Isolario: a Do-ut-des Approach to Improve the Appeal of BGP Route Collecting

Enrico Gregori, Alessandro Improta, and Luca Sani
Institute of Informatics and Telematics, Italian National Research Council
Pisa, Italy

Abstract

The incompleteness of data collected from BGP route collecting projects is a well-known issue which potentially affects every research activity carried out on the analysis of the Internet inter-domain routing. Recent works explained that one of the possible solutions is to increase the number of ASes feeding these projects from the Internet periphery, in order to reveal the hidden portion of peering connectivity of their upstream providers. The main problem is that these projects are currently not appealing enough for the network administrators of these ASes, which are typically not aware of their existence or not interested enough to share their data. Our contribution is Isolario, a project based on the do-ut-des principle which aims at persuading network administrators to share their routing information by offering services in return, ranging from real-time analyses of the incoming BGP session(s) to historic analyses of routing reachability. To the best of our knowledge, Isolario is the only route collecting project publicly available which offers a set of services to its users to encourage their participation, aiming at increasing the amount of BGP data publicly available for research purposes.

1 Introduction

Route collectors deployed by the Route Views project of the University of Oregon \[32\] and the Routing Information Service (RIS) project of the Réseaux IP Européens Network Coordination Center (RIPE NCC) \[31\] have been an invaluable source of information for researchers all over the world for the past twenty years. Data collected from these projects greatly contributed to shed light on the knowledge concerning the Internet structure (e.g. \[8,13,21,24,34\], to mention just a few), which has been lost the day after the NSF’s privatization in 1995, when regional networks started to buy national-scale Internet connectivity from private long-haul networks growing since the early 90s \[19,25\]. Route collectors are nothing more than simple servers that mimic the role of border routers and which establish sessions with various organisations using the Border Gateway Protocol 4 (BGP) \[29\]. BGP is the de-facto standard protocol used in inter-domain routing, and it is used to establish logical connections between pair of Autonomous Systems (ASes) to exchange reachability information to be used in the BGP decision process of the ASes involved. Those pieces of information are carried in UPDATE messages in the form of path attributes, each with its own meaning in the routing process. Route collectors behave like one of the two ends of the logical connection, but they only collect incoming BGP messages without generating any routing traffic directed to the other party. Thus, they are able to receive in real-time the best routes chosen by the BGP decision process of the connected AS Border Router (ASBR), and data collected allows to study the routing characteristics of the connected AS. Needless to say, these attributes represent a potential gold mine of information about the Internet ecosystem for researchers, and they can be found in Multi-threaded Routing Toolkit (MRT) export format \[6\] files in the website of each project.

However it is not all a bed of roses. Data collected by Route Views and RIS is indeed known to be largely incomplete \[14,26\]. Moreover, most of the organisations which decided to participate in these projects are very large Internet Service Providers (ISPs) \[14\] and, as a consequence, data collected by these projects could lead to biased results, depending on the analysis carried out. For example, they fail to reveal the largest part of the peering ecosystem \[7,16\] mostly due to the nature of their participants, which lead several researchers to

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\(^1\)An Autonomous System is defined as "a set of routers under a single technical administration", which administration "appears to other ASes to have a single coherent interior routing plan and presents a consistent picture of what networks are reachable through it" \[15\].
believe that the Internet was following a power-law node degree distribution when analyzed at the AS-level abstraction [1, 2, 11]. We believe that the main cause of these drawbacks is the voluntary basis on which these projects rely on. In our opinion most of the largest ISPs are attracted by the opportunity to exhibit their interconnections to potential customers, while the administrators of the smallest organisations may not find any strong motivation to join a route collecting project.

To overcome this polarization and the lack of routing information we developed Isolario, a non profit research project which aims to improve the knowledge about the Internet ecosystem by enhancing the appeal of the classic concept of BGP route collector. To do that, Isolario provides a set of services to the network administrators of each AS participating aimed at easing their jobs. These services are built on top of the BGP flow which is collected, analysed and finally shared with the research community. To the best of our knowledge, Isolario is the only research project publicly available which tries to push network administrators to participate and increase the number of data sources of BGP data available for research purposes in addition to mere route collecting. In detail, this paper describes the architecture of Isolario, focusing in particular on the design choices and the challenges engaged to build a route collecting system able to support the implementation of real-time and historical data services. Finally, we describe briefly the set of services built on top of either the route collecting software or the archival system, some of which are already available on Isolario. With these services a network administrator participating to Isolario would be able, for example, to detect in real-time pathological inter-domain routing events like route flapping without increasing the computational load on its routers or introducing third-party software.

The rest of the paper is organised as follows. Section 2 describes the state of the art on BGP collecting systems publicly available. Section 3 introduces the Isolario system and its architecture while Section 4 describes the route collecting engine and the archival system. Section 5 focuses on the services developed so far, introducing examples of both real-time and historic analysis services. Finally, Section 6 concludes the paper.

2 Related work

The art of BGP route collecting dates back to 1997, when data collection was performed by the Measurement and Operations Analysis Team (MOAT) of the National Laboratory for Advanced Network Research (NLANR) project [22]. Since then, the concept of route collecting has not changed significantly. Route collection is performed by servers which mimic the behaviour of an ASBR using a routing suite like Quagga [28]. Route collectors establish BGP sessions with organisations which voluntarily agree to participate, and regularly dump routing information. Data was initially extracted via shell scripting, dumping regular Routing Information Base (RIB) snapshots. Then, thanks to the introduction of MRT [6] the data format has been standardized and every single packet in BGP sessions established towards route collectors was caught and stored, thus making available the possibility to re-create the BGP flow collected in a given period of time to investigate network issues. NLANR has ceased its activities some years ago, but route collecting was carried on by the Route Views project at University of Oregon [32] – which collects MRT data since 2001 – and by the Routing Information Service (RIS) at the Réseaux IP Européens Network Coordination Center (RIPE NCC) [31] – which collects MRT data since 1999. Both projects made publicly available periodic RIB snapshots and a collection of every single BGP packet collected at different time intervals.

A step forward from the classic concept of BGP route collector has been achieved with BGPmon [4], a tool developed at Colorado State university to enable the real-time monitoring of BGP routing information in addition to simple route collecting. The idea is to replace classic routing suites with dedicated software which is able to provide a public live BGP data stream in XML format, in addition to being able to mimic a BGP border router and store routing information. This flow can be exploited to perform a wide range of experiments and analyses, as well as homemade BGP monitoring systems. However, even though this idea is extremely interesting, up to date not many organisations have decided to join this project and only a few of those who joined announce a full routing table [14]. In our opinion, the main reason of this phenomenon is that BGPmon still fails to provide a strong motivation to potential data sources to feed their project with their BGP routing information. By providing a real-time flow, BGPmon increases only the appeal of data and the amount of potential data users, while the appeal for potential BGP data sources remains unaltered.

We believe that a good idea to attract new BGP data sources would be to provide a set of services to each

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2http://www.nlanr.net/
3Route Views provides RIB snapshots every 2 hours, RIS every 8 hours. Route Views dumps UPDATE messages every 15 minutes, RIS every 5 minutes.
4http://bgpmon.netsec.colostate.edu/peer-list.html
network administrator who decides to participate which could be useful to manage their network in real-time and/or to search their historic routing data to investigate for network issues. To the best of our knowledge, up to date no route collecting project pursed a similar approach. RIPE NCC has done something in this direction with their project RIPEstat [30], but the data is freely provided to public, without any need to connect an ASBR to their RIS project. RIPEstat is indeed a toolbox that ease the access to the various datasets maintained at RIPE NCC – such as DNS and RIS routing data – and offers a list of widgets to analyse any public network composing the Internet, with additional information for all those networks registered in RIPE database. A similar tool has been developed by the Internet Research Lab of UCLA with the Cyclops project [9], which do not collect any BGP route but uses external data source (e.g. looking glasses, route servers and BGP data from Route Views and RIS) to compare the behaviour of a given network as observed by data collected with the behaviour intended by the AS administrator. Both tools provide up to date only a posteriori services, since they both exploit routing data dumps and can only be used in a posteriori analyses, i.e. after a problem has occurred.

3 Architecture overview

Isolario is a distributed system devised to collect, parse, elaborate BGP data sent from the ASBRs of its participants – hereafter feeders – and to provide results to network administrators of the participating ASes – hereafter Isolario users – by introducing the minimum amount of delay as possible. To achieve that, Isolario makes use of three main components, as depicted in Figure [1] i) Web core, ii) System core, and iii) Enhanced Route Collectors (ERCs). Each component is designed to be modular and scalable, to allow the introduction of new pieces of equipment in a plug-and-play fashion without affecting the user experience. In addition to that, components are interconnected via TCP, in order to allow the deployment of part of the system in different parts of the world. Isolario system has been designed to fulfill two main purposes. On one side, it must be able to establish and maintain BGP sessions with each feeder, collecting at the same time routing information in the MRT repository. On the other side, it must be able to react to user service input requests by computing and elaborating BGP incoming packets or historic data and providing the requested service output(s).

An Isolario user interacts with the web core component (Figure 2) from a private area of the Isolario website, where every service available can be accessed.
As soon as a service has been chosen, it is created a dedicated WebSocket session between the Web core and the user web browser on which user requests and results will flow in real-time. WebSockets are chosen to allow the server to send data directly to the user browser as soon as new data is available, avoiding costly and unuseful polling traffic being generated by the web browser or explicit refresh requests from the user. On the Web core side, HTTPS and WebSocket flows are dispatched by a proxy module respectively to the Webserver or to the related service module which will propagate the traffic to the system core. To minimize the amount of unuseful routing data in the system, each service also identifies which portion of IPv4/IPv6 space is interested by the user query, and generates dedicated messages to configure filters on the proper ERC(s).

The system core component (Figure 3) then handles user requests propagated by the web core as well as filter configuration messages. This component is composed by a set of real-time service modules and a set of historic service modules. The real-time service modules dispatch user requests and filter configuration messages to the related service modules located on ERCs, and aggregates results based on the partial results received from each ERC (if required). On the opposite, historic services fetch data from the Historic Data Storage and Retrieval System (HDSRS), which is designed to allow fast access to stored routing data. Details about the HDSRS can be found in Section 4.2.

Finally, each ERC has the role to establish and maintain active BGP sessions towards a set of feeders, dispatching every single BGP packet which matches filtering criteria towards service modules. Every BGP session on ERCs is maintained by the Route Collecting Engine (RCE), which also shoots every 2 hours a snapshot of its RIB and dumps every 5 minutes the full sequence of BGP packets received in the last 5 minutes in MRT format. RCE details are provided in Section 4.1. To inject the incoming BGP packets into the system as soon as possible, we introduced a dedicated Man In the Middle (MIM) module between each feeder and our system. This module forwards the BGP packets to the RCE and, at the same time, applies the filter configuration messages received from the system core. Every single incoming BGP packet matching the filter criteria is then forwarded also to the proper service module, which will perform all the required elaborations. Results obtained from service modules are finally propagated back to the user through the Isolario system and the WebSocket session.

4 Towards acceptable user experience

Isolario system is founded on the reciprocal usefulness criterion, also known as the do-ut-des principle. This principle is known since Roman ages and has been used as political motto by several statesmen in history, such as Constantine the Great. To apply this principle successfully, the ruler typically gave something valuable like booty or land, in return for loyalty and armed support by the retinue. In Isolario’s case, this principle says that to attract as many AS administrators as possible, Isolario has to provide as many useful and interesting (and thus valuable) services as possible, still guaranteeing to every Isolario user the best user experience. In this sense, Isolario system has been designed with particular focus on reducing data processing delays. In this section we describe two of the most important parts of the system, which allow users to receive results as soon as possible: the Route Collecting Engine and the Historic Data Storage and Retrieval System.

4.1 Route Collecting Engine

One of the main characteristic of Isolario is the availability of services dedicated to the real-time analysis of the incoming BGP flows, either focused on portions of the Internet routing table or focused on the reachability of a given network prefix from every perspective available in Isolario (see Section 5). Services belonging to this set share two common main requirements: a) BGP
data has to be received by interested services as soon as they arrive to any route collector, without any additional delay, and b) services have to be able to access the RIB of route collectors as soon as possible to retrieve the BGP path attributes required at any time. While the first requirement is satisfied by design thanks to the MIM module described in Section 3, the second requires a dedicated route collecting engine able to maintain over time the best routes received from each feeder, store them in MRT files and, at the same time, able to provide the status of any of the stored Network Layer Reachability Information (NLRI) with the minimum delay as possible to any requesting service. To the best of our knowledge, the requirements described above cannot be completely fulfilled by any of the routing suites publicly available. On one side, general purpose routing suites (e.g. Quagga, Bird, XORP and exabgp) implement routing functionalities that are not needed for the purpose of route collecting (e.g. BGP decision process and proper import/export policies), introducing unnecessary computation overhead and delays. On the other side, routing suites efficient in terms of RAM and CPU load which would allow fast access to RIB content from external services do not have built-in support for generating periodic dumps of RIB and updates in MRT format. To completely satisfy the above requirements we created a dedicated component named Route Collecting Engine (see Figure 5). This component is a) scalable with respect to the number of feeders, b) has full support of MRT dumps (periodic RIB snapshots and collections of BGP UPDATE messages received over time), and c) allows services to safely read the content of the RIB of route collectors while its content is modified by incoming BGP packets.

![Figure 5: Route Collecting Engine (RCE)](image)

4.2 Historic Data Storage and Retrieval System

Differently from real-time services, the only requirement of historic services is that the system has to provide fast access to historic data in order to retrieve results to the users’ web browser as soon as possible. In particular, data access speed should be neither route-dependent nor time-dependent, i.e. routing data should be accessible with complexity $O(1)$ from the dedicated handler independently from the amount of information stored in the system. Routing data is typically maintained in MRT files (e.g. Route Views, RIS). MRT files are time sorted sequences of BGP packets collected by multiple sources and which contain information related to the (potentially) whole IPv4/IPv6 space as announced by each BGP peer monitored. Even though it is possible to organize file names to ease the access to obtain routing data related to the time span requested by the service, it is still required to read the whole file to discern information related to the route(s) under analysis from the rest of the data. More importantly, this has to be done every time an historic service requests routing information, making this approach to be unfeasible to our ends. To guarantee fast replies to service requests, we designed the Historic Data Storage and Retrieval System (HDSRS) (see Figure 6), which is based on a new logical file organisation.

![Figure 6: Historic Data Storage and Retrieval System (HDSRS)](image)

5 Service overview

In the eye of any Isolario user, the most important parts of the system are the services built on top of the architecture described in Section 3. Services are indeed the do part of the do-ut-des principle, and thus the main reason of the participation of the user to the project and the key to attract new potential users. Up to date we developed
four main categories of services, depending on the data source exploited: flow-based services, subnet-based services, historic services and alerting services. Here in this section we provide a brief description of each of these categories, together with some examples of services already available to use.

5.1 Flow-based services

Some of the possible routing problems that a common network administrator could face during a normal workday are caused by the behaviour of its BGP neighbours. For example, network performances could degrade due to high routing UPDATE volumes from one of its peers, or some destinations on the Internet could not be reachable simply because its provider is not announcing them anymore (for any reason). In theory a network administrator should monitor the routing tables of each ASBR under control 24/7 to understand at glance whether the AS is experiencing these problems, but this is not feasible. A possible approach is to perform multiple accesses to the ASBRs via Command Line Interface (CLI) trying to understand if something is wrong. Another alternative is to use third-party monitoring tools – increasing the CPU load on the ASBR itself – or to create ad-hoc software directly fed by the ASBR – if resources and know-how are available. In practice, the most common way to discover these malfunctions is through the complaints of people inside the AS organisation. In the worst case scenario, however, the network problem could go unnoticed and could cause a loss of revenue, depending on the business of the organisation. Isolario provides a valid alternative to that by offering to each Isolario user a set of real-time monitoring services based on the BGP flow(s) that the user organisation established with Isolario, without increasing the CPU load on the peering ASBR or requiring the installation of additional software on the user-side.

The schema followed by this class of services is depicted in Figure 8. As soon as the user triggers the requests from the web browser, the related service generates a proper set of filter configuration messages to allow BGP data of interest to flow in the system. For example, if users request to analyse the routing related to X.Y.0.0/16, the service will receive in real-time every UPDATE message where X.Y.0.0/16 is explicitly announced or withdrawn, as well as every UPDATE message announcing or withdrawing subnets (e.g. X.Y.1.0/24) or supernets (e.g. X.0.0.0/8) of the indicated prefix. The set of filter configuration message
and their effect on the system strictly depend on the needs of each service. These messages are then parsed and elaborated from the given service module on ERCs and the requested results are provided back to the user, together with some related statistics (see for example Figure 7). Note that the parsing and elaboration phase is performed in real-time, and that results are shown in real-time on the user web browser as well by exploiting the WebSocket protocol.

Up to date, every Isolario user can use BGP Flow Viewer (BFV), which shows the UPDATE messages that the Isolario route collector is receiving from the ASBR(s) managed by the user, and which allows to quantify the amount of routing traffic currently generated by the given ASBR(s), Routing Table Viewer (RTV), which allows users to analyse portions of the routing table announced by their ASBR(s) – which coincide with the best routes identified by the BGP decision process of the ASBR – and to monitor their evolution, allowing users to investigate possible reachability problems in real-time (see Figure 7), and Route Flap Detector (RFD), which allows users to detect route flaps in real-time, allowing them to take the opportune countermeasures.

### 5.2 Subnet-based services

One of the most (work related) desires of a common network administrator is that the networks he/she manages are reachable from everyone everywhere at anytime. This desire cannot be achieved simply with correct management of the networks of the AS managed, and it requires also excellent network planning skills to choose the best BGP neighbours and their role (provider or peer). For example, an AS could benefit in being connected to an Internet Exchange Point (IXP) where several AS of interest are co-located, and/or in selecting multiple providers which guarantee different performances in different regions of the world. The main problem is that it is extremely hard – if not impossible – for any network administrator to understand and prove the efficacy of the choice made, and how these choices impact on the other ASes composing the Internet. For example, if AS X peers with AS Y at an IXP, the network administrator of X cannot assume in any way that Y is going to use the same IXP to route back all the traffic towards the networks of X. This because every single AS has its own perspective of the Internet, and there is no collaboration in creating a big picture. The only public tools that network administrator could use so far to obtain a different perspective about their networks are looking glasses or MRT data collected by Route Views and RIS. On one side, looking glasses are easy to access but can offer just a snapshot of the reachability of the network under analysis from the single perspective of the AS which provide the looking glass access. This means that the network administrator would not be able to understand if the networks under analysis are experiencing route flaps or if network problems occurred.

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3. Route flapping is a rapid sequence of route state changes which have a heavy impact on router efficiency [13]. Route flaps are classified in RFD according to the classification of BGP dynamics originally defined by Labovitz et al. [17] and then redefined by Li et al. [20].

4. A looking glass is a software run by several ASes to allow public but limited access to their BGP routers, in order to ease Internet routing troubleshooting.
before or after the looking glass access. On the other side, MRT data can provide more perspectives than looking glasses, but their analysis require know-how and often the development of dedicated software. Moreover, they can just show the past behaviour of network reachability, and not the present. Given its innovative structure, Isolario is able to merge the pros of the two approaches and to provide results in real-time, thus allowing network administrators to check the reachability of their networks with just a couple of clicks.

The schema followed by this class of services is depicted in Figure 10. Each service generates a set of filter configuration messages to allow BGP data to flow in the system but, differently from flow-based services, these messages are sent to filters regulating every incoming BGP flow. For example, if the user requires to analyse the routing related to X.Y.Z.0/24, the service will receive in real-time every UPDATE message where X.Y.Z.0/24 is explicitly announced or withdrawn, as well as every UPDATE message announcing or withdrawing subnets or supernets of the indicated prefix from every incoming BGP flow available in Isolario. These messages are then parsed and elaborated from the given service module locally on ERCs and then each partial piece of information is merged in the service module in the system core. Finally, the requested results are provided to the user, again together with some related statistics (see for example Figure 9). So far, the only service currently available in this class is the self-descriptive Subnet Reachability (SR).

5.3 Historic data services

Historia magistra vitae is an old proverb which means that the study of the past should serve as a lesson to the future. This also applies to network administrators, which may learn from the analysis of UPDATE messages announced in the past something about the resilience and robustness of their routing system. For example, a network administrator would benefit to understand how its reachability was dented during a catastrophe like the 9/11 or which network its routing system was not able to reach during accidental submarine cable cuts or malicious cyber attacks. Moreover, a window in the past could help in troubleshooting current routing problems and could help in choosing the correct peers and providers to diversify the connectivity of their AS. Historic information are thus extremely useful, but to date network administrators were required to analyse MRT data by themselves, or to create their own historic repository privately inside their own AS, creating their private route collecting systems. Isolario exploits HDSRS (see Section 4.2) to provide each user something similar to a time machine. So far, we developed the historic aliases of some of the flow-based and subnet-based services described above, Historic Routing Table Viewer (HRTV) and Historic Subnet Reachability (HSR). The former service allows users to investigate the routing related to a given portion of the Internet in a given time period, basing on data they announced to Isolario. The latter allows them to investigate the routing related to their own network prefixes during given periods of time.

5.4 Alerting services

Services described so far assume the physical presence of users, which need to actively interact with Isolario via their web browser. Obviously, this is not always possible. According to Murphy’s law, outages and peculiar network events are more likely to happen when the network administrator is not checking real-time services (for whatever reason) than when they are logged in Isolario. Needless to say, in several cases it is extremely important that network administrators act as fast as possible to fix their network problems to avoid, for example, huge business losses, security issues and/or a lot of annoyed customers. To help them in their work, Isolario devised a special class of services aimed at monitoring BGP flows provided by feeders in order to catch and notify interesting events for users. Such events may be related to BGP packet content or to protocol fluctuations – like route flaps or temporary network unreachability – or may be related to serious security issues, like prefix hijack attempts and bogons [35, 27].

Every service in this class runs 24/7 typically following the rules that each user set up in the service web page. Depending on the service chosen, filter configuration messages will flow following the schema described in flow-based or subnet-based services, with
the service configuration set by the user. As soon as BGP messages of interest reach the system core, the service will identify whether an alarm has to be triggered or not. If an alarm is triggered, every data related will be retrieved to the interested user both through the Isolario website (if connected) and through the communication channels indicated by the user in the alarm configuration phase, like for example e-mail and/or HTTP/HTTPS POST messages. Note that notifications triggered when the interested user is not online are collected on the web core and made available at its next login.

Besides the general alerting features described above, a further interesting example of service in this class is the Prefix Hijack Detector (PHD). A prefix is considered to be hijacked whenever an AS announces, maliciously or not, prefixes out of its own address space. PHD is currently set up to identify from every single perspective available in Isolario any attempt of hijack of any subnet belonging to one of the Isolario feeders and communicate that to the related user. In particular, PHD is able to detect three main classes of hijack events, as described in [13]: false origin hijacks whenever an AS announces as its own a network prefix belonging to another AS, covered and covering hijacks whenever an AS announces respectively as its own a subnet or a supernet of a network prefix belonging to another AS.

6 Conclusions and future work

The lack of interest in route collecting project is the major cause of the incompleteness of BGP data collected by Route Views and RIS. To increase the interest of network administrators in sharing their routing information we proposed Isolario, an enhanced route collecting project based on the do-ut-des principle. To increase the number of BGP data sources, Isolario offers a set of useful services to help network administrators in troubleshooting network reachability problems in exchange for their IPv4/IPv6 BGP full routing tables. These services and the whole Isolario architecture have been developed with particular care to user experience in order to attract as many network administrators as possible. To achieve that, we developed a dedicated route collecting engine which is designed for BGP route collecting and which allows fast RIB dumps – thus enabling real-time services to obtain the steady routing information of a given subnet as fast as possible – and a historic data storage and retrieval system which guarantees fast access to routing information to historic services and avoids repeatedly read operations of the same (possibly large) MRT files.

Isolario is currently accepting new feeders. MRT data collected from the feeders will be made available on the Isolario website (https://www.isolario.it) and a free trial of Isolario services – limited to Isolario AS connectivity (AS 2598) – is available to the public. To join Isolario, we require feeders to establish (at least) one BGP session with one of our route collectors and to announce us their routes towards all the Internet destinations. In the very near future we plan to increase the number of services available to broaden the usefulness of Isolario and to ease the user access to services.

References

[1] Albert, R., and Barabási, A.-L. Statistical Mechanics of Complex Networks. Reviews of Modern Physics 74, 1 (2002), 47–97.
[2] Barabási, A.-L., and Albert, R. Emergence of Scaling in Random Networks. Science 286 (1999), 509–512.
[3] Berkowitz, H., Davies, E. B., Hares, S., Krishnaswamy, P., and Lepp, M. RFC 4098 - Terminology for Benchmarking BGP Device Convergence in the Control Plane, 2005.
[4] BGP Monitoring System (BGPmon). http://bgpmon.netsec.colostate.edu/.
[5] The BIRD Routing Daemon Project. http://bird.network.cz/.
[6] Blunk, L., Karir, M., and Labovitz, C. RFC 6396 - Multi-Threaded Routing Toolkit (MRT) Routing Information Export Format, 2011.
[7] Chatzis, N., Smaragdakis, G., Feldmann, A., and Willinger, W. There is More to IXPs Than Meets the Eye. ACM SIGCOMM Computer Communication Review 43, 5 (2013), 19–28.
[8] Chen, Q., Chang, H., Govindan, R., Jamin, S., Shenker, S. J., and Willinger, W. The Origin of Power Laws in Internet Topologies Revisited. In Proc. of IEEE INFOCOM (2002), vol. 2, pp. 608–617.
[9] Chi, Y.-J., Oliveira, R., and Zhang, L. Cyclops: The AS-level Connectivity Observatory. ACM SIGCOMM Computer Communication Review 38, 5 (2008), 5–16.
[10] ExaBGP. https://github.com/Exa-Networks/exabgp.
[11]Faloutsos, M., Faloutsos, P., and Faloutsos, C. On Power-law Relationships of the Internet Topology. In Proc. of ACM SIGCOMM (1999), pp. 251–262.
[12]Fette, I., and Melnikov, A. RFC 6455 - The WebSocket Protocol, 2011.
[13]Gao, L. On Inferring Autonomous System Relationships in the Internet. IEEE/ACM Transactions on Networking 9, 6 (2001), 733–745.
[14]Gregori, E., Improta, A., Lenzini, L., Rossi, L., and Sani, L. On the Incompleteness of the AS-level Graph: a Novel Methodology for BGP Route Collector Placement. In Proc. of ACM SIGCOMM IMC (2012), pp. 253–264.
[15]Hawkinson, J., and Bates, T. RFC 1930 - Guidelines for creation, selection, and registration of an Autonomous System (AS), 1996.
[16]He, Y., Siganos, G., Faloutsos, M., and Krishnamurthy, S. Lord of the Links: A Framework for Discovering Missing Links in the Internet Topology. IEEE/ACM Transactions on Networking 17, 2 (2009), 391–404.
[17] Labovitz, C., Malan, G. R., and Jahanian, F. Internet Routing Instability. *IEEE/ACM Transactions on Networking* 6, 5 (1998), 515–528.

[18] Lad, M., Massey, D., Pei, D., Wu, Y., Zhang, B., and Zhang, L. PHAS: A Prefix Hijack Alert System. In *Proc. of USENIX Security Symposium* (2006), vol. 15.

[19] Leiner, B. M., Cerf, V. G., Clark, D. D., Kahn, R. E., Kleineberg, L., Lynch, D. C., Postel, J., Roberts, L. G., and Wolff, S. A Brief History of the Internet. *ACM SIGCOMM Computer Communication Review* 39, 5 (2009), 22–31.

[20] Li, J., Guido, M., Wu, Z., Purpus, E., and Ehrenkranz, T. BGP Routing Dynamics Revisited. *ACM SIGCOMM Computer Communication Review* 37, 2 (2007), 5–16.

[21] Li, L., Alderson, D., Willinger, W., and Doyle, J. A First-principles Approach to Understanding the Internet’s Router-level Topology. *ACM SIGCOMM Computer Communication Review* 34, 4 (2004), 3–14.

[22] McGregor, T., Braun, H.-W., and Brown, J. The NLAMR Network Analysis Infrastructure. *IEEE Communication Magazine* 38, 5 (2000), 122–128.

[23] Miltenburg, W. A. Research on RIS Route Collectors. https://labs.ripe.net/Members/wouter_miltenburg/Researchpaper.pdf.

[24] Moore, D., Shannon, C., Voelker, G. M., and Savage, S. Internet Quarantine: Requirements for Containing Self-propagating Code. In *Proc. of IEEE INFOCOM* (2003), vol. 3, pp. 1901–1910.

[25] Norton, W. B. *The Internet Peering Playbook: Connecting to the Core of the Internet*. DrPeering Press, 2014.

[26] Oliveira, R., Pei, D., Willinger, W., Zhang, B., and Zhang, L. The (In)Completeness of the Observed Internet AS-level Structure. *IEEE/ACM Transactions on Networking* 18, 1 (2010), 109–122.

[27] Qiu, J., Gao, L., Ranjan, S., and Nucci, A. Detecting Bogus BGP Route Information: Going Beyond Prefix Hijacking. In *Proc. of SecureComm* (2007), pp. 381–390.

[28] Quagga Routing Suite. http://www.nongnu.org/quagga/.

[29] Rekhter, Y., Li, T., and Hares, S. RFC 4271 - A Border Gateway Protocol 4 (BGP-4), 2006.

[30] RIPE NCC RIPEstat. https://stat.ripe.net/.

[31] RIPE NCC Routing Information Service. http://www.ripe.net/data-tools/stats/ris/routing-information-service.

[32] University of Oregon Route Views Project. http://www.routeviews.org.

[33] XORP. http://www.xorp.org/.

[34] Yegneswaran, V., Barford, P., and Ullrich, J. Internet Intrusions: Global Characteristics and Prevalence. *ACM SIGMETRICS Performance Evaluation Review* 31, 1 (2003), 138–147.

[35] Zhang, Z., Zhang, Y., Hu, Y. C., and Mao, Z. M. Practical Defenses Against BGP Prefix Hijacking. In *Proc. of ACM CoNEXT* (2007), pp. 1–12.