The Internet Geographical PoP Level Maps

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Abstract. Inferring the Internet PoP level maps is gaining interest due to its importance to many areas, e.g., for tracking the Internet evolution and studying its properties. We introduce DIMES's Internet PoP-level connectivity maps, annotated with geographical information and created using a structural approach to automatically generate large scale PoP level maps. The generated PoP level maps dataset is presented and a detailed analysis of a map is provided. PoP level maps have a wide range of applications, introduced in this work. We survey some of these applications and propose further opportunities for future research.

1 Introduction

The Internet is one of the most interesting networks to study. It is a man-made network, used by billions of people in their everyday life. The structure of this network is of a special interest, as every service provider applies his own policies and design rules to his portion of the network, called an Autonomous System (AS). The AS level is most commonly used to draw Internet maps, as it is relatively small (tens of thousands of ASes) and therefore relatively easy to handle. An AS may represent a local ISP as well as a large company spanning across continents. The connectivity and growth of this network is driven by a large number of factors: from business agreements between service providers, local population growth, technological trends and more. Looking at the Internet topology from the AS level is thus coarse: it does not indicate the size of the AS nor local aspects and does not provide any geographic notion. IP and Router level maps represent the other extreme: they contain too many details to suit practical purposes, and the large number of entities makes them very hard to handle.

Service providers tend to place multiple routers and other networking equipment in a single location called a Point of Presence (PoP). The equipment placed in a PoP is used to serve a certain area and to connect it to higher hierarchies within the AS. A PoP is owned by one AS, however several PoPs owned by different vendors many times reside within the same campus, that provides them the infrastructure they need. For studying the Internet evolution and for many other tasks, PoP level maps give a better level of aggregation than router level maps with a minimal loss of information. PoP level graphs allow to examine the size of each AS network by the number of physical co-locations and their connectivity instead of by the number of its routers and IP links, which is an important contribution. The points of presence are not only counted, but also provided with a geographical location and information about the size of the PoP. Using PoP level graphs one can detect important nodes of the network, understand network dynamics, examine types of relationships between service providers as well as routing policies and more.

While aggregating IPs to AS-level is a fairly simple task, PoP level maps are more difficult to create. Andersen *et al.* [2] used BGP messages for clustering IPs and validated their PoP extraction based on DNS. Rocketfuel's [16] generated PoP maps using tracers and DNS names. The iPlane project also generates PoP level maps and their connectivity [9] by first clustering IP interfaces into routers and then clustering routers into PoPs. They did so by estimating the length of the reverse path, with the assumption that reverse path length of routers in the same PoP will be similar.

Assigning a location to an IP address, let alone a PoP, is a complicated task. The most common way to do so is using a geolocation service. Geolocation services use DNS resolution [16], hand-labeled hostnames [1], user's information provided by partners [3], and more. Geolocation services are not highly accurate, as we showed in [14]. Thus a measurement based approach was suggested to approximate the geographical distance of network hosts [10, 7, 8].

This work presents PoP level connectivity maps generation and analysis, based on an algorithm described in [5]. The traceroute measurements used in this work were generated by DIMES, a highly-distributed Internet measurements infrastructure [13]. DIMES achieves high distribution of vantage points by employing a community based distribution methodology that uses Internet users' PCs for measurements.

2 PoP Level Maps Construction

A PoP is a group of routers which belong to a single AS and are physically located at the same building or campus. In most cases [11, 6] the PoP consists of two or more backbone/core routers and a number of client/access routers. The client/access routers are connected redundantly to more than one core router, while core routers are connected to the core network of the ISP. The algorithm we use for PoP extraction looks for bi-partite subgraphs with delay constraints in the IP interface graph of an AS; no aliasing to routers is needed [5]. The bi-partites serve as cores of the PoPs and are extended with other nearby interfaces.

To identify the geographical location of a PoP, we use the geographic location of each of its IPs. As all the PoP IP addresses should be located within the same campus, the location confidence of a PoP is significantly higher than the confidence that can be gained from locating each of its IP addresses separately. The location of an IP address is obtained from numerous geolocation databases, and the PoP's location is set to the median of all PoP's IP locations. Every PoP location is assigned a range of convergence, representing the expected location error range based on the information received from the geolocation databases.

Further discussion of the extraction and geolocation algorithms is provided in our previous works [5, 14].

The connectivity between PoPs is an important part of PoP level maps [15]. We generate PoPs connectivity graph using unidirectional links. We define a link L_{SD} as a the aggregation of all unidirectional edges originating from an IP address included in a PoP S and arriving to an IP address included in a PoP D. Each of the IP level links has an estimate of the median delay measured along it, with the median calculated on the minimal delay of a basic DIMES operation. A basic DIMES operation is comprised of four consecutive measurements and all measured values are roundtrip delays [5].

3 Data Set

The collected dataset for PoP level maps is taken from DIMES [4]. We use all traceroute measurements taken during weeks 42 and 43 of 2010, totaling 33 million, which is an average of 2.35 million measurements a day. The measurements were collected from over 1308 vantage points, which are located in 49 countries around the world.

The 33 million measurements produced 9.1 million distinct IP level edges (no IP level aliasing was performed). Out of these, $258K$ edges had less than the median delay threshold, and had sufficient number of measurements to be considered by the PoP extraction algorithm. A total of 4098 PoPs where discovered, containing 67422 IP addresses. The geographic spread of these PoPs around the world is shown on Figure 1 (left). Although the number of discovered PoPs is not large, as the algorithm currently tends to discover mainly large PoPs while missing many access PoPs, the large number of IP addresses and the spread around the world allow a large scale and meaningful PoP level connectivity evaluation.

The PoP level connectivity map generated from the data set [15] contains 86760 links, which are an aggregation of 1.65 million edges. Out of the 4098 discovered PoPs in week 42, 2010, 4091 have at least one PoP level link. 2405 PoPs have outgoing links, and 4073 PoPs have incoming links. Out of those, 18 PoPs have only outgoing links and 1686 have only incoming links. Note that a PoP without any PoP level links, or a PoP with only incoming or outgoing links still have additional IP-level connecting edges. As the full map is too detailed to display, a partial map is shown in Figure 1 (right), demonstrating the connectivity between 430 ASes on PoP level.

Almost all the IP edges that are aggregated into links are unidirectional: 99.2%. This is a characteristic of active measurements: the number of vantage points is limited in number and location, thus most of the edges can be measured only one way. However, at PoP links level, 6.5% of the links are bi-directional: eight times more than the bi-directional edges. This demonstrates one of the PoPs strengths, as it provides a more comprehensive view of the networks' connectivity without additional resources. The average number of edges within a unidirectional link is 7.5, and the average number of edges within a bidirectional link is 44.7. This is not surprising, as it is likely that most of the bidirectional

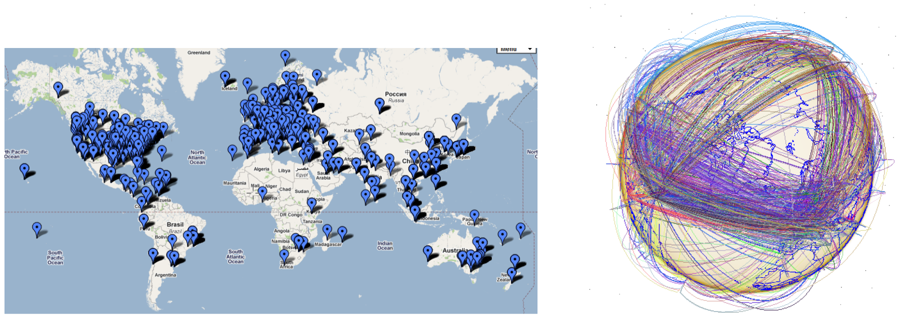

Fig. 1. An Internet PoP Level Location Map (left) and a Partial Connectivity Map (right) - Week 42, 2010

links will connect major PoPs within the Internet's core and thus be easily detected.

An additional view of edges aggregation into links is given by Figure 3. The X-axis shows the number of edges aggregated into a link, while the Y-Axis is the number of PoP-level links. The graph shows a Zipf's law relation between the two, as 82.6% of the links aggregate ten edges or less, and less than 2% aggregate 100 edges or more. The large number of edges per link is explained by the fact that a measured edge is not a point-to-point physical connection: Take two routers, A & B, connected by a single fiber; If one of the routers has 48 ports, and we measure through each one of them, we detect 48 edges between the two routers (incoming port i on router A and the single connected incoming port of router B). We find that the number of links per PoP also behaves according to Zipf's law.

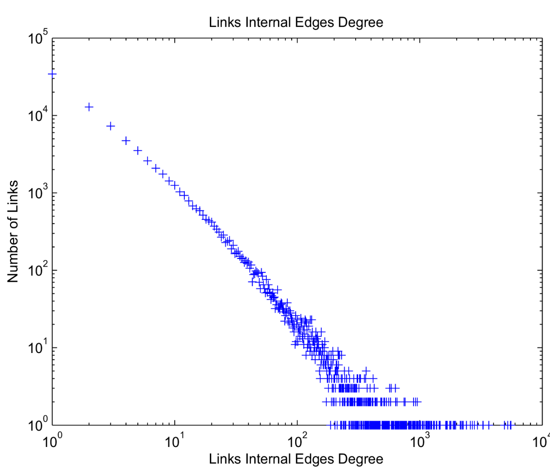

Fig. 2. Number of Edges within a Link vs. Number of PoP Level Links

Looking at the number of links by destination PoP, 46% of the PoPs are connected by 10 links or less and the average number of links per PoP is 21. Most of the PoPs are connected to PoPs outside their AS: 71.5% of the source PoPs and 99% of the destination PoPs. Interestingly, only 62.2% of the destination PoPs have links within their AS, which indicates that many PoPs are detected only thanks to inter-AS measurements, and thus that the detected PoPs are probably large ones and not small local access PoPs. We believe this is also the reason why few destination PoPs have a small number of links: PoPs with a large number of links to other ASes are more likely to be discovered by our algorithm.

4 Applications of PoP Level Maps

PoP level maps can be leveraged for a large number of research interests. The most obvious area is the study of Internet network topology, as it represents a level of the network that was barely considered in the past. Tying a geographic location and a size to a PoP, PoP level maps offer an opportunity to investigate service providers' actual presence and influence on the network. An additional benefit is the ability to study types of relationships (ToR) between service provider on different locations around the globe.

An additional aspect of PoP level maps relates to cyber security research. As shown by Schneider *et al.*[12], DIMES's PoP level map can be leveraged to study the robustness of a network. The Map can also be used for several Geolocation purposes, such as improving the accuracy of Geolocation databases [14] and for distance estimation.

Another application of PoP level maps is the study of Internet's evolution. By adding the maps as a new indicator, on top of economic, geographic and demographic parameters, a better understanding of the network's growth can be achieved.

5 Conclusion and Future Work

We presented here DIMES's PoP-level connectivity maps. The PoP level connectivity maps provide a new look at the Internet's topology with a better level of aggregation than router level maps and more information than AS level maps. The maps provide network topology information, annotated with geographic location and link delay, thus providing a large-scale look on the Internet using a light data set.

The PoP level links maps are now available through the DIMES website [4] for download, and can be useful to researchers in the fields of complex networks, Internet topology, Geolocation, and more.

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