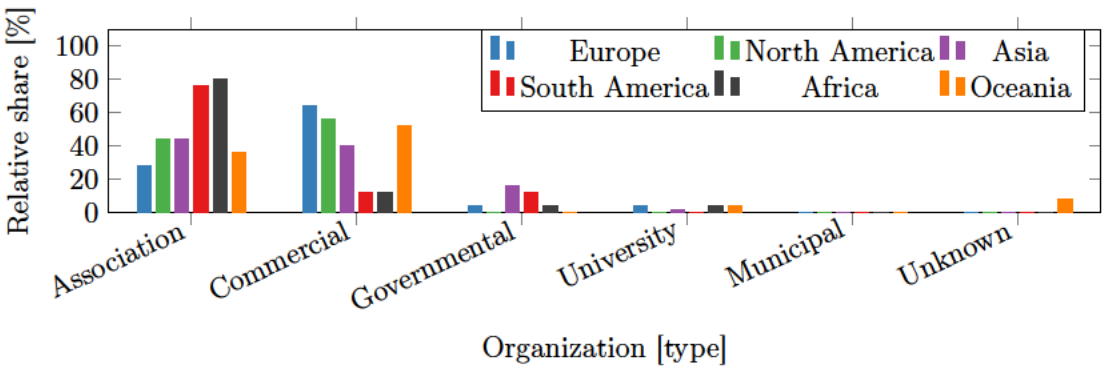
Data sources: The type of organization is included in the PCH dataset, which is described in the Section 2.1. PCH distinguishes between association, commercial, governmental, university, municipal and unknown types of organizations. We crosscheck the values for the top five per continent manually. The full results can be found in Appendix B. The determination of the organization type is hard, because the type can change over time or might be facade by a complex company structure. As an example, the DE-CIX is managed by a commercial GmbH which is owned by an association. Our analysis shows that 6.66% (2 of 30) of the considered entries for the organization type in PCH are potentially incorrect. Additionally, we were unable to validate one IXP (NiCE OpenIXP) because we could not find detailed information about its organization structure.



(a) All IXPs



(b) Top five IXPs by member count



(c) Rank 6 to 30 of IXPs by member count

Figure 2.11: Distribution of organization types of IXPs per continent (PCH)

Organization type fraction of IXPs per continent: The organization type distribution of IXPs aggregated per continent are shown in Figure 2.11. Results across all IXPs are displayed in Figure 2.11a. The largest fraction of IXPs with an association organization type are in South America. The difference between Europe and North America is not large. Europe has about 6% more IXPs with an association organization type. North America has about 26% of IXPs with an unknown organization type and Europe has only 16%. The data quality for North America is might be worse because the type of organization was determined for about 10% less IXP than for European.

Figure 2.11b shows the organization type distribution of the top five IXPs by members count and Figures 2.11c of rank 6 to 30 by members count. The proportions between the top five IXPs and rank 6 to 30 is more different for European IXPs than for the other continents, i.e. 60% of rank 6 to 30 are commercial in contrast to 20% (1) of the top five. The unknown organization type share is less for the first 30 IXPs by size, only Oceania has an unknown organization share.

All top five IXPs on all continents have either an association or commercial organization type with two exceptions: one university IXP in Asia, the HKIX Hong Kong, and a governmental IXP in North America, Intered Panamá. Our manual inspection has indicated that the Intered Panamá has likely an association organization type and is mislabeled. Association as an organizational type is an indicator that the IXP is managed according to the interests of its members. This influences the pricing policy and neutrality of the IXP. In contrast, a commercial IXP is managed according to its own interests. For example, if the operator also operates the point of presences (PoPs) of the IXP, it is not in his interest to connect alternative PoPs. In Section 2.7 and Section 2.8 we examine this topic in detail.

2.5 IXP Peering Costs

The cost of peering varies greatly between IXPs and continents. The public availability of IXP prices is rare and therefore difficult to evaluate.

Data sources: Many IXPs do not offer publicly available pricing information. For the top five IXPs per continent, we inspect the websites to see if pricing information is publicly available. Detailed results can be found in Appendix B. An additional source for peering cost information is maintained by Job Snijders et al.[23] It lists a subset of

[23] `http://peering.exposed/` (07.2020)

IXPs unevenly distributed over the continents. On 22.04.2020 it included 65 European, 25 North American, 6 Asian, 8 African, three Oceanic and one South American IXP.

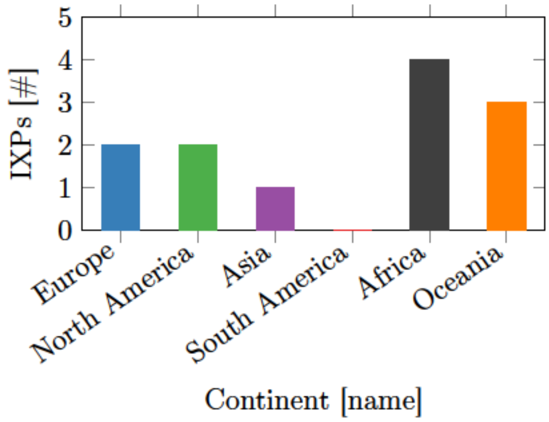


Figure 2.12: Share of IXPs with publicly available price information of the top five IXPs by member size per continent

Availability: Figure 2.12 shows the number of IXPs with publicly available price information per continent. Africa has the highest number with four IXPs and South America the lowest with zero. For most of the IXPs price information is only available via a personal request.

Through personal communication we received the information that the pricing policy of the IXPs is often not transparent and can vary from member to member.

Price comparison: Figure 2.13 shows the average cost for a 10G link at an IXP per continent as boxplot. The cost information are fully taken from sheet of Job Snijders. Asia has the highest cost for a 10G link followed by Europe and Africa. Only the value for Europe is representative as the number of IXPs included for Asia and Africa is low. North America is the only continent with zero cost IXPs are part of the lower quartile, and overall, the median cost of a 10G link is the lowest across all continents.

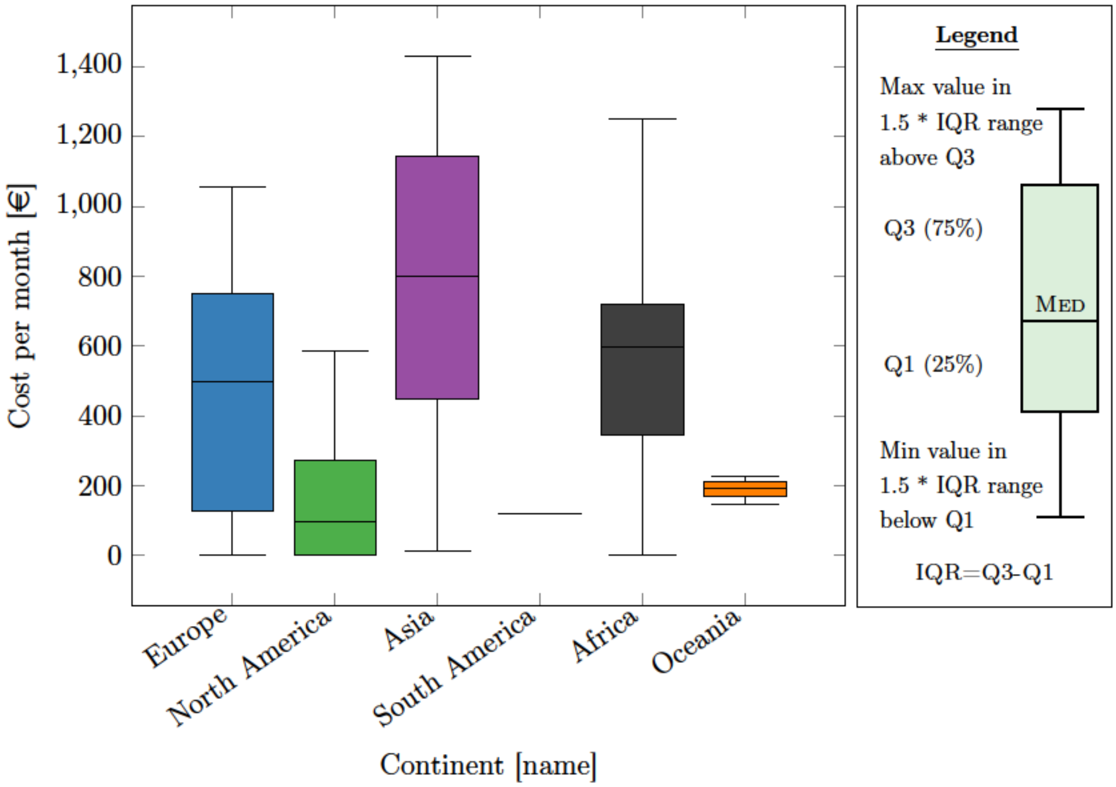
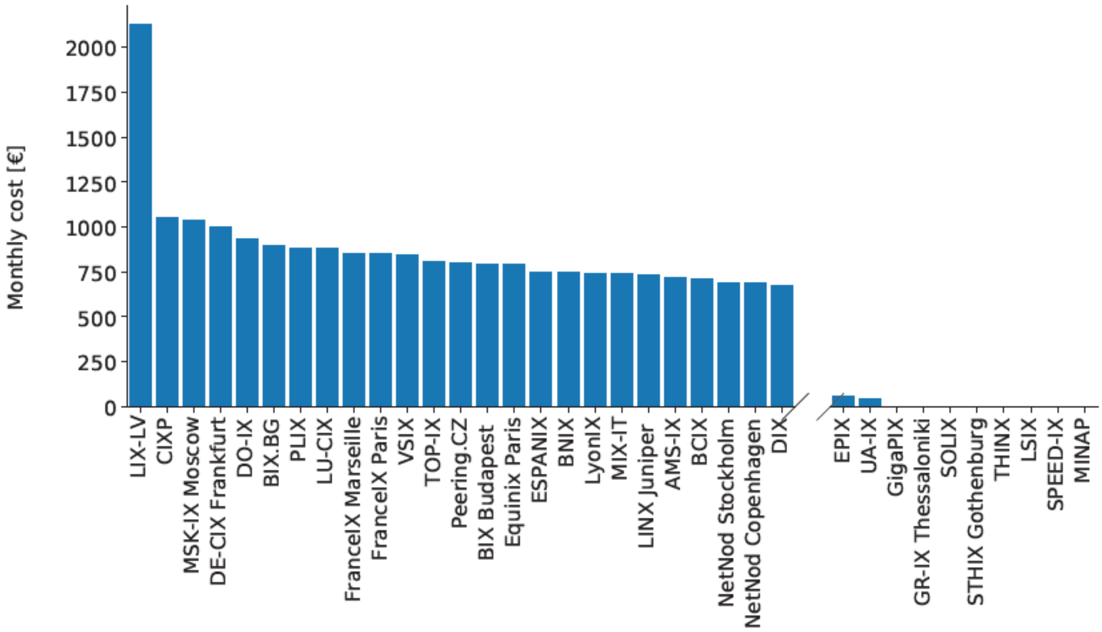
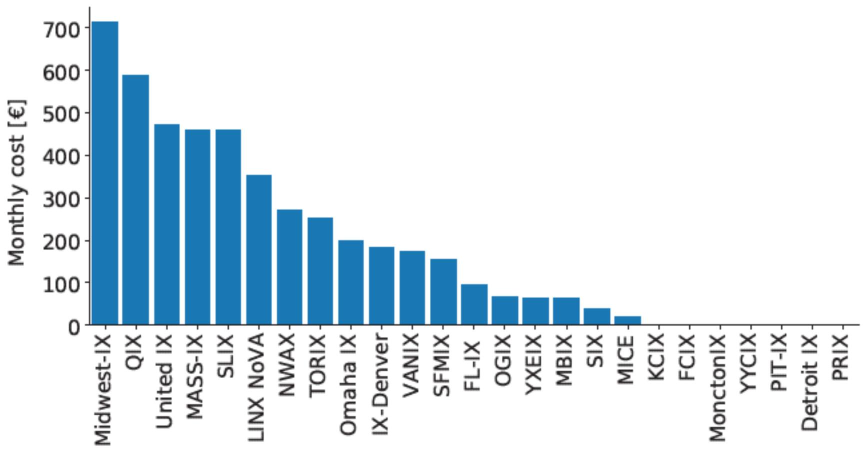


Figure 2.13: Average 10G link cost at IXPs per continent (Data by Snijders et al.)

A detailed breakdown for North America and Europe is shown in Figure 2.14. Since Europe is strongly represented in the data set, we only show the margins. The x-axis shows the IXPs ranked by cost and the y-axis shows the cost of the 10G link in Euro. It can be seen that in Europe one 10G link at many IXPs costs more than 600€. In contrast, in North America a 10G link costs more than 600€ on the Midwest-IX only. With the LIX-LV, Europe has an IXP that is almost twice as expensive as the next one. Such outliers cannot be seen in North America.



(a) IXPs ranked by cost in Europe



(b) IXPs ranked by cost in North America

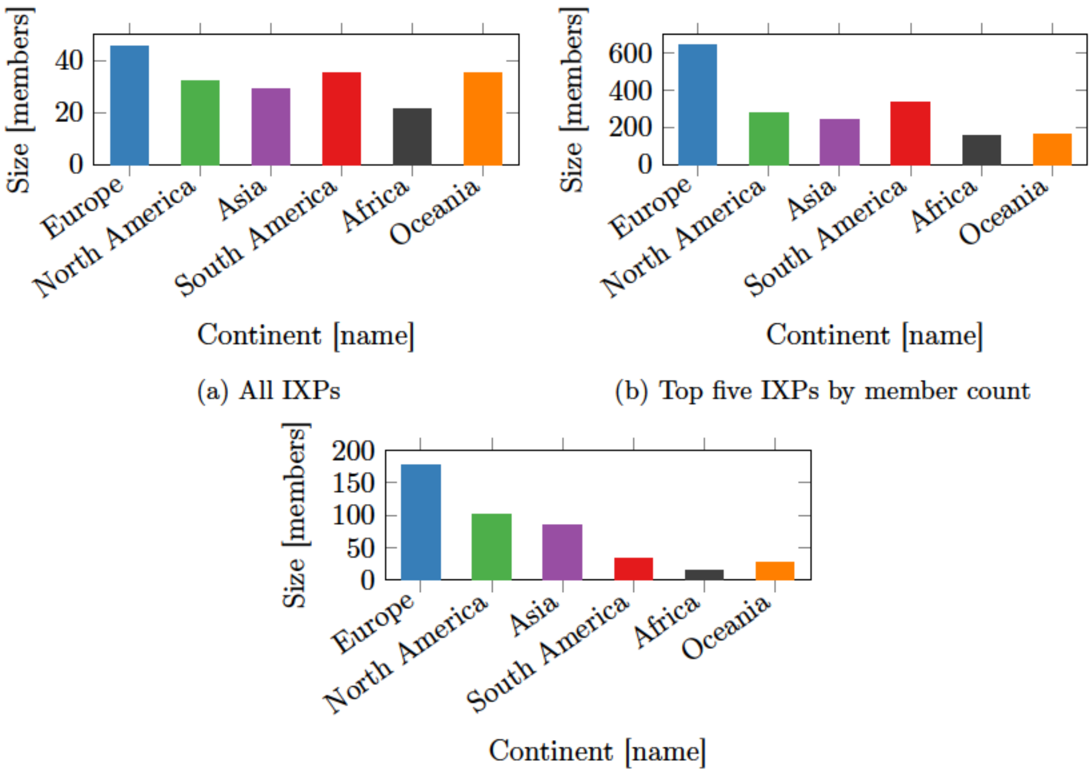
Figure 2.14: Breakdown of IXP monthly cost of 10G link for Europe and North America (Data by Snijders et al.)

2.6 Dimensions of IXPs in Size and Throughput

We investigate several dimensions of IXPs, their number of members, the link speed of members and their throughput. The question of this analysis is to determine the current status and evolution of IXP dimensions by continent.

2.6.1 IXP Size by Member Count

The number of members is a strong metric for the size and relevance of an IXP. IXPs with many members are more attractive to customers because they connect the customer to more other networks than smaller ones.



(a) All IXPs

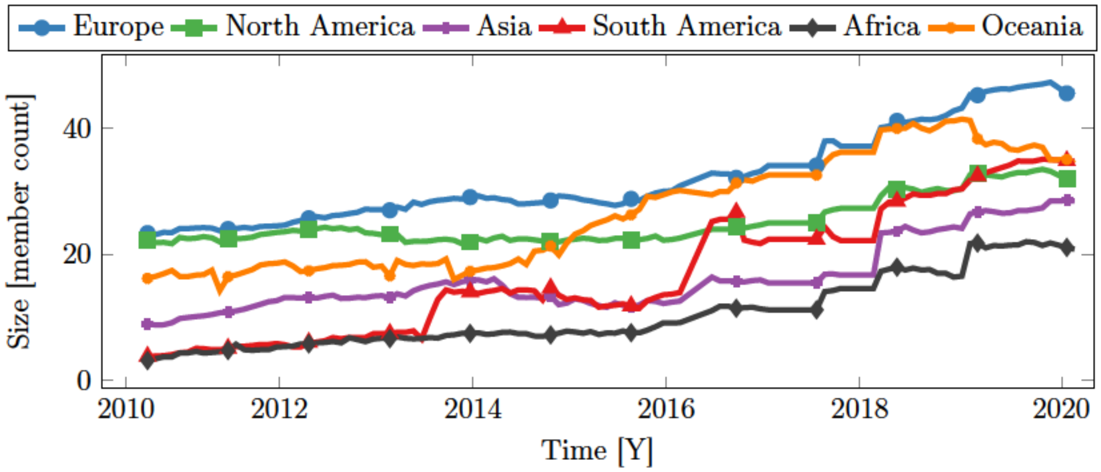
(b) Top five IXPs by member count

(c) Rank 6 to 30 of IXPs by member count

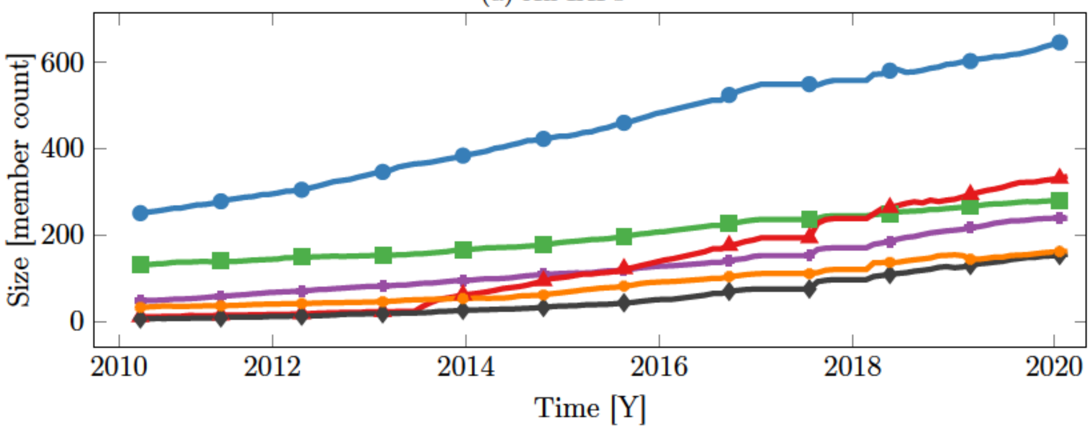
Figure 2.15: Average IXP size by member count per continent (PeeringDB)

The calculated average member count for each continent is shown in Figure 2.15. Results across all IXPs are displayed in Figure 2.15a. Europe has the largest average IXP size with more than 45 members, Oceania and South America follow with 35 members. Africa has the smallest average size with less than 22 members.

The IXP size difference between the continents is larger for the top five IXPs per continent shown in Figure 2.15b. With almost 650 members Europe has the highest IXP size. In second place is South America with almost 300 fewer members. The size differences of IXPs between North America, Asia, Oceania and Africa are smaller. Figure 2.15c shows the sizes for rank 6 to 30. South America drops from second to fourth place. This indicates that South America has few very large IXPs and otherwise only small ones.



(a) All IXPs



(b) Top five IXPs

Figure 2.16: The historical evolution of the average IXP size by member count per continent

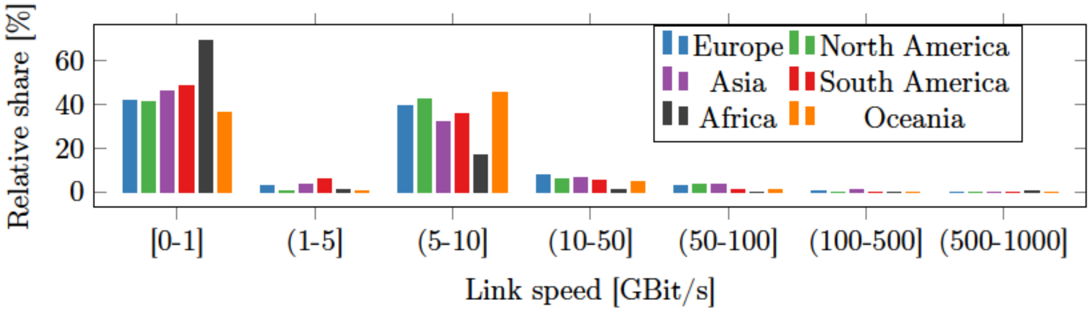
The historical evolution of the average IXP size by member count is shown in Figure 2.16. Over all IXPs (Figure 2.16a) Europe has the largest IXP size and the distance to the other continents are much bigger than in Figure 2.16a which shows that in Europe the large IXPs are much larger than the average. Between 2010 and 2014, North America takes second place, with Oceania taking over in 2014. The size of the South American IXPs is growing in irregular steps. These characteristics can be explained by updates of the records of large IXPs in the PeeringDB. In 2013, the number of members of PTT Metro São Paulo was changed from about 60 to about 145 in one day.

Between 2010 and 2015 Europe and North America have the largest IXP sizes among the top five IXPs shown in Figure 2.16b. In 2017 South America takes the second place and North America drops one place down. Over the entire period Europe has the largest IXP size by far. The difference in size between all and the top five for Oceania and South America strengthens our previous assumption that South America has an unequal size distribution while Oceania has an equal size distribution.

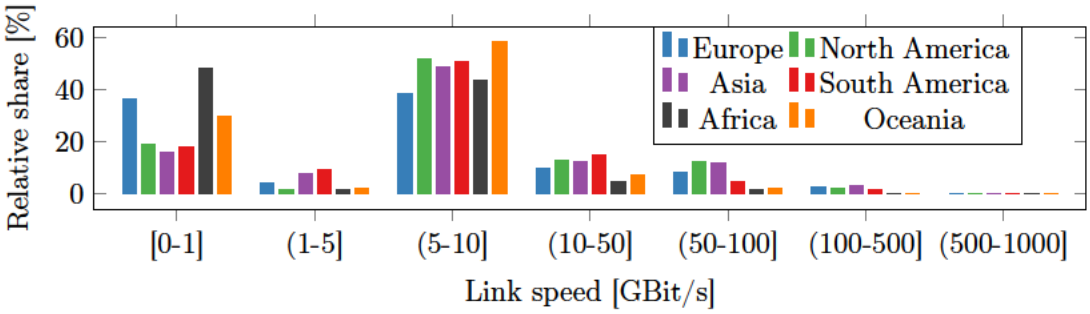
2.6.2 IXP Throughput

Besides member count, the throughput is an important dimension of an IXP. The PCH dataset includes throughput information only for a small subset of IXPs. Member link speeds are available for most of the IXPs in the PeeringDB dataset.

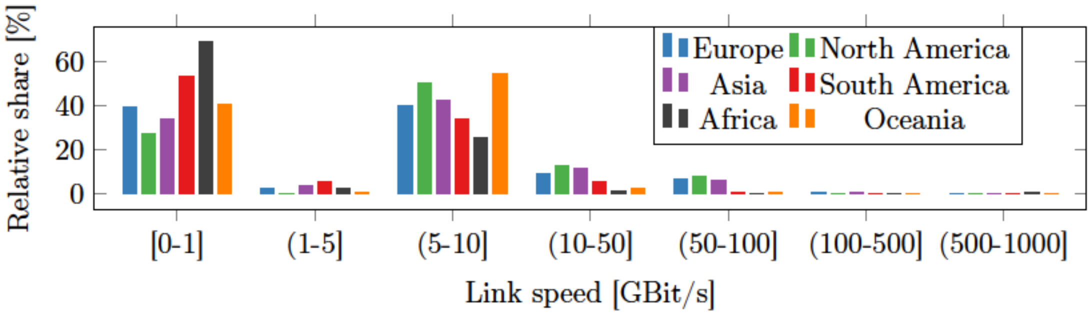
IXP link speeds: Figure 2.17 shows the link speed distribution per continent. Over all IXPs Africa has the largest share of links ≤1GBit with about 70%. Only Oceania has less than 40% of links ≤1GBit. Figure 2.17b shows the differences between the ≤1GBit and 5≤10GBit link share are larger for the top five than for all IXPs. This indicates that large IXPs have more traffic, because the top five IXPs per continent have more members connected via links larger links. The ≤10GBit link shares of the top five IXPs and rank 6 to 30 in Africa differ by more than 40%. This suggests that most of the smaller IXPs only have links ≤1GBit. This phenomenon does not occur on the other continents.



(a) All IXPs



(b) Top 5 IXPs by member count



(c) Rank 6 to 30 IXPs by member count

Figure 2.17: Link speed distribution per continent (PeeringDB)

Maximum IXP throughput calculation: We calculate the maximum IXP throughput per continent from the link speed information. The sum of the speed for each link of an IXP gives the maximum throughput of that IXP. The sum of all maximum throughput of a continent divided by the number of IXPs with link information gives the average maximum throughput per continent. Note that our results are only an estimate and probably do not reflect the real physical capacities. The division of a physical network interface into several smaller ones for customers of resellers such as RETN[24] or IXREACH[25] possibly distorts the actual value [42] as the link capacity may appear twice in the PeeringDB. However, this issue requires further investigation.

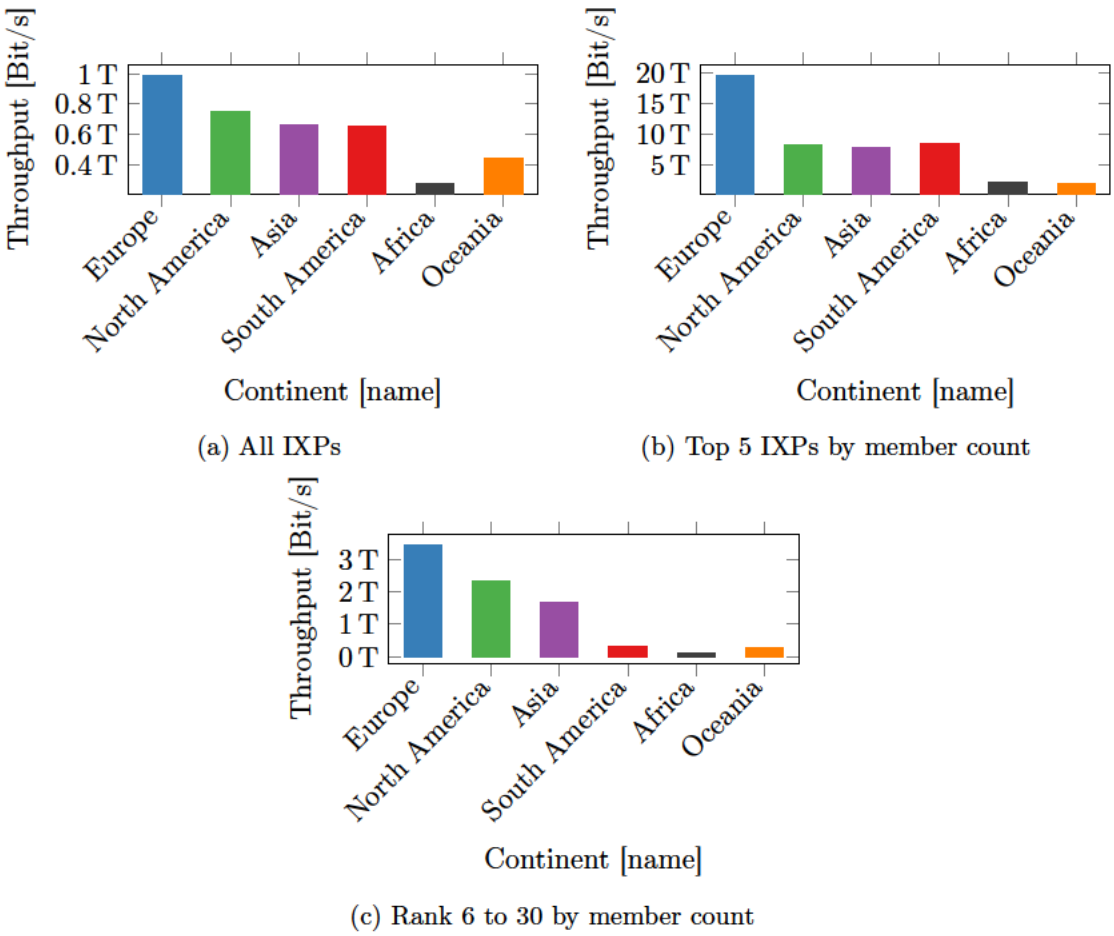
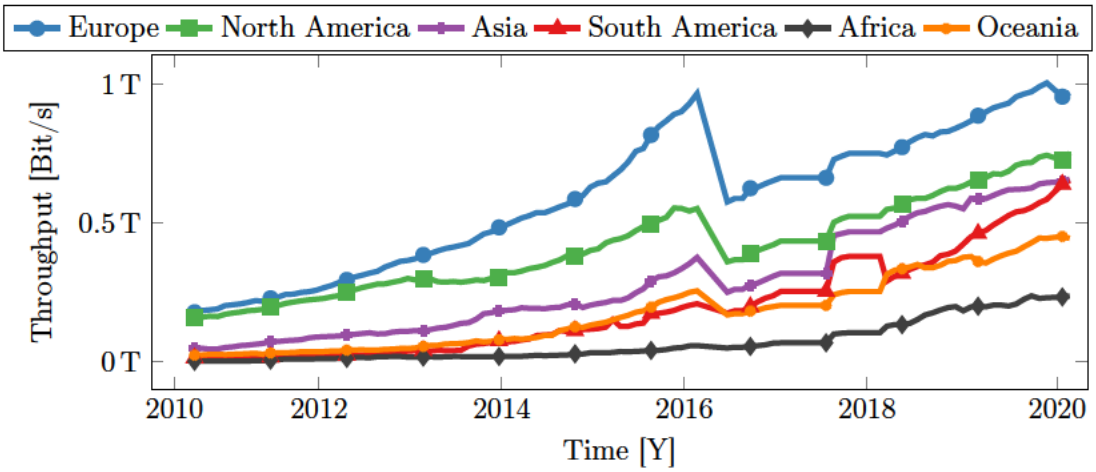


Figure 2.18: Estimated average maximum throughput of IXPs per continent based on link speed information (PeeringDB)

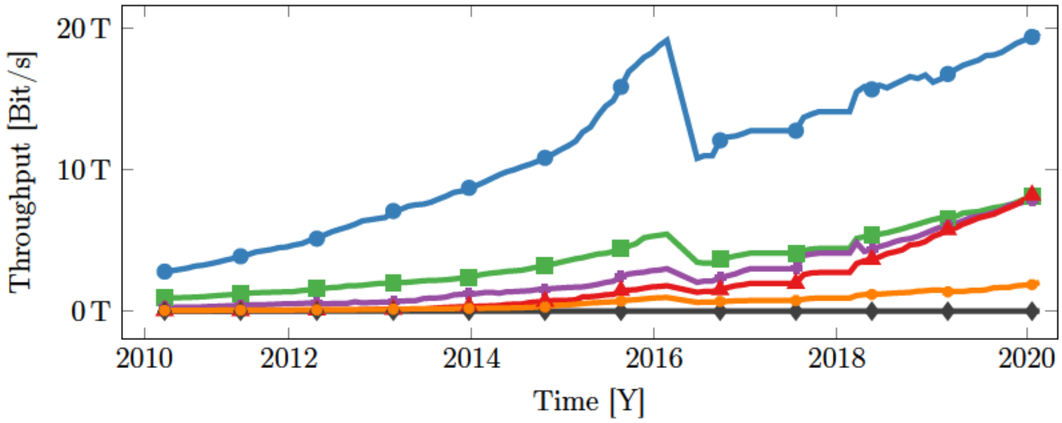
Estimated IXP throughput: The estimated average maximum IXP throughput per continent is shown in Figure 2.18. Among all IXPs shown in Figure 2.18a. With about 990 GBits/s Europe has the highest maximum throughput value. North America follows with about 750 GBits/s. The third and fourth places are taken by Asia and South Africa with about 650 GBits/s. Africa has the lowest throughput with about 280 GBits/s.

[24] `https://retn.net/services/remote-ix/` (06.2020)
[25] `https://www.ixreach.com/services/remote-peering/` (06.2020)

The average throughput for the top five IXPs by member count per continent shown in Figure 2.18b are significantly greater for most continents. Europe clearly has the highest value with more than 19 TBits/s. South America follows with nearly 9 TBits/s. North America and Asia both have about 8 TBits/s and Africa and Oceania about 2 TBits/s throughput. It is interesting to observe that for the IXPs ranked 6 to 30 by number of members displayed in Figure 2.18c. South America falls from second to fourth place. This indicates that not only the IXP size but also the maximum IXP throughput in South America is unequally distributed. There are few IXPs with a high or medium estimated throughput but many with low.



(a) All IXPs



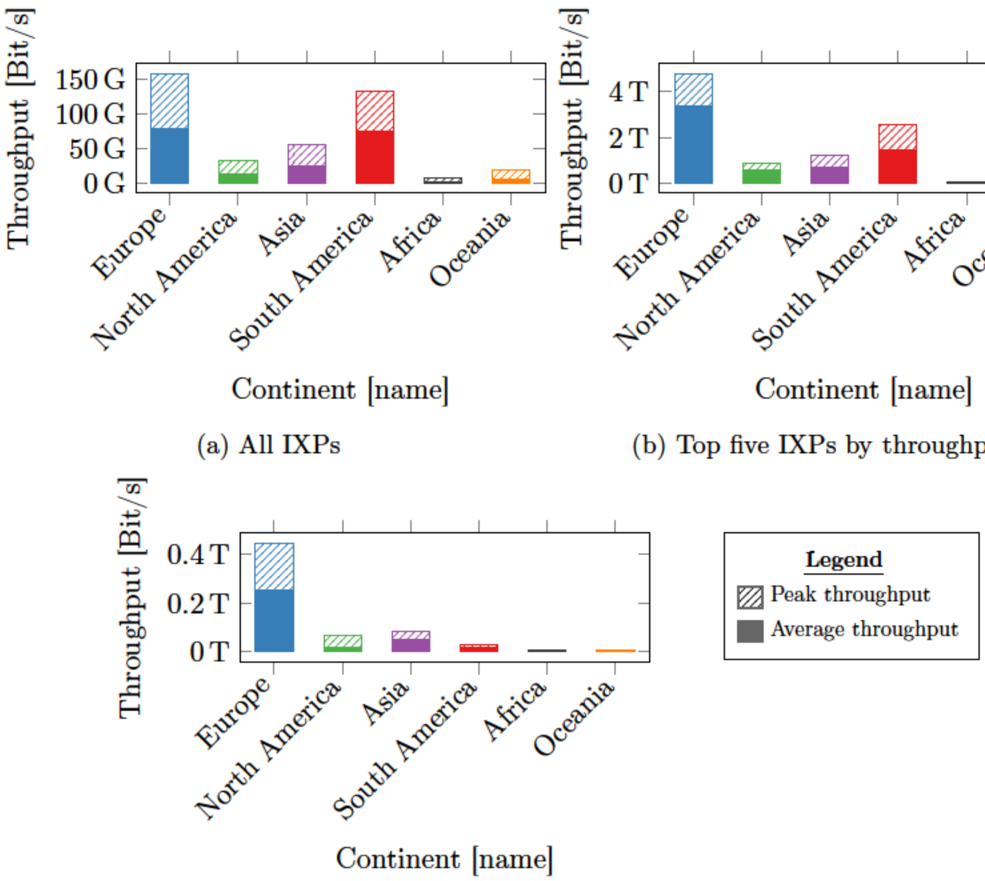
(b) Top five IXPs

Figure 2.19: Evolution of the estimated average maximum throughput of IXPs per continent based on link speed information (PeeringDB)

The evolution of the estimated maximum IXP throughput per continent is shown in Figure 2.19. We have filtered the data, because many clearly wrong values for the link speed are included. The wrong values may be caused by swapping the unit GBits vs. MBits. The still visible peaks in 2016, for example, in both sub figures. Europe has clearly the highest values across all IXPs (Figure 2.19a) and the top five IXPs by member size (Figure 2.19b). Across all IXPs the distances between the continents are smaller and since 2018 the average throughput across all continents grows similar. For the top five IXP, this characteristic is not visible and the distance between Europe and the other continents is much greater. The evolution of the estimated maximum throughput for the top five IXPs by member size of North America, Asia and South America is similar. Africa has no visible growing across the top five IXPs by member size.

Real IXP throughput: The PCH dataset contains traffic throughput stats for a subset of IXPs. Figure 2.20 shows the average and peak IXP throughput as stackplot per continent. The throughput differs strongly from continent to continent. Across all IXPs, Europe and South America have the highest values. For Europe, the peak values are more than twice the average value. Asia shows the same characteristics, but with significantly lower values.

The more IXPs are summarized, the faster the traffic throughput shrinks. This can be explained by the fact that the values are only available for a small subset of IXPs and that there are more IXPs with low throughput than with high throughput in the dataset. The difference between the peak and average throughput values is lower for the top five IXPs by throughput per continent shown in Figure 2.20b than for all IXPs. One explanation for this is that for many IXPs only peak values and not the mean values are set. Figure 2.20b and Figure 2.20c show that there are few IXP with massive throughput in South America. In contrast, Europe has more IXPs with high throughput. This matches our observations from the estimated throughput values. North America has very few real throughput values in contrast to our calculated values. This could be due to the fact that members of the IXPs in North America disclose their link speeds, but the IXPs do not disclose their full throughput [44].



(a) All IXPs

(b) Top five IXPs by throughput

(c) Rank 6 to 30 IXPs by throughput

Figure 2.20: IXP throughput per continent (PCH)

Capacity utilization of IXPs: The calculated maximum throughput values are significantly greater than the real throughput values from PCH. There are tow possible explanation, the possible double counting of physical connections, as mentioned above, which could affect the behavior of resellers, as well as the fact that only for a subset of IXPs are throughput values available.

Name	Continent	Members	Throughput [Bit/s] Avg.	Peak	Calc. max	Usage
DE-CIX Frankfurt	Europe	870	5.79T	9.07T	37.81T	24%
SIX	North America	320	1.08T	1.56T	9.53T	16%
Open IXP	Asia	199	600G	1.03T	12.84T	8%
PTTMetro São Paulo	South America	1038	4.78T	8.99T	29.07T	31%
NAPAfrica Johannesburg	Africa	180	685G	986G	7.54T	13%
Mega IX Sydney	Oceania	218	120G	180G	2.20T	8%

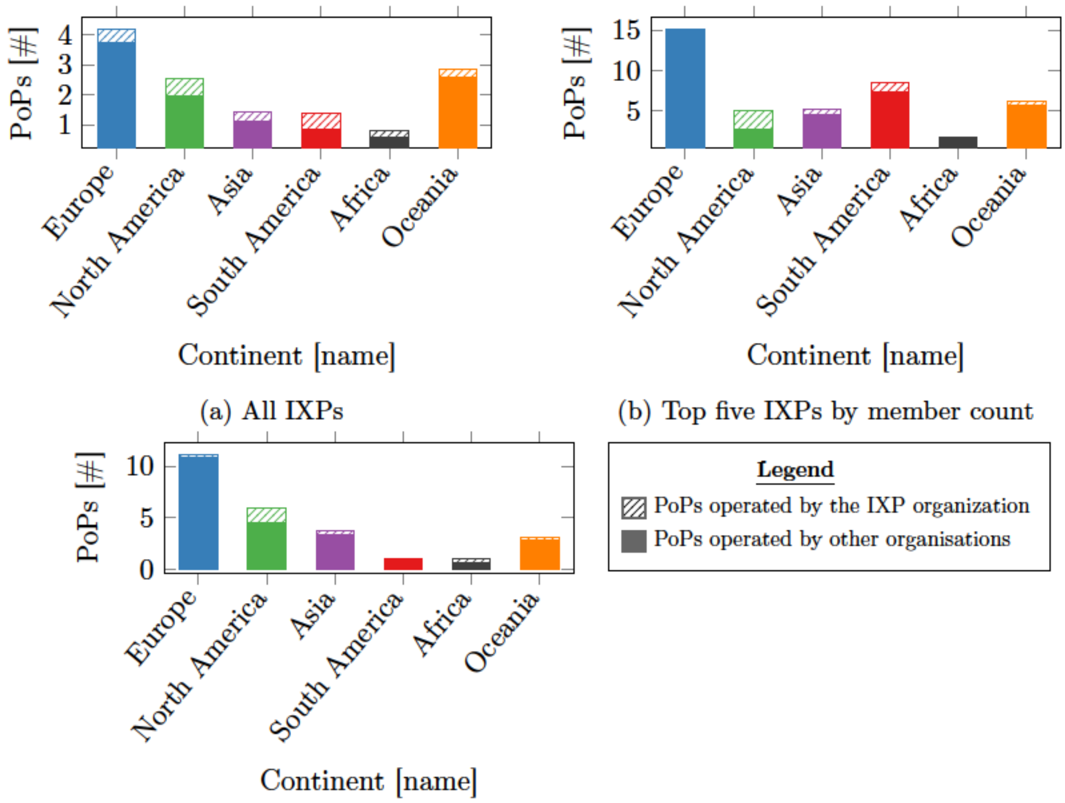
Table 2.1: Top IXPs per continent selected by throughput
(PCH and PeeringDB dated 06.2020)

Table 2.1 shows the top IXPs with throughput information available per continent. The table contains the average throughput value (Avg.), the peak throughput value (Peak) and our (with the previous introduced method calculated) maximum throughput value for each IXP (*Calc. max*). The last column shows the capacity utilization of the IXP ($\frac{peak}{calc.\ max} * 100$). Overall IXPs, the capacity utilization is low, only DE-CIX with 24% and PTTMetro São Paulo with 31% have values higher than 20%. Unfortunately, there is no public information about the actual utilization of the IXPs, but our calculated capacity utilization very likely shows that the IXPs do not operate at their limits. This is confirmed by the operators of DE-CIX[26]. According to the description of the infrastructure at DE-CIX Frankfurt, as much as 48TBit throughput is possible[27].

2.7 Points of Presence of IXPs and Their Members

Remote peering (RP) and IXPs such as NL-ix, which are spread over many countries and cities, open the question about the physical presence of the IXPs and their members. An IXP has Point of Presents (PoPs), which are historically relatively close to each other to minimize costs and ensure low latency. In these PoPs the IXP infrastructure is accessible. In contrast, RP allows the connection to an IXP from a remote location.

[26] `https://www.de-cix.net/en/news-events/news/big-upswing-in-internet-usage-due-to-covid-19-measures` (07.2020)
[27] `https://www.de-cix.net/en/access/the-apollon-platform/setup-frankfurt` (07.2020)



(a) All IXPs

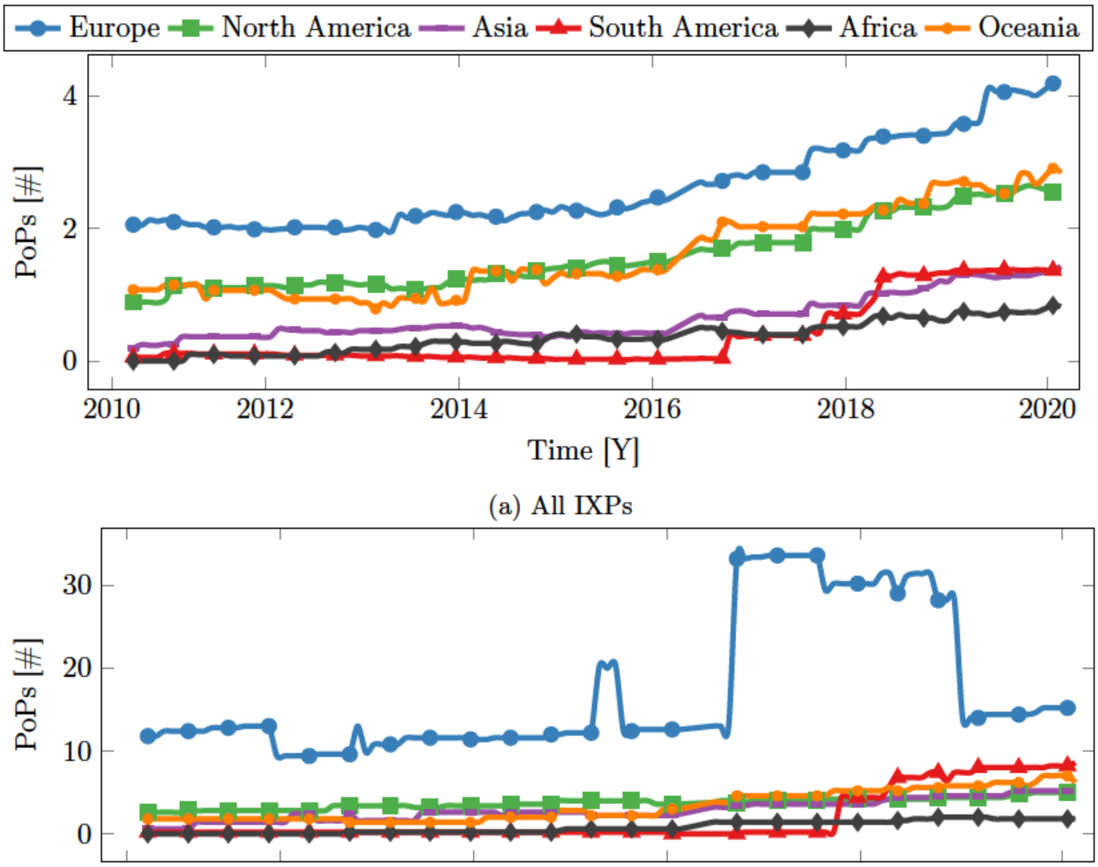
(b) Top five IXPs by member count

(c) Rank 6 to 30 IXPs by member count

Figure 2.21: Average number of PoPs per IXP and continent (PeeringDB)

PoPs of an IXP: An IXP has PoPs in which their members are physically present. Figure 2.21 displays as stackplot the average number of PoPs per IXP and continent. The hatched areas in the bars show the number of PoPs operated by the IXP organization. Europe has the highest number overall. Figure 2.21b shows that the top five IXPs in Europe have more than 15 PoPs on average per IXP compared to only five in North America. This high rate could be explained by the common practice in Europe to operate IXPs and PoPs separately, which is not the case in North America [44]. Our results show that in North America, significantly more PoPs are operated by the operators of IXPs as in Europe. In Europe there are zero PoPs operated by IXPs operators of the top five IXPs with the highest number of members. In contrast, 2.2 out of 5 PoPs in North America are operated by the IXP organization. Across all IXPs, South America has the largest percentage of PoPs operated by the IXP operators, however, the average number of PoPs per IXP is very low with 1.39.

The evolution of the average number of PoPs per IXP and continent since 2010 is displayed in Figure 2.22.



(a) All IXPs

(b) Top five IXPs by member count

Figure 2.22: Evolution of the average number of PoPs per IXP and continent

For the five IXPs per continent shown in Figure 2.22b, this value fluctuates strongly over the years. A reason is that the top five IXPs by member count per continent change over the years because the number of members per IXP changes and new IXPs are founded. In Europe, the average of the top five is approximately 30 between 2016 and 2018, but drops abruptly by around 50% in 2018. At this point NL-ix, which has about 90 PoPs, has dropped from the top five, which significantly reduces the average.

Points of presence of IXP members: IXP members can connect to an IXP through different methods. Either directly at PoPs or through resellers and partner IXPs via remote connections. A remote connection allows an AS to peer at one IXP from a remote data center, even one located in another city or country. We already mentioned that under the consideration of link speeds in Section 2.6.

In 2018, 23.4% of all member ASes of 30 IXPs considered by Nomikos et al. were connected via remote peering [42]. This shows that the existence of RP cannot be ignored.

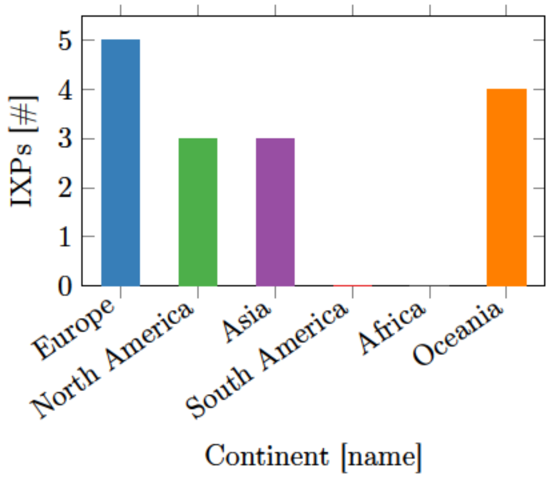


Figure 2.23: Number of IXPs in the top five by member count per continent offering remote peering

We checked the top five IXPs by member count per continent to determine if they offer Remote Peering (RP). The results are shown in Figure 2.23. With 5 of 5 Europe has the highest remote peering share followed by Oceania with 4 of 5. The top five IXPs in South America and Africa do not provide RP. Even if an IXP itself does not provide RP, it may be possible to connect remotely through a reseller. As an example, RETN[28], IXREACH[29] and Atrato[30] offer remote peering at all major IXPs in Europe, North America and Asia. We do not investigate the RP topic further, as it has already been extensively studied [42, 13].

[28] `https://retn.net/services/remote-ix/` (06.2020)
[29] `https://www.ixreach.com/services/remote-peering/` (06.2020)
[30] `http://atrato-ip.com/products/remote-ix/` (06.2020)

2.8 Transit and PoP Provider Neutrality of IXPs

IXPs are managed according to different business models, which not only affect organizational structures [44], but impact neutrality as well. Neutral means in this context that members are free to choose their transit AS as well as their PoPs independent of the operator or provider. Figure 2.24 displays the results of our manual check of the top five IXPs per continent. All top five IXPs in Europe, South America and Africa are transit and PoPs provider neutral. In Asia 4 out of 5 and in North America and Oceania 3 out of 5 are neutral.

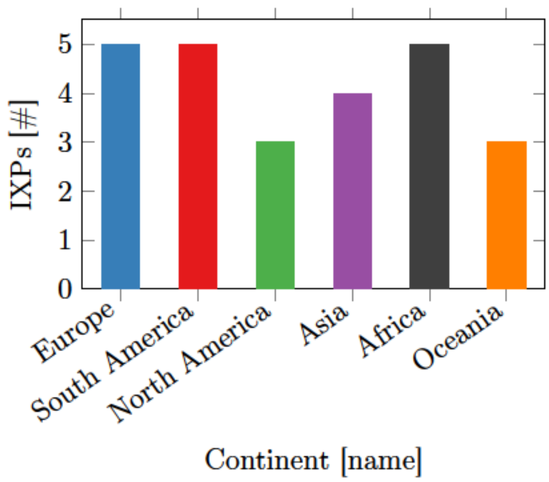


Figure 2.24: Number of IXPs in the top five by member count per continent which are transit and PoP provider neutral

We examined in Section 2.7 if a PoP are operated by the IXP operator or not. It became visible that in North America many of the IXPs are not PoP operator neutral. This is consistent with the findings of [44].

In our sample inspection, the IXPs with a commercial type of organization tend not to be transit provider neutral. This is coherent with our findings on PoPs. The PoPs of commercial IXPs are often operated by the IXP operator. The neutrality of the transit provider is not easy to determine and needs further investigation, as this information is only partially publicly available.

2.9 Variety of IXP Providers and Members

We examine the variety of IXP providers, members and the composition of IXPs based on the PeeringDB network type to better understand the IXP ecosystem. The composition of IXP member and its change over the years as well as which AS are most strongly represented in IXP, are subjects of this Section.

2.9.1 Fraction of IXP Member Types

PeeringDB includes information on the network type of IXP members which we used to understand the composition of IXPs. Members (ASes) are divided into the following types:

- Internet service providers (**ISP**) include cable or DSL providers. Examples: AT&T US (AS7132), 1&1 Versatel Deutschland GmbH (AS8881) or Swisscom (AS3303).
- Content providers (**Content**) most notably content delivery networks (CDNs) and providers of streaming content. Examples: Facebook (AS32934), Akamai (AS20940) or Microsoft (AS8075).
- Network service providers (**NSP**) like transit ASes or other network infrastructure service providers. Examples: Hurricane Electric (AS6939), RETN (AS9002) or Level3 Carrier (AS58682).
- Non-profit associations (**Non-Profit**). Examples: Chaos Computer Club e.V. (AS50472), NIC.br (AS14026) or Linux Foundation (AS54073).
- **Enterprise** networks include organizations whose main business is not the internet infrastructure. Examples: Walmart (AS17374), Cisco Systems, Inc. (AS109) or Uber Technologies Inc. (AS63086)
- Educational or research networks (**Research**). Examples: Packet Clearing House (AS42), NORDUnet (AS2603) or Education Networks of America, Inc. (AS11686).
- **Not Disclosed** or **Unknown** bundles organizations that did not report the type of their organization or whose type is missing in the record. Examples: Layer 7 networks (AS14721) or Otto (AS16378). Note that the unknown type was only used for a short time span.

Distribution of member types per continent: The distribution of member types per continent is shown in Figure 2.25. Across all IXPs displayed in Figure 2.25a most members are ISPs, NSPs and content providers. Africa and South America are an exception. They both have a very large proportion of ISPs but only a few content providers. South America has the highest ISP share overall. The ISP share across all sub-figures of North America is relatively low. This can be explained by the ISP variety. In North America are more large ISP and less number of ISPs in general than in Europe. This leads to a lower number of ISPs at the IXPs. The PeeringDB dataset contains 1219 ISPs for North America and 4003 ISPs for Europe (03.2020). Overall the research and non-profit share is small among the top five IXPs by member count shown in Figure 2.25b. The difference of the non-profit share between rank 6 to 30 by member size and all IXPs is small. South America has the highest non-profit share with about 17% and a low research share. Africa has the largest research network share for rank 6 to 30 and across all IXPs, while North America has the largest share when looking at the top five IXPs.

The differences can be partly explained by the age of the Internet in the specific continents. For example, it only makes sense for content providers to become active in regions where many of their customers are located. This is only possible for continents with a well-developed internet structure. The high proportion of research in North America is caused by the fact that the Internet was established as a research network in North America and that many universities and research networks still participate in it today [1].

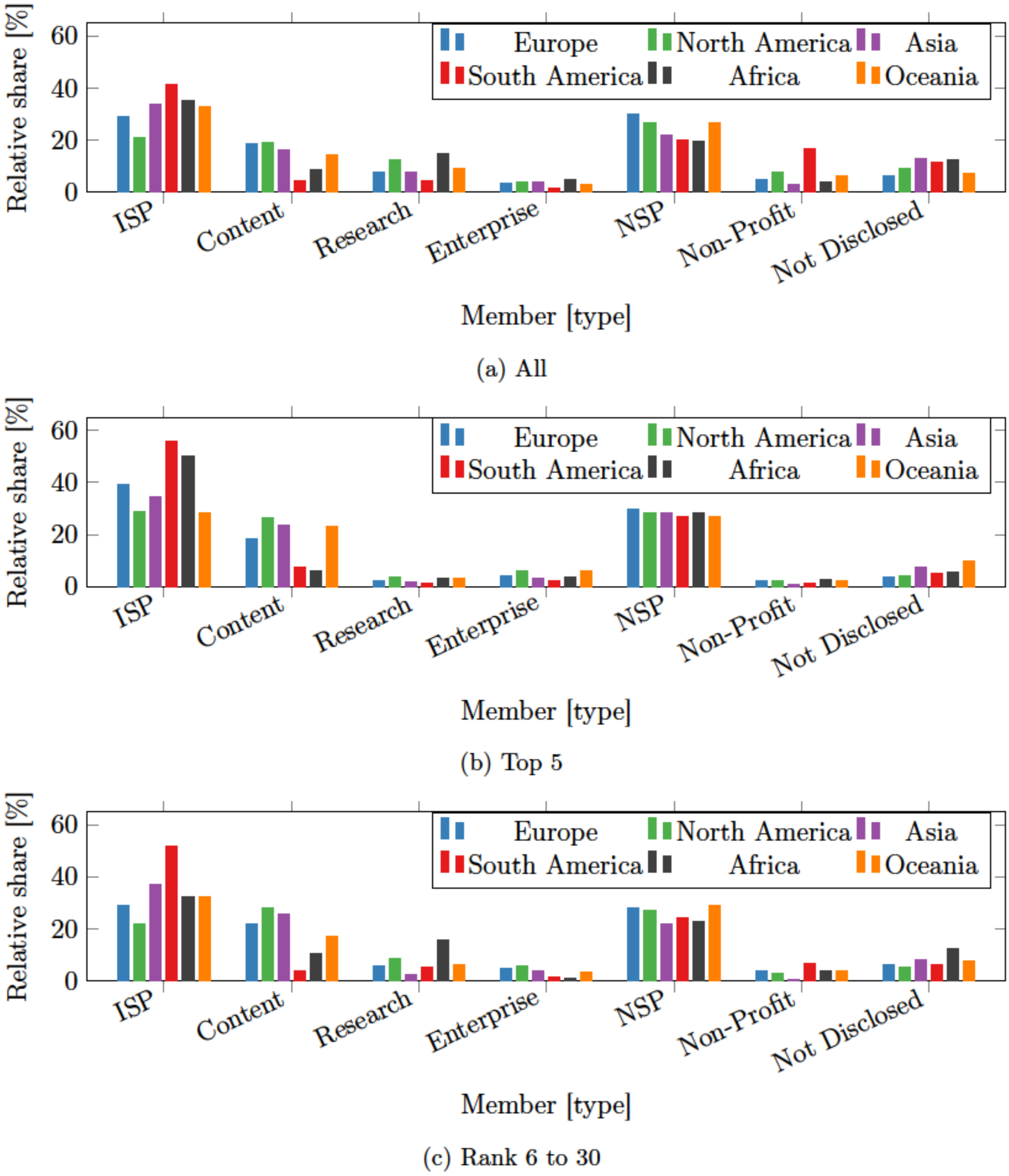
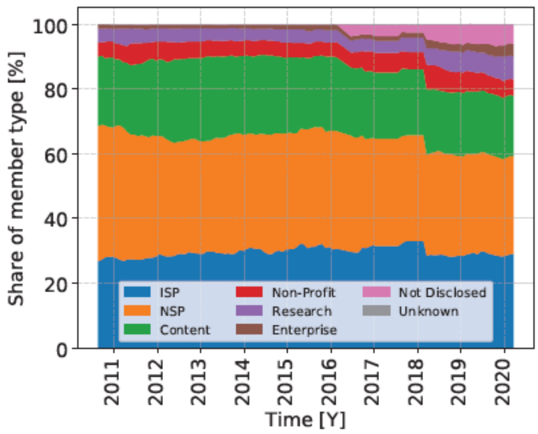


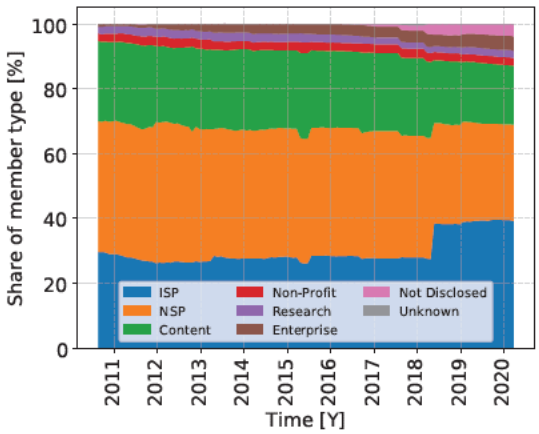
Figure 2.25: Distribution of types of IXP members per continent (PeeringDB)

Evolution over the last 10 years: The following six figures show how the member type distribution evolution over the last 10 years per continent. We only inspect IXPs with existing member information.

Figure 2.26 shows that the main members of European IXPs are NSPs, ISPs and content providers since 2010. In 2016, the undisclosed share grows and pushes the other types down, although their share remains roughly the same across all IXPs shown in Figure 2.26a. Among the top five IXPs by member size displayed in Figure 2.26b only major changes happens in 2018. A cut in NSP and content makes space for more ISPs and to a lower extent not disclosed members. These characteristics can be explained by the fact that the database schema of the peering DB changed from 10.03.2018 to 11.03.2018. This probably account into changes from a longer period of time to a single date. For example, Datagroup (AS3326) is present at 8 IXPs since 10.03.2018 and before that at 0.



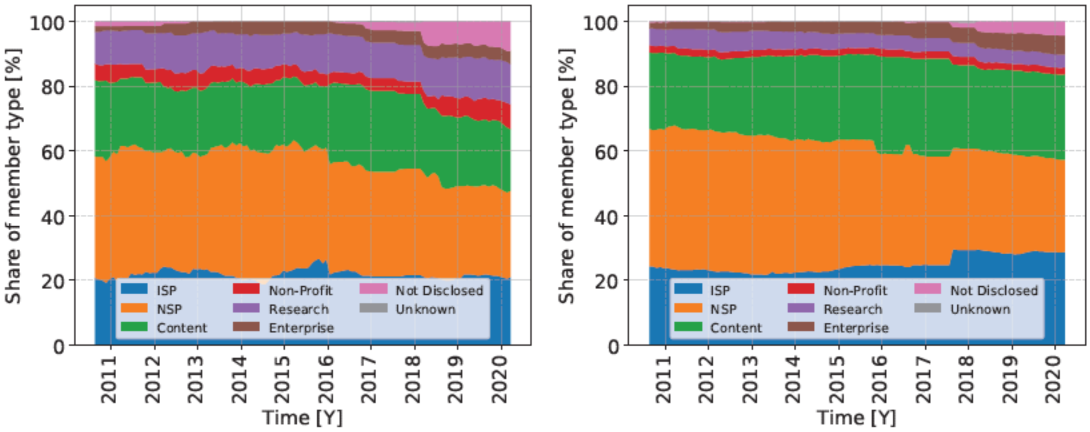
(a) All IXPs



(b) Top five by member count

Figure 2.26: Evolution of the distribution of IXP member types in Europe (PeeringDB)

The evolution of the member distribution of North American IXPs is shown in Figure 2.27 and is comparable to the distribution in Europe. In contrast to Europe the ISP share is lower and the research share is higher. We have already seen this in Figure 2.25. The historical role of research networks in North America has its origins in the early days of the modern Internet [14]. From the middle of 2018, the share of non-profit members in North America is closer to the European share.

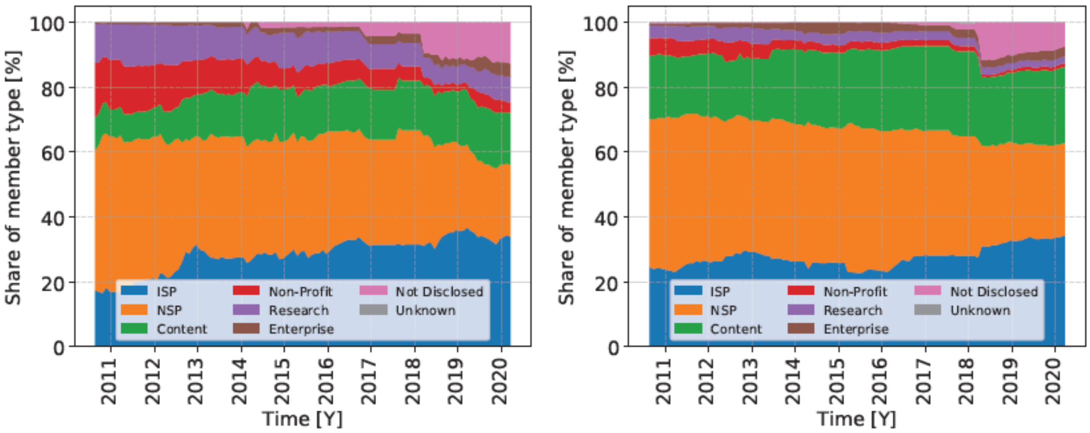


(a) All IXPs

(b) Top five by member count

Figure 2.27: Evolution of the distribution of IXP member types in North America (PeeringDB)

The content provider share in Asia (Figure 2.28) is lower than in Europe and North America across all IXPs. However, it is growing continuously. The content provider share is larger when focusing on the top five IXPs by member count. The growth trend is also visible. A clear difference to the previous two continents is the low enterprise share.



(a) All

(b) Top five

Figure 2.28: Evolution of the distribution of IXP member types in Asia (PeeringDB)

South America (Figure 2.29), in contrast to the continents previously considered, the proportion of content providers is lower and the proportion of non-profit members is higher over the entire period. The ISP share grows strongly over the years. The same effect is even more apparent when looking at the top five IXPs by member count. The non-profit share differs strongly between all IXPs and the top five. Even more than in Asia.

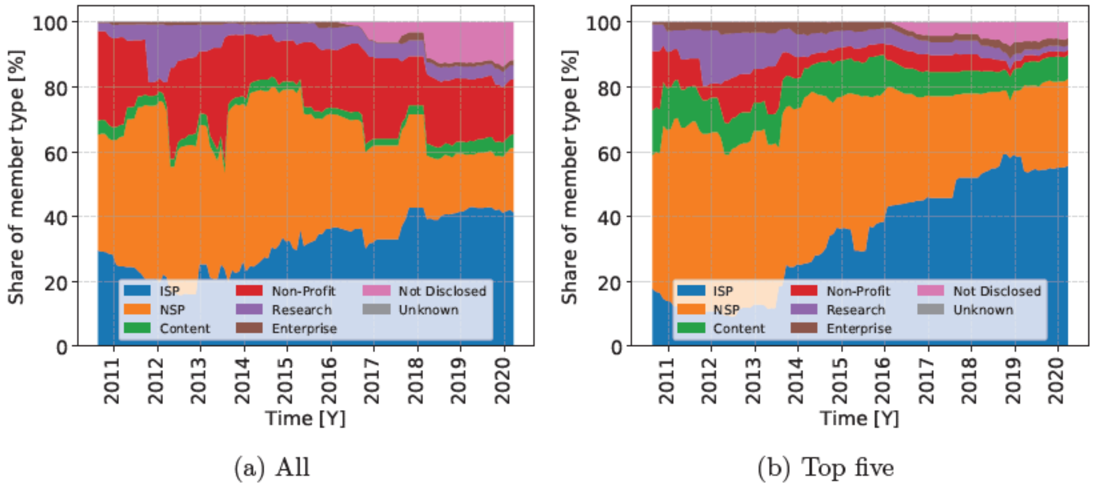
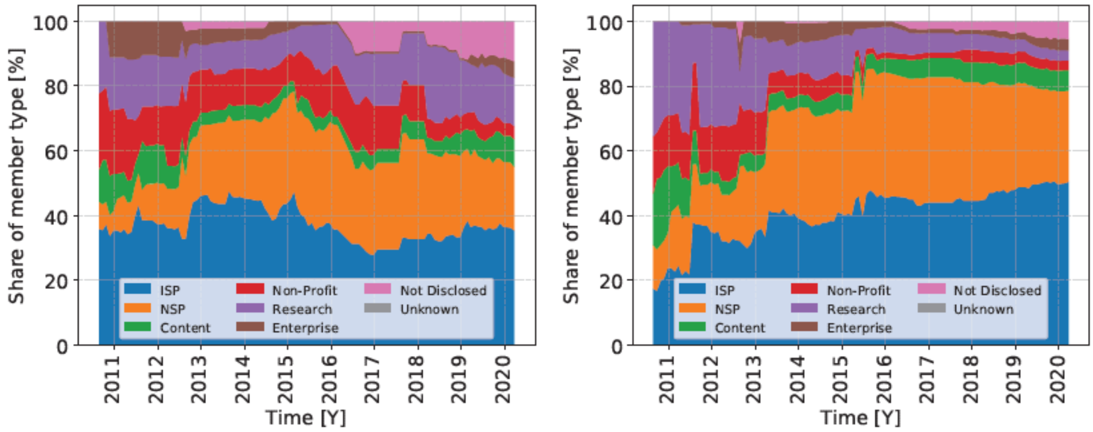


Figure 2.29: Evolution of the distribution of IXP member types in South America (PeeringDB)

The evolution of the African distribution over the last 10 years of IXP member types is shown in Figure 2.30. The ISP share is relatively high while the content provider share is very low. Overall the distribution of all member types fluctuates over the years. Across the top five IXPs by number of members, the ISP share is growing, displacing the research and non-profit share. Overall IXPs the ISP share tends to be less.

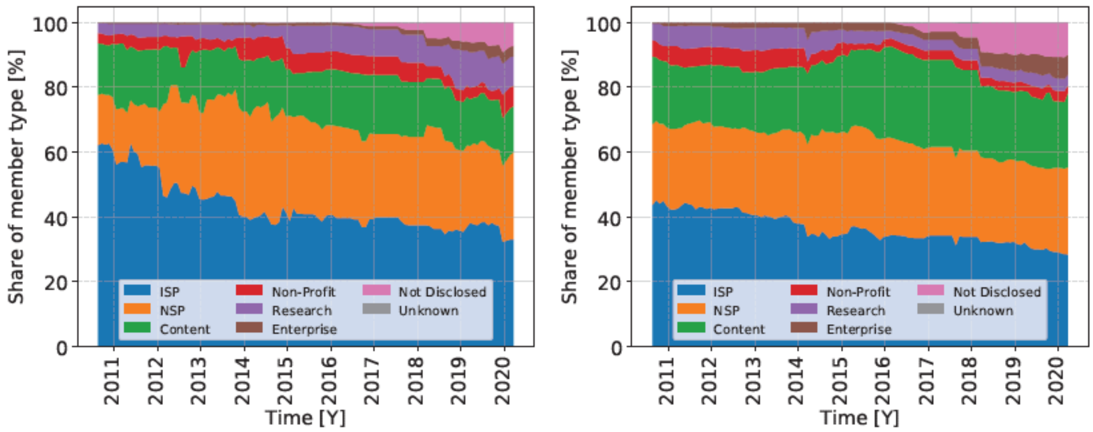


(a) All

(b) Top five

Figure 2.30: Evolution of the distribution of IXP member types in Africa (PeeringDB)

With approximately 60% ISPs Oceania (Figure 2.31) has the highest ISP share in 2010. The ISP share decreases over the years making space for NSP and not-disclosed shares. The difference between the distribution across all IXPs and the top five by member count is much smaller than on the other continents.



(a) All

(b) Top five

Figure 2.31: Evolution of the distribution of IXP member types in Oceania (PeeringDB)

South America and Africa stand out the most in the distribution of members, as they have the smallest share of content providers. We see the same characteristic in Figure 2.25.

The share of NSPs is slowly shrinking across all continents and the share of ISPs is growing for all continents except Oceania. Overall, the high proportion of ISP and NSP members is notable.

2.9.2 AS Presence at IXPs

In addition to the composition of membership types, the question of the presence of specific AS at IXPs is relevant to evaluate the variety of IXP members. We determine the number of IXPs per continent at which an AS is present. The results are shown in Tables 2.3 to 2.9. The percentage in the tables shows the share of IXPs where the AS is present on the continent. In this context, by the variety of IXP members we mean how different the composition of members per IXP is. Are the same ASes always represented or not? If the percentage of ASes on a continent is high, the variety is probably low and few AS are very important on this continent.

ISP	Content	NSP	Non-Profit
Research	Enterprise	Not Disclosed	Route Server

Table 2.2: Member type colors

The background of each row of the following Tables is colored with the color of the member type listed in Table 2.2 from the PeeringDB.

AS	Name	IXPs [%]
AS6939	HURRICANE	38.30
AS13335	CLOUDFLARE	36.52
AS15169	GOOGLE	28.37
AS8075	MICROSOFT	26.60
AS32934	FACEBOOK	24.11
AS20940	AKAMAI	17.38
AS3856	PCH	17.02
AS42	WOODYNET	17.02
AS2906	NETFLIX	12.77
AS10310	YAHOO	12.06

Table 2.3: Top 10 ASes in Europe

AS	Name	IXPs [%]
AS6939	HURRICANE	49.39
AS13335	CLOUDFLARE	39.02
AS42	WoodyNet	32.93
AS3856	PCH	32.93
AS20940	AKAMAI	28.66
AS8075	MICROSOFT	25.00
AS15169	GOOGLE	25.00
AS10310	YAHOO	21.95
AS16509	AMAZON	19.51
AS22822	LLNW-PHX1	17.68

Table 2.4: Top 10 ASes in North America

In Europe (Table 2.3) and North America (Table 2.4) most of the ASes are content providers and in both continents global players dominate. With PCH and WoodyNet research networks are represented as well.

AS	Name	IXPs [%]
AS15169	GOOGLE	23.33
AS20940	AKAMAI	22.00
AS13335	CLOUDFLARE	20.67
AS16509	AMAZON	20.00
AS8075	MICROSOFT	18.67
AS42	WoodyNet	17.33
AS3856	PCH	16.67
AS32934	FACEBOOK	16.00
AS6939	HURRICANE	15.33
AS2906	NETFLIX	14.00

Table 2.5: Top 10 ASes in Asia

AS	Name	IXPs [%]
AS26162	NIC.BR	40.24
AS20121	NIC.BR	40.24
AS14026	NIC.BR	32.93
AS28573	CLARO	29.27
AS52376	CABASE	28.05
AS1916	RNP	24.39
AS20144	L-ROOT	18.29
AS28329	G8	17.07
AS14840	COMMCORP	14.63
AS16735	CTBC	13.41

Table 2.6: Top 10 ASes in South America

The member types of the top 10 ASes with the highest IXP presence differ strongly between continents. In Asia (Table 2.5) most of the ASes are content providers while NSPs dominate in South America (Table 2.6). These differences are consistent with the content share from the previous analysis of the member type. In Asia, Europe and North America global players dominate. In contrast, the ASes with the highest IXP presence in South America are regional ASes. The variety of South America is relatively low because there are six ASes which are present at more than 24% of the South American IXPs. The member variety of Asian IXPs is higher, because only four ASes are present at more than 20% of the Asian IXPs. China differs in the distribution of members from the other Asian countries. Table 2.7 shows the top 10 ASes from China which are all owned by Chinese organizations. There are no global players represented.

AS	Name	IXPs [%]
AS45093	WEEK5	23.08
AS45090	CNNIC-TENCENT	23.08
AS59027	WEXCHANGE	23.08
AS48301	YANGFANG	23.08
AS24144	LSHIYGROUP	23.08
AS139023	LSHIY	23.08
AS208266	Alanyhq-Networks	23.08
AS63541	CHINACACHE	15.38
AS18245	Founderbn	15.38
AS56282	VClouD	15.38

Table 2.7: Top 10 ASes in China

In Africa (Table 2.8) with PCH and WoodyNet two research and non-profit networks are strongly represented. In contrast to Europe and North America half of the top 10 are NSPs. The variety of top IXP members in Africa is high, with only two ASes represented in more than 20% of African IXPs.

AS	Name	IXPs [%]
AS42	WOODYNET	49.12
AS3856	PCH	47.37
AS6939	HURRICANE	17.54
AS13335	CLOUDFLARE	15.79
AS37100	SEACOM	15.79
AS63293	FACEBOOK	15.79
AS30844	LIQUID	14.04
AS15169	GOOGLE	14.04
AS25818	CMCNETWORKS	14.04
AS26415	VERISIGN	14.04

Table 2.8: Top 10 ASes in Africa

AS	Name	IXPs [%]
AS38195	SUPERLOOP	40.91
AS13335	CLOUDFLARE	38.64
AS8075	MICROSOFT	36.36
AS58511	ANYCAST	31.82
AS4826	VOCUS	31.82
AS54113	Fastly	31.82
AS20940	AKAMAI	31.82
AS133480	INTERGRID	29.55
AS24516	VIRTUTEL	29.55
AS4764	ABB	27.27

Table 2.9: Top 10 ASes in Oceania

With SUPERLOOP owned by an Oceanic organization, the AS with the highest IXP presence is a regional network (Table 2.9). In contrast to Africa, variety is low, with all top 10 ASes represented at more than 27% of Oceanic IXPs.

AS	Name	IXPs [%]
AS6939	HURRICANE	30.17
AS13335	CLOUDFLARE	30.04
AS42	WOODYNET	22.34
AS15169	GOOGLE	22.21
AS3856	PCH	22.08
AS8075	MICROSOFT	22.82
AS20940	AKAMAI	20.28
AS32934	FACEBOOK	16.94
AS16509	AMAZON	14.51
AS2906	NETFLIX	12.32

Table 2.10: Top 10 ASes over all continents

Table 2.10 shows the top 10 ASes with the highest IXP presence over all continents. These are mostly big commercial organizations. Two ASes (Hurricane and Cloudflare) are present at about 30% of all IXPs. This is a higher share than the highest share in Asia. In total, 7 out of 10 AS are present at more than 20% of all IXPs worldwide.

The continents with the highest peering variety are Africa and Asia. In Asia, the AS with the highest IXP presence is present at 23% of all Asian IXPs. In total, only four ASes are present at more than 20% of Asian IXPs. Africa has two ASes (WoodyNet and PCH) which are present at over 47% of the African IXPs while all other ASes are present at less than 18%.

North America and Oceania both have ASes that are present at more than 40% of the ASes of the continent. In total, 8 out of 10 ASes in North America and 10 out of 10 ASes in Oceania are represented at more than 20% of the IXPs of the continent.

2.9.3 Variety of IXP Operator Organizations

The variety of the IXP operator organizations is another aspect we investigate. Information on the IXP organizations is included in the PeeringDB entry only since 2016. As an alternative indicator, we extract the domain from the e-mail address of the technical and business contacts. If these fields are not filled, we use the website field. We manually check if the domain is a stable indicator for the IXP operator. In the case of the DE-CIX organization, we obtain data for 11 of 15 IXPs with this method.

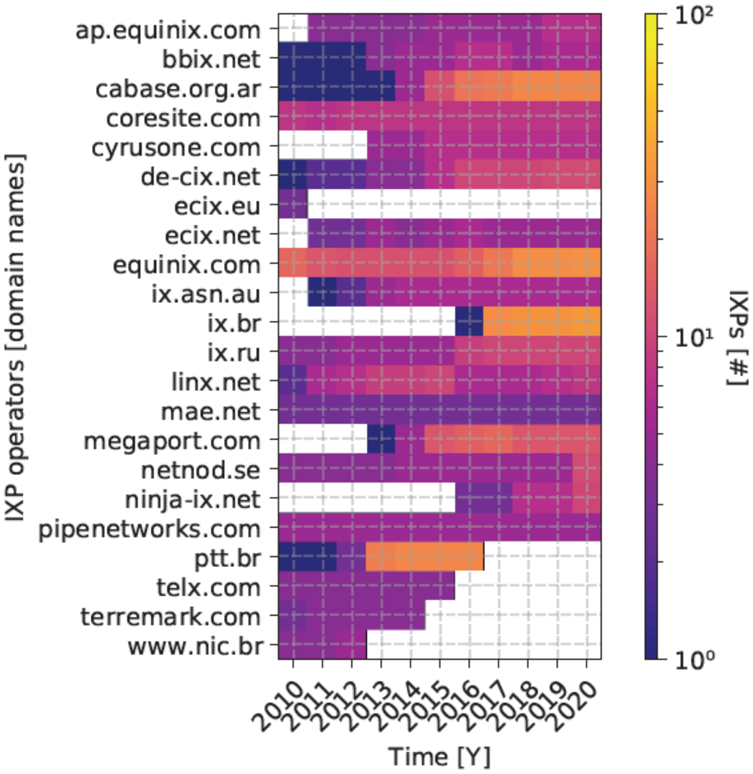


Figure 2.32: Cumulative top 10 IXP operators since 2010 (PeeringDB)

Our results for the top 10 IXP operators by domain are shown as matrix plot in Figure 2.32. The y-axis shows the IXP operator domains and the x-axis shows the years. If a field is not filled, the Operator has operates zero IXPs in this year. Equinix has stable high values over the whole period. PTT.br seems to have changed to IX.br because IX.br appears in 2018 when PTT.br disappears, and they have values in the same range. Overall there are three IXP operators who operate more than 25 IXPs in 2020: *(i)* Equinix (equinix.com)[31] has high values over the whole period and operates in North America, Europe, Asia and Oceania, *(ii)* Cabase (cabase.org.ar)[32] and *(iii)* IX.br[33] operate IXPs only in South America. Overall the variety of IXP operators is relatively high although in some regions, such as South America, almost all IXPs are operated by a single operator. There is a tendency of the IXP operators to grow continuously over the years. For example, this becomes clear when you look at DE-CIX (de-cix.net) and IX.ru.

[31] `https://ix.equinix.com/home/` (07.2020)
[32] `https://www.cabase.org.ar/que-es-un-nap-3/` (07.2020)
[33] `https://ix.br/localidades/atuais` (07.2020)

2.10 Estimated Impact of IXP Outages

The increase in size (Section 2.6) and relevance (Section 2.2) of IXPs leads us to the question of the impact of IXP outages on the Internet infrastructure. This question has already been examined in detail [22]. We consider the question from the perspective of the ASes that peer at the IXP. We choose the top three European IXPs and identify at which IXP and private facilities their members are present (in Europe and elsewhere in the world). A facility is a point of presence (PoP) of an IXP or a private data center at which an AS is peering. We use this data to estimate the impact of outages for the peering ASes based on three dimensions and normalize all values per IXP. We estimate the impact for DE-CIX Frankfurt, AMS-IX and LINX LON1 and the size of the values differ between the IXPs. A high value at the DE-CIX (max 600G links) is higher than a high value at LINX LON1 (max 400G links), but the relevance of each link might be comparable for ASes.

1. The **locality** dimension stands for the existing compensation possibility via peering of an AS and consists of the number of facilities in Europe (fac-eu) as well as the IXPs (ixps-non-eu) and facilities (fac-non-eu) outside of Europe. In the event of an IXP outage it is possible to route parts of the traffic via private peering at facilities or separate IXPs at which the AS is present.

$$\textit{locality(AS)} = \textit{norm(fac-eu(AS))} + \textit{norm(ixps-non-eu(AS))} + \textit{norm(fac-non-eu(AS))} \tag{2.1}$$

   We use Equation 2.1 to estimate the locality dimension (*locality(AS)* returns the locality dimension value of an AS). The number of facilities and IXPs are counted per AS and all values are normalized to the interval [0,1] and then summed up per AS. It provides an estimate for the compensation possibility of an IXP outage via peering.

2. The link speed of ASes at the IXP is part of the **capacity** dimension. The traffic that possibly needs to be compensated by the outage of the IXP via alternative routes depends on the link speed. For ASes with high link speed at the IXP it is more difficult to compensate the lower throughput and higher latencies that are very likely to occur due to alternative routing in case of an outage [22]. We set the

number of provider ASes against the link speed, as it is more realistic to compensate higher connection speeds when more providers are available.

$$capacity(AS) = norm(providers(AS)) - norm(link\text{-}speeds(AS)) \tag{2.2}$$

Equation 2.2 estimates the capacity dimension of each AS (*capacity(AS)* returns the capacity dimension value of an AS). The sum of the link speeds of an AS number of provider is subtracted from the number of providers of the AS. Both values are normalized to values in the interval [0,1].

3. The additional **costs** resulting from an IXP outage are difficult to determine. It is clear that costs increase with the traffic volume as packets must be routed via the providers of an AS instead. In addition to the traffic volume, the IP prefix reachability of the IXP is also important. It specifies how many of the globally announced IP prefixes are reachable via the IXP [6]. These IP prefixes must be compensated in case of an outage which leads to higher costs.

$$costs(AS) = norm(locality(AS)) - \frac{prefix\text{-}reachability(IXP)}{all\text{-}prefixes\text{-}of} \tag{2.3}$$

Equation 2.3 is used to estimate the cost dimension based on the share of IP prefixes that can no longer be reached via the IXP during the outage (*costs(AS)* returns the costs dimension value of an AS). We only consider IPv4 prefixes, as IPv6 is still not fully deployed in Europe [4, 18]. The number of all reachable IP prefixes is taken from HE[34] (965 102 prefixes on July 21st) while the prefix reachability is calculated from the routing table dumps of the RIPE RIS collectors RRC01 (LINX-LON1)[35], RRC03 (AMS-IX)[36] and RRC12 (DE-CIX Frankfurt) [37] (*prefix-reachability(IXP)* returns the prefix reachability of an IXP). We subtracted prefix reachability of the IXP of the **locality** dimension of the AS which might compensate the traffic partly.

We compare the three dimensions in scattered 3D plots (Figure 2.34, Figure 2.36 and Figure 2.38). The cost dimension has values between minus one and two, the capacity dimension values between zero and one, and the locality dimension has values between

[34]`https://bgp.he.net/report/netstats` (08.2020)
[35]`http://data.ris.ripe.net/rrc01/` (08.2020)
[36]`http://data.ris.ripe.net/rrc03/` (08.2020)
[37]`http://data.ris.ripe.net/rrc12/` (08.2020)

zero and three across all considered IXPs. A low value indicates that the AS is severely affected in this dimension. Overall, for all ASes the traffic that would normally be routed through the IXP must instead be routed through the provider or through private peering within the facilities. This would result in high transit costs and probably lead to a higher latency and lower throughput. A higher value indicates that the AS is more flexible due to its many provider ASes and private facilities. Note that the values of the dimensions are not a strong measure of the impact of outage in this dimension, but rather an estimated indicator.

2.10.1 DE-CIX Frankfurt

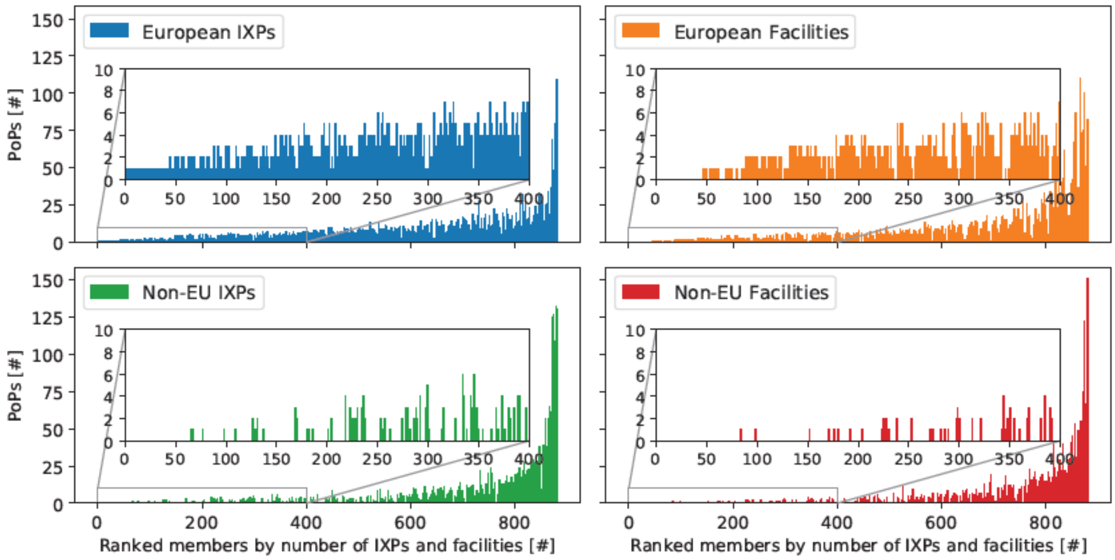


Figure 2.33: PoPs of DE-CIX Frankfurt members ranked by number of IXPs and facilities where the member is present

Figure 2.33 displays the PoP diversity for the members of DE-CIX Frankfurt in Germany. The upper left sub figure shows the number of IXPs in Europe where the members are present and the lower left sub figure shows the number of IXPs outside of Europe where the AS is present. The IXP under consideration (DE-CIX Frankfurt) is included. The upper right sub figure shows the number of facilities in Europe where the AS is present and the lower right sub figure shows the number of facilities outside Europe where the AS is present. The zoom in the upper left sub figure points out that 162 (18%) ASes are present at DE-CIX Frankfurt only. These ASes are mostly local companies such as media companies or hosters. More than half of all members are not represented at an IXP outside Europe. The complete list of ASes that are only peering at DE-CIX can be found in Appendix C.1.

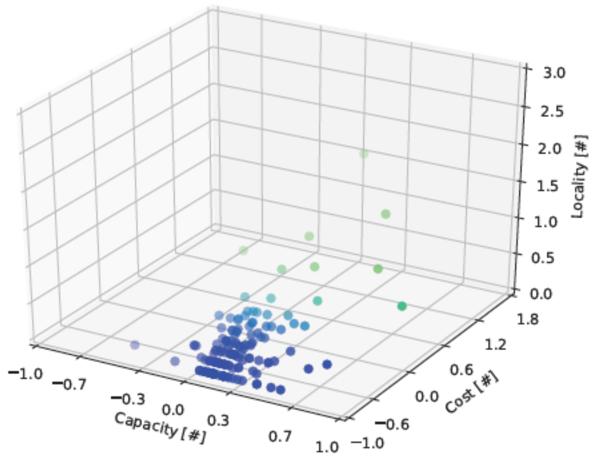


Figure 2.34: Distribution of the IXP outage dimensions of ASes that only peer in Europe at DE-CIX Frankfurt

The distribution of the calculated values per dimensions of the ASes that only peer in Europe at the DE-CIX Frankfurt is displayed in Figure 2.34. Most of this ASes have values in the lower half of the value space of the locality dimension. 65 out of 162 (40%) ASes have values higher than or equal to 0.2 and 18 (11%) higher than 0.5 in the locality dimension. These low values indicate that most ASes have none or few other peering possibilities and are therefore not able to compensate an outage via them. The values for the capacity dimension are mostly in the upper half of the value space. 154 out of 162 (95%) ASes have values higher than or equal to 0.2 and 51 (31%) ASes have values higher than or equal to 0.5. The AS with the lowest capacity dimension value (-0.4375) is AS49666 (Telecommunication Infrastructure Company) which is a Tehran AS with an undisclosed PeeringDB network type. This indicates that most ASes might be able to partially compensate their links via their provider ASes. The values of the costs dimension are lower. 7 out of 162 (4%) ASes have values higher than or equal to 0. Which means that most ASes have mostly costs dimension values in the lower half of the value space and the compensation of the IP prefix reachability is not possible for many ASes. The AS with the lowest costs dimension (−0,8835) and locality dimension (0) values are AS12316 (Finanz Informatik Technologie Service GmbH & Co KG) which is a small European NSP. Overall, most of the DE-CIX members have low values across all three dimensions and an outage would affect them severely.

2.10.2 AMS-IX

The PoP diversity of the members of AMS-IX in Amsterdam is shown in Figure 2.35. The AMS-IX has more members present at other IXPs in Europe than DE-CIX. About 117 ASes (13%) are only present at AMS-IX in Europe. However, outside Europe the results are similar to those of DE-CIX. The full list of members can be found in Appendix C.2.

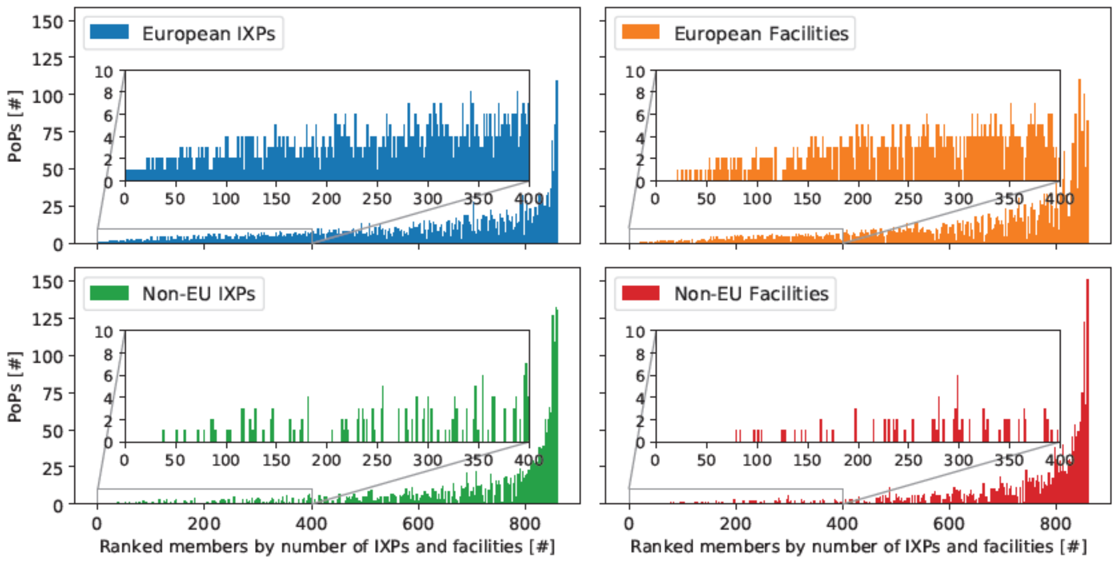


Figure 2.35: PoPs of AMS-IX members ranked by number of IXPs and facilities where the member is present

Figure 2.36 shows the distribution of the calculated values per dimensions of the ASes that only peer at AMS-IX. Most of them have locality dimension values in the lower half of the value space. 56 out of 117 (47%) ASes have values higher than or equal to 0.2 in the locality dimensions. That is similar to the distribution of the DE-CIX. Most of the ASes have capacity dimension values in the lower half of the capacity dimension, which is lower than in case of the DE-CIX. 66 out of 117 (56%) ASes have values higher than or equal to 0. The low capacity dimension values indicate that most ASes are not able to compensate an outage in the capacity dimension. The values of the costs dimension are more distributed, but most values are similar to DE-CIX in the lover half of the value space. 20 (17%) ASes have values higher than 0.5. 10 out of 117 (9%) ASes have a costs dimension value higher than or equal to 0. Overall, in contrast to DE-CIX, there are more ASes which are possibility able to compensate the outage partly in the costs dimension. AS16150 (Availo Networks AB), a European NSP, has the lowest costs dimension (-0.8835) and locality dimension (0.0) values. Overall, the costs dimension and locality value distribution are similar to DE-CIX. In contrast to DE-CIX, more outliers are visible in the distribution across all dimensions.

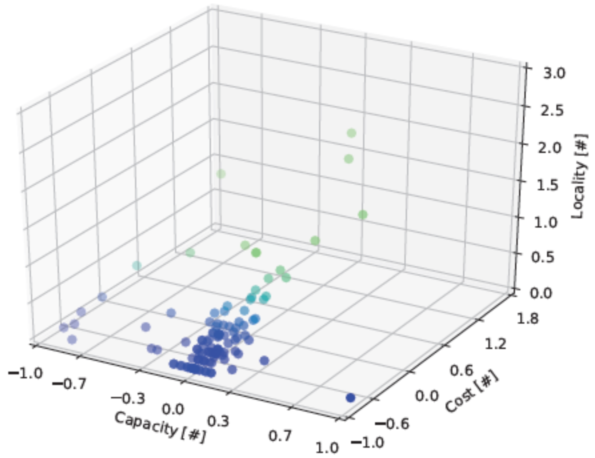


Figure 2.36: Distribution of the IXP outage dimensions of ASes that only peer in Europe at the AMS-IX

2.10.3 LINX LON1

Figure 2.37 shows the PoP diversity of the members of LINX LON1 in London. The results are very similar to AMS-IX, but there are only about 92 (13%) ASes present exclusively at LINX LON1. The full list of members can be found in Appendix C.3.

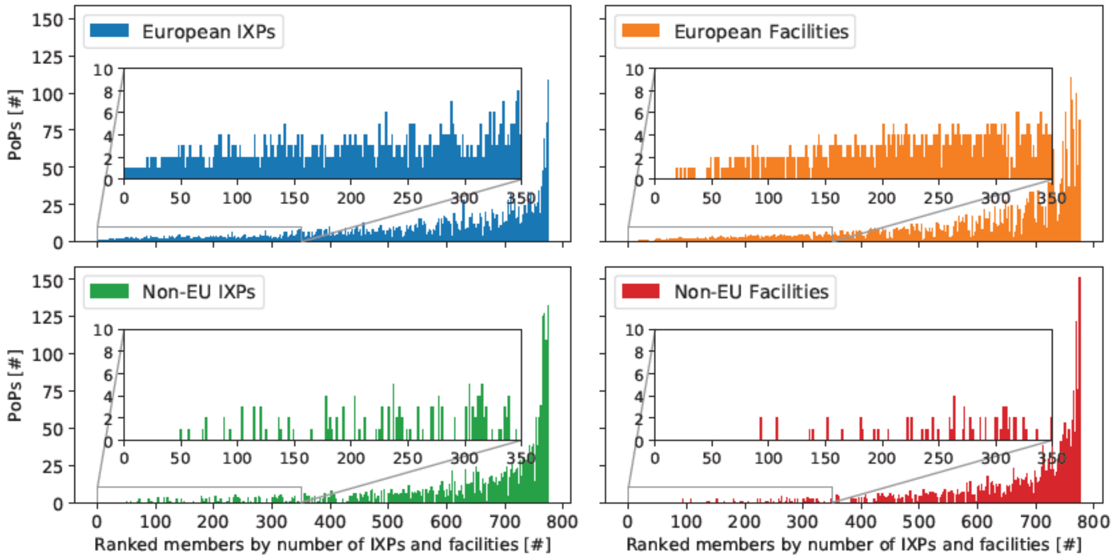


Figure 2.37: PoPs of LINX LON1 members ranked by number of IXPs and facilities where the member is present

The distribution of the dimension values of ASes only present at LINX LON1 is shown in Figure 2.38. 63 out of 92 (68%) of the ASes have locality dimension values higher than or equal to 0.2 and are located in the upper half of the value space. This distribution is similar to DE-CIX and AMS-IX and again, compensation of an outage in the locality dimension is probably not possible for most ASes. The capacity dimension has mostly values in the middle of the value space and therefore the values are minimally smaller than with DE-CIX and larger than with AMS-IX. This indicates that for about half of the ASes a compensation of the capacity dimension via their provider ASes might be possible. The values of the costs dimension are spread across the full value space but only 10 out of 92 (10%) ASes have costs dimension values higher than or equal to 0. Therefore, most of the values are in the lower half of the value space. This distribution is similar to DE-CIX and AMS-IX. AS4004 (GLOBAL-SPLK), a European NSP, is the AS with the lowest costs dimension (-0.8835) and locality dimension (0) at LINX LON1. The values of the costs dimension are more distributed than in case of the DE-CIX and the AMS-IX. However, the main distribution of the costs dimensions and the locality dimensions is comparable to that of DE-CIX and AMS-IX. The capacity dimensions are between the values of DE-CIX and AMS-IX.

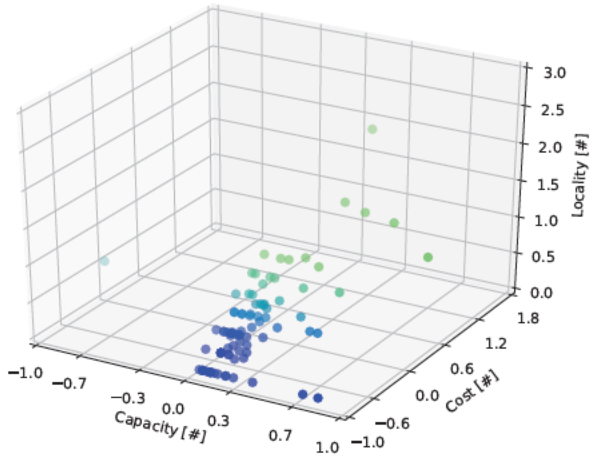


Figure 2.38: Distribution of the IXP outage dimensions of ASes that only peer in Europe at the LINX LON1

2.10.4 Interim Summary

Overall, the outage of a large IXP may completely shutdown the local access of its members from the Internet in the region. Perhaps some alternative traffic delivery via transit providers is possible, but only at higher costs and latency. For members that normally connect to their provider AS via the failed IXP, the consequences are severe and could lead to the complete exclusion of the AS from the Internet.

An outage of DE-CIX Frankfurt would impact the most ASes. It has the most members and with 18% (162 ASes) the most ASes that peer exclusively at it in Europe. Furthermore, the members that are only present at the DE-CIX have the lowest costs dimensions values but relatively high locality dimension values. The values across all dimensions are not widely distributed. The AMS-IX has the lowest capacity values with 66 out of 117 (56%) ASes with values higher than or equal to 0 and the distribution of the values across all dimensions are higher than in case of the DE-CIX. The members that are only present at the LINX LON1 have the highest locality dimension values and the highest values distribution across all dimensions. Overall, the values of the dimensions are higher, which indicates that the ASes, which only peer at LINX LON1, might compensate the outage rather well.

A possible improvement for the calculation of the dimensions would be to weight the individual components of the dimensions differently. However, due to the many uncertainties regarding the actual capacities and compensation possibilities of ASes, we decided against it.

2.11 Interim Conclusion

In this chapter we showed that the IXPs differ per continent, historically and today. Europe and South America have the largest IXPs by member count and throughput even though both differ in the multiplicities size of their IXPs: South America only has few large IXPs and Europe has a lot of large IXPs. In contrast to others, the European and Oceanic IXPs have a wide distribution of remote peering. A large share of IXPs from both continents changed their field of activity with time, now acting as transcontinental providers in addition to performing local traffic switching [13]. Furthermore, few North American and Asian IXPs actually do this, as well.

The capacity of an IXP considered according to, throughput, link speed and member count seems not only dependent on the economic situation of the continent, but seem linked to the evolution of the Internet.

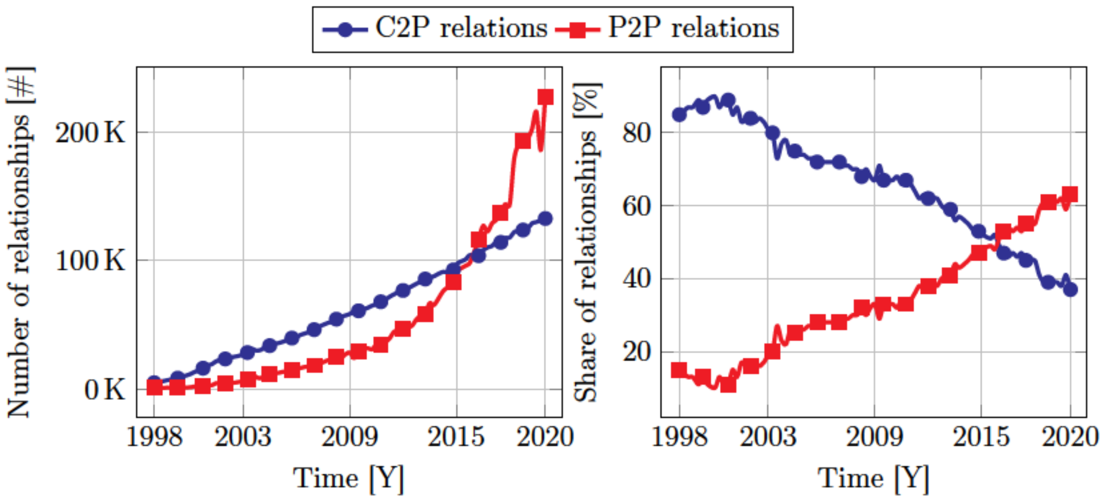
In 2008, all IXPs were located in Europe, North America and Asia. Now, in 2020 IXPs exist all over the world and the portion of traffic that passes through IXPs is around 20% [6]. Our analysis shows that the main members of IXPs are Internet service providers (ISPs), network service providers (NSPs) and content providers, historically and today.

3 Evolution of Peering Relationships

The two peering types at IXPs are public and private peering. Public peering uses peer-to-peer (P2P) relationships, that allow participants to exchange traffic at the same hierarchical level. Traffic that does not address participants or their customers is usually not routed via peer-to-peer relationships. In contrast, via customer-to-provider (C2P) relationships a customer can route all traffic and the provider forward it for a fee [21]. We use the CAIDA AS-relationship data [10] produced with the mythology introduced in [38] to examine the evolution of peering relationships over the last 22 years.

3.1 Evolution of the C2P and P2P Ratio

Figure 3.1 shows the ratio of C2P and P2P relation and their absolute values. The absolute number of C2P relationships grows continuous, as displayed in Figure 3.1a.



(a) Absolute values

(b) Relative shares

Figure 3.1: Evolution of customer-to-provider (C2P) and peer-to-peer (P2P) relationships

In 2015 the number of P2P relationships surpassed the number of C2P relations. The growth rate of P2P relationships has been increasing since 2010. The relative shares (Figure 3.1b) shows that in 2020 about 60% of all relationships are P2P relations. This shows that the relevance of P2P relationships is higher in 2020 than 2010. The increasing relevance of P2P relationships implies that the relevance of IXPs is increasing too, but the relevance of IXPs is difficult to determine and was discussed in Section 2.2.

3.2 Evolution of AS Relationships

The following three Figures show the evolution of the five top ASes by number of relationships since 1998 as a matrix plot. Their y-axis shows the AS number while the name of the organization and the x-axis shows the year.

The evolution of the top five ASes by number of customers is shown in Figure 3.2. There is little movement in the top five. Most of the AS have grown continuously in their customer base since 1998. Cogent (AS174) with about 6000, Level 3 (AS3356) with about 5400 and ATT (AS7018) with about 2500 have been the ASes with the most customers since 2010. Overall seven ASes play a central role on the Internet in 2020. They all belong to the most central AS since 1998, which form the Tier 1 networks [1].

The importance of large carrier ASes appears to be increasing rather than decreasing, and large ASes do not tend to participate in public peering on a large scale because their customer base is growing and the large carrier ASes are not often present at IXPs (see Section 2.9 and Figure 3.4). This is consistent with the findings of [6, 36].

The evolution of top five ASes by number of provider relationships is displayed in Figure 3.3. The movement in the top five is significantly stronger than in the provider ASes. Most prominent are Cloudflare and Akamai. Cloudflare appears in 2009 for the first time and has significantly more provider relationships from year to year, up to 104 in 2020. Akamai is already visible since 2001. In 2020 Akamai has 120 provider relations. Cloudflare, Akamai and most of the other ASes are content delivery networks (CDNs) or other data provider like Microsoft (AS12076) or Google (AS15169). CDNs represent the networks with the most customer-producer relationships (C2P) which is consistent with

[1] https://en.wikipedia.org/wiki/Tier_1_network#List_of_Tier_1_networks

the common practice of CDNs to use anycast routing to access different servers in different regions with the same IP address. Anycast routing is used to optimize performance and reliability of services [12].

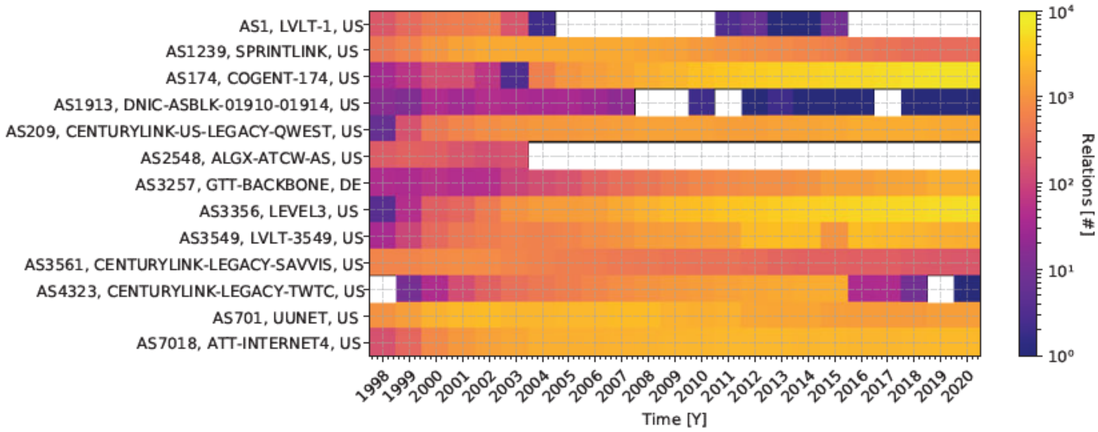


Figure 3.2: Cumulative top five ASes by number of customer since 1998

The evolution of the top five ASes by number of P2P relationships is shown in Figure 3.4. The fluctuation of the AS in the top five by number of P2P relationships is significantly higher than for C2P or provider-to-customer (P2C) relations and has been growing even faster since 2004. Overall the values are lower than in Figure 3.3. Unfortunately, the PeeringDB dumps do not include any information on public peering for this period, so we cannot verify this. However, it is likely that there was a strong increase in public peering in the end-2000s. Most of the networks are ISPs and NSPs which are the main members of IXPs (see Section 2.9). An exception to our previous statement is the Tier 1 network GTT (AS3257) which was one of the top five ASes by number of P2P relationships between 1999 and 2001. However, the number of P2P relationships is constantly decreasing down to 77 in 2020.

Figure 3.3: Cumulative top five ASes by number of providers since 1998

Overall, a consolidation of the large carry networks can be observed, although it has remained at a similar level since 1998. The diversity of C2P and P2P relationships is increasing more and more. Thus, a slight consolidation trend of CDN networks such as Akamai and Cloudflare can be observed, because they have by far the most provider ASes.

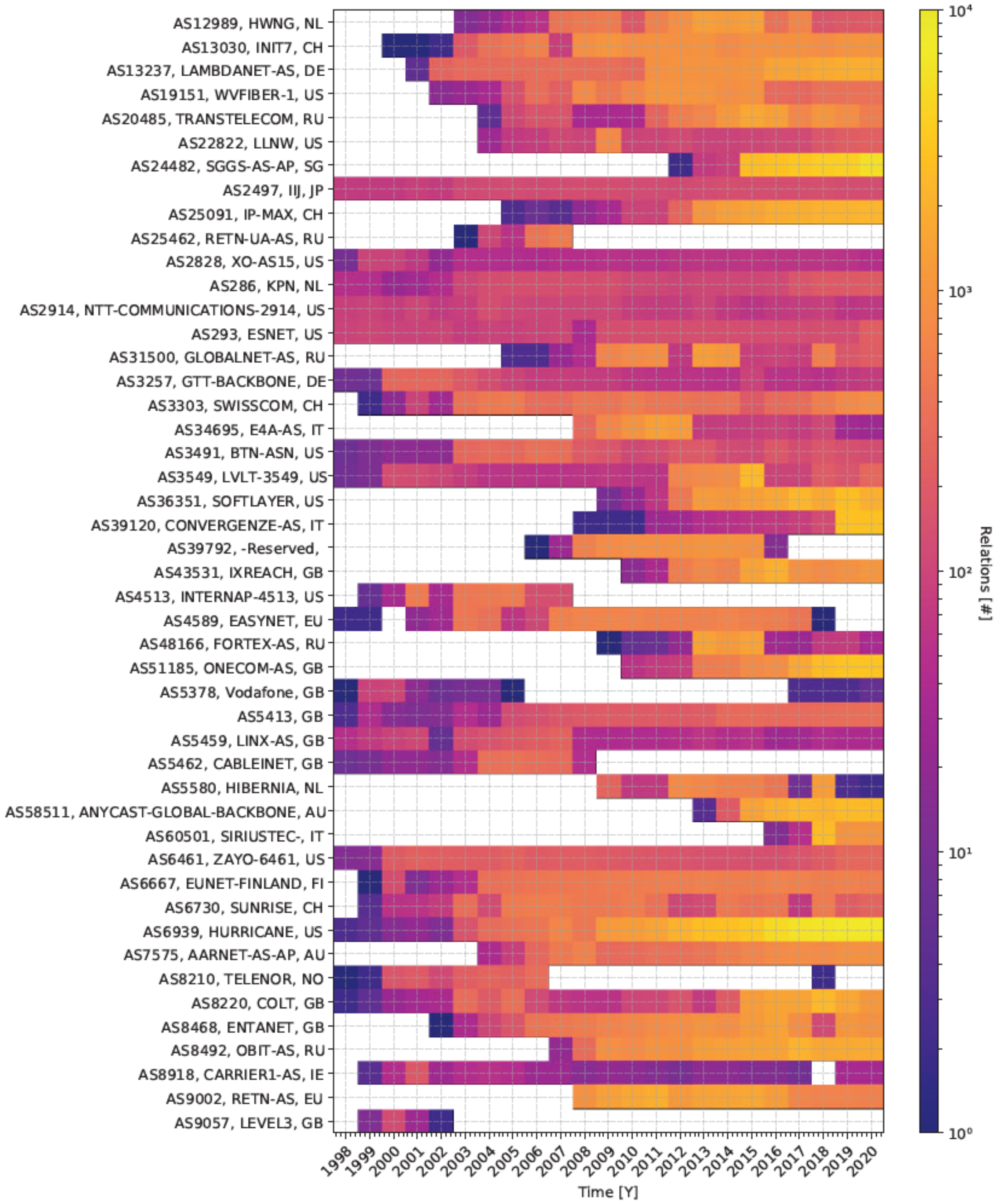
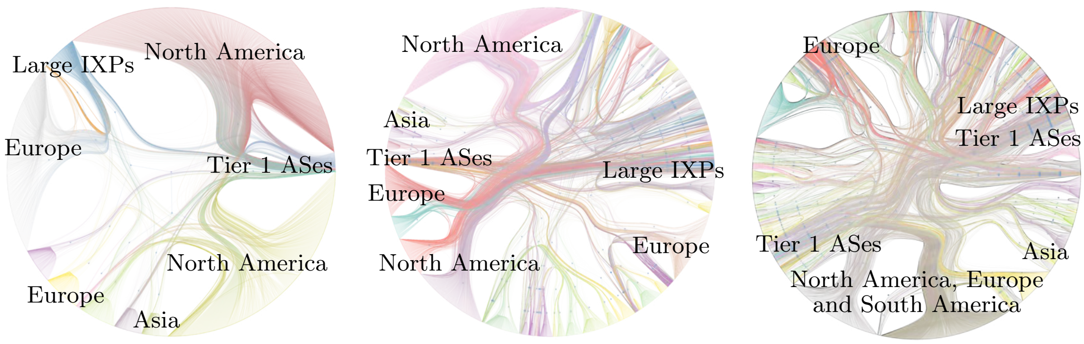


Figure 3.4: Cumulative top five ASes by number of P2P relationships since 1998

4 Evolution of the Internet Structure

The Internet Structure has changed from a hierarchical structure with a clear national backbone level (Tier 1) at the top and regional access providers (Tier 2) below to a topology formed from dominant large content providers besides the Tier 1 networks in the first decades of the 21th century [30]. We study this changes and analyze the Internet structure with a view to possible further structural changes and consolidation trends.

Dataset: We use the CAIDA AS-relationship dataset [10] to create graphs of the Internet routing structure, which forms the basis of the following analyzes. The dataset contains AS relationships differentiated by peer-to-peer (P2P) and customer-to-provider (C2P) relationships. We previously used the same database in Chapter 3.

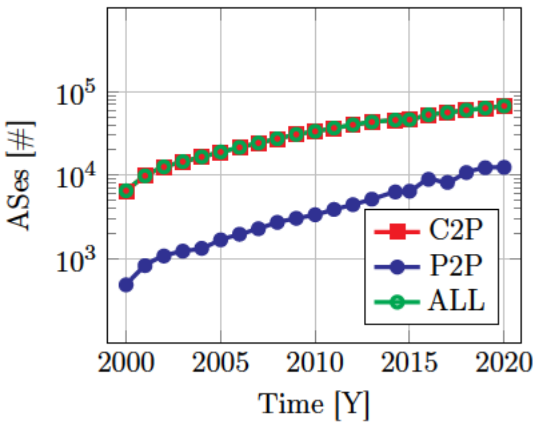


(a) 2000 (b) 2010 (c) 2020

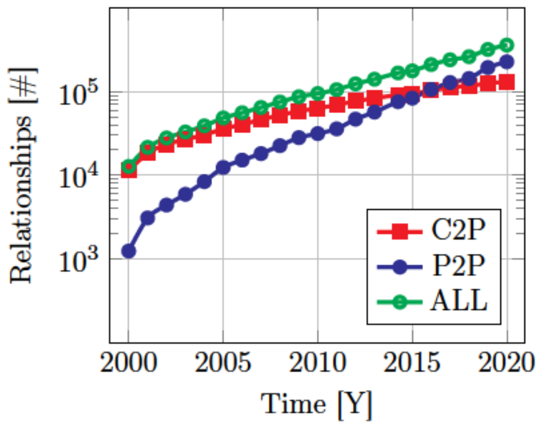
Figure 4.1: Hierarchical block structure [46] of the Internet routing structure of the last two decades

Analyzes: The evolution between 2000 and 2009 is researched in detail [30, 16]. We focus our attention on the evolution since 2010 but first we show an overview of the evolution of the Internet routing structure as hierarchical block structure [46] since 2000 (Figure 4.1). In the hierarchical block structure the ASes are arranged on a circle and the relationships between them are mapped as lines. ASes are clustered in regions of the circle based on their relationships. The hierarchical block structure between 2000 (Figure 4.1a) and 2010 (Figure 4.1b) differ strongly. The clusters are more interlinked and the number of relationships and ASes are significantly higher and there are more clusters visible. Another important change is that the number of visible IXPs is growing. These differences will even increase between 2010 and 2020. The interconnections between the clusters are higher and the strong concentration of links from several clusters in one small point occur less frequently in 2020 (Figure 4.1c). This characteristic is caused by changes in the topology of the Internet. We study these changes between 2010 and 2020 in more detail below.

Figure 4.2 shows the evolution of the number of ASes and relationships in the Internet structure since 2000. It is distinguished between customer-to-provider (C2P), peer-to-peer (P2P) and both relationships (ALL). The number of ASes and edges grows constantly and mostly all have C2P relationships, as seen in Figure 4.2a. The evolution of the relationships are already mentioned in Chapter 3, but at this point we see once again that in 2015 the number of P2P relationships will overtake the number of C2P relationships. The number of ASes grows between 2000 and 2003 following the not linear trend predicted by Faloutsos et al. [19]. Since 2004, the number of AS is growing linearly.



(a) Number of ASes per type of relationship



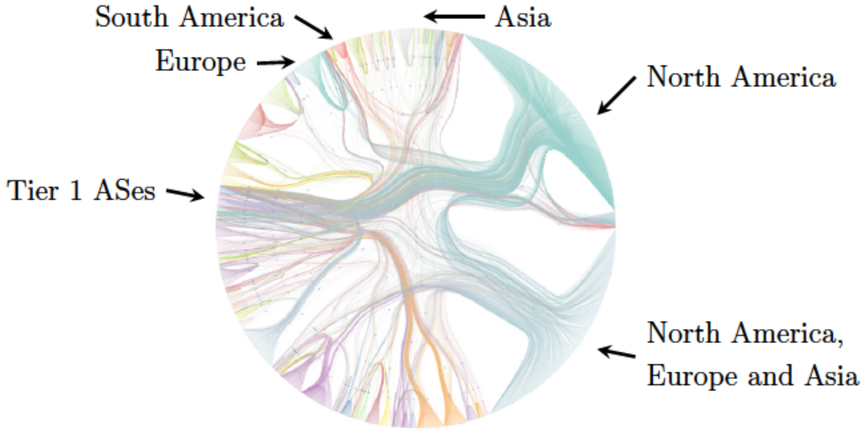
(b) Number of relationships per type

Figure 4.2: Number of ASes and relationships of the Internet structure since 2000

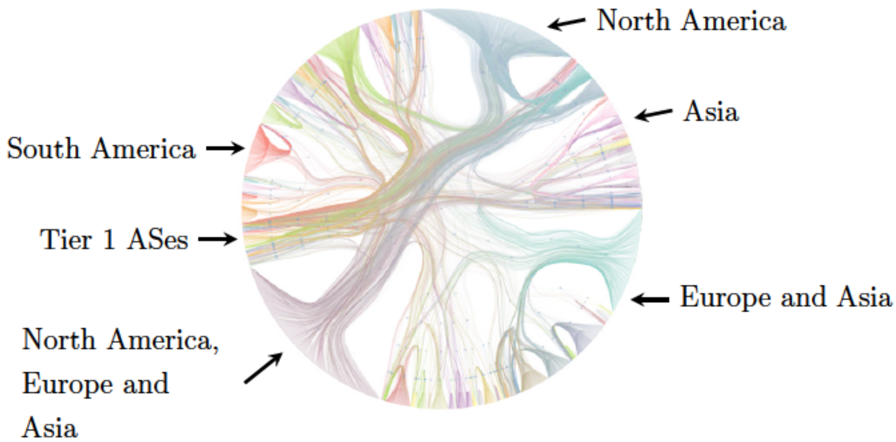
4.1 Hierarchical Block Structure of AS Relationships

We calculate the hierarchical block structure [46] of C2P, P2P and for all relationships for 2010, 2015 and 2020. In the hierarchical block structure the ASes are arranged on a circle and the relationships between them are mapped as lines. ASes are clustered in regions of the circle based on their relationships. This results in clusters showing IXPs, countries and continents. We identify IXPs by identifying the clusters with the highest match to the members listed in the PeeringDB. The geographical regions are determined by identifying the geographical origin of the ASes of a cluster based on their WHOIS information. If a country or continent is dominant in a cluster, we assume that this represents the dominant region. Often, however, there are several clusters that can be assigned to the experience region, for example peering facilities, IXPs or other peering structures.

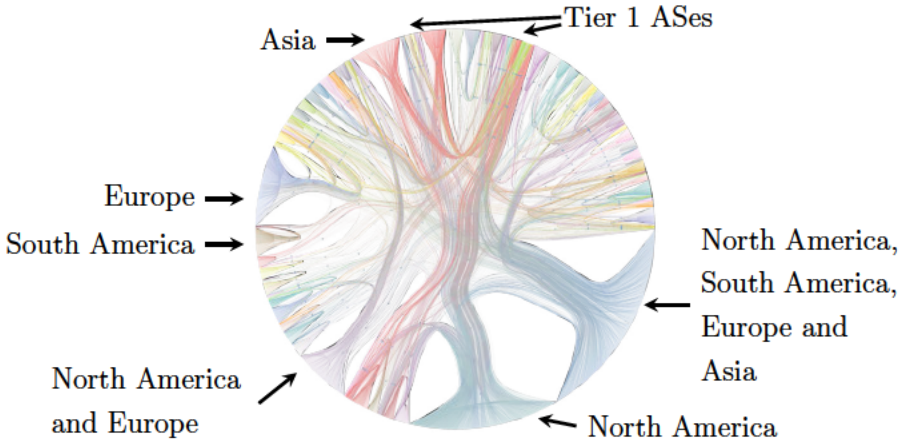
C2P relationships: The evolution of the hierarchical block structure formed by C2P relationships are displayed in Figure 4.3. In 2010 (Figure 4.3a) two large clusters represent North America and in one of them, many European ASes are represented as well. On the left side are many bundled small clusters to which many edges lead. These are mostly Tier 1 networks, and they have a large impact on the hierarchy of the internet in 2010. One small cluster contains mainly South American ASes, and the clusters representing mainly Asian countries have few connections to other regions. Figure 4.3b shows the structure in 2015. The two large regions with North American and European ASes still exist, but the South American cluster became larger and many Asian ASes are part of large clusters combined with North American and European ASes. The highly interconnected Tier 1 networks have a similar position and impact on the hierarchical block structure as in 2010. However, there are often several clusters that can be assigned to the same geographical region, e.g. peering facilities, IXPs or other peering structures and, the clusters are mostly dominated by geographic regions. In contrast to 2015, the hierarchical block structure shows significantly more small clusters and a higher interconnection between them in 2020 (Figure 4.3c). The two large regions with mostly North American and European ASes are still visible, but there was an increase in South American ASes. The position of the Tier 1 ASes is no longer so prominent, and they are mainly found in two instead of one circle section.



(a) 2010



(b) 2015



(c) 2020

Figure 4.3: Hierarchical block structures [46] of the C2P relationships of the last decade (CAIDA AS relationship data)

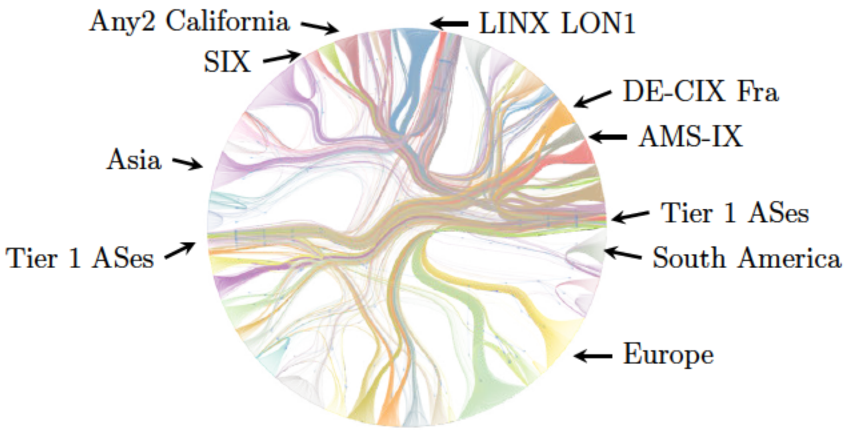
The number of ASes, the number of clusters of the hierarchical block structure and the average cluster size are displayed in Table 4.1. The average cluster size grows strongly from 2015 to 2020.

Year	Num. ASes	Num. clusters	Avg. cluster size
2010	33381	107	311.97
2015	45962	142	323.67
2020	68004	135	503.73

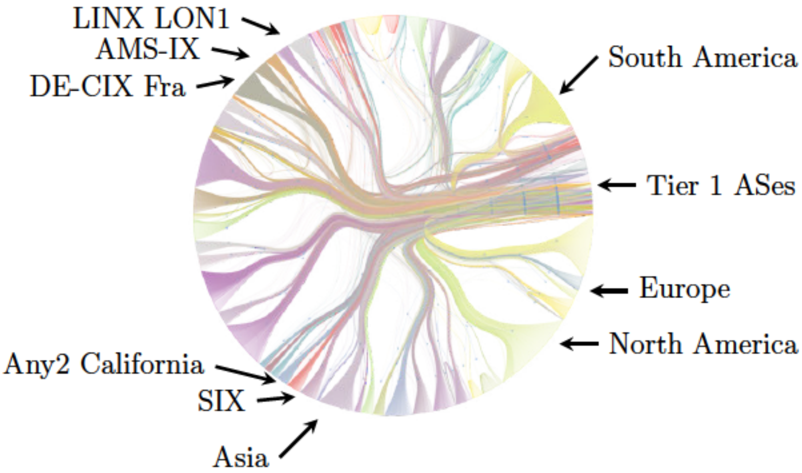
Table 4.1: Hierarchical block structure properties (C2P relationships)

P2P relationships: In 2010, the hierarchical block structure of the P2P relationships shows LINX LON1 as largest IXP and DE-CIX Frankfurt and AMS-IX are visible, too (Figure 4.4a). The clusters of European IXPs have a high degree of convergence. This means that a cluster has 84% intersection with the AMS-IX members and 80% intersection with DE-CIX members. This makes a clear assignment difficult. We choose the largest cluster with the highest degree of intersection. The North American IXPs show a clearer picture. Visible large North American IXPs are SIX Seattle and Any2 California which are arranged on the circle near to LINX LON1. The cluster which represents South America is relatively small and there are no clear larger North American clusters visible in 2010. The Tier 1 networks occupy a privileged position, which is not consistent with our previous results. There is no second area to which most clusters have dependencies, but rather regional dependencies. This changes between 2010 and 2015.

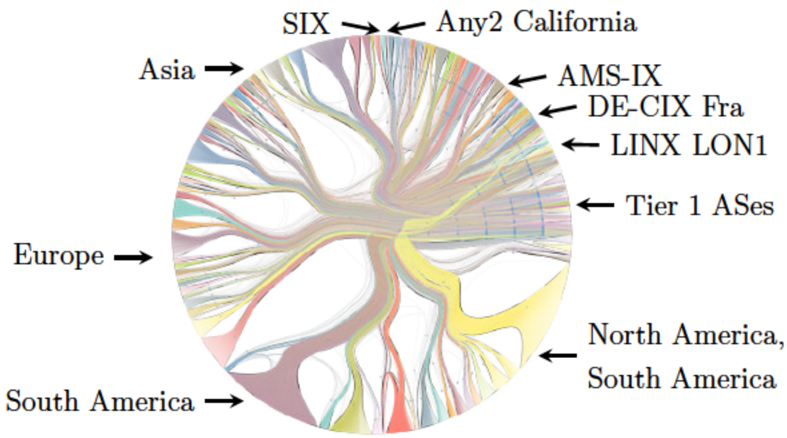
Figure 4.4b shows that in 2015 most clusters have edges to one area on the circle which represents the Tier 1 networks. The South American and European clusters are larger and a large North America cluster has arisen. The European IXPs are clearly visible but do not take a prominent position. This changes by the year 2020 (Figure 4.4c). The European IXPs and Tier 1 ASes form the backbone of the hierarchy consisting of the P2P relationships. Almost all clusters have edges to clusters in this backbone area. The number of visible South American ASes is growing. There are significantly more ASes from different countries of origin in the same cluster. This indicates stronger international connectivity.



(a) 2010

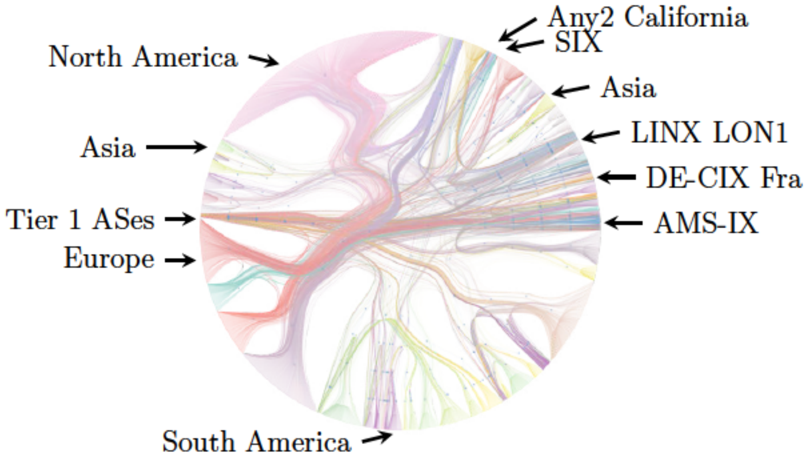


(b) 2015

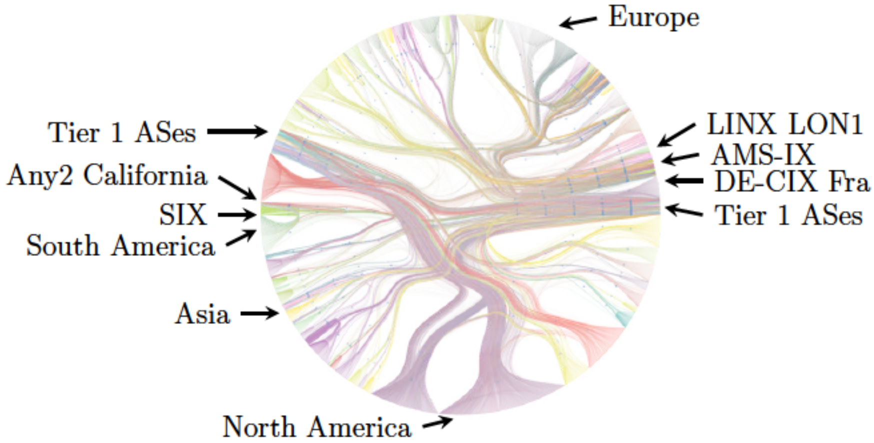


(c) 2020

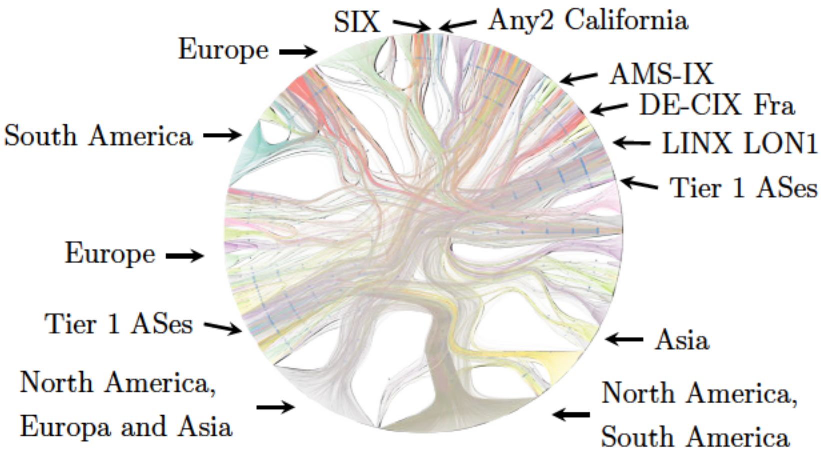
Figure 4.4: Hierarchical block structures of the P2P relationships of the last decade (CAIDA AS relationship data)



(a) 2010



(b) 2015



(c) 2020

Figure 4.5: Hierarchical block structures of the Internet routing structure of the last decade (CAIDA AS relationship data)

Table 4.2 shows the evolution of the number of clusters and ASes in addition to the average cluster size. In contrast to the average cluster size of the C2P relationships (Table 4.1) the average cluster size shrinks few from 2015 to 2020.

Year	Num. ASes	Num. clusters	Avg. cluster size
2010	3736	103	36.27
2015	6906	135	51.15
2020	13319	277	48.08

Table 4.2: Hierarchical block structure properties (P2P relationships)

All relationships: The evolution of the hierarchical block structure formed by C2P and P2P relationships are displayed in Figure 4.5. In 2010 (Figure 4.5a), the Tier 1 ASes are all located in a very small area, consisting of several small clusters on the left side of the circle. The large IXPs form a larger area at the opposite side of the circle. North America forms one large clusters which is relatively strong connected which the smaller European cluster. Figure 4.5b shows that in 2015 the structures are similar but there are more relationships in general and the Tier 1 ASes are now located in two areas. North America forms two large clusters in contrast to one in 2010.

In 2020 (Figure 4.5c), the dependencies between the clusters are higher and no single area is identifiable which is most important for the rest of the Internet graph. The North American cluster still exist, but they contain, aside from the North American ASes, a lot of South America, Asian, and European ASes. The European IXPs have more clusters dependent on them than the American IXPs. Overall in 2020, the interconnections between the cluster are clearly higher than 2015 which leads to a stronger mixing of the ASes in the clusters and a strong interconnection of the clusters. The stronger interconnection leads to smaller clusters and fewer white areas in the graph. Table 4.3 shows that the average cluster size shrinks by about 25% from 2015 to 2020.

Year	Num. ASes	Num. clusters	Avg. cluster size
2010	33486	162	206.70
2015	46172	230	200.74
2020	68289	444	153.80

Table 4.3: Hierarchical block structure properties (All relationships)

4.2 Number of AS Relationships Distribution

The average number of AS relationships grows fast and is still growing. This is visible in previous Figure 4.2 and leads to a higher average node degree. In this Section we study the evolution of AS relationships which are represented as node degree in our calculated graphs.

C2P relationships: Figure 4.6 shows that the average number of provider ASes is stable since 2010, but the max values are growing. The boxplot shows that the values around the median are similar since 2010. The distribution shows that most ASes have only few provider ASes.

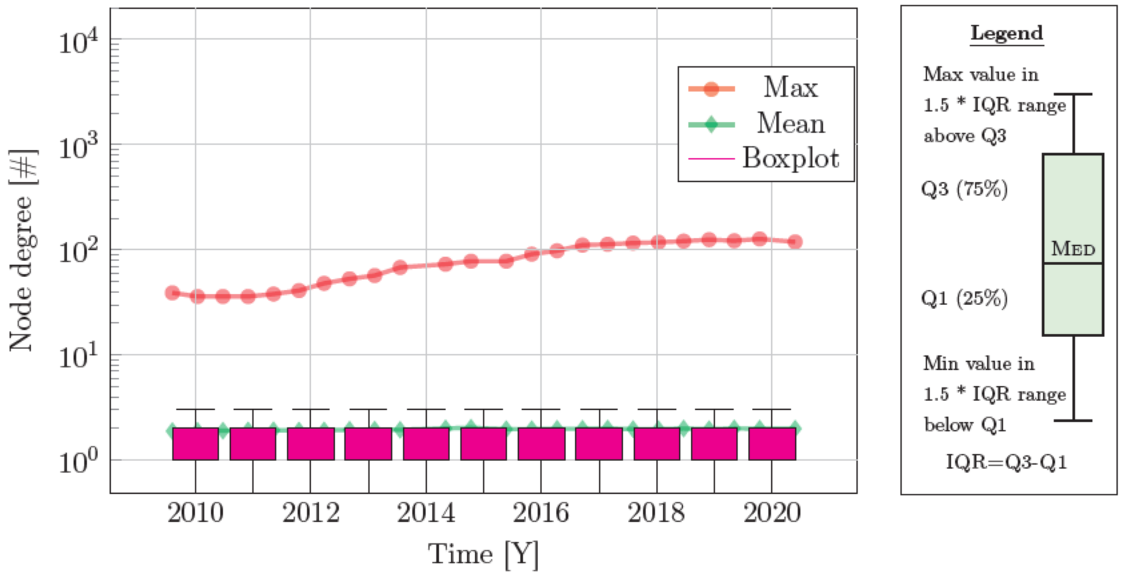


Figure 4.6: Out average node degree of C2P relationships (Number of providers)

The average number distribution of customers of all ASes is shown in Figure 4.7. The median and the whole boxplot are not visible because all values are zero. This can be explained by the fact that there are many stub ASes without customers and only a smaller subset of ISPs and transit ASes with a lot of customers (39% in 2020 according to the CAIDA AS Classification dataset [8]).

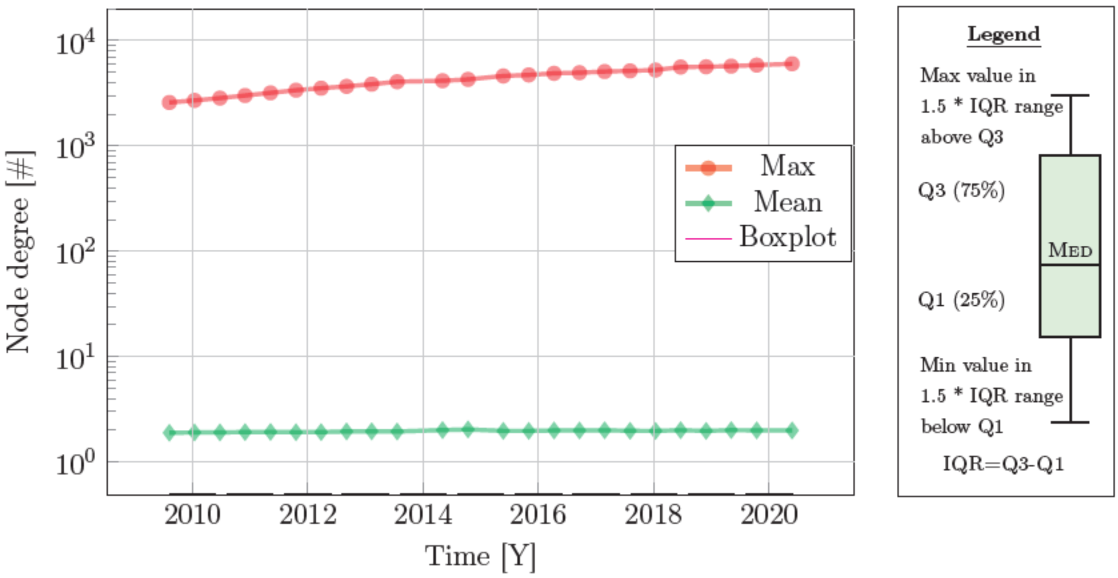


Figure 4.7: In average node degree of C2P relationships (Number of customers)

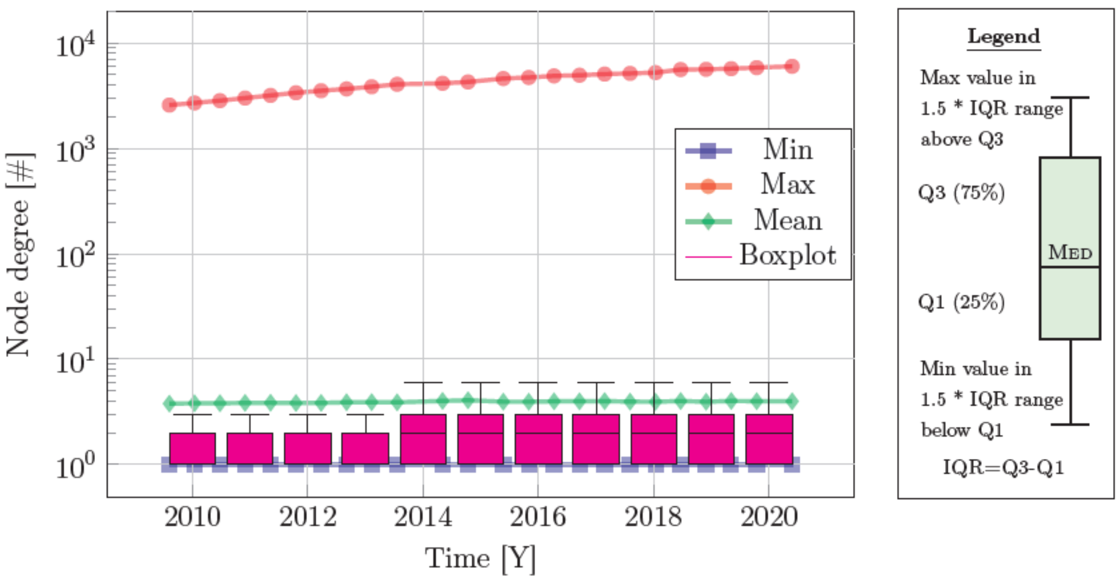


Figure 4.8: Total average node degree of C2P relationships

The total average number of customer-to-provider (C2P) relationships are displayed in Figure 4.8. The average max values are growing constantly and since 2010 the mean and median values increase. This increase is not clearly visible in Figure 4.7 and Figure 4.6

combined number of customers and providers shift the distribution so that there is an increase in the median values.

P2P relationships: The total evolution of P2P relationships are shown in Figure 4.9. There is no difference between the number of in and out relationships for P2P relationships. The number of P2P relationships is growing in the maxima and in 2014 around the median. The P2P minimum values is constantly two and higher than the C2P minimum values. In 2018, the upper quartile of the boxplot is not on the minimum line. We can not explain this behavior, maybe it is caused by inconsistent data.

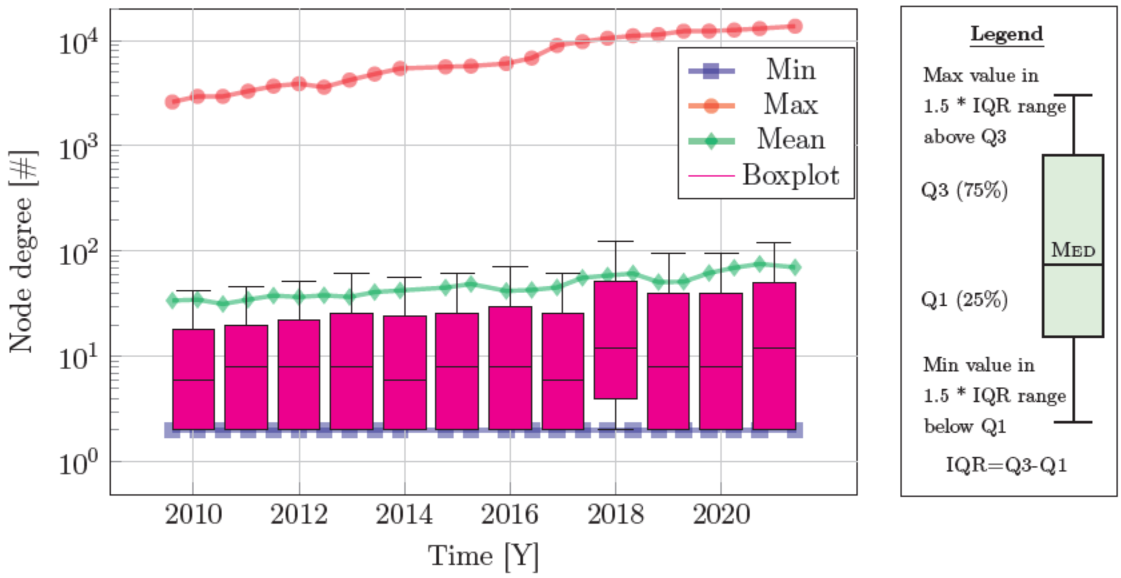


Figure 4.9: Node degree of P2P relationships

All relationships: The combined average number of P2P relationships and providers are shown in Figure 4.10. The minimum values are constantly one and the mean and maximum values are growing constantly. In 2014 the upper quartile (Q3) of the boxplot increases from two to three but the median values stay at one.

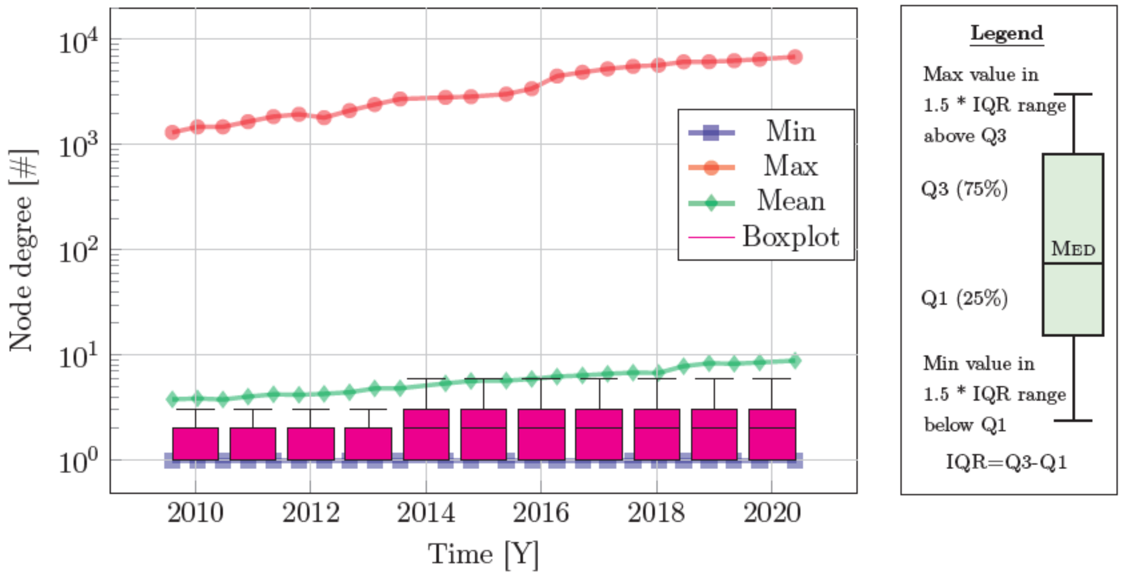


Figure 4.10: Out average node degree of all relationships

The average number of customer or P2P relationships are shown in Figure 4.11. There are little difference to Figure 4.7 because there are many ASes without P2P relationships. This indicates that the impact of the P2P relationships on the average node degree of all ASes is low.

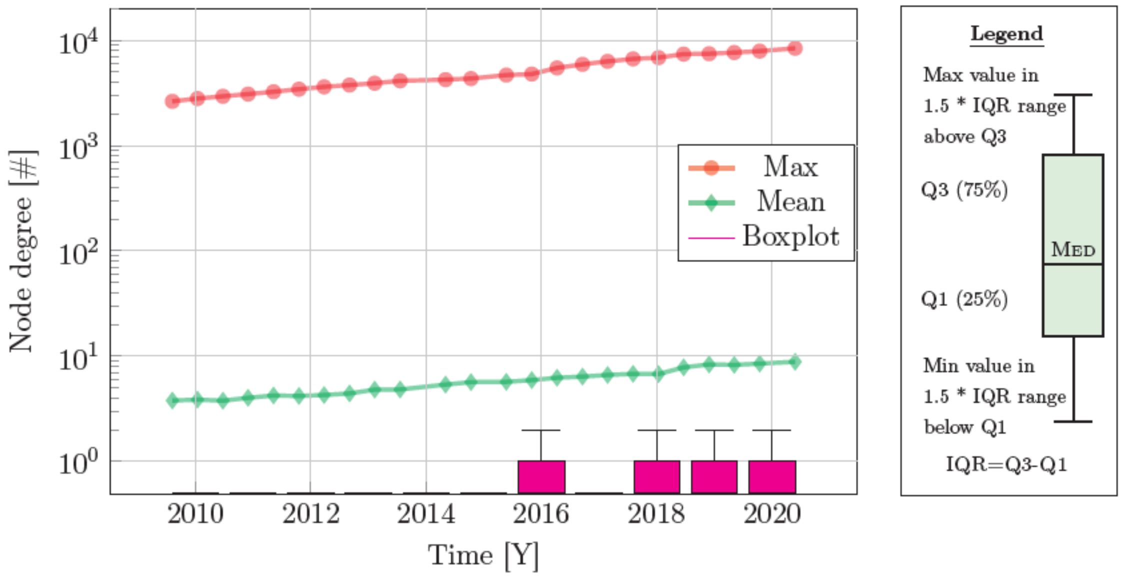


Figure 4.11: In average node degree of all relationships

Figure 4.12 shows the evolution of the average number of both relationship types. The mean and maximum values are growing constantly like the CP2 and P2P mean and maximum values. But only since 2016, with exception to 2017, values around the median are present. The total number of relationships per ASes are shown in Figure 4.12. The boxplot values are constant over the entire period while the mean and maximum grows. In 2016, the maximum values are growing faster.

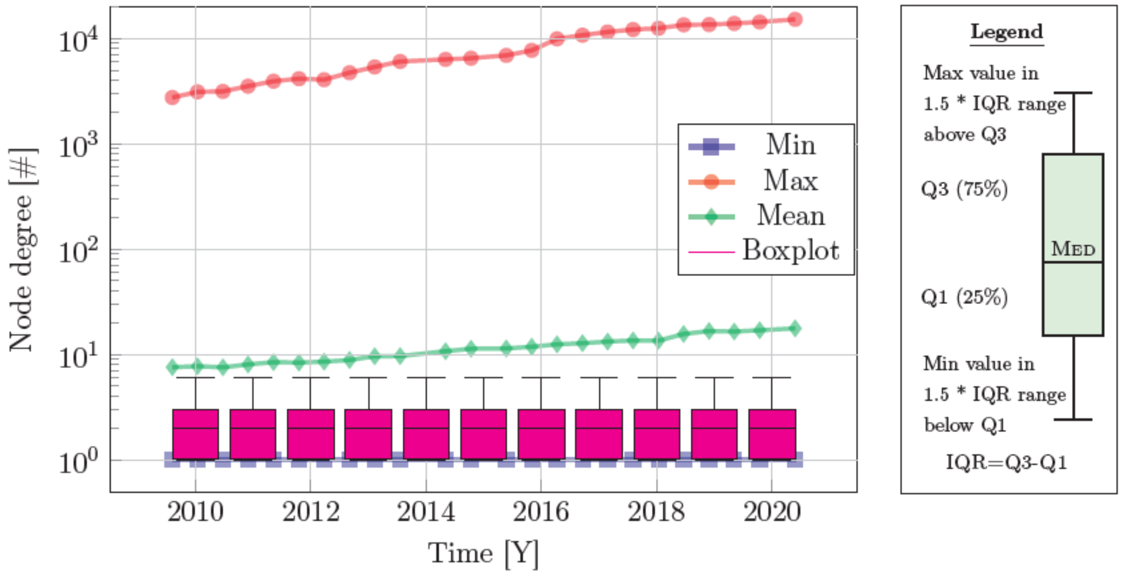


Figure 4.12: Total average node degree of all relationships

4.3 Centrality of the Internet Structure

Besides the simple routing graph properties we study the centrality. Centrality metrics are typical algorithms which are used to compute the relevance and importance of individual vertices [35]. We choose two centrality metrics which are often used for the analysis of large networks, the pagerank and betweenness centrality metrics [40, 24]. For the creation of the graphic representation of the Internet and the calculation of the centrality, we used the graphic tool [45]. The idea of pagerank centrality is that edges of important vertices should be ranked higher than edges of less important vertices. The rank $r(V)$ of a given vertex V is defined as:

$$r(V) = \sum_{Q \in B_V} \frac{r(Q)}{|Q|}, \quad where \quad \begin{aligned} B_V &= \textit{all vertices have edges to } V, \\ |Q| &= \textit{number of out edges from } Q \end{aligned} \tag{4.1}$$

The rank of a vertex indicates how important this vertex is in the graph [31, 3]. The betweenness centrality is based on the weights of the shortest paths through a vertex. We calculate the betweenness centrality for each vertex to all other vertices in the graph [7]. Both centralities are represented by numbers between 0 and 1, with larger numbers representing a higher significance and centrality of the vertex in the graph.

Pagerank centrality: The pagerank values of all C2P relationships are displayed in Figure 4.13. The maximum values are stable over the entire period. In contrast, minimum and mean values are decreasing. The boxplot overlays the minimum line and shows a very low value distribution. The stable maximum values indicates that the pagerank values of the central ASes stay in the same range since 2010. The decreasing boxplot and mean values might be caused by the fact that the number of small ASes grows faster than the number of large ASes, which are relative stable.

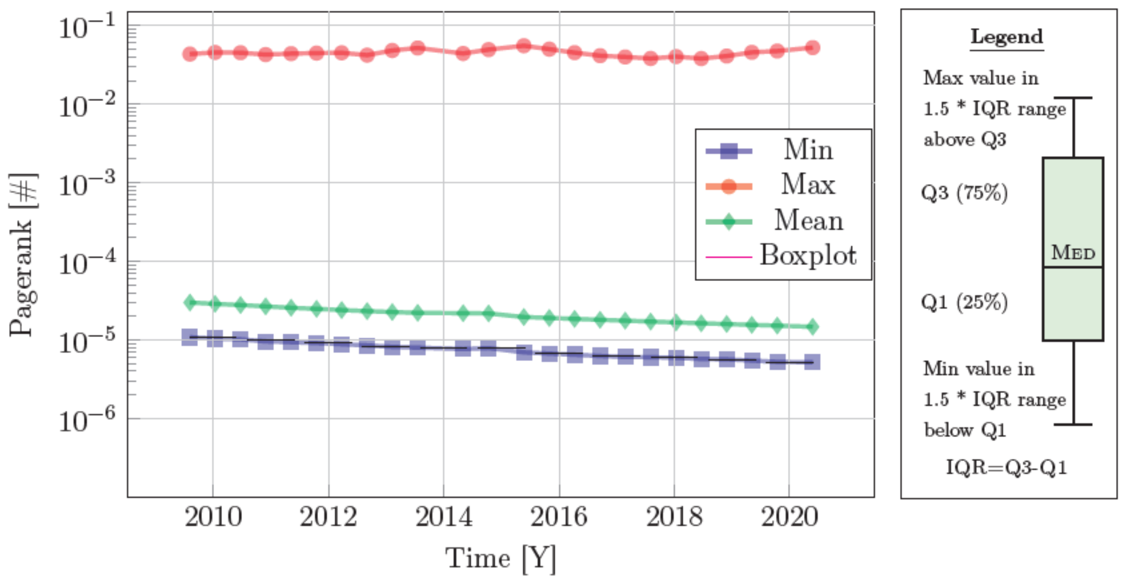


Figure 4.13: C2P relationships

To compensate the discrepancy between ASes with many Customers and ASes with few or no Customers, we have filtered out all pagerank values of non-ISPs or non-transit ASes based on the CAIDA AS classification dataset [8]. This procedure filters out the stub ASes and other ASes which usually do not take relevant positions in the Internet graph, because ASes do not normally offer routes for other ASes. The filtered values are shown in Figure 4.14. The contrast between filtered and non filtered values is low. Only the mean line is a little higher and the boxplot show a slightly larger distribution around the median. This imbalance is visible between ISPs and transit providers too.

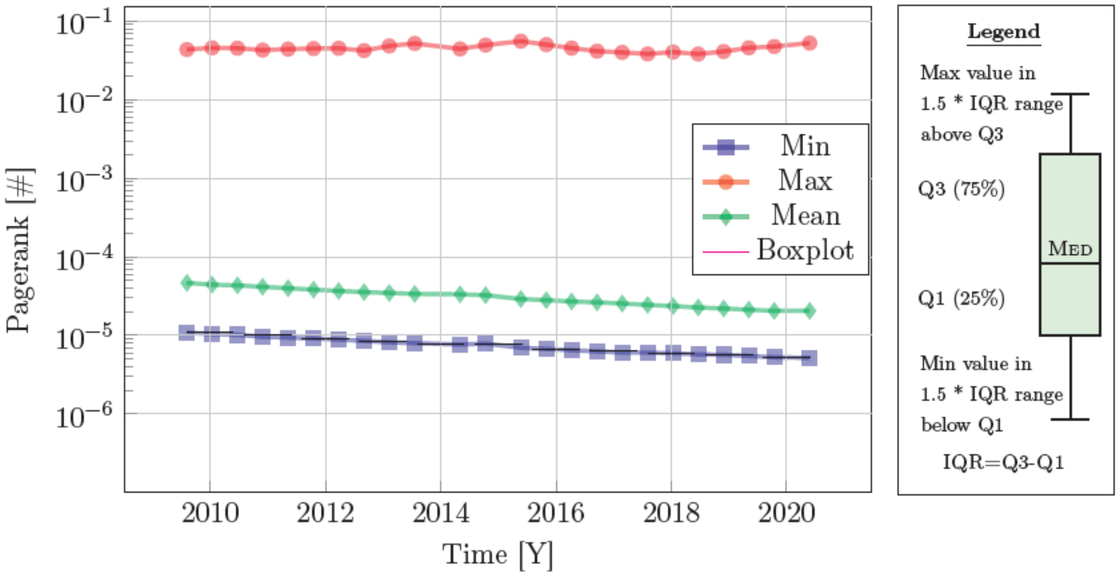


Figure 4.14: C2P relationships (Only ISPs)

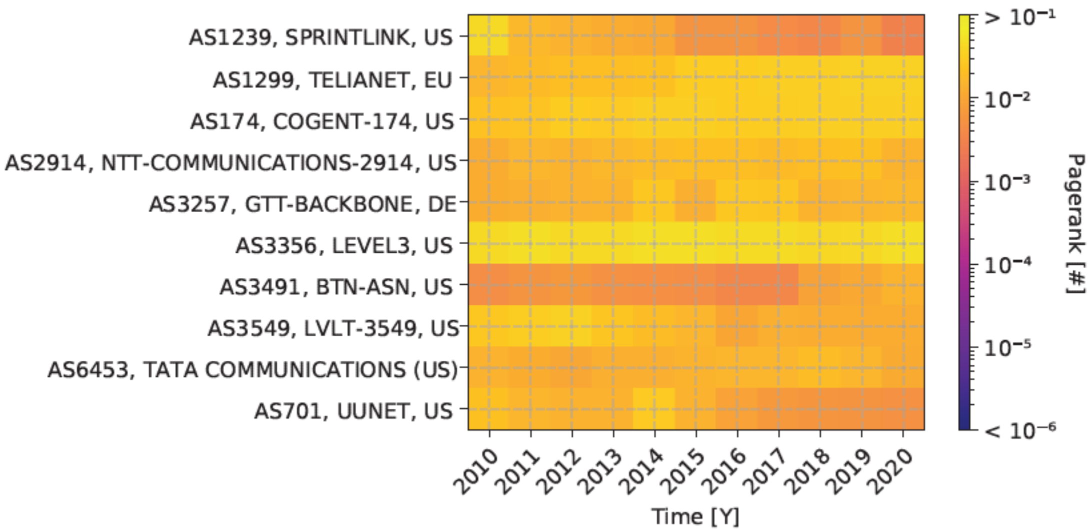


Figure 4.15: Cumulative top five ASes by pagerank values of C2P relationships

The evolution of the top five ASes by pagerank value per year of C2P relationships of the last decade are shown in Figure 4.15. The ASes with the highest values over the entire period are LEVEL 3 (AS3356) which is a Tier 1 network[1]. Only COGENT-174 (AS174) is not a Tier 1 network but has a high CAIDA ASRank[2] and is listed as major network and can reach almost the entire Internet without a transit provider[3].

Figure 4.16 shows the distribution of the pagerank centrality of the ASes connected only via P2P relationships. The maximum values are not as stable as C2P relationships but remain in a similar range over time. The boxplot ranges between the mean and minimum values. The lower whisker values are on the minimum line. The pagerank centrality of the ASes in the graph formed by the P2P relationships is low on average, whereas the maxima remain stable and even show a slight growth tendency.

[1] https://en.wikipedia.org/wiki/Tier_1_network#List_of_Tier_1_networks
[2] https://ASRank.caida.org/asns/174
[3] https://en.wikipedia.org/wiki/Tier_1_network#Other_major_networks

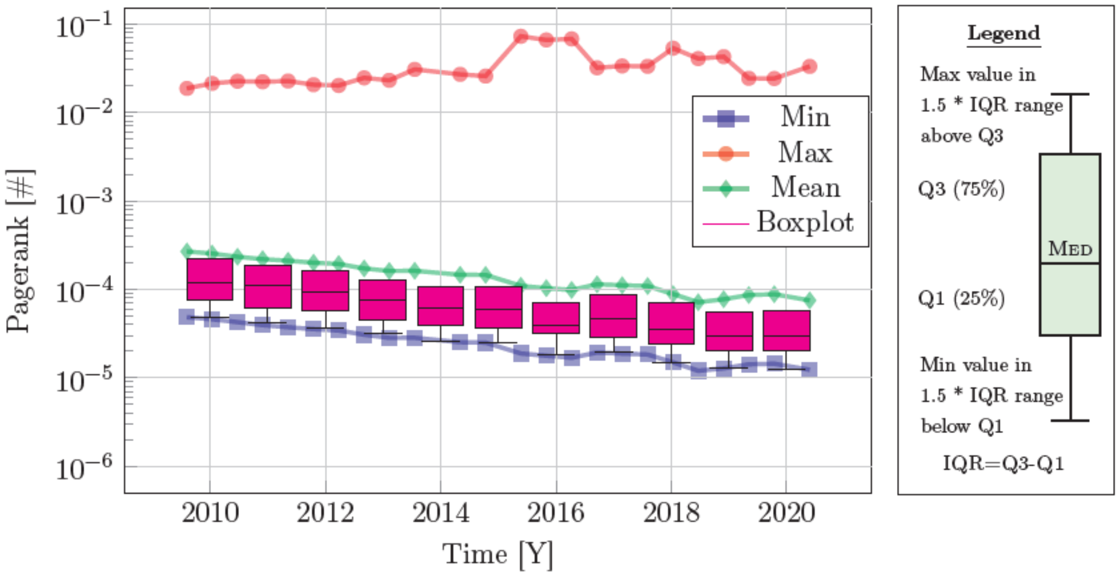


Figure 4.16: P2P relationships

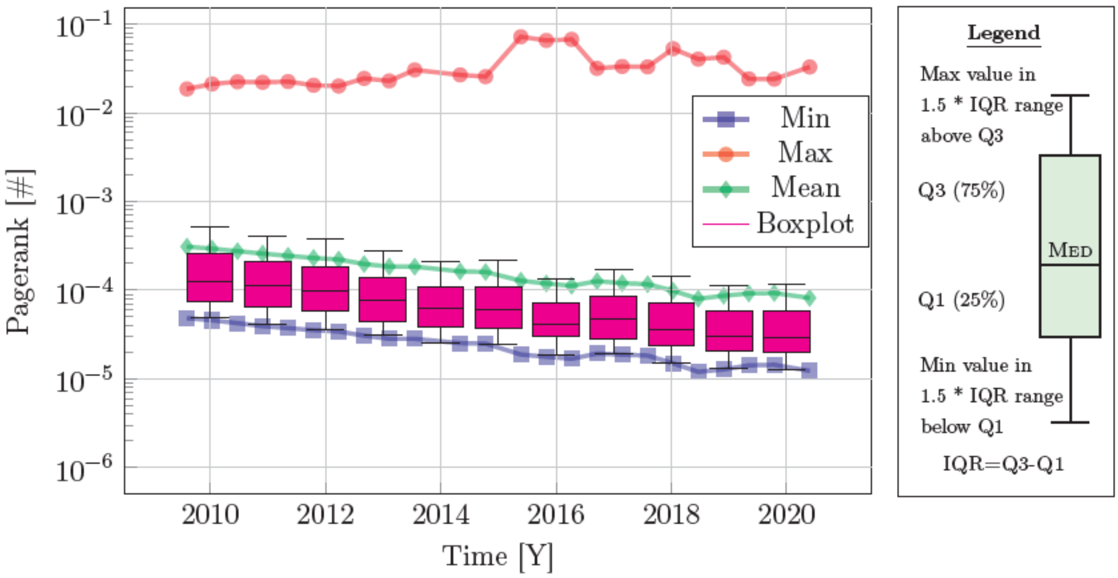


Figure 4.17: P2P relationships (Only ISPs)

The pagerank value distribution from only ISPs and transit providers is show in Figure 4.17. The maximum values are on the same range and all other lines are slightly moved upwards. In contrast to the unfiltered values, upper whisker of the boxplot are higher than the mean line. This means that there are larger fluctuations around the median when only ISPs and transit providers are considered.

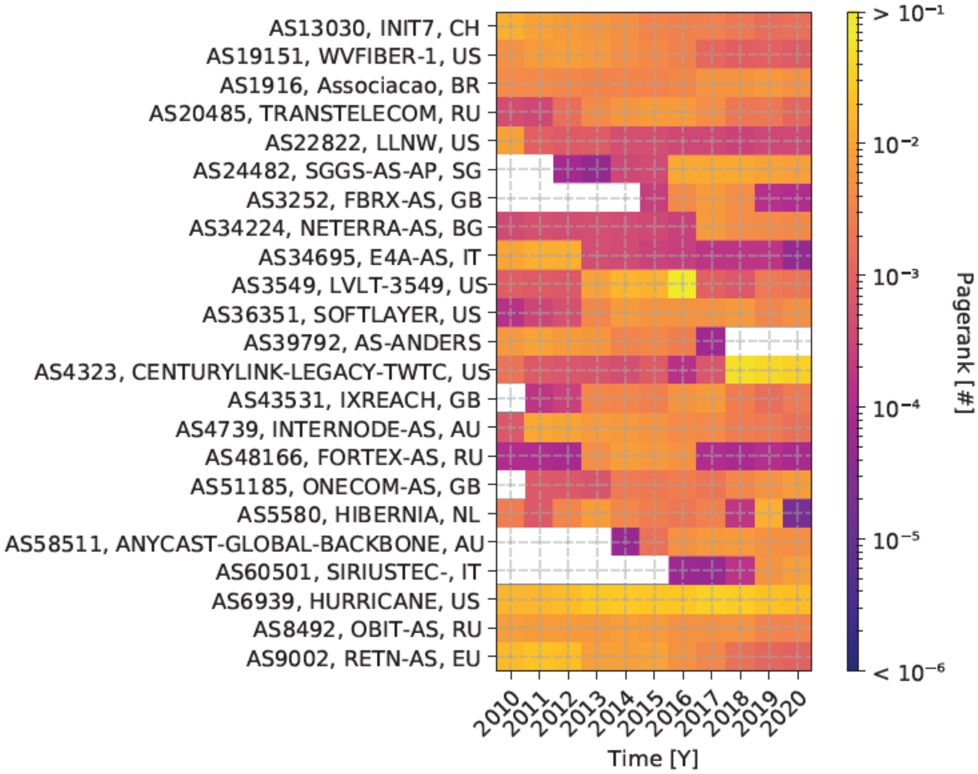


Figure 4.18: Cumulative top five ASes by pagerank values of P2P relationships

The number of ASes which are part of the top five ASes by pagerank value of the P2P relationships is higher than for the C2P relationships (Figure 4.18). Only the values for HURRICANE (AS6939) are high over the entire period. The high fragmentation of the values is constant with our previous findings as shown in Figure 3.4.

Figure 4.19 shows the pagerank values of the graph formed from all P2P relationships and C2P relationships. The pagerank distribution shrinks but the boxplot shows that a larger fraction of ASes has values higher than the minimum values since 2018.

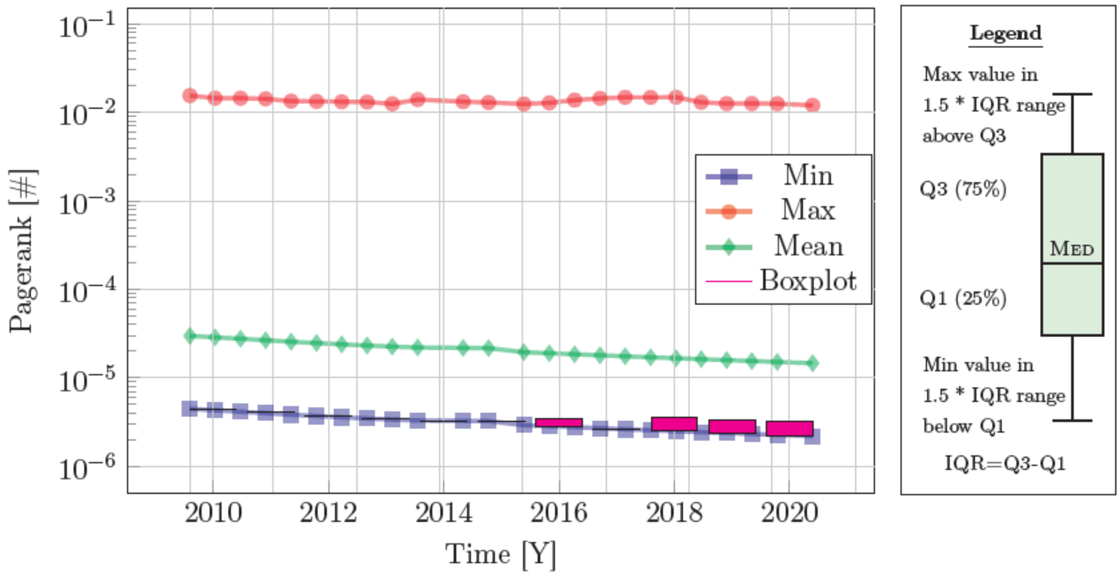


Figure 4.19: All relationships

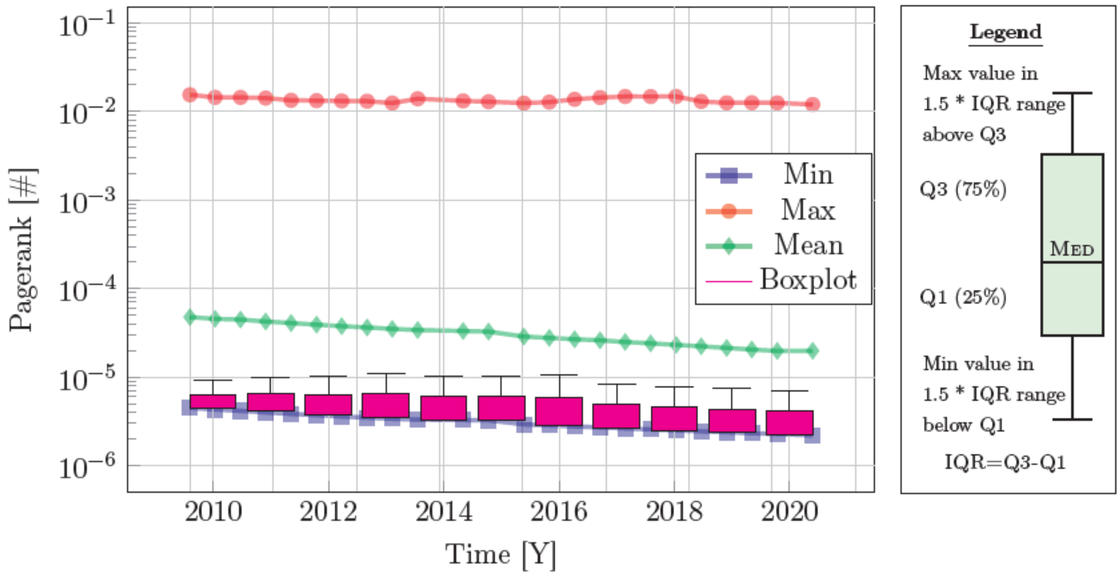


Figure 4.20: All relationships (Only ISPs)

The evolution of the pagerank distribution of ISPs and transit providers is shown in Figure 4.20. The contrast with only ISPs and Transit ASes and all ASes is higher for all relationships than for the subset. The maximum, mean and min values are relative constant but the boxplot shows a higher upper quartile (Q3) value and upper whisker values are visible. The upper quartile (Q3) shows a constant value up to 2016 and then follows the descending trend. This trend is in contrast to that shown by the unfiltered boxplot (Figure 4.19).

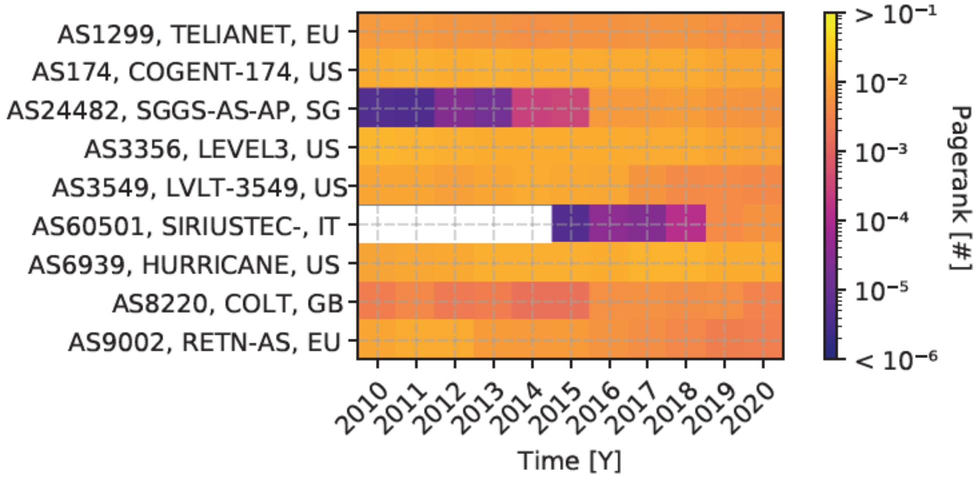


Figure 4.21: Cumulative top five ASes by pagerank values of all relationships

The top 10 ASes by pagerank value over the last ten years are displayed in Figure 4.21. The ASes with the highest values over the entire period are COGENT (AS174) and LEVEL3 (AS3356) which are both Tier 1 networks and HURRICANE (AS6939) which is a large network service provider (NSP). SGGS-AS-AP (AS24482) and SIRIUSTEC-IT (AS60501) both have P2P relationships with large ASes, which are leading in their high Pagerank values, although both do not have a high CAIDA ASRank or reach the entire Internet without a transit AS. One possible explanation why not all Tier 1 networks have a high pagerank value is that many of these networks do not make their peering relationships public. We mentioned that previously in Chapter 3.

Betweenness centrality: The calculated betweenness values are overall lower than the pagerank values. Figure 4.22 shows the betweenness values of C2P relationships. The minimum values are completely zero and are therefore not displayed. The boxplot shows only the medians, which are equally constant zero, this is most likely caused by the high number of stub ASes. The max and mean values are not constant but stay in the same region over the entire period.

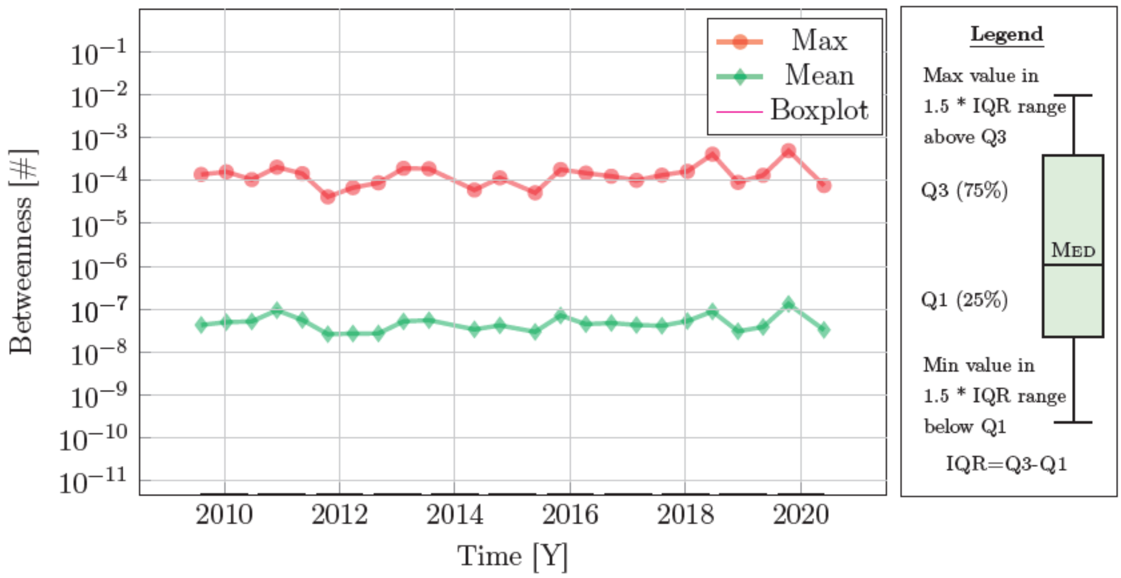


Figure 4.22: C2P relationships

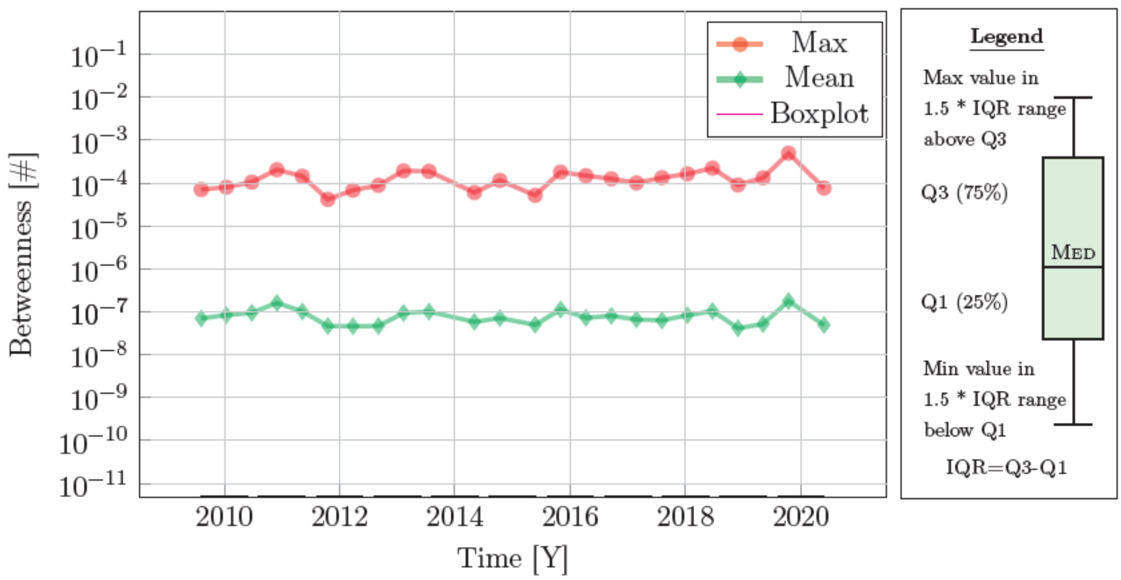


Figure 4.23: C2P relationships (Only ISPs)

We filter out all values of ASes which are not ISPs or transit providers for the betweenness centrality, just like we did for the pagerank centrality. The filtered C2P relationship values are shown in Figure 4.23. The filtered values caused the mean and max values so shift slightly upwards and the pattern of the maximum values to change slightly.

The changed maximum course shows that there are ASes with maximum betweenness values, which are not ISPs or transit providers. This was not the case with the pagerank values.

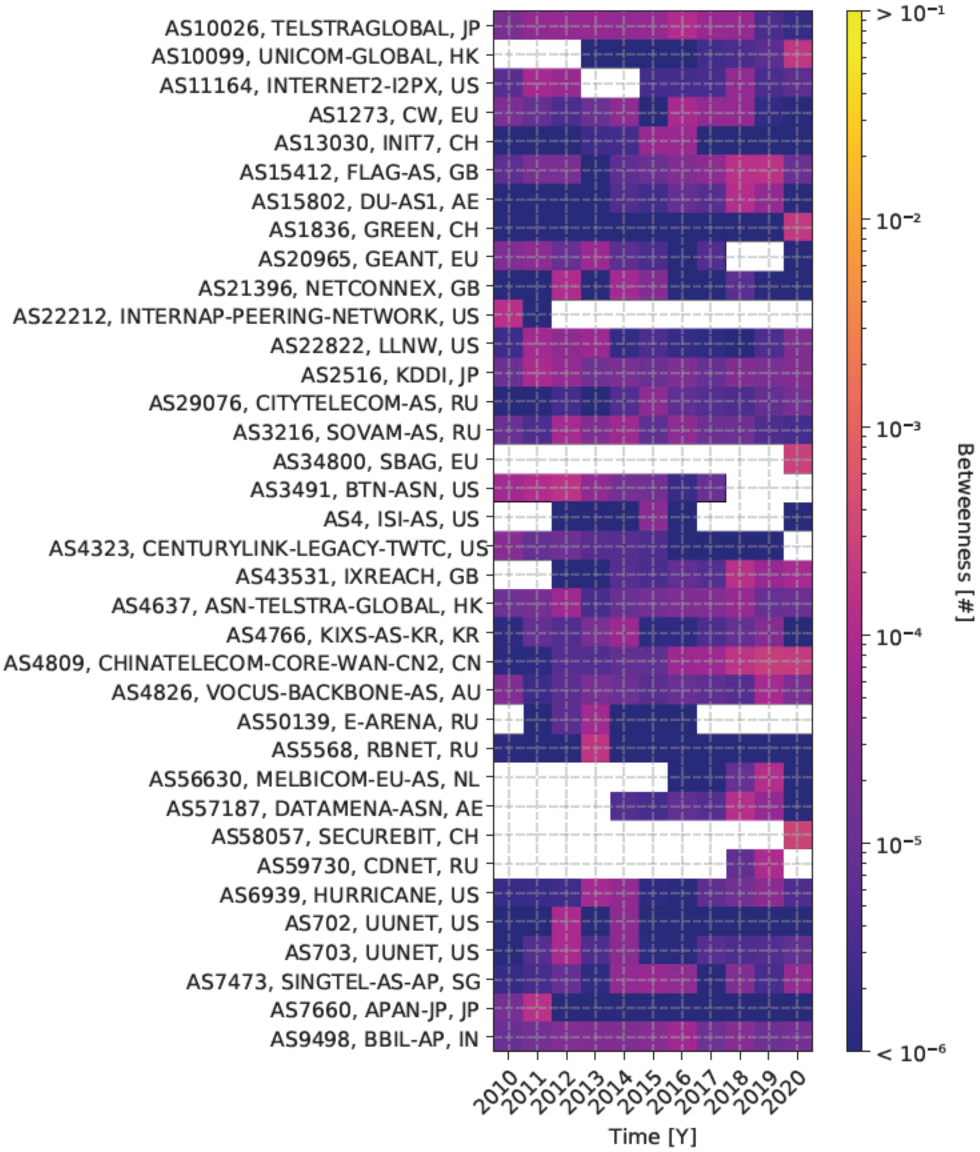


Figure 4.24: Cumulative top five ASes by betweenness values of C2P relationships

The ASes that have been in the top five ASes since 2010, which are in the top five ASes by betweenness of the C2P relationships since 2010, are shown in Figure 4.24. The number of ASes are clearly higher than the number of ASes for the pagerank centrality of the

C2P relationships. The betweenness centrality of the ASes fluctuate widely and some ASes appear only for a short period, for example CDNET (AS59730) or ISI-AS (AS4). This means that the AS has a betweenness value of zero for this time. Overall, the betweenness values fluctuate strongly and no Tier 1 or other major ASes have constant high values.

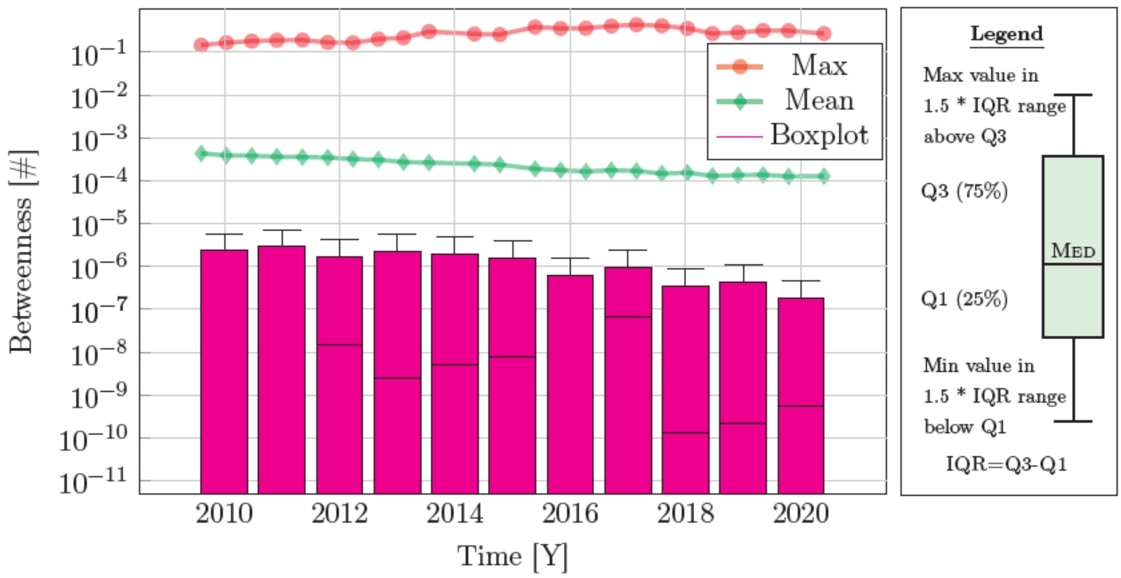


Figure 4.25: P2P relationships

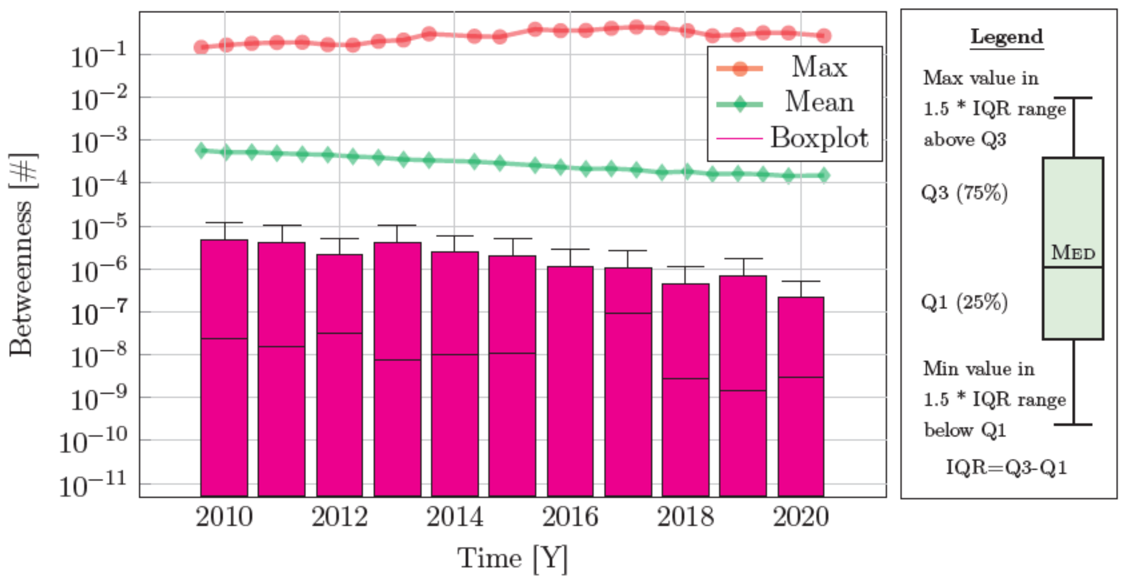


Figure 4.26: P2P relationships (Only ISPs)

The betweenness distribution for the P2P relationships are shown in Figure 4.25. The max values are growing slowly between 2010 and 2018. Then, the values slowly decrease. The mean line and the upper quartile of the boxplot shrink constantly. In contrast, the median fluctuates strongly between 0 and 10^{-7}.

The betweenness values of ISPs and transit providers are displayed in Figure 4.26. The mean and maximum values are similar to Figure 4.25, and the median fluctuates less. Overall, the differences between the filtered and unfiltered values are few.

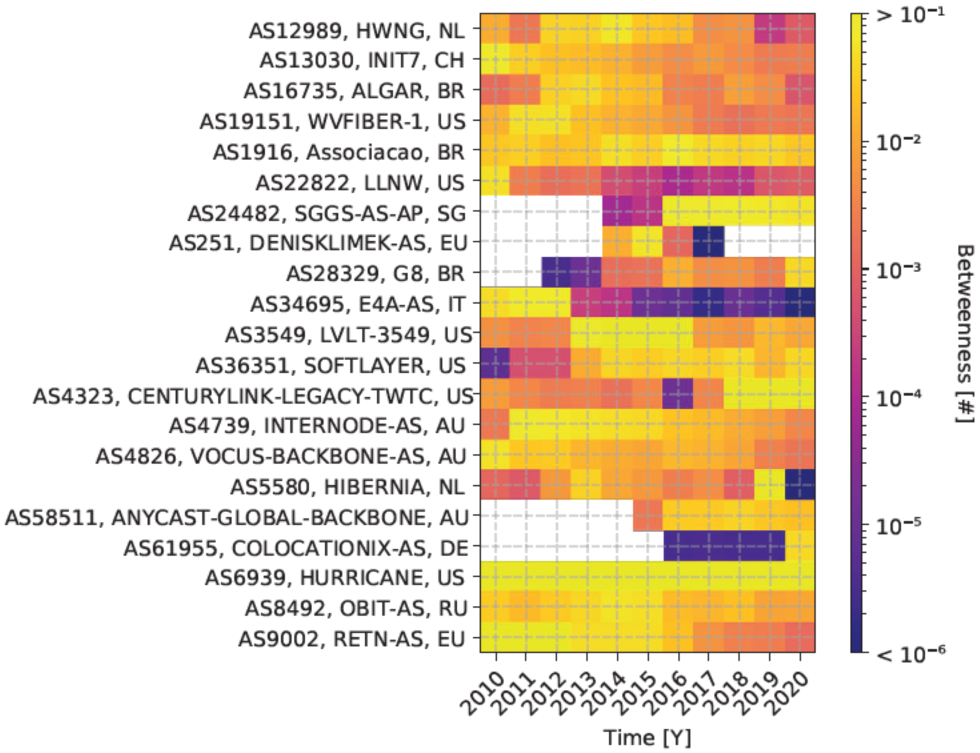


Figure 4.27: Cumulative top five ASes by betweenness values of P2P relationships

Figure 4.27 shows the top five ASes by betweenness of the graph formed by P2P relationships. In contrast to the pagerank results the number of ASes for P2P relationships are higher than the number of ASes for C2P relationships and the values are lower in general. HURRICANE (AS6939) has the highest values since 2010. Since 2018, CENTURY-LEGACY-TWTC (AS4323) shows similar high values. There is no Tier 1 network represented and it is noticeable that many countries are represented. This indicates that the betweenness values identify the central ASes of a region rather than the central ASes of the whole network in case of the P2P relationships.

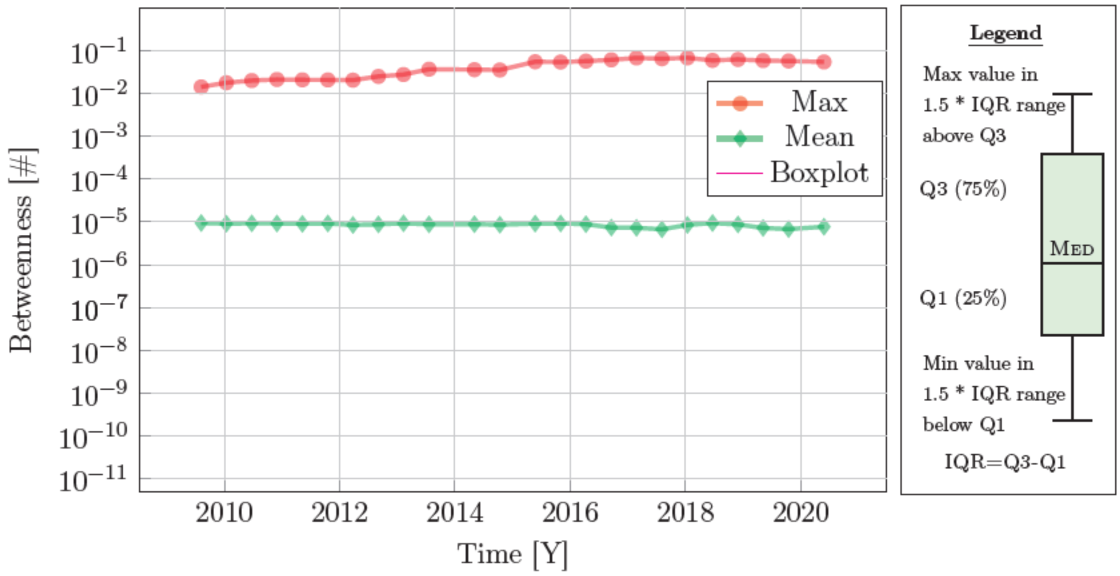


Figure 4.28: All relationships

The betweenness of the graph formed out of all relationships are shown in Figure 4.28. Mean and maximum values are visible. The whole boxplot is zero and the maximum grows slow between 2010 and 2018 and shrinks since 2018. In contrast to the values of the graph, which was created only from the C2P relationships, nearly no fluctuations can be seen.

Figure 4.29 shows the filtered betweenness values. Only the values of ASes which are ISPs or transit providers are used. The maximum values are similar to the unfiltered values but the mean line go up a little. In contrast to the unfiltered values, the boxplot shows values in the upper quartile and has upper whisker values. The median stays the whole time at zero. That the boxplot show values shows that ISPs and transit providers have higher betweenness values than stub ASes. It certainly corresponds to the reality that ASes, which forward traffic for others or enable access to the internet, are more important for the structure of the Internet than stub ASes.

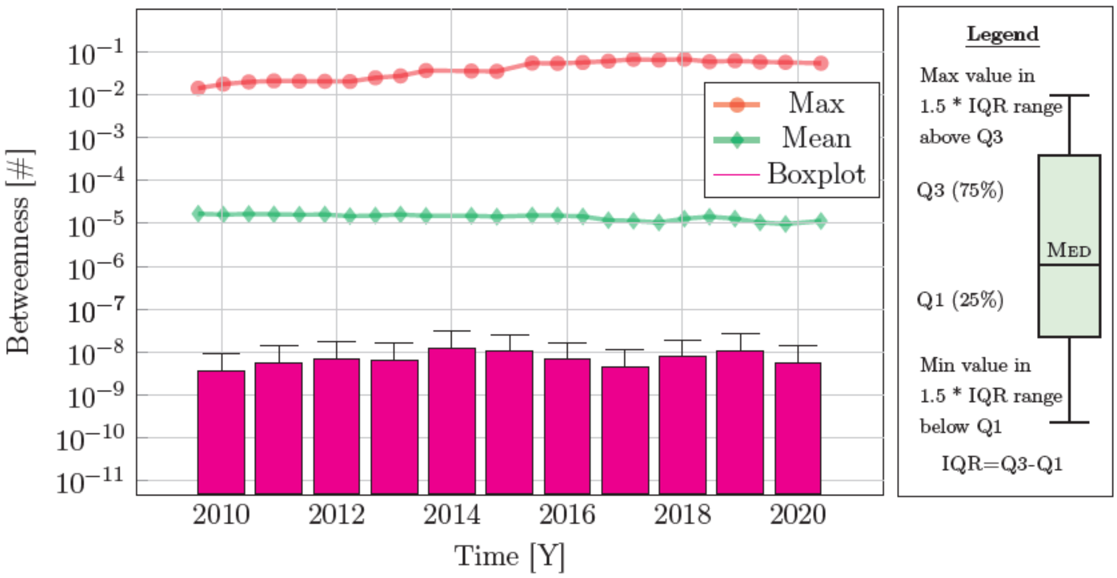


Figure 4.29: All relationships (Only ISPs)

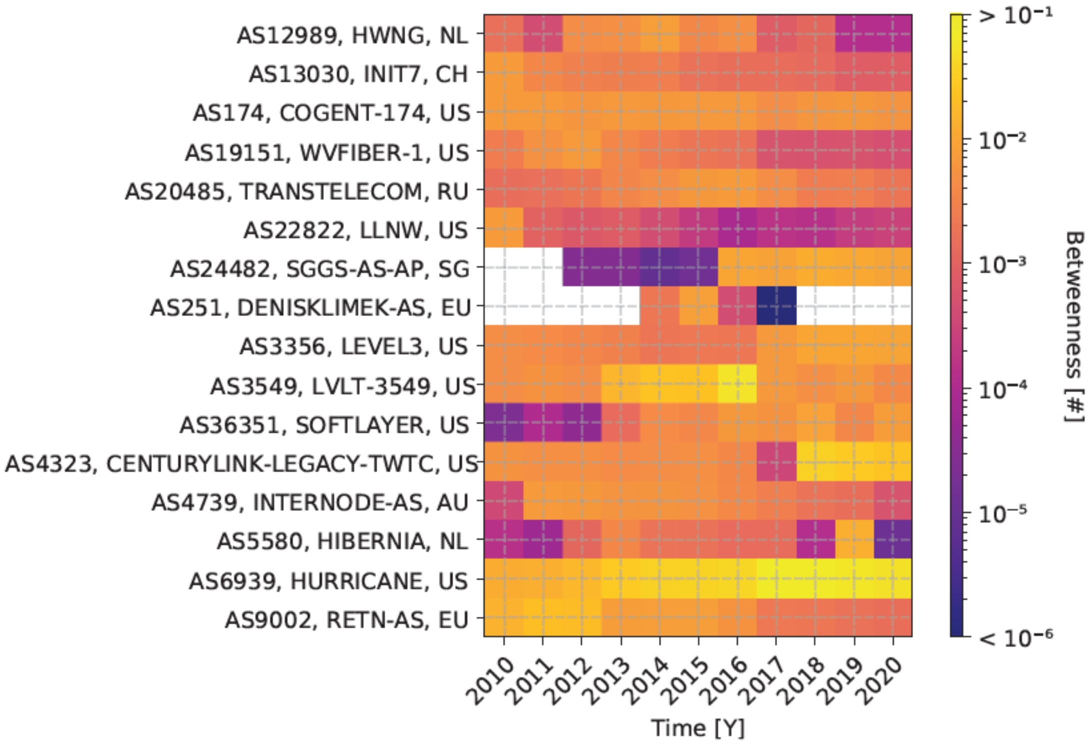


Figure 4.30: Cumulative top five ASes by betweenness values of all relationships

The top five ASes by betweenness are shown in Figure 4.30. By far the highest betweenness values has HURRICANE (AS6939) over the entire period. With LEVEL3 (AS3356) only one Tier 1 network is represented which indicates that the betweenness centrality might not be the best metric to identify the most central and important networks of the Internet graph based on AS relationship information.

4.4 Spectral Analyzes of the Adjacency Matrix

The adjacency matrix spectrum of a graph can be used to determine the average node degree, the existence of loops and independent sets of a graph [50]. We introduce three example graphs with the corresponding adjacency matrix spectral spectrum of the graph and show how these properties are visible in their graph spectrum. The adjacency matrix is defined for directed graphs as

$$Aij = \begin{cases} 1 & \text{if } (j, i) \in E \\ 0 & \text{otherwise} \end{cases}$$

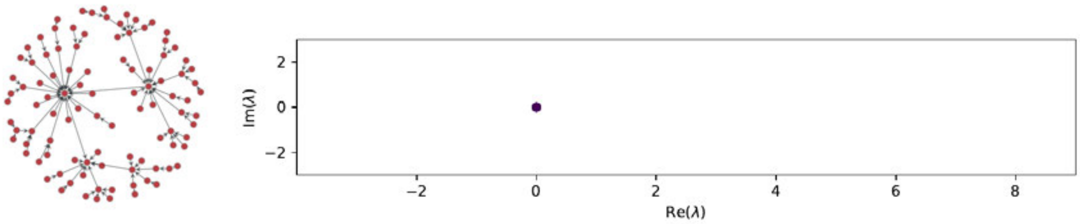
where E is the edge set[4]. The set of eigenvalues of the adjacency matrix is called the spectrum of the graph and is represented as complex number with a real and an imaging part [50]. In our examples we look at how the two parts of the complex number can be interpreted. A simple assignment of which part represents which graph properties is not possible [29].

Figure 4.31 shows a graph with an adjacency matrix spectrum which is zero. The graph (Figure 4.31a) has clear regions and no edges between the regions and one central node exist in the graph. Only three of 100 nodes have more than five children, and most nodes have only one outgoing edge and no children.

$$A = \begin{pmatrix} 0 & 1 & \cdots & 0 \\ 0 & 0 & \cdots & 1 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 \end{pmatrix}$$

[4] https://graph-tool.skewed.de/static/doc/spectral.html#graph_tool.spectral.adjacency

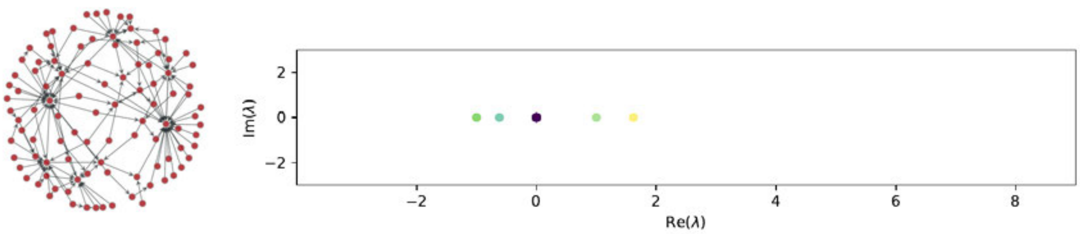
The adjacency matrix spectrum 4.31b shows this simple graph structure, because the matrix A has mostly zero values. The zero graph spectrum shows that the graph does not contain cycles. In general, all graphs that have a tree structure always have a null graph spectrum. This means that they are not specified by the adjacency matrix spectrum [41].



(a) Graph (b) Adjacency matrix spectrum

Figure 4.31: Graph with fewer interconnections and globally important nodes

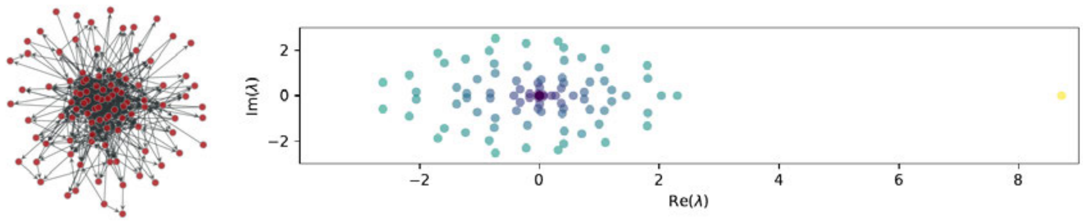
Figure 4.32 shows a more interconnected graph with the corresponding adjacency matrix spectrum. The adjacency matrix of this graph contains more non-zero values than the previous one, which usually appear in grouped form. There are only values on the x-axis visible which shows the real part of the spectrum. The highest value (the yellow dot) lies between the average node degree and the highest vertex degree in the graph [50]. This value is an upper bound for the average node degree. The graph contains communities visible in the spectrum via the values on the x-axis [33]. That the values are not symmetric and negative values exist shows that the graph is not strongly connected. Strongly connected graphs have a path from each node to all other nodes [34].



(a) Graph (b) Adjacency matrix spectrum

Figure 4.32: Graph with fewer interconnections and regional important nodes

Our example for a complex graph with high interconnected nodes are shown in Figure 4.33. There are values distributed on both axes, which are spread between -2 and 2 on both axis. The x-axis shows again that the graph contains communities, is not strongly connected and the highest value on the x-axis is higher than 8 (yellow dot). The complex part of the eigenvalues are hard to interpret [33] but can help to identify some properties of complex directed graphs: "whether a graph is nearly acyclic, whether a graph is nearly symmetric, and whether a graph is nearly bipartite" [29]. Figure 4.33a shows relatively high complex values, which indicates that the graph is not acyclic. That the complex values are not near to the real line (x-axis) it is indicated that the graph is not symmetric. In case the complex values are partially mirrored along the complex line (y-axis) this indicates that the graph is bipartite [29]. This is not the case in Figure 4.33b.

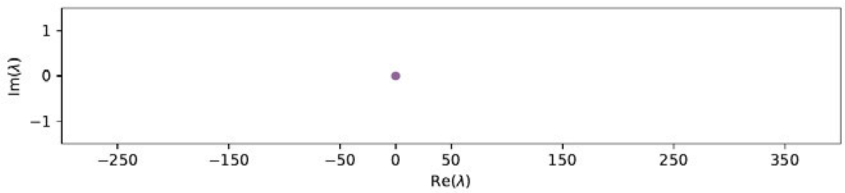


(a) Graph (b) Adjacency matrix spectrum

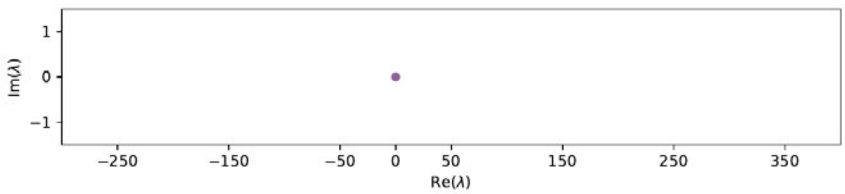
Figure 4.33: Graph with high interconnections

We calculate and interpret the adjacency matrix spectrum of the graphs formed by C2P, P2P, and both relationships. To show the changes over the years, the spectrum for 2010, 2015 and 2020 is calculated for all three graphs created from the relationship types.

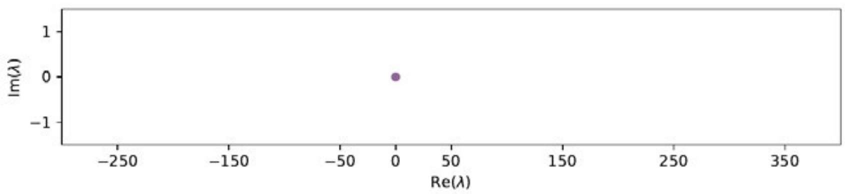
C2P relationships: The adjacency spectrum of the graph formed by the C2P relationships for 2010, 2015 and 2020 are shown in Figure 4.34. The adjacency matrix spectrum for all years shown is zero, which shows that the graph does not contain circles and is comparable to the simple graph in Figure 4.31. This characteristic fits to the hierarchical structure of C2P relationships. Overall there are no evolution visible across the years.



(a) 2010



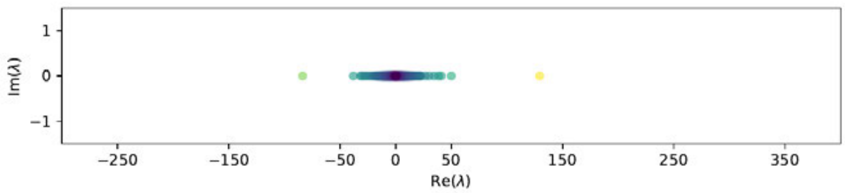
(b) 2015



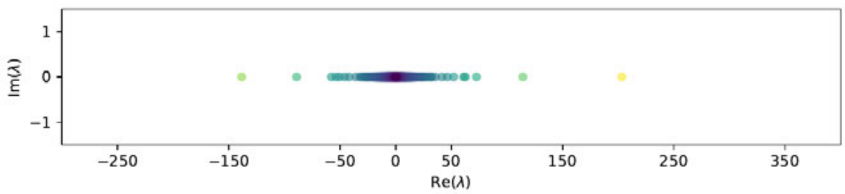
(c) 2020

Figure 4.34: Adjacency matrix spectrum of C2P relationships

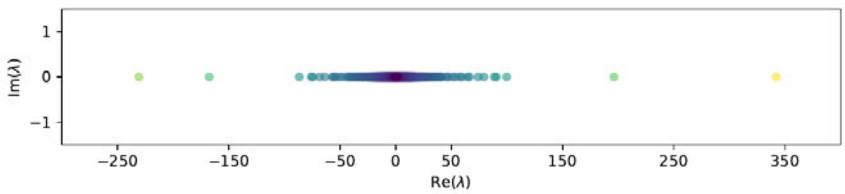
P2P relationships: Figure 4.35 shows the adjacency matrix spectrum of the P2P relationships for 2010, 2015 and 2020. In contrast to the spectrum of the C2P relationships the spectrum of the P2P relationships changes between the years. The graphs are comparable to our example graph shown in Figure 4.32. The highest real value is growing from less than 150 to approximately 350, which indicates a growing average node degree. That the values are mostly near to the y-axis indicates that most of the ASes have a low node degree. Our previous studies confirm that (Figure 4.12).



(a) 2010



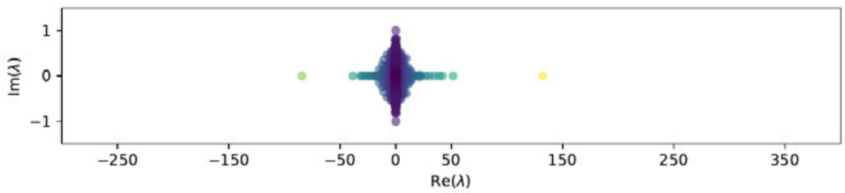
(b) 2015



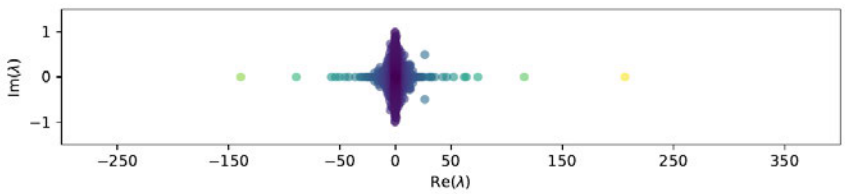
(c) 2020

Figure 4.35: Adjacency matrix spectrum of P2P relationships

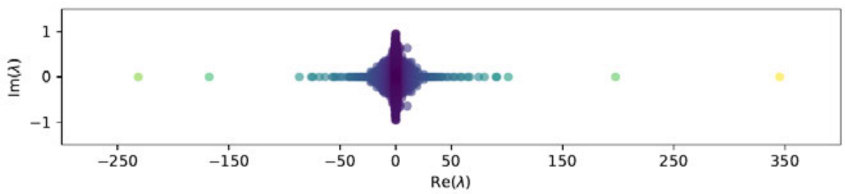
All relationships: The graphs formed by the combined C2P relationships and P2P relationships of 2010, 2015 and 2020 are displayed in Figure 4.36. There are real and complex values visible. The real values are similar to the spectra of the P2P relationships (Figure 4.35) but in addition, complex values exists. The real values show that the graph contains communities and is not strongly connected. The number of communities seems to be growing visible in the number of values on the x-axis. That the complex values are not near to the real line (x-axis) indicates that the graph is not symmetric. That there are values mirrored on the complex axis (y-axis) indicates that the graph is partly bipartite. Again the highest real value is growing from less than 150 to approximately 350, which indicates a growing average node degree. The distribution of the number of relationships per AS are similar to the P2P relationships.



(a) 2010



(b) 2015



(c) 2020

Figure 4.36: Adjacency matrix spectrum of all relationships

4.5 Interim Conclusions

The Internet is still growing and the interconnections between the ASes are more international connected which are leads to a changed cluster composition. The origin countries of the ASes no longer automatically lead to ASes from the same region ending up in the same cluster. The large ASes seem to be peering more and more internationally. This means that transit providers are no longer primarily international, but many other ASes are doing so as well. This is consistent with the results of Labovitz et al. [30] from 2010. However, this tendency seems to have increased strongly between 2015 and 2020. The changes in the Internet routing structure mean that the graph formed from the AS relationships has become increasingly more complex over the years. Nevertheless, in order to identify the real traffic flows, a traffic flow analysis is needed. In this work, we primarily consider the control plane and the real traffic flows are not visible to us. Our centrality results show that the Tier 1 networks still occupy a very central role in the structure of the Internet today but based on the AS relationships, IXPs are increasingly relevant and will take on a comparable role in 2020. The pagerank centrality metric provides much more realistic values than the betweenness centrality. The results of the Pagerank analyses are consistent with our other results, but more research is needed for centrality based on real traffic flows.

5 Economic Aspects of the Internet

The distribution of the economic aspects of the Internet is not directly part of the AS relationships which we studied previously. The distribution of IPv4 and IPv6 space among organization and the number of ASNs which are assigned to an organizations makes developments like the exhaustion of IPv4 addresses visible. Data for this analysis can be extracted out of WHOIS information. The WHOIS information are stored in WHOIS databases which can be queried via the WHOIS protocol [23]. These databases are operated from the regional Internet registries (RIRs). Each database contains information about the resources and organizations in the region of the specific RIR [26].

5.1 WHOIS Dataset

We use a regenerated version of the RIR databases by Johann Schlamp, Leitwert[1] which combines information about the number of IPv4 prefixes (WHOIS *inetnum* object[2]), IPv6 prefixes (WHOIS *inetnum6* object) and ASNs (WHOIS *auth-num* object[3]) for 2013 and 2020 for each handle out of all large RIR databases. The handles are the *mnt-handle* object[4] (As example *DTAG-RR*) or in case of DNS zone entries the handles are created following the schema *<sld>/<tld>* (As example, *telekom/de*) is used. The dataset makes it possible to observe changes in the resource distribution following the handles. However, the handles of an organization are not combined and it is not possible to create the mapping of the handles to an organization from the data set, because not enough

[1] `https://www.leitwert.net/` (08.2020)

[2] `https://www.ripe.net/manage-ips-and-asns/db/support/documentation/ripe-database-documentation/rpsl-object-types/4-2-descriptions-of-primary-objects/4-2-4-description-of-the-inetnum-object` (08.2020)

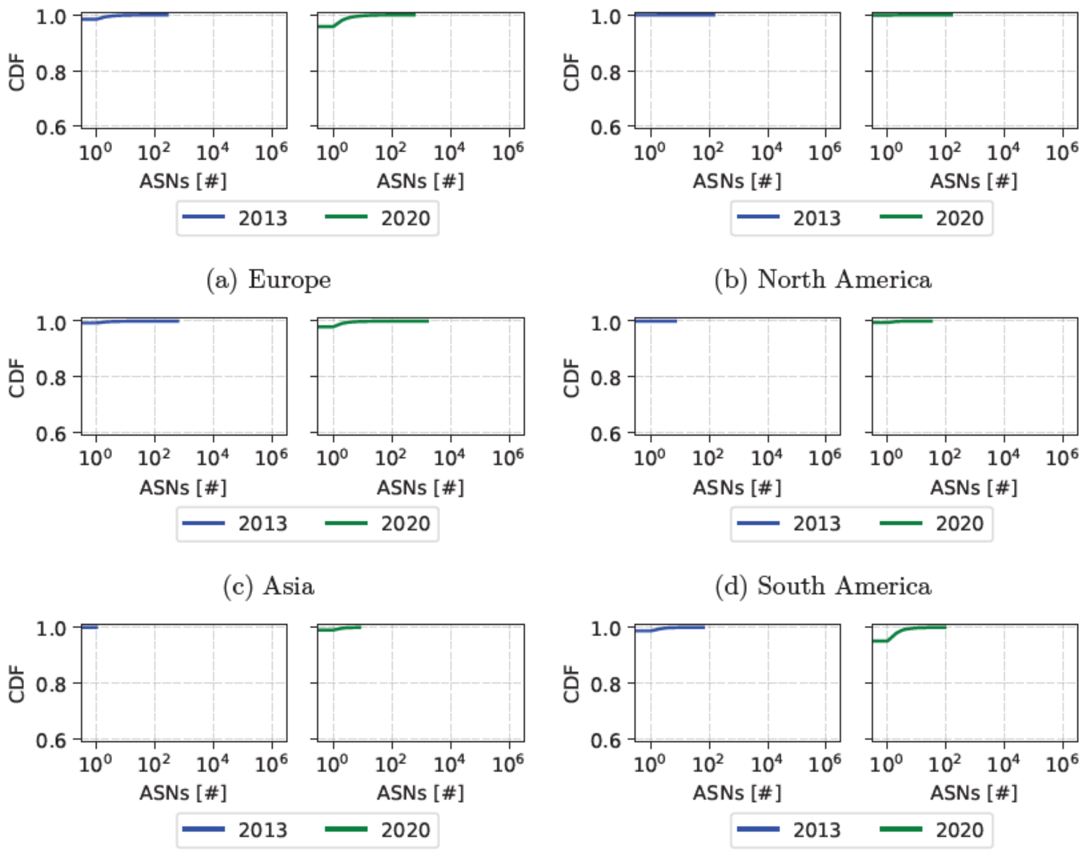
[3] `https://www.ripe.net/manage-ips-and-asns/db/support/documentation/ripe-database-documentation/rpsl-object-types/4-2-descriptions-of-primary-objects/4-2-1-description-of-the-aut-num-object` (08.2020)

[4] `https://www.ripe.net/manage-ips-and-asns/db/support/documentation/ripe-database-documentation/rpsl-object-types/4-1-description-of-attributes-common-to-all-objects` (08.2020)

information is contained. The number of *inetnum* objects and not the number of IP addresses is counted. The *inetnum* objects can describe different large IP ranges, which means that the number of IP addresses cannot be read from the number of objects.

5.2 Evolution of the Economic Aspects

The distribution of the number of ASNs of a handle per continent are shown as a cumulative distribution function (CDF) in Figure 5.1. Overall, most handles hold one or zero ASN in 2013 and 2020. Europe, Asia and Oceania have more handles with more than one ASNs in 2020. The distribution in North America, South America and Africa remains almost unchanged.



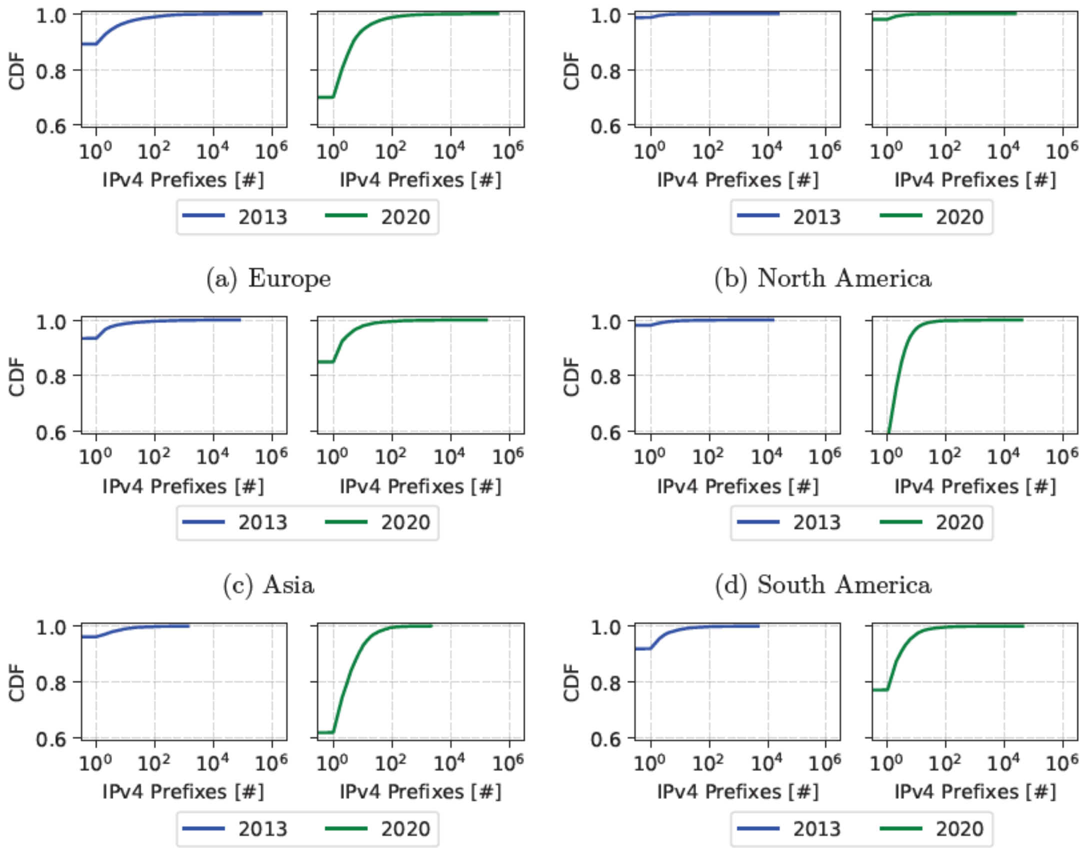
(a) Europe (b) North America

(c) Asia (d) South America

(e) Africa (f) Oceania

Figure 5.1: Evolution of the distribution of ASNs among handles

The lack of IPv4 addresses is partly visible in Figure 5.2 which shows a CDF plot of the distribution of the IPv4 prefixes per continent. The distribution changes strongly for all continents except North America. North America is special in this case, because the ARIN (RIR for North America) has handed out more than twice the number of */8* IPv4 prefixes than other RIRs [47]. The high number of */8* IPv4 prefixes seems to give the North American handles enough addresses to compensate the exhaustion of IPv4 addresses even in 2020. Africa (Figure 5.2e) and South America (Figure 5.2d) have the largest differences in their IPv4 prefix distribution. However, all continents have more handles with lesser or zero IPv4 prefixes in 2013 than in 2020.



(a) Europe (b) North America

(c) Asia (d) South America

(e) Africa (f) Oceania

Figure 5.2: Evolution of the distribution of IPv4 space among handles

The distribution of the IPv6 prefixes (Figure 5.3) shows the upper side of the IPv4 prefixes distribution. This means that handles that do not have IPv4 prefixes compensate this with IPv6 prefixes. In 2020 the number of handles with more IPv6 addresses increase.

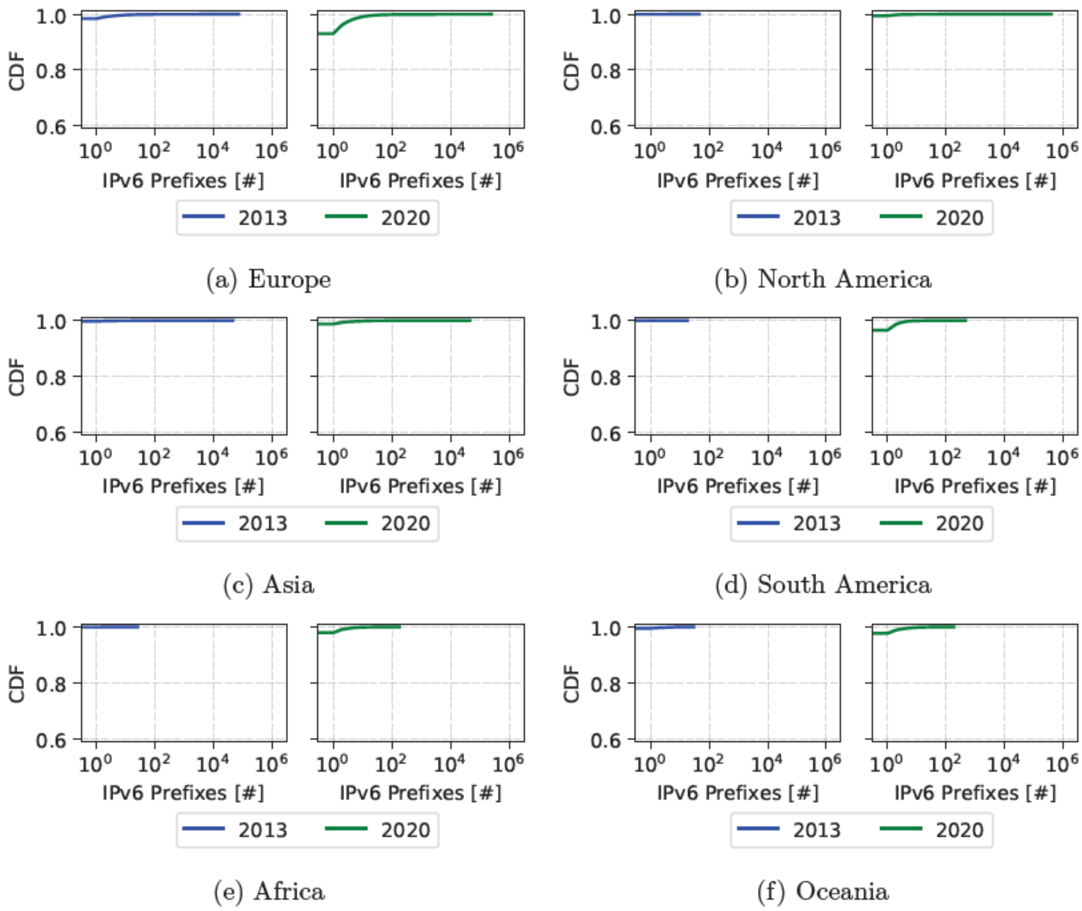


Figure 5.3: Evolution of the distribution of IPv6 space among handles

Numeric distribution: A summary of the numeric distribution of the Internet resources per continent for 2013 is displayed in Table 5.1. Africa has only 20 handles which have an AS number and no handle with more than one ASN. In contrast, Europe has 32 059 with ASNs and one handle has 256 ASNs assigned. The number of ASNs across all continents (Tot.) per handle is only 0.022 which shows that most handles have no ASN. The continent which the highest number of prefixes is Europe with 5 006 264. The average number of prefixes per handle across all continents is 2.581. With an average of

31.098 prefixes per handle Europe has the higher value. The average number across all continents of IPv6 prefixes per handle is lower with 0.091.

		2013						
ASNs	Avg.	0.199	0.007	0.091	0.008	0.003	0.134	0.022
	Max	256	142	598	7	1	64	598
	Tot.	32059	26593	24045	651	20	3719	88215
IPv4 prefixes	Avg.	31.098	0.647	9.868	1.122	1.024	3.092	2.581
	Max	422295	22358	77012	14678	1357	4719	422295
	Tot.	5006264	2155215	2588149	82047	6350	85757	9930497
IPv6 prefixes	Avg.	1.020	0.001	0.672	0.005	0.007	0.066	0.091
	Max	71666	45	46628	18	26	30	73339
	Tot.	164292	5864	176363	367	48	1843	351214
Continent		EU	NA	AS	SA	AF	OC	Tot.

Table 5.1: Internet resource distribution per continent in 2013

Table 5.2 shows the Internet resource distribution in 2020. The total number of ASNs are approximately twice of the value in 2013 for all continents. The differences for IPv4 prefixes are few in contrast to the IPv6 prefixes values. The average number of IPv6 prefixes across all continents is, with 0.622 higher than in 2013 which is in line with the growing IPv6 usage [15].

		2020						
ASNs	Avg.	0.452	0.012	0.271	0.131	0.229	0.499	0.055
	Max	567	151	1602	31	8	91	533
	Tot.	72921	41664	71133	9588	1423	13843	212454
IPv4 prefixes	Avg.	35.538	1.083	12.067	5.143	5.510	10.119	3.425
	Max	413484	22355	169544	37780	2163	41866	413484
	Tot.	5721018	3604402	3164904	376100	34148	280644	13176832
IPv6 prefixes	Avg.	7.156	0.293	0.880	0.306	0.240	0.358	0.622
	Max	247635	386425	46628	452	178	183	513528
	Tot.	1152065	976366	230886	22444	1493	9948	2394497
Continent		EU	NA	AS	SA	AF	OC	Tot.

Table 5.2: Internet resource distribution per continent in 2020

Top five handles by each economic aspect: The following tables show the top five handles for each economic aspect in 2013. Table 5.3 shows the top five handles by number of ASNs. Three of the top five handles are smaller RIRs which may reserve

ASNs by assigning them to themselves as long as they do not assign them to one of their customers. This explains the large decrease in the number of ASNs between 2013 and 2020 for these handles. Gmail|com and signet|nl are the only handles in the top five which are no RIRs. gmail|com and does not show any significant decrease in the number of ASNs. We have not found an explanation why gmail and signet have so many ASNs, nor do we understand how these high values were calculated.

		ASNs		IPv4 prefixes		IPv6 prefixes	
Handle	Continent	2013	2020	2013	2020	2013	2020
idnic|net	AS	533	240	0	0	0	0
gmail|com	NA	322	308	6319	1233	81	156
cnnic|net.cn	AS	170	22	0	0	0	0
netup|ru	EU	133	43	226	77	0	0
signet|nl	AS	106	33	2977	1	0	0

Table 5.3: Top five handles by number of ASNs in 2013

The handles with the highest number of IPv4 prefixes (Table 5.4) are all internet service providers (ISPs). The high values occur because the ISPs split their IP space into many small slices which they than distribute to their customers, but still manage. This approach seems to be most common in Europe, as four out of the five organizations are from Europe. Two of the organizations (kpn|net and kpn|com) belong together, but were not aggregated accordingly.

		ASNs		IPv4 prefixes		IPv6 prefixes	
Handle	Continent	2013	2020	2013	2020	2013	2020
telecomitalia|it	EU	4	6	382396	410492	72	444
kpn|net	EU	3	2	142200	71295	1	1
kpn|com	EU	8	17	108644	93934	12	20
interbusiness|it	EU	6	2	100578	50830	0	0
jsinfo|net	AS	1	1	68911	2	0	0

Table 5.4: Top five handles by number of IPv4 prefixes in 2013

The top five handles by number of IPv6 prefixes are shown in Figure 5.5. The number grows strongly for telkom|de and signet|nl. For hetzner|de and grazag|at the number of IPv6 prefixes decrease. Overall the evolution of the distribution of IPv6 prefixes per handle shows no clear trend across the top five handles by IPv6 prefixes. But the numeric distribution (Figure 5.2) shows that the average number of IPv6 prefixes per handle is higher in 2020 than 2013.

		ASNs		IPv4 prefixes		IPv6 prefixes	
Handle	Continent	2013	2020	2013	2020	2013	2020
hetzner|de	EU	0	0	18089	381	24125	238
telekom|de	EU	0	0	53833	74193	702	47818
grazag|at	EU	0	0	387	193	665	42
soipl|co.in	AS	6	2	4	4	256	256
signet|nl	EU	4	4	1577	1822	237	1892

Table 5.5: Top five handles by number of IPv6 prefixes in 2013

6 Conclusion

In this work, we examined three major questions: *(i)* Can we observe consolidation trends in ASes, organizations and IXPs, *(ii)* what is the composition of the IXP ecosystem and how it has changed in the last ten years, *(iii)* are there structural changes in the AS graph and what do these changes consist of. The main findings on the objectives are as follows.

(i) We show that large transit networks and IXPs play a fundamental role in the routing and exchange of network traffic and seven ASes are present at more than 20% of all IXPs worldwide. The ASes with the highest IXP presence are mostly large content providers (CLOUDFLARE, GOOGLE, MIRCROSOFT and AKAMAI). We show that an outage of a large IXP has strong impacted on his members and routing in thr region and identified three dimensions that are affected in an AS in case of an IXP outage: locality, capacity and cost. We identify the ASes, which only peer at DE-CIX Frankfurt, AMS-IX and LINX LON1 and calculate for each AS values for each dimension. The DE-CIX has the most exclusive members 18% (160 ASes) and the lowest average values across all dimension. This means that the members of the DE-CIX are mostly not able to compensate the outage partly. An analysis of the distribution of the economic aspects of the Internet per continent based on WHOIS information shows that the distribution depends on how strongly the Internet is established in a continent. The portion of IPv6 addresses is higher and the number of IPv4 prefixes becomes smaller faster in continents which joined the Internet later (Africa, South America). North America shows the lowest evolution in the distribution of IPv4 and IPv6 addresses. There is a consolidation of Internet resources in North America and partly in Europe and Asia visible,as they have more IPv4 addresses.

(ii) The IXP throughput and the member size are growing constantly and more and more IXPs are founded all over the entire world. The relevance of IXPs is hard to determine, we confirm that approximately 20% of end-to-end Internet routes traverse IXPs and the relevance of IXPs for small businesses is increasing. We looked at the IXPs distinguished

by continent and their members count. Europe has the most IXPs and the IXPs with the highest average number of members and the highest average IXP throughput. In Europe, the size of the top five IXPs by member size is clearly higher than the member count of all IXPs in Europe. This contrast is smaller for the other continents. South America shows a strong growth in IXP size, throughput and number of points-of-present (PoPs) since 2017. The composition of IXPs by PeeringDB member type shows clear difference between continents where the Internet infrastructure is already established (North America, Europa, Asia and Oceania) and those where it is still growing (South America and Africa). The most prominent finding is that the content providers are very weakly represented in Africa and South America.

(iii) Structural changes are visible in the AS graph. The ratio of customer-to-provider (C2P) and peer-to-peer (P2P) relationships are flipped at the end of 2015, at which point there are more C2P relationships than P2P. In 2020, 62% of all relationships are P2P relationships, which shows that the relevance of P2P relationships is growing. The total number of relationships continues to grow. The relevance of the large transit ASes is still given. The ASes with the most customers (up to 6000 in 2020) are still mostly Tier 1 networks. The hierarchical block structures of the Internet topology shows that the number of links between the ASes are growing and IXPs seem to take an increasingly important position in the Internet structure. The increased number of interconnections between the ASes lead to a greater mixing of origin countries of the ASes, i.e. more ASes out of different countries peer with each other. C2P relationships do not follow this trend as strongly. Even in 2020, they still build relatively to geographical clusters of ASes. We identify the major ASes in the Internet structure with centrality metrics. The most realistic results we obtain with the pagerank centrality metric. The ASes with the highest centrality values are mostly Tier 1 ASes which is in line with our assumptions and other findings. The complexity of the Internet structure is growing, which is visible in the distribution of the adjacency matrix spectra. The mean and maximum numbers of AS relationships are constantly increasing and the rising number of interconnections between ASes again indicate an increase in complexity.

We mostly study the control plane and further research of the data plane is needed to crosscheck our findings. As an example, the amount of traffic exchange via public peering can only be determined when the data plane is considered. The impact of an IXP outage, the composition of the three dimensions needs to be studied more closely and the results of our structural analyses must be further elaborated.

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A IXP Dataset Record Details

A.1 PeeringDB

Endpoint	Description
ix	IXP object with id, name, org_id, location, notes and contact information fields
ixlan	IXP network object with id, ix_id, name, mtu, description and route server asn fields
ixpfx	IXP prefix object with id, ixlan_id, protocol, and prefix fields
org	Organization object with id, name, notes and contact information fields
fac	Facility object with id, org_id, net_count, coordinates, name, notes and contact information fields
net	Network (AS) object with id, org_id, asn, name, notes, peering policy and information fields
netfac	Mapping between Network (AS) and facility
netixlan	Mapping between Network (AS) and IXP network object name, speed, ipaddr4, ipaddr6 and is_rs_peer fields
poc	Contact information object with id, net_id, role and contact information fields
ixfac	Mapping between IXP and facility

Table A.1: Data object description (PeeringDB)

A.2 PCH

Endpoint	Description
ixp	IXP object with id, name, url, location, notes, address and additional information fields
subnet	Subnet object with prefix, name, number of subnet member, IXP id, status and additional information fields
subnet details	Subnet member details object with IP, name, ASN, organization name and additional information fields

Table A.2: Data object description (PCH)

A.3 IXPDB

Endpoint	Description
provider	IXP object with id, PeeringDB-id, name, region, organization-id, url, address and additional information fields
participant	AS objects with IP addresses of each participated IXP, ASN and additional information fields
provider subnet	IXP subnet object with prefixes, name, and route server ASNs fields
participant	AS objects with IP addresses of each participated IXP, ASN and additional information fields

Table A.3: Data object description (IXPDB)

A.4 HE

Endpoint	Description
IXP list	IXP list containing name, member count region, city
IXP detail view	IXP detail information containing URL, URL to IXP statistics, region, country, city, contact information and IXP network prefixes

Table A.4: Data object description (HE)

B Results of Manual Analysis

Name	Org type	RP	Price info	Neutrality	Stats
AMS-IX	Association	✓	✓[1]	✓	✓
DE-CIX	Association	✓	✗[2]	✓	✓
LINX	Association	✓	✓[3]	✓	✓
NL-ix	Commercial[4]	✓	✗[5]	✓	✓
MSK-IX	Commercial	✓	✗[6]	✓	✓

Table B.2: Europe top five IXPs overview

Name	Org type	RP	Price info	Neutrality	Stats
Any2 California	Commercial	✓	✗[7]	✗	✗
SIX	Association	✓	✓[8]	✓	✓
torix	Association	✗	✓[9]	✓	✓
Equinix IBX San Jose	Commercial	✓	✗[10]	✗	✗
Intered Panamá	Association[11]	✗	✗[12]	✓?	✗

Table B.3: North America top five IXPs overview

[1] `https://www.ams-ix.net/ams/service/internet-peering` (03.2020)
[2] `https://www.de-cix.net/en/locations/germany/frankfurt` (03.2020)
[3] `https://www.linx.net/products-services/servicefees/` (03.2020)
[4] PCH value is Association
[5] `https://www.nl-ix.net/` (03.2020)
[6] `https://www.msk-ix.ru/en/` (03.2020)
[7] `https://www.coresite.com/solutions/interconnection/peering-exchanges/any2-internet-peering-exchange/any2-peering-participants` (03.2020)
[8] `https://www.seattleix.net/join` (03.2020)
[9] `https://www.torix.ca/pricing/` (03.2020)
[10] `https://www.equinix.com/` (03.2020)
[11] PCH value is Governmental
[12] `http://intered.org.pa/intered/` (03.2020)

Name	Org type	RP	Price info	Neutrality	Stats
NiCE OpenIXP	Commercial?	✓?	✗[13]	✓?	✓
HKIX	University	✓	✓[14]	✓	✓
IIX	Association	✗	✗[15]	✓	✗
iAdvantage IXP	Commercial	✓	✗[16]	✗	✗
JPIX	Commercial	✗	✗[17]	✓	✓

Table B.4: Asia top five IXPs overview

Name	Org type	RP	Price info	Neutrality	Stats
PTTMetro São Paulo	Association	✗	✗[18]	✓	✓
PTTMetro Rio de Janeiro	Association	✗	✗[19]	✓	✓
PTTMetro Porto Alegre	Association	✗	✗[20]	✓	✓
PTTMetro Fortaleza	Association	✗	✗[21]	✓	✓
CABASE IXP Buenos Aires	Association	✗	✗[22]	✓	✗

Table B.5: South America top five IXPs overview

Name	Org type	RP	Price info	Neutrality	Stats
INX	Association	✗	✓[23]	✓	✗
NAPAfrica Johannesburg	Commercial	✗	✓[24]	✓	✓
IXPN	Association	✗	✓[25]	✓	✓
TIX	Association	✗	✗[26]	✓	✓
DINX	Association	✗	✓[27]	✓	✓

Table B.6: Africa top five IXPs overview

[13] `http://www.openixp.net/` (03.2020)
[14] `http://www.hkix.net/hkix/Charge/ChargeTable.htm` (03.2020)
[15] `https://www.iix.net.id/` (03.2020)
[16] `https://www.iadvantage.net/index.php/solutions-and-services/connectivity-solutions` (03.2020)
[17] `https://www.jpix.ad.jp/en/service_charge.php` (03.2020)
[18] `https://ix.br/adesao/sp` (03.2020)
[19] `https://ix.br/adesao/rj` (03.2020)
[20] `https://ix.br/adesao/rs` (03.2020)
[21] `https://ix.br/adesao/ce` (03.2020)
[22] `https://www.cabase.org.ar/nap-buenos-aires/` (03.2020)
[23] `https://www.inx.net.za/display/pub/INX+FAQ` (03.2020)
[24] `https://www.napafrica.net/features-and-benefits/` (03.2020)
[25] `http://ixp.net.ng/join-ixpn/fees-and-charges/` (03.2020)
[26] `http://tix.or.tz/` (03.2020)
[27] `https://www.inx.net.za/display/pub/INX+FAQ` (03.2020)

Name	Org type	RP	Price info	Neutrality	Stats
Mega IX Sydney	Commercial	✓	✓[28]	✗	✗
NSWIX	Association	✗	✓[29]	✓	✓[30]
Equinix Sydney	Association	✓	✗[31]	✓	✓
Mega IX Melbourne	Commercial	✓	✓[32]	✗	✗
PIPE Sydney	Commercial	✓	✗[33]	✓	✗

Table B.7: Oceania top five IXPs overview

[28] https://www.megaport.com/pricing/ (03.2020)
[29] https://www.ix.asn.au/peering-pricing/ (03.2020)
[30] https://metrics.ix.asn.au (03.2020)
[31] https://www.equinix.com/ (03.2020)
[32] https://www.megaport.com/pricing/ (03.2020)
[33] http://www.pipenetworks.com/pipeix-connect.php (03.2020)

C ASes which are only present at one European IXP

The following Tables list the members which are only present at the DE-CIX, AMS-IX or LINX LON1. Information included in the Tables are the AS-Number (**ASN**), the AS owner (**Owner**), number of IXP outside Europe which the AS is present (**IXPs other**), number of facilities in Europe (**Fa. EU**) and outside Europe (**Fac. other**), number of provider ASes (**Prov.**) and the speef of the connections to the IXP (**Link speed**). A facility is a point of presence (PoP) of an IXP or a private data center where the AS is present.

C.1 DE-CIX

AS type colors:

ISP	Content	NSP	Non-Profit
Research	Enterprise	Not Disclosed	Route Server

	ASN	Owner	IXPs other	Fac. EU	Fac. other	Prov.	Link speed
1	AS33082	ISC-F-AS, US	0	0	0	2	1G, 1G
2	AS6900	AS6900, DE	0	0	0	2	1G
3	AS8391	KNIPP-AS Martin-Schmeisser-Weg 9, DE	0	0	0	2	1G
4	AS42416	COMNET-AS, NL	0	0	0	5	1G
5	AS21336	INFORENT-AS, DE	0	0	0	2	1G
6	AS42605	FRA-VRNETZE, DE	0	0	0	3	1G
7	AS22300	WIKIA, US	0	0	0	2	1G
8	AS15743	NETDE net.de AG, DE	0	0	0	3	10G, 20G
9	AS9189	ACCOM, DE	0	0	0	2	200M
10	AS12348	AS12348 Hermann-Glockner-Str. 7, DE	0	0	0	4	1G
11	AS12316	FITSNET FITS Internet Backbone, DE	0	0	0	1	10G

12	AS10282	DIALIP-PR, US	0	0	0	1	10G
13	AS20633	UNIFFM-NET cords@rz.uni-frankfurt.de 20101227, DE	0	0	0	2	1G
14	AS12975	PALTEL-AS PALTEL Autonomous System, PS	0	0	0	8	1G
15	AS42459	FOBUL, BG	0	0	0	4	10G
16	AS200187	CLOUDKLEYER-AS, DE	0	0	0	2	1G
17	AS47169	HPC-MVM-AS, HU	0	0	0	3	1G
18	AS24582	SYNNET-1 synaix Gesellschaft fuer angewandte Informations-Technologien mbH, DE	0	0	0	3	1G
19	AS5409	TPL-ASN Robert-Bosch-Str. 20, DE	0	0	0	2	1G, 1G
20	AS25081	HDIT-AS, DE	0	0	0	3	1G
21	AS25068	KONICA-MINOLTA-EMEA-HEADQUARTER-AS, DE	0	0	0	2	10G
22	AS9038	BAT-AS9038, JO	0	0	0	7	10G
23	AS62363	EGW-AS, AT	0	0	0	3	1G
24	AS12625	AS12625 GERMANY, DE	0	0	0	3	10G, 10G
25	AS43509	BV-ZAHLUNGSSYSYSTEME-AS, DE	0	0	0	2	10G, 10G
26	AS197915	ALL-FOR-ONE-AS, DE	0	0	0	2	3G, 3G
27	AS199421	MTI-TELEPORT, DE	0	0	0	3	10G
28	AS34086	SCZN-AS, DE	0	0	0	2	5G
29	AS28748	ALPHACRON-AS AlphaCron Datensysteme, DE	0	0	0	2	1G
30	AS44974	REGIONETSW-AS, DE	0	0	0	3	2G
31	AS41033	D2-AS, GB	0	0	0	1	10G
32	AS200278	KNTINTERNET, DE	0	0	0	3	2G
33	AS33848	PORSCHE-AS, DE	0	0	0	3	10G, 10G
34	AS18676	AVAYA, US	0	0	0	10	10G, 10G
35	AS60051	EARTHLINK-DMCC, IQ	0	0	0	2	10G
36	AS47895	R-LINE-AS, RU	0	0	0	3	30G
37	AS203347	YALWA-AS, DE	0	0	0	1	N/A
38	AS197063	AS-PFALZCONNECT, DE	0	0	0	2	10G
39	AS196954	EPCAN epcan breitband loesungen, DE	0	0	0	5	10G
40	AS209400	KURPFALZTEL, DE	0	0	0	2	5G
41	AS21277	NEWROZ-TELECOM-ASN, IQ	0	0	0	7	10G
42	AS49958	EVO-AS, GB	0	0	0	2	10G, 10G

43	AS34432	PHH-AS, DE	0	0	0	4	10G
44	AS60979	KISG4, DE	0	0	0	2	10G, 10G
45	AS39257	INC, DE	0	1	0	2	10G
46	AS47215	FILOO-ASN Rhedaer Strasse 25, DE	0	1	0	3	10G
47	AS13054	FREINET Freiburg, Germany, DE	0	1	0	3	10G
48	AS29404	ELBRACHT-COMPUTER-AS, DE	0	1	0	2	10G
49	AS201764	MGMTP, DE	0	1	0	4	1G
50	AS9022	TWL-KOM-AS Donnersbergweg 4, DE	0	1	0	3	10G
51	AS198570	STNB-AS, DE	0	1	0	2	1G
52	AS61244	EURO-SAT, DE	0	1	0	1	10G
53	AS60169	GFIT-AS, DE	0	1	0	3	40G
54	AS203507	AVIRADE Kaplaneiweg 1, DE	0	1	0	6	10G
55	AS12480	ASILK, DE	0	1	0	3	1G, 1G
56	AS16316	TMT, DE	0	1	0	3	10G
57	AS199790	IPTELECOMBULGARIA-AS, BG	1	0	0	4	10G
58	AS198018	TRIVAGO-, DE	1	0	0	7	10G, 10G
59	AS20830	GLOBALAIRNETWORK-AS, DE	0	1	0	3	1G
60	AS12510	SAP_DC_WDF network/mail abuse to abuse@sap.com, DE	0	1	0	3	10G, 10G
61	AS29624	KRICK-TECHNOLOGIC-AS Mainparkring 4, DE	0	1	0	2	10G
62	AS9197	BECOMGMBH-AS Germany, D-35578 Wetzlar, DE	0	1	0	2	1G
63	AS30766	GGEWNET-AS Dammstrasse 68, DE	0	1	0	2	1G
64	AS60752	AOSSIA-AS, BG	0	1	0	4	1G
65	AS49666	TIC-GW-AS, IR	1	0	0	9	300G
66	AS12808	DTMS-AS, DE	0	1	0	1	1G, 1G
67	AS196714	TNETKOM-AS, DE	0	1	0	2	10G
68	AS396986	BYTEDANCE, US	0	0	1	3	100G
69	AS42587	MAGNAEU, AT	0	1	0	2	1G, 1G
70	AS207419	HYBRIS, DE	0	1	0	2	10G, 10G
71	AS207588	IQ-PRIMETELECOM, IQ	0	1	0	2	10G
72	AS12312	ECOTEL, DE	0	2	0	2	10G, 10G
73	AS2857	RLP-NET, DE	0	2	0	4	10G, 10G
74	AS41289	DWD-AS, DE	0	2	0	2	1G, 1G

75	AS20810	NETCOM-KASSEL Netcom Kassel, DE	0	2	0	1	20G, 20G
76	AS8823	AUTONOMOUSSYSTEMROCKENSTEI DE	0	2	0	7	10G
77	AS20771	CAUCASUS-CABLE-SYSTEM CCS Autonomous System, GE	0	2	0	5	10G
78	AS24679	SSERV-AS, DE	0	2	0	5	10G
79	AS38016	NOK-ION-LABS Nokia IP/Optical Networks Labs, AU	1	0	1	0	1G
80	AS49024	FHE3, DE	0	2	0	2	10G
81	AS39216	ALSARD, IQ	0	2	0	7	10G
82	AS42390	THECLOUD-DE, GB	0	2	0	3	2G
83	AS21161	ASN-BECHTLE Neckarsulm, DE	0	2	0	6	10G
84	AS47372	BIG3AS, DE	0	2	0	3	10G
85	AS48152	DIGITAL-REALTY-, DE	0	2	0	4	10G, 10G
86	AS12748	IAV, DE	1	1	0	4	10G
87	AS42652	DELUNET, DE	0	2	0	4	100G
88	AS200185	XANDMAIL-ASN, DE	0	2	0	3	10G
89	AS196819	TWK-KL-AS, DE	0	2	0	3	10G
90	AS200561	PLACETEL, DE	0	2	0	3	1G
91	AS41998	NETCOMBW-AS, DE	0	2	0	4	100G
92	AS205881	MAN, DE	0	2	0	2	10G, 10G
93	AS196968	ILM-PROVIDER-AS, DE	0	2	0	2	10G
94	AS263626	G-LAB Telecom Informatica LTDA - ME, BR	2	0	0	4	1G
95	AS262376	NOVANET TELECOMUNICACAO LTDA, BR	2	0	0	1	1G
96	AS12857	TDS, DE	0	2	0	3	10G
97	AS8319	NETHINKS-AS NETHINKS GmbH, DE	0	3	0	2	10G
98	AS8879	DTS-SYSTEME DTS Systeme GmbH, DE	0	3	0	2	5G, 5G
99	AS8469	PIRONETNDH-AS CANCOM Pironet AG & Co. KG, DE	0	3	0	2	10G, 1G
100	AS39915	PREM-AS, IE	0	3	0	12	1G
101	AS41412	MIVITEC-AS, DE	0	3	0	4	10G
102	AS20849	CONTINUM, DE	0	3	0	3	10G
103	AS58010	UVENSYS, DE	0	3	0	4	10G
104	AS50061	PWC-EUROPE PricewaterhouseCoopers Europe, DE	0	3	0	2	10G
105	AS268696	TUDDO INTERNET LTDA, BR	3	0	0	2	500M
106	AS23201	Telecel S.A., PY	3	0	0	1	5G
107	AS52866	Iveloz Telecom, BR	2	0	1	3	500M

108	AS42705	TALIA Talia provides VSAT network and hosting services worldwide., GB	0	2	1	11	10G
109	AS21473	MANET-AS Koschatplatz 1, DE	0	4	0	2	10G
110	AS6083	POSIX-AFRICA, ZA	1	2	1	1	100M
111	AS29037	TELIKO-AS, DE	0	4	0	4	10G
112	AS34624	MEGASPACE-AS, DE	0	4	0	5	2G
113	AS62023	NYNEX, DE	0	4	0	2	10G
114	AS50533	ITENOS ITENOS GmbH, DE	0	4	0	5	10G
115	AS55805	MOBICOM-AS-MN MobiCom Corporation, MN	2	1	1	3	10G
116	AS50020	RACCOM-AS, BG	0	4	0	2	1G
117	AS13045	HTP-AS, DE	0	4	0	3	50G
118	AS52937	FHP TELECOMUNICACAO E COM VAREJISTA DE PRODUTOS DE, BR	4	0	0	4	500M
119	AS263421	NR Telecom EIRELI - ME, BR	3	0	1	3	1G
120	AS19318	IS-AS-1, US	2	0	2	4	10G
121	AS24088	HTCHCMC-AS-VN Hanoi Telecom Joint Stock Company - HCMC Branch, VN	2	0	2	7	1G
122	AS268976	P16 Telecom, BR	3	0	1	2	1G
123	AS11432	Telium Telecomunicacoes Ltda, BR	4	0	0	8	1G
124	AS53180	Infortel Telecomunicacoes e Servicos EIRELI - ME, BR	2	0	2	2	10G
125	AS25560	RHTEC-AS rh-tec IP Backbone, DE	0	5	0	2	10G
126	AS31400	ACCELERATED-IT, DE	0	5	0	5	10G
127	AS44066	DE-FIRSTCOLO www.first-colo.net, DE	0	5	0	6	50G, 50G
128	AS12678	BADOO-U, GB	2	1	2	5	20G
129	AS51862	PROFITBRICKS-AS, DE	0	4	1	4	N/A
130	AS12897	HEAGMEDIANET Darmstadt, Germany, DE	0	5	0	4	20G
131	AS35313	BH-INFONAS-ASN, BH	2	2	1	2	1G
132	AS39499	HAWE-AS, PL	0	5	0	0	10G
133	AS265269	MEGA TELEINFORMATICA EIRELI, BR	3	0	2	2	750M
134	AS61102	INTERHOST, IL	1	1	3	4	10G
135	AS262354	Ligue Telecomunicacoes Ltda, BR	5	0	0	2	1G
136	AS28202	Rede Brasileira de Comunicacao Ltda, BR	3	0	2	4	1G
137	AS29686	PROBENETWORKS-AS, DE	0	6	0	3	10G
138	AS20686	BISPING ISP & Citycarrier, Germany, DE	0	6	0	4	1G
139	AS21413	ENVIA-TEL-AS D-09114 Chemnitz, DE	0	6	0	5	20G, 20G
140	AS10158	KAKAO-10158-AS-KR Kakao Corp, KR	6	0	0	5	1G

141	AS53162	VOIPGLOBE SERVICOS DE COM MULTIMIDIA VIA INTERNET, BR	2	0	4	3	1G
142	AS262503	PAULO DE TARSO DE CARVALHO BAYMA FILHO, BR	6	0	0	3	500M
143	AS38193	TWA-AS-AP Transworld Associates (Pvt.) Ltd., PK	1	3	3	5	40G
144	AS20459	TELECOM-NAMIBIA-AS, NA	3	2	2	2	10G
145	AS3580	PLANET, US	3	0	4	2	1G
146	AS52873	SOFTDADOS CONECTIVIDADE, BR	6	0	3	3	20G
147	AS27281	QUANTCAST, US	4	1	4	3	10G, 10G
148	AS3786	LGDACOM LG DACOM Corporation, KR	5	1	4	7	20G
149	AS33011	BOXNET, US	4	1	5	7	2G
150	AS6695	DECIX-AS DE-CIX Management GmbH, DE	0	11	0	0	10G, 10G, 10G
151	AS4837	CHINA169-BACKBONE CHINA UNICOM China169 Backbone, CN	1	3	7	8	N/A
152	AS55967	BAIDU Beijing Baidu Netcom Science and Technology Co., Ltd., CN	6	1	5	4	10G
153	AS22381	Megatelecom Telecomunicacoes Ltda, BR	3	0	9	6	400M
154	AS17639	CONVERGE-AS Converge ICT Solutions Inc., PH	9	0	6	16	1G
155	AS61832	Fortel Fortaleza Telecomunicacoes Ltda, BR	7	0	8	9	20G
156	AS32425	SKB3-ARIN-BGP, US	10	0	6	3	N/A
157	AS28663	FLYS INTERATIVA LTDA, BR	11	0	6	6	1G
158	AS18403	FPT-AS-AP The Corporation for Financing & Promoting Technology, VN	11	1	6	13	20G
159	AS53889	MICFO, US	1	1	19	1	1G
160	AS22356	Durand do Brasil Ltda, BR	12	0	12	4	2G
161	AS262589	INTERNEXA BRASIL OPERADORA DE TELECOMUNICACOES S.A, BR	13	0	21	11	20G
162	AS29838	AMC, US	9	3	40	5	2G, 1G

C.2 AMS-IX

AS type colors:

ISP	Content	NSP	Non-Profit
Research	Enterprise	Not Disclosed	Route Server

	ASN	Owner	IXPs other	Fac. EU	Fac. other	Prov.	Link speed
1	AS46235	TWN, US	0	0	0	2	1G
2	AS16150	PORT80-GLOBALTRANSIT, SE	0	0	0	1	20G
3	AS33796	BNAA-AS, DK	0	0	0	1	10G
4	AS6834	AS6834, DK	0	0	0	3	1G
5	AS6777	AMS-IX-RS, NL	0	0	0	0	1G, 10G
6	AS12327	IDEAR4BUSINESS-INTERNATIONAL-LTD, EU	0	0	0	0	1G
7	AS3333	RIPE-NCC-AS Reseaux IP Europeens Network Coordination Centre (RIPE NCC), EU	0	0	0	4	10G, 10G
8	AS132536	DGNET-AS-AP Dot Gold Data Exchange Center, US	0	0	0	0	1G
9	AS59940	PULSEPOINT-EU, NL	0	0	0	2	10G
10	AS50968	HOSTMASTER-AS, MD	0	0	0	1	1G
11	AS21478	PLEX Plex ASN, NL	0	0	0	2	1G
12	AS32421	BLCC, US	0	0	0	1	10G
13	AS41041	VCLK-EU-, SE	0	0	0	1	10G, 10G
14	AS63113	GLOBECORP-NETWORKS, CZ	0	0	0	2	100G
15	AS203040		0	0	0	0	100M
16	AS202169	SSN-AS, ES	0	0	0	3	10G
17	AS205943	ASRODASALIR, NL	0	0	0	4	10G, 10G
18	AS27024	-Reserved AS-, ZZ	0	0	0	0	250M
19	AS209530	-Reserved AS-, ZZ	0	0	0	0	200M
20	AS208844	VTECH-EU, NL	0	0	0	0	10G
21	AS204006	IQOPTION, CY	0	0	0	5	10G
22	AS56396	TURN, GB	0	1	0	2	40G
23	AS44259	TRANSQUALITY-AS, NL	0	1	0	0	1G
24	AS47172	GREENHOST, NL	0	1	0	2	10G
25	AS49820	PICTURA-NET, NL	0	1	0	1	1G
26	AS47143	TDHN, GB	0	1	0	3	10G
27	AS58209	KPTNETWORK-AS, NL	0	1	0	1	40G
28	AS11179	ARYAKA-ARIN, US	1	0	0	26	1G, 1G
29	AS42567	MOJHOST-EU, NL	0	1	0	3	10G
30	AS47748	DATICUM, BG	0	1	0	2	100M
31	AS1101	IP-EEND-AS IP-EEND BV, NL	0	1	0	1	10G
32	AS204995	RTB-HOUSE-AMS, NL	0	1	0	2	10G, 100G
33	AS205689	WHATBOX-, NL	0	1	0	2	10G

34	AS200478	TABOOLA-AS, IL	1	0	0	8	10G
35	AS56583	BJN-AS, NL	0	1	0	4	10G
36	AS34868	ANYCAST-AS https://anycast.io, DE	0	2	0	2	1G
37	AS47344	PRC, SA	0	2	0	1	10G
38	AS196689	DIGICUBE01, FR	0	2	0	1	500M
39	AS29263	HAAGNET-AS, NL	0	2	0	1	1G, 1G
40	AS197219	TWEEAT, NL	0	2	0	2	1G
41	AS24730	ASN-NETHOLDING Autonomous System for Netholding., NL	0	2	0	1	10G
42	AS49653	DELTAWEB-AS, IT	0	2	0	2	250M
43	AS42555	OPTIC-COM-EU, BG	0	2	0	2	1G
44	AS47973	DIGITAL-REALTY-, NL	0	2	0	6	10G, 10G
45	AS262788		0	1	1	0	1G
46	AS196752	TILAA, NL	0	2	0	3	10G
47	AS203101	NAVARINO-POP, NL	0	1	1	4	10G, 10G
48	AS9115	INFB-AS9115, GB	0	2	0	3	1M
49	AS5416	Internet Service Provider, BH	2	0	0	6	10G
50	AS262807	Redfox Telecomunicacoes Ltda., BR	2	0	0	2	500M
51	AS47582	ANSONNET-AS-UK, GB	2	0	0	1	100G
52	AS26914	SYNOPTEK, US	0	2	1	7	10G
53	AS12634		0	3	0	0	1G, 1G
54	AS24167	ASGCNET Academia Sinica Grid Computing Center, TW	1	1	1	2	1G
55	AS35156	BLACKBOARD-AS, NL	1	1	1	2	1G
56	AS54183	PEER39-ASN, US	3	0	0	1	10G, 10G
57	AS47065	PEERING-RESEARCH-TESTBED-USC-UFMG-AS47065, US	3	0	0	10	1G
58	AS49685	ITIS-AS Signet B.V., NL	0	3	0	3	30G, 30G
59	AS7415	ADSAFE-1, US	2	0	1	7	10G, 10G
60	AS32338	HOSTISERVER, AI	1	1	1	3	10G
61	AS200981	GRAPESHOT-UK-1, GB	3	0	0	4	10G, 10G
62	AS12315	QSP-AS, NL	0	3	0	1	10G
63	AS38090	PEARLABYSS-AS-KR pearlabyss, KR	1	1	1	10	10G, 10G
64	AS202425	INT-NETWORK, SC	0	3	0	1	100G

65	AS133613	MTEL-AS MTel telecommunication company ltd., MO	2	0	1	3	N/A
66	AS262532	VAS Freitas Servicos de Internet Ltda, BR	3	0	0	2	1G
67	AS24642	NL-CAVEO, NL	0	4	0	2	10G
68	AS9167	WEBPARTNER WEBPARTNER A/S is a Danish Internet Service Provider, DK	0	4	0	1	1G
69	AS5583	ORANGE-BUSINESS-SERVICES-BENELUX Orange Business Services (formerly Equant) AS for BENELUX, NL	2	0	2	1	10G
70	AS39318	NUCLEUS, BE	0	4	0	0	1G
71	AS14558	AFS-6, US	0	3	1	1	1G
72	AS37187	SKYBAND, MW	2	1	1	3	500M
73	AS63541	CHINACACHE Beijing Blue I.T Technologies Co.,Ltd., CN	4	0	0	2	10G
74	AS56611	REBACOM-AS, NL	0	4	0	3	10G
75	AS43293	PROXILITY-AS, NL	0	4	0	1	1G
76	AS61029	BITENCY-AS, NL	0	4	0	4	10G
77	AS15703	TRUESERVER-AS TrueServer BV AS number, NL	0	5	0	3	100G
78	AS20495	WEDARE wd6.NET B.V, NL	0	5	0	4	10G
79	AS8744	MEGAMAX-AS Nizhny Novgorod, RU	0	5	0	2	10G
80	AS27589	MOJOHOST, US	2	1	2	3	10G
81	AS21221	INFOPACT-AS The Netherlands, NL	0	5	0	3	10G, 10G
82	AS23947	MORATELINDONAP-AS-ID PT.Mora Telematika Indonesia, ID	3	0	2	6	10G
83	AS8502	IOAS-15, DK	0	5	0	1	20G, 20G
84	AS207083	HOSTSLIM-GLOBAL-NETWORK, NL	0	4	1	2	10G
85	AS210269	HOSTCIRCLE-, NL	0	5	0	3	10G
86	AS48283	SIDN-ANYCAST, NL	0	5	0	3	1G
87	AS55536	PSWITCH-HK PACSWITCH IP NETWORK, HK	3	0	2	1	1G
88	AS263528	VIACOM NEXT GENERATION COMUNICACAO LTDA, BR	5	0	0	4	1G
89	AS8608	QINIP Esprit Telecom B.V., NL	0	6	0	3	10G, 10G
90	AS52438	PLANISYS S.A., AR	1	1	4	3	1G
91	AS265187	STEEL WEB PROVEDORES DE ACESSO LTDA, BR	3	0	3	5	1G
92	AS55799	IPTELECOM-AP IPTELECOM ASIA, MY	0	0	6	6	1G

93	AS50763	MCKAYCOM, GB	2	2	3	3	1G
94	AS58952	FRONTIIRCOLTD-MM Frontiir Co. Ltd, MM	5	0	2	4	1G
95	AS43366	OSSO, NL	0	7	0	2	10G
96	AS60924	ORIXCOM, AE	1	4	2	5	1G
97	AS17408	ABOVE-AS-AP AboveNet Communications Taiwan, TW	7	0	1	5	100M
98	AS26163	DATAGRAM, US	2	0	7	2	10G
99	AS33915	TNF-AS, NL	0	9	0	1	40G, 40G
100	AS4761	INDOSAT-INP-AP INDOSAT Internet Network Provider, ID	6	0	3	5	10G
101	AS62715	CODE42, US	5	1	5	7	10G
102	AS8315	SENTIA, NL	0	10	1	6	10G
103	AS23106	AMERICAN TOWER DO BRASIL-COMUNICACAO MULTIMIDIA LT, BR	5	0	6	5	10G
104	AS40805	JMF-WAVEFLY, US	7	0	4	5	10G
105	AS28283	Adylnet Telecom, BR	5	0	7	5	1G
106	AS38158	CBN-NETWORKS-AS-ID PT. Cyberindo Aditama, ID	8	0	4	5	10G
107	AS1200	AMS-IX1, NL	0	13	0	0	1G, 1G
108	AS14907	WIKIMEDIA, US	5	3	6	11	20G
109	AS135391	AOFEI-HK AOFEI DATA INTERNATIONAL COMPANY LIMITED, HK	5	2	8	13	100G
110	AS58580	FASTRACK Fastrack Technology, AU	7	2	6	5	1G
111	AS35017	SWIFTWAY-AS Netherlands, GB	0	6	11	2	20G
112	AS293	ESNET, US	6	2	9	2	10G
113	AS17451	BIZNET-AS-AP BIZNET NETWORKS, ID	12	1	7	10	10G
114	AS63399	DIALPAD, US	14	1	10	13	1G
115	AS64050	BCPL-SG BGPNET Global ASN, SG	12	1	14	11	100G
116	AS63956	COLO-AS-AP Colocation Australia Pty Ltd, AU	16	0	17	6	N/A
117	AS54825	PACKET, US	14	3	19	9	20G

C.3 LINX LON1

AS type colors:

ISP	Content	NSP	Non-Profit
Research	Enterprise	Not Disclosed	Route Server

	ASN	Owner	IXPs other	Fac. EU	Fac. other	Prov.	Link speed
1	AS29006	POBOX-AS, GB	0	0	0	2	50M
2	AS4004	GLOBAL-SPLK, US	0	0	0	1	10G
3	AS34407	WAVECREST-AS01, GB	0	0	0	2	500M
4	AS57228	AXIANS-UK-AS, GB	0	0	0	1	1G
5	AS62244	WBTSUK-AS, GB	0	0	0	1	1G
6	AS199706	BLOCK-AS, GB	0	0	0	1	1G
7	AS203520	XANTARO, DE	0	0	0	2	1G
8	AS203231	V4VOIP, GB	0	0	0	1	1G
9	AS42543	OPENMARKET, GB	0	0	0	2	1G
10	AS206934	BFC-UK, GB	0	0	0	3	10G
11	AS201261	WATERSHED, GB	0	0	0	2	1G
12	AS41379	NTA-AS, GB	0	0	0	4	N/A
13	AS40339	JUMP-TRADING-LLC, US	0	0	0	8	10G
14	AS5377	MARLINK-EMEA, NO	0	0	0	5	100M
15	AS200147	ASHTL, GB	0	0	0	3	1G
16	AS60377	TOOB, GB	0	0	0	2	10G
17	AS43338	RATIONAL-AS, GB	0	0	0	4	1G
18	AS1921	NICAT NIC.at head office Salzburg, AT	0	0	0	16	1G
19	AS10361	BLOOMBERG-NET, US	0	0	0	14	N/A
20	AS34746	AXA_INSURANCE, GB	0	1	0	2	100M
21	AS8950	LOGICALISUK, GB	0	1	0	2	1G
22	AS51159	THINKSYSTEMSUK-ASN, GB	0	1	0	3	100M
23	AS51823	MTNETWORKSLTD, GB	0	1	0	2	1G
24	AS50468	CITRUS-AS, GB	0	1	0	5	1G
25	AS61215	IIJ-EXLAYER-AS, GB	0	1	0	2	1G
26	AS198554	DXI-AS, GB	0	1	0	2	1G
27	AS47762	WESTCLOUD-AS, GB	0	1	0	3	100M
28	AS198313	SYSTEMHOST, GB	0	1	0	0	1G
29	AS15773	INCLARITY, GB	0	2	0	2	1G
30	AS29297	LINKCONNECT-AS Linkconnect services Ltd, UK Business to business ISP, GB	0	2	0	1	1G
31	AS47999	TCL-AS, GB	0	2	0	4	1G
32	AS35399	ITIO-AS, GB	0	2	0	3	100M
33	AS42044	CENTRALNIC CentralNic Registry AS Number, GB	0	2	0	3	100M
34	AS49401	BINKNET, GB	0	2	0	0	1G
35	AS206483	REDMATTER, GB	2	0	0	4	1G
36	AS48825	FAST2HOST, GB	0	2	0	1	1G
37	AS57276	OPTIMITY, GB	0	2	0	3	10G
38	AS203582	MTS, GB	0	2	0	2	N/A
39	AS203649	GOINTERNET, GB	0	2	0	2	1G

40	AS202596	GNETWORK, GB	0	2	0	2	10G
41	AS43599	NWEWN-AS, GB	0	3	0	2	1G
42	AS33854	HOSTIT-AS-NN, GB	0	3	0	2	1G
43	AS7642	DHIRAAGU-MV-AP DHIVEHI RAAJ-JEYGE GULHUN PLC, MV	1	0	2	5	10G
44	AS37678	BOFINET, BW	3	0	0	3	10G
45	AS199188	PRIMEXM www.primexm.com, DE	0	1	2	3	1G
46	AS14717	ECINET, US	3	0	0	5	1G
47	AS206999	OAKFORDIS, GB	0	3	0	1	1G
48	AS56258	PGAS-AS-ID PT. PGAS TELEKOMU-NIKASI NUSANTARA, ID	3	0	0	4	1G
49	AS41107	BACKBONE-CONNECT, GB	0	3	0	3	N/A
50	AS328146	Saint-ICT-AS, ZA	2	0	1	3	1G
51	AS43256	KIN-AS, BE	1	1	1	3	1G
52	AS44749	PINNACOM-ISP, GB	0	3	0	1	1G
53	AS31708	COREIX-UK-AS London, Great Britain, GB	0	4	0	6	10G
54	AS56730	WIREHIVE-AS, GB	0	4	0	2	1G
55	AS12576	EE Ltd, GB	0	4	0	2	200G, 200G
56	AS20681	SAXOBANK, DK	0	3	1	3	1G
57	AS6779	ICLNET-AS Fujitsu AS, GB	0	4	0	2	10G
58	AS19324	DOSARREST, US	4	0	0	4	10G
59	AS37363	FAIRCAPE, ZA	2	0	2	2	1G
60	AS36868	EIS, MU	3	0	1	2	N/A
61	AS50292	STRATOGEN, GB	0	5	0	12	1G
62	AS34270	INETC Internet Connections Ltd, GB	0	5	0	1	10G
63	AS41695	VOSTRON-AS, GB	0	5	0	1	1G
64	AS62217	VOOSERVERS, GB	1	2	2	4	2G
65	AS24931	DEDIPOWER, GB	0	4	1	3	10G
66	AS38719	DREAMSCAPE-AS-AP Dreamscape Networks Limited, AU	5	0	0	6	1G, 1G
67	AS37349	Aptus, TZ	2	1	2	4	1G
68	AS59659	SECURUS, GB	0	5	0	3	2G
69	AS37697	webmasters, MZ	3	0	2	4	1G
70	AS60945	VELOXSERV VeloxServ Communications Ltd, GB	0	5	0	4	10G
71	AS17494	BTTB-AS-AP Telecom Operator & Internet Service Provider as well, BD	1	0	4	5	10G
72	AS14492	DATAPIPE, US	3	0	3	5	1G
73	AS6648	BAYAN-TELECOMMUNICATIONS Bayan Telecommunications, Inc., PH	4	0	2	11	1G
74	AS36131	IMO, US	3	1	2	10	20G
75	AS18059	DTPNET-AS-AP DTPNET NAP, ID	5	0	1	7	1G

76	AS37239	ICTGLOBE, ZA	3	0	3	3	1G
77	AS55081	24SHELLS, US	2	1	3	4	10G
78	AS6643	JIVECOMMUNICATIONS, US	4	0	2	12	1G
79	AS49425	DIGITAL-REALTY-UK, GB	0	6	0	5	10G, 10G
80	AS60255	INTERNETTYUK, GB	0	6	0	1	5G
81	AS58500	CITRANET-AS-ID Citra Internet Exchange, ID	2	0	5	0	1G
82	AS13360	TRITONDIGITAL, CA	1	2	4	8	10G
83	AS9605	DOCOMO NTT DOCOMO, INC., JP	4	0	3	5	10G
84	AS18283	CCV Fureai Channel Inc., JP	3	0	4	4	1G
85	AS4800	LINTASARTA-AS-AP Network Access Provider and Internet Service Provider, ID	6	1	4	8	1G
86	AS328366	FirstnetTechnology-AS, ZA	6	1	4	3	1G
87	AS33182	DIMENOC, US	4	1	8	20	1G
88	AS9354	TDNC Community Network Center Inc., JP	9	0	4	6	3G
89	AS6619	SAMSUNGSDS-AS-KR SamsungSDS Inc., KR	6	2	7	14	1G
90	AS17978	SERVCORP SERVCORP AUSTRALIAN HOLDINGS LTD, AU	6	1	9	10	1G
91	AS9505	TWGATE-AP Taiwan Internet Gateway, TW	9	0	9	7	1G
92	AS2497	IIJ Internet Initiative Japan Inc., JP	14	1	10	6	10G

Erklärung zur selbstständigen Bearbeitung einer Abschlussarbeit

Gemäß der Allgemeinen Prüfungs- und Studienordnung ist zusammen mit der Abschlussarbeit eine schriftliche Erklärung abzugeben, in der der Studierende bestätigt, dass die Abschlussarbeit „— bei einer Gruppenarbeit die entsprechend gekennzeichneten Teile der Arbeit [(§ 18 Abs. 1 APSO-TI-BM bzw. § 21 Abs. 1 APSO-INGI)] — ohne fremde Hilfe selbständig verfasst und nur die angegebenen Quellen und Hilfsmittel benutzt wurden. Wörtlich oder dem Sinn nach aus anderen Werken entnommene Stellen sind unter Angabe der Quellen kenntlich zu machen.“

Quelle: § 16 Abs. 5 APSO-TI-BM bzw. § 15 Abs. 6 APSO-INGI

Erklärung zur selbstständigen Bearbeitung der Arbeit

Hiermit versichere ich,

Name: ____________________

Vorname: ____________________

dass ich die vorliegende Masterarbeit – bzw. bei einer Gruppenarbeit die entsprechend gekennzeichneten Teile der Arbeit – mit dem Thema:

Measuring and Quantifying Consolidation Trends in the Internet Core

ohne fremde Hilfe selbständig verfasst und nur die angegebenen Quellen und Hilfsmittel benutzt habe. Wörtlich oder dem Sinn nach aus anderen Werken entnommene Stellen sind unter Angabe der Quellen kenntlich gemacht.

[redacted]

Ort	Datum	Unterschrift im Original