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INSTITUTO DE INFORMÁTICA
PROGRAMA DE PÓS-GRADUAÇÃO EM COMPUTAÇÃO

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Improving Internet Cartography from a Different Point of View

PhD Work Plan

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Porto Alegre
October 2018

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CONTENTS

1 INTRODUCTION

This document presents a research plan in the context of Internet measurements, to be developed during the PhD, in cooperation with Kimberly Claffy[1] and Bradley Huffaker[2]. It follows the context of an ongoing collaboration with the same group at CAIDA/UCSD, because of another PhD student.

Context. Recently, Autonomous Systems (ASes) are interconnecting their networks at peering infrastructures, such as Internet Exchange Points (IXPs) and colocation facilities (GIOTSAS et al., 2015) to achieve efficient and resilient traffic delivery (YAP et al., 2017; SCHLINKER et al., 2017; MARCOS et al., 2018). These infrastructures simplify interconnection among networks within a region, improving network performance with lower latencies and better routing efficiencies (e.g., fewer AS hops for end-to-end paths) (CHATZIS et al., 2013b). The possibility for direct interconnection between ASes makes inter-domain traffic to bypass transit providers and flow directly between edge networks, flattening the Internet's hierarchical structure (LABOVITZ et al., 2010).

Relevance of geolocation information. Understanding the developments in the Internet topology is crucial to achieving the goals of network performance and resilience. Such task is challenging due to the growing complexity of networking infrastructure and security aspects (GIOTSAS et al., 2015). Geolocation inferences about peering interconnection (e.g., multilateral agreements (GIOTSAS et al., 2013)) and topology elements (e.g. router IP addresses (SCHEITLE et al., 2017; HUFFAKER; FOMENKOV; CLAFFY, 2014)) can enhance the understanding of the dynamics of Internet traffic, improve traffic delivery and infrastructure planning (CALDER et al., 2013), and increase responsiveness to outages and attacks (GIOTSAS et al., 2017; MARCOS et al., 2018).

Current limitations. There is currently no methodology that generates geolocation inferences about peering interconnections or topology elements accurately while being scalable. The two types of approaches (i.e., active or passive) fail to attend both requirements at the same time. Measurement-based geolocation methodologies (active) provide accurate results, but rely on a high number of vantage points (i.e., hosts with known locations) from measurement infrastructures as Ark (CAIDA. . . , 2018) or RIPE Atlas (RIPE. . . , 2018) to geolocate targets on the Internet via active probing. It generates a large volume of incoming traffic to the targets, produces a massive amount of collected data and is a time-consuming task to collect data and generate geolocation inferences,

[1] <http://www.caida.org/~kc/>
[2] <http://www.caida.org/~bhuffake/>

which makes it not scalable. On the other hand, passive approaches (e.g., geolocation databases) presents solutions readily available to users but highly depends on a combination of hostname hints, domain registry information, and other heuristics to obtain geolocation knowledge. Generally, the exact methodology for generating the results of these approaches are proprietary. These characteristics make the majority of the geolocation conclusions to be inaccurate and unreliable.

IXPs. In this context, IXPs emerge as potential candidates to improve the mapping of the Internet, due to the capacity of performing both approaches. These infrastructures play a global role in the Internet's topology because they hold large volume of information on data and control planes and carry traffic from a significant fraction of the Internet (CHATZIS et al., 2013a). They are increasingly being deployed all over the world, supporting a growing number of network members and peering interconnections (GIOTSAS et al., 2017). The available data and growing interconnection of ASes in IXPs enable higher visibility and knowledge about the all the connected networks and topology elements, showing potential in generating geolocation inferences.

Proposal. In this plan, we will investigate the potential of IXPs as anchors to improve the Internet mapping and generate geolocation inferences of peering interconnections and topology elements. We aim to produce a hybrid approach combining the benefits of both active (i.e., accuracy) and passive (i.e., scalability) solutions. Our method intends to correlate data from active measurements performed from inside of the IXP with analysis of already existing information from control and data planes (e.g., BGP) to produce geolocation knowledge.

Our goal is to develop a methodology that is, at the same time, *accurate*, *scalable* and *systematic*. More specifically, it must be: (i) *accurate* by providing valid, correct and reliable geolocation conclusions; (ii) *scalable* by using few but key vantage points and generating little processing and networking overhead; and (iii) *systematic* by not relying in complex and ad-hoc solutions and being easily usable by researchers and network operators. We plan to deploy and validate our methodology using the Brazilian IX ecosystem, to which we have access.

Expected contributions. We believe that leveraging IXPs as scalable vantage points will provide greater visibility and understanding about the geolocation of peering interconnections and network elements. The proposed work expects to generate the following benefits: (i) improvement on the mapping of peering interconnections and topology elements; (ii) discovery of gaps in existing physical and measurements (BGP) infrastructures; (iii) identification of how connectivity between ASes varies in developing areas (e.g., Latin America) and across different regions, and (iv) enhancement on knowledge about topology redundancy. We expect that by improving the geolocation inferences of peering interconnections and topology elements, events involving Internet topology that impact user experience or disrupt services ('ROUTER. . . , 2018; ROUTER. . . , 2015; NANOG. . . , 2018) will be repaired faster and more efficiently.

Outline of the proposal. Chapter 2 provides background and terminology. Chapter 3 presents the state-of-the-art and the main related work. In Chapter 4, we present the proposal work. In Chapter 5, we show the expected methodology, set of steps and schedule. Chapter 6 provides the expected results and main contributions. Finally, in Chapter 7, we present the expected coursework of the Ph.D. course.

2 PEERING INFRASTRUCTURES

Peering infrastructures are comprised of both Internet exchange points (IXP) and colocation facilities. They are responsible for exchanging a growing volume of traffic between different networks, support thousands of network members, and are widely available all over the world.

2.1 Internet Exchange Points

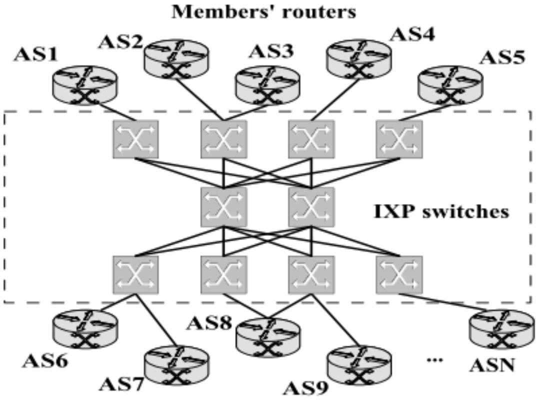
Internet Exchange Points are physical network infrastructures where a set of autonomous systems can interconnect their networks to exchange traffic. Figure 2.1 shows a typical IXP architecture. IXPs provide a shared switching fabric where participating networks can interconnect their routers. The switch fabric carries the traffic resulting from public and private peering of all interconnected ASes. Each IXP provides one or more *core switches* in the shared fabric for redundancy. They also associate with several Colocation Facilities and install *access switches* to reach city-level interconnection with other networks (GIOTSAS et al., 2015).

Historically, IXPs can be considered as the successors of Network Access Points (NAPs), which were responsible for the smooth transition from the monolithic government network to the modern Internet (CHATZIS et al., 2013b). Since 1995, the four existing NAPs have been replaced by more than 850 IXPs in 200+ cities around the world, interconnecting 50k+ networks (INTERNET. . . , 2018; AGER et al., 2012; GIOTSAS et al., 2015).

Studies reveal that existing Internet Exchange Points are responsible for transferring amounts of data similar to Tier 1 Internet Service Provider (ISPs) (AGER et al., 2012). Chatzis et al. (CHATZIS et al., 2013a) report that one of the largest European IXPs can observe traffic from a large portion of the Internet, including 42K+ routed ASes, almost all 450K+ routed prefixes and around a quarter billion IP addresses from all the countries around the globe.

Richter et al. (RICHTER et al., 2014) point a growth of 10-20% annually in the membership rates of ASes connecting in IXPs and of 50-100% per year in traffic rates. Kotronis et al. (KOTRONIS et al., 2015) show that about 40% of IP prefixes advertised on the Internet can be reached directly from around 5 IXPs. Besides, despite the focus to deploy peering infrastructures in Europe and USA (CHATZIS et al., 2013b; CHATZIS

Figure 2.1: A typical IXP architecture (AGER et al., 2012)



et al., 2015), studies reveal that developing regions as Latin America, and Africa are recently increasing the adoption of IXPs to enhance network performance (BRITO et al., 2016; FANOU; VALERA; DHAMDHERE, 2017).

2.2 Colocations Facilities

Colocation facilities (Colos) are physical locations which provide essential infrastructures like power, space, cooling, physical security, and storage to their associated autonomous systems. More specifically, it is a place where operators of multiple networks place their networking equipment for interconnection (INTERCONNECTION. . . , 2014). The provided amenities lower the infrastructure costs and drive small and medium providers to house their equipment (storage, server, routers) in the Colos.

The Colos platform connects the member's network to various IXPs, transit networks, cloud/content providers and other ASes in multiple locations worldwide. In large metropolitan areas, a colocation facility operator may install various facilities in the same city, interconnected, to allow access from ASes present at one facility to networks at another facility in the same region (GIOTSAS et al., 2015). Large carrier-neutral companies such as Equinix and Telehouse are the leading operators of colocation facilities all over the world (KOTRONIS et al., 2017).

3 RELATED WORK

We now present the state-of-the-art on the main topics related to the proposed work. In Section 3.1 and Section 3.2, we present the efforts to improve the accuracy of mapping peering interconnections and topology elements to physical locations, respectively. The work mentioned in these sections shows vast potential and opportunity to improve the generation of geolocation inferences. Current solutions either rely on a large number of active measurements and decentralized probes to achieve accurate results or provide rich inferences for just a subset of topology elements.

3.1 Mapping of peering interconnections and infrastructures

Measuring and mapping the Internet at AS-level is valuable to understand the underneath structure of the topology. However, it considerably abstracts rich information about connectivity between networks at the Internet. Accurate knowledge of interconnection geolocation helps network troubleshooting, outage detection, and attack diagnosis. Recent efforts attempt to infer peering matrices (i.e., who peers with whom at which IXP) and map interconnections to physical locations where they occur.

Augustin et al. (AUGUSTIN; KRISHNAMURTHY; WILLINGER, 2009) proposes a method to detect IXPs, identify IXP-specific peering matrices and better understand the IXP substrate of the Internet's AS-level ecosystem. The mechanism detected 278 IXPs and discovered the existence of about 44K IXP-related peering links. However, the method is costly both in time and number of active measurements. Kotronis et al. (NOMIKOS; DIMITROPOULOS, 2016) extend the traceroute tool with the capability of inferring if and where an IXP was crossed. Results show that approximately one out of five paths crosses an IXP and that IXP-paths usually cross no more than a single IXP.

Giotsas et al. (GIOTSAS et al., 2015) propose an algorithm to infer the physical interconnection facility where an interconnection occurs among all possible candidates. The methodology provides accurate results but is unable to scale to large scenarios involving several colocation facilities, IXPs and ASes, given a large amount of active probing resources needed. The initial process of mapping networks and IXPs to facilities, required by the methodology, is manual and time-consuming to be developed/updated.

3.2 Mapping of topology elements

The geolocation of network elements, mainly mapping the IP addresses of routers to physical locations with precision is a crucial task. Precise knowledge of router geolocation helps to detect BGP threats, estimate the geographic presence of ASes and customize content delivery. It is possible to geolocate IP addresses through public or commercial databases, delay-based or DNS-based methods.

Gharaibeh et al. (GHARAIBEH et al., 2017) compare router geolocation coverage and reliability in four popular geolocation databases. The authors show that despite having a high coverage at country-level, databases are not accurate in geolocating routers at neither country- nor city-level, even if they agree significantly among each other. Poese et al. (POESE et al., 2011) evaluates five IP geolocation databases. The results show that the vast majority of entries in the databases are biased to few popular countries. For example, a single country (e.g., United States) concentrates more than 45% of the entries in these databases. Besides, the entries do not reflect official IP allocations and BGP routing tables.

Topology-based Geolocation (TBG) (KATZ-BASSETT et al., 2006) converts Internet route measurements from landmarks to target into constraints to geolocate the target and all of the routers along the path. The drawback is that the methodology is very sensitive to measurement errors, such as inflated latencies. GeoPing (PADMANABHAN; SUBRAMANIAN, 2001) uses active delay measurements and needs landmarks with known geographic locations to geolocate a target host. It combines measurements to estimate the coordinates of a host. However, the geolocation of a target can only be accurately predicted if there is a landmark near the target host.

The work of Huffaker et al. (HUFFAKER; FOMENKOV; CLAFFY, 2014) and Scheitle et al. (SCHEITLE et al., 2017) propose methods to geolocate routers based on geography-related strings in hostnames and validate the results with active measurements from different decentralized probes. Despite showing accurate results, the scope of both proposals is restricted since only a small subset of routers have apparent geographic hints in their DNS names. For example, (HUFFAKER; FOMENKOV; CLAFFY, 2014) mention that only 3.6M of nearly 19M nodes ($\sim$19%) in their dataset have apparent geographic hints in their DNS names.

4 PROPOSED WORK

The recent studies on the characteristics of Internet Exchange Points show the potential of these infrastructures for the emergence of new solutions involving Internet mapping. Their central roles in topology enable higher visibility and knowledge about the network, showing potential in generating geolocation inferences.

This Ph.D. work plan seeks to investigate techniques to explore Internet Exchange Points as vantage points to improve the Internet mapping and generate geolocation inferences of peering interconnections and topology elements. We aim to produce a hybrid approach combining the advantages of both active (i.e., accuracy) and passive (i.e., scalability) solutions. First, our method intends to perform active measurements campaigns from inside of the IXP to obtain a preliminary geolocation knowledge about the Internet topology. Next, we plan to gather already collected information on control and data planes (e.g., BGP) and correlate with the active measurement data previously obtained to increase the accuracy of the generated inferences. Finally, we will use other available public and private data sources (e.g., flow samples) to validate our results.

Our goal is to develop a methodology that is, at the same time, *accurate*, *scalable* and *systematic*. More specifically, it must be: (i) *accurate* by providing valid, reliable, and correct geolocation conclusions; (ii) *scalable* by using few but key vantage points and generating little processing and networking overhead; and (iii) *systematic* by not relying in complex and ad-hoc solutions. We intend to produce a methodology that can be used by academia and industry for the development of new research and by network operators to apply to practical situations. We plan to deploy and validate our methodology using the Brazilian IX ecosystem, to which we have access.

First, we aim to enhance geolocation inferences in developing regions such as Latin America, which show rich, but weakly examined, peering infrastructures (IX. . . , 2018; BRITO et al., 2016). Next, we aim to extend our methodology to other worldwide available IXPs and develop a better understanding of the geolocation characteristics of these infrastructures in the Internet Topology.

Research Questions. In this work, we aim to answer the following research questions: can IXPs be used as vantage points to generate geolocation inferences about peering interconnections and Internet topology? How can we obtain accurate geolocation of infrastructure elements from inside the IXP? Is it possible to correlate active measurement data with collected information on control and data planes (e.g., BGP) to improve the

Internet cartography? Which and how many IXPs are necessary to have a precise vision of the Internet? What are the implications of using this approach concerning computational cost, network traffic, and privacy? How is it possible to measure in a scalable and automatized way?

Risks and limitations. There are a few challenges and risks in the proposed research. Due to the low representation of existing measurement projects in developing areas (e.g., Latin America), there could be gaps in infrastructure and methodologies which could affect our geolocation inferences. We could face performance problems as IXPs not being good vantage points (VP) to improve Internet mapping or providing inaccurate results when using few IXPs given that their visibility, individually, may not perfect. Besides that, we could also face bureaucratic challenges as IXPs could not see a clear advantage of being used as VPs.

5 METHODOLOGY

We now present the methodology, schedule, and collaboration of the proposed work. First, we outline the main steps needed to develop the research described in this plan (Section 5.1). Next, in Section 5.2, we detail a proposed schedule for the entire Ph.D. period, composed of actions and their expected duration. Finally, we conclude describing the intended collaboration with one of the leading research groups in the topic of the Ph.D. plan (Section 5.3).

5.1 Steps

1. **Monitoring and study of state-of-the-art**: we will perform an in-depth state-of-the-art study and monitoring of themes related to the work during all the duration of the Ph.D. Also, in the initial period of the course, we will conduct a detailed examination and reproduction of the main related existing methodologies.
2. **Methodology modeling**: in this step, we will develop a systematic methodology using IXPs as vantage points to map and produce geolocation inferences, seeking to answer the proposed research questions. Also at this stage, we will analyze the potential data to be used and design the data collection campaigns and data preparation.
3. **Data collection**: in this phase, we will perform the data collection. At this stage, we will execute active measurements campaigns and collect data already available from different sources. More specifically, we will perform active measurements from inside of the IXP to obtain a preliminary geolocation knowledge about the Internet topology. Next, we will gather already collected information on control and data planes (e.g., BGP) and correlate with the active measurement data previously obtained to increase the accuracy of the generated inferences.
4. **Data preparation**: in this point, the collected data will be preprocessed and prepared, including the combination of data from different sources, to serve as input for the proposed methodology. The collection of control plane information (e.g., BGP) and measurements campaigns tends to generate a significant amount of data. In order to process all data efficiently and without imposing resource and performance overheads to the IXP, we plan to use cloud environments (e.g., Azure) capable of

dealing with a massive volume of data.

5. **Methodology evaluation**: in this step, we will use de collected and preprocessed data to evaluate and validate the effectiveness of the developed methodology, identifying its features and limitations.
6. **Methodology validation**: the final step of the study, we will validate the obtained results of the proposed methodology. For the validation, we plan to contact network operators and IXPs, use privileged data from inside the IXPs as flow samples, make use of ground-truth datasets and include other sources of information to improve the verification of our results.

5.2 Proposed schedule

1. In-depth state-of-the-art study and monitoring about themes related with thesis;
2. Development of a systematic methodology using IXPs as vantage points to map and produce geolocation inferences;
3. Qualification Exam;
4. Examination of proficiency in English;
5. Examination of proficiency in a foreign language;
6. Data collection and preprocessing
7. Period reserved for doctorate sandwich;
8. Evaluation, review and reassessment of the proposed methodology;
9. Validation the obtained results of the proposed methodology;
10. Thesis Proposal Defense;
11. Improvement of the methodology considering the results obtained in previous activities, also considering contributions and recommendations of the evaluation committee of the thesis proposal;
12. Thesis writing;
13. Thesis defense;
14. Participation in conferences and symposia related to the theme of the thesis;
15. Writing and submitting articles for conferences and periodicals based on the results obtained during the studies and evaluations, related to the theme of this doctoral proposal.

Table 5.1: Schedule of activities during the Ph.D. period

Activities	2019/1	2019/2	2020/1	2020/2	2021/1	2021/2	2022/1	2022/2
1	■	■	■	■	■	■	■	■
2		■	■					
3		■						
4		■						
5		■						
6		■	■					
7			■	■				
8			■	■				
9				■	■			
10				■				
11					■	■		
12				■	■	■	■	
13								■
14	■	■	■	■	■	■	■	■
15	■	■	■	■	■	■	■	■

5.3 Collaboration

The proposed Ph.D. is joint work with the University of California San Diego (UCSD) in cooperation with Kimberly Claffy[1] and Bradley Huffaker[2]. The collaboration aims to expand the existing relationship between both universities and presents the opportunity for a sandwich doctorate. The second year of Ph.D. is expected to be located at CAIDA/UCSD. The funding for the away period is yet to be determined.

[1] <http://www.caida.org/~kc/>
[2] <http://www.caida.org/~bhuffake/>

6 EXPECTED RESULTS

We now present the expected results of the Ph.D. First, we describe the main contributions of the proposed work in Section 6.1. Finally, in Section 6.2, we present some of the leading journals (Table 6.1) in which the results obtained during the doctorate can be published and some of the main conferences related to the research areas involved in this plan (Table 6.2).

6.1 Main Contributions of the Thesis

The following contributions are expected with the development of the proposed work:

1. Analysis of the potential of Internet Exchange Points to be used as scalable vantage points to map and generate geolocation inferences, as well as its strengths and limitations;
2. Discovery of gaps in existing physical and measurements (BGP) infrastructures;
3. Identification of connectivity between ASes varies in developing areas (e.g., Latin America) and across different regions;
4. Enhancement on knowledge about topology redundancy;
5. Improvement in the efficiency of traffic delivery for ASes;
6. Formalization of a methodology to improve the mapping of peering interconnections and topology elements by exploiting the characteristics of the Internet Exchange Points, introducing new datasets and scalability;
7. Development of a prototype of the proposed methodology, allowing its applicability in practical situations and the development of new research investigations.

It is also expected that during the development of this work there will be the participation of master and scientific initiation students, performing work related to the doctoral thesis proposed in this plan. The participation in the training of these student's knowledge is then considered as one of the possible contributions.

6.2 Publications

The development of Ph.D. activities will generate results which will be used as a basis for the writing of articles for journals and congresses. Table 6.1 presents some of the main journals in which the results obtained during the doctorate can be published, while Table 6.2 presents some of the leading conferences of the research areas involved in this plan.

Table 6.1: Journals related to Ph.D.

Journal	**Impact Factor**	**Qualis**
Communications of the ACM	4.027	A1
IEEE/ACM Transactions on Networking	3.376	A1
Elsevier Computer Networks	2.516	A1
ACM CCR	2.008	B1

Table 6.2: Conferences related to Ph.D.

Conference	**Acceptance Rate**	**H-index**	**Qualis 2016**
ACM Internet Measurements (IMC) Conference	24.7%	75	A1
Network Traffic Measurement and Analysis Conference (TMA)	39.2%	–	–
Passive and Active Network Measurement Conference (PAM)	40.8%	–	A2
ACM Special Interest Group on Data Communication (SIGCOMM) Conference	18%	67	A1
ACM International Conference on emerging Networking EXperiments and Technologies(CoNEXT)	17.2%	35	A1
IEEE Conference on Computer Communications (INFOCOM)	20.9%	80	A1
USENIX Symposium on Networked Systems Design and Implementation (NSDI)	15.4%	62	A1

7 COURSEWORK

We now present the expected coursework to be taken in PhD course. Table 7.1 shows the courses and the number of credits that will be taken during the PhD. All courses sums a total of 20 credits, agreeing with the minimum required for the doctorate degree.

Table 7.1: Courses to be taken in PhD

Code	**Period**	**Period**	**Credits**
CMP410	Teaching Practice I	2019/1	1
CMP230	Computer System Security	2019/1	4
CMP182	Computer Network	2019/1	4
CMP411	Teaching Practice II	2019/2	1
CMP267	Novel Internet Architectures and Paradigms	2019/2	4
CMP223	Computer System Performance Analysis	2019/2	4
CMP600	Qualification Exam	2019/2	2

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