On the Incompleteness of the AS-level Graph: a Novel Methodology for BGP Route Collector Placement

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ABSTRACT

In the last decade many studies have used the Internet AS-level topology to perform several analyses, from discovering its graph properties to assessing its impact on the effectiveness of worm-containment strategies. Yet, the BGP data typically used to reveal the topologies are far from being complete. Our contribution is three-fold. Firstly, we analyse BGP data currently gathered by RouteViews, RIS and PCH route collectors, and investigate the reasons for its incompleteness. We found that large areas of the Internet are not properly captured due to the geographic placement of the current route collector feeders and due to BGP filters, such as BGP export policies and BGP decision processes. Secondly, we propose a methodology to select the optimal number of ASes that should join a route collector project to obtain a view of the Internet AS level topology closer to reality. We applied this methodology to the global AS-level topology and to five regional AS-level topologies, highlighting that the particular characteristics of the Internet at a regional level cannot be ignored during this process. Thirdly, we provide a characterization of the ASes that we found to be part of at least one optimal solution set. By analysing these ASes we found that the current route collector infrastructure is rarely connected to them, highlighting that much more effort should be made in devising a route collector infrastructure that ideally would be able to capture a complete view of the Internet.

IMC'12, November 14–16, 2012, Boston, Massachusetts, USA.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Network topology*; C.2.2 [**Computer-Communication Networks**]: Network Protocols—*Routing protocols*; C.2.3 [**Computer-Communication Networks**]: Network Operations—*Network monitoring*

Keywords

Autonomous Systems, BGP, incompleteness, Internet, measurement, topology

1. INTRODUCTION

During the last few years, the Internet has become more and more part of the everyday life of billions of people. Thanks to the Internet, it is now possible to do things that just a couple of decades ago would have been impossible, such as sending mail to the other side of the world in less than a second, checking one's bank account from home and retrieving any kind of information at any time with just a couple of clicks. Despite its increasing pervasiveness, very little is known about the real structure of the Internet and what happens to data once they have left the home router. This is a major issue, since it means that is impossible to detect any structural problem or Achilles' heels until an outage occurs.

To address this problem, several researchers started to analyse the Internet in a topological perspective in the hope of revealing any potential weaknesses at any level. The AS-level topology represents one of the most interesting perspectives. In this topology each node is represented by an AS that represents an organization (or part of it) that manages a certain amount of IP subnets, while the edges are represented by BGP connections between pairs of ASes. The most common approach is to exploit data gathered by BGP route collectors and/or Traceroute monitors and, then, to extract AS-level information about the Internet. Although several works have highlighted problems in using traceroute data to infer AS-level information – such as aliasing [1], biasing [2] and router-to-AS mapping [3, 4] – only a few have investigated the limitations of the BGP approach, and in doing so have mainly focused on the incompleteness of data gathered via BGP route collectors.

Our contribution is threefold. Firstly, we analyse the BGP data currently gathered by RouteViews, RIS and PCH route collectors, highlighting and explaining the causes of their incompleteness. We show that the current view of the Internet is extremely *narrow* – due to the extremely low number of ASes that are actively feeding the route collectors – and *biased* – due to the nature of the feeding ASes, which is mostly managed by worldwide ISPs. This top-down view does not allow the route collector infrastructure to discover a large set of p2p connections that may be established among ASes that are part of the lower part of the Internet hierarchy, as already highlighted in [5, 6, 7, 8]. In addition to this classic analysis we developed an innovative metric, named *p2c-distance*, which takes into account the presence of BGP decision processes and BGP export policies crossed by BGP UPDATE messages before reaching a route collector. This then provides a better understanding of the level of completeness of the data gathered. Unlike other approaches, we are thus able to analyse and quantify the level of incompleteness of BGP data by relying only on the route collector infrastructure and without exploiting any private data.

Secondly, in order to overcome the large amount of incompleteness highlighted, we select the minimum number of ASes that should provide full routing information to the route collector infrastructure. To do that we formulate a Minimum Set Cover (MSC) problem that exploits the inter-AS p2c-distance within a generic AS-level topology. Even though the MSC has been proved to be NP-complete [9], our methodology exploits the graph properties extracted the MSC solution. We first reduce the size of the graph in which the solution has to be searched by *a*) leveraging on the extreme low densities of the covering matrices, *b*) applying classic mathematical reduction techniques to these matrices and *c*) using a brute force approach on the remaining uncovered components of the original covering matrix.

Thirdly, we analyse and compare the solutions obtained by applying this methodology on the global topology and five regional AS-level topologies of the Internet, highlighting the impact that the geographical peculiarities of the Internet have on the selection of the optimal set of ASes. As already highlighted in [10], geography plays an important role in routing decisions inside worldwide ASes and, consequently, also on the establishment of local economic inter-AS relationships and on the related BGP export policies. Typically the routing decisions are carried out at a continental level. Thus, to have full coverage of a given world-wide AS and its neighbors, multiple BGP connections with the route collectors need to be set up, one for each continent where the ASes are located. Furthermore, we also carry out an analysis of the current status of the route collector regional infrastructure by identifying how many ASes in the optimal solution are currently connected to them, by working out how many new ASes should be connected in each region, and by providing their typical characteristics. We found that some parts of the world, such as Africa, completely hide their p2p connectivity from the current route collector infrastructure. To the best of our knowledge, this is the first work to provide a constructive and systematic approach to enhance the coverage of the current route collectors from a geographical perspective, by identifying the ASes that should feed them in every continent. We also provide a ranked list of ASes, which highlights those ASes that should be given more priority in joining a route collector project.

The paper is organized as follows. Section 2 describes briefly the state of the art about the studies on BGP data and its incompleteness. An analysis of the current view of the route collector infrastructure is given in Section 3. In Section 4 we describe the proposed monitor placement methodology and we define the p2c-distance. Section 5 analyses the results of the methodology on the global topology and on the five regional topologies. Section 6 concludes the paper.

2. RELATED WORK

Some issues about the extent of the incompleteness of BGP data were initially raised in [11], but only several years later was the first attempt to quantify such incompleteness performed. In [12], the authors compared the topology inferred from BGP data and the topology inferred from data contained in the Internet Routing Registries (IRRs), highlighting that about 40% of connections were missing in BGP-derived topologies. This topic was then to some extent neglected, but was recently re-evaluated in [13] and [5]. In [13] there is an analysis of the BGP data obtained from each AS participating in RouteViews and RIS, and their contribution was found to be heavily redundant. A completely different approach was applied in [5]. The AS-level topology inferred via BGP data was compared with a ground truth made up of proprietary router configurations of two major ISPs (a Tier-1 and a Tier-2 ISP), of two research networks (Abilene and GEANT) and several content providers. Their results were significant, but they are not reproducible and are heavily biased by the ground truth selected. Nevertheless, this work can still be considered a milestone in the analysis of the incompleteness of BGP data. Its most relevant result was that economic relationships established between ASes strongly affect the information that can be revealed by each monitor. The main rationale behind this lies in the economic-driven nature of the inter-domain routing introduced in [14], where the most common types of inter-AS economic relationships – provider-to-customer (p2c), customer-to-provider (c2p), peer-to-peer (p2p) and sibling-to-sibling (s2s) – are identified and where the related BGP export policy are described. In particular, an AS announces to its customers and siblings the routes obtained by its peers, customers, providers and siblings, while it announces to its providers and peers only the routes related to its customers (see Fig. 1). This means that p2p connections are hidden from any of the providers or peers of a given AS. Based on the above, in [5] was claimed that most of the connections that are missing are p2p connections, and that monitors should be placed in the periphery of the Internet to discover them. A similar conclusion about the invisibility of p2p connections was also drawn in [6], which proposed a tool based on traceroute probes that is able to discover missing p2p connections established on Internet Exchange Points (IXPs).

Despite this strong evidence of the incompleteness of BGP data gathered by route collectors, only a few works have addressed the issue of how new BGP monitors should be located to minimize this lack of information. In [15], the authors extended a model based on techniques developed in biological research for estimating the size of populations to work on the Internet AS graph. Their results showed that thousands of connections are missing, and the authors estimated that 700 route monitors would be able to see almost the totality of the connections. However, their heuristic only marginally took into account the existence of inter-AS economic relationships, thus the optimal number of route monitors found was seriously underestimated, as will be highlighted in Section 5.

3. THE DARK SIDE OF BGP-BASED MEASUREMENTS

Without any doubt, BGP data is the best data to infer the Internet AS-level topology, since the AS-level information is directly contained in the *AS Path* BGP attribute and no further heuristics have to be applied. BGP route collectors receive BGP routing information from cooperating ASes, hereafter *BGP feeders*, to which they establish a BGP session. Thanks to these routing data it is possible to re-create the dynamics of the inter-domain routing as seen from BGP feeders. In this section we analyse the incompleteness of BGP data from a different perspective. First, we outline the current route collector projects. Then, we focus on the analysis of data gathered by these projects and on the contribution of each of their BGP feeders. Finally, we investigate the impact of the geographical distribution of route collectors has on the ability to discover regional Internet properties.

3.1 BGP Route Collector Projects

There are three main projects that collect BGP data and make it publicly available on the web: RouteViews, RIS and PCH. RouteViews was conceived at the University of Oregon [16] as a tool for Internet operators to obtain real-time information on the global routing system from the perspectives of several different backbones and locations. Since its birth in 1997, this project has provided an invaluable amount of BGP data through its route collectors. RIS (Routing Information System) was developed by Réseaux IP Européens (RIPE), the European Internet Registry, which collects and stores Internet routing data from several locations around the globe deployed on the largest IXPs [17]. It offers also several tools that allow the Internet community to easily read and use BGP data. PCH (Packet Clearing House) [18] is a non-profit research institute that supports operations and analysis in the areas of Internet traffic exchange, routing economics and global network development. Since July 2010, PCH has been making BGP data available on its website, collected by several route collectors deployed on distinct IXPs. We gathered and analysed the BGP routing information provided by these three projects during February 2012. In this time interval, the number of active route collectors which provided BGP data in MRT format (RFC 6397) were 10 for RouteViews, 13 for RIS and 51 for PCH. Table 1 details the number of BGP feeders per route collector and their geographical location.

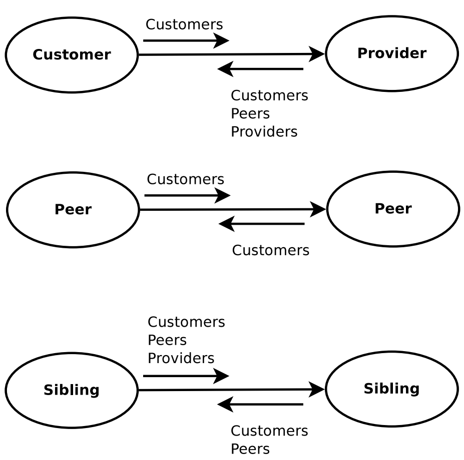


Figure 1: Inter-AS economic relationships

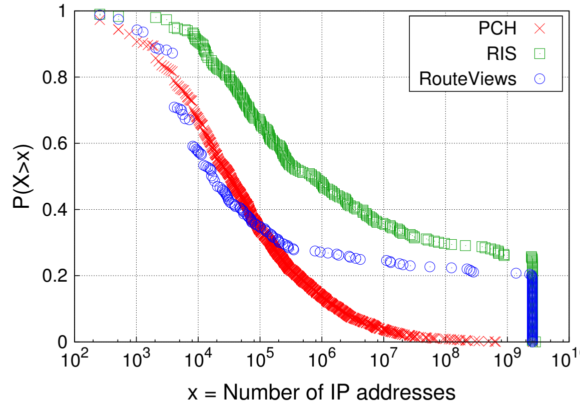


Figure 2: CCDF of the amount of IPv4 space obtained by each project

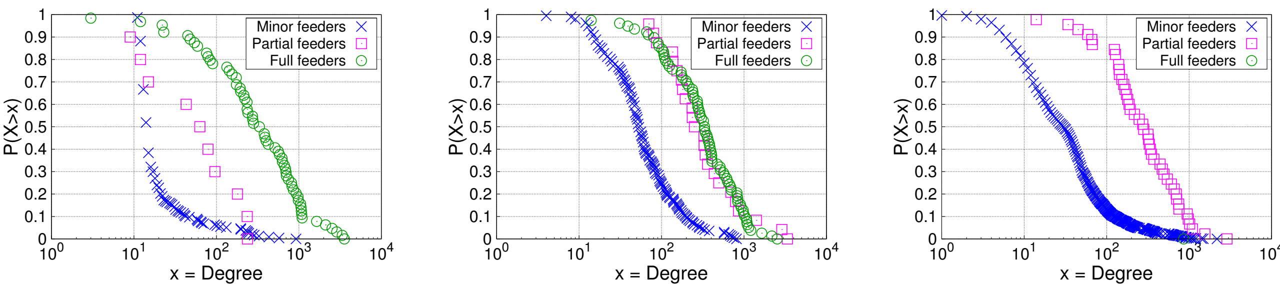
3.2 BGP feeder contribution analysis

Despite the well-known aims of these route collector projects, several of their BGP feeders do not provide any relevant contribution [8]. To better quantify the total contribution of BGP feeders, we subdivide them on the basis of the amount of IPv4 space[1] that each of them advertised to the route collectors (Table 1): *minor feeders* announce an IPv4 space smaller than that of a single /8 subnet, *full feeders* announce an IPv4 space closer to the full Internet IPv4 space currently advertised[2] (more than two billion IP addresses), while *partial feeders* include those ASes in between. Following this subdivision, the number of full feeders is 65 for RouteViews, 78 for RIS and 1 for PCH. Together they make up a set of 120 feeders, i.e. 5.99% of the total number of feeders. Figure 2 shows the amount of non overlapping IPv4 addresses announced from the BGP feeders of each project. In RouteViews and RIS projects, only about one in four/five feeders announce the full routing table (represented by the vertical tail of the CCDFs) to the route collectors, while in PCH the percentage is much lower.

A feature that can be used to gain a deeper insight into

[1] We compute the IPv4 space considering only *not overlapping* subnets, i.e. those subnets that are not included in any other subnet

[2] More information about the current IPv4 space advertised can be found at http://www.potaroo.net/tools/ipv4



(a) RouteViews (b) RIS (c) PCH

Figure 3: CCDF of the node degree of ASes connected to route collectors

these different classes of BGP feeders is their node degree distribution (Fig. 3), which is computed on the union of the AS-level topologies inferred from RouteViews, RIS and PCH datasets. In each project the full feeder set is mainly composed of ASes that have developed a large number of BGP connections, which is a typical behavior of transit ISPs. To confirm this, we analysed the nature of these ASes by browsing their websites and parsing their entries in the IRRs. We found that 10 out of 13 Tier-1 ASes[3] are well-known national/international ISPs.

Since the vast majority of full feeders are large ISPs, the view of the Internet (at the AS-level) extracted from these projects is likely to represent more the Internet viewed by some of the most important ISPs in the world rather than the real Internet. A view of the Internet from the top of the AS hierarchy is not able to discover a large number of connections. In fact, due to BGP export policies, a route collector connected with ASes that are part of the top of the hierarchy is not able to reveal all the p2p connections that are established at the lower levels. On the other hand, the lower in the hierarchy the BGP feeder is located, the greater the chance to gathering information about an AS path involving a previously hidden p2p connection. Consider for example Fig. 4. In this case, if the route collector R is connected to AS E at the top of the hierarchy, it cannot reveal either the p2p connection between A and B, or the p2p connection between C and D. On the other hand, if R is connected to AS A, it can reveal the p2p connection between A and B, but not between C and D. It is fundamental that the route collector establishes a c2p relationship with its feeders. Otherwise, even if the route collector is connected to A, the connection (A, B) will not be revealed. A real example of the importance of obtaining the full routing table from BGP feeders located in the lowest part of the Internet hierarchy is represented by PCH. This data source is potentially extremely useful for discovering hidden AS connections, since its route collectors are deployed on 51 different IXPs and connected to 1,697 ASes, about three times the total number of BGP feeders of RIS and RouteViews. In addition, many of its BGP feeders have small node degree value (Fig. 3), which is a rough indication of their location at the bottom of the Internet hierarchy.

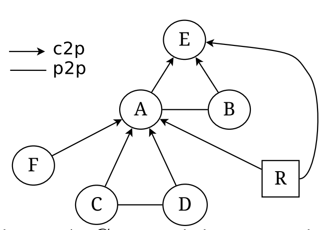


Figure 4: Connectivity scenario I

Nevertheless, as shown in Table 2, the number of AS connections detected by BGP data gathered by PCH and not discovered by RouteViews and RIS is extremely low, since 84,037 connection out of the total 85,674 discovered connections are already revealed by RouteViews and/or RIS. This happens because PCH mainly establishes p2p connections with its BGP feeders, i.e. its route collectors obtain only the routes announced by the customers of its BGP feeders. Consequently, it is likely that almost every connection found by PCH represents a p2c (c2p) economic agreement. Thus the issue of p2p connection discovery has not been solved even though it currently represents the largest set of hidden connections [6, 7, 19], greatly limiting the topology discovery potentiality of its route collectors.

A deeper insight into the amount of information provided by each BGP feeder can be found by analysing the difference between the direct node degree and the inner node degree

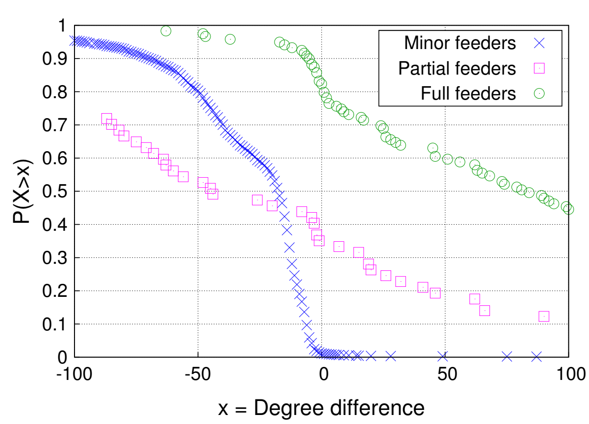


Figure 5: CCDF of the degree difference of BGP feeders

[3]A full list of ASes part of the Tier-1 set can be found at http://en.wikipedia.org/wiki/Tier_1_network

Route collector (Country)	*total feeders*	*# of feeders*		
		full	partial	minor
RouteViews				
route-views2 (US)	33	30	3	0
route-views4 (US)	15	13	2	0
route-views6 (US)	12	0	0	12
route-views.eqix (US)	14	10	0	4
route-views.isc (US)	13	10	0	3
route-views.kixp (KE)	1	0	0	1
route-views.linx (UK)	23	18	1	4
route-views.saopaulo (BR)	231	4	2	225
route-views.sydney (AU)	8	4	4	0
route-views.wide (JP)	4	2	0	2
RIS				
rrc00 (NL)	19	17	1	1
rrc01 (UK)	70	10	11	49
rrc03 (NL)	71	5	5	61
rrc04 (CH)	12	5	1	6
rrc05 (AT)	40	8	2	30
rrc07 (SE)	14	2	3	9
rrc10 (IT)	17	3	5	9
rrc11 (US)	26	8	3	15
rrc12 (DE)	45	11	4	30
rrc13 (RU)	19	9	1	9
rrc14 (US)	16	5	3	8
rrc15 (BR)	12	6	3	3
rrc16 (US)	6	1	1	4
PCH				
akl.pch.net (NZ)	7	0	0	7
ams.pch.net (NL)	390	0	17	373
atl.pch.net (US)	50	0	4	46
ber.pch.net (DE)	27	0	1	26
bos.pch.net (US)	2	0	0	2
bru.pch.net (BE)	5	0	0	5
bur.pch.net (US)	43	0	9	34
cai.pch.net (EG)	2	0	0	2
cdg.pch.net (FR)	120	0	1	119
chix.pch.net (US)	2	0	1	1
cpt.pch.net (ZA)	8	0	0	8
dac.pch.net (BD)	10	0	0	10
dub.pch.net (IE)	36	0	0	36
equinix-paris.pch.net (FR)	103	0	1	102
eze.pch.net (AR)	1	0	0	1
fra.pch.net (DE)	355	0	14	341
hkg.pch.net (HK)	34	0	4	30
iad.pch.net (US)	104	0	15	89
icn.pch.net (KR)	2	0	1	1
jpix.pch.net (JP)	33	0	2	31
ktm.pch.net (NP)	16	0	0	16
lax.pch.net (US)	24	0	6	18
lga.pch.net (US)	44	0	7	37
lhr.pch.net (UK)	330	0	16	314
lonap.pch.net (UK)	80	0	1	79
mia.pch.net (US)	44	0	6	38
mnl.pch.net (PH)	4	0	0	4
mpm.pch.net (MZ)	6	0	0	6
muc.pch.net (DE)	12	0	2	10
nbo.pch.net (KE)	2	0	0	2
nl-ix.pch.net (NL)	72	0	3	69
nrt.pch.net (JP)	9	0	2	7
nyiix.pch.net (US)	82	0	9	73
ord.pch.net (US)	45	0	6	39
paix-sea.pch.net (US)	12	0	4	8
pao.pch.net (US)	69	1	14	54
per.pch.net (AU)	7	0	0	7
sea.pch.net (US)	77	0	6	71
sfinx.pch.net (FR)	29	0	2	27
sgw.pch.net (SG)	64	0	7	57
sin.pch.net (SG)	16	0	0	16
sna.pch.net (US)	131	0	8	123
syd.pch.net (AU)	44	0	0	44
tie-ny.pch.net (US)	26	0	2	24
trn.pch.net (IT)	44	0	1	43
vie.pch.net (AT)	87	0	2	85
waw.pch.net (PL)	192	0	1	191
wlg.pch.net (NZ)	5	0	0	5
yow.pch.net (CA)	1	0	0	1
yyz.pch.net (CA)	33	0	2	31
zrh.pch.net (CH)	105	0	1	104

Table 1: February 2012 route collector status

(Fig. 5). The *direct* node degree of a BGP feeder X is defined as the cardinality of the set of its neighbors that are discovered using only BGP data directly announced by X to a route collector, and the *inner* node degree of X is defined as the cardinality of the set of its neighbors that are discovered using BGP data announced by every BGP feeder but X. A similar approach was proposed in [20], but with a different purpose.

It is thus possible to differentiate between two different classes of behavior of BGP feeders: *a*) ASes that announce just a partial view of the Internet (degree difference < 0), like those ASes that consider the route collectors as peers and not as customers, and *b*) ASes that contribute with connections not contained in any AS path announced by other BGP feeders (degree difference > 0), such as p2p and p2c connections that are hidden from the other BGP feeders due to the effect of BGP export policies crossed during the propagation of the routing information.

The first class is typical of minor feeders, whose connectivity is mostly discovered via other feeders (Fig. 5). On the other hand, the second class is typical of full feeders, that typically introduce previously undiscovered AS connections involving them.

However, some full feeders partially hide some of their interconnectivity despite advertising their full routing table to a route collector project. This phenomenon has been recorded in about 20% of the full feeders (see negative values of degree difference in Fig. 5) and is caused by the BGP decision process on the feeder side. Depending on the policies established among ASes and on technical decisions, some direct connections may not be announced to the route collector. However, for the same economic and technical reasons it is possible that the same direct connections hidden from the route collector are announced to other neighbors, propagated on the Internet, and finally detected by the route collector from another feeder as a side effect. Some other slight exceptions are related to minor and partial feeders with a positive degree difference (less than 5%). These feeders are likely to be located in the bottom part of the Internet hierarchy and some of their p2c connections may result as hidden to the route collector infrastructure because of the cross effect of their multi-homed nature and of multiple BGP decision process crossed by UPDATE messages before reaching the route collector infrastructure.

This last phenomenon highlights that the presence of multiple BGP decision processes along the AS path may limit the completeness of AS-level topology collected, since each BGP AS border router selects and announces only the best route per-destination (RFC 4271) to their neighbors. In summary, the information that a BGP feeder announces to the route collector is the result of its BGP decision process which, in turn, is fed only with routes that are the result of the BGP decision processes of its neighboring ASes, and so on. Each BGP decision process, from an AS-level measurement perspective, is a route filter, which can potentially reduce the AS-level connectivity information received from each route collector. As a consequence, the higher the dis-

	RouteViews	*RIS*	*PCH*
# of nodes	41,062	41,085	40,855
# of edges	112,854	134,903	85,674
# of common edges	84,037		

Table 2: Topology characteristics

Region	*# BGP feeders*	*# full feeders*
Africa	10	0
Asia-Pacific	159	15
Europe	1,279	68
Latin America	13	6
North America	444	42
World	2,004	120

Table 3: Geolocation of BGP feeders

tance of an AS from the BGP route collectors, the higher the number of BGP decision processes crossed and, thus, the higher the probability that one or more of them will filter out some AS connections.

3.3 Geographical coverage

The incompleteness of BGP data is even stronger if analysed from a geographical perspective. Table 3 details the total number of BGP feeders as well as the number of them that supply the full routing table to any of route collector projects. To perform this analysis we geolocated the IP address of each BGP feeder using the Maxmind GeoIPLite database [21] and considering the world being subdivided into five macro-regions: Africa, Asia-Pacific (i.e. Asia and Oceania), Europe, Latin America (the Caribbean, Central America, Mexico and South America) and North America. Table 3 highlights that most full feeders are located either in Europe or in North America. Interestingly, in Africa no full feeder is found even though Africa hosts one route collector of RouteViews and four of PCH. This means that every inference about the African part of the Internet is mostly obtained through views located in different regions. Thus, some relevant characteristics of the African part of Internet may be hidden from the current route collectors. This is not only a problem regarding Africa, in fact the number of feeders in other regions is low as well.

4. A NOVEL METHODOLOGY TO DEAL WITH BGP DATA INCOMPLETENESS

Given the large amount of incompleteness highlighted in Section 3, the first step to infer the real Internet AS-level topology and its properties is to introduce a larger number of new BGP feeders that announce their full routing tables. To quote Sir Arthur Conan Doyle, *"It is a capital mistake to theorize before you have all the evidence. It biases the judgment"*. One of the biggest obstacles is the vast number of ASes that make up the Internet. Obtaining routing information from each of them would require the participation of thousands administrators in a project that may not be appealing for many of them.

Given this situation, we focus on those ASes that play a major role in Internet connectivity, i.e. those ASes that offer IP transit to other ASes. Although there are far fewer of them than the total number of ASes, these ASes contribute

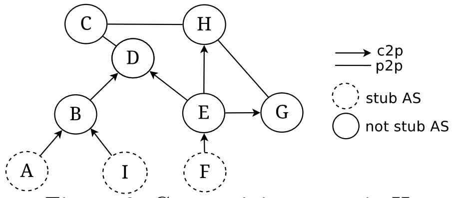


Figure 6: Connectivity scenario II

substantially to provide Internet connectivity. In fact, both world-wide ISPs and small/medium ISPs are part of this set of ASes. This latter class of ASes is known to be the cause of the largest number of p2p connections [22] that are currently hidden from the route collector infrastructure.

In this section, we propose a methodology to identify the minimal set of BGP feeders that would be needed to gather as much BGP data as possible *about* the ASes whose connectivity plays a major role in their economic market, thus minimizing the number of hidden connections present in the core of the Internet and, at the same time, minimizing the impact of BGP filters, such as BGP export policies and BGP decision processes.

4.1 A new metric: p2c distance

As already highlighted, a major role in filtering is due to inter-AS economic relationships because of their influence on the amount of routing information that each AS announces to each other. Given the BGP export policies related to each economic relationship [14], a necessary (but not sufficient) condition for a route collector to reveal the full connectivity of a given AS is that there exists at least one AS path that is made up exclusively of p2c connections from that AS to the route collector. This is because only customers in a p2c connection are able to obtain routes towards all Internet destinations. In order to limit the filtering effects of BGP decision processes, it is preferable that routing information arrives at a route collector having crossed the lowest number of p2c connections as possible.

On the basis of the two conditions hypothesized above, we define a new metric that is able to capture the level of completeness of data gathered by the current set of route collectors. The *p2c-distance* of one AS X from another AS Y is defined as the minimum number of consecutive p2c connections that connect X to Y in the considered economic topology or, likewise, the minimum number of consecutive c2p connections that connect Y to X. This metric easily quantifies the distance and the amount of transit connections crossed by any BGP UPDATE message to reach a route collector, and can be exploited to reveal which part of the Internet is well-monitored and which part is still a dark zone. Note that this metric still relies on an inference made on the current Internet AS-level topology, but the p2c and c2p connections have been proved to be extremely accurate [5, 6, 7, 8].

To better understand how this metric works, consider the connectivity scenario depicted in Fig. 4. In this example, the route collector R has a p2c-distance of 1 from AS A and E, while the p2c-distance from B, C, D and F is not defined. This means that R has the possibility to reveal every p2p connection established by A, B and E. On the other hand, it also means that R is not able to reveal the p2p connectivity of C, D and F in any way, thus R will not reveal the connection (C, D) in any AS path. Nevertheless, R can discover the p2c (c2p) connectivity of each AS of the scenario.

4.2 BGP feeder selection

Given the definition of p2c-distance, a complete view of the Internet can only be obtained by connecting a route collector to each stub AS, as already concluded in [5]. Stub ASes are ASes typically managed by local access providers (which provide connectivity to end users but not to other

ASes) and organizations that do not have the Internet transit as part of their core business (e.g. banks and car manufacturers), and appear in BGP data as the originating element, i.e. the right-most element, in every AS path that involves them. Due to the nature of their related organizations, these ASes tend to be customers in the economic relationships established with other ASes, representing a perfect starting point to minimize the p2c-distance of all ASes that make up the Internet. However, since p2c connections are already discovered by route collectors connected to the top of the hierarchy [5], most BGP data collected from a hypothetical route collector infrastructure connected to each of them would be redundant. Moreover, since it is not possible to infer a priori which stub AS is actually interested in establishing p2p connections, it is impossible to reduce the number of route collectors required to obtain full Internet AS-level connectivity. This means that, based on February 2012 BGP data, we need to have a connection to 33,845 ASes out of 41,127. This makes this approach practically unfeasible. We believe that a good trade-off between the possibility to discover hidden p2p connections and the feasibility of obtaining such data is represented by ASes that are actually interested in deploying p2p connections to improve the quality of their services, i.e. *non-stub ASes* [22]. The lack of interest of stub ASes in establishing p2p connections is highlighted by the fact that only 7% of them participate in at least one IXP[4], where ASes typically interconnect with settlement-free p2p connections to reduce the amount of their traffic directed to their providers (see [6, 19] and [24] for more details on IXPs).

Specifically, we aim to select new BGP feeders such that each non-stub AS has a finite and bounded p2c distance from the route collector infrastructure to minimize the effects of BGP filters and, consequently, increasing the possibility to reveal the hidden p2p connectivity of the actual core of the Internet. As will be shown later on, stub ASes will play a key role in the solution of the problem, even though we are not actually focusing on their connectivity.

4.2.1 Problem description

We model the problem of finding the optimal number of BGP feeders as an MSC problem which can be formulated as follows:

$$\text{Minimize} \quad \left(\sum_{AS_i \in \mathcal{U}} x_{AS_i} \right) \tag{1}$$

subject to

$$\sum_{AS_i : n \in S^{(d)}_{AS_i}} x_{AS_i} \geq 1 \qquad \forall n \in \mathcal{N} \tag{2}$$

$$x_{AS_i} \in \{0, 1\}, \qquad \forall AS_i \in \mathcal{U} \tag{3}$$

where $\mathcal{U} = \{AS_1, AS_2, \ldots, AS_n\}$ is the set of ASes, $\mathcal{N} \subset \mathcal{U}$ is the set of non-stub ASes and $S^{(d)}_{AS_i}$ represents the *covering set* of AS_i, i.e. the set of ASes in $\mathcal{N}$ that have a p2c-distance value of at most d from AS_i, and x_{AS_i} is 1 if $S^{(d)}_{AS_i}$ is part of the final solution, 0 otherwise. Note that AS_i belongs to $S^{(d)}_{AS_i}$ for any $d \geq 0$. The parameter d defines the maximum number of BGP decision processes[5] that the update messages by each non-stub AS will traverse before reaching a BGP feeder and, thus, indicates the number of filters encountered that can cause loss of information. Note that imposing $d = 0$ implies that the solution is composed of the entire set of non-stub ASes. The larger the value of d, the heavier the filtering effect introduced by BGP decision processes but the smaller the number of required BGP feeders and, thus, the number of required BGP connections. This thus, makes the solution more feasible. To better understand the problem consider the scenario depicted in Fig. 6. In this example, $\mathcal{U} = \{A, B, C, D, E, F, G, H, I\}$ and $\mathcal{N} = \{B, C, D, E, G, H\}$. Thus we compute $S^{(1)}_A = S^{(1)}_I = \{B\}$, $S^{(1)}_B = \{B, D\}$, $S^{(1)}_C = \{C\}$, $S^{(1)}_D = \{D\}$, $S^{(1)}_E = \{E, D, G, H\}$, $S^{(1)}_F = \{E\}$, $S^{(1)}_G = \{G\}$, $S^{(1)}_H = \{H\}$.

The goal of this MSC problem is to obtain the minimum number of elements of $\mathcal{S}^{(d)}$ such that their union is $\mathcal{N}$ or, in other words, to select the minimum number of BGP feeders from $\mathcal{U}$ such that the p2c-distance of any non-stub AS from at least one of them is at most d. Returning to the example depicted in Fig. 6, one of the optimal solutions to cover every non-stub AS is $\{S^{(1)}_B, S^{(1)}_C, S^{(1)}_E\}$, i.e. we should select ASes B, C and E as BGP feeders.

4.2.2 Positioning algorithm

To carry out the MSC problem we introduce a directed graph $G^{(d)}(\mathcal{V}, \mathcal{E})$ where $\mathcal{V} = \{i \mid AS_i \in \mathcal{U}\}$ is the set of nodes and $\mathcal{E} = \{(i, j) \mid i, j \in \mathcal{V} \wedge AS_j \in \mathcal{N} \wedge AS_j \in S^{(d)}_{AS_i}\}$ is the set of edges. In other words, the set of nodes is represented by the full set of ASes, while an edge directed from node i to node j represents that the non-stub AS_j is contained in $S^{(d)}_{AS_i}$. The adjacency matrix related to the graph $G^{(d)}$ is a $|\mathcal{V}| \times |\mathcal{E}|$ matrix $A^{(d)}$ such that $A^{(d)}_{ij} \in \{0, 1\}$, and $A^{(d)}_{ij} = 1$ if $(i, j) \in \mathcal{E}$ and is made up of one row per AS and one column per non-stub AS. The problem can thus be translated into selecting the minimum number of rows such that $\sum_i A^{(d)}_{ij} \geq 1$ for every j.

Given the potentially high number of elements in the problem, a direct brute-force approach to solve it would not be effective. Nevertheless, we can still manage to obtain its exact solutions by reducing the size of the problem through applying matrix reduction techniques that are well known in the mathematical optimization literature, such as the possibility to delete dominated rows in the adjacency matrix without changing the solvability of the problem [25, 26].

In detail, we propose an algorithm that firstly consists in an iterative reduction process, consisting of four phases (Fig. 7): *phase a*) Selection of those ASes that are the only elements covering one or more non-stub ASes, *phase b*) Deletion of of dominated covering sets, *phase c*) Verification of whether if the dominated elements deleted during phase b) can be interchanged with the elements inserted so far in the solution, *Phase d*) Decomposition plus further inspection, in which the optimal solution is exhaustively searched on the reduced adjacency matrix and the algorithm checks whether

[4]We collected the set of ASes that participate to at least one IXP by downloading and parsing the participant list web page of 190 active IXPs. Data is available at [23].

[5]The number of BGP decision processes encountered before reaching a route collector is $d + 1$, since BGP feeders introduce an additional BGP decision process before providing BGP data to the route collectors.

1 **Input:** distance d, $S^{(d)}_{AS_i} \forall AS_i \in \mathcal{U}$
2
3 $Pool = \mathcal{U}$
4 $\mathcal{P} = \emptyset$
5 $\mathcal{A} = \emptyset$
6 $\mathcal{R} = \emptyset$
7 $\mathcal{D} = \emptyset$
8 $Old\_Pool = \emptyset$
9
10 **while** $Pool \neq Old\_Pool$
11 $\quad Pool = Old\_Pool$
12 $\quad$ **foreach** $AS_i \in \mathcal{N}$
13 $\quad\quad$ **if** $|\{AS_k \mid AS_k \in Pool \wedge AS_i \in S^{(d)}_{AS_k}\}| == 1$
14 $\quad\quad\quad$ **remove** AS_k from $Pool$
15 $\quad\quad\quad$ **insert** AS_k into $\mathcal{P}$
16 $\quad\quad\quad$ **foreach** $AS_j \in Pool$
17 $\quad\quad\quad\quad S^{(d)}_{AS_j} = S^{(d)}_{AS_j} - S^{(d)}_{AS_k}$
18 $\quad\quad\quad\quad$ **if** $|S^{(d)}_{AS_j}| == 0$
19 $\quad\quad\quad\quad\quad$ **remove** AS_j **from** $Pool$
20
21 $\quad$ **foreach** $AS_i \in Pool$
22 $\quad\quad$ **foreach** $AS_j \neq AS_i \wedge AS_j \in \mathcal{P}$
23 $\quad\quad\quad$ **if** $S^{(d)}_{AS_i} = S^{(d)}_{AS_j}$
24 $\quad\quad\quad\quad$ **remove** AS_j **from** $Pool$
25 $\quad\quad\quad\quad$ **insert** (AS_i, AS_j) **in** $\mathcal{A}$
26 $\quad\quad\quad$ **else if** $S^{(d)}_{AS_i} \subset S^{(d)}_{AS_j}$
27 $\quad\quad\quad\quad$ **remove** AS_i **from** $Pool$
28 $\quad\quad\quad\quad$ **insert** $((AS_j, AS_i))$ **in** $\mathcal{D}$
29 $\quad\quad\quad$ **else if** $S^{(d)}_{AS_j} \subset S^{(d)}_{AS_i}$
30 $\quad\quad\quad\quad$ **remove** AS_j **from** $Pool$
31 $\quad\quad\quad\quad$ **insert** $((AS_i, AS_j))$ **in** $\mathcal{D}$
32
33
34 **foreach** AS_i **in** $\mathcal{P}$
35 $\quad$ **foreach** AS_j **in** $\mathcal{D}(AS_i, AS_j)$
36 $\quad\quad$ **if** $S^{(d)}_{\mathcal{P}} = S^{(d)}_{\mathcal{P}-AS_i+AS_j}$
37 $\quad\quad\quad$ **insert** (AS_i, AS_j) **in** $\mathcal{I}$
38 $\quad$ **foreach** AS_j **in** $\mathcal{A}(AS_i, AS_j)$
39 $\quad\quad$ **insert** (AS_i, AS_j) **in** $\mathcal{I}$
40
41 $\{Subpool\}$ = decompose($Pool$)
42
43 **foreach** $Subpool_k$ **in** $\{Subpool\}$
44 $\quad \{\mathcal{P}_k\}$ = brute_force($Subpool_k$)
45 $\quad$ **foreach** $\mathcal{P}_{k_l}$ **in** $\{\mathcal{P}_k\}$
46 $\quad\quad$ **foreach** AS_i **in** $\mathcal{P}_{k_l}$
47 $\quad\quad\quad$ **foreach** AS_j **in** $\mathcal{D}(AS_i, AS_j)$
48 $\quad\quad\quad\quad$ **if** $S^{(d)}_{\mathcal{P}_{k_l}} = S^{(d)}_{\mathcal{P}_{k_l}-AS_i+AS_j}$
49 $\quad\quad\quad\quad\quad$ **insert** $\mathcal{P}_{k_l} - AS_i + AS_j$ **in** $\{\mathcal{P}_k\}$
50 $\quad\quad\quad$ **foreach** AS_j **in** $\mathcal{A}(AS_i, AS_j)$
51 $\quad\quad\quad\quad$ **insert** (AS_i, AS_j) **in** $\mathcal{I}$
52 $\quad \mathcal{P} = \mathcal{P} \bigcup \mathcal{P}_{k_0}$
53 $\quad \mathcal{R}_k = \{\mathcal{P}_{k_l}\}_{l>0}$
54
55 **Output:** solution set $\mathcal{P}$, alternative solution sets $\mathcal{R}$, interchangeable AS set $\mathcal{I}$

Figure 7: MSC resolver algorithm

any of the dominated elements deleted during phase b) may still be part of at least one optimal solution. Fig. 7 details the above phases.

Initially in phase a) (lines 12–19) the algorithm verifies the presence of any AS_k which is the only AS to cover a certain non-stub AS_i. More formally, the algorithm verifies if there is a set of ASes that covers a non-stub AS_i with cardinality equal to one (line 13). In this case AS_k is removed from $Pool$ and is inserted into the solution set $\mathcal{P}$ (lines 14–15) and, as a consequence, every non-stub AS in $S^{(d)}_{AS_k}$ is considered to be covered. Thus, each element in the set $S^{(d)}_{AS_k}$ is removed from every remaining covering set $S^{(d)}_{AS_j}$ (lines 16–17). Eventually, whenever one of the covering is emptied, the related AS is removed from the $Pool$ (lines 18–19).

The same concepts are exploited in phase b) (lines 21–31), in order to check whether any covering set is already included in another set and, thus, can be put aside during the remaining computation. More formally, for each pair (AS_i, AS_j) the algorithm verifies if the related covering sets overlap each other exactly (line 23) or if one of the two dominates the other (lines 26 and 29). In the first case the pair (AS_i, AS_j) is put into the *alias set* $\mathcal{A}$, while in the second case the pair that comprises the dominating and the dominated ASes is put into the *dominated set* $\mathcal{D}$. In both cases, the computation continues by removing one AS of the pair from $Pool$. In the first case AS_j is arbitrarily removed (line 24), while in second case the dominated AS is removed (lines 27 and 30). The arbitrary removal of AS_j in the first case does not affect the results of the computation, since both ASes are completely interchangeable, i.e. their covering set is exactly the same. By reducing the number of elements in $Pool$, this phase may mean that additional non-stub ASes are covered by a single AS in $Pool$, so that new elements that have to be part of the final solution can be identified. Consequently, phases a) and b) are repeated until $Pool$ cannot be reduced any further (line 12).

In phase c) (lines 34–39) the dominated elements that have been recorded are analysed to check if any of them could be part of one of the solutions, by verifying if they can be substituted with the related dominating elements and maintaining, at the same time, full coverage of $\mathcal{N}$. More formally, to verify if the dominated element AS_j can be substituted with its dominating element AS_i, the set of covered non-stub ASes $S^{(d)}_{\mathcal{P}}$ is compared with the set $S^{(d)}_{\mathcal{P}-AS_i+AS_j}$, which is obtained by switching AS_j with AS_i in $\mathcal{P}$. If the sets are equal (line 36), then AS_j is recorded being interchangeable with AS_i in the set of interchangeable ASes $\mathcal{I}$ (line 37).

Since the problem cannot be reduced any further, an exhaustive approach to obtain an exact solution is required. Phase d) (lines 41–53) firstly aims to solve the problem by further reducing the problem by applying the usual mathematical techniques to reduce the adjacency matrix $A^{(d)}$ (line 41) into independent sub-matrices. These sub-matrices can still be seen as small and independent MSC sub-problems, but due to their limited size they can be practically solved by applying a brute-force algorithm (line 44) or a branch-and-bound algorithm. To obtain all the possible solution sets $\{\mathcal{P}_k\}$ for the considered sub component k, we still have

	# *ASes*					
	AF	*AP*	*EU*	*LA*	*NA*	*W*
ASes	770	6,576	17,657	2,490	16,032	41,127
Edges	1,980	19,829	77,465	8,175	43,331	144,475
Non-stub ASes	229	1,589	3,697	659	2,531	7,282
p2c	1,380	14,868	39,812	4,844	33,701	93,898
p2p	533	4,737	37,225	3,231	9,430	49,251
s2s	31	158	359	54	323	1,256

Table 4: Main characteristics of AS-level topologies

p2c-distance	*# not stub ASes*					
	AF	*AP*	*EU*	*LA*	*NA*	*W*
1	0	15	67	6	39	120
2	0	78	165	21	126	310
3	0	124	252	47	165	489
> 3	229	1,372	3,213	585	2,202	6,363

Table 5: Regional distribution of p2c-distances

Region	$\lvert\mathcal{P}\rvert$ ($\lvert\mathcal{P}\cup\mathcal{I}\cup\mathcal{R}\rvert$)		
	$d = 1$	$d = 2$	$d = 3$
AF	117 (214)	97 (182)	95 (197)
AP	931 (1,688)	848 (1,666)	834 (1,625)
EU	2,271 (4,641)	2,089 (4,545)	2,063 (4,438)
LA	393 (707)	363 (669)	360 (660)
NA	1,535 (3,233)	1,428 (3,133)	1,409 (3,027)
W	4,311 (9,232)	3,937 (9,116)	3,859 (8,875)

Table 6: Positioning algorithm results

to test each of the dominating-dominated pairs in a similar way as is done in phase c). However, unlike phase c), the tests are performed on each solution $\mathcal{P}_{k_l}$ found, and whenever AS_j can substitute AS_i, a new solution is inserted into $\{\mathcal{P}_k\}$ (line 51).

As result of this procedure, the algorithm provides: *i*) a set $\mathcal{P}$ of ASes composed of the set of ASes that were inserted into the solution during phase a) and of one of the solution sets for each component found (in the algorithm indicated as $\mathcal{P}_{k_0}$); *ii*) a set $\mathcal{R}$ of ASes related to each component k found during phase d) consisting of the possible solutions not taken into account in $\mathcal{P}$; and *iii*) a set $\mathcal{I}$ containing all the ASes that can be interchanged.

Thus, $\mathcal{P}\cup\mathcal{I}\cup\mathcal{R}$ is the set of all the ASes that are part of at least one optimal solution, i.e. the set of ASes that are candidates for BGP feeders, while $\mathcal{P}$ is the solution found by the algorithm. The cardinality of $\mathcal{P}$ is the exact number of BGP feeders that should be selected from the set of candidates $\mathcal{P}\cup\mathcal{I}\cup\mathcal{R}$ in order to solve the MSC problem.

5. TOWARDS AN IDEAL ROUTE COLLECTOR INFRASTRUCTURE

Finding a list of ASes that should become BGP feeders exploiting the methodology illustrated in Section 4.2.2 entails computing the p2c-distances between ASes on a suitable economic-tagged AS-level Internet topology. A good starting point would seem to be the classic global AS-level topology of the Internet tagged according to one of the economic tagging algorithms proposed in the literature. However, as shown in our recent work [10], this could lead to misleading and incomplete results. An AS connection present in the global topology may hide multiple connections between the same two ASes but located in different geographic regions, each potentially regulated by different economic relationships. Applying our methodology to this coarse-level representation of the Internet may thus lead to an underestimation of the correct number of BGP feeders required to obtain a complete view of the Internet core. To illustrate this we show both the results obtained by applying our methodology to the global topology of the Internet, referred to as *World (W)*, and to five regional topologies: *Africa (AF)*, *Asia-Pacific (AP)*, *Europe (EU)*, *Latin America (LA)*, *North America (NA)*.

We first show the impact of the geography in BGP feeder selection, highlighting that the analysis of the Internet from a global point of view underestimates the number of BGP feeders required. Then, we analyse the candidate feeders selected by our methodology, identifying their particular characteristics. Finally, we compare the coverage of the current BGP feeders with the ideal set drawn by our methodology.

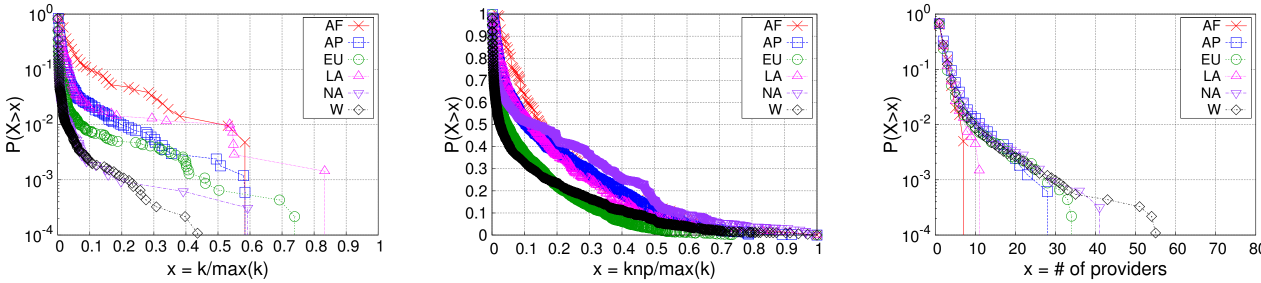
5.1 Global vs regional analysis

The global and the regional topologies have been inferred using the same BGP data analysed in Section 3 and exploiting enhanced versions of the algorithms[6] described in [27] and [10], which can be found in an internal report [23]. The main characteristics of these topologies are reported in Table 4.

Firstly, we compute the p2c-distances for each of the available topologies, as required by the positioning algorithm. Note that these values can also be used to highlight which zones of the Internet are poorly captured by the route collector infrastructure, thus providing further proof of the incompleteness of the current collected topologies. To confirm this, we analysed the p2c-distances of each non-stub AS from the route collector infrastructure by considering only routing information obtained via full feeders (see Table 5). Note that we consider to be ∞ the p2c-distance of ASes that cannot reach any route collector using only p2c connections. Most ASes are currently either too far from the route collector infrastructure or cannot be reached by any route collector via c2p connections alone, thus potentially representing hideouts for AS connectivity which need further investigation.

Once the p2c-distances had been calculated, we applied the positioning algorithm to each of the economic topologies available. The results are summarized in Table 6, where are shown the cardinality of the solution set $\mathcal{P}$ and, in round brackets, the cardinality of the candidate set $\mathcal{P}\cup\mathcal{I}\cup\mathcal{R}$ for each topology. In each geographic scenario the number of BGP feeders required is significantly smaller than the number of non-stub ASes (Tables 4 and 6). More importantly, the sum of BGP feeders required by regional scenarios is higher than the number of those required by the *World* scenario. This result was expected since the complete capture of the connectivity of an AS with a large geographic range may entail deploying multiple BGP feeders around the world. The inter-regional ASes typically follow a regional principle to route their traffic, in order to maximize their performance and minimize latency. To do this, they tend to subdivide their ASes into different routing areas by exploiting the features of Interior Gateway Protocols (IGPs) such as OSPF and IS-IS and they set up connections that can only be exploited in regional traffic routing. A total of 965 of 7,282 non-stub ASes are present in more than one single geographical topology and thus may fit this description.

[6]The results shown in this paper are obtained using the most conservative economic topology obtained by applying the algorithms described in [27] and [10] with the time parameter $N_{MAG} = 1$. Results for the remaining topologies can be found at [23]



(a) Normalized node degree (b) Normalized average provider degree (c) Number of providers

Figure 8: CCDF of node properties of candidate BGP feeders

d	# candidate BGP feeders					
	AF	*AP*	*EU*	*LA*	*NA*	*W*
Full feeders	0 (−− %)	7 (46.67 %)	22 (32.35 %)	4 (66.67 %)	16 (38.10 %)	40 (33.33 %)
Partial feeders	1 (100 %)	3 (23.08 %)	10 (30.30 %)	2 (66.67 %)	5 (21.74 %)	15 (26.32 %)
Minor feeders	3 (33.33 %)	47 (34.81 %)	407 (33.78 %)	75 (33.63 %)	117 (30.47 %)	621 (33.99 %)

Table 8: Characteristics of feeders of the current route collector infrastructure

5.2 Candidate feeder analysis

We now focus on the characteristics of the elements of the set of candidate BGP feeders found by applying the monitor placement algorithm with parameter $d = 1$, which represents the best trade-off between AS-level connectivity discovery and the number of BGP feeders required. With $d = 1$, the positioning algorithm finds the set of BGP feeders required to obtain BGP routing information filtered by at most two BGP decision processes from each non-stub AS: the source AS and the BGP feeder itself. The results obtained with other values of d are available at [23].

Table 7 and Figure 8 show the most relevant characteristics of these elements. Figure 8 depicts a) the degree distribution, b) the *average provider degree* (k_{np}) distribution, where k_{np} is computed for each AS as the average degree of its providers, and c) the number of providers of the candidate feeders. Note that graphics a) and b) have been normalized with the maximum value of the node degree (k) found in the related region, in order to allow full-scope analysis and to trace the characteristics of a typical candidate BGP feeder. The most frequent classes of ASes found to be candidate are: a) stub ASes (see Table 7), b) ASes that have set up a small number of BGP connections (see Fig. 8a), and c) ASes that have chosen a rather small number (see Fig. 8c) of small-medium ISPs (see low-medium values of the normalized k_{np} in Fig. 8b) to be their providers.

Only a small percentage of these ASes are present on at least one IXP (see Table 7), and this implies that their typical interconnectivity behavior is to not establish public peering with other ASes. Thus, we can conclude that the typical AS that should become a BGP feeder of the current route collector infrastructure is a small multi-homed AS, that has set up multiple connections with different regional providers to guarantee route diversity and increase the reliability of its reachability. This is not surprising since these ASes are likely to be located at the bottom of the hierarchy and, thanks to multi-homing can cover several non-stub ASes at once.

5.3 Current status of the route collector infrastructure

We now analyse how many of the current BGP feeders are present in the ideal set of candidates found via the methodology proposed in Section 4. Their distribution for each region is shown in Table 8, as well as the percentage of the total number of feeders in the region that fall into that category. The main result is that only a small percentage of the current full feeders are actually part of an optimal solution in any of the topologies analysed. This is a direct consequence of their position in the Internet hierarchy, as already shown in Section 3. These ASes are not likely to have a large number of providers, thus their contribution is limited. Nevertheless, there are few other classes of current BGP feeders in the set of candidates, thus highlighting that, in terms of p2c-distance, only a few of them are placed in an optimal position. It is also interesting to understand how many BGP feeders should be added to the current route collector infrastructure in order to improve the quality of data. To determine these values, we used the methodology illustrated in Section 4.2.2 considering the current set of full feeders $\mathcal{F}$ as part of the initial set of solution $\mathcal{P}$, and considering the number of additional BGP feeders as $n = |\mathcal{P}| - |\mathcal{F}|$. Results per each geographic region are reported in Table 9.

Region	$\lvert\mathcal{P} \cup \mathcal{I} \cup \mathcal{R}\rvert$	
	On IXPs	*Stubs*
AF	27 (12.79 %)	114 (54.03 %)
AP	472 (28.04 %)	942 (55.97 %)
EU	1,931 (41.60 %)	2,250 (48.48 %)
LA	204 (29.14 %)	394 (56.29 %)
NA	406 (12.55 %)	1,509 (46.67 %)
W	2,944 (31.88 %)	4,221 (45.72 %)

Table 7: Characteristics of candidate BGP feeders

Region	$n = \lvert\mathcal{P}\rvert - \lvert\mathcal{F}\rvert$		
	$d = 1$	$d = 2$	$d = 3$
AF	117	97	95
AP	922	843	831
EU	2,249	2,072	2,050
LA	389	359	357
NA	1,519	1,423	1,405
W	4,266	3,785	3,714

Table 9: Additional feeders required in each region

A comparison of the number of additional ASes required and the number of non-stub ASes (see Table 4) reveals that the methodology covered every non-stub AS with a number of new BGP feeders which is about 50-60% of the number of non-stub ASes in each region. In addition, a priority for each AS found to be part of $\mathcal{P}$ can be identified by recording the amount of non-stub ASes that are found to be uniquely covered by an element in $\mathcal{P}$ during phase a) of the methodology[7]. The higher this value is, the larger the coverage of the element considered. The distribution of these values can be found in Fig. 9, while the complete AS ranking is available at [23].

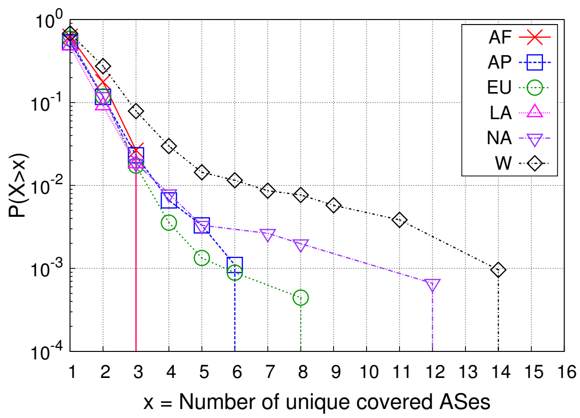


Figure 9: CCDF of the number of ASes uniquely covered

The number of elements covered uniquely by a single AS is never too large, since typically a customer demands its Internet reachability to a set of well-known ISPs. The distribution of this priority index also allows us to make a priority selection, adding first those ASes with the highest number of unique covered AS values (see Fig. 9). Exploiting this priority selection, by just adding a number of ASes comparable to the current number of feeders, the route collectors can now see about one in three non-stubs in each region (see Table 10). This means that the capture of a more complete AS-level view of the Internet is a feasible task in terms of numbers of elements to be connected and, consequently, of costs. Thus our methodology would seem to be a very useful tool to drive the growth of the route collector infrastructure.

It must be stressed that our methodology extracts the optimal solution for the input data provided, thus, if a new BGP feeder is introduced, the solution may no longer be optimal. In any case, it still represents an upper bound to the number of additional full feeders needed. In fact, the introduction of new data may add previously hidden connections and may lead the tagging algorithm exploited to infer a higher number of p2c connections. These new connections may change the p2c-distance of several ASes that might be reached by exploiting a lower number of feeders. However, it would still be possible to apply the methodology once again on the new data to obtain a new optimal value.

[7]The same ranking value is also inherited by every element in $\mathcal{I}$ that is related to an element in $\mathcal{P}$ due to their interchangeability. However, only one of them is required to be connected.

Region	*# Not stub ASes covered*	
	Current status	*Top priority introduction*
AF	0 (0.00%)	71 (31.00%)
AP	88 (5.54%)	452 (28.45%)
EU	209 (5.65%)	958 (25.92%)
LA	26 (3.95%)	148 (22.49%)
NA	148 (5.85%)	728 (28.77%)
W	384 (5.27%)	2,137 (29.35%)

Table 10: Coverage improvements by doubling the number of BGP feeders

6. CONCLUSIONS

The BGP route collector projects that have been developed to date are extremely valuable for researchers, as they are the most reliable source of information for gathering data on the infrastructure of the Internet. However, BGP data are currently only collected from a small amount of ASes, thus limiting the quality of the inferences that can be drawn from analysing such data. Studies on Internet topology structure must be fully aware of the high level of incompleteness of BGP data, since a topological analysis of the Internet as viewed from these monitors is like analysing a roadmap of a given country where the highways are known, but most of the secondary roads are not shown!

In this paper, we have quantitatively evaluated the currently available BGP route collector infrastructure, showing that it is only able to reveal complete AS-level connectivity information about a very small number of ASes. The current BGP feeders that are contributing with their full routing tables are typically large ASes such as provider-free and worldwide ISPs. This implies that the current vision of the BGP route collector projects cannot capture any of the p2p connections that small or medium-sized ASes may establish. The only solution to deal with this incompleteness is to dramatically increase the number of BGP feeders of these projects. In this perspective, we have outlined a systematic methodology to infer the minimum number of ASes that the route collector projects should introduce as BGP feeders in order to maximize the amount of information that can be collected. We found that multi-homed ASes with a small-medium size are the most useful contributors in a topology discovery perspective.

Our methodology provides a useful tool to select those ASes that are the most useful in enhancing the quality of topology information data. We are aware that this kind of data is extremely hard to obtain, but we also believe that the greatest problem in data gathering is that ASes are not stimulated enough to join any of the current projects, since no direct service is offered by the projects in change of the voluntary participation of ASes. Thus, it makes sense to imagine that currently the route collector projects are used by several large ISPs to promote their reachability. In particular, it might be a good idea to create services based on the real-time analysis of the inter-domain routing from different points of view in return of full routing tables, following the *do ut des* principle. Such services would be valuable for many ASes, ranging from local ISPs to CDNs, and thus encourage them to participate. Otherwise, it might be useful to exploit alternative tools to improve the amount of data available. Specifically, some of the traceroute-based projects [28, 29, 30, 31] are able to bypass the reluctance in disclosing the routing information of AS owners by placing agents directly on user applications and, thus, obtaining data that would not be collected otherwise.

7. ACKNOWLEDGMENTS

We would like to thank Massimo Pappalardo (University of Pisa) and Paolo Nobili (University of Salento) for their very useful advice provided during the formulation and solution of our MSC problem.

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