Advanced Geolocation Techniques and Geopolitical Integration for a Resilient Internet Infrastructure

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Abstract

Governments and institutions are alarmed by the number of recent incidents that have compromised the confidentiality, availability, and integrity of critical infrastructure and services, and exposed the fragility of the Internet architecture. BGP offers limited performance and security mechanisms to protect the integrity of exchanged routing information and to provide authentication and authorisation of the advertised IP address space. Instead, each AS operator implicitly trusts that the routing information exchanged through BGP is accurate. As a result, the Internet backbone is potentially exposed. To better inform BGP administrators when choosing their routing paths, this thesis seeks to improve and advance current geolocation techniques, integrating geopolitical considerations into IP routing and introducing new IPv4 and IPv6 tools. By examining three distinct but interrelated aspects - improving current IP geolocation methods - enabling data routing for end users and network administrators - introducing a new IPv6 method of IP geolocation - this research aims to contribute to a more secure, efficient, and geographically aware Internet infrastructure. The thesis begins with an investigation of current techniques for geolocating hosts using passive, active, and hybrid methods. This is followed by a survey of the fundamental problems that IP geolocation techniques must address. The survey points to the obvious difficulties in using Delay-Distance models and suggests that the use of Return-Trip Times can lead to highly misleading results. The thesis builds on this current work by introducing new procedures and methodologies to create fine-grained multilayer maps of the structure of the Internet. Next, the thesis explores the additional benefits that IPv6 can bring to IP geolocation. IPv6 introduces a significant evolution in the area of Internet Protocols which resolves many of the issues with the limitations of IPv4 and provides

an improved framework for the future of the Internet. The concept of extension headers is a feature that enhances the IPv6 protocol's flexibility and functionality, and it is key among these advancements. The thesis conceptualises the design of a new IPv6 extension header, which aims to incorporate a geopolitical dimension into each data packet, optionally allowing network paths to be dynamically adjusted based on country codes of transit networks. The thesis builds on this tool by developing a new IPv6 tool to map network infrastructure, aiming to surpass current methodologies in accuracy, comprehensiveness, and utility. The tool provides a more precise and comprehensive mapping of the network's topology, including geolocation data and peer connections of network nodes. The thesis discusses how we can build on these foundational tools by combining them to produce new fault-finding techniques and a robust network analysis methodology. These methods and tools will benefit BGP administrators by informing them of better routing decisions, helping to avoid possible single points of failure, and enhancing overall network resilience. Finally, we discuss some limitations of the proposed approach and summarise some next steps needed towards accurate and complete Internet infrastructure maps.

Acknowledgements

Acknowledgements you may want to make. **(this is not required when submitting your thesis before your viva and you can add a dedication in your final thesis after your viva if you wish.)**

Declaration

I declare that the work presented in this thesis is, to the best of my knowledge and belief, original and my own work. The material has not been submitted, either in whole or in part, for a degree at this or any other university. This thesis does not exceed the maximum permitted word length of 80,000 words, including appendices and footnotes, but excluding the bibliography. A rough estimate of the word count is: 36201

Paul McCherry

The publication shown below has been created directly from the thesis, from which large portions of this published work is used:

P. McCherry, V. Giotsas, and D. Hutchison (May 2023). "On Improving the Accuracy of Internet Infrastructure Mapping". In: *IEEE Access, vol 11.* Insititute Of Electrical and Electronic Engineers, pp. 59935–59953. DOI: 10.1109/ACCESS.2023.3281333

The following publications have been generated while developing this thesis, and to an extent have guided the thesis into what it has become:

H. Alshaer, N. Uniyal, K. Katsaros, K. Antonakoglou, S. Simpson, H. Abumarshoud, H. Falaki, P. McCherry, C. Rotsos, T. Mahmoodi, R. Nejabati, D. Kaleshi, D. Hutchison, H. Haas, and D. Simeonidou (2020). "The UK Programmable Fixed and Mobile Internet Infrastructure: Overview, Capabilities and Use Cases Deployment". In: *IEEE Access, Vol 8.* Insititute Of Electrical and Electronic Engineers, pp. 175398–175411. DOI: 10.1109/ACCESS.2020.3020894

S. Simpson, A. Farshad, P. McCherry, A. Magzoub, W. Fantom, C. Rotsos, N. Race, and D. Hutchison (Nov. 2019). "DataPlane Broker: Open WAN control for multi-site service orchestration". In: *2019 IEEE Conference on Network Function Virtualization and Software Defined Networks (NFV-SDN)*, pp. 1–6. DOI: 10.1109/NFV-SDN47374.2019.9040084

C. Rotsos, A. Marnerides, A. Magzoub, A. Jindal, P. McCherry, M. Bor, J. Vidler, and D. Hutchison (Nov. 2020). "Ukko: Resilient DRES management for Ancillary Services using 5G service orchestration". In: *2020 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)*, pp. 1–6. DOI: 10.1109/SmartGridComm47815.2020.9302980

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Chapter 1

Introduction

1.1 Background

A flourishing economy depends on a resilient Internet which is crucial for the advancement of a country, forming a backbone for modern society to progress and prosper, supporting businesses, fuelling innovation, and connecting communities. There is much more to network resilience than simply preventing network failures or disaster recovery. A resilient network acknowledges the inevitability of incidents, prioritising robust system design, rapid restoration of services, and pre-emptive planning to mitigate the impact of outages.

The Internet was originally designed to be resilient and capable of routing requests around outages, but in recent years, the growing use of Content Delivery Networks (CDNs), increased centralisation, and the trend toward Internet flattening are arguably affecting the intended resilient nature of the Internet (Gill, Arlitt, Li, and Mahanti, 2008) (Merrill and Narechania, 2023).

The latter paper (Merrill and Narechania, 2023) expresses concerns about the current trends of departing from the older decentralised Internet tier 1,2 and 3 model to a more flattened and concentrated Internet where CDNs establish their own proprietary networks directly with Internet Service Providers. Their results suggest that this flattening reflects a change in the topology of the Internet, and

argue that it is difficult to overstate the significance of this change for the structure of the Internet. They argue that this change means that the Internet has effectively shifted away from data packet transmission across the tier 1 providers and towards a network of CDNs. Although this new model has helped deliver better and more secure services to a wide range of countries around the world and enabled new applications such as streaming audio and video, it has not come without a cost. There are now central points of failure on the network that resist scrutiny and oversight. These CDNs are effectively black boxes that frustrate efforts to improve reliability.

Recent global outages such as Fastly (Duffy, 2021), (Rockwell, 2021), (Medina, 2021), the Akamai outage (Akamai, 2021) and more recently the Australian national outage arguably caused by Optus (Reuters, 2023), are becoming worryingly common.

The Internet is a vast and complex mesh of Autonomous Systems (ASs) with few tools and limited capabilities to measure the topology, leaving many aspects of the Internet structure as an opaque cloud. To understand, analyse and resolve Internet routing issues, researchers and network operators need to be able to view the routing topology; however, protocols have been designed in such a way as to mask many details of Internet operation (Merrill and Narechania, 2023). This lack of public visibility into the Internet's structure affects the effectiveness of risk assessments and disaster planning, which can have detrimental effects on security and reliability.

Current tools such as Traceroute to infer geolocation have been shown to have many limitations and challenges (Willinger and Roughan, 2013), whilst the use of BGP (Border Gateway Protocol) to map the Internet infrastructure results in many geolocation ambiguities (Winter, R. Padmanabhan, King, and Dainotti, 2019), (Giotsas, Smaragdakis, Huffaker, Luckie, and Claffy, 2015).

1.2 Motivations for Internet Cartography

A report by the UK National Cyber Security Centre (NCSC, 2021) highlighted the importance of the stability of IP-based networks and argued that the need for increased security of routing information that underpins the delivery of Internet services has increased dramatically. It is therefore paramount to develop appropriate methods and practices to make BGP more secure, thus maintaining the integrity of the routing system which relies almost exclusively on it. The European Network and Information Security Agency (ENISA) concluded in a 2015 report (ENISA, 2015) that the current lack of structural transparency is the biggest obstacle to addressing the inherent vulnerabilities and architectural shortcomings of the Internet routing system.

Knowledge of the geographical locations of the Internet infrastructure is a necessary requirement for cyber situational awareness. It can allow us to understand and mitigate risks related to topological vulnerabilities and design more resilient networks and routing policies (Motamedi, Rejaie, and Willinger, 2015). For example, the ability to predict what would happen if a colocation facility or Internet Exchange (IXP) fails can inform better fallback policies and more efficient resource allocation.

To develop appropriate prediction techniques, we must measure the relevant routing paths and infer the interconnection points traversed. Analysis of these paths can provide clues about connectivity changes that will prevent choke points, single point failures, or serious performance degradation due to the failure of a facility. Consequently, researchers and network engineers can design and evaluate new protocols and services or analyse the vulnerability of the network infrastructure.

Critics will argue that transparency reduces the amount of time that potential adversaries waste on finding relevant attack vectors and allows them to find the 'low hanging fruit' more quickly. However, transparency enables proactive identification and resolution of vulnerabilities before they can be exploited, reducing the overall attack surface. Transparency also fosters collaboration between security professionals, leading to faster and more effective solutions to emerging threats.

By exposing weaknesses, organisations can prioritise their defences, ensuring that security measures are robust and well-tested, rather than relying on obscurity, which can create a false sense of security. As data breaches show, determined attackers will find vulnerabilities regardless. Transparency allows defenders to stay ahead, closing gaps before they are widely exploited, and builds trust with stakeholders by demonstrating a commitment to security and accountability, which is essential in today's interconnected digital environment.

Although it is true that transparency can inform attackers, the greatest danger lies in relying solely on obscurity, which often results in overlooked vulnerabilities. A balanced approach that includes transparency, combined with strong and well-designed security measures, is more effective in the long term.

1.3 Thesis Outline

This thesis is organised as follows:-

Chapter 1 provides a background on the current state of IP Geolocation, the motivations, and the objectives of this thesis. Chapter 2 reviews the current methods and literature, while also providing the terminology and preliminaries of Internet cartography. In Chapter 3, we introduce and evaluate current methods and tools. Chapter 4 uses the tools and methods described in Chapter 3 to introduce and evaluate a new idea of using Internet Exchange Points as Vantage Points to get closer to populated areas, thus reducing overall error margins. Chapter 5 uses the methods described in Chapter 4 which creates Vantage Points from IXPs along with many other new ideas and methods to finally create fine-grained multilayer maps of the Internet infrastructure.

Chapter 6 introduces an advanced IPv6 network infrastructure mapping tool, designed to enhance and expand the capabilities of existing mapping tools such as traceroute.

Chapter 7 introduces an innovative IPv6 extension header that incorporates geopolitical awareness into network routing, which will provide network administrators and end users with some control over the route their data packets take across the Internet.

Chapter 8 discusses the tools and methods that have been proposed in this thesis, while Chapter 9 provides a conclusion and a look ahead to possible future work in this important area.

1.4 Objectives and Scope of the Thesis

The first section presents the current techniques in IP Geolocation and builds upon that research by developing new methods in IP infrastructure mapping with the ultimate goal of creating fine-grained multilayer maps of the Internet infrastructure that are currently lacking. The aims of this work are as follows.

In Chapters 1-5

- To extend DNS-based geolocation from city-level to facility-level and address shortcomings of the state-of-the-art tools with respect to their limited geographical coverage.

- Introduce a new technique to create constraints in DNS geohints inference. While past work has relied on RTT measurements, our work uses traceroute-derived constraints by combining IXP datasets with forward and reverse traceroute measurements to observe the bidirectional interfaces.

- Construct a data set of facility-level landmarks that can be used in future research work to improve RTT-based geolocation.

- To illustrate the applicability of our work by geolocating a number of IPs at the level of colocation facilities, and then show that our method can create detailed maps of interconnection infrastructures at large metropolitan Internet hubs including London.

- To evaluate the inferences and estimate its success using a carefully curated dataset obtained by two of the largest London IXPs.

In Chapter 6

- Introduce a new tool for mapping IPv6 network infrastructure, with the objective of surpassing current methodologies in accuracy, comprehensiveness, and utility.

- Detail the necessity for such a tool, discussing enhancements over existing technologies, outlining the proposed changes to network protocols and infrastructure,
- Demonstrate the tool's potential benefits for network analysis and troubleshooting.
- Attempt to offer a more detailed visualisation of the structure of the Internet, addressing both technical implementations and the broader implications for network research and administration.

In Chapter 7

- Design a new IPv6 extension header to conceptualise and detail the design of a novel header that incorporates geopolitical information in the form of country code bitfields.
- Evaluate technical feasibility and, if possible, to assess the practicality of implementing and deploying the new extension header in real-world network environments, considering current router capabilities and infrastructure
- Analyze security and privacy implications, critically examining the security and privacy concerns that may arise from the use of the proposed extension header, especially in the context of international data transmission and legal compliance.
- Study the impact of geopolitical routing, investigating the potential impacts and benefits of incorporating geopolitical considerations into IPv6 routing, from both technical and policy perspectives.

In Chapter 8

The thesis provides an extensive discussion on the tools and methods proposed in Chapters 1 and 5 and looks at the future of IP Geolocation based on the new ideas proposed in Chapters 6 and 7 and further discusses many of the security issues.

In Chapter 9

The thesis ends with the conclusions that can be drawn and points toward the next steps that need to be taken.

1.5 Contributions

Using existing state-of-the-art tools, new methods and procedures have been created to discover and develop finer-grained maps of the Internet infrastructure. These new methods can facilitate a better understanding of the resilience of the Internet infrastructure and allow for the prioritisation of robust system design, rapid restoration of services, as well as providing vital data for pre-emptive planning.

A new IPv6 extension header has been conceptualised and presented, which aims to incorporate a geopolitical dimension into each data packet, allowing administrators and end-users to dynamically adjust network paths based on country codes of transit networks. This addresses a growing need for data controllers and processors to comply with the data protection laws of each country.

A new IPv6 network infrastructure mapping tool has been conceptualised and presented which represents a significant step forward in addressing the limitations of current Internet mapping methodologies. The new tool paves the way towards the design of more sophisticated applications. This tool offers a more precise and comprehensive mapping of the Internet topology, including geolocation data and peer connections of network nodes. The proposed changes to the node information protocol, along with modifications to router kernels and installation procedures, underscore a holistic approach to improving the accuracy and utility of network mapping.

1.6 Chapters and Explanation of Material

This section explains the origin of material for the chapters in this thesis. Chapters 2, 3, 4 and 5 are based on material published in 'On Improving the Accuracy of Internet Infrastructure Mapping' (McCherry, Giotsas, and Hutchison, 2023) in which McCherry conducted the bulk of the research and technical work in the publication. The rest of the chapters were composed for the benefit of the thesis by McCherry.

Chapter 2

Related Work

This chapter introduces the terminology and preliminaries of mapping the Internet infrastructure and reviews the relevant literature on Internet cartography.

2.1 Traditional IP Geolocation Methods

Mapping network infrastructure has been a foundational aspect of understanding and optimising the Internet's functionality, with various tools and methodologies developed over the years to explore and document this complex landscape. The early tools and techniques involved tools such as Ping, which was designed to measure the reachability of hosts across an IP network. Ping works by sending ICMP (Postel, 1981) "echo request" packets to the target host and listening for "echo response" replies. Ping has been instrumental in diagnosing network connectivity issues. Traceroute was developed in 1988 and allows the mapping of the path of packets through an IP network in transit to their destination. The traceroute program incrementally sets the Time To Live (TTL) values of subsequent ICMP packets and then observes the node where the packet is dropped, which is revealed through ICMP REPLY "time exceeded" messages. The REPLY messages contain the IP address where the packet was dropped, and traceroute measures the time delay between sending the REQUEST packet and receiving the REPLY packet.

Furthermore, ICMP messages have been used in various network diagnostic tools to map network infrastructure by identifying active hosts and potential routing issues. However, the use of Ping and Traceroute to map the Internet infrastructure has been shown to produce many small to large errors over the years (Motamedi, Rejaie, and Willinger, 2015), (Willinger and Roughan, 2013), (Oliveira, Pei, Willinger, B. Zhang, and L. Zhang, 2010). This has not deterred researchers from attempting to improve IP geolocation using a host of various methods based on these tools.

IP-based geolocation maps an IP address to the geographical location of a real-world Internet-connected device. IP geolocation can attempt to map an IP address to different granularities, including latitude and longitude, interconnection facility, metropolitan area, or country. IP geolocation methods can be broadly classified into three types: passive, active, and hybrid.

2.1.1 Passive IP Geolocation

Passive methods involve the collection and synthesis of geolocation information from databases and websites. For example, Domain Name Service (DNS) LOC records are DNS records proposed in 1996 in RFC1876 (Davis, Vixie, Goodwin, and Dickinson, 1996) that are designed to hold the geographical coordinates of the IP address host. However, they are rarely created by administrators (Graham-Cumming, 2014).

Another source of passive geolocation data is the WHOIS protocol (Daigle, 2004), which stores information on the owners of Internet resources, including IP addresses. Among this information is often the address of the organisation or individual to which an IP address is assigned. WHOIS servers are operated by the five Regional Internet Registers (RIRs), which are also responsible for the allocation and registration of Internet resources. However, it is often left to network administrators to update the information, which can become outdated without timely maintenance. In addition, WHOIS maps IP addresses to a registered administrative location, which may not reflect their actual location.

Geofeeds, another example of passive IP geolocation, are self-published IP

geolocation data that provide geolocation coordinates and are described in the Internet Engineering Task Force (IETF) RFC8805 (Kline, Duleba, Szamonek, Moder, and Kumari, 2020). Finally, several commercial geolocation services that use proprietary methods provide location data to subscribers, such as Maxmind (Maxmind, 2024), IP2Location (IP2location, 2024), and Neustar (Neustar, 2024). However, past research on the accuracy of these databases shows that commercial databases can be highly inaccurate (Gharaibeh, Shah, Huffaker, H. Zhang, Ensafi, and C., 2017) (Poese, Uhlig, Kaafar, Donnet, and Gueye, 2011) (Shavitt and Zilberman, 2011), especially for router and infrastructure IPs.

A technique used by many commercial IP geolocation companies is to build a database of mappings between Geolocation and IP addresses over time. This data can come from many sources such as end users, the results of traceroute projects, DNS lookups, and other sources, however, geolocation databases are notoriously difficult to keep up to date, and their accuracy depends on the source and age of the data they reference (Poese, Uhlig, Kaafar, Donnet, and Gueye, 2011).

2.1.2 Active IP Geolocation

Active IP geolocation is based on network-level latency measurements between a node with a well-known location (landmark) and the IP address that must be geolocated. Assuming that the Speed of the Internet (SoI) is known, the latency can then be translated to the distance from the landmark (V. Padmanabhan and Subramanian, 2001). Although active geolocation tends to be more accurate than passive geolocation, it incurs a much higher measurement overhead, and it is hard to scale to geolocation of millions of IP addresses. Additionally, the SoI is not fixed, but depends on the transmission medium and the network conditions. Geoping is one of the earliest active geolocation techniques introduced in 2001 by Padmanabhan and Subramanian. Geoping measures the latency between multiple landmarks and creates a latency vector for each landmark. It then measures the latency from all the landmarks to the target IP and geolocates it to the landmark with the most

similar latency vector.

In 2006, 'Constraint-Based Geolocation' (CBG) was proposed as an improvement of Geoping (Gueye, Ziviani, Crovella, and Fdida, 2006). CBG also employs measurements from multiple landmarks but combines the measured delays using multilateration, which can geolocate IPs not only in the locations of the landmarks but also in the area between them. In 2022 a new algorithm based on router error training was proposed (Zu, Z. Luo, and F. Zhang, 2022), which requires an exhaustive mapping of the Metropolitan Area Network (MAN) of the city where the target IP should be located to infer its street address location. Although this technique achieves high accuracy, it is limited to cities with a suitably large number of measurement vantage points.

2.1.3 Hybrid IP Geolocation Methods

Hybrid IP Geolocation techniques aim to combine passive and active geolocation to alleviate their individual limitations. To depart from oversimplified models, it has been argued that it is necessary to identify the geolocation of Internet infrastructure (NCSC, 2021), which would provide a useful tool for detecting poor routing structures and understanding why damaging routing events occurred. A method in which a combination of data sources could be used, such as crowd-sourcing, reverse DNS records, tagged naming schemes, Return Trip Time (RTT) delay-distance models, and Internet exchange points, was proposed. The following methods attempt to use one or more of these data sources.

In "Topology-Based Geolocation" (TBG), the authors argue that the directness of a network path from a landmark to a particular target cannot be predicted, and a single conversion factor for the entire network is not sufficient to capture the intricate details of the network topology and routing policy (Katz-Bassett, John, Krishnamurthy, Wetherall, Anderson, and Chawathe, 2006). This method also uses multilateration, as used in CBG, but issues traceroute measurements instead of pings to map the entire IP path between a landmark and the target IP. The intermediate

IP hops are geolocated using location hints in their reverse DNS records, allowing more detailed knowledge of the network and the traversed locations.

Spotter is a model-based active geolocation service and uses a probabilistic approach to derive a generic model of the relationship between network delay and geographic distance rather than using a predetermined SoI value or separate calibration data for each point of reference (Laki, Mátray, Hága, Sebok, Csaba, and Vatta, 2011). This delay distance model was then used to geolocate an IP address. The authors of "Towards street-level client-independent IP geolocation" refined the granularity of CBG to achieve street-level geolocation (Wang, Burgener, Flores, Kuzmanovic, and Huang, 2011). To this end, they mine web-based geolocation hints for locally hosted web servers to significantly expand the list of passive landmarks. They tried to leverage the observation that "many entities host their Web services locally", but since then the trend of cloud-hosted services and resource centralisation certainly inhibit the applicability of their technique.

The developers of Octant claim that it is a comprehensive framework for the Geolocalization of Internet Hosts and that it considers the locations of intermediate routers as landmarks to geolocate the target (Wong, Stoyanov, and Sirer, 2007). Furthermore, Octant considers both positive and negative constraints, which define where the node can and cannot be. Then it tries to geolocate the target IP as an error minimisation constraint satisfaction problem. Although Octant achieves better accuracy than CBG, the authors noted that extracting useful positive and negative information is a challenge. In contrast to CBG and TBG, the authors allowed for circuitous routes and used intermediate routers as secondary landmarks to reduce the latency errors caused by this issue. Octant refers to a proprietary database of router DNS names for geographical locations to use routers as secondary landmarks. Their conclusion was that in many cases the closer the landmark, the greater the accuracy, which is a common finding in all active geolocation methods.

RIPE ATLAS is a multiengine geolocation platform operated by RIPE NCC that uses active IP geolocation as well as passive methods to locate the geographical

coordinates of the targets (RIPE, 2015). One of the ATLAS geolocation engines uses a method called Single Radius, which first finds the AS that announces the prefix that contains the target IP, and then locates the RIPE Atlas probes that are close to the target IP. Pings are then sent from these probes, and any delays of more than 10ms are discounted. The probe with the minimum latency to the target IP is then selected, and the distance is calculated using the signal transmission speed through the optical fibre of 0.66c. All cities within this distance from the probe are then ranked by numerous factors, such as population density, and the highest-ranked one is inferred as the location of the IP. A major problem is that RIPE probes are heavily biased toward Europe and North America and become quite sparse in Latin America, Asia, and Africa. This may indicate that other methods, such as the shortest ping or CBG, yield comparable results in these regions.

New approaches involve the use of the Border Gateway Protocol (BGP), which is the protocol used to make routing decisions between Autonomous Systems (AS) on the Internet. BGP was not designed as a mapping tool, but data derived from BGP tables by researchers haa been crucial to understanding the topology of the Internet at a macro level (Giotsas, Smaragdakis, Huffaker, Luckie, and Claffy, 2015). Projects such as RouteViews (RouteViews, 2024) and RIPE NCC (RIPE, 2015) have aggregated BGP information to analyse and visualise Internet paths and interconnections between ISPs. Giotsas et al. developed a method known as Constrained Facility Search (CFS), which combines data from various sources such as Internet Exchange websites, PeeringDB, and traceroute measurements to infer the connection facility of a specific IP address (Giotsas, Smaragdakis, Huffaker, Luckie, and Claffy, 2015). Using this method, they were able to locate 71% of the router interfaces to a specific facility.

Scheitle et al. (Scheitle, Gasser, Sattler, and Carle, 2017) developed a method called Hints-Based Geolocation (HLOC) (Scheitle, Gasser, Sattler, and Carle, 2017), which extracts geohints from router DNS names, similar to Octant (Scheitle, Gasser, Sattler, and Carle, 2017). It then validates these hints by selecting several RIPE

Atlas probes based on the extracted geohints and measuring the RTT values between them and the domain. This solution compares a previously compiled database of router DNS names and codes with target DNS names. Interestingly, the authors investigated and proposed a latency delay of 9ms over a maximum distance of 900km to accommodate packet buffering, processing, and scheduling delays. If total latency is considered low, the target geocoordinates are assumed to be those of the router, and the hint provided by the router's DNS name is verified.

Motamedi et al. extended the geolocation of interconnection facilities to private and cloud interconnections using the Belief Propagation algorithm on a specially defined Markov Random Field graphical model (Motamedi, Yeganeh, Chandrasekaran, Rejaie, Maggs, and Willinger, 2019).

Livadariu et al. (Livadariu, Dreibholz, Al-Selwi, Bryhni, Lysne, Bjørnstad, and Elmokashf, 2020) identified that DNS names do not accurately map geolocations without improved lookup tables and proposed the use of Looking Glass servers as additional landmarks. They also investigated the accuracy of RIPE IPMAP against various methods, such as WHOIS, DNS, geolocation databases, and HLOC. They find that various approaches can disagree even at the country level and raise the point that organisations may be unaware of the countries through which their traffic is routed. They also found that geolocation databases fail to accurately locate IPs that belong to international ASes on many occasions, and that commercial geolocation databases appear to use information from WHOIS, which can often be wrong, as their primary source of data.

Luckie et al. demonstrated a significantly improved DNS for geolocation lookups by compiling an extensive list of regular expressions (Luckie, Huffaker, Marder, Bischof, Fletcher, and Claffy, 2021). Dan et al. applied Machine Learning to the task of learning DNS names and their locations, showing that their work significantly outperformed previous academic baselines and was complementary and competitive with commercial databases (Dan, Parikh, and Davison, 2021a).

In further research, Dan et al. proposed an IP geolocation technique that exploits

the concept of IP interpolation, according to which if at least two IPs within a /24 prefix are in the same location, then all IPs in that prefix are also in that location (Dan, Parikh, and Davison, 2021b). In addition, they took advantage of the observation that there is a strong correlation between delay differences along a traceroute path and physical distance.

In-band Operations, Administration, and Maintenance (IOAM) is a network measurement and monitoring technology. IOAM is a relatively new approach that embeds data collection information directly into data packets as they traverse the network (Iurman and Donnet, 2020). This is a method that allows for detailed tracking and measurement of packet flows and offers granular insights into network performance and topology. IOAM enables devices to sample service traffic in real time at high speed, adds IOAM information (metadata, including the device ID, inbound and outbound interfaces, and timestamp) to the sampled data, and can proactively send the sampled data to an analyser for analysis. In this way, the network running status is detected and monitored in real time. IOAM is gaining traction and is supported by various network equipment manufacturers and standards bodies, but its deployment across the Internet is not uniform, and it is more commonly found in specific networks that prioritise detailed performance monitoring and operational visibility.

Over the years, several large-scale projects have aimed to map the Internet's infrastructure comprehensively. The Centre for Applied Internet Data Analysis (CAIDA) has conducted extensive research and mapping efforts (CAIDA, 2024), using a variety of tools, including Traceroute and BGP, to analyse Internet topology, connectivity, and performance issues. Another large-scale project, Internet Atlas, is an effort to map the physical infrastructure of the Internet, including cables and data centres, to better understand the physical underlying mechanisms of the global Internet (Berkeley, 2024). Measurement Lab (M-Lab) is a collaboration between researchers worldwide to collect open data on Internet performance in an effort to make the Internet's infrastructure more transparent (Mlab, 2024).

2.2 Challenges

Several past works determined that techniques that try to measure the Internet topology and geolocation IP addresses using traceroutes suffer several problems (Motamedi, Rejaie, and Willinger, 2015) (Willinger and Roughan, 2013), which we summarise in this section.

The first step in developing improved infrastructure maps is to investigate and assess the fundamental limitations of state-of-the-art Internet cartography. The scarcity of valid ground truth data sources is a classic problem in IP Geolocation. Motamedi et al. (Motamedi, Yeganeh, Chandrasekaran, Rejaie, Maggs, and Willinger, 2019) remark on the notoriety of a lack of ground-truth data sets. This scarcity of valid data sources means that researchers must rely on incomplete or coarse-grained abstractions of Internet topology. These abstractions miss many details of interconnections and render them largely irrelevant to real-world Internet engineering problems (Oliveira, Pei, Willinger, B. Zhang, and L. Zhang, 2010), and many of the findings based on simplistic models are controversial or misleading, due to the incompleteness and inaccuracies of the maps produced (Willinger and Roughan, 2013).

Layer 2 clouds are largely opaque to tools that use traceroutes. Willinger and Roughan found that Internet connections that appear to have trivial or simple IP layer topologies can have complex layer-2 topologies. Technologies such as Software-Defined Networking (SDN) and Multi-Protocol Label Switching (MPLS) can further complicate this situation by creating logical layer-2 and layer-3 networks without physical devices. Measurements often see only one layer, creating misunderstandings regarding the true resilience of a network. Furthermore, traceroute-based measurements can return the RTT of a proxy server, which may be several miles away. In fact, Padmanabhan and Subramanian (V. Padmanabhan and Subramanian, 2001) observed that a significant fraction of proxies clients were located several hundred to thousands of kilometres from the location of the proxies. Network delay measurements are oblivious to this and incorrectly return the location

of the proxy server.

Traceroute RTT includes both application-layer and network-layer delays, and if a measurement device is overloaded or underresourced, then the RTT times may be inflated. This is a problem that RIPE Atlas probes may encounter (especially older versions) (Holterbach, P, Randy, and Laurent, 2015).

The RTT can also be inflated by circuitous routes, which happen when the network path between two endpoints does not follow the shortest geographical path. For example, Figure 2.1 shows that an ICMP packet travels from Blackpool to Lancaster, through London and Manchester. Blackpool to Lancaster is approximately 40 km apart: however, this packet travels approximately 800 km one-way.

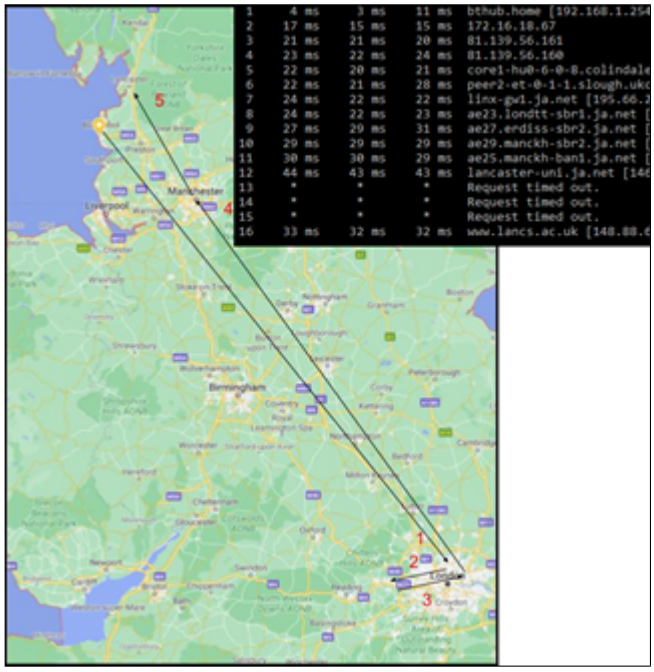


Figure 2.1: Example of circuitous route from Blackpool to Lancaster

Generally, the RTT is divided by 2 to give a delay approximation on the one-way journey; in this case, the RTT is 32ms, therefore, the one-way journey from Blackpool to Lancaster took approximately 16ms. The signal transmission speed through the optical fibre is estimated as .66 $\times$ speed of light (c), where the speed of light is approximately 3×10^8 metres per second. Dividing the distance of 40 km by 0.66c gives the time that the packet should have taken on a direct one-way journey

is 0.2 of a millisecond. However, we know that the packet travelled approximately 800 km on its one-way journey from Blackpool to Slough and returning north to Lancaster, which should have taken 4 milliseconds over this circuitous route. Therefore, the remaining 12 milliseconds should be allocated to packet scheduling, packet processing, interface delays, and other factors. Indeed, as pointed out by the authors of HLOC, they include a latency delay of 9ms to account for these issues.

Another complication of traceroute-based measurements is the diversity of infrastructure in different regions of the world (Candela, Gregori, Luconi, and Vecchio, 2019), leading to different delay coefficients. These delay coefficients are not only hard to estimate but also very dynamic, as the infrastructure and the related network phenomena can change very frequently.

2.3 Summary

Although active IP geolocation can provide real-time updates and requires no administrative upkeep, many active IP geolocation solutions employ active measurements, notably traceroute, to discover network interfaces and topology. However, the traceroute tool was designed primarily for troubleshooting and its use in network discovery is not what it was designed for. Therefore, the results cannot always be trusted.

Problems such as circuitous routes, different router configurations, route congestion, and technologies such as microwave links, SDN, ATM, and MPLS clouds can have varying effects on delay-based geolocation techniques. Passive methods suffer from out-of-date or completely incorrect information; therefore, both active and passive methods appear to have their own strengths and weaknesses. A hybrid mix of active and passive techniques has the potential to alleviate these weaknesses and offer the most accurate IP geolocation solutions.

To depart from oversimplified models, it has been argued that it is necessary to identify the geolocation of Internet infrastructure (Aben, 2013), which would provide

a useful tool for detecting poor routing structures and understanding why damaging routing events occurred. Aben proposed a method in which a combination of data sources could be used, such as crowd-sourcing, reverse DNS records, tagged naming schemes, RTT delay-distance models, and Internet Exchange Points.

The key contribution of the methods developed in Chapters 4 and 5 is that they will extend DNS-based geolocation from the city level to the facility level and address shortcomings of state-of-the-art geolocation techniques with respect to their limited geographical coverage. We showcase the applicability of our work by geolocating over a thousand IP addresses at the level of colocation facilities. Although the data set is small, to the best of our knowledge it is the first working prototype at this level of granularity and illustrates that our method can create detailed maps of interconnection infrastructures at metropolitan Internet hubs.

Chapter 3

Introduction of Geolocation and Routing Tools

3.1 Introduction

This chapter begins by introducing the tools used by researchers and analysts in the IP Geolocation arena and the current methods used and built upon by the tools developed in Chapters 4 and 5 of this thesis. It then examines and evaluates these current methods to ensure that there is a firm basis for the new tools developed later in this thesis.

3.2 OpenStreet Map

OpenStreetMap (OSM) (Openstreetmap, 2024) is an open-source project that creates a freely editable geographical database in which tags can be created to provide information about elements, as shown in Figure 3.1. It is used extensively in this thesis to portray geolocation data.

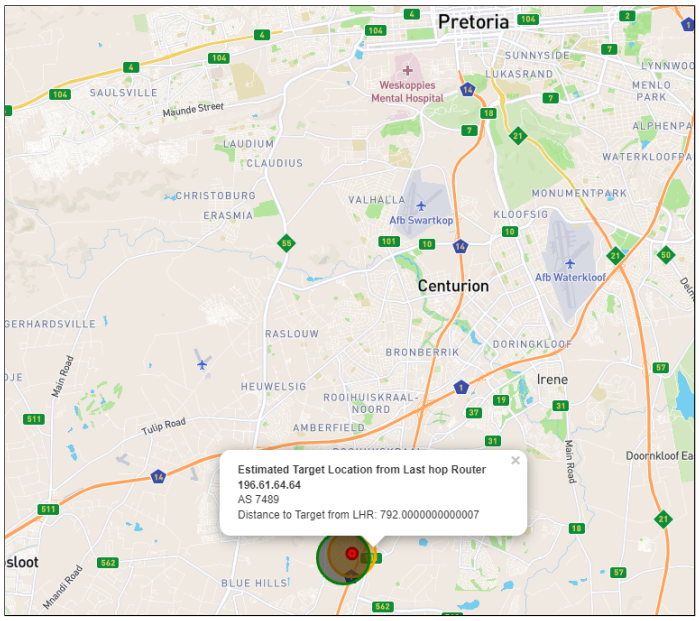


Figure 3.1: Example Element Tagging using PeeringDB and OpenStreetMap

3.3 Internet Exchanges

According to Motamedi et al. (Motamedi, Rejaie, and Willinger, 2015), the Point of Presence (PoP) is the ideal resolution for the geographical mapping of the network infrastructure. Motamedi described PoP as a concentration of routers that belong to an AS; however, for the purpose of this thesis, PoP is simply a facility where a router and its interconnections are housed. This thesis proposes a new method to map the Internet infrastructure using this PoP layer, starting with the discovery of the geolocation of each interconnection facility in the UK.

Internet Exchange Points (IXP) are key physical infrastructures in the Internet ecosystem. They allow Internet Service Providers (ISPs), content delivery networks (CDNs), and other large enterprise networks to interconnect directly, rather than through third-party networks. Direct interconnections serve multiple purposes in reducing costs, improving the latency of data exchange between networks, and improving bandwidth capacity whilst increasing redundancy and reliability of the Internet infrastructure. Data centres typically host IXPs, offering a central location in which to store their networking equipment, such as switches and routers that

facilitate the exchange of Internet traffic. Internet Exchange Points can be viewed as the main crossroads of a country's Internet communications and excel at keeping data local to that country.

Internet Exchanges consist of a set of switches through which participating Internet service providers, transit providers, and content delivery networks (CDN) exchange data. They are housed in colocation facilities, are generally located close to large populations, and are therefore essential to the Internet network infrastructure. IXPs connect the facilities where they interconnect at layer 2; therefore, data entering an IXPs network at one facility can traverse the IXP network and exit at any other facility where the IXP interconnects. There are two methods by which an organisation may wish to connect to an IXP, direct peering, or remote peering. Direct peering requires an organisation to have physical presence at a colocation facility where the IXP also has a presence, while remote peering allows an organisation to peer with the IXP using one of the IXP's partners, generally over layer 2 Multiprotocol Label Switching (MPLS) clouds.

Should a network wish to exchange traffic through an IXP, it is usually the case that a peering agreement is set up between two network operators. This ensures that the two network operators agree to exchange traffic between their networks without charging each other. However, the terms of these agreements can vary depending on the volume of traffic exchanged and the type of data. If traffic volumes are significantly unbalanced, then other compensation terms may be agreed. Once the agreements are in place, the networks are physically connected to the IXP switches. This connection can be made through a direct physical link if they have their own network equipment on site at the IXP location, or it can be connected using a virtual connection and facilitated by a third party.

Once physical connections are established, the networks can start exchanging traffic. Should a user request data from one network from a service on another network, the data can now be directly routed through the IXP, which bypasses transit over other, possibly distant, networks, reducing latency and providing a

better experience for the user. The Border Gateway Protocol (BGP) is used to route and manage traffic flow. IP address ranges are announced by networks using BGP to other networks, which allows for the efficient routing of data to its destination.

3.4 RIPE Atlas Platform

RIPE Atlas has been mentioned already, but in this chapter we discuss this platform in more detail as its use in this thesis has been of particular importance.

In 2010 the Reseaux IP Europeen's Network Coordination Centre (RIPE NCC) began developing the ATLAS platform, which collects information on Internet connectivity and reachability through thousands of measurement devices around the world (RIPE, 2015) to gain a better understanding of the state of the IP layer of the Internet in real time.

IP-based geolocation is the mapping of an IP address to the geographic location of a real-world connected device to the Internet. IP geolocation can involve mapping the device's IP address to latitude and longitude, country, region (city), or facility (premises) (Gueye, Ziviani, Crovella, and Fdida, 2006). Capturing an accurate view of the Internet topology can allow researchers and network engineers to design and evaluate new protocols and services or to analyse the vulnerability of network infrastructures (Motamedi, Rejaie, and Willinger, 2015).

One of the first IP Geolocation approaches developed was the Shortest Ping method (V. Padmanabhan and Subramanian, 2001), which chooses the landmark with the shortest Return Trip Time (RTT) to the target IP address as being the approximate geographical location of the target IP. Since then many researchers have attempted to improve the accuracy of IP geo-location (Katz-Bassett, John, Krishnamurthy, Wetherall, Anderson, and Chawathe, 2006) (Gueye, Ziviani, Crovella, and Fdida, 2006) (Scheitle, Gasser, Sattler, and Carle, 2017) (Wong, Stoyanov, and Sirer, 2007).

RIPE ATLAS developers designed their solution for geolocating the core Internet

infrastructure, IPmap's Single-Radius Engine, to incorporate the Shortest Ping method (Du, Candela, Huffaker, Snoeren, and Claffy, 2020). This requires a number of landmarks that are geographically close to the target IP Address (Du, Candela, Huffaker, Snoeren, and Claffy, 2020),(Katz-Bassett, John, Krishnamurthy, Wetherall, Anderson, and Chawathe, 2006),(Gueye, Ziviani, Crovella, and Fdida, 2006),(V. Padmanabhan and Subramanian, 2001). Therefore, the more landmarks, or 'probes' in IPmap's case, that are deployed in a specific region, the greater the chance that one is geographically close to the target of interest and therefore the greater the accuracy. RIPE's IPmap uses more than 11,000 probes worldwide and currently provides the largest number of landmarks for research, test, and troubleshooting purposes (RIPE, 2015).

In 2015 Giotsas et al. (Giotsas, Smaragdakis, Huffaker, Luckie, and Claffy, 2015) developed a method they named Constrained Facility Search (CFS) which infers the physical interconnection facility where an interconnection occurs. This is a hybrid method of geolocation relying on the passive collection of records from user maintained databases and Network Operating Centre websites, as well as active traceroute measurements carried out by the RIPE Atlas platform, LG servers, IPLANE Project and CAIDAs ARK platform. They also supplement this data with BGP queries from Looking Glass servers which gave them information about the peering router such as ASN and IP information. The authors claim that the accuracy of this method outperforms heuristics based on naming schemes and other IP geolocation methods.

3.5 Internet Topology Data Kit

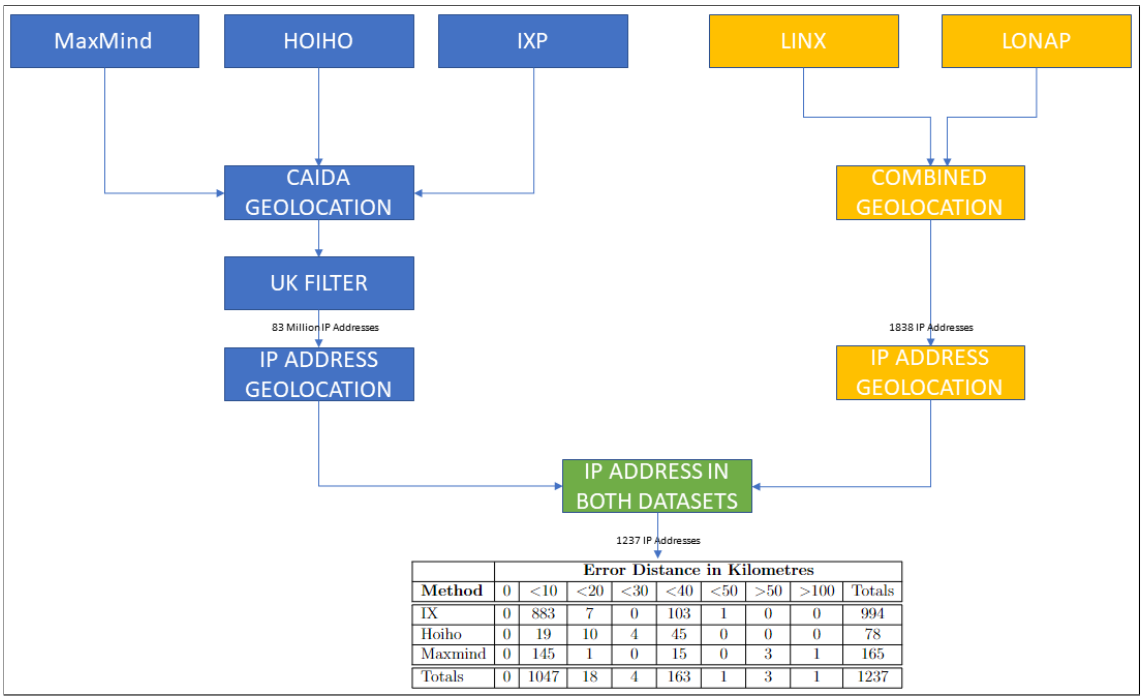
A primary concern of IP geolocation is the lack of ground-truth data against which new methods can be accurately tested. However, there are some databases that claim to hold up-to-date and accurate information.

The Centre for Applied Internet Data Analysis (CAIDA) maintains a large database of calculated router IP geolocations. This database is a part of CAIDA's Internet Topology Data Kit (ITDK). The ITDK contains data about connectivity and routing gathered from a large cross-section of the global Internet and is useful for studying the topology of the Internet at the router-level, amongst other uses.

ITDK is generated using various methods, combining sources from various websites and databases across the Internet(CAIDA, 2024). The source dataset used in testing in this chapter is based upon the 2021-03 dataset which combines 3 router geolocation datasets from MaxMind, Holistic Orthography of Internet Hostname Observations (HOIHO) and an internally generated IXP database that has been collated from sources such as BGP Looking Glass servers, Wikipedia list of Internet exchange points, PeeringDB website, and Packet Clearing House (PCH).

Using ground-truth geolocation data available directly from two of the largest Internet Exchanges in the UK, London Internet Exchange (LINX) and London Access Point (LONAP), the precision of the CAIDA dataset was tested. 83 million UK-based IP addresses from the CAIDA dataset were downloaded along with 1.7 million interface/node names and their geolocations. Each of these IP addresses was linked to the location of that node name as indicated by the CAIDA data set. The geolocation of the CAIDA dataset was then compared with that of the LINX / LONAP dataset, where an IP address appeared in each of the datasets, as shown in Figure 3.2.

It should be noted that whilst the LINX/LONAP dataset is accurate to facility location level, the CAIDA dataset is accurate only to city level. So, whilst CAIDA may show an IP as being in London, the LINX/LONAP dataset can give the actual name and address of the Facility where that IP address is hosted.



	Error Distance in Kilometres								
Method	0	<10	<20	<30	<40	<50	>50	>100	Totals
IX	0	883	7	0	103	1	0	0	994
Hoiho	0	19	10	4	45	0	0	0	78
Maxmind	0	145	1	0	15	0	3	1	165
Totals	0	1047	18	4	163	1	3	1	1237

Figure 3.2: Comparing CAIDA Geolocation with Ground Truth Data

The LINX/LONAP combined dataset contains 1838 IP addresses with a known geolocation; of these, 1237 were also contained within the CAIDA dataset and therefore 601 IP addresses were unknown to CAIDA. This shows that the CAIDA dataset does not have access to the fullest possible set of IXP data and combining these website sources, such as LINX, LONAP, EQUINIX etc., within the CAIDA dataset would immediately improve the number of known IP addresses whilst also improving the CAIDA dataset.

	Error Distance in Kilometres								
Method	0	<10	<20	<30	<40	<50	>50	>100	Totals
IXP	0	883	7	0	103	1	0	0	994
Hoiho	0	19	10	4	45	0	0	0	78
Maxmind	0	145	1	0	15	0	3	1	165
Totals	0	1047	18	4	163	1	3	1	1237

Table 3.1: Comparing CAIDAs three Source Datasets for Geolocation Accuracy

As can be seen in Table 3.1, all 3 methods were only able to geolocate to the

resolution of the city (less than 10km), hence why none of them managed to locate the IP addresses accurately. The less-than 10 kilometres error distance column is the most populated and is mainly due to the number of accurately calculated city locations. For example, each of the 3 methods locates the centre of London at slightly different coordinates, CAIDA's in-house IXP method locates any London based IP addresses as being at Charing Cross in London, whilst, HOIHO locates London based IP addresses at Heathrow Airport in London and Maxmind locate London based IP addresses at Westminster in London. Although these are all close to the actual facilities, they do represent errors in distance that the LINX/LONAP combined dataset is able to geolocate more accurately. It can also be seen that in the 'less than 40 Km' column the errors are high. This is because all three CAIDA methods were unable to distinguish between the City of Slough and the City of London. All three methods geolocate any IP addresses located in Slough to the individually estimated centres in London; hence there is an error distance of approximately 35 Kilometres which is the distance from Slough to London. It is puzzling why CAIDA's in-house IXP method should do this, as its use of data from sources such as PeeringDB and Packet Clearing House provides more accurate information, and this method would be expected to be able to distinguish between Slough and London. One final note is that whilst the Maxmind database maps these IP addresses to the Westminster Geocoordinates, it fails to indicate any city at all. Therefore, it should be noted that a search for 'London' within the MaxMind dataset would fail to find these IP addresses.

3.6 Constraint Based Geolocation

In order to test Constraint Based Geolocation (CBG) on the UK infrastructure, the RIPE ATLAS platform has been employed to create 900+ (32x31) traceroutes between each of 32 RIPE anchors, whose IP address and geo-location are known. As there is fairly good RIPE coverage in parts of the UK it was expected that CBG

would perform well; however, this was not the case. For example, the RIPE ATLAS probe 6562 shown in figure 3.3 (yellow circle) is located in Whitechapel, London, and it has many RIPE ATLAS probes (red circles), which can be used as vantage points (VP) close by, so one would assume this would provide a good opportunity for CBG's triangulation algorithm.

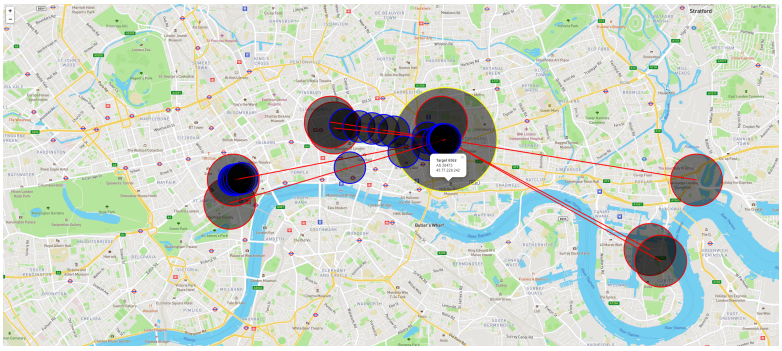


Figure 3.3: RIPE ATLAS Probe Distribution close to target

As can be seen in figure 3.4, CBG's method is to draw a greater circle around each Vantage point that has a radius of

$$RTT \times \text{Packet Speed In Fibre} \times 0.5$$

where RTT is the round trip time of an ICMP packet from Vantage point to target and the packet speed in fibre is the often used 0.66 x Speed of Light(Sol) (where SoL is approx 300km per millisecond) and 0.5 is due to the distance required only being in one direction (RTT is round trip time).

It is then expected that these greater circles will intersect, forming a smaller target area which would then create a more accurate geo-location result. However, this was not the case; not only was triangulation completely ineffective since the larger circles do not even intersect, but the estimated possible location area was 125 km wide (smallest green circle) as seen in Figure 3.4, which is much worse than expected. In contrast, RIPE'S IPMAP single-radius engine locates the target to the nearest city of Bethnal Green, which is approximately 3km radius; however,

this may be somewhat biased in favour of IPMAP as the target is one of RIPE'S own known anchors, which provides RIPE with its actual location. The cause of this poor CBG result is the latency across the Internet and is depicted in figure 3.3 where the red lines represent packet speeds of less than 0.2 x speed of light (0.66 x speed of light is expected). According to RIPE the anchors themselves should be connected to high-speed links and therefore issues such as last-mile latency should not prove a factor, so one has to wonder where these delays are originating from.

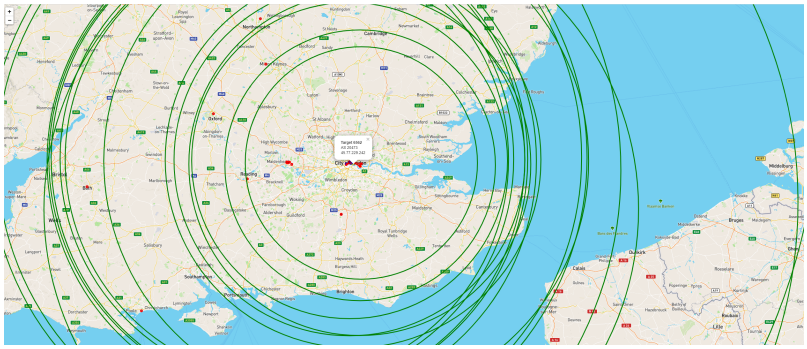


Figure 3.4: Using Constraint Based Geolocation to Geolocate a Target RIPE Probe

There are various types of delay that can affect the RTT values. Transmission delays are caused by the originating device, which in this case is the RIPE vantage point anchor; could these be underspecified? Processing delays are caused by the ISP or various networks en route which need to process the packet header to decide on its route, propagation delays are caused by the type of medium a packet travels through, and, from a highly connected device to another highly connected device as is the case with RIPE anchors, one would expect the best possible medium. Finally, queueing delays are caused by the amount of time a packet waits to be processed on the target device, which again is a RIPE anchor, and suspicion would again have to fall on the specification of the device.

Table 3.2 below shows the outcome of using CBG to geo-locate each of the rest of the anchors with similar unsatisfactory results ranging from target location accuracy of between 65km and 4000 km. The constrained column details whether CBG was able to reduce the location area with overlapping greater circles. In all cases where

this happened, the constrained area only reduced the overall area by a negligible amount.

Probe	**IP Add**	**Constrained**	**Location Accuracy in km**
6087	5.57.16.65	no	125
6182	141.170.19.12	yes	450
6214	178.237.173.220	no	150
6382	90.223.193.3	no	80
6405	37.10.44.14	yes	275
6423	176.74.17.75	yes	200
6446	185.40.232.202	yes	165
6451	107.162.220.5	no	75
6471	52.56.61.239	yes	175
6499	153.92.43.251	no	400
6501	37.143.141.141	no	750
6512	80.82.241.134	yes	650
6515	153.92.43.249	yes	450
6516	153.92.43.250	yes	450
6519	46.227.202.97	no	400
6532	109.232.177.220	no	2750
6552	185.57.191.228	no	825
6559	185.97.160.7	no	65
6562	45.77.229.242	no	125
6609	185.184.236.30	no	650
6647	5.62.127.14	no	650
6670	92.223.59.77	no	125
6674	194.50.88.164	no	4000
6695	194.81.236.229	yes	265

Probe	IP Add	Constrained	Location Accuracy in km
6699	35.234.152.175	yes	265
6716	82.148.224.6	no	215
6738	185.232.117.201	yes	165
6843	86.188.235.234	no	2500
6879	90.223.193.1	no	115
6892	164.39.242.17	no	165
6945	156.154.80.254	no	65
6948	193.57.144.24	no	140
6971	46.101.90.215	no	65
7021	185.194.168.88	no	515

Table 3.2: CBG Accuracy using RIPE Probes

In order to discover exactly where this latency is occurring, a request for the installation of an additional RIPE anchor was made and accepted by RIPE. Lancaster University's Information Systems Services (ISS) agreed to host this RIPE anchor after looking into the relevant technical and security issues. More installations at other Universities such as Edinburgh and Bristol would allow for an end-to-end latency test where every aspect of a traceroute between two anchors can be thoroughly investigated. This would also have the bonus of increasing RIPE coverage across the UK and provide Universities with RIPE credits, which can be used by future researchers to create measurements on the RIPE platform.

3.7 RIPE's Single-Radius Method

The RIPE single-radius method uses 4 steps to locate target IP addresses (Du, Candela, Huffaker, Snoeren, and Claffy, 2020).

1. Map the target IP to the AS, announcing its containing prefix using RIPE Routing Information Service (RIS) BGP data. RIS is a routing data collection platform that collects data on BGP. Find a set of RIPE Atlas probes topologically close to the target IP. Schedule a ping measurement from the selected probes. Return an estimated measurement duration to the user.

2. Collect all resulting RTTs and discard those above 10ms. Convert remaining RTTs to one-way latencies, RTT /2. This filtering assumes that geolocation using distant probes (e.g. on another continent) is not effective.

3. Select probe p with minimum latency and convert it to distance d using a distance delay coefficient of 2/3 c.

4. Use the location of p as the centre of circle C with radius d. Select 100 closest cities to p using the RIPE Worlds database, based on the shortest distance between p and the city. Select only cities inside circle C, hence lower latencies yield fewer cities. Rank cities and return the highest-ranked one to the user.

Taking Atlas's obfuscation policy into account, Atlas Probe 16430 is located within a 1 km radius of the city of Johannesburg in South Africa. It has an IP address of 154.126.223.204. Using this probe as a sample target yields a result that returns Johannesburg as the nearest city and an RTT value of 7.095553 ms. this

would equate to a greater circle around Johannesburg with an error radius of:-

$$\begin{aligned} DistancetoTarget &= Time * Speed \\ DistancetoTarget &= (rtt/2) * (.66 * c) \\ DistancetoTarget &= (7.095553/2) * (.66 * 300000) \\ DistancetoTarget &= 3.5477765 * 198000 metres \\ DistancetoTarget &= 702 km \end{aligned} \tag{3.1}$$

where c equates to the Speed of Light at 300,000 metres per millisecond, rtt is the round trip time and 0.66c is the Average Packet Speed in a Fibre Optic Medium.

This greater circle would encompass most of South Africa and obviously cannot be used for accurate geolocation due to this huge target radius. However, using the RTT value to calculate the greater circle error radius for the single-radius engine may be unfair. According to Du et al. (Du, Candela, Huffaker, Snoeren, and Claffy, 2020) and Gharaibeh et al. (Gharaibeh, Shah, Huffaker, H. Zhang, Ensafi, and C., 2017), a threshold used in previous geolocation studies suggests that the average perimeter of metropolitan areas is approximately 40 km. This places the target IP address somewhere in the Johannesburg metropolitan area.

3.8 Shortest Ping Method

The Shortest Ping method could also use the RIPE Atlas platform. A researcher would manually group a selection of probes that are within the estimated target area and carry out the first 3 steps of RIPE's Single-Radius method. Once the results are returned, the probe with the smallest RTT value can be chosen and the probe would be at the centre of a greater circle with a radius of RTT/2.

Using the same sample target of 154.126.223.204 and the other 66 probes as sources to ping the target, this second method results in the probe 1000492 having the smallest round-trip time. Probe 1000492 is located in Elandsfontein in South

Africa. It has a one-way trip time of 0.236335 ms, which is equivalent to a target radius of 47 km, as shown in Figure 3.5. The red circle depicts this probe's calculated target area, and the green circles show the discounted probe target area, which did not have the shortest ping.

If any of the other probes greater circles had intersected the red greater circle, we could add the Constraint Based Geolocation (CBG) method using multilateration (Gueye, Ziviani, Crovella, and Fdida, 2006) to further reduce the target radius. Unfortunately, in this case, no other probes intersect, thus this method cannot be used because the probe with the shortest ping is in the hop paths of all other chosen probes. This appears to be a very common scenario where the last few hops target all routes via the same path, thus the CBG method cannot be used.

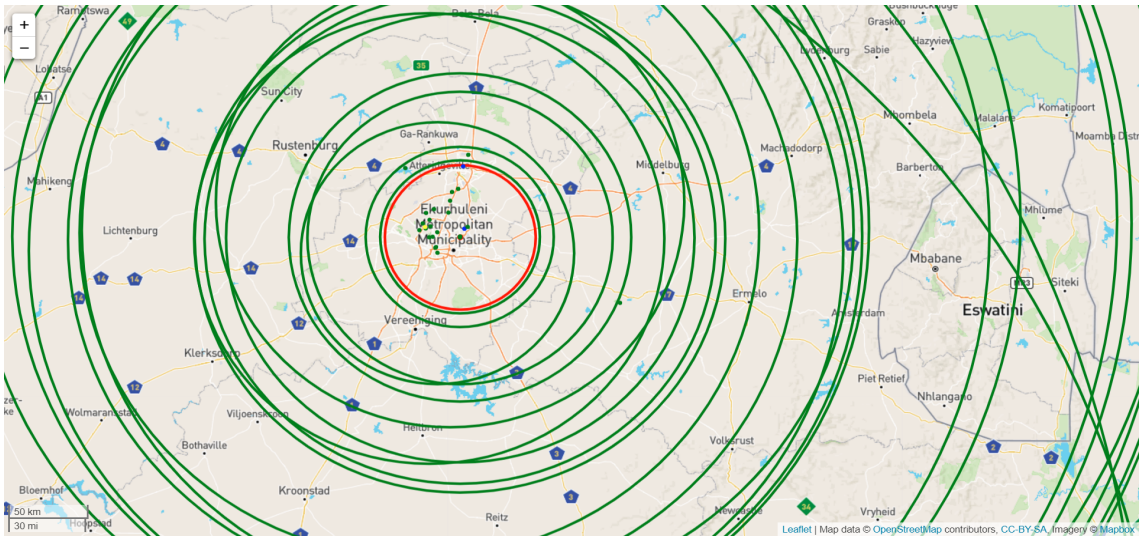


Figure 3.5: Geo-locating IP address 154.126.223.204 Using Shortest Ping

This method offers similar accuracy to that of the Single-Radius engine, 47km target radius vs 40km target error radius, over the single-radius method. The Single-Radius engine seems convoluted when the shortest ping method returns a similar accuracy using fewer steps. It should be noted that if CBG were an option, that is, if there is more than one route to the target in any measurement, then the accuracy of the shortest ping method would improve.

3.9 Summary

RIPE ATLAS developers designed their solution for geolocating core Internet infrastructure, viz. IPMAPs Single-Radius Engine, to incorporate the Shortest Ping method (Du, Candela, Huffaker, Snoeren, and Claffy, 2020). This requires a number of landmarks that are geographically close to the target IP Address (Katz-Bassett, John, Krishnamurthy, Wetherall, Anderson, and Chawathe, 2006), (Gueye, Ziviani, Crovella, and Fdida, 2006), (V. Padmanabhan and Subramanian, 2001). Therefore, the more landmarks, or probes in IPMAP's case, that are deployed in a specific region, the greater the chance that one is geographically close to the target of interest and therefore the greater the accuracy. RIPE's IPMAP uses more than 11,000 probes worldwide and currently provides the largest number of landmarks for research, test, and troubleshooting purposes (RIPE, 2015).

In 2020 Du et al. evaluated the accuracy, coverage, and consistency of RIPE's IPMAP Single-Radius engine (Du, Candela, Huffaker, Snoeren, and Claffy, 2020). They recognised that their findings had a geographical bias of ground truth due to the fact that most IP addresses from their ground-truth dataset were located in western Europe and the contiguous US. They determined that Single-Radius accuracy appears to differ by region and realised that their results may not hold in all regions.

Ding et al. (Ding, X. Luo, Dengpan, and Liu, 2017) agree with Du et al. and further observe that there are many classical delay-based IP geolocation algorithms (Katz-Bassett, John, Krishnamurthy, Wetherall, Anderson, and Chawathe, 2006) (Gueye, Ziviani, Crovella, and Fdida, 2006) (Scheitle, Gasser, Sattler, and Carle, 2017) (Wong, Stoyanov, and Sirer, 2007) that are suitable for richly connected networks such as the United States and Western Europe. However, Ding et al. conclude that delay-distance correlation algorithms are seriously affected where regions are poorly connected, but also believe that the delay distance correlation of some subnetworks within those regions may be better than the overall regional delay distance correlation (Ding, X. Luo, Dengpan, and Liu, 2017).

Du et al suggest a potential improvement to the Single-Radius method such as using a multilateration engine which would use results from multiple probes to improve results in regions where Atlas node deployment is sparse. Shichang et al. reason that to obtain more accurate results, a multilateration method such as constraint-based geolocation (CBG) should select probing hosts and landmarks that are in the same richly connected subnetwork with the target host (Ding, X. Luo, Dengpan, and Liu, 2017).

For Constraint-Based Geolocation to be useful and multilateration/triangulation to be a success, multiple IP-to-Geographical landmarks must be available; however, if RIPE node deployment is sparse as suggested by Du et al. then CBG is unlikely to be successful due to a lack of landmarks. The problem is how to increase the number of known landmarks that are close enough to target addresses and thereby improve the possibility of utilsing the CBG method. The method proposed in the next chapter uses Internet Exchange Points (IXP) and Interconnect Facilities to add additional landmarks that may be closer to target IP addresses to increase IP geolocation accuracy. The main influencing factors for accuracy when using these facilities is the ability to detect which of the IXP facilities involved in the IXP are being used in the route to the target and how far the IXP is from the target. Furthermore, if 2 or more IXP facilities are involved in the target measurements, then the use of CBG may further increase the accuracy.

Chapter 4

Internet Exchanges as Additional Landmarks

4.1 Introduction

In order to use Internet Exchange Points (IXP) as landmarks, a list of a country's Internet Exchanges, facilities, and their geographical locations is required. A list of ASs and the facilities that host each AS is also required, all of which for the majority can be accessed at PeeringDB. PeeringDB is a freely available user-maintained database of networks, facilities and Internet Exchanges that provides comprehensive details on address, geolocation, and other useful information (PeeringDB, 2024). PeeringDb identifies IXPs, Facilities, and Networks by its own identification numbers, and these identification numbers are used in the following chapters.

To increase geolocation accuracy, additional landmarks need to be close to the centres of populations where IP addresses will be at their maximum usage. Internet Exchange Points (IXP) are an ideal solution because of their proximity to population centres and could be used as additional landmarks as their geographical locations and IP address ranges are publicly known. However, there is a problem with the use of IXPs as Vantage points, although much research has been carried out, the task of geolocating the physical interfaces of IXPs is still a challenging problem (Motamedi,

Rejaie, and Willinger, 2015). This chapter aims to overcome this problem.

IXPs are located near population centres and are connected to retain the maximum amount of local traffic within their own country (Scheitle, Gasser, Sattler, and Carle, 2017). IXPs are also allocated their own IP address ranges, so any traceroutes that pass through these points can be geolocated to the IXP facilities' published geographical addresses. Return Trip Times can then be calculated from the IXP to the target instead of the source to the target, reducing packet trip distance, thus reducing errors caused by latency, link congestion, circuitous routes, infrastructure diversity, and buffering. A further benefit of using IXPs as landmarks is that RIPE probes as well as RIPE anchors can be used as sources to further increase the number of vantage points; this is because the IXPs are closer to the target than the source, the geo-location coordinates are known, and the RTT will be much reduced. This technique could be used in poorly connected or richly connected networks such as the UK to further improve the accuracy of IP geolocation, and this will help with risk assessment and mitigation.

4.2 Multi Facility IXPs

As mentioned above, Motamedi et al. pointed out a problem with the use of IXPs as landmarks which is their use of multiple facilities that have different geographical locations that are connected at layer 2. This makes it much more difficult to geolocate the location of the required IP address. A packet may route through a specific IXP network with an IP address assigned to that IXP, but in many cases that IP address can be in one or more different physical locations. Motamedi et al. (Motamedi, Rejaie, and Willinger, 2015) developed a method called Mi2 which maps interconnections within a given co-location facility; however, they do not attempt to map an IXP that spans multiple geo-dispersed facilities, preferring to leave this problem to future work (Motamedi, Rejaie, and Willinger, 2015). Giotsas et al. (Giotsas, Smaragdakis, Huffaker, Luckie, and Claffy, 2015) use BGP community

values to infer many hidden peer-to-peer links across IXPs, and tools such as Bdrmap (Luckie, Dhamdhere, Huffaker, and Clark, 2016) and MAP-IT (Marder and Smith, 2016) attempt to infer border interfaces; however, none of these methods has been designed to geolocate, or "pin", the interface to a geographical location.

Once the packet reaches an IXP it is very difficult to know which facility it reached and which facility it came from (Motamedi, Rejaie, and Willinger, 2015). In some cases, an IXP has only one facility, so this makes it easy as in the case of Figure 4.1

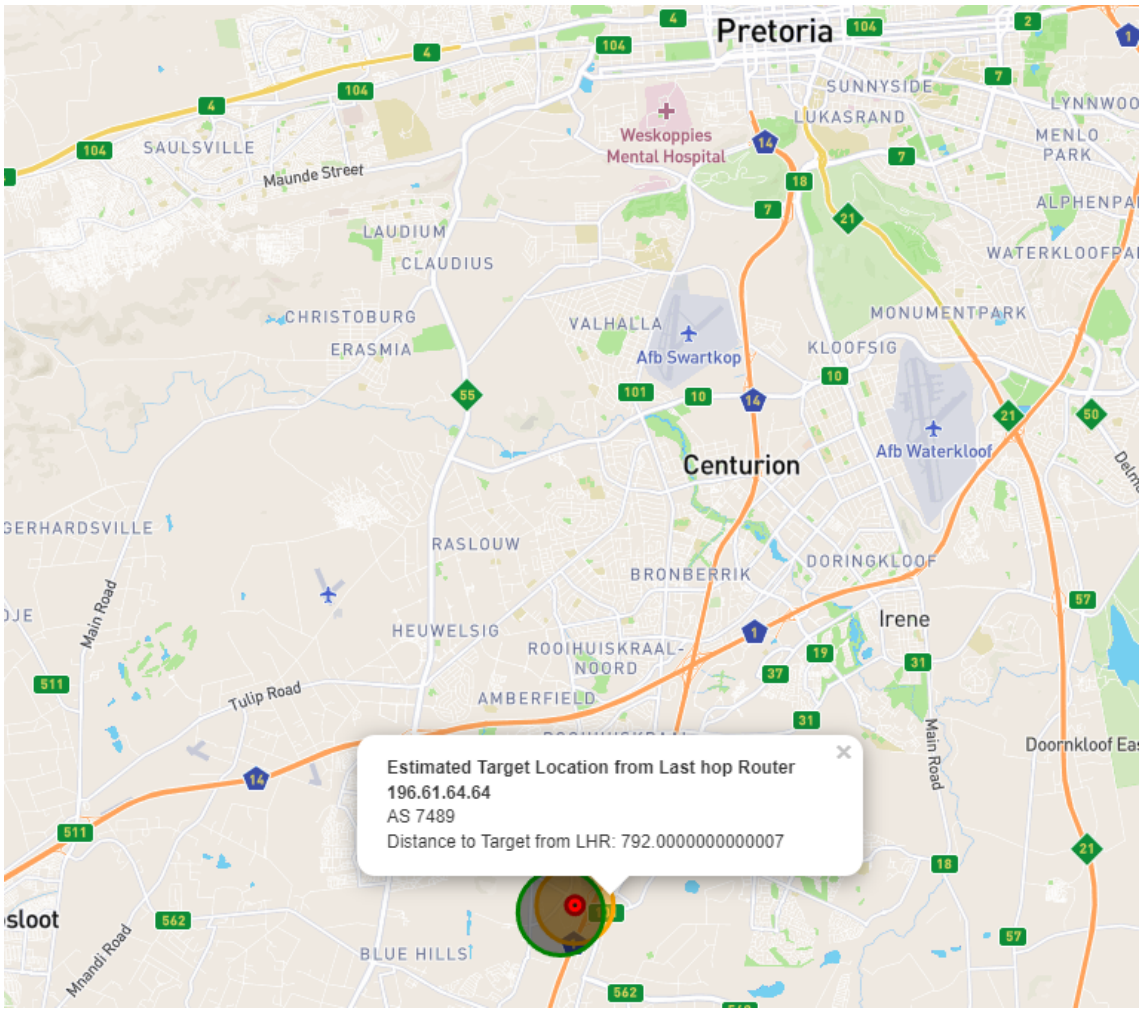


Figure 4.1: Geolocating an IXP with a single facility

which shows the estimated target location (green circle) and the actual target location (red circle) to be very accurate (within 720 metres). However, when multiple

facilities are involved, sense checks must be added to the geolocation tool to calculate the facility from which the packet is entering/exiting. In some cases, the sense checks are easy when the facility is not in the correct country or the facility is too far away from the target for a Speed of Light (SoL) sense check to provide a logical distance to the target. It is proposed that a traceroute will show the upstream and downstream ASNs, and it is hoped that the discovery of a facility shared by both the IXP and the ASN will point to the traceroute's exact path through an IXP. BGP communities or BGP AS-PATH information may also add more detail or validation (Giotsas, Smaragdakis, Huffaker, Luckie, and Claffy, 2015) .

4.3 Resolving the issue of Multi Facility IXPs

Knowing the entry and exit routes that a packet takes in an IXP provides additional Vantage points (VPs), as we can access the geolocation of those facilities from PeeringDB. A Python program was developed to provide a method that could detect which facilities a packet enters and exits a multi facility IXP. This method has the following steps:-

- Create a traceroute from source to target using RIPE atlas probes
- Detect which IXP the packet traverses using a list of prefixes used by UK IXPs gathered from PeeringDB.
- Using RIPE whois, Identify the ASN that the packet travels to after leaving the IXP.
- From PeeringDB Find the common facility for the IXP and the ASN.
- Calculate the RTT value from Facility to target as the result of RTT(target) – RTT(IXP common facility) .
- Calculate the distance from Facility to target.

By detecting the exiting interface, the effective RTT to the target can be reduced and, therefore, the overall error radius; see Figure 4.2.

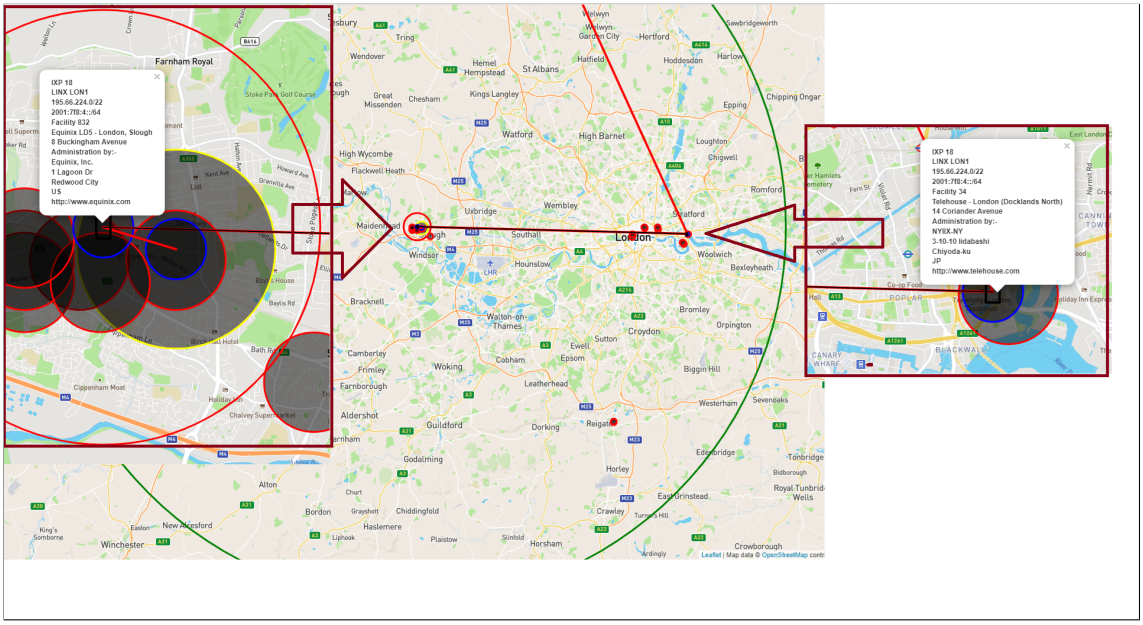


Figure 4.2: The red circle shows the error distance of this method compared against the error radius of Constraint Based Geolocation (CBG) denoted by the green circle.

This is an improvement in accuracy compared to other active IP geolocation methods, and it became evident that a paper based on this method could be produced – see (McCherry, Giotsas, and Hutchison, 2023). This method can also allow for the discovery of the ingress facility by discovering the ASN of the router before arriving at the IXP facility, and this could be used to help with secondary information on the IXP such as bandwidth allocations.

4.4 Limitations

However, it became apparent that there was a problem with this method, namely that facilities using remote peering to connect to IXPs will not have a common facility with that of the IXP that traceroutes pass through, and this presented a problem. If remote peering occurs before entering a facility, then there is no problem because we are only interested in the exiting facility as in Figure 4.3.

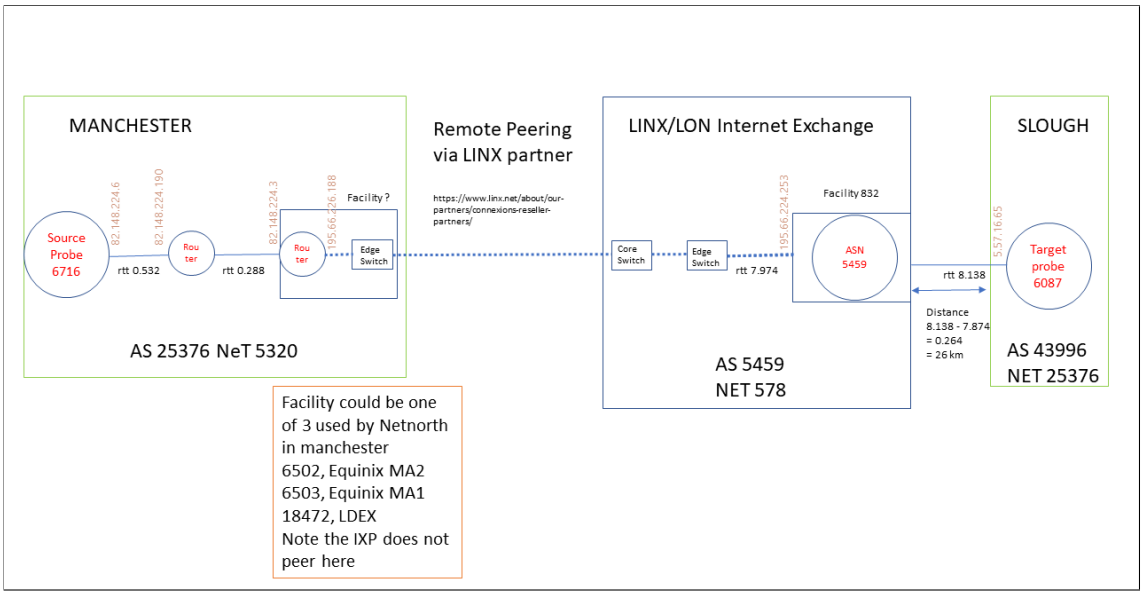


Figure 4.3: Remote Peering before entering an IXP network

If remote peering occurs between the IXP and the target, then we cannot be sure from which of the IXP facilities a traceroute will exit. We can infer the ASN of the next hop after the IXP which will provide us only with the facilities that a packet may traverse: see Figure 4.4. This would impose a minor limitation on this new method.

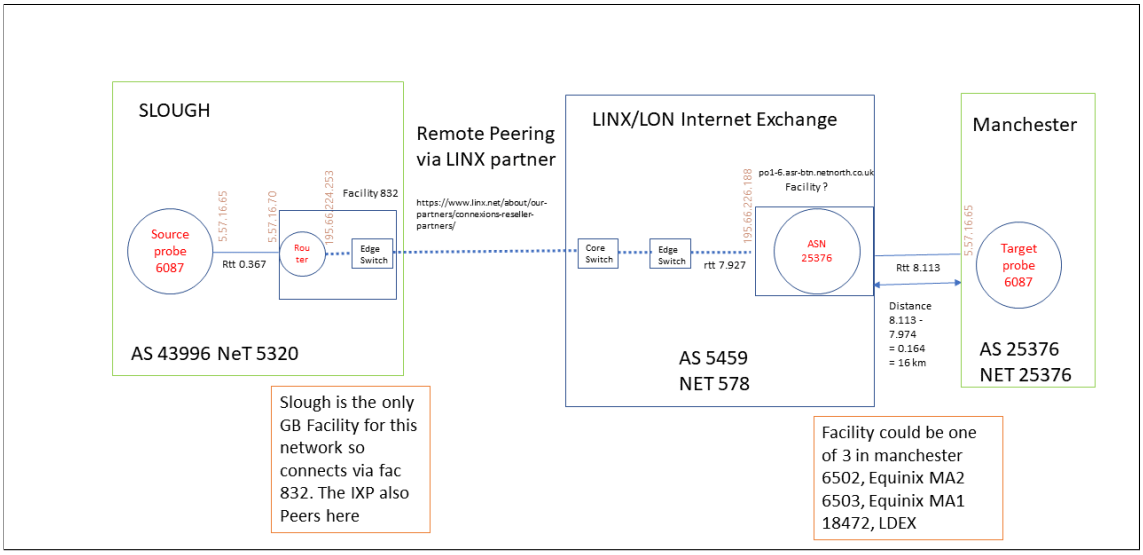


Figure 4.4: Remote Peering after leaving an IXP network

In this example, we are using a target probe whose geolocation is already known, but if this was not the case, the error radius would be the combination of the calculated distance from each of the three possible exiting facilities as shown in Figure 4.5.

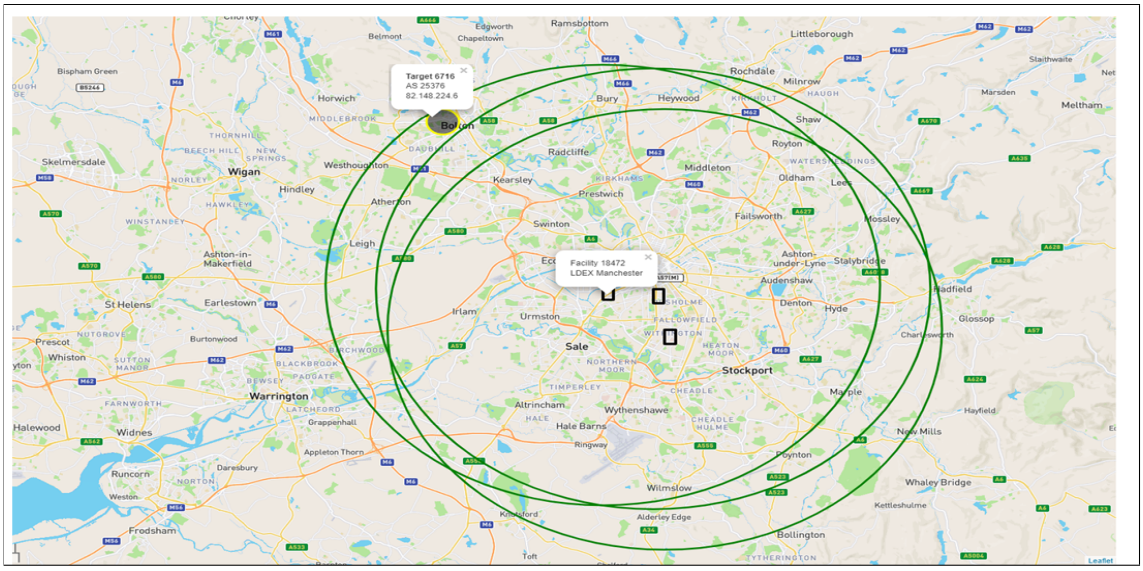


Figure 4.5: Three possible exiting facilities leads to a larger error radius consisting of all three greater circles combined

4.5 Proof of Concept

The first step in developing a technique for mapping Internet infrastructure involves mapping interconnection facilities to their geophysical coordinates. Internet exchange directories are publicly available at many locations, such as the Packet Clearing House website (PCH) (PCH, 2024), the IXPDB website (IXPDB, 2024), and the PeeringDB website (PeeringDB, 2024). Among these directories, PeeringDB has the most comprehensive list. Simple data extraction can be performed because PeeringDB is a freely available network database that contains a well-updated list of IXPs (Internet Exchange), facilities, and their geolocations, as well as a REST API. PeeringDB also facilitates the global interconnection of networks in Internet Exchanges, data centres, and other interconnection facilities. However, as Kloti et al. (Klöti, Ager, Kotronis, Nomikos, and Dimitropoulos, 2016) points out, PeeringDB is also incomplete as the data from some IXPs will not be included in the PeeringDB database. This causes additional failures in the code to recognise the geographical location of the IP addresses registered with those IXPs.

4.6 South Africa

In order to test the method, South Africa was chosen because of its simpler Internet infrastructure. In 2008, due to the lack of a copper wire backbone, data transmission across the African continent was difficult. Only three submarine fibre optic cables connected the entire continent to the global Internet, of which two were located in North Africa (Ngari and Petrack, 2024). Since then the addition of more submarine cables has vastly improved global Internet connectivity and, due to advances in fibre-optic technology, Africa has a chance to leapfrog over the older copper infrastructure found in first-world countries to design and build a continent wide modern fibre-optic backbone. As can be seen in Figure 4.6, this process has begun.

South Africa currently has 67 active RIPE Atlas Nodes and, to establish proof of method, each probe is used as a source and a target to create a matrix of 67 x 66

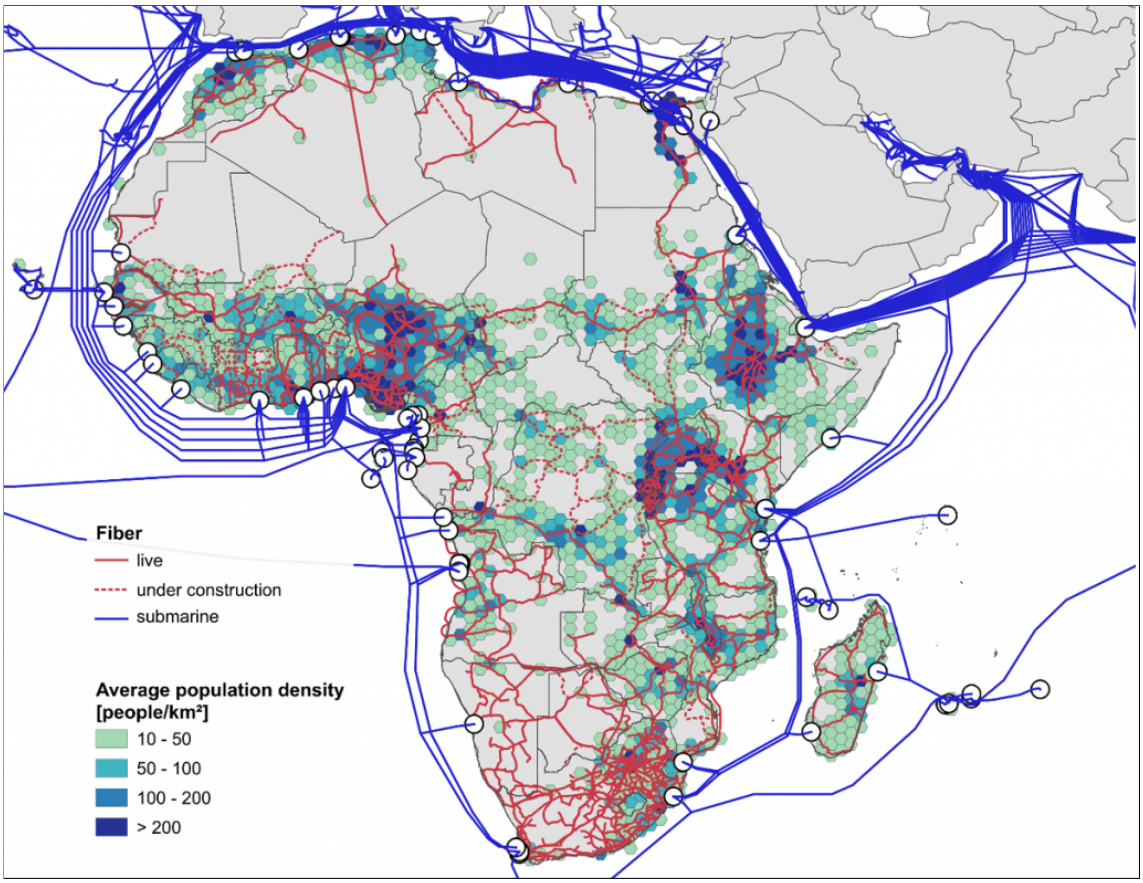


Figure 4.6: Visualization of fibre infrastructure and population density in Africa. Reproduced from (Ngari and Petrack, 2024)

traceroutes across South Africa with each probe acting as a target for the other 66 source probes. This creates 4422 traceroutes in total with more than 40,000 hops across South Africa.

For each traceroute, we can ignore all the hops up to the hop containing an IP address that is recognised as belonging to an Internet Exchange Point (IXP). We then need to establish the AS to which this IP address connects and the facilities where this AS is hosted.

4.6.1 Method Overview

Step 1 of the proposed new geolocation method involves querying the PeeringDB REST API to obtain a list of a country's facilities and their geographical coordinates.

These facilities are then mapped onto OpenStreetMap (OSM), a collaborative project to create a freely editable geographic database of the world. PeeringDB identifies each facility through a unique identification number, which we use to reference facilities in this paper.

In Step 2 of this process, we query again the PeeringDB API to find in which of these facilities Internet Exchanges have deployed their switching equipment to build an OSI layer 2 map of the IXP network infrastructure. When available, additional information is downloaded from each Internet Exchange website, such as the connection speeds of the peering ports.

Step 3 involves the execution of traceroute measurements using the RIPE ATLAS platform and using probes that are in the same country as the target to reduce errors. Traceroutes are created in both directions, to and from each probe, creating a mesh of thousands or even hundreds of thousands of measurements.

Step 4 maps each hop to a facility where possible using a combination of DNS lookups, Internet Exchange website information, and PeeringDB data. This information also creates a list of valuable Vantage point information that will be useful for future research. To map these intermediate hops, a tool was created, which reads the data from the traceroute measurements created in Step 3, and queries various sources, such as PeeringDB, DNS, and Internet Exchange websites, to locate the position of the router where these hops are interfacing, considering the previously discovered facility and IXP information.

4.6.2 Single Facility Example

Taking into account Atlas's obfuscation policy, Atlas Probe 1000237 is located at Samrand Business Park, 37 km north of Johannesburg. It has an IP address of 154.126.223.204 and is selected as the target probe. Traceroute measurements are created from each of the other probes to this target. The measurements in which we are interested are :-

- Fastest RTT times from IXP to target.

- Fastest RTT time from IXP to Last Hop Router (LHR)
- Fastest RTT time from target to Last Hop Router (LHR)

Figure 4.7 shows the four fastest measurements. The four measurements each show their respective hop's IP address and the RTT time to that hop. The final five columns display the IXP to target RTT time (i to t), the IXP to last hop router RTT time (i to lr), the target to last hop router RTT time (t to lr), the source probe to last hop router RTT time (s to lr), and finally the source to target RTT time (s to t). Each of these columns has the fastest relative RTT time coloured green.

Source Pro	hop1 ip	hop1 rtt	hop2 ip	hop2 rtt	hop3 ip	hop3 rtt	hop4 ip	hop4 rtt	hop5 ip	hop5 rtt	hop6 ip	hop6 rtt	hop7 ip	hop7 rtt	hop8 ip	hop8 rtt	hop9 ip	hop9 rtt
1000492	169.255.0.129	0.136	169.255.0.[illegible]	0.226	196.60.9.24	1.39	197.189.193.1	2.368	197.189.1[illegible]	2.727	129.232.223.26	1.281	196.61.64.64	1.301				
14968	63.223.6.89	0.396	63.223.48.[illegible]	16.963	223.48.70	16.594	196.33.119.97	16.958	168.209.8[illegible]	16.917	168.209.86.217	17.17	196.26.0.10	16.561	196.223.14.99	17.659	197.189.193.1	18.558
18169	146.231.130.1	11.664	146.231.0.[illegible]	0.74	192.42.99.246	0.849	192.42.99.253	1.705	155.232.[illegible]	28.89	155.232.6.10	28.67	155.232.6.70	28.978	155.232.152.70	21.451	155.232.1.60	29.119
19994	192.168.88.254	0.414	10.24.24.[illegible]	4.217	102.132.201.249	4.419	154.0.4.178	4.514					196.223.14.99	6.041	197.189.193.1	7.18	197.189.193.46	7.202

Source Pro	hop10 ip	hop10 rtt	hop11 ip	hop11 rtt	hop12 ip	hop12 rtt	hop13 ip	hop13 rtt	hop14 ip	hop14 rtt	hop15 ip	hop15 rtt	i to t	i to k	t to k	s to k	s to t
1000492	[illegible]												-0.089	-0.109	0.02	1.281	1.301
14968	197.189.193.46	18.671	129.232.223.26	17.66	196.61.64.64	17.691							0.032	0.001	0.031	17.66	17.691
18169	155.232.128.70	29.003	196.60.9.24	29.992	197.189.193.1	30.907	197.189.193.46	30.408	129.232.223.26	29.751	196.61.64.64	30.008	0.016	-0.241	0.257	29.751	30.008
19994	129.232.223.26	5.557	196.61.64.64	5.565									-0.476	-0.484	0.008	5.557	5.565

Figure 4.7: Fastest time to Target 196.61.64.64, Probe 1000237
Red: IXP, Orange: Last Hop Router, Green: Fastest RTT

From the 66 traceroute measurements we find that source probe 18169 has the fastest time from IXP to target of 0.016 milliseconds, as highlighted by the green box in the "i to t" column, and hop 11 uses the IP address 196.60.9.24 which according to Peerindb belongs to NAPAFRICA Internet Exchange based in Johannesburg with a PeeringDB assigned IXLAN identification of 592. This is connected to a PeeringDB-assigned network identification of 9791 (see Figure 4.8).

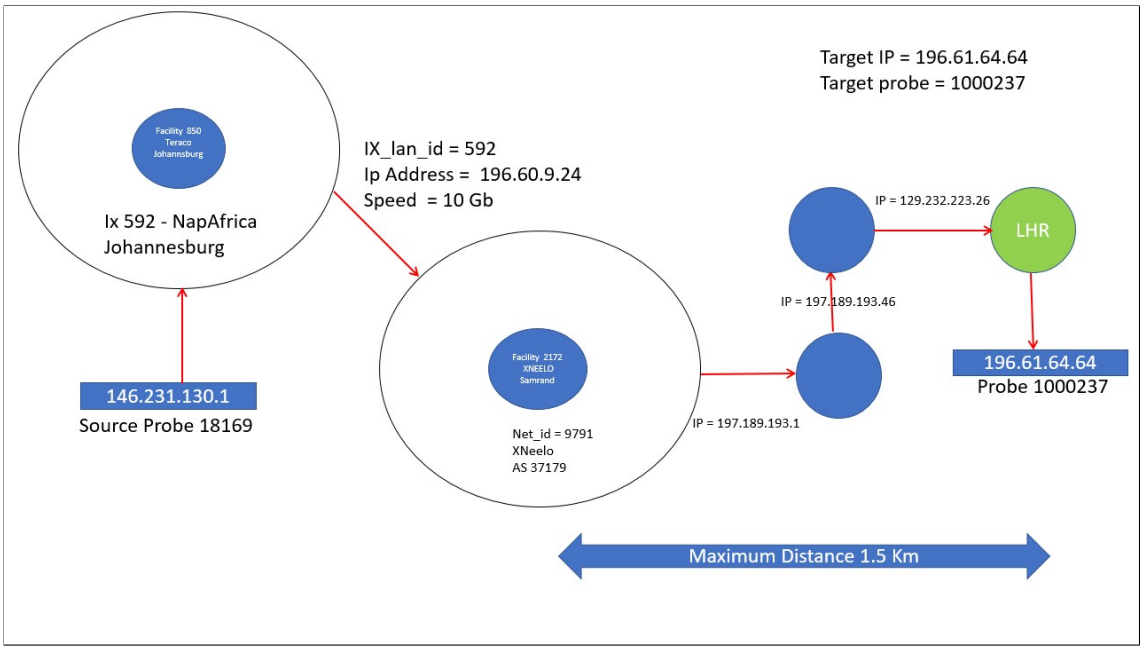


Figure 4.8: Single Facility IP Geolocation

Network 9791 belongs to a hosting company named Xneelo who owns AS37179 and we can see from PeeringDB that this network/AS is hosted at only one facility which is in Samrand, South Africa, with a latitude of -25.927622 and a longitude of 28.140755.

Using the 'Distance to Target' calculation (4.1), we establish that the target is no more than 1.5 km from the Samrand Facility. It is likely to be at the same location when packet processing and latency is taken into account. :-

$$\begin{aligned} DistancetoTarget &= Time \times Speed \\ DistancetoTarget &= (rtt/2) \times (0.66 \times c) \\ DistancetoTarget &= (0.016/2ms) \times (0.66 \times 300000km/sec) \\ DistancetoTarget &= 0.000008sec \times 198000km/sec \\ DistancetoTarget &= 1.584km \end{aligned} \tag{4.1}$$

where c equates to the Speed of Light at 300,000 kilometres per second, rtt is the round trip time and 0.66c is the Average Packet Speed in a Fibre Optic Medium

In order to verify the process we can compare this estimated location with the actual location of the probes provided by the RIPE Atlas platform, and taking into account RIPE's one-kilometre probe obfuscation policy we see that the estimation and actual location are almost exactly the same as shown in Figure 4.9. This confirms that the method works and can achieve far more accurate IP geolocation than current state-of-the-art methods such as Single-Radius or shortest ping.

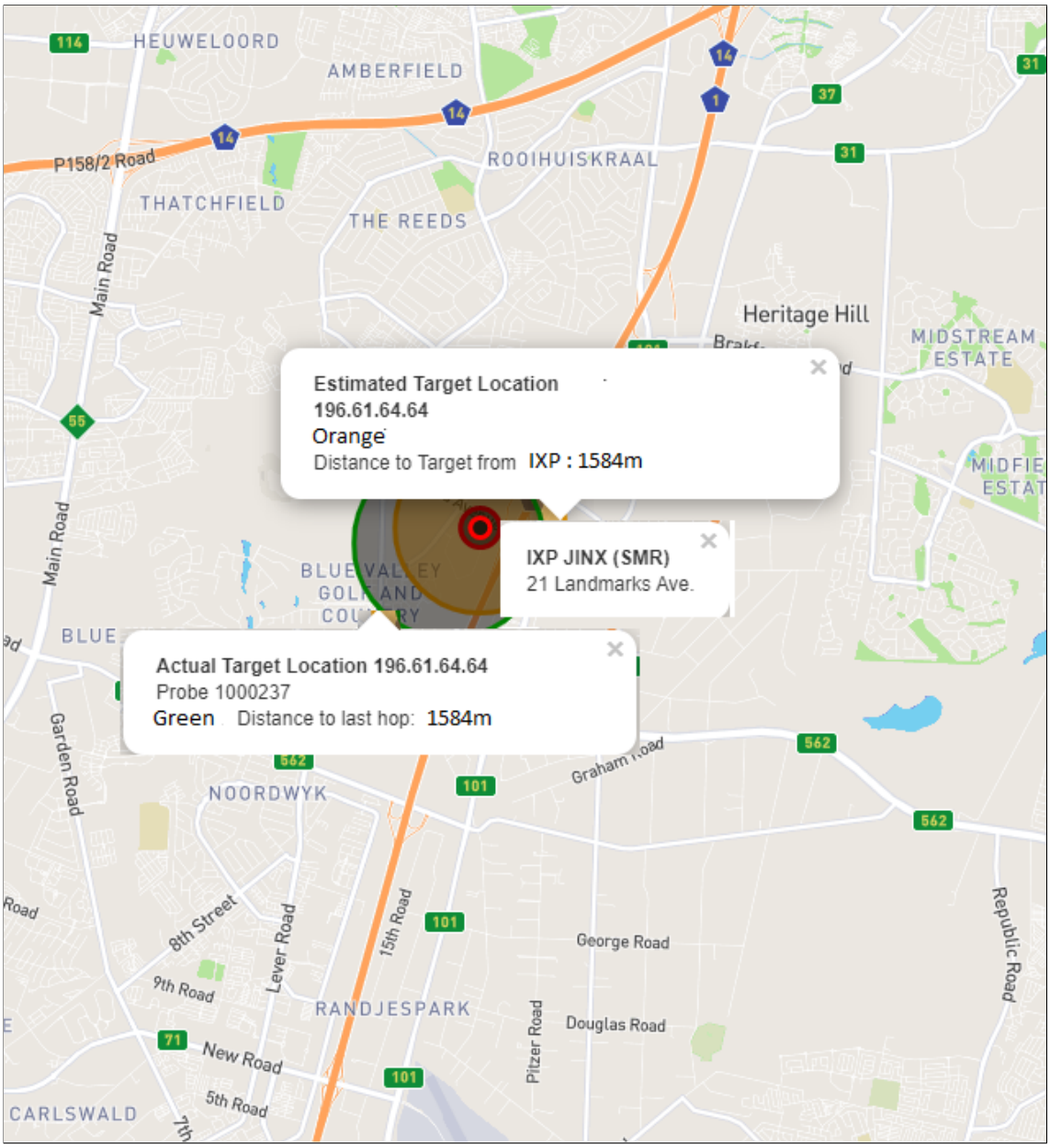


Figure 4.9: Estimation Vs actual location Orange = Estimated, Green = Actual(Taking into account RIPEs 1 km Obfuscation Policy

4.6.3 Multi Facility Example

Probe 22221 is situated in Cape Town, has an IP address of 196.40.111.174, and is selected as the target probe; traceroute measurements are created from each of the other probes to this target. The measurements in which we are interested are :-

- Fastest RTT times from IXP to target.
- Fastest RTT time from IXP to Last Hop Router (LHR)
- Fastest RTT time from target to Last Hop Router (LHR)

Figure 4.10 below shows the three fastest measurements. The three measurements each show their respective hop's IP address and the RTT time to that hop. The final five columns display the IXP to the target RTT time (i to t), the IXP to last hop router RTT time (i to lr), the target to last hop router RTT time (t to lr), the source probe to last hop router RTT time (s to lr), and finally the source to target RTT time (s to t). Each of these columns has the fastest respective RTT time coloured green.

From the 66 traceroute measurements we find that source probe 1000707 has the fastest time from IXP to the target of 0.023 milliseconds, and hop 9 uses the IP address 196.223.22.98 which belongs to CINX IX. PeeringDB assigns this IXP an identification of 344. CINX uses three facilities in Cape Town, and this IP address peers with a PeeringDB assigned identification of 9791 which is Xneelo PTY known as AS37153. XNeelo only has one facility, which is in Samrand, Johannesburg, with a peering assigned facility identification of 2172. This facility is more than 1200 km away, and a simple sense check would warn that it is impossible for a packet to travel that distance in 0.023 milliseconds. Xneelo must have some presence locally that is not documented, most likely a remote peering connection as discussed in Section 4.4

Source Probe	hop2 ip	hop2 rtt	hop3 ip	hop3 rtt	hop4 ip	hop4 rtt	hop5 ip	hop5 rtt	hop6 ip	hop6 rtt	hop7 ip	hop7 rtt
1000707							100.65.0.193	0.367	150.222.93.193	0.923	150.222.92.66	1.094
13720	41.206.197.12	0.649	41.206.192.235	0.895	196.1.56.99	0.816	41.85.0.197	0.965	41.85.0.58	0.792	196.10.140.21	0.891
6179	196.223.14.47	11.412	41.84.13.37	17.53	41.66.133.2	17.852			196.40.111.174	19.356		

Source Probe	hop8 ip	hop8 rtt	hop9 ip	hop9 rtt	hop10 ip	hop10 rtt	hop11 ip	hop11 rtt		i_to_t	i_to_lr	t_to_lr	s_to_lr	s_to_t
1000707	150.222.92.43	1.417	196.223.22.98	1.166	196.40.102.70	13.869	196.40.111.174	1.189		0.023	12.703	-12.68	13.869	1.189
13720			196.40.111.174	0.915						0.024	0	0.024	0.891	0.915
6179										7.944	6.44	1.504	17.852	19.356

Figure 4.10: Fastest time to Target 196.1.58.54, Probe 13720 (Red = IXP, orange = Last Hop Router)
Red: IXP, Orange: Last Hop Router, Green: Fastest RTT

The packet's RTT time at the IXP was 1.166 ms, and the packet's RTT time at the target was 1.189 ms. Therefore a packet took approximately (1.189ms - 1.166ms)/2 to travel the distance from IXP to reach its destination, which therefore took 0.0115 milliseconds and this equates to a maximum distance of:-

$$\begin{aligned} DistancetoTarget &= Time \times Speed \\ DistancetoTarget &= (rtt/2) \times (0.66 \times c) \\ DistancetoTarget &= (0.023ms/2) \times (0.66 \times 300000km/sec) \\ DistancetoTarget &= 0.0000115sec \times 198000km \\ DistancetoTarget &= 2.277km \end{aligned} \tag{4.2}$$

The maximum distance from the IXP is 2.277 km; however, we do not know from which of the 3 CINX facilities the packet transited. Therefore, the possible target area is a combined area of 2.277 km around each of the 3 facilities (orange circles) as shown in Figure 4.11. The actual target location is shown as a green circle, taking into account RIPE's obfuscation policy. The red dots are the locations of the three CINX facilities. It can be seen that the actual location of the target is well enclosed within one of the three estimated circles.

An additional point to note is the RTT time for hop 10, which is over 13ms. It could be of interest to XNEELO why this latency is occurring at this hop. A DNS lookup, using NSlookup, of this IP address gives the value 'core-access-switch1-vlan1001.cpt.host-h.net.'; presumably, CPT is short for Cape Town. Perhaps it is caused by traffic engineering, i.e. low priority for packets with that specific routers destination, or ICMP packets, but it may be that the packet is travelling all the way to Xneelos facility in Johannesburg for no essential reason. However, this hop does not seem to affect packets in transit, as the final hop RTT is back to within a reasonable latency. Resolving small issues such as this could result in improved network latency and greater network efficiency.

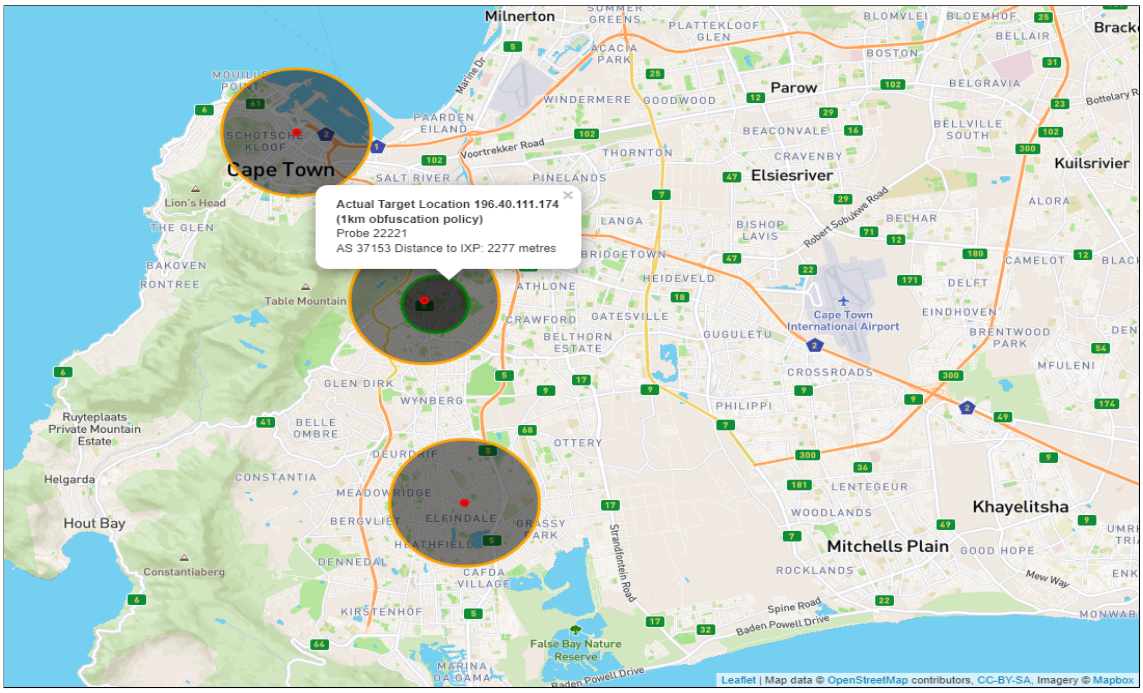


Figure 4.11: Multi Facility Example

4.7 Testing the use of IXPs on the UK Infrastructure

A list of UK-based facilities was extracted from PeeringDB along with the geographical coordinates of each facility. Where facility records have no geolocation information available, the facility's address is entered into Nominatim (nominatum, 2024), which is a tool to search OSM data by name and address (geocoding) and generate synthetic addresses of OSM points (reverse geocoding). There are occasions when addresses do not return any geocoding data; in this case, the address of the facility must be entered manually. Of the 235 UK facilities listed by PeeringDB (as of 16/2/2023), only sixteen facilities had to be manually geolocated. Figure 4.12 shows the number of facilities (black rectangles) geolocated in the London area using PeeringDB, Nominatim, and OSM.

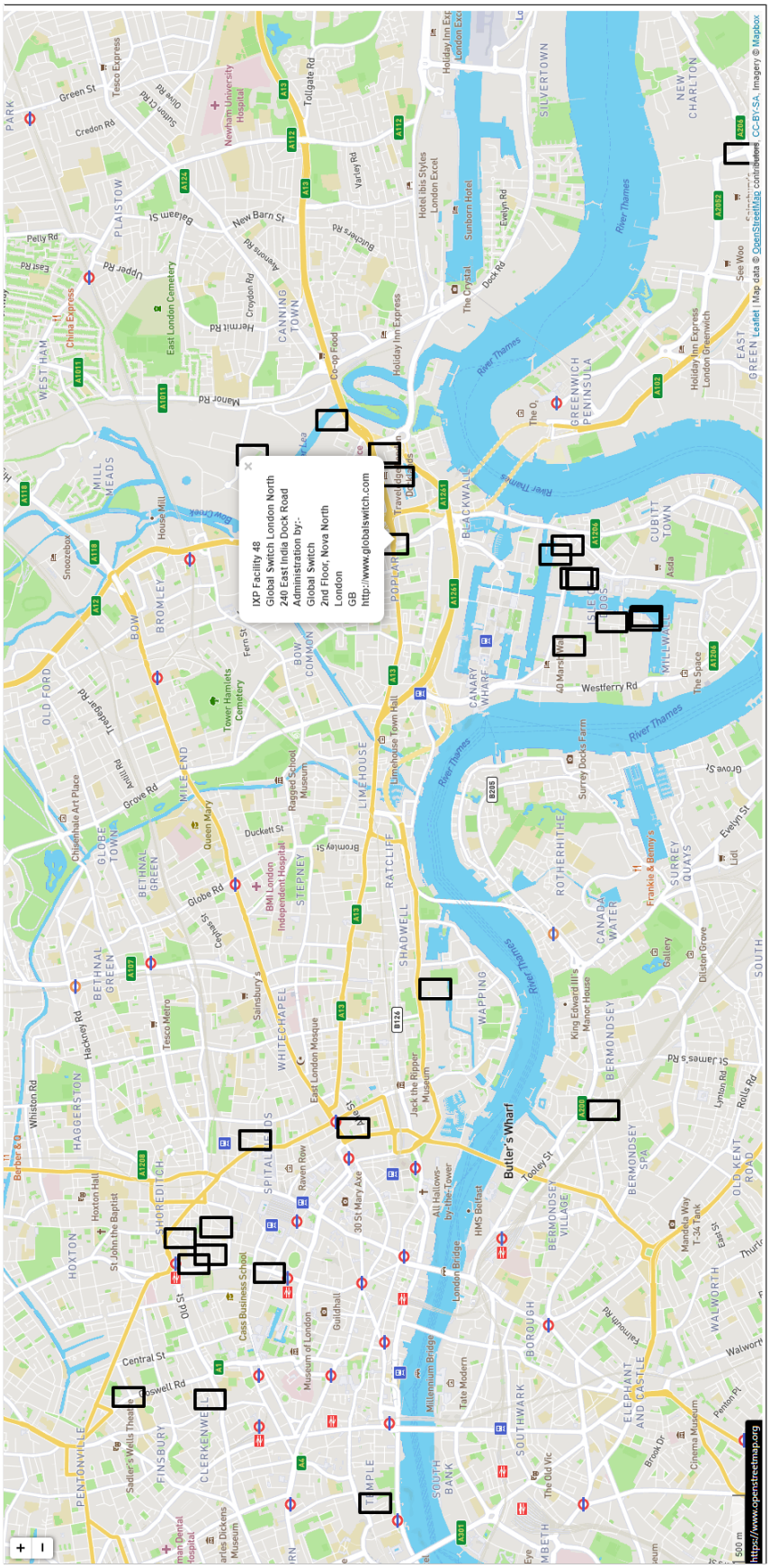


Figure 4.12: Geo-Mapping Interconnection Facilities using PeeringDB and OpenStreetMap

According to PeeringDB, there are currently 26 Internet Exchanges in the London area, although two are listed with no connected networks. Packet Clearing House (PCH) lists 15 active IXPs, whereas the IXPDB website lists nine IXPs with connected networks. To map an Internet Exchange, PeeringDB is queried to discover the facilities at which each IXP publicly interconnects, and these layer 2 networks are mapped to OpenStreetMap, as shown in Figure 4.13. Public information is not available to map the actual physical cables, so, while point-to-point connections are depicted in this Figure, the exact nature of the network topology is uncertain. It is possible that the network could involve various forms of mesh configuration, where some or many points may be interconnected. However, the principle of the Layer 2 logical network remains consistent regardless of the details of the physical connection.

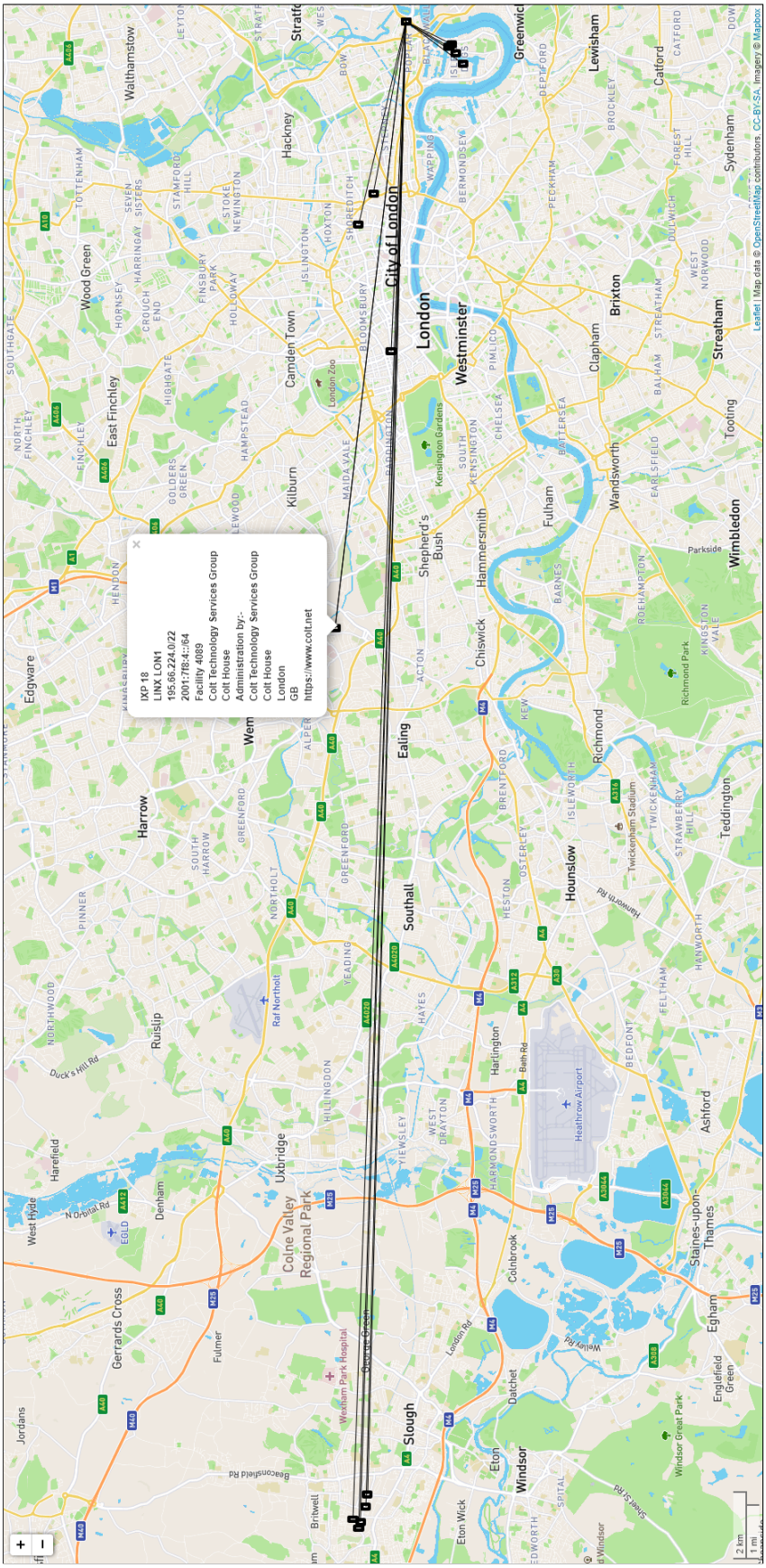


Figure 4.13: LINX LON1 IXP showing its Public Peering Facilities and its Layer 2 Network

Once the public peering points from PeeringDB have been mapped, we can refer to the IX website to collect any additional IXP public peering facilities that may have been missed by PeeringDB. For example, LINX London is one of the largest Internet Exchanges in the world with one of the highest numbers of participants. The information available on the LINX Internet Exchange website is comprehensive and includes the ASN, IP address, connection location, connection speed, relevant routers, ports, and port type. The location and IP information allow us to geolocate the interconnection with great accuracy, whereas the service speed allows us to understand the maximum bandwidth that a connection can use, perhaps allowing for future investigation of any cause of congestion. In addition, many ports are marked with a port type 'Connexions', which are LINX's reseller partners, and provide information on clients who connect using remote peering. According to the LINX website, there are eight UK facilities to which LINX LON1 interconnects, which PeeringDB has failed to list. These are connections to other LINX IXPs such as LINX Manchester, LINX Wales, and LINX Scotland.

Probes and anchors on the RIPE Atlas platform were chosen to create measurements across the UK infrastructure to build a snapshot of the connections between UK facilities. The RIPE Atlas has over 600 active probes and anchors located throughout the UK, which can be used as a bootstrap to create a detailed infrastructure map. Traceroutes using CAIDA's ARK platform (CAIDA, 2024) and Looking Glass (LG) servers, where available, can also add details to the overall picture.

One problem with using a traceroute is that a packet may take any one of the possible routes where load balancing is involved. Paris Traceroute (Augustin, Cuvellier, Orgogozo, Viger, Friedman, Latapy, Magnien, and Teixeira, 2006) avoids this problem by adapting the header fields of the probe packet in a manner that allows all probes to follow the same path; per-flow load balancing is an option. The RIPE ATLAS platform uses the Paris Traceroute as default. Although it cannot enumerate paths in all situations, it has been shown to perform considerably better

than the classic traceroute.

4.7.1 Discovering Target Locations using IXPs as Landmarks

First of all a traceroute must be created from a source ATLAS RIPE probe towards a target IP address. At each hop towards the target, a test is carried out to see if the IP address matches known IXP IP addresses. If the test proves successful, we can then take note of the IP address and ASN of the entry point and compare its peering facilities with the IXPs peering facilities. If we find a single facility that is shared between the entry ASN and the IXP then we can be sure that this facility is the correct one that is used by the route. The exit facility is discovered in a similar fashion, whereby the IP address and ASN of the hop leaving the IXP is noted and its peering facilities are compared with the IXP peering facilities. If the exit ASN and IXP share only a single facility, we can be assured that the facility is the correct exit facility. For example: Probe 6182 is located in Leeds and has an IP address of 141.170.19.12. Probe 6087 is located in Slough and has an IP address of 141.170.19.12. A traceroute from the Leeds probe 6182 routes via the following hops as shown in Figure 4.14:-

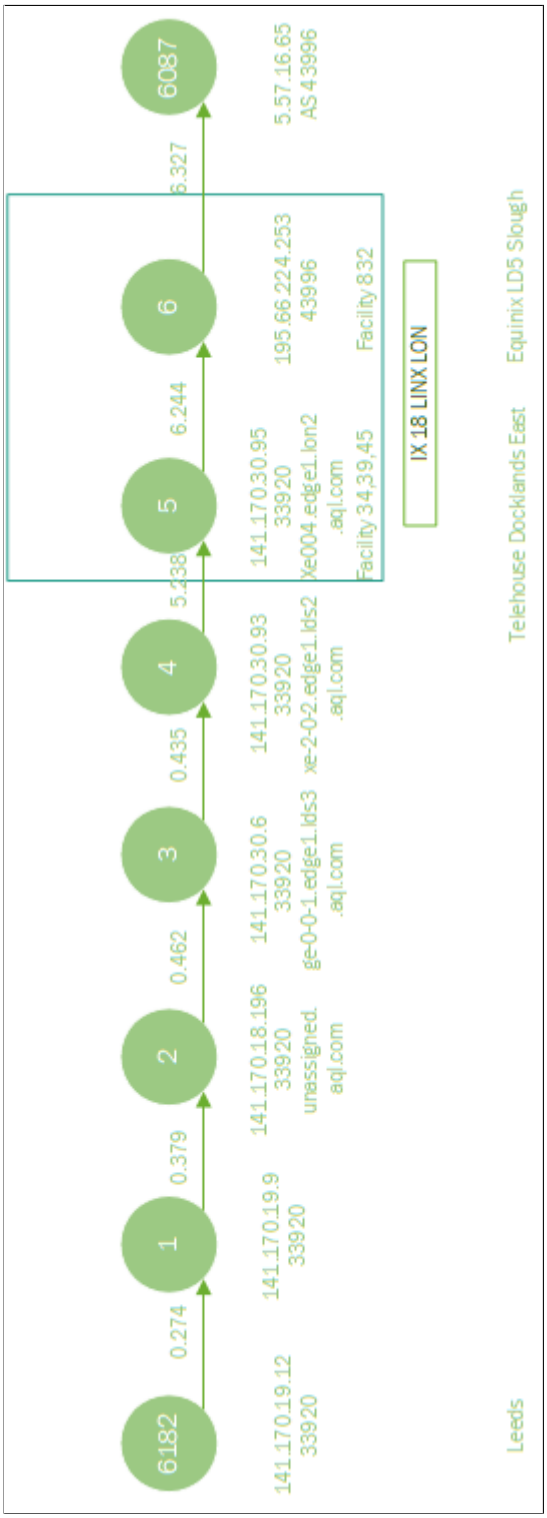


Figure 4.14: Discovering an IXP's exit facility

Hop 5 is the IXP entry hop; its IP address is owned by AS33920, and its peering facilities are the following PeeringDB assigned identifications [39, 45, 896, 76, 2384, 34].

Hop 6 is IXP 18 and its IP address is hosted by Linx LON whose peering facilities according to PeeringDB are [34, 39, 40, 43, 45, 46, 79, 399, 534, 832, 2262, 835, 4404, 4360, 4089, 3152, 6535, 3399].

Hop 7 is the IXP exit hop; its IP address is owned by AS43996, and its peering facilities are [832, 63, 1, 705, 225, 58].

Comparing entry facilities with IXP facilities results in 3 facilities that are possible candidates [39, 45, 34]; however, all of these are owned by Telehouse in London and are in a tight geographical area in London Docklands, so for this purpose any of the three can be chosen as the entry facility. It should be noted that in many cases only one facility is shared between the IXP and the entry ASN making this process much more accurate. It should also be noted that in some cases two or more geographically distant ASN's are shared between the IXP and the entry ASN making the process far more difficult. However, if traceroutes are sent from multiple locations towards the target then the number of shared facilities may be reduced. Additional sense checks, such as the speed of light over a distance, may also eliminate certain facilities.

We carry out the same process for the exiting ASN's (43996) facilities which are [832, 63, 1, 705, 225, 58] and discover that the only facility that is shared between the IXP and the exiting ASN is 832, which is Equinix LD5 located in Slough and therefore this must be the exiting facility as shown in Figure 4.15. If it were the case that we were unable to narrow down the number of facilities, for example, if all 6 of the facilities listed above hosted ASN 43996 then we would have to draw possible geolocation areas around all 6 IXPs as discussed in Section 4.6.3

It should also be noted that in this case we have not discovered the exact facility where the packet enters the IXP; the packet could enter the IXP at any of the three Telehouse facilities based in the Docklands in London and shown as black

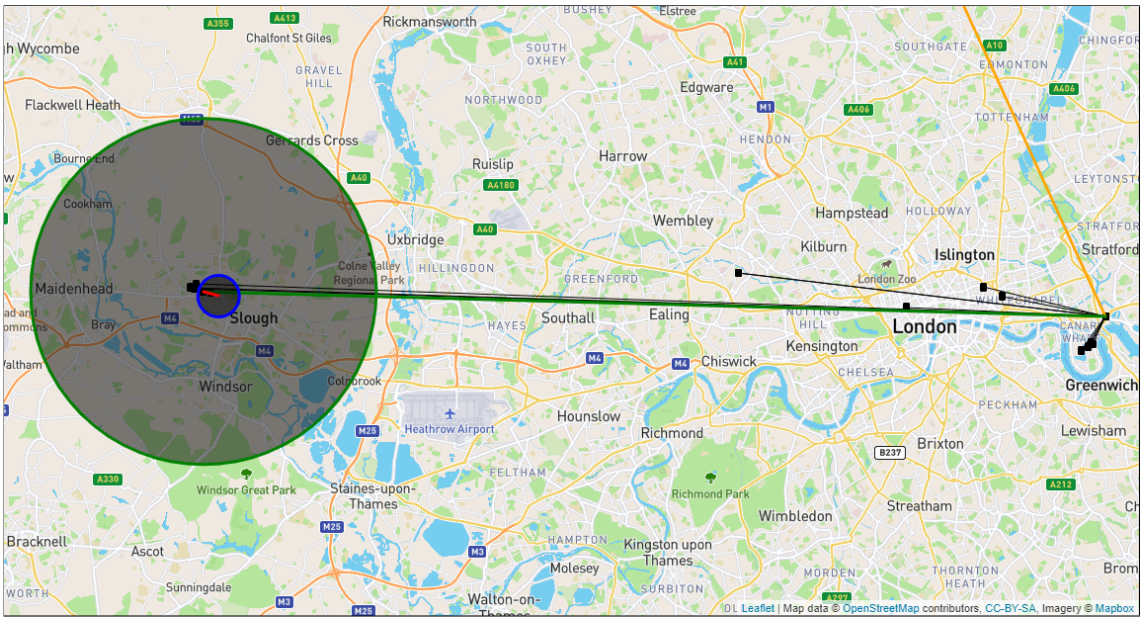


Figure 4.15: Using an IXP as a Vantage Point

rectangles in Figure 4.15. However, this is not important as we are only interested in geolocating the target, and for that, we are using the exiting IXP as the nearest Vantage point. The orange line intersecting with the Telehouse facilities denotes the packet path, and as a visual cue regarding estimated speed, the orange colour shows that the speed of the packet is travelling slightly less than optimal. After entering the IXP LINX LON1, the packet then travels through the IXP Layer 2 network towards the exiting facility; this is shown as a green line and denotes the packet is now estimated to be travelling faster at close to the maximum packet speed in a fibre medium.

Upon discovery of the exiting facility, we now have a Vantage point that should be far closer than any existing VPs. Closer Vantage points reduce geolocation errors that are caused by latency factors such as processing, queueing, congestion, and transmission delays and are multiplied by the number of intermediate routers that are crossed.

To discover the approximate location of the target IP address, we can now subtract the RTT value of the exiting IXP hop from the RTT value of the target

hop: $6.327 - 6.244 = 0.083$ms. This equates to the maximum time it can take for a packet to travel from the IXP exit facility to the target and return. We can multiply this by the commonly used speed of a packet in a fibre medium which is 0.66 x speed of light which equals approximately 200km per millisecond, and hence 200 *.083 = 16.6km. This figure is for the round trip and, in fact, we only need the one-way distance so we can half this figure to give an approximate target distance from the facility of 8.3km. The blue circle shows the actual target location according to RIPE ATLAS taking into account its 1km obfuscation policy, whilst the green circle shows the calculated estimated location area. At this point, it can be seen that the packet takes a considerable amount of time to travel the actual distance to the target, and the visual cue for this is that the line is now red. This also accounts for the relatively large target area.

4.8 Summary

This chapter explores the innovative use of Internet Exchange Points (IXPs) as Vantage points to improve the accuracy of IP geolocation and reduce errors associated with traceroute methods. Using the strategic positioning of IXPs, which are typically located near major population centres, the study proposes that these facilities can serve as closer reference points, minimising issues such as congestion, latency, and circuitous routing paths that often skew geolocation data.

The chapter introduces a methodology for identifying and utilising IXPs as key geolocation markers. It discusses resolving the challenges associated with multi-facility setups, ensuring that geolocation can benefit from the presence of these IXPs without being confounded by their complexity.

Proofs of concept are provided using data from South Africa and the United Kingdom, demonstrating the effectiveness of employing IXPs as geolocation landmarks. By reducing the geographical distance between the source and the target of the traceroute and avoiding unnecessary detours through less direct routes, the

approach promises enhanced accuracy and reliability in the analysis of network paths.

Ultimately, the chapter underscores the potential of IXPs to act as pivotal landmarks in geolocation efforts, contributing to a more precise mapping of network topologies and improving the Quality of Service for end users.

The use of IXPs as vantage points is shown to provide very accurate IP Geolocation when the exiting facility can be determined. The method of comparing the ASN of the IXP and the ASN of the next-hop IP address to determine the correct facility is used in Chapter 5, but is effectively made redundant by the introduction of IXP gateway databases (which various Internet Exchanges began making available to the public towards the end of the research carried out for this thesis). The new method for discovering the location of IXP facilities is introduced in Chapter 5.

Chapter 5

Improving Internet Infrastructure Mapping

5.1 Introduction

This chapter builds on previous methods for using Internet Exchange Points (IXPs) as Vantage Points to create fine-grained multilayer maps of the Internet structure.

Chapter 2.2 details the difficulties in using Delay-Distance models and suggests that the use of Round Trip Times (RTTs) can lead to highly misleading results. This chapter develops a new procedure that combines state-of-the-art methods to avoid many of the fundamental problems in Internet topology mapping while creating finer-grained Internet maps than those currently available. The procedure is tested on the UK infrastructure by conducting a series of tests using distributed measurement points provided by the RIPE Atlas platform.

Roadmap In Section 5.2, we detail the objectives of this chapter. Section 5.3 provides an overview of the proposed procedure. Section 5.4 discusses the use of the RIPE ATLAS platform and the usage metrics. In Section 5.5, we test the new procedure, and in Section 5.6, the procedure is automated by creating rules that can be used by a new software tool that is developed, and the results are provided.

5.2 Objectives

The objectives of this chapter are as follows.

- To extend DNS-based geolocation from city-level to facility-level and address shortcomings of the state of the art with respect to their limited geographical coverage.
- Introduce a new technique to create constraints in DNS geohints inference. Although past work has relied on RTT measurements, our work uses traceroute-derived constraints by combining IXP datasets with forward and reverse traceroute measurements to observe any differences in the forward and reverse measurements.
- Construct a dataset of facility-level landmarks that can be used in future research work to improve RTT-based geolocation.
- To illustrate the applicability of our work by geolocating a number of IPs at the level of colocation facilities, and then show that our method can create detailed maps of interconnection infrastructures at large metropolitan Internet hubs including London.
- To evaluate the inferences and estimate its success using a carefully curated dataset obtained by two of the largest London IXPs.

5.3 Overview

The new procedure will use a combination of methods, databases, and tools described in the subsequent chapters with the aim of improving the mapping of the Internet infrastructure to a facility level.

Step 1 of this process involves querying the PeeringDB REST API to obtain a list of UK-based facilities and their geographical coordinates. These facilities are then mapped onto OpenStreetMap (OSM), a collaborative project to create a freely

editable geographic database of the world. PeeringDB identifies each facility through a unique identification number, which we use to reference facilities in this paper.

In Step 2 of this process, we query again the PeeringDB API to find in which of these UK facilities Internet Exchanges have deployed their switching equipment to build an OSI layer 2 map of the IXP network infrastructure. Additional information is downloaded from each Internet Exchange website, such as the connection speeds of the peering ports.

Step 3 involves the execution of traceroute measurements using the RIPE ATLAS platform, which has over 600 probes in the UK, allowing traceroutes to be created in both directions, to and from each probe, creating a mesh of over 350,000 measurements.

Step 4 maps each hop to a facility where possible using a combination of DNS lookups, Internet Exchange website information, and PeeringDB data. This information also creates a list of valuable Vantage Point information that will be useful for future research. To map these intermediate hops, a software tool was created, which reads the data from the traceroute measurements created in Step 3, and queries various sources, such as PeeringDB, DNS, and the Internet Exchange websites, to locate the position of the router where these hops are interfacing, considering the previously discovered facility and IXP information.

5.4 RIPE ATLAS Measurements

The use of the RIPE ATLAS platform requires credits which can be spent to request User-Defined Measurements (UDMs) from the platform. RIPE Atlas probe hosts earn these credits for the time their probes remain connected and for the number of measurement results they generate. This is designed to serve as a means of measuring the level of contribution to and consumption of resources in the RIPE Atlas system.

In putting the method into action, we carried out 1190 traceroutes in both the forward and reverse directions between 35 ATLAS Anchors. The following formula was used to calculate the RIPE Atlas credit cost of a user-defined measurement:-

$$Traceroutecreditcost = 10 \times N \times (\frac{S}{1500} + 1) \tag{5.1}$$

Where: N = Number of packets per traceroute (default is 3), S = packet size (default is 40)

Thus, the total approximate cost is $1190 \times 30\times \approx 1 = 35700$ credits.
It should be noted that measurements do not necessarily have to be limited to the RIPE ATLAS platform but can be carried out whenever access to both ends of the traceroute is possible. In addition, most RIPE ATLAS measurements are publicly available for read-access without requiring credits, and a search of two existing measurements, where the target and source become the source and target, can be used.

5.5 The Method in Action

Where possible, each hop on a traceroute was assigned to a facility using a combination of DNS lookup, Internet Exchange website information, and PeeringDB information. The combined information creates new Vantage Points on the way to destinations; these will be invaluable in further research, especially when there is a

dearth of ground-truth data, as many researchers have recognised.

5.5.1 Example of Network Mapping

An example of this logical network mapping is shown in Figure 5.1, where a traceroute is first carried out from probe 6515 towards probe 6087.

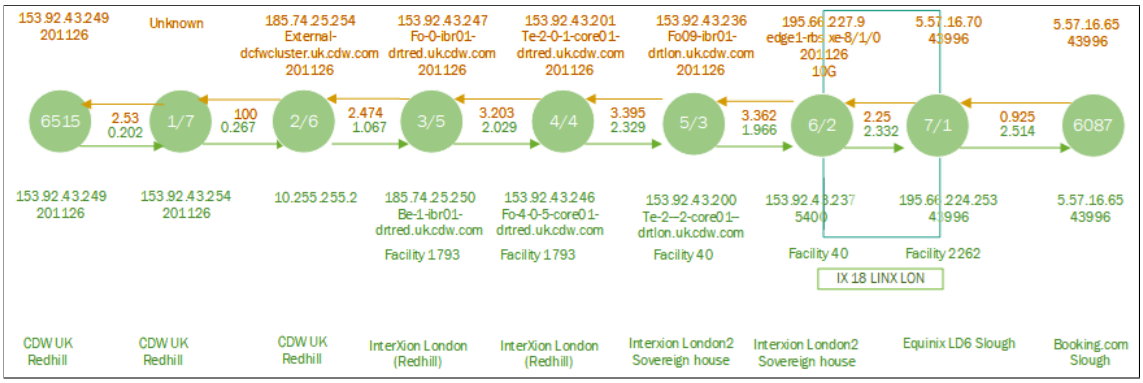


Figure 5.1: Forward and reverse traceroute measurements between two probes demonstrating facility and IXP mapping.

The IP address of each hop corresponds to an ingress port interface on a router located in a specific location. The hop times for this measurement are listed in Table 5.1.

Hop	RTT (m/s)	IP Address	DNS
1	0.202	153.92.43.254	
2	0.267	10.255.255.2	
3	1.067	185.74.25.250	Be-1-ibr01-drtred.ukcdw.com
4	2.0153	192.43.246	Fo-4-0-5-core01-drtred.ukcdw.com
5	2.329	153.92.43.200	Te2–2-core01-drtlon.ukcdw.com
6	1.966	153.92.43.237	
7	2.332	195.66.224.253	
8	2.514	5.57.16.65	

Table 5.1: Traceroute Measurement Table

A DNS look-up for each IP address on the route can provide useful information regarding the location of the port/router combination. For example, in Figure 5.1,

we find that the first hop has no assigned DNS name and is probably the default gateway of the probe owner (CDW UK). The RTT value of 0.202ms suggests that the router is co-located with the probe. The second hop uses a private 10.0.0.0 subnet range, which could be a Local Area Network (LAN), Virtual Private Network (VPN), or Multiprotocol Label Switching (MPLS) connection, and the RTT value suggests that this is also local.

In the third hop, we now have an IP address with a DNS name of 'be-1-ibr01-drtred.uk.cdw.com', which would indicate that it is in the Redhill facility. Cross-checking with PeeringDB, we find that CDW does, in fact, peer at Facility 1793 Interxion Redhill, so we can be confident that because we know the geolocation of the facility, we now have a new IP address/geolocation combination and, therefore, a new Vantage Point for use in future IP geolocation work. The hop 4 DNS name shows that we are still in Redhill, but the DNS suggests that we have now moved from an edge router to the core router; this IP address/geolocation combination is a new VP. The hop 5 DNS name shows that we are now at a core router in London, and PeeringDB states that the only facility where CDW interconnects in London is Facility 40 Interxion, thus creating another VP that will be verified on the return traceroute.

Hop 6 also displays a London DNS name that must still be in the same facility as hop 5, which provides another IP/geo combination or VP. The diagram shows the route through an Internet Exchange Point. The only indication that hop 6 is still located at the same facility as hop 5 is that the DNS name appears to show a possible LINX gateway interface; later results on the return traceroute will eventually prove this. Hop 7 has an IP address within the assigned prefix range of LINX LON1 IX of 195.66.224.0/22. We know that the traceroute is now exiting the Internet Exchange, and by cross-checking the LINX Internet Exchange website, we are given the facility name for this IP address, viz. Facility 2262 Equinix LD6 along with other secondary information such as port speed (10G), organisation, IPv6 information, and router/port name. Cross-referencing the facility name in PeeringDB provided vital

geolocation data, and another VP was added to the ground-truth dataset. We can also assume that the previous hop was an Internet Exchange entry point. Finally, the traceroute ended at the target address. The next step was to create a traceroute measurement in the reverse direction from probe 6087 to probe 6515, which is shown in green from right to left in Figure 5.1. The traceroute timings are listed in Table 5.2.

Hop	RTT (m/s)	IP Address	DNS
1	0.925	5.57.16.70	
2	2.25	195.66.227.9	edge1-rbsxe-8/1/0
3	3.362	153.92.43.236	Fo09-ibr01-drtlon.ukcdw.com
4	3.395	153.92.43.201	Te-2-0-1-core01-drtred.ukcdw.com
5	3.203	153.92.43.247	Fo-0-ibr01-drtlon.ukcdw.com
6	2.474	185.74.25.254	External-dcfwcluster.uk.cdw.com
7	unknown	185.74.25.254	
8	2.53	153.92.43.249	

Table 5.2: Reverse Traceroute Measurement Table

Hop 1 provides little information on its location and, at this stage, we can only assume that it is a gateway router. Hop 2's IP address is within the LINX LON1 prefix range, so we know that the packet is now exiting the Internet Exchange. By checking the LINX Internet Exchange website, we are given the facility for this IP address, which is facility 40 at Interxion London, along with the other secondary information mentioned earlier, such as the connection's 10Gb service speed. The DNS name closely resembled the DNS name from hop 6 on the forward leg. Therefore, it is safe to assume that they belong to the same router. In addition, we can surmise that hop 1 must have been the entry point for the Internet Exchange, which we already located at Facility 2262 Equinix LD6 in Slough. Therefore, two additional Vantage Points can be added to the ground truth dataset. Hop 3 has a London DNS name, stating that it is a port on the core01 router, similar to hop 5 on the outward leg. Therefore, this must be performed at facility 40 in London, adding another VP to the ground truth dataset. Hop 4 has a Redhill DNS name similar to hop 4 on the outward leg.

Therefore, we know that the packet has now travelled to the Redhill 1793 Interxion facility, adding another VP to the table. The DNS name of Hop 5 shows that the packet is still in Redhill but has now moved to an edge router, adding another VP to our VP table, as shown in Table 5.3.

Hop 6 has the DNS name of 'external-dcfw-cluster.uk. cdw.com', which does not provide any clues regarding its location. The IP address of hop 7 in this direction is unknown; however, the forward traceroute shows that hop 2 ends at a private IP address of 10.255.255.2; therefore, the remote end of this connection must also be in this private subnet range. This coincides with the unknown IP address in the reverse traceroute at hop 7, and it is assumed that this interface does not reply to ICMP packets. Another verification of this assertion is to examine hop 3 on the forward traceroute with hop 6 on the reverse traceroute, both of which are in the 185.74.25.x subnet range. This indicates that we can be confident we are not dealing with asynchronous routes. Because this is the last hop, we can safely conclude that this is the initial gateway router that connects to the probe. The results of this method allowed us to build a detailed picture of the infrastructure between these two probes by combining information from our three sources (DNS, PeeringDB, and LINX websites), as shown in Figure 5.2. This diagram shows a traceroute from RIPE Probe 6515 to RIPE Probe 6087, which first passes through three routers (blue circles) on its way to the Interxion and LINX LON1 interconnection facility at the Interxion Sovereign House in London.

In Figure 5.2, colour coding is used only as a visual cue to denote the approximate transmission speeds over these hops. The approximate speeds were calculated by dividing the distance between hops by the difference in time between the previous hop and this hop. However, it should be noted that each router may prioritise ICMP packets differently depending on their target, and timings can also suffer from packet forwarding decisions, circuitous routes, different router configurations, and congestion, and the time taken does not always reflect distances. A different method can divide the overall RTT time of the hops by the distance from the source

IP Address	Facility	Longitude	Latitude	DNS	Port	Speed
185.74.25.250	1793	51.2476	-0.1571	be-1-ibr01-drt-red.uk.cdw.com.	none	Unk
153.92.43.246	1793	51.2476	-0.1571	fo-4-0-5-core01-drt-red.uk.cdw.com.	none	Unk
153.92.43.200	40	51.4998	-0.0107	te-2-0-1-core01-drt-lon.uk.cdw.com	none	Unk
153.92.43.237	40	51.4998	-0.0107	fo-0-0-0-20-ibr01-drt-lon.uk.cdw.com.	none	Unk
195.66.224.253	2262	51.5243	-0.6380	None	edge5-eq4 xe-3/0/3	10G
195.66.227.9	40	51.4998	-0.0107	None	edge1-rbs xe-8/1/0	10G
153.92.43.236	40	51.4998	-0.0107	fo-4-0-5-core01-drt-lon.uk.cdw.com.	none	Unk
153.92.43.201	1793	51.2476	-0.1571	te-2-0-1-core01-drt-red.uk.cdw.com.	none	Unk
153.92.43.247	1793	51.2476	-0.1571	fo-0-0-0-20-ibr01-drt-red.uk.cdw.com	none	Unk
185.74.25.254	1793	51.2476	-0.1571	external-dcfw-cluster.uk.cdw.com	none	Unk

Table 5.3: Vantage Points Table

to the intermediate router. However, this also has its own problems. For example, delays due to administrative packet forwarding decisions, circuitous routes, different

router configurations, and router congestion will multiply timing errors depending on the number of intermediate routers between the source and hop. In Figure 5.2, the green lines indicate relatively fast connections. Red lines denote slow speeds, that is, less than 100 km/ms, and yellow lines denote medium speeds, that is, 100 km/ms to 200 km/ms, whereas green lines are used for anything greater than 200 km/ms. However, it should be emphasised that this is only a rough indication of transmission speeds, regardless of the method used. The ICMP packets then pass through two additional routers before entering the Internet Exchange Layer 2 network on their way to Slough. The packets exit the LINX LON1 Internet Exchange at the Slough Equinix Facility and are routed to probe 6087.

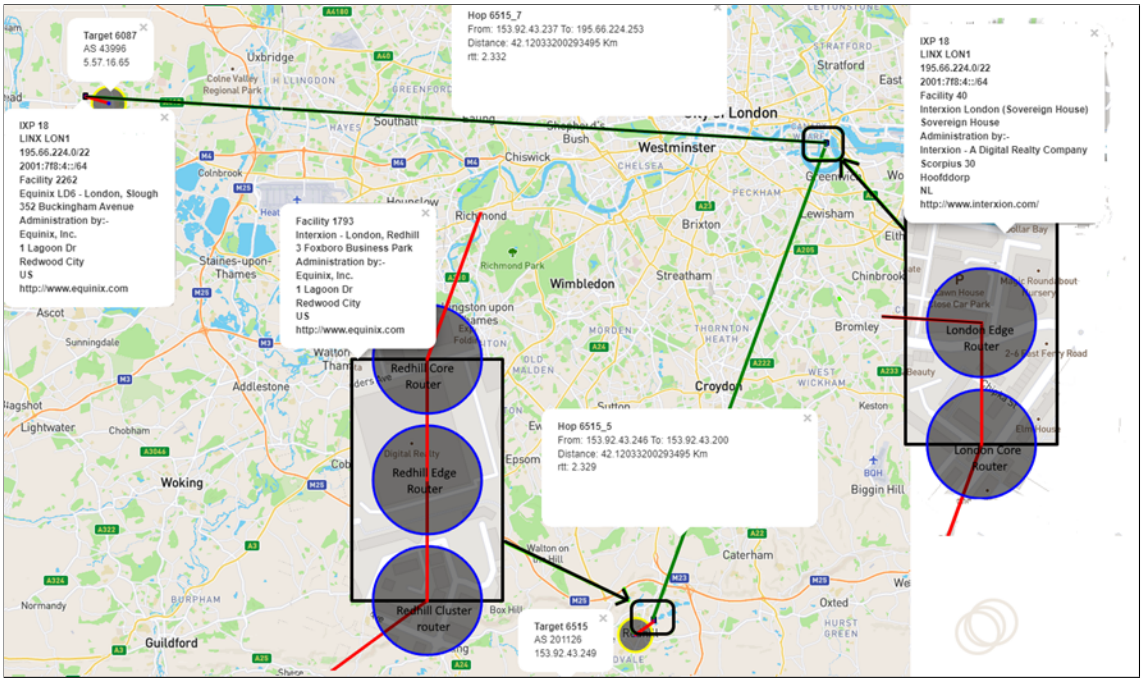


Figure 5.2: Example of UK Infrastructure Mapping incorporating LINX LON1 Internet Exchange Point.

The reverse measurement from RIPE Probe 6087 to RIPE Probe 6515, shown in Figure 5.1, follows the same path in this case, but it is highly likely that many measurements will follow alternative reverse paths. In fact, both forward and reverse measurements may even take different paths at contrasting times of the day, depending on congestion, providing further details about the network infrastructure

and additional Vantage Points. It would be useful to test this hypothesis in future studies. It is interesting to note that in this example and in this reverse direction, ICMP packets seem to be given low priority at hops 3, 4 and 5 and their RTT timings reflect this. It seems unlikely that this is due to congestion or other problems, as the RTT timings at the rest of the interfaces are in line with outward-bound measurements.

To improve confidence in the results, additional validation of the IP address location within the VP Table could involve contacting the various facilities or AS organisations to confirm the location. This would be a very slow method, but would guarantee 100% confidence in the result. This method provided good validation in several cases. For example, at hop 3 in the results, the hop IP address has a DNS address, indicating that it is hosted at Redhill. PeeringDB confirms that probe owners (CDW UK) interconnect at the Redhill Interxion Facility and there are no other options. This would suggest that without contacting the facility or CDW UK, we can be confident that we have the correct location. The location of Hop 2 in the results is a little more obtuse; its DNS name, 'external-dcfw-cluster.uk.cdw.com', refers to an external cluster, but does not provide a city name. However, it is connected to hop 1, which appears to be CDW's gateway router at 153.92.43.254 through a private network, perhaps a VPN or a point-to-point connection. The IP address of hop 3 is 185.74.25.250, while the egress IP address of hop 2 is 185.74.25.254, indicating that it is on the same LAN or possibly on a point-to-point link. The RTT difference in timing between hop 2 (0.267ms) and hop 3 (1.067ms) indicates that it is likely that the router at hop 3 is not local to hop 2. An educated guess would be that this external cluster router is situated at either CDWs Redhill offices or at the Redhill facility, but full validation would have to be confirmed by contacting the facility or CDW UK. In the meantime, the two offices are only one mile apart, and either geolocation would provide a useful Vantage Point. So, from these various confidence levels we could add a confidence column to the VP table as shown in Table 5.4, where a 1 is fully confident, a 2

is probable, a 3 is likely, and a 4 is "best guess". A score of 1 indicated that the facility or the company confirmed the validation. A score of 2 indicates where the DNS name corresponds to a facility location and there are no other possible facilities. A score of 3 would indicate where various other factors, such as LAN IP addresses link two hops, as between hops 2 and 3, or perhaps RTT times between the two hops make it impossible for the router to be geolocated elsewhere. A score of 4 was assigned if only minor evidence indicated its location. Further reinforcement of these IP geolocations could result from additional traceroute measurements from RIPE probes located within the AS that owns the hop's IP address.

IP Address	Facility	Longitude	Latitude	Conf	DNS	Port	Speed
185.74.25.250	1793	51.2476	-0.1571	2	be-1-ibr01-drt-red.uk.cdw.com.	none	Unk
153.92.43.246	1793	51.2476	-0.1571	2	fo-4-0-5-core01-drt-red.uk.cdw.com.	none	Unk
153.92.43.200	40	51.4998	-0.0107	2	te-2-0-1-core01-drt-lon.uk.cdw.com	none	Unk
153.92.43.237	40	51.4998	-0.0107	2	fo-0-0-0-20-ibr01-drt-lon.uk.cdw.com.	none	Unk
195.66.224.253	2262	51.5243	-0.6380	2	None	edge5-eq4 xe-3/0/3	10G
195.66.227.9	40	51.4998	-0.0107	2	None	edge1-rbs xe-8/1/0	10G
153.92.43.236	40	51.4998	-0.0107	2	fo-4-0-5-core01-drt-lon.uk.cdw.com.	none	Unk
153.92.43.201	1793	51.2476	-0.1571	2	te-2-0-1-core01-drt-red.uk.cdw.com.	none	Unk
153.92.43.247	1793	51.2476	-0.1571	2	fo-0-0-0-20-ibr01-drt-red.uk.cdw.com	none	Unk
185.74.25.254	1793	51.2476	-0.1571	3	external-dcfw-cluster.uk.cdw.com	none	Unk

Table 5.4: Vantage Points Table with Confidence Column

5.6 Automating the Method

In this section, we describe the automation of this method. Thirty-five probes were used, each targeting the other 34 probes, to create a mesh of 1190 traceroutes across London and South England. The results of each hop on a traceroute are first passed through a filter that tests the hop results against five assumptions (or rules).

5.6.1 Gateway Router Location - Rule 1

If this is the first hop, it is assumed that the first router encountered will probably be the gateway router for the source probe. This may or may not be in the same location as that of the probe. A gateway is a network node used in telecommunications that connects two networks. Gateways serve as an entry and exit point for a network, as all data must pass through or communicate with the gateway before being routed. In most IP-based networks, the only traffic that does not go through at least one gateway is traffic flowing among nodes on the same local area network segment. In this method, we class the gateway router as being the first router encountered and therefore only need to apply this rule to the first hop. Rule 5 is similar to Rule 1 and is applied to all hops that do not meet any of the other rules, the difference being that Rule 1 applies only to hop 1 and performs an initial sanity check.

To provide a sanity check, a test is conducted to discover whether the RTT to this router is less than 1ms; if less than 1ms, it is assumed that the gateway router is in the same location as the source probe. This is the only use of the delay-distance model. However, this could be verified through further tests. We begin by testing to ensure that the hop's IP address is not the target, as it has been found that in some cases the RTT responses are blocked or packets are discarded by some or all of the intermediate routers on the way to the target (occasionally, the first IP address encountered is the target address). Once a valid IP address has been determined, a reverse IP lookup is performed. If the IP address returns a DNS name, then this is put through a series of search patterns to discover the likely town or city

where the IP address is located. If a town or city name was discovered, we checked which facilities were in that town or city. If there are multiple facilities in the town, we compare the AS interconnections of each facility with those of the ASN of the previous hop, which will hopefully reduce the list to a single facility.

If multiple facilities or no facilities were returned, we attempted the reverse traceroute method. In this case, we created a traceroute probe from the target back to the source and compared the first hop of the forward tracker with the last hop of the reverse traceroute. If both IP addresses are in the same subnet prefix, we can assume that the penultimate interface on the reverse traceroute is an interface on the forward traceroute's first-hop router. A reverse DNS lookup of the IP address of this interface is performed. Any resulting DNS address is again filtered through a series of regular expression (REGEX) search patterns in an attempt to discover its location by comparing various parts of the DNS address with the United Kingdom town or city names where facilities are known to be located.

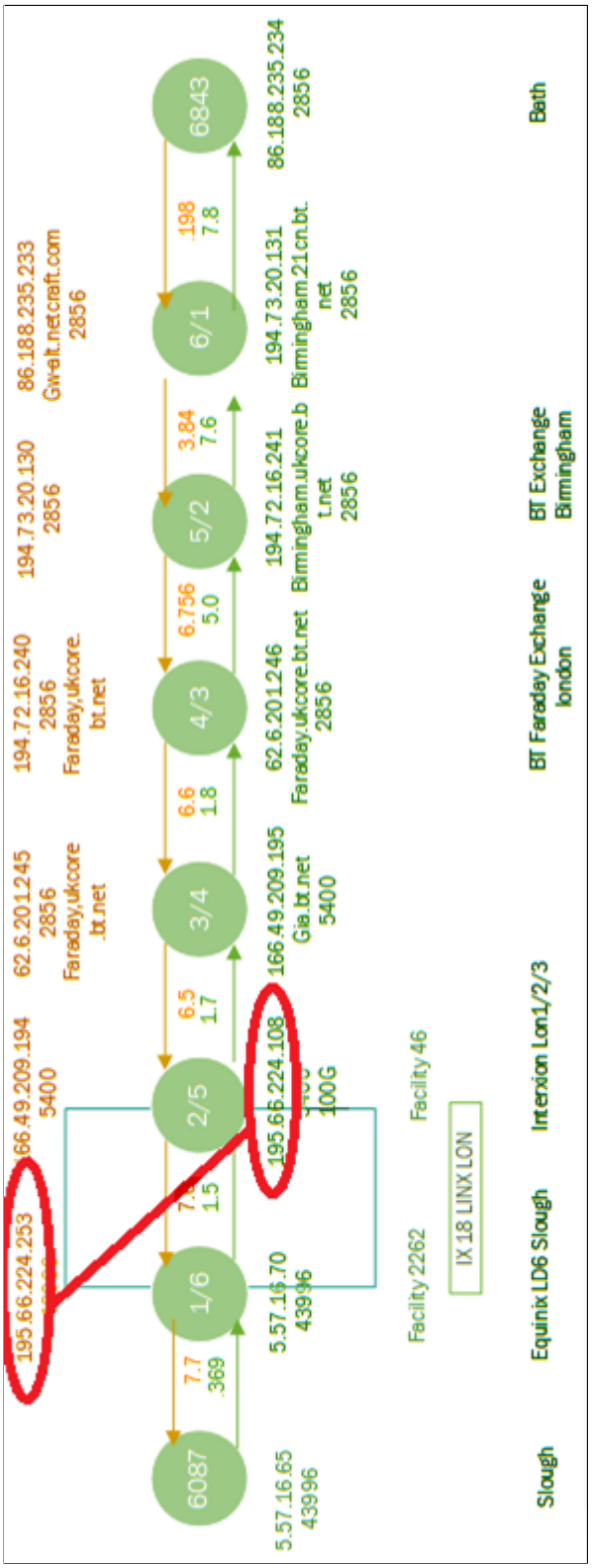


Figure 5.3: Forward and reverse traceroutes from IP address 5.57.16.65 to 86.188.235.234, showing outgoing and incoming IP addresses in same prefix range.

Figure 5.3 shows an example traceroute from RIPE Probe 6087 to RIPE Probe 6843, and the reverse path where the first router encountered at IP address 5.57.16.70 has an RTT of 0.369ms, which is a good indication that this router is in the same location as the source probe. However, we can attempt to verify this by examining the other side of this router by carrying out a reverse traceroute from RIPE Probe 6843 back to Probe 6087. In this case, we can examine the penultimate incoming interface and compare the IP address prefixes, where it is found that the incoming IP address 195.66.224.253 is in the same prefix range as the outgoing IP address of 195.66.224.108, indicating that we are dealing with the same first-hop router on both the outward and return journeys. Therefore, DNS clues to the location of the incoming interface also provide us with the location of the outgoing interface.

A search of the LINX IXP membership database shows that the IP address 195.66.224.253 belongs to Booking.com and is located at the Equinix LD4 facility. A database lookup at PeeringDB provides the geo-coordinates of the Equinix LD4 facility, which shows that it is on a specific street in Slough. This return traceroute in Figure 5.3 has provided us with the location of the outgoing traceroute's first hop interface because the outgoing interface of this router with an IP address of 5.57.16.70 is an interface on the same router as that of the geolocated interface with an IP address of 195.66.224.253; both of these IP addresses along with the geocoordinates of Equinix Facility LD4 can be used in our Vantage Points table.

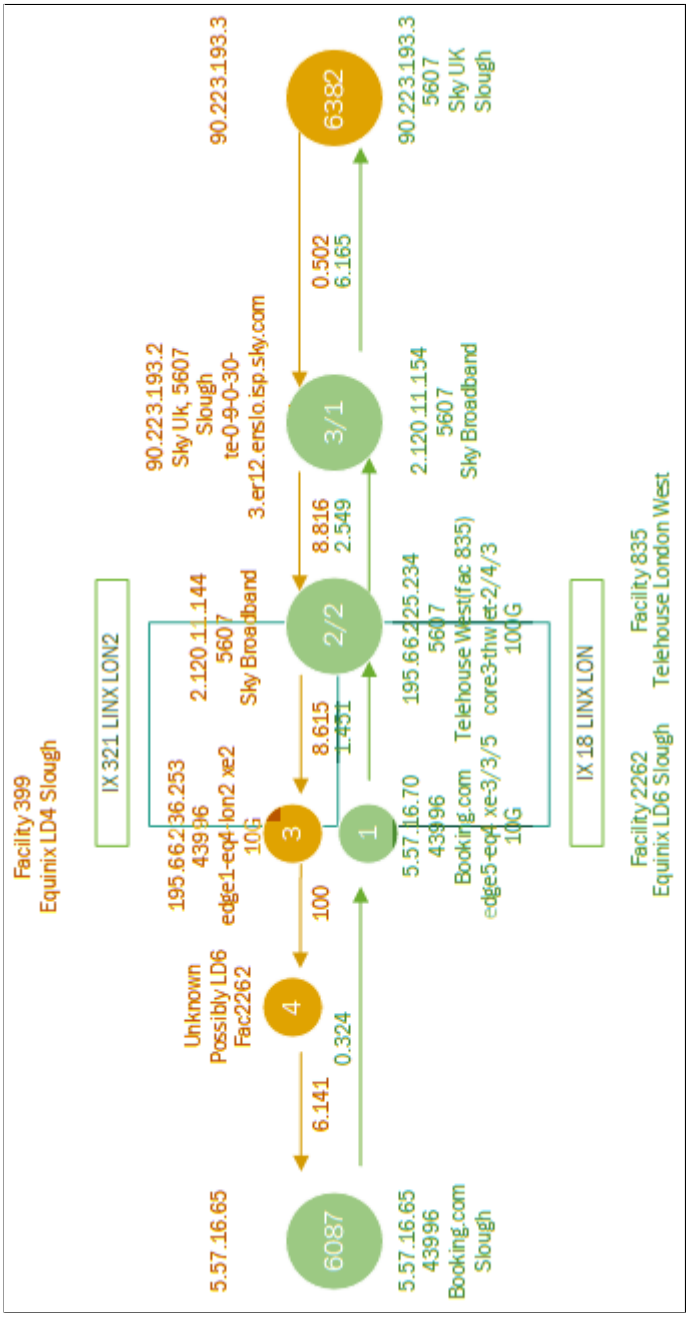


Figure 5.4: Forward and reverse traceroutes from IP address 5.57.16.65 to 90.223.193.3, showing incoming penultimate IP address blocked and outgoing IP addresses at 195.66.225.234. Also showing asynchronous forward and reverse routes using different Internet Exchanges on the forward and return legs.

We need to compare this traceroute with that shown in Figure 5.4, where the penultimate incoming hop has not returned an IP address because the packet is discarded or blocked, whereas the forward hop after the initial router has an IP address of 195.66.224.234. In this case, we cannot determine that this is the same router, and as can be seen in the figure, it would appear that the forward and reverse paths are asynchronous, using different Internet Exchanges on the forward (IXP 18 LINX London) and reverse routes (IXP 321 LINX London2). An additional point to make here is that the packet route seems to follow a somewhat circuitous route from the Slough Equinix LD6 facility to the London Telehouse West facility and then back to the Slough Equinix LD4 facility (Equinix advertises local cross-connects between LD6 and LD4). This example shows that these methods may offer Internet Exchanges with some opportunities to improve the network speed and reduce congestion. In the first scenario, it was fortunate that the penultimate return hop was across an Internet Exchange, where a list of IP addresses and their facility locations was readily available. However, the penultimate return hop may be another connection, as shown in Figure 5.5.

In this case, the reverse lookup is 'Birmingham.21cn.bt.net', which our REGEX search script would normally locate to Birmingham. However, this first-hop router cannot possibly be located in Birmingham because the initial probe is located in Bath; with a 0.198ms RTT to this router, the sanity check locates the router in Bath, which contradicts the reverse DNS lookup. In this case, the result of the RTT sanity check is prioritised over the results of the reverse traceroute method.

If the list cannot be reduced to a single facility, the central coordinates of the city or town are returned for use as a general location. A list of UK towns and cities and their central coordinates was downloaded from the Office for National Statistics (ONS), which provides free and unrestricted access to a definitive source of geographical products.

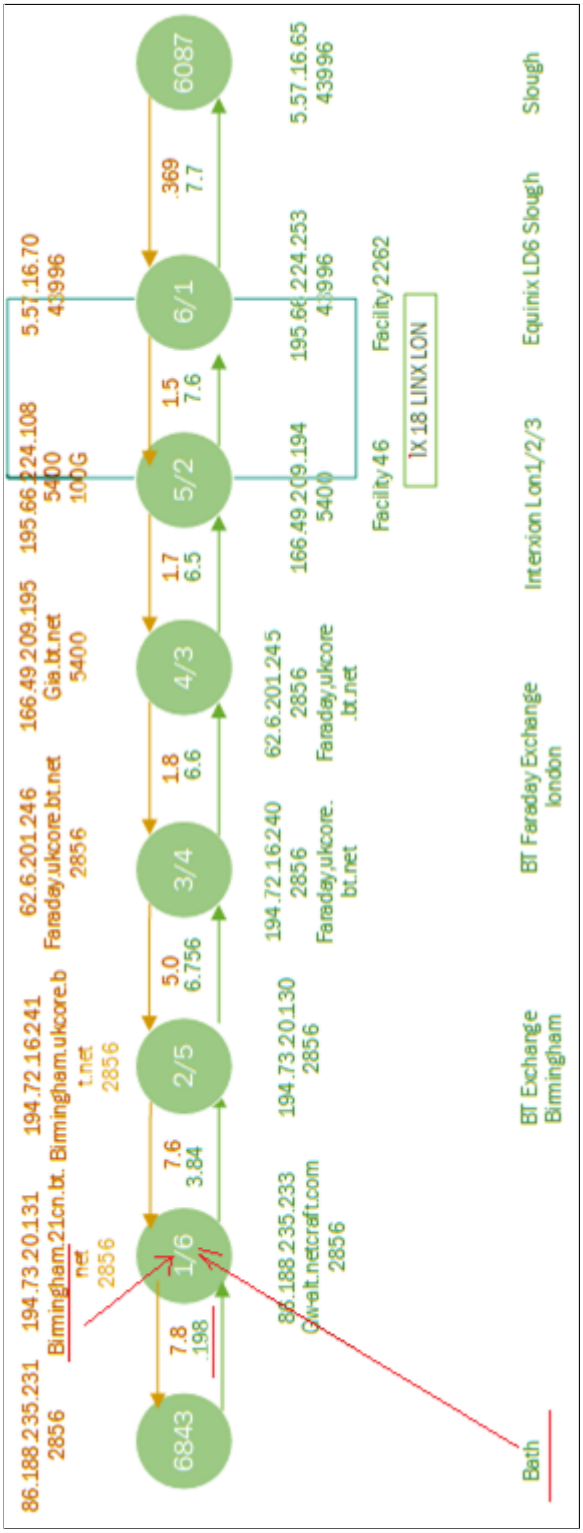


Figure 5.5: Forward and Reverse traceroutes from IP address 86.188.235.231 to 5.57.16.65, showing false positive in finding IP address location.

5.6.2 Private IP address - Rule 2

All IPv4 addresses can be divided into two main groups: global (public, external), which are those used on the Internet, and private (local, internal), which are those used in LANs and can also be used in VPNs, cross-connections, or site-to-site links.

If the IP address of this hop is within a private subnet range and the previous hops are not, then the packet has crossed a LAN, VPN, or site-to-site link. However, because it is a private IP address, there is little benefit in locating its true coordinates, as private IP addresses cannot be added to a Vantage Point table because of their possible use in multiple locations. If the location of this router is considered important, a comparison of the difference between the RTT values of the previous and successive RTTs provides clues as to whether the location of this router is local or remote to the previous router. Some private IP addresses have been geolocated in this manner.

5.6.3 Target IP address - Rule 3

If the hop under consideration corresponds to the target IP address, its coordinates are those of the target probe, which can be discovered within the RIPE ATLAS database. if something other than a RIPE ATLAS probe has been used as a target then a reverse DNS lookup can be carried out to discover any further information as to the location and perhaps provide some verification of the results returned from the RTT values.

5.6.4 IXP Test - Rule 4

This rule determines whether the IP address of a hop is registered on an Internet Exchange. A test is conducted on each hop's IP address to determine if it falls within any IX-registered prefix. The initial design would then look at the previous hop to discover the ASN entering this IXP and compare it with a list of IXPs and their ASN peers from PeeringDB in an attempt to discover the sole facility where

the IXP and previous ASN are peers. Therefore, it would provide an entry facility. The same method is then applied to the existing facility using the successive hop ASN. However, finding the entry facility in this manner is unnecessary, as the IXP entry facility is not as important as the exit facility, which can be used more easily as an ideal Vantage Point to discover the possible location of a given IP address. Furthermore, in the initial design, the exit facility was found using a process in which it looked at the successive hop to discover the ASN exiting this IXP and compared it with a list of IXPs and their ASN peers in an attempt to discover the only facility in which the IXP peers with the successive ASN. However, this becomes unnecessary after discovering that the IXPDB database, an authoritative, comprehensive, and public source of data related to IXPs, provides a list of IX-registered IP addresses along with the facility where they are located (IXPDB, 2024). The IXPDB database also integrates the data from third-party sources. The website provides a comprehensive and corroborated view of the global landscape of interconnections. The combined data can be viewed, analysed, and exported through a Web-based interface or API.

It is this IXPDB database that is now initially interrogated in an attempt to discover whether the IP address of a hop is registered on an Internet Exchange. It was discovered that the IXPDB database is not as comprehensive as advertised; some IXPs mark their IP to facility information as private, so no information is uploaded to IXPDB. One of these IXPs is Equinix, which plans to release this information in the (near) future. In cases where the IP address cannot be found in the IXPDB database but we have discovered that the IP address of the hop falls within an IX-registered IP prefix range, we revert to the method previously discussed of comparing the successive ASN with the known peers of each Internet Exchange. This is described in more detail in Chapter 4.

5.6.5 DNS Lookup - Rule 5

If no other rule is applicable, then a DNS lookup is made on the IP address of this hop, and any resulting DNS address is passed through a series of REGEX search strings to extract the city name or town from the reverse DNS address. Each part of a DNS address is compared with a list of known towns and cities in which facilities are located. If part of a DNS address matches the beginning of a town or city name, then the facilities for that town are extracted. If this list of facilities contains only one facility, the hop IP address is successfully located. However, if no facilities are located, we can attempt a reverse traceroute to discover the outgoing interface of the router. This is similar to the procedure described in Rule 1, where both outgoing and incoming IP addresses are in the same prefix range, and we can then make a safe assumption that the incoming and outgoing interfaces are on the same router. If this traceroute is successful in discovering the outgoing IP address, we can attempt to carry out a reverse DNS lookup on that IP address and pass any results through our REGEX search to discover the town and facilities, as described previously. If all of these methods fail, we must classify this as a failure to find the location of the IP address; therefore, we are unable to add this IP address to our Vantage Point table.

Referring back to our previous example in Figure 5.1, at hop 2 on the forward route we have a private IP address that would normally be impossible to geolocate. However, it will complete the routing diagram for this particular traceroute if we know the exact location of this particular hop. If we examine the reverse traceroute, we can see that the reverse hop provides us with a DNS address 'External-dcfwcluster.uk.cdw.com'.

Combining this with our rules regarding sanity checks and incoming/outgoing IP addresses on the same subnet range, we can safely assume that the router with an incoming hop of 10.255.255.2 on the forward traceroute and an incoming hop of 185.74.25.254 on the reverse traceroute is indeed the same router, and therefore we can geolocate this 10.255.255.2 and the reverse 185.74.25.254 IP address to Redhill.

5.6.6 Automated Results

To demonstrate the proposed method, 1190 traceroutes were created using the RIPE ATLAS platform with an API tool specifically written to create the necessary measurements on the platform.

Once the measurements are completed using RIPE ATLAS, the second API tool reads all the measurements from it and creates a local JSON file. The third tool reads the JSON file and discovers the likely geocoordinates of each hop, creating another JSON file and a Vantage Point table as output. The fourth optional tool maps these results to an OpenStreetmap, as shown in Figure 5.2.

The results of applying the described rules and methods through an automated process are presented in Table 5.5. This table also shows the effect of the IXPDB data on the final results. The first two columns show that the complex 'Common_Fac' method was used to discover IP address locations; however, once the LINX and LONAP Internet exchange data were added from IXPDB, this method became almost redundant. It is expected that once all IXP datasets become available, the 'Common_Fac' method will not need to be used.

Rules and Methods	**Before Add LYNX Data**		**After Add LYNX Data**		**After Add LONAP Data**	
	Failures	Successes	Failures	Successes	Failures	Successes
Regex	3244	2760	3244	2760	3218	2760
Reverse_Tr	3085	0	3065	0	3064	0
Reverse_DNS	35	17	35	17	10	0
Common_Fac	52	855	52	40	10	19
Fac_To_IP	0	0	92	815	29	878
Rule1	634	2003	634	1986	634	1987
Rule2	126	236	126	236	126	236
Rule3	0	1243	0	1243	0	1243
Rule4	35	855	35	855	10	897
Rule5	1254	32	1254	33	1254	33

Table 5.5: Rules and Methods Success and Failure Table

Although the rules have already been described above and the methods have been discussed at several points in this paper, we now provide a summary list for convenience.

REGEX is a process in which a hop's DNS address is filtered through a series of regular expressions to find a town or city name. It was found that in-depth knowledge of the network region is required to provide the correct tests for the REGEX method.

Reverse traceroute is the process of discovering the IP address of the outgoing interface to discover the location of a router via a second interface located on the same router, which may provide better clues regarding the router's location.

Reverse DNS is where an IP address is looked up in an attempt to discover its DNS address. This method is typically used in conjunction with the REGEX method and can also be combined with the Reverse Traceroute method.

Common Facility is one of the earliest processes used in our work and was designed to geo-locate a router where a packet enters and exits an Internet Exchange. This was done by comparing the ASN entering a facility with the ASN peer at each Internet exchange. This has been largely superseded by the Facility to IP Table described below.

Facility to IP Table consists of an API lookup of the IXPDB website, which holds a comprehensive list of Internet exchange-registered IP addresses and their locations.

The rules described in 5.6 use these methods as described below.

1. The Gateway Router Location Rule 1 uses the following methods:-

    - Reverse DNS
    - REGEX
    - Reverse Traceroute
    - Reverse DNS of the ip address returned from the Reverse Traceroute
    - Regex of the DNS returned from the Reverse Traceroute.

2. The Private IP address - Rule 2 only carries out a test to see if the IP address lies within a private IP address range and does not use any of the methods.

3. The Target IP address - Rule 3 uses the following methods:-

    - Reverse DNS

4. The IXP Test - Rule 4 uses the following methods:-

    - Common Facility later made mostly redundant by Facility to IP Table

5. The DNS Lookup - Rule 5 applies to all hops that have not fallen into one of the rules above. It is similar to Rule 1 without the initial Delay-Distance test and uses the following methods:-

    - Reverse DNS
    - REGEX
    - Reverse Traceroute
    - Reverse DNS of the ip address returned from the Reverse Traceroute.
    - Regex of the DNS returned from the Reverse Traceroute.

It should be noted that many of the IP addresses were tested multiple times using different traceroutes; therefore, a much larger number of successes and failures occurred compared with the discrete number of IP addresses. The first two columns of Table 5.5 show the original success and failure rates for each rule and method used. The second two columns show the success and failure rates once the IXPDB data that apply to the LINX Internet Exchange are added. The software stops relying on the complex method of determining the facility by comparing the ingoing/outgoing ASNs with the IXP facilities, as shown in red, and begins by using the IXPDB database, as shown in green. Finally, the third set of columns shows the results when the LONAP Internet Exchange data from the IXPDB database is added. The Reverse Traceroute method shows zero successes, but this is not a test in itself, it must be combined with reverse DNS in order to provide a result.

Of 1,190 traceroutes used in the test, 1,047 individually discrete IP addresses were discovered, of which 372 were geolocated to a confidence level of 3 and above. However, three of those IP addresses are anycast, which means that they are shared by devices in multiple locations. This prevents them from being geolocated to a single location. Therefore, we were able to geolocate 369 IP addresses.

Of these 369 successfully geolocated IP addresses, 102 were geolocated without a DNS lookup. By analysing the individual contribution of each geolocation rule described in the previous section, we arrive at the following observations:-

- 12 IPs were geolocated by Rule 1 using a sanity check on the RTT value. Due to these 12 IP addresses being at hop 1 in each traceroute we can confidently use the RTT value to predict the delay-distance values.
- 33 IPs were geolocated by Rule 3, which are the target IP addresses.
- 102 IPs were geolocated by Rule 4, using the facility's location.
- 211 of the successful IP addresses were located by Rule 5, where the geolocation is discovered using a combination of REGEX and previous rules.

Table 5.6 summarises these statistics according to geolocation rules. If we rule out the 26 private IP addresses from our formulae because private addresses only provide a location pertaining to that specific traceroute, we end up with a total of 343 vantage points out of a possible 1021 distinct IP addresses, which gives a success rate of 33.6%.

Rule 1 - Hop 1 Sanity Checks	12
Rule 2 - Private IP Addresses	26
Rule 3 - Target IPs	33
Rule 4 - Facility Location	90
Rule 5 - Regex and other methods	211 (3 excluded because they were anycast)
TOTAL	372 (3 excluded due to being anycast)

Table 5.6: Rules Total Successful Geolocations

Luckie et al. downloaded 1.39 million IP addresses from the CAIDA ITDK 2020/2021 datasets. It was discovered that 220,000 had geohints and from these 220,000 they geolocated 183,000 which works out at 7.1% of the original 1.39 million. Although our initial dataset contains only 1047 discrete IP addresses, the location of 369 of them represents 33.6%, which is a significantly higher percentage.

5.7 Transition to IPv6 and Future Considerations

As we have seen, the new IPv4 geolocation methods and tools significantly enhance the granularity and precision of Internet infrastructure mapping. These advances address many existing challenges and offer promising solutions for IPv4-based networks. However, the Internet is now rapidly transitioning to IPv6, driven by the need for a larger address space and improved functionality.

Given the limitations of IPv4 and the impending global shift towards IPv6, it is imperative to explore how our geolocation techniques can be adapted and enhanced for IPv6. IPv6 not only provides a vast address space, but also introduces new features and capabilities that can be leveraged to improve geolocation and routing security. The thesis will now focus on IPv6 and the improvements that this can offer in IP Geolocation.

Chapter 6

IPv6 - The Future for IP Geolocation

6.1 Introduction

Accurate maps of the Internet infrastructure would allow network engineers and operators to improve and optimise the allocation of network resources such as backup routes, routers, proxies, replica servers, and data centres. Detailed and complete maps of the Internet's topology, annotated with the geographic locations of network equipment, could help with the study of a wide range of security-related problems and protocols. Locating the source of malicious traffic or assessing the vulnerability of the Internet to blackouts or attacks on parts of its physical infrastructure would inform network planners of the best possible recovery solutions.

Over the years, Traceroute, Ping, and the Border Gateway Protocol (BGP) have been used by many researchers to discover the location of routers and hosts on the Internet. Traceroute and Ping are primarily diagnostic tools used to measure the route path and latency to a destination IP address, whilst BGP is a routing protocol designed to manage how packets are commercially routed across the Internet, none of which were designed for determining geographical locations. In fact, Motamedi et al. (Motamedi, Rejaie, and Willinger, 2015) state that the uses of these tools

are merely 'engineering hacks' that researchers have proposed to collect information about the Internet topology.

The accuracy of IP-based geolocation can be affected by many factors such as circuitous routes, dynamic IP address allocation, the use of proxy servers or VPNs, and layer 2 clouds such as MPLS and ATM that are generally opaque to a traceroute.

This chapter proposes a brand new method for discovering the network topology by designing a new network mapping tool that is based on the IPv6 Node Information Queries protocol described in RFC 4620 (Crawford and Haberman, 2006). The Internet Engineering Task Force (IETF) developed IPv6, which was intended to replace IPv4 and would deal with the long-anticipated problem of IPv4 address exhaustion. In December 1998, IPv6 became a Draft Standard for the IETF. The KAME project was launched in 1998 (Kudou, Suzuki, Hagino, Yamamoto, Shima, Uehara, Wakikawa, Mitsuya, Momose, Jinmei, and S., 2006) and concentrated on the research and development of IPv6 technologies, succeeding in the global standardisation of basic IPv6 specifications and establishing the framework required for the commercial marketing of IPv6 technologies. The project included the development of a protocol for asking an IPv6 node to provide certain network information, such as its hostname, IP addresses, or fully qualified domain name. In addition, Crawford and Haberman (Crawford and Haberman, 2006) state that a direct query mechanism for other information has been found to be useful in serverless environments and for debugging.

This introduction emphasises the need for a more accurate and resilient mapping tool given the inadequacies of Traceroute, Ping, and BGP to capture the full complexity of the Internet topology. Section 6.2 explains the necessity for a new geolocation tool. In Section 6.3 the challenges of introducing a new tool are investigated. Section 6.4 sets the aim of creating a superior IPv6 mapping tool, focussing on a detailed visualisation and security implications. In Section 6.5, the document proposes essential changes to the Node Information Protocol, router kernels, and installation processes to enable this advanced mapping capability,

enhancing data accuracy and security. Section 6.6 describes the operational design of the tool, including iterative queries for comprehensive network mapping. Section 6.7 outlines measures to safeguard the tool's use, addressing potential risks and configuration options.

6.2 Necessity for a new purpose-built IP Mapping tool

The mapping of the network infrastructure has long been essential for optimising and understanding the functionality of the Internet. Traditional IPv4 geolocation methods typically involve databases that map IP addresses to geographical locations using data from various sources, such as traceroute results, DNS lookups, and user reports. However, many of these methods often rely on delay-distance formulas to estimate the geographic location of IP addresses based on network latency measurements. Such formulas have been shown to be seriously inaccurate due to various factors, including network congestion, routing asymmetries, and circuitous paths that introduce errors in latency-based estimates.

Despite their utility, these methods have shown limitations and inaccuracies in mapping Internet infrastructure, producing errors ranging from small inaccuracies to significant deviations. Studies have demonstrated these shortcomings, highlighting the need for more accurate and reliable mapping techniques. Additionally, traditional IP geolocation methods, which rely on databases that map IP addresses to geographical locations, often suffer from outdated or inaccurate data, further complicating precise infrastructure mapping.

The emergence of IPv6 offers a promising avenue to improve the accuracy of geolocation. IPv6 provides enhanced capabilities over IPv4, allowing for the introduction of a more precise mapping of the Internet infrastructure. The greater functionality of IPv6 enables new geolocation methodologies that can overcome the limitations of previous tools by providing more detailed and accurate network topology information. Such an innovative approach could represent a significant advancement in geolocation technology, addressing previous limitations, and offering a robust solution for the mapping of the Internet infrastructure.

6.3 Challenges and Ethical Considerations

Mapping the Internet's infrastructure involves navigating technical, logistical, and ethical challenges such as improving the accuracy and completeness of geographically locating network infrastructure. New technologies such as dynamic routing, load balancing, proxies, and the use of content delivery networks (CDNs) obscure the true path data packets take, creating erroneous conclusions and making it difficult to map the network accurately. Privacy and security considerations must be taken into account when collecting and publishing detailed network topology information and must be balanced against the risk of exposing vulnerabilities to malicious actors.

Attempts to map the network infrastructure reflect the evolving complexity of the Internet and the continuous development of tools and methodologies to better understand it. Basic utilities like ping and traceroute to advanced protocols like BGP and IOAM have provided valuable insights into the Internet's structure and performance, even as the landscape continues to change. However, these tools are not designed to provide a complete and accurate map of the Internet infrastructure. A complete solution to this mapping problem has eluded researchers to date, and there are still many challenges that have remained largely unsolved and require new ideas, as now explored in this thesis.

6.4 Objectives and Scope of this Chapter

The primary scope of this chapter is to introduce a new tool for mapping IPv6 network infrastructure, with the aim of surpassing current methodologies in accuracy, comprehensiveness, and utility. Objectives include detailing the necessity for such a tool, discussing enhancements over existing technologies, outlining the proposed changes to network protocols and infrastructure, and demonstrating the tool's potential benefits for network analysis and troubleshooting.

The work described here is intended to offer a more detailed visualisation of the Internet's structure, addressing both technical implementations and the broader

implications for network research and administration. This chapter also attempts to address many of the related security issues; however, these range in complexity from simple to highly complex. Detection and mitigation often require a combination of monitoring tools, firewall rules, and changes in network configuration. The key to effectively managing these issues lies in maintaining a secure and updated network infrastructure, using intrusion detection systems, and implementing best practices for network security.

6.5 Concept and Structure

This thesis proposes an extension to IPv6 Node Information queries as specified in RFC 4620 (Crawford and Haberman, 2006). Currently, the mechanism can be used to learn the addresses and names of nodes and is also useful when there are no global routing or DNS name services available.

According to RFC 4620 A 'Node Information Query' (NI Query) message is sent by a Querier node to a Responder node in an ICMPv6 packet addressed to the Queried Address. Currently, the query can contain a Subject Address or a Subject Name. The Responder sends a 'Node Information Reply' (NI Reply) to the Querier, containing information associated with the node at the Queried Address. Both NI Query and NI Reply have the same format (see Figure 6.1) and are carried in ICMPv6 packets.

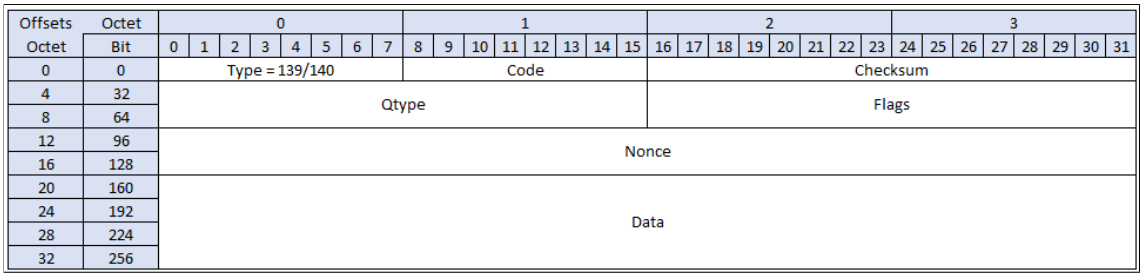


Figure 6.1: Node Information Messages

The Type field is an 8-bit identifier and is an NI Query when set to 139 and an NI Reply when set to 140.

When the Type field is set to NI Query, the code field can currently contain the following options:-

- 0 - Indicates that the Data field contains an IPv6 address that is the Subject of this query.
- 1 - Indicates that the Data field contains a name that is the Subject of this query, or is empty, as in the case of a NOOP.

- 2 - Indicates that the Data field contains an IPv4 address that is the Subject of this Query.

When the Type field is set to NI Reply, the code field can currently contain the following options:-

- 0 - Indicates a successful response. The Response Data field may or may not be empty.
- 1 - Indicates that the Responder refuses to supply the answer. The Response Data field will be empty.
- 2 - Indicates that the QType of the Query is unknown to the Responder. The Response Data field will be empty.

The Checksum field stores an IPv6 checksum.

The QType field is a 16 bit field that designates the type of information requested in an NI Query or supplied in a NI Reply. Currently, there are five values of QType specified.

- 0 - No Operation
- 1 - unused
- 2 - Node Name
- 3 - Node Addresses
- 4 - IPv4 Addresses.

The Flags field are QType specific flags that may be defined for certain Queries and Replies.

The Nonce field is an opaque 64-bit field to help avoid spoofing and/or to aid in matching Replies with Queries. Its value in a query is chosen by the Querier. Its value in a Reply is always copied from the corresponding Request by the Responder. The Nonce must be a random or good pseudo-random value to foil spoofed replies.

The Data field in an NI query will currently contain the subject's address or name and contains the information specified by the QType in a reply. It is important to note that the length of the data may be inferred from the IPv6 header's Payload Length field as detailed in RFC8200 (S. Deering and R. Hinden, 2017), the length of the fixed portion of the NI packet, and the lengths of the ICMPv6 header and intervening extension headers.

6.5.1 Proposed Changes

To achieve the goals set out in this document, changes to the Node Information Query and Reply protocols, router's kernel, and equipment installation procedures are required.

6.5.1.1 Node Information Protocol Changes

The QType field currently uses the options shown in Figure 6.2.

Qtype	Qtype Name
0	NOOP
1	unused
2	Node name
3	Node Addresses
4	IPv4 Addresses

Figure 6.2: QType options

It is proposed to make changes to the NI Query format by adding additional options to the QType field where:-

- 5 - Indicates that the Data field contains a list of the IP addresses of the node's peers.
- 6 - Indicates that the Data field contains the node's geo-location.

6.5.1.2 Router Kernel Changes

The proposed options will require some changes to a router's kernel. To provide the data for option 5 the routing table needs to be interrogated to provide the peer's IP addresses for each interface. Additionally, a new Access Control List (ACL) will need to be added, which has the ability to test and allow for Node Information Queries, and for additional security, can also test for the source originator which may be from a list of trusted IP addresses.

6.5.1.3 Router Installation Procedural Changes

To provide the data for QType option 6 it is proposed that upon initial installation of a router or middlebox, the geolocation data of the installed equipment is entered. For increased security, the actual location can be obfuscated by entering slightly offset data to protect privacy.

6.6 Network Mapping Tool

A tool similar to traceroute could be developed using a node's peer IP addresses which would be returned using one of the new options described above from a Node Information Query. Altogether, this tool would make three queries to a given node :-

1. Using one of the existing QType options (QType = 3 Node Addresses) Query the Node for its set of interface IP addresses.
2. Using one of the proposed new QType options (QType = 6 Node Geo-location) query the node for its Geo-location.
3. Using one of the proposed new QType options (QType = 5 Node Peers) query the node for its peer IP addresses.

Figure 6.3 shows an example of a user interrogating a Node Responder and receiving geolocation data, interface IPs and peer IPs which can be saved to a

JSON file. The tool can then iterate over the adjoining nodes using the information in this JSON file addresses to collect further information gradually, building up a comprehensive geographical network map.

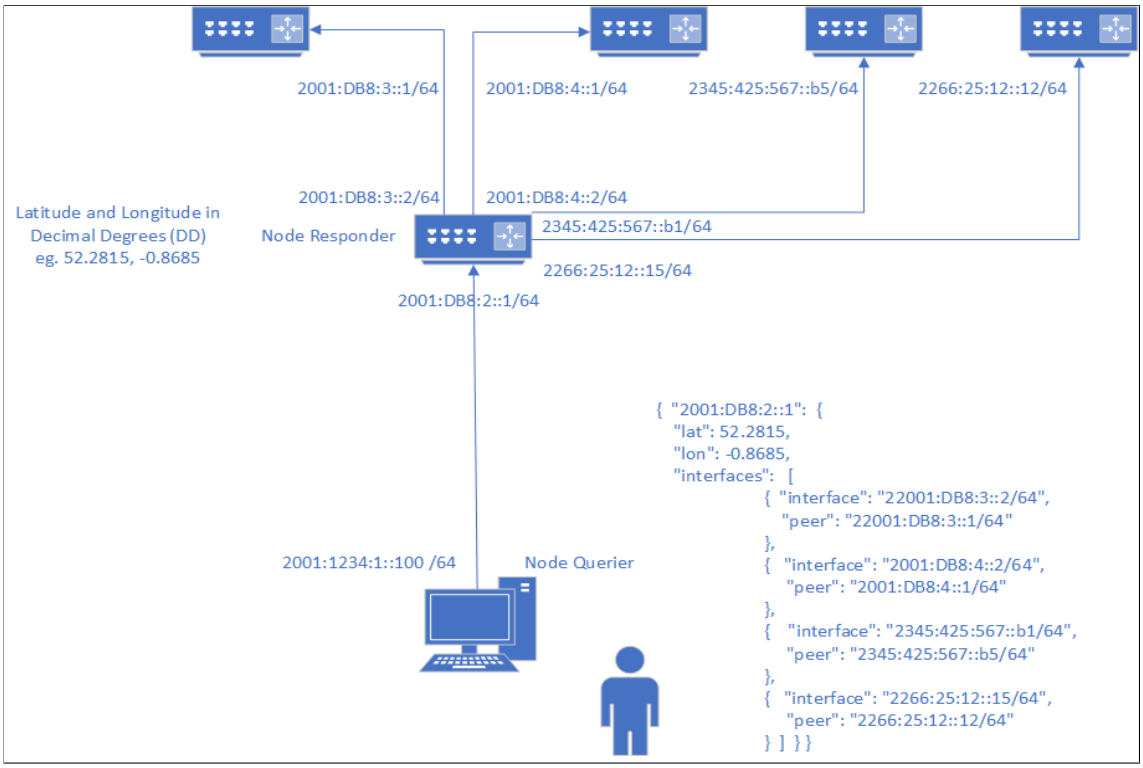


Figure 6.3: Tool Router Iteration

6.7 Implementing Security

The following are legitimate uses of the extended options that the software tool adds to the ICMP extended Echo functionality:-

- To determine the geolocation of an IP address.
- to determine the peers to which a router connects.

However, malicious parties may be able to use the tool to obtain additional information such as:-

- Interface bandwidth.
- The type of device that supports the interface (e.g., vendor identity).
- The operating system version that the device uses.

Understanding this risk, network operators often establish policies that restrict access to the ICMPv6 Extended Echo functionality. In order to enforce these policies, nodes that support ICMP Extended Echo functionality must support the following configuration options:-

- Enable/disable the ICMP Extended Echo functionality. By default, the ICMP Extended Echo functionality is disabled.
- Define the L-bit enabled settings. By default, the option to set the L bit is enabled and the option to clear the L bit is disabled.
- Define enabled query types (i.e., by name, index, or by address); by default, all query types are disabled.
- For each enabled query type, define the prefixes from which ICMP Extended Echo Request messages are permitted.
- For each interface, determine whether the ICMP Echo Request messages are accepted.

When a node receives an ICMP Extended Echo Request message that it is not configured to support, it must silently discard the message. In order to protect local resources, implementations should rate-limit incoming ICMP Extended Echo Request messages.

In order to foil spoofed reports, the Nonce must be a random or good pseudo-random value. Where multiple independent processes are used to send NI queries, the Nonce value may be used to deliver replies to the correct process. Each process must check the received Nonce and ignore extraneous responses (Crawford and Haberman, 2006). The Responder must return a NI Reply with ICMPv6 Code = 2 and no Reply Data if the QType is unknown. The Responder should rate-limit such replies as it would ICMPv6 error replies (Conta, S. Deering, and M. Gupta, 2006) and IP Security (IPsec) should be used (Mühlbauer, Feldmann, Maennel, Roughan, and Uhlig, 2006) where true communication security is required.

Chapter 7

Geopolitically Aware Routing

7.1 Introduction

IPv6 introduced a significant evolution in the area of Internet protocols, which resolved many of the issues with the limitations of IPv4. Clearly, IPv6 provides an improved framework for the future of the Internet. One of the improvements is the concept of extension headers (EHs); these are designed to improve and enhance the protocol's flexibility and functionality.

This chapter looks at the development of a novel IPv6 extension header, tailored to incorporate geopolitical awareness into network routing. The new extension header aims to incorporate a geopolitical dimension into each data packet, optionally allowing network paths to be dynamically adjusted based on country codes of transit networks. This addresses a growing need for data controllers and processors to comply with the data protection laws of each country, respecting the geopolitical sensitivities which are inherent in global data transmission. The ethical, security and policy considerations surrounding the implementation of this new extension header will be examined, offering a comprehensive view of how it intersects with societal and regulatory concerns. Although the focus of this chapter is on IPv6, the methods and tools developed for IPv4 geolocation provide a solid foundation for our IPv6 advancements. The transition from IPv4 to IPv6 geolocation is not a divergence,

but rather an evolution that builds on our previous work. The techniques discussed in this chapter will complement and enhance our existing IPv4 tools, providing a comprehensive suite of geolocation and routing solutions for both current and future Internet architectures.

In summary, this chapter will strive to combine advanced protocol design and practical, legal, and ethical considerations in an increasingly complex global Internet infrastructure.

In Section 7.2 we justify the need for a Geo-political Extension Header and briefly outline IPv6's evolution from IPv4, focussing on the role and functionality of existing headers. Section 7.3 provides more detail about IPv6 extension headers, while Section 7.4 reiterates the objectives of this chapter. In Section 7.5, we present the design of the new extension header: the conceptual framework, technical specifications, and the integration strategy with IPv6. In Section 7.6, we discuss methods for router configuration and country code administration. Section 7.7 considers technical, security, privacy, and operational challenges. In Section 7.8 we discuss what would be necessary to create a test environment to simulate the Internet environment using the new IPv6 header. In Section 7.9, we address relevant technical feasibility issues.

7.2 Need for a Geo-politically Aware Extension Header

When it comes to the transfer of personal data outside the European Union (EU) and the European Economic Area (EEA), the United Kingdom Data Protection Act 2018 (UK-Government, 2023) (DPA), which is the UK's implementation of the EU's General Data Protection Regulation (EU-GDPR), has rules regarding the countries through which data packets can transit. Personal data can be freely transferred within the EU and EEA countries, as they all maintain the same level of data protection. Under the EU-GDPR, the UK has been considered a third country since Brexit. However, the UK has been granted adequacy, which means that personal data can flow from the EU/EEA to the UK without additional safeguards. Likewise, the Data Protection Act allows for data transfers to the EU/EEA as it considers them adequate.

However, stricter regulations are attached to the transfer of personal data outside these regions. According to the UK Data Protection Act 2018, such transfers can only be made to countries that provide an adequate level of data protection, as determined by the UK Government, or under certain conditions such as:

- Adequacy Decisions: The UK Government can determine that a non-EU country offers an adequate level of data protection. This allows for the easier transfer of data to these countries.
- Standard Contractual Clauses (SCCs): These are legal contracts drawn up between the data sender and the recipient in the non-EU country, ensuring the protection of personal data.
- Binding Corporate Rules (BCRs): These are internal rules adopted by multinational companies to allow transfers within the same corporate group to entities in countries without adequacy decisions.

- Specific Derogations: In absence of an adequacy decision or SCCs/BCRs, transfers can be made under specific conditions such as explicit consent from the individual whose data is being transferred, or for the performance of a contract.

A landmark ruling by the Court of Justice of the European Union (CJEU) on 16 July 2020, known as Schrems II, was made in the case of Data Protection Commissioner v. Facebook Ireland and Maximillian Schrems (Case C-311/18), and the decision has significant implications for international data transfers between the European Union (EU) and countries outside the EU, particularly the United States. The CJEU invalidated the EU-US Privacy Shield framework, which was a mechanism used by companies to legally transfer personal data from the EU to the United States (Tracol, 2020).

The court found that the US surveillance laws did not provide an adequate level of protection for personal data, as required by the General Data Protection Regulation (GDPR). Specifically, the court was concerned that US law did not afford EU citizens sufficient rights to challenge US government access to their data. Secondly, the court imposed stricter requirements on the use of SCC's where companies must now assess data protection laws in the destination country to ensure that they provide an adequate level of protection to that in the EU and implement additional safeguards if this is not the case. Thirdly, organisations are required to perform thorough data transfer impact assessments (DTIAs) to evaluate whether the legal framework of the importing country meets the EU's standards for data protection and, if this is not the case, they must take additional steps to protect the data. This has led to significant challenges for companies that transfer data internationally especially those that rely on US based services.

As of March 21, 2022, new mechanisms for international data transfers have been introduced in the UK, including the International Data Transfer Agreement (IDTA) (ICO, 2022a) and the UK Addendum to the EU Standard Contractual Clauses (SCC) (ICO, 2022b). These tools are necessary for ensuring that any personal data

transferred outside the UK is protected by appropriate safeguards, particularly when transferring data to countries that do not have an "adequacy decision" from the UK government.

In essence, while the core principles of the UK Data Protection Act 2018 remain relevant, the mechanisms and tools for international data transfers have evolved, and organisations must now ensure compliance with the latest requirements, such as using the IDTA or the UK Addendum to the SCCs for cross-border data transfers (Kapko, 2024).

The new Standard Contractual Clauses (SCCs) introduced several important changes compared to the old SCCs, reflecting the evolving data protection landscape, especially post-Brexit. The new SCCs are modular and designed to cover different data transfer scenarios, including transfers between controllers, processors, and subprocessors. This is a significant change from the old SCCs, which were more rigid and less adaptable to different contractual relationships. The new SCCs require organisations to perform detailed data transfer impact assessments. This ensures that data protection levels in the destination country are adequate and in line with GDPR standards. Data importers must notify data exporters and data subjects if they receive government access requests and assess the legality of the orders, potentially challenging them if necessary. Controllers and processors under the new SCCs are required to demonstrate compliance with data protection principles, reflecting the emphasis of GDPR on accountability. This includes keeping detailed records of processing activities and implementing appropriate technical and organisational measures (Lawbite, 2022).

The UK Addendum to the International Data Transfer Agreement (IDTA) provides a way for UK-based organisations to continue using the EU Standard Contractual Clauses (SCCs) for international data transfers while ensuring compliance with UK-specific data protection laws. The UK addendum modifies the EU SCCs by replacing EU-specific legal references with UK equivalents, making them applicable under UK law post-Brexit and allowing organisations that operate across

both the EU and UK to use a single set of SCCs for data transfers by adding the UK addendum simplifying compliance and reducing administrative burden. Businesses had until March 2022 to update existing contracts that were based on old SCCs. After this date, all such contracts must comply with the IDTA or include the UK Addendum (ICO, 2022a).

The route that data packets take can often involve countries that do not meet these EU and UK GDPR standards, and organisations must ensure that the appropriate safeguards are in place to protect the data during its transit. There is also an emphasis on accountability and transparency, which requires data controllers and processors to take responsibility for ensuring that any personal data is protected throughout its journey, regardless of the countries it transits through. This has led to increased scrutiny and changes in the way organisations manage data flows, often requiring more direct and secure data transfer routes.

Beyond the legal requirements for data transfer, there are several other compelling motivations for developing a geopolitically aware IPv6 extension header.

1. Security concerns: as cyber threats become more sophisticated, it is important to ensure that data does not traverse through regions with lax cybersecurity standards or where data interception is more likely is crucial. A geopolitically aware extension header can help mitigate these risks by enforcing secure routing paths.

2. Compliance with international regulations: beyond the UK's legal framework, various countries have specific regulations regarding data sovereignty and privacy. A geopolitically aware header could help organisations comply with these diverse regulations by ensuring that data transits only through compliant jurisdictions.

3. Performance optimization: routing data through geopolitically stable regions can improve network performance and reduce the likelihood of data loss or corruption due to political instability, censorship, or network disruptions in

certain regions.

4. Ethical considerations: some organizations may wish to avoid routing data through regions with known human rights violations or where data might be used for unethical purposes. A geopolitically aware routing option allows organizations to align their data transmission practices with their ethical standards.

5. Resilience and redundancy: in the event of geopolitical tensions or conflicts, having the ability to dynamically adjust routing paths to avoid affected regions can enhance the resilience and redundancy of the Internet infrastructure, ensuring continuous and reliable data transmission.

6. The Border Gateway Protocol is a powerful protocol for managing inter-domain routing but it has inherent limitations when it comes to enforcing precise routing paths based on geopolitical considerations. Whilst BGP can be configured to influence routing decisions through policies and AS path preferences, it lacks the capability to explicitly and reliably route traffic away from specific undesirable countries, this is because BGP focuses on path selection based on network performance and policy, rather than the granular control over geographic routing. The proposed IPv6 extension header solution addresses these limitations by providing a mechanism that embeds geopolitical routing requirements directly into the packet headers.

These motivations, combined with legal considerations, provide a strong case for the development and implementation of a geopolitically aware IPv6 extension header.

7.3 Background on IPv6 and Extension Headers

On November 17, 1994. RFC 1883, Internet Protocol, Version 6 (IPv6) Specification, was drafted by the Internet Engineering Steering Group, and the proposed standard resulting from this was published in 1995. The core set of IPv6 protocols became an IETF draft standard on August 10, 1998. One of the main opportunities of IPv6 is that extension headers are a fundamental part of the design, and these provide a flexible method in which we can extend IPv6 functionality to include new ideas that were not conceived during its initial design.

The rapid expansion of the Internet has exhausted its 4 billion IPv4 addresses, and the introduction of IPv6 marks a significant evolution in Internet technology. IPv6 addresses this limited address space and also introduces a more efficient and flexible protocol design. The implementation of extension headers improves the functionality and scalability of IPv6 and is a key feature among these advancements.

Some applications and upper-layer protocols assume that a packet is unmodified in transit (Thaler, 2011), except for a few well-defined fields such as the TTL field, this also includes protocols that define their own integrity-protection mechanisms such as checksum fields. However, Network Address Translation devices and other middle boxes can also modify the contents of packets and the IPsec architecture (Mühlbauer, Feldmann, Maennel, Roughan, and Uhlig, 2006) added security to the IP model, although transport-mode IPsec is not currently widely used over the Internet.

IPv4 has a rigid format, whilst IPv6 adopts a more modular approach using a fixed-size base header with optional extension headers. This more streamlined approach creates an easy-to-use standard packet structure while allowing for additional features, ensuring efficient packet processing. Extension headers are critical for customising packet handling for specific functions, such as security, routing, and fragmentation.

The Hop-by-Hop (HBH) Options header is used to carry optional information. In the first version of the IPv6 specification (B. Hinden and S. E. Deering, 1998), all

nodes along a packet's delivery path were required to process Hop-By-Hop options, which proved to be impractical due to:-

- Current High Speed Routers were unable to process the hop-by-hop options at wire speed.
- Packets containing Hop-by-Hop options would often be sent to the "slow path". Degrading performance for possibly important traffic.
- A Denial of Service attack on the router could be created by exploiting a mechanism that forces external packets to the routers "slow path" which means that the "slow path" is at risk of being flooded.
- Packets could contain multiple Hop-by-Hop options, making the previous issues worse by increasing the complexity required to process them.

There are many issues with the use of extension headers, particularly those that need to be processed by nodes along a packet delivery path (R. Hinden and Fairhurst, 2020). The IPv6 specification was updated and published in 2017 (S. Deering and R. Hinden, 2017) and changed the procedures for nodes encountering Hop-By-Hop extensions. However, these changes allowed routers to only examine and process Hop-By-Hop headers if configured to do so. This change meant that routers complied with the IPv6 specification even when they did not process the Hop-By-Hop header, which does not fix the problems highlighted above, merely circumventing them.

APNIC Labs measured the drop rate of IPv6 packets that contain an HBH extension header consisting of an 8 octet padding option (Huston, 2022). They added this option to the TCP data streams and then checked to see if the receiver acknowledged receipt of this packet in the TCP sequence number flow. They made 5000 measurements per day for 65 days in 2022 from a set of IPv6 servers to a collection of IPv6 client hosts, they found that the average drop rate of the HBH option was 92% although APNIC's measurement cannot discern between network

drop and host drop. Additionally, some manual tests have shown that many IPv6 implementations discard incoming packets with unexpected HBH extension headers.

In their draft, Hinden and Fairhurst (R. Hinden and Fairhurst, 2020) make various recommendations, firstly that IPv6 nodes "MUST only process a Hop-by-Hop Options header if it can be done in the fast path of the router," as shown in Figure 7.1.

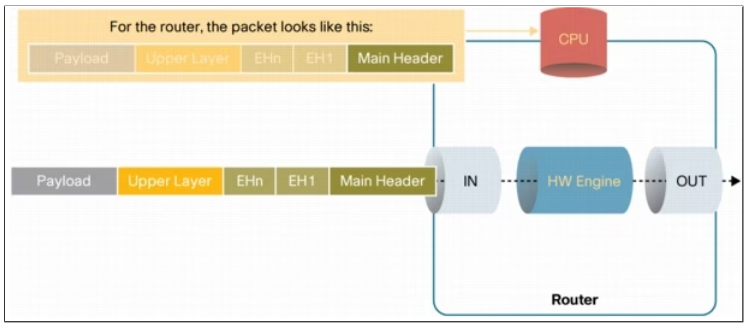


Figure 7.1: Forwarding IPv6 Packets with Extension Headers other than Hop-by-Hop in the absence of ACLs via the 'Fast Path' (Cisco, 2006)

Secondly, only one option should be contained within a Hop-By-Hop extensions header to simplify processing. However, according to Cisco (Cisco, 2006), all vendor equipment has been designed to forward IPv6 traffic that contains a Hop-by-Hop Extension Header to go through the slow forwarding path; see Figure 7.2.

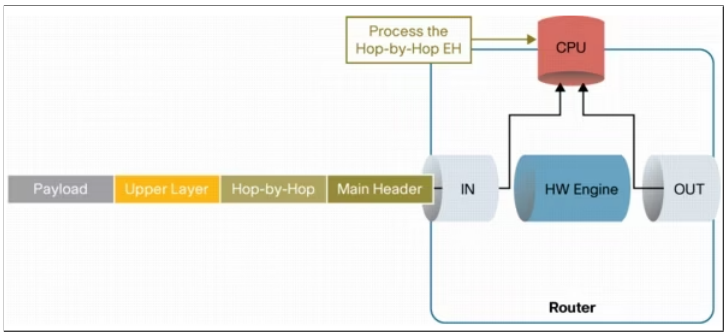


Figure 7.2: Forwarding IPv6 Packets with the Hop-by-Hop Extension Header via the 'Slow Path' (Cisco, 2006)

Therefore, currently 'Fast Path' forwarding is not feasible in the case of any packet containing a Hop-By-Hop extension header. This will obviously add some

limitations to the use of a geopolitical extension header which uses a Hop-By-Hop Extension Header, however, if secure transit is of a higher priority than speed of transit then the use of this header is still a viable option.

7.4 Objectives and Scope of this Chapter

At this point it is appropriate to summarise the objectives and revisit the scope of this key chapter, as follows.

Summary of objectives:

Design a new IPv6 Extension Header: to conceptualise and detail the design of a novel IPv6 extension header that incorporates geopolitical information in the form of country code bitfields.

Evaluate technical feasibility: if possible, assess the practicality of implementing and deploying the new extension header in real-world network environments, considering the current router capabilities and infrastructure.

Analyse security and privacy implications: critically examine the security and privacy concerns that may arise from the use of the proposed extension header, especially in the context of international data transmission and legal compliance.

Study the impact of Geopolitical routing: investigate the potential impacts and benefits of incorporating geopolitical considerations into IPv6 routing, both from technical and policy perspectives.

Scope revisited:

Technical design and specification: the chapter focuses on the technical aspects of designing the new extension header, including its structure, intended functionality, and integration with the IPv6 protocol.

Router configuration and country code management: exploration of methods for administering country codes at the router level.

Network performance and compatibility analysis: evaluation of how the new extension header might affect network performance, including processing overhead,

bandwidth implications, and compatibility with existing network hardware and protocols.

Security and compliance review: examination of the security risks and compliance challenges associated with the use of the extension header, including data privacy and cross-border data flow concerns.

Practical and ethical considerations: discussion of practical deployment challenges and ethical implications of geopolitical-aware routing, including the potential for censorship or regional isolation.

7.5 Proposed IPv6 Extension Header Design

7.5.1 Overview

According to the United Nations (UN, 2024) there are currently 195 countries on the Earth. The proposed solution requires that each country require a bit set to zero or a bit set to one to allow or disallow transit. It is proposed that a 32 byte field will cover this, plus provision for additional support for the formation of new countries. IPv6 extension headers, such as the Routing Header or Destination Options Header, often vary in size but generally aim to be as small as possible to minimise processing overhead and maintain efficiency. For example, the basic size of a Routing Header can vary, but common implementations often involve relatively small sizes, typically in the range of 8-16 bytes, depending on the number of included addresses. The Fragment Header is smaller, often just 8 bytes, as it only needs to carry essential fragmentation information. However, it is not unusual for extension headers to vary in size depending on the specific use case. A 32 byte field is feasible within the IPv6 standard, as the protocol is designed to accommodate variable-length headers. The key consideration is to ensure that the added processing load and potential impact on network performance are justified by the functionality provided by the new header.

This concept requires modification of the router firmware and its table structure. A country field will need to be added to each interface within the IFIndex (Interface Index: see Section 7.6 for a more complete description). This table will be populated manually during initial installation. Scalability will need to be investigated especially considering the dynamic nature of network topologies and international routing paths. This will also add a small amount of processing at each router. The impact on network performance would need to be carefully evaluated. There are security and privacy implications, potential interception, or misrouting of packets are just some of the issues faced. Reliance on ICMP error responses adds complexity. Where the route is disrupted, a router will have to check if an

alternative "Safe Path" exists. Routers will return an ICMP error message if they detect that there is no safe alternative route.

7.5.2 Concept and Structure

It is proposed that any data packet travelling across the Internet that is required to avoid transiting specific countries should include an IPv6 Hop-By-Hop (HBH) Extension Header (EH) that informs all transited routers of the countries that the packet should not be routed through. It is expected that a network administrator will enable this "Safe Path" option at his gateway router so that any IP communication exiting their network will have the extension header injected into each packet. Alternatively, individual users/developers may wish to select the "Safe Path" option within their application to ensure that only the data from their particular application follows a "Safe Path". A "Safe Path" option can be provided within an application by the developer to allow a user to select it. Additionally, they would be able to select the countries through which they do not wish this data to travel. This will inject the HBH header into all outgoing data packets whilst the option is selected.

Routers will have been modified to tag each of their interfaces with the destination countries; see Section 7.6. When a packet is processed at each router, the Hop-By-Hop extension header will be read, and the router will match, using 'OR' logic, the bits which are set to one in the Extension Header against those that are set in the outgoing interface country field within the IFIndex table. If, for example, an extension header has the first 3 bits of the 'Do Not transit' field set. This would be compared with a routers' interfaces proposed new IFIndex table 'countries' field, and if any of the first three bits are set in this field, the packet will not be allowed to transit any interfaces where a countries "Do Not Transit" bit is set; this is where the 'OR' logic is applied, see Figure 7.3. The router must either look for a backup route or send an ICMPv6 "Destination Unreachable" error (type = 1) back to the source.

HBH Header	1	1	1	0	0	0	.....
Interface E0/0 'Countries'	1	0	0	0	0	0	.....
result	1	OR 0	OR 0	OR 0	OR 0	OR 0	= 1

Figure 7.3: Example of Logic used between a HBH and a Router Interfaces Countries Field

7.5.3 Crafting the Safe Path Extension Header

IPv6 allows nodes along a packet path to optionally process a Hop-by-Hop header (S. Deering and R. Hinden, 2017)

The Hop-by-Hop Options header can carry a variable number of "options" that are encoded by the type length value (TLV) as shown in Figure 7.4. However, the proposed geopolitical header will contain just a single option.

Offsets	Octet	0								1								2								3							
Octet	Bit	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
0	0	Option Type = 100NNNNN								Option length = 00100000																							
4	32																																
8	64																																
12	96																																
16	128	Do Not Transit' Field																															
20	160																																
24	192																																
28	224																																
32	256																																

Figure 7.4: IPv6 with Hop-By-Hop Extensions header and Geo-political Field

The Option Type field is an 8 bit identifier where the two highest-order bits signify the action that must be taken if the processing IPv6 node does not recognise the option type (S. Deering and R. Hinden, 2017):-

1. 00 - skip over this option and continue processing the header.

2. 01 - discard the packet.

3. 10 - discard the packet and, regardless of whether or not the packet's Destination Address was a multicast address, send an ICMP Parameter Problem, Code 2, message to the packet's Source Address, pointing to the unrecognised Option Type.

4. 11 - discard the packet and, only if the packet's destination address was not a multicast address, send an ICMP Parameter Problem, Code 2, message to the packet's source address, pointing to the unrecognised option Type.

The third-highest-order bit of the Option Type specifies whether or not the Option Data of that option can change en-route to the packet's final destination:-

- 0 - Option Data does not change en route
- 1 - Option Data may change en route

In the case of our geopolitical extension header, the data will not change and therefore this bit will be set to 0 as shown in Figure 7.4.

The final 5 bits of the Option Type field (denoted by 'NNNNN' in Figure 7.4) is the option type assigned by the Internet Assigned Number Authority (IANA). This will be added once we have registered our extension header with IANA.

The option length field will be set to 32 (octets) to provide adequate space for the data.

7.5.4 Country Code Bitfields

The 32 byte Data field will consist of 195 bits (and 61 spare bits) with a bit set to one for each relevant country on the user's "do not transit" list.

The United Nations (UN) (UN, 2024) recognises 193 countries and 2 "Observers States", the Holy See/Vatican City and Palestine, which are self-ruling territories but not full-fledged countries bringing to a total of 195 countries. It was hoped to use an international standard such as the ISO 3166 standard – Codes created and maintained by the International Organisation for Standardisation (ISO) for the representation of names of countries and their subdivisions or the telephone codes used by the International Telecommunication Union (ITU) in ITU-T standards E.123 and E.164; however, these numbers do not lend themselves easily to this solution. The ISO numbers end at 894 and the ITU numbers end at 999 which

means that a minimum of 894 or 999 bits would have to be reserved. This equates to 112 bytes, which is significantly more than the 64 bytes of extension header data that cisco's hardware accelerated platforms are designed to handle (Cisco, 2006). Cisco's selected size is considered sufficient to handle the most common chains of EH currently used with various IPv6 traffic types and services. In Cisco routers, when the size of the EH chain exceeds the resources allocated in hardware and the upper-layer protocol filters are applied, the IPv6 traffic will be software switched by the Line-Card CPU.

Instead, we will use an alphabetical coding standard in which each country is assigned a code in alphabetical order. A 32 bit field allows for 256 countries, of which only 195 are currently used at this time, leaving 61 bits spare for the creation of new countries. Countries that cease to exist can be left in place and not used or replaced in router firmware updates by new countries. The list and the bits assigned to the countries are shown in Figure 7.5.

Code	Country name	Code	Country name	Code	Country name	Code	Country name	Code	Country name	Code	Country name	Code	Country name	Code	Country name
1	Afghanistan	26	Bulgaria	51	East Timor	76	Iceland	101	Lithuania	126	New Zealand	151	Sao Tome and Principe	176	Tonga
2	Albania	27	Burkina Faso	52	Ecuador	77	India	102	Luxembourg	127	Nicaragua	152	Saudi Arabia	177	Trinidad and Tobago
3	Algeria	28	Burundi	53	Egypt	78	Indonesia	103	Macedonia	128	Niger	153	Senegal	178	Tunisia
4	Andorra	29	Cambodia	54	El Salvador	79	Iran	104	Madagascar	129	Nigeria	154	Serbia	179	Turkey
5	Angola	30	Cameroon	55	Equatorial Guinea	80	Iraq	105	Malawi	130	Norway	155	Seychelles	180	Turkmenistan
6	Antigua and Barbuda	31	Canada	56	Eritrea	81	Ireland	106	Malaysia	131	Oman	156	Sierra Leone	181	Tuvalu
7	Argentina	32	Cape Verde	57	Estonia	82	Israel	107	Maldives	132	Pakistan	157	Singapore	182	Uganda
8	Armenia	33	Central African Republic	58	Ethiopia	83	Italy	108	Mali	133	Palau	158	Slovakia	183	Ukraine
9	Australia	34	Chad	59	Fiji	84	Jamaica	109	Malta	134	Palastine	159	Slovenia	184	United Arab Emirates
10	Austria	35	Chile	60	Finland	85	Japan	110	Marshall Islands	135	Panama	160	Solomon Islands	185	United Kingdom
11	Azerbaijan	36	China	61	France	86	Jordan	111	Mauritania	136	Papua New Guinea	161	Somalia	186	United States of America
12	The Bahamas	37	Colombia	62	Gabon	87	Kazakhstan	112	Mauritius	137	Paraguay	162	South Africa	187	Uruguay
13	Bahrain	38	Comoros	63	The Gambia	88	Kenya	113	Mexico	138	Peru	163	South Sudan	188	Uzbekistan
14	Bangladesh	39	Republic of the Congo	64	Georgia	89	Kiribati	114	Micronesia, Federated States of	139	Philippines	164	Spain	189	Vanuatu
15	Barbados	40	Democratic Republic of the Congo	65	Germany	90	Korea, North	115	Moldova	140	Poland	165	Sri Lanka	190	Vatican
16	Belarus	41	Costa Rica	66	Ghana	91	Korea, South	116	Monaco	141	Portugal	166	Sudan	191	Venezuela
17	Belgium	42	Cote d'Ivoire	67	Greece	92	Kuwait	117	Mongolia	142	Qatar	167	Suriname	192	Vietnam
18	Belize	43	Croatia	68	Grenada	93	Kyrgyzstan	118	Montenegro	143	Romania	168	Swaziland	193	Yemen
19	Benin	44	Cuba	69	Guatemala	94	Laos	119	Morocco	144	Russia	169	Sweden	194	Zambia
20	Bhutan	45	Cyprus	70	Guinea	95	Latvia	120	Mozambique	145	Rwanda	170	Switzerland	195	Zimbabwe
21	Bolivia	46	Czech Republic	71	Guinea-Bissau	96	Lebanon	121	Myanmar (Burma)	146	Saint Kitts and Nevis	171	Syria	196	
22	Bosnia and Herzegovina	47	Denmark	72	Guyana	97	Lesotho	122	Namibia	147	Saint Lucia	172	Tajikistan	197	
23	Botswana	48	Djibouti	73	Haiti	98	Liberia	123	Nauru	148	Saint Vincent and the Grenadines	173	Tanzania	198	
24	Brazil	49	Dominica	74	Honduras	99	Libya	124	Nepal	149	Samoa	174	Thailand	199	
25	Brunei	50	Dominican Republic	75	Hungary	100	Liechtenstein	125	Netherlands	150	San Marino	175	Togo	200	

Figure 7.5: Proposed Country Codes

Each code is the reference to the relevant bit within the field, for example, Bulgaria is code 26 so this would be bit 26 of the countries field in the IFIndex table discussed in section 7.6. It will also be the reference to the relevant bit in the Countries field of the Hop-By-Hop extension header. However, as the first 16 bits are taken up by Option Type and Option Length fields, the Countries field begins at bit 16 so Bulgaria is referenced by its code of 26 plus an offset of 15 which is equal to bit 41 of the Hop-By-Hop extension header. Continuing with this example, if Bulgaria is a country that should not be transited, then the country field would be coded as shown in Figure 7.6. This method allows for the selection of multiple undesirable countries by simply setting the desired bits.

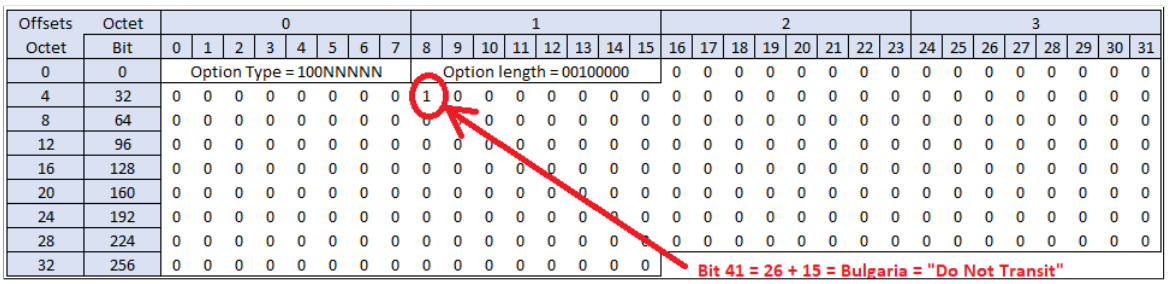


Figure 7.6: Example of setting Country Code

7.6 Router Configuration

The Interface Index (IFIndex) value is one of the most commonly used identifiers in SNMP-based network management applications. It is a unique identification number associated with a physical or logical interface. RFC1213 (MIB2)(McCloghrie and Rose, 1991) defines an initial IFIndex as follows:

"Each interface is identified by a unique value of the IFIndex object, and the description of the IFIndex constrains its value as follows: Its value ranges between 1 and the value of IFNumber. The value for each interface must remain constant at least from one re-initialisation of the entity's network management system to the next re-initialisation."

The latest Cisco IOS releases add support for an IFIndex value that can persist across reboots, which proves particularly useful not only for our solution but for other features such as :-

- SNMP: monitoring the interfaces counters
- Netflow: reporting of the interface IFIndex
- RMON: events/alarms based on specific interfaces
- EXPRESSION/EVENT MIB: creation of a new MIB variable based on interface counters.

The format of the IFIndex table would therefore be updated with a countries field which would denote the countries that each interface connects to as shown in Figure 7.7

	Name	Type	Description
	size	INTEGER32	the size of this row
	ifIndex	INTEGER32	The interfaces ifIndex
	enablePersistence	INTEGER32	1 if persistence is enabled
	ifDescr	OCTECT STRING	The Interface Description
*Proposed New Field	countries	ARRAY[INTEGER32]	32 bytes where a bit set to 1 = destination country(ies)

Figure 7.7: Proposed change to the IFIndex table

7.6.1 Router Behaviour

Routers that are not configured to support Hop-by-Hop options are not expected to examine or process the contents of this option as per RFC 8200.

Routers that support Hop-by-Hop Options but are not configured to support this Option should read the two highest-order bits of the Extension Header Option Type Field to determine whether to skip over this header or discard the packet and send an ICMP error message in accordance with RFC 8200.

Routers that support this geopolitical extension header will initially follow the rules laid out in Section 7.5.3

7.6.2 Interface Country Tagging

The tagging of each interface to the relevant countries could be carried out upon the initial installation of a router. It is at this time that an engineer creates the connections to its peers, and choosing the destination countries of each of the routers peers should not add overly to the workload. Alternatively, a Node Information Query as described in Chapter 6 could be sent to a router's upstream routers to enquire about the upstream routers' country of location. This may be a better method as it could be done automatically without any manual intervention on the part of the installation engineer.

7.6.3 Integration with IPv6 architecture

The first step of this procedure would require the router installation engineer to configure the country or countries to which each of the router interfaces is connected. This information will be stored within the proposed additional countries field inside the IFIndex table as discussed in Section 7.6.

Secondly, should a company consider it part of their policy, there are 2 alternative methods of tagging outgoing data packets:

1. A network administrator or engineer could enable an option on a host computer which would inject the Geopolitical header containing the countries he does not wish any packets to transit into all outgoing packets.

2. Alternatively, this could be left to individual users and provided as an option at the application layer where a user can choose to add the geopolitical header to an outgoing file.

Thirdly, as this packet traverses the network, routers will perform an additional routing action, perhaps using an Access Control List (ACL), which will be to check their IFIndex table for the interface that the packet will be sent out. If this proves to be a country in the do not transit list then the router will check for alternative

paths, and if this proves fruitless will either discard the packet, return an ICMP Destination unreachable error message or ignore the header and forward the packet regardless.

This new method incorporates the following procedure:

1. A router's firmware will be updated to change the IFIndex table to include a 32 byte field for each interface.

2. During initial installation an engineer will set corresponding bits within this field dependent on the country that each of the routers interfaces connects too. The engineer will also configure an Access Control list (ACL).

3. On receipt of a packet containing this header the ACL will check the country field against its IFIndex to ensure that the next hop destination country is not on the "Do Not Transit" list.

4. If the interface's destination country is on the "Do Not Transit" list then the router may check for an alternative path and if unsuccessful send an ICMP Destination Unreachable message back to the source. If the router does not check for an alternative path then it will also send a ICMP Destination Unreachable message back to the source.

5. If the router is successful in finding a valid interface it forwards the packet.

7.6.4 Policy-Based Routing Approaches

The Hop-By-Hop type field shown in Figure 7.4 allows for differences in company policies. This will allow the network administrator or user to be able to decide whether a router which does not recognise this header should continue routing the packet or discard the packet and send an error message back. Whilst the second option, discard and send error message may be the default setting, it may be a company's policy to add the extension header to all outgoing data as "Best Effort",

but allowing for data to continue to be transmitted should it come across routers which do not support this header.

7.7 Implementation Challenges

7.7.1 Technical and Operational Challenges

This option shares the characteristics of all other IPv6 Hop-by-Hop Options, along with the fact that, as discussed in Section 7.3, routers currently do not support it in the Fast Path. Therefore, it could be used to degrade the performance of a router; however, this option is no different than other uses of IPv6 Hop-by-Hop options headers.

Many firewalls and middleboxes will examine and process an entire IPv6 packet before it makes a decision to either forward or discard a packet, due to differences in extension header formatting this process can be slow and clumsy. Some firewalls will drop any packet they cannot recognise, and several widely used firewalls do not recognise all the extension headers that have been standardised since the IPv6 protocol was introduced (Carpenter and S. Jiang, 2013).

7.7.2 Security and Privacy Considerations

It is common for routers to ignore the Hop-by-Hop option header or to drop packets containing a Hop-by-Hop options header. Routers implementing IPv6 accordingly only examine and process the Hop-by-Hop Options header if explicitly configured to do so. This emphasises the need to ensure that the data being transmitted across networks remains protected against unauthorised access, tampering, and potential misuse. The extension header will include sensitive geopolitical routing information; it must be designed with robust security measures to prevent exploitation and to maintain the confidentiality and integrity of transmitted data. This is crucial to maintaining trust in the network infrastructure and ensuring compliance with

various legal and regulatory frameworks that govern data protection.

IPv6 packets incorporating the Geopolitical Extension Header can be authenticated using the IPAuthentication Header (Kent, 2005a). A node should include an Authentication Header when sending a geopolitical extension header if a security association exists for use with the IP Authentication Header for the destination address. The security associations may have been created through manual configuration or through the operation of some key management protocol. Received Authentication Headers in IPv6 packets containing Geopolitical Extension Headers should be verified for correctness, and packets with incorrect authentication should be ignored and discarded. This addresses the potential risks associated with the widespread adoption of the proposed IPv6 extension header. The importance of securing the extension header against misuse or exploitation by malicious actors must be emphasised, particularly as it could be used to manipulate routing paths for unauthorised or harmful purposes. It highlights the need to implement robust security measures to protect sensitive geopolitical routing information and to ensure that data privacy is maintained during transmission across various jurisdictions. This consideration is crucial to prevent the extension header from becoming a vector for attacks or privacy breaches, ensuring that it contributes positively to network security and compliance with data protection regulations.

It should be possible for the system administrator to configure a node to ignore any messages including a Geopolitical Extension Header that are not authenticated using either the Authentication Header or Encapsulating Security Payload. It is expected that a node will default to allowing unauthenticated messages.

The information learned through this method should not be trusted for making security-relevant decisions unless other mechanisms beyond the scope of this document are used to authenticate this information. Confidentiality issues are addressed by the IP Authentication Header (Kent, 2005a) and the IP Encapsulating Security Payload (Kent, 2005b).

It is widely believed within the industry that the use of the ICMP protocol can

add a security issue to the entire solution; however, ICMP is a suite of protocols designed to facilitate communication and error reporting between network devices. Its use in network diagnostics, error reporting, and management tasks are key functions and the idea that potential skilled attackers cannot gain information about a network if ICMP is disabled provides no real security benefits while actively impeding essential network functionalities and is a counterproductive practice. (Bartels, 2024)

7.8 Testing and Evaluation Framework

A successful deployment of the method depends upon several components being implemented and deployed:-

- Router support in nodes as described at Section 7.6.
- Support in the sending node and upper layer protocols as described in Section 7.6.3.

The extended Berkeley packet filter (eBPF) is becoming a recognised method for the testing of IPv6 Extension Headers (Iurman, Vyncke, and Donnet, 2023). eBPF can do so much more than just packet filtering, making the acronym eBPF nonsensical, and therefore eBPF is now considered to be just a standalone term (eBPF, 2024), whilst eBPF is suited to host systems making it easy to inject Extension headers into outgoing and incoming packets. Hop-By-Hop requirements include the need to process the extension header within the transited routers. eBPF does not currently have this functionality; in fact, it seems impossible to find any tools which allow a router's kernel software to be easily edited to allow for new Hop-By-Hop extension headers.

A different method of testing could be the use of Programming Protocol-independent Packet Processors (P4), which is an open source programming language that lets end users dictate how networking infrastructure operates. P4 controls

integrated circuits in network forwarding devices such as switches, routers, and network interface cards. It is similar to OpenFlow in many respects; however, instead of targeting the control plane, P4 is focused on the data plane. A programmable data plane brings with it a number of advantages:

- It is easy to add new features, supporting new protocols (BGP, OSPF, Spanning Tree, etc)
- Remove unused protocols: free up space for it to focus solely on what the user wants it to do.
- Greater visibility: P4 allows users to program in rules to forwarding devices. It can, for example, create a tag for each packet as it passes through a router or switch. Doing so allows network engineers to get a potentially unprecedented level of visibility into the routing paths of packets to determine network latency.

7.9 Feasibility and Impact Analysis

There are some necessary prerequisites for this kind of approach to be viable. All hosts, routers, and all forms of sundry middleware need to support this option.

1. IPv6 packets that carry this HBH option are not arbitrarily discarded by devices on the path or by the destination host.
2. All forwarding devices recognise this HBH option and will compare the country codes against those of their interfaces before forwarding packets that contain this HBH extension header.
3. All IPv6 hosts will make local adjustments to their routing protocol based on the country code information.
4. All IPv6 protocol implementations need to support a socket option to allow upper-layer protocols to inject this Hop-By-Hop extension header.

7.10 Summary

The proposed IPv6 Geopolitically Aware Extension Header could play a critical role in addressing the complexities of global data routing. This chapter outlines the technical and legal challenges inherent in implementing such a system while highlighting its potential to enhance both security and privacy in network operations. By integrating geopolitical considerations into routing decisions, this extension header offers a forward-looking solution to ensure compliance with international regulations and protect data integrity across diverse jurisdictions. The chapter underscores the importance of rigorous testing and evaluation to validate the efficacy of this approach, ultimately advocating its adoption as a means to enhance the resilience and security of the global Internet infrastructure.

Chapter 8

Discussion

This chapter begins with a discussion regarding the tools and methods proposed in Chapters 1 to 5 which deal with the current methods of IP Geolocation, and then discusses the IPv6 proposals presented in Chapters 6 and 7.

Relatively little research has been done on geolocating IP addresses to the facility level. Luckie et al. (Luckie, Dhamdhere, Huffaker, and Clark, 2016) were able to geo-locate 7.1% of IP addresses at the city level when comparing their data set against the CAIDA ITDK data set (CAIDA, 2024). When trying to compare our data set with the CAIDA ITDK datasets, it was only possible to compare city locations because the CAIDA data set is based on city-level resolution rather than facility level. Although the CAIDA dataset has 1.7 million UK nodes, our dataset has 492 overlapping IP addresses for comparison. Of the 1,047 distinct IPs in our dataset, 288 were geolocated at the city level by CAIDA and 369 at a facility level by our method; this includes 89 new IPs that were not in the CAIDA dataset. Given that these promising results are preliminary, we next need to demonstrate scaling the solution to millions of traceroutes and different regions.

8.1 IPv4 Geolocation

The solution proposed in Chapter 5 uses a confidence level mechanism to provide some idea of the precision of the methods explained in this paper. Of the 1190 traceroutes employed in the test, 1021 individually discrete IP addresses were found, of which 343 were geolocated using the procedure and methods described. This gives a success rate of 33.6% in geolocating the 1021 IP addresses to a confidence level of 3 or higher where a 1 is fully confident, a 2 is probable, a 3 is likely and a 4 is a "best guess", as discussed in Section 5.5.1

A REGEX filter is one of the main components of this solution. First, the DNS name of each IP address is discovered, and then it is entered into a REGEX script in an attempt to discover the town or city where it is located. Although several researchers have already worked on this issue, such as Luckie et al. (Luckie, Huffaker, Marder, Bischof, Fletcher, and Claffy, 2021) and Dan et al. (Dan, Parikh, and Davison, 2021a), a new solution has been created and reported here, specifically designed for the UK Internet infrastructure. The limited number of UK towns where 179 facilities are located makes the process of geolocating Internet infrastructure slightly easier, allowing for some amount of brute-force techniques to be used, for example, searching for specific facility names. However, there is much room for improvement; an investigation of the 3000+ failures of this REGEX technique would lead to more comprehensive results. The machine learning techniques of Dan et al. and the learning of geographic naming conventions from Luckie et al. could also significantly improve these results.

The five rules presented in this solution have evolved over time, and as new processes have been discovered; some have become more relevant, while others are less relevant. When none of the previous rules apply, Rule 5 uses a set procedure to try to narrow down the IP address location:-

1. Attempt to discover the DNS address of this IP.

2. The DNS address is processed through a REGEX solution to discover a

possible city or town name.

3. Find all the facilities in that city or town and narrow them down to one facility using other DNS hints, sanity checks, ASN lookups, and RTT values.

4. If no Facilities were found, perform a reverse traceroute, if available, and subject any reverse DNS to the same REGEX filter.

5. Failing all of this, carry out a Common Facility comparison to determine the facilities at which the previous ASN and current ASN interconnect.

If none of these methods proved successful, we were unable to locate the IP address. Additionally, Rule 1 also uses this same procedure as a secondary method to attempt to discover where the gateway router is located if it is not immediately obvious.

In Step 2, DNS parsing uses a regular expression script similar to that developed by Luckie et al. (Luckie, Huffaker, Marder, Bischof, Fletcher, and Claffy, 2021) and Dan et al. (Dan, Parikh, and Davison, 2021a). In many cases, generic regular expressions automate the discovery of a facility and its coordinates. However, it should be noted that the success of a regular expression script is highly dependent on the knowledge of the local infrastructure. The regular expression script employed was developed purely for the UK, where detailed information can also be hard coded. For example, British Telecom uses its own telephone exchanges as facilities, and these are not listed in PeeringDB. However, the locations of BT's DNS addresses are easily identified when the script is provided with the necessary expression. Some of the BT DNS names provide the telephone exchange town such as 'acc1-te0-0-0-0.kingston.ukcore.bt.net', which is in Kingston-upon-Thames. Others are slightly more obtuse, such as 'core2-hu0-7-0-3.southbank.ukcore.bt.net', which is located at Columbo House, London. Others are listed after the name of the property such as 'core3-hu0-6-0-0.faraday.ukcore.bt.net' which corresponds to Faraday House in London. Therefore, many of these locations must be added to the list of regular expressions, and many other companies have equally obtuse DNS addresses. NTT,

for example, appears to have misspelled London in all their DNS names, for example 'ae-2.r21.londen12.uk.bb.gin.ntt.net'. Faelix has identified facilities with names, such as AEBI, its full DNS name is 'eth5.aebi.m.faelix.net', which corresponds to PeeringDB's facility number 46, which is the Interxion facility in London.

The results of the use of traceroutes in measurements should be interpreted with caution. Although this method avoids many of the challenges described in Chapter 2.2, there are still limitations that need to be addressed. ICMP echo packets are often treated as second-class by routers and target hosts. This means that ICMP echo requests and responses may have a lower priority than traffic, which is considered more important. The end result indicates that the round trip time reflected by the traceroute can easily be different from that experienced by other higher priority traffic types. In addition, because routers may consider ICMP traffic to have a small packet size, they can experience different routing paths compared to fully laden TCP or UDP packets. However, the goal of this method is to create maps of the Internet infrastructure and not to be overly concerned about packet timings. With the exception of using RTT values as a secondary check, RTT values are not a major part of this method.

It should also be noted that this method works well because of the abundance of RIPE probes located in the UK, and it is likely that the use of this method will not be as effective in regions where RIPE probes are sparse, such as Africa, Russia, or China. In these cases, other traceroute platforms, such as CAIDA's ARK platform, could be used, where the IP address and geolocation are already known to be used as sources and targets to initiate traceroutes.

While building up this detailed visualisation of the UK Internet infrastructure, the method additionally creates a dataset of IP addresses to geolocations: the Vantage Points or VPs. With more than 600 probes in the UK, it is theoretically possible to create a mesh of over 300,000 traceroutes, each discovering on average 1–10 IP address/geocoordinate combinations, providing a data set of more than one million VPs from which future research on IP geolocation can be based. In addition,

it should be noted that the IXPDB dataset is seemingly an untouched source of Vantage Points/Landmarks, which can be used in future research; additionally, the IP address-to-geolocation pairs that can be derived from this data are naturally located close to population centres.

8.2 OpenstreetMap

OpenStreetMap is not capable of effectively displaying all fine-grained information regarding Internet infrastructure; therefore, research into improved methods for visualising this information would prove useful. For example, Virtual Reality may provide better methods for visualising interconnections, routing of data, geographical data. OpenStreetMap and other products can now convey information that can then be rendered in 3D, and it would be useful to investigate the efficacy of these products compared to this 2D view.

8.3 High Latency issues

In Section 3.6 we discovered a high-latency issue with the RIPE probes in and around the London area. In order to discover exactly where this latency is occurring it would be useful to be fully in control of the source and target probes at each end of a traceroute to fully analyse where the delays are occurring. The installation of additional RIPE anchors at other Universities such as London, Edinburgh, and Bristol would allow end-to-end latency tests where every aspect of a traceroute between two RIPE ATLAS Probes can be thoroughly investigated.

8.4 IPv4 Geolocation Future work

Future work could also involve creating the same traceroute measurements over extended periods and using different routes, adding alternative hops as backup paths, or finding completely new paths, allowing new infrastructure details to be realised

and more Vantage Points to be created. The various methods and rules presented in this study evolved over time. At the beginning of this research, discovering the entry and exit points of a packet crossing an Internet Exchange was a complicated process to find the common peers of an IXP against a preceding or succeeding ASN. However, the IXPDB website has made this task much easier by providing the facility name and cross-reference to the PeeringDB number for each IX-registered IP address. The IXPDB website is a previously untouched mine of useful Vantage Points that are close to population centres.

8.5 IPv6 Geolocation

Chapters 6 and 7 look toward the future, introducing new ideas based on IPv6. However, what happens in the event that IPv6 never fully replaces IPv4? The proposal to add IPv6 style Extension Headers to IPv4 (Herbert, 2024) would provide an interim solution to this problem. This specification allows the core IPv6 Extension Headers defined in RFC8200 (S. Deering and R. Hinden, 2017) to be used with IPv4. These Extension Headers include Hop-by-Hop Options, Destination Options, Routing Header, and Fragment Header. The Authentication Header (Kent, 2005a) and the Encapsulating Security Payload (Kent, 2005b) are already usable with IPv4.

This specification is still only an Internet Draft and is classed as a "Work in Progress"; therefore, should this fail to be approved for publication, then the solution will still work in a limited fashion much as Traceroute does now. Traceroute only works when routers ICMP replies are enabled; if they are not enabled, then researchers and analysts have to move on to those parts of the Internet that allow ICMP replies. The same will happen for these solutions; if IPv6 is not enabled on a router or the changes to the router kernel have not been implemented to a specific router, then researchers will need to analyse routes where they are enabled.

8.6 Extension Header Recognition

The steps required to obtain recognition for a new IPv6 Extension Header are significantly difficult. The first step is to engage with the IETF, write a draft proposal, and submit it for peer review. We would then need to get a Hop-By-Hop Options Type assignment from IANA from the "Destination Options and Hop-by-Hop Options" (Section 5) sub-registry of the "Internet Protocol Version 6 (IPv6) Parameters" registry (Bradner and Paxson, 0200). The new Extension Header type assignment would need to be mentioned in the IETF RFC that describes our Extension Header. The next step is even more challenging; we would need to get our newly approved Extension Header implemented across the Internet. We would have to convince network equipment manufacturers to be able to pass our packets and process them as described above.

The new Extension Header would need to be implemented in core Internet routers, service provider networks, subscriber CPE, enterprise networks, and cloud infrastructure. We would also need to get the Extension Header permitted to be forwarded across all firewalls, deep packet inspection (DPI) systems, load balancers, and other middleboxes. We would also need to ensure that other security functions like Intrusion Prevention Systems (IPSs), packet brokers, web proxy services, malware prevention systems, and other filters do not accidentally or intentionally block IPv6 packets with our new Extension Header. The final step would be to implement the new Extension Header in every IPv6 protocol stack of operating systems such as Apple macOS, iOS, iPadOS, Microsoft Windows, Google (for Android and ChromeOS), Linux and many other Operating Systems.

Without full industry support, parts of the global infrastructure would not recognise the new extension header and this could give rise to issues such as:

- Packet dropping: routers or devices not recognizing the header might drop packets containing the new extension, resulting in failed transmissions and communication breakdowns.

- Routing issues: non-compliant routers might ignore the header, leading to unintended routing paths that do not adhere to the geopolitical restrictions intended by the extension, undermining its purpose.
- Interoperability challenges: inconsistent support across the global infrastructure could lead to significant interoperability challenges, complicating the deployment and effectiveness of the extension header.
- Fallback mechanisms: the infrastructure will need robust fallback mechanisms to handle unrecognised headers, ensuring that packets can still be routed, albeit without the additional controls intended by the extension.

8.7 Optional Tracking Field

Whilst conceptualizing this header, more thought was put into the possibility of adding a second 32 byte field, which would record the countries of the router interfaces through which the packet had passed. Although this might prove interesting and perhaps useful, the security aspects of providing a writable field were considered to outweigh significantly the possible benefits.

8.8 IPv6 Geolocation Fault Finding

One major issue that has been identified is a concern about the added complications of debugging any network problems that the proposals in Chapter 7 would create. An analyst would need to differentiate between when packets are lost due to the geofencing proposal in Chapter 7 and when they are lost due to other causes. To resolve this matter, the ideas proposed in Chapter 6 could additionally allow for a router's country code peer connections to be analysed. This would provide sufficient reporting to investigate problems caused by geofencing.

Also, this would require an additional Node Information Protocol Change to the Qtype field. A Qtype of 5 would not only return a list of IP addresses of the

nodes peers as proposed in Section 7.6 but would also return the contents of the new "countries field" by asking the router to interrogate its IFTable.

The data returned would then consist of 3 pieces of information for each of the router's interfaces as shown below:-

```
###### Data in JSON Format ########
{ "2001:DB8:2::1": { # Router IPv6 Address
        "lat": 52.2815, # Router Latitude
        "lon": -0.8685, # Router Longitude
        "interfaces": # Router interfaces
                [               {
                "interface": "22001:DB8:3::2/64",
                "peer": "22001:DB8:3::1/64",
                "countries": 32 Bytes
                },
                {
                "interface": "2001:DB8:4::2/64",
                "peer": "2001:DB8:4::1/64",
                "countries": 32 Bytes
                },
                {
                "interface": "2345:425:567::b1/64",
                "peer": "2345:425:567::b5/64",
                "countries": 32 Bytes
                },
                {
                "interface": "2266:25:12::15/64",
                "peer": "2266:25:12::12/64",
                "countries": 32 Bytes
                }
                ]
                }
}
```

The countries field would be a set of 32 bytes indicating the countries to which a particular interface is connected, as shown previously in Figure 7.5.

8.9 Segment Routing

Building on the capabilities discussed in Sections 6.6 and 8.8, segment routing emerges as a powerful tool to enhance the precision and control of packet routing within the global Internet.

Source routing is a routing methodology that allows the sender to either partially or fully determine the route a packet will take through the network. This is in contrast to traditional routing, where routing decisions are made incrementally at each router/node along the path. This allows for easier troubleshooting and allows a host to 'know' all possible paths to the destination.

Segment routing is a type of source routing that is being developed by the IETF (Filsfils, Nainar, Pignataro, Cardona, and Francois, 2015) and is specified in RFC 8402. In a segment-routed network, an ingress router may prepend a header to packets that contain a list of segments, which are instructions that are executed on subsequent routers in the network. These instructions may be forwarding instructions, such as an instruction to forward a packet to a specific destination or interface. With segment routing, the network no longer needs to maintain a per-application and per-flow state. Instead, it obeys the forwarding instructions provided in the packet.

Segment Routing can operate with an IPv6 data plane, and integrates with the rich multi-service capabilities of MPLS (Multiprotocol Label Switching), including Layer 3 VPN (L3VPN), Virtual Private Wire Service (VPWS), Virtual Private LAN Service (VPLS), and Ethernet VPN (EVPN). This capability would ensure that the user has a suitable path available before even sending the data.

Segment Routing could make use of the JSON file described in Sections 6.6 and 8.8 by using it as the input to a tool which would be capable of predetermining a route through a network to avoid those countries that a user deems undesirable for their data to transit.

Using the information returned from the node information query, network administrators can establish predetermined paths for data transmission. This capability allows for the prepending of route instructions directly to each packet header, ensuring that packets follow the exact path intended, adhering to both geopolitical and performance requirements.

For example, the JSON file returned from a NODE Information Query as

described in Section 6.6 and augmented with the additional country field as described in Section 8.8 would be analysed to discover a transit path through the network. All interfaces on each router which contained a country code in a user's 'No Transit' country code list would be removed from the data packets possible routing path. Once a valid path is found through the Internet to the destination, this route would prepend the route instructions within each packet header, which all segment routers on the transit path would obey.

Figure 8.1 shows a valid route (green line) from the UK to the USA if a user had designated Russia and China as 'No Transit' countries.

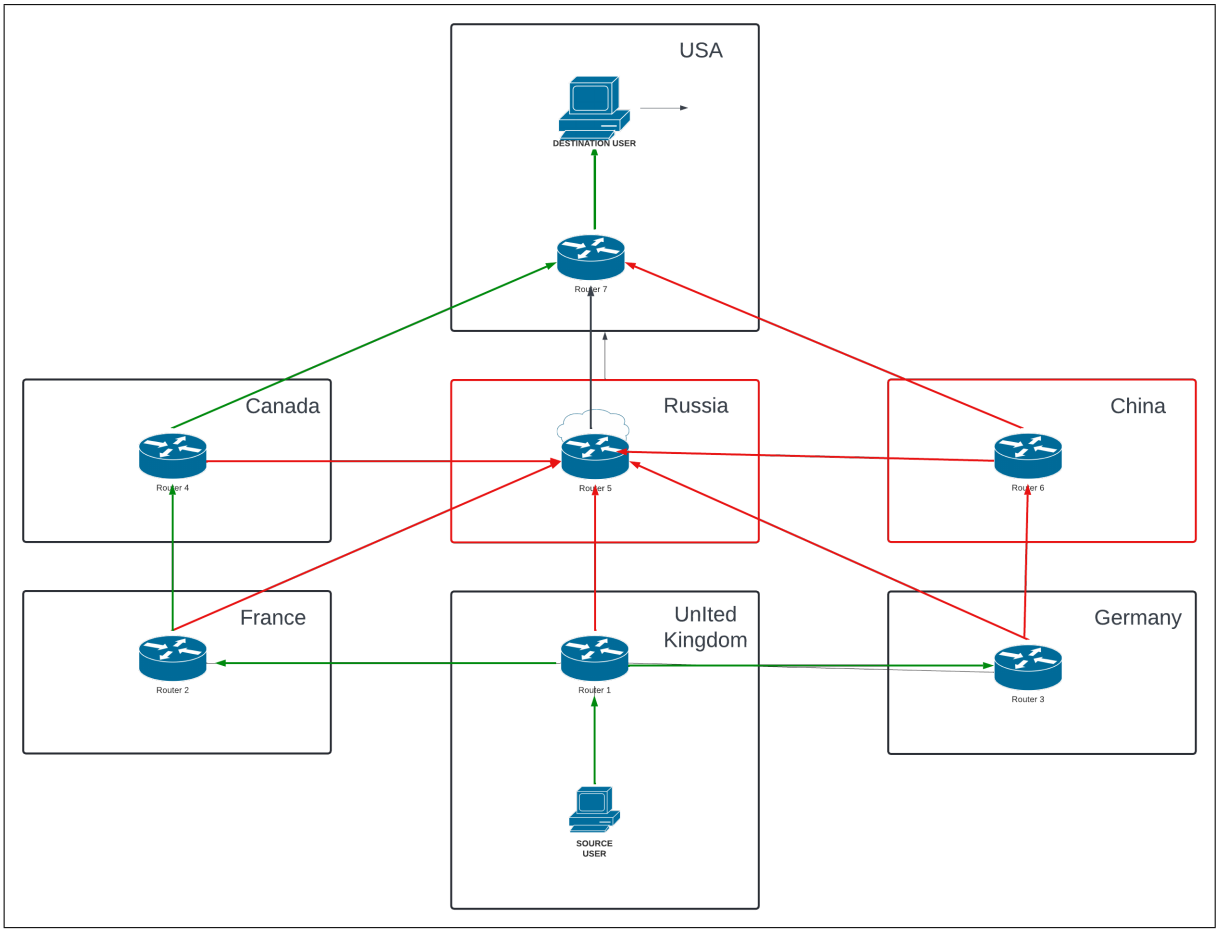


Figure 8.1: Example of Segment Routing by Transit Country

Segment routing is particularly valuable when precise control over the path a packet takes is necessary. This includes scenarios where geopolitical restrictions

must be enforced, specific network performance goals are required, or redundancy and fault tolerance need to be ensured. By embedding route instructions within the packet header, segment routing eliminates the need for per-hop state maintenance in intermediate routers, streamlining the routing process and reducing complexity. This approach is essential in scenarios where predefined routing paths must be strictly followed to meet legal, security, or operational requirements. Segment routing ensures that the data adheres to the intended route, leveraging the detailed network information gathered through the node information query.

8.10 Security

The IPv6 solutions proposed in Chapters 6 and 7 introduce advanced capabilities for routing and network management. However, these enhancements also expose the infrastructure to significant security risks. Unauthorised access, data interception, and malicious exploitation of the network could compromise the integrity and confidentiality of the global infrastructure. The following sections of this chapter offer some solutions to the issues posed.

8.10.1 Using an Authentication and Authorisation Server

Additional security could be added by introducing a trusted authentication and authorisation server. ICMPv6 NI Query functionality allows the Subject Address to be different from the Queried Address. Therefore, all queries could go through a specific server as shown in Figure 8.2 that authenticates the queries by applying strict security measures (1) before passing them to routers and middle boxes (2). It will then forward the "Echo Replies" back to the originator of the query (3). This will allow network administrators to confine requests for this information to specific queries originating from the IP Addresses of these trusted authentication servers.

This server ensures that only authorised and authenticated users can access sensitive routing and network information. It protects network integrity by

preventing unauthorised users from querying or manipulating network infrastructure and protects against potential security breaches. Furthermore, it ensures that sensitive network information is only accessible to trusted entities, protecting against data leaks. The server would also mitigate the risk of attackers gaining access to routing information, which could be exploited for malicious purposes and limits access to legitimate users, preventing the abuse of network resources and protecting the infrastructure from unnecessary load. This layer of security is crucial for maintaining the integrity and confidentiality of the network.

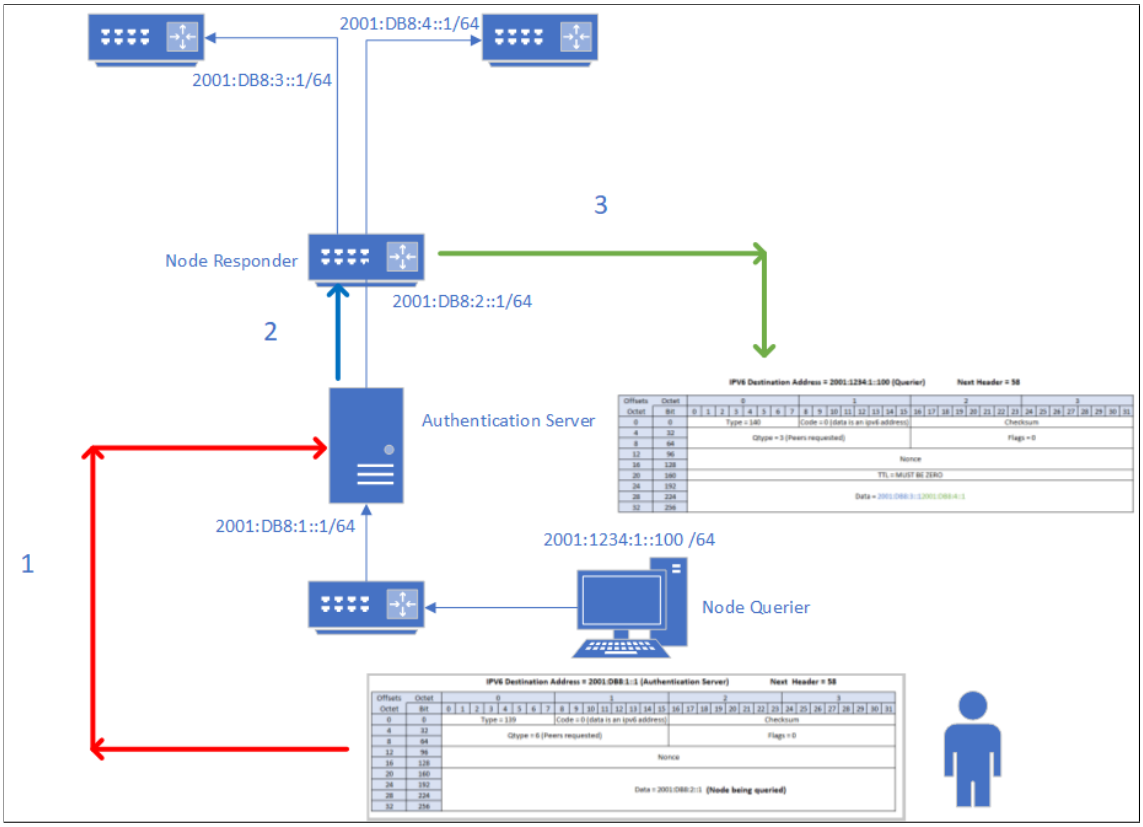


Figure 8.2: IPv6 Node queries and Replies via an Authentication Server

8.10.2 Alternative Method using TLSA

However, as already pointed out, this solution would use ICMPv6 replies, which are known to be disabled in many routers to ensure that ICMP flooding does not take

place and, therefore, it is likely that the ICMP requests and replies may be blocked in transit in some cases.

An alternative method could involve the use of HTTPS requests to download the JSON file. However, this would require each router to provide a web-based interface. This method could use the TLS authentication record (TLSA), which associates a TLS server certificate or public key with the domain name where the record is found. A TLSA record stores the fingerprint of a TLS/SSL certificate in the DNS of the domain where the router resides. This DNS record provides an additional layer of validation and verification for TLS connections, ensuring that users can authenticate to the router to which they are connecting. However, it does not provide authorisation, and either an authorisation server would still be required or each router could provide authorisation although this would not scale well.

However, even with the introduction of a suitable authorisation method, this solution is still not without its problems. TLSA also requires DNSSEC to be enabled along with a web server service on each router. These services would use valuable CPU cycles, and this solution may be rejected by router manufacturers.

8.10.3 Privacy Enhancing Technologies (PET)

Hiding sensitive data from malicious parties requires advanced methods using the latest information hiding techniques (IHT) and privacy enhancement technologies (PET). PETs are a wide range of technologies that allow organisations to collect, share, and use data while mitigating the privacy risks that arise from these activities (ICO, 2024). PETs can involve the random injection of data to make it look like noise or synthetic data which is generated from real data using machine learning and provides similar results to the real data. The Information Comissioners Office provides a list of PETs that may be applicable to this solution. Further research into these technologies may be useful to avoid providing a potential misuse of the information that the methods and tools described in this thesis can provide.

8.11 Testing and Evaluation Framework

The changes discussed in this and previous chapters require changes to the operating system kernel, which traditionally has always been difficult to attempt due to its central role and high requirement towards stability and security.

8.11.1 Enhanced Berkeley Packet Filter (eBPF)

eBPF is a technology that can run sandboxed programs in the operating system kernel within a privileged context. It extends the capabilities of the kernel, without requiring one to change the kernel source code or load new kernel modules. eBPF allows developers to run programs that add additional capabilities to the operating system at runtime compiled with the aid of a Just-In-Time (JIT) compiler and verification engine.

The wide-scale deployment of eBPF suffers with the problem that it is challenging to build applications that are compatible across a wide range of Linux distributions. This is because the eBPF code must be compiled on the target host to make sure that the program is compatible. Also, each host may have a different kernel, and so kernel struct layouts may have changed. So, a system running Linux 5.5 would need a different compilation to that of, for example, a Linux 5.8 system. If testing on different Linux distributions is required, the eBPF community has developed libbpf + CO-RE, which encodes the struct offsets of kernel structs for a given kernel version. CO-RE uses the BPF Type Format (BTF) that enables the BPF program loader to make adjustments to the precompiled eBPF code so that it looks at the right offsets in memory (Nakryiko, 2020).

Although the use of eBPF may be good for testing, it is primarily designed for Linux and has been tightly integrated into the Linux kernel. While eBPF is native to Linux, there have been efforts to bring similar capabilities to other operating systems, such as Windows. However, the most robust and widely used implementations of eBPF are found in the Linux ecosystem. Routers built on Linux

distributions such as BIRD (Bird, 2024) could of course provide a useful test bench, but this implementation would not be suitable for general deployment on the Internet at large.

8.11.2 Programming Protocol-independent Packet Processors (P4)

An alternative testing framework that may be better suited to the global Internet is the P4 programming language, which can control packet forwarding planes on network devices (Bosshart, Daly, Gibb, Izzard, McKeown, Rexford, Schlesinger, Talayaco, Vahdat, Verghese, and Walker, 2014). P4 works in conjunction with SDN control protocols like OpenFlow, and its three goals are that it should allow programmers to change the way routers and switches process packets once they are deployed, switches should not be tied to any specific network protocol, and finally programmers are allowed to be able to describe packet processing functionality independently of the specifics of the underlying hardware.

The discussions and methodologies presented in this chapter highlight the potential of advanced programming languages such as P4 and eBPF to transform how we manage and secure the Internet infrastructure. Both P4 and eBPF offer unique advantages and can be strategically employed depending on the specific requirements and constraints of the network environment.

P4, with its high performance and data plane programmability, is particularly suited for real-time geolocation checks in high-speed networks. eBPF, with its flexibility and ease of deployment, provides a powerful alternative to existing Linux-based systems, offering extensive monitoring capabilities.

8.12 Summary

By integrating these advanced techniques with the geolocation tools and methodologies developed in this thesis, we can significantly improve the accuracy, security,

and resilience of the Internet infrastructure. Future work should focus on further refining these approaches, exploring their combined potential, and addressing any implementation challenges to fully realise their benefits.

Chapter 9

Conclusion and Future Work

9.1 IPv4 Geolocation Conclusion

The purpose of the research presented in Chapters 1 through 5 was to investigate the current methods used by Internet mapping techniques to determine the optimum method to develop fine-grained infrastructure maps. The research then built on these methods by developing tools and techniques that can help create fine-grained infrastructure maps. Specifically, the new method developed in this work uses four newly created Python tools that gather the locations of UK facilities and maps them to OpenStreetMap. The tools also locate all UK IXPs and maps the network structure and interconnection facilities. The tools then create measurements from the selected RIPE ATLAS probes to create a UK infrastructure map by geolocating every hop within each traceroute, where possible. As a by-product of this method, a useful IP address to geolocation data set was created that researchers can use for future studies.

It is believed that the work reported in Chapters 1 to 5 has successfully achieved its objectives of discovering and developing a new method to create fine-grained maps of the UK's Internet infrastructure leveraging advanced geolocation methods and combining data from various sources. The tools and methodologies developed provide a fine-grained map of the UK's Internet infrastructure, significantly

enhancing the accuracy of IP geolocation. This represents a considerable advance over existing geolocation techniques. However, even this improved accuracy is far from perfect; Chapters 6 and 7 then examine how we can leverage the enhanced capabilities of IPv6 to improve security and IP geolocation.

9.2 IPv6 Geolocation Conclusion

Existing tools and methods that use traceroute, such as Spotter (Laki, Mátray, Hága, Sebok, Csaba, and Vatta, 2011), Octant (Wong, Stoyanov, and Sirer, 2007), and HLOC (Scheitle, Gasser, Sattler, and Carle, 2017), are inadequate for precise Internet mapping, as they do not accurately determine the geographical locations of nodes and paths in many cases due to their use of traceroute with its many inherent limitations (Motamedi, Rejaie, and Willinger, 2015). The new tool described in Chapter 6 leverages IPv6 Node Information Queries, as detailed in RFC 4620, (Crawford and Haberman, 2006) to extract detailed node data, including geolocations and peer relationships. It offers a more comprehensive and accurate view of the Internet's structure than tools relying on traceroute and avoids the inherent and fundamental issues surrounding traceroute by utilising IPv6's extended Node Information Queries for gathering comprehensive data including node geolocations and peer connections. The new IPv6 network infrastructure mapping tool exceeds current methodologies in precision and completeness. Using IPv6 node information queries, the tool provides detailed real-time information on the Internet structure, including geolocations and peer relationships of network nodes.

This development represents a significant step forward in addressing the limitations of current Internet mapping methodologies and paves the way towards the design of more sophisticated applications. By leveraging the IPv6 Node Information Queries protocol, the tool offers a more precise and comprehensive mapping of the Internet's topology, including geolocation data and peer connections of network nodes. The proposed changes to the node information protocol, along

with modifications to router kernels and installation procedures, underscore a holistic approach to improving the accuracy and utility of network mapping.

The tool's design emphasises the importance of security, implementing measures to safeguard against misuse while enabling legitimate research and network administration activities. With the introduction of extended query options and the ability to obtain detailed geographical and connectivity data, researchers and network operators will be much better equipped to analyse, troubleshoot, and optimise the Internet infrastructure.

9.3 IPv6 Geopolitical Routing Conclusion

The objective of Chapter 7 was to conceptualise the design and evaluate a new IPv6 extension header, which aims to incorporate a geopolitical dimension into each data packet, allowing network paths to be dynamically adjusted based on country codes of transit networks. This would address a growing need for data controllers and processors to comply with the data protection laws of each country, respecting the geopolitical sensitivities which are inherent in global data transmission. The conceptual design of a new IPv6 extension header incorporating geopolitical dimensions is a novel contribution.

BGP (Border Gateway Protocol) does not inherently provide fine-grained control over routing paths based on geopolitical boundaries, but it can influence traffic routing away from specific countries by manipulating route preferences. BGP selects the best route based on routing policies and metrics (Cisco, 2023), but lacks the ability to directly enforce country-specific routing restrictions. In contrast, the solution proposed in Chapter 7 of this thesis introduces an IPv6 extension header specifically designed to enforce geopolitical routing rules. This ensures that data does not transit through undesirable countries and provides for precise control of routing paths. This capability is achieved by embedding routing preferences and restrictions directly into the packet headers, which are then interpreted by routers to

avoid specific jurisdictions. Thus, while BGP can be configured to influence routing decisions, it does not provide the explicit, enforceable control over geopolitical routing that the proposed IPv6 extension header offers. The solution in Chapter 7 is more targeted and robust in addressing the need to route data away from specific countries based on legal, security, or ethical considerations.

This header can dynamically adjust network paths based on country codes, addressing data protection laws and geopolitical sensitivities. The first two of these goals, conceptualisation and design, are believed to have been met; however, the evaluation has proven to be very difficult, as explained in Chapter 7.8. Despite the challenges in implementation and evaluation, this proposal demonstrates a forward-looking approach to improving Internet security and compliance.

Geoff Huston, Chief Scientist at APNIC, is particularly pessimistic about the use of Hop-By-Hop extension headers (Huston, 2022) where he agrees with the view that 'Hop-By-Hop options are still not practical to be used widely in the Internet and many operational routers are configured to drop all packets containing a Hop-By-Hop option header.' (R. Hinden and Fairhurst, 2020). Strangely, this statement was written by the same people who then proposed a Hop-by-Hop extension header to find the maximum MTU size between a source and a destination. However, it is interesting to note that this statement was removed in a later draft (R. Hinden and Fairhurst, 2021). In their white paper, 'IPv6 Extension Headers (EH) Review and Considerations', Cisco argue that EHs are considered a powerful tool in extending IPv6 to adapt to future protocol requirements and service needs. It is expected that other uses will be identified for the existing EHs and that new EHs will be defined (Cisco, 2006). The Internet Engineering Task Force (IETF) continues to provide recommendations on the use of IPv6 hop-by-hop options (Vyncke, Chittimaneni, Kaeo, and Rey, 2021). Concerns surrounding the use of IPv6 Extension Headers as expressed by Huston (Huston, 2022), are valid, but Cisco's endorsement of IPv6 extension headers as powerful tools gives greater credence to the new mapping tool proposed in Chapter 7 as it uses these headers to

allow for dynamic routing adjustments based on country codes, ensuring that data paths comply with geopolitical regulations.

9.4 Conclusion

This work not only contributes to the technical fields of network engineering and cybersecurity, but also addresses broader considerations of Internet resilience, privacy, and ethical data use. As the Internet continues to evolve, tools like the ones proposed in this document are essential for maintaining an open, secure, and efficient global network. The ongoing collaboration between academics, industry professionals, and policy makers will be crucial in ensuring the successful deployment and adoption of such innovations, ultimately improving our understanding and management of the complex digital landscape that underpins modern society.

9.5 Limitations and Proposed Future Studies

It is worth reiterating that the European Network and Information Security Agency (ENISA) concluded in a 2015 report (ENISA, 2015) that the current lack of structural transparency is the biggest obstacle to addressing the inherent vulnerabilities and architectural shortcomings of the Internet routing system.

The new method described in Chapter 5 increases the accuracy of IP geolocation by a large amount, from 7.1% to 33.6% using a highly curated set of input data. However, the fundamental issues of using traceroute as discussed in Section 2.2 still apply to this method and, as Motamedi et al. point out, all of these methods are little more than engineering hacks (Motamedi, Rejaie, and Willinger, 2015) and may produce large discrepancies between what we think the network looks like and what it is in reality.

The introduction of an IPv6 network infrastructure mapping tool, as discussed in Chapter 6, designed to enhance and expand the capabilities of existing mapping tools such as traceroute, offers a new and comprehensive approach to capture

detailed and real-time information on the Internet structure, including IP addresses of router interfaces, their peers, and geolocations. This tool is aimed at providing researchers and network administrators with a sophisticated visualisation of the Internet topology that presents a significant step forward in the precision and comprehensiveness of mapping the Internet infrastructure.

The effectiveness of the tool proposed in Chapter 6 can be compromised in areas with low adoption of IPv6 or outdated infrastructures. Its deployment strategy should include modular adaptations that can still operate under limited IPv6 use. This approach ensures that even networks at different stages of IPv6 integration can benefit from the tool, promoting a wider adoption of IPv6 through demonstrated efficacy.

In Chapter 7 we acknowledge the drawbacks of our new IPv6 extension header, for example:

- Using ICMP replies to warn of failures in routing can be prone to flooding.
- Debugging of network problems is made harder due to the additional checks on whether failures are due to geofencing.
- Older routers and middleboxes would have to be replaced.

However, issues with ICMP flooding have been around for a long time and the problems need to be resolved, noting that ongoing ICMP issues are outside the scope of this thesis. All equipment has to be replaced at some point, and therefore older routers will eventually give way to new equipment. New tools specifically designed for network analysis can include geofencing diagnosis, as discussed in Chapter 8. Hence, all of these problems are not insurmountable given enough time along with the will to succeed.

As we explore innovative methods to improve IPv6 geolocation and routing, leveraging the P4 programming language presents a promising approach. P4 allows for the programming of the data plane, which enables the implemention of

geolocation checking directly where packet forwarding occurs. This approach offers several advantages:

1. Performance and efficiency: by performing geolocation checks in the data plane, we can achieve real-time processing speeds, minimizing latency and improving overall network performance.

2. Flexibility: P4's programmability allows us to define and update geolocation policies dynamically, adapting to changing geopolitical considerations and network conditions.

3. Security: real-time geolocation checks improve security by ensuring that data packets comply with geopolitical routing policies, reducing the risk of unauthorised data transit.

4. Scalability: the distributed nature of data-plane operations ensures that our geolocation checking mechanism can scale with increasing network traffic and complexity.

Future work should look at the possibilities of developing P4 programs that use IPv6 extension headers to extract and verify geolocation information. These programs could be integrated into network devices, ensuring seamless operation with existing infrastructure. State management techniques will be used to efficiently handle geolocation data, ensuring that data plane operations remain performant. Rigorous tests could be performed to validate the accuracy and security of the P4 programs, ensuring that they meet the desired performance and reliability standards. By integrating P4 into our geolocation checking framework, we can enhance the capabilities of our IPv6 geopolitical routing method, providing a robust and scalable solution for modern Internet infrastructure. The testing of the new IPv6 Extension Header described in Chapter 7 could be carried out using network simulation software such as GNS3 or Cisco Packet Tracer, which allows the creation of complex network topologies using virtual routers and switches. Quagga can be used to test

and experiment with routing decisions and is an open-source routing software suite that provides implementations of various routing protocols. FRRouting (FRR) is an open source routing stack that supports multiple routing protocols. The BIRD Internet Routing Daemon is a lightweight routing daemon that supports IPv4 and IPv6. It is commonly used for testing and small-scale deployments. However, it seems that none of these packages provides a simple method of introducing and processing a new IPv6 Extension Header, and this would be a useful addition to any of these solutions by providing researchers and engineers with a simple method of testing new ideas.

Experience from testing is an expected input to any decision to progress this specification. Appropriate inputs might include:

- Reports of implementation experience
- Measurements of the number of paths where the method can be used
- Measurements showing the benefit realised or the implications of using different options in the Extension Header.

Although the idea of using country codes inside the Hop-By-Hop IPv6 extension header seems a fine approach, current practical experience with Hop-By-Hop headers in the public IPv6 Internet makes the prospects for this header a challenge. The key functionality of IPv6 extension headers is believed still to be a solid foundation for the ongoing growth and diversification of the Internet and demonstrates its adaptability to future Internet needs and challenges. It is nevertheless appropriate and timely to focus on extension header problem resolution, in order for IPv6 to reach its true potential.

The new tools and methods detailed in Chapters 6 and 7 are based on the implementation of IPv6 on the global stage. In 2020, researchers were lamenting the slow deployment of IPv6 and the imminent depletion of IPv4 addresses (Livadariu, Elmokashfi, and Dhamdhere, 2020). However, recently the trend appears to have turned around; for example, Google is showing a 15% increase in IPv6 users since

2020 to 45% in 2024 who use IPv6 to access their site (Google, 2024). The number of BGP entries in the router BGP forwarding table has increased from 80,000 entries in 2020 to more than 200,000 in 2024, as shown in Figure 9.1.

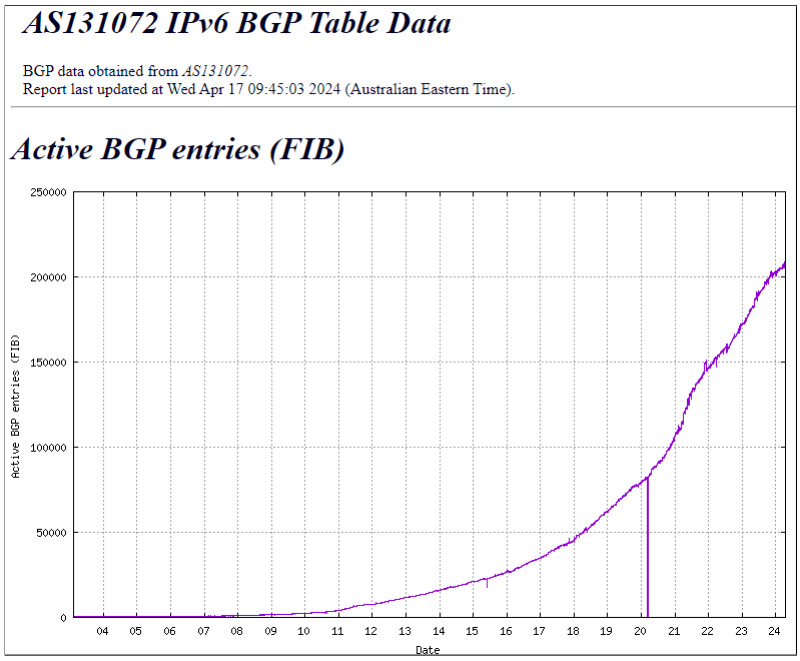


Figure 9.1: Active BGP Entries (FIB) (Huston, 2024)

IPv6 offers so many opportunities for Internet improvement that resolving extension header security issues should be a major focus of researchers and analysts. These conclusions emphasise the need for a strategic focus on the security and functionality enhancements provided by IPv6 extension headers in the development of the IPv6 network infrastructure mapping tool. By resolving these critical security issues and demonstrating the practical benefits of IPv6, the tool would not only advance network management capabilities but also encourage the resolution of long-standing challenges associated with IPv6 deployment globally. This forward-looking approach will help catalyse the broader adoption and optimisation of IPv6 across diverse regions and network setups.

9.6 Final Thoughts

The advances offered in this thesis represent significant steps towards a more secure and resilient Internet infrastructure. By leveraging advanced geolocation techniques, innovative IPv6 extension headers, and comprehensive network mapping tools, this thesis has laid the groundwork for a future where IP geolocation is greatly enhanced and this will lead to more secure BGP routing decisions. Continued research and collaboration will be essential to fully realise the potential of these technologies and ensure the ongoing stability and security of the global Internet infrastructure.

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