

Anycast for DDoS

Master's Thesis

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Contents

1	Introduction	3
2	Research Questions and Related Work	5
2.1	DDoS	5
2.1.1	DDoS attack types	6
2.1.2	DDoS Defenses	7
2.1.3	Network/service reconfiguration as a DDoS Defense	7
2.2	IP-anycast	8
2.2.1	Catchment measurement	9
2.2.2	Controlling catchment	10
3	Methodology & Measurements	11
3.1	Mapping attack traffic to anycast instances	11
3.1.1	Anycast Testbed	11
3.1.2	DDoS Attack data	12
3.2	Measurements	12
3.2.1	Anycast deployments	12
3.2.2	DDoS attacks	13
3.3	Prepending strategies	14
3.3.1	Vacuum cleaner	15
3.3.2	Redistribute to large sites/ Save the children	15
3.3.3	Dynamic redistribution/ Breakwaters	16
3.4	Prepending method	16
4	Results	17
4.1	Vacuum cleaner	17
4.1.1	Measurements with global anycast configuration	18
4.1.2	European anycast configuration: Copenhagen and Paris blackhole	20
4.1.3	No big 3 anycast configuration: Copenhagen blackhole	21
4.1.4	Summary	22
4.2	Save the children	22
4.2.1	Measurement with a global anycast configuration	23
4.2.2	Measurement with Europe based anycast configuration	24
4.3	Dynamic redistribution	27
4.3.1	Measurements with global anycast configuration	27
4.3.2	Measurements with Europe based and without 3 largest site configurations	27

4.4	Summary	29
5	Discussion & Conclusion	32
5.1	Discussion	32
5.1.1	Side effects, collateral damage and precision	32
5.1.2	Reliability	33
5.1.3	Ethics	33
5.1.4	Effectiveness	34
5.2	Challenges & Future work	34
5.2.1	Mapping method	34
5.2.2	Testbed	35
5.3	Conclusion	35
A	All prepping results	37

Chapter 1

Introduction

Large DDoS attacks, such as the one on Dyn [8], are becoming more frequent and increasing in size. Distributed Denial of Service (DDoS) attacks generate as much traffic as possible from different locations on the Internet simultaneously and send it to a service with the goal of overloading it and thereby denying real clients access. The attack on Dyn generated an estimated 1.2 Tbps of malicious traffic by using a large amount of Internet connected IoT devices. Dyn is not the only company that has been under attack from DDoS traffic, and will not be the last. But DDoS attacks also occur on Internet critical infrastructure such as the root and top-level Domain Name Servers (DNS) servers [6]. Potentially bringing the whole Internet on its knees, when a simple translation of “google.com” to an IP address might become impossible. Major CDN’s, DDoS protection services, root and TLD DNS servers and other large networking companies, e.g. Cloudflare or Akamai, and Dyn too [3], use IP Anycast in their networks for “natural” resilience against DDoS attacks. Anycast is a form of IP addressing where one IP address is advertised to be present on multiple globally routable networks, by the owner of that IP address. Whereas traditional IP addresses are present on one location in the Internet as far as the global routing system, BGP, is concerned. Connecting to an anycast IP address means that the user is routed to the site decided by BGP, which is often the site with the shortest path. Anycast allows a service to scale across multiple locations transparently to the end user because the service remains available at the same IP address. The scaling and distribution of one service via anycast brings, among other benefits, an increased resilience under large amounts of network traffic. This property becomes more and more important as DDoS attacks on critical infrastructure and ordinary websites and services occur more often and only seem to increase in size [5]. Large CDN’s and DDoS protection services rely on anycast to spread the load over multiple sites to help mitigate the initial effects of large amounts of DDoS traffic, after which filtering and other mitigation solutions kick in. This simple load sharing is effective as shown in [22], but other effects anycast has or might have on DDoS traffic is not yet well understood. The main reason for this is that anycast is configured using BGP, the global routing framework, which has to take into account peering and routing policies that prevent a simple mapping from networks to their closest anycast site.

Research Questions & Contributions In this work we investigate the impact of DDoS attacks on anycast services and the possibilities of anycast reconfiguration as a possible mitigation against the effects of a DDoS attacks. To analyse the effects of a DDoS attack on anycast services we combined DDoS attack data and an anycast testbed developed for research purposes. We used DDoS attack data from captured real DDoS attacks [2] and simulated DDoS attacks based on captured botnet traffic. The anycast testbed consists of 9 sites spread around the world and is capable of measuring which IPs reach each instance using active measurements. DDoS attack defense and mitigation is a popular and broad subject and active research domain. One mitigation method used to alleviate the effects of a DDoS attack is (anycast) network reconfiguration. Anycast services are generally configured to spread the traffic load across sites according to site capacity. But anycast services can be reconfigured to spread the load of DDoS traffic in various other ways. The anycast service could for instance be configured to redirect all (DDoS) traffic to one site with scrubbing devices installed. We reconfigured the anycast testbed using a method called AS-path prepending and measured the impact of several of these mitigation strategies. Several other anycast configuration and manipulation methods exist, such as BGP communities, but we decided to choose AS-path prepending only to be able to evaluate this method more thoroughly and prevent attribution problems when two methods are used at the same time. The goal of this research is formulated as follows:

Exploring whether IP-anycast reconfiguration and manipulation can minimize the impact of DDoS attack traffic on an anycasted service.

To reach this goal we address the following related research questions:

- RQ 1** Which anycast configuration scenarios exist and what are the positive effects for DDoS traffic mitigation that AS-path prepending might achieve?
- RQ 2** Which AS-path prepending strategies yield positive effects for mitigating DDoS traffic depending on the scenario?
- RQ 3** Based on the answers to the previous questions what would be an effective way to automatically determine the best AS-path prepending strategies depending on the scenario?

The results show that although the reconfiguration and mitigation goals can be achieved, AS-path prepending is not a reliable method for DDoS traffic redistribution in an anycast service. Some strategies such as moving all traffic to a specific site were more reliable, but came with unwanted side effects. Other strategies such as containing the traffic to a few sites performed worse. In all cases the reconfiguration affected non-DDoS traffic as well as DDoS traffic which is usually undesirable.

The rest of the report will provide an overview of the related work in anycast and DDoS research in the next chapter. Followed by a chapter on the approach and the methods used to evaluate the impact of DDoS traffic on the anycast testbed. In the next chapter the results are presented and discussed in detail. And in the final chapter we discuss the limitations of this work, the recommendations on future work and we present our conclusions.

Chapter 2

Research Questions and Related Work

In this chapter we present the background on DDoS and mitigation approaches. In the first section we will introduce DDoS attacks and existing mitigation solutions. The next section will discuss IP-anycast and research related to its behavior and manipulation of this behavior. And finally we will combine these two subjects with the main research question and more detailed subquestions.

2.1 DDoS

Distributed Denial of Service (DDoS) attacks are attacks on Internet services or hosts aimed at overloading the target host or service with more traffic it can handle from many different sources. These attacks are difficult to defend against because the attack traffic comes from many different sources and can easily be confused with legitimate traffic. Another difficulty is that the distributed nature of the attacks often require the cooperation from many different parties who are not affected themselves to effectively defend against them.

DDoS attacks have become a common problem in the Internet. Several reports have shown significant increases in the number and volume of attacks over 2016 [7] [14]. Arbor Networks reported an increase of the number of DDoS attacks of 8% over 2016 where almost half of the respondents who experienced DDoS attacks did so with a frequency of 11 attacks per month or more. In the same report the respondents, from government organizations, educational institutes and enterprises, reported average total cost estimates ranging from \$10000 to over 1 million dollar.

DDoS attacks traffic volumes have reached peaks of 600Gb/s to 1.2Tb/s in 2016, enough to cause trouble for almost any target. Average traffic volumes have also increased and the number of attacks over 2016 has doubled [7] [14]. Two of the most notable recent attacks are the one on the security blog KrebsOnSecurity [20] of around 600Gb/s in September 2016 and the one on DNS provider Dyn in October 2016, performed with the IoT botnet Mirai, reportedly hitting a 1.2 Tb/s traffic volume [32].

To achieve the high traffic volume often required for DDoS attacks an attacker needs a large number of host to generate traffic, so called "bots" or

”zombies”, which together form a ”botnet”. There exist various different technical means to create a botnet and to communicate with it. Performing a DDoS attack however, does not have to require any technical skill as there exists DDoS-for-hire services, also called ”booters”, which rent out botnets to perform DDoS attacks [25].

2.1.1 DDoS attack types

DDoS attacks come in many different types and flavors, as outlined in [21]. One important but subtle distinction is between *semantic* and *brute-force* attacks, also called flooding attacks. Brute-force attacks use seemingly legitimate traffic to deplete the victims computing resources or try to completely fill the network pipe to the Internet. Semantic DDoS attacks exploit a weakness or bug in a specific protocol to consume more resources than the victim can handle while requiring less resources from the attacker side than would be required in a brute-force attack. An example of a semantic attack is a SYN-flood attack [23], which is aimed at filling up a hosts connection pool by opening many connections but never closing them. Brute-force attacks can also be executed with the help of protocol flaws or bugs to generate a large amount of traffic but these are not semantic attacks because the effect on the victim is still the depletion of resources due to sheer volume without abuse of protocol flaws or bugs on the victim side. Sometimes the distinction is less clear. Traffic from brute-force attacks can be indistinguishable from regular traffic to the victim and therefore very hard to filter.

Attacks can be further categorized based on the type of target. Some attacks target the network and aim to completely consume the available network bandwidth of the target’s network. Other attacks are aimed specifically on a certain application, resource or host. Brute-force attacks are typically aimed at either consuming the host’s or application’s resources, or the available network bandwidth. In the last quarter of 2016 more than 98% of DDoS attacks was aimed at the infrastructure level, including network bandwidth, according to [7].

A special kind of brute-force attacks are so called reflector attacks. In these attacks the attacking hosts do not send traffic to the victim directly, but they use mis-configured third party services to relay traffic to the victim. Reflector attacks are effective in hiding the sources of attack since the victim only sees traffic from legitimate third-party services. Some reflector attacks can increase the amount of traffic generated by the attacker hosts because the response sent to the target is larger than the request sent by the attacking host. Therefore, these attacks are often also called amplification attacks.

An example are DNS-amplification attacks which use reflection and amplification to generate large volumes of traffic to the target. The attacking botnet sends queries which generate a large response, such as an ANY query, to an open DNS-resolver (a DNS resolver which accepts queries from anyone) with the source IP-address set to the target’s IP-address. This relatively small query will cause the open resolver to send a much larger response to the target, effectively amplifying the volume of traffic an attacking botnet can generate.

Reflector attacks effectively hide the source IP-addresses of the attackers botnet, while the target sees attack traffic from valid source IP-addresses. The validity of the source IP-address of attack traffic is an important aspect of

DDoS attacks. Attackers almost always spoof the source IP-address to hide the attacking machines and confuse defenders. Spoofing IP-addresses makes it difficult to filter traffic based on IP-address as the attacker can change the spoofed IP-addresses the botnet uses frequently and even spoof the IP-address of legitimate users, causing filtering to block legitimate users. Reflection attacks are one of the few cases, except for non-spoofed traffic, in which the target can see the real IP-addresses from which the traffic is generated, i.e. the IP-addresses of the intermediaries.

Other characteristics include the type of traffic, the traffic rate and the impact on the victim. There are many more differences between several types of DDoS attacks, but the aspects highlighted in this section are most relevant to this work. For more information on the different types of DDoS attacks and their differences refer to [21] and [23]

2.1.2 DDoS Defenses

DDoS defense strategies are usually divided along the lines of reactive and preventive measures, the deployment location and the level of cooperation needed. Preventive measures are meant to prevent DDoS attacks from happening before they start, e.g. fixing flaws in Internet protocols that allow DDoS attacks to occur. Reactive measures deal with the mitigation of the effects of a DDoS attack. The first step in reacting to a DDoS attack is detecting the attack. Detection methods fall in two broad categories: pattern recognition and anomaly detection. The second step is responding to the attack. Attack responses include identification of the attack sources, filtering of the attack traffic based on the detection method used or identified attack sources and reconfiguration of the target network to add more resources or isolate attack traffic [21] [23].

Both preventive and reactive methods can be further classified based on the deployment location of the defense. Defense methods can focus on the source networks, intermediate networks or the target network.

An example of a preventive method is egress filtering at the source network. Egress filtering blocks outgoing traffic from IP-addresses that do not belong in the network and thus prevents certain DDoS attacks that rely on spoofing IP-addresses outside of the source network [23] [17].

2.1.3 Network/service reconfiguration as a DDoS Defense

In this research we will focus on the use of network reconfiguration via IP-anycast to mitigate the effects of a brute-force DDoS attack. Brute-force DDoS attacks aim to overload the network or hosts of a service and changing the network topology can be used to allow the service the either handle the high load of DDoS traffic or isolate the DDoS traffic from (parts of) the service. Network reconfiguration is a first step in mitigating the effects of a DDoS and helps keeping the service available, but it does not stop a DDoS attack in any way. Other mitigation methods such as filtering of attack traffic will be needed in addition to reconfiguration, but these methods will often need time to discover the difference between attack and legitimate traffic. In the meantime network reconfiguration helps keeping the service available for its users.

One commonly found network reconfiguration technique is the use of overlay networks to improve service resilience and protect against DDoS attacks by

reconfiguration of the network in the event of failures of parts of the network[28] [10]. These networks consist of public nodes that act as gateways to protected services. Many papers have covered the use of IP-anycast to create overlay networks that take advantage of the scaling and distribution of traffic properties that IP-anycast can provide. Some proposed overlay networks that provide filtering before allowing traffic to reach the target service, using the distribution of traffic and scaling properties of IP-anycast to facilitate the filtering process [13] [29] [19]. In [18] an anycast proxy network is used to hide the target services from the attackers and only allow proven legitimate clients to access the service. Another use of IP-anycast for DDoS protection is proposed in [34] to provide an ad-hoc IP-anycast overlay to services under DDoS and using the replication and increased scale of a large anycast deployment to absorb the DDoS traffic. All techniques referred to above that use IP-anycast depend on the fact that the IP-anycast will provide the resource multiplication and distribution of traffic needed to handle the load of a DDoS attack before filtering or another mitigation method is applied and the clean traffic is send on to the receiving target. While this may apply to large anycast providers with over-provisioned anycast deployments that can handle the traffic volume of all current large DDoS attacks, this does not always have to be the case. This research will focus on how anycast deployments can handle large volumes of attack traffic by reconfiguring the anycast deployment itself. Anycast deployments do not always have the required scale and capacity required to handle the large traffic volumes generated by DDoS attacks or an uneven traffic distribution might cause single sites to collapse [22]. Manipulation of anycast deployments is currently done manually and is not always effective. A more sophisticated and thought out way of reconfiguring the anycast in the event of a DDoS attack is therefore necessary.

2.2 IP-anycast

IP-anycast is a form of IP-addressing, where one IP-address is reachable on multiple locations on the Internet and refers to multiple different hosts. As opposed to commonly used unicast IP-addresses which only belong to one host. Each location on which the anycast IP address can be reached is called an anycast site or instance, and may consists of one or a group of servers. Users who try to reach the anycast IP address are routed to the topologically "closest" instance as determined by the Border Gateway Protocol (BGP), the global routing system. The subset of users who reach a particular anycast instance is called that instance's catchment. The anycast IP address is also referred to as the anycast prefix, because most networks in the Internet do not propagate BGP announcements of a single IP-address but only accept announcements of IP subnets covered by a /24 prefix or larger. Anycast instances can be a *global*, their presence is announced to the whole Internet, or *local*, their announcement in BGP contains the so called **no-export** attribute, and only visible in the local and/or neighboring ASes.

Since the routing system, BGP, determines which instance traffic from each network reaches, anycast catchment for a service is largely dependent on the workings of BGP. BGP routes traffic from one network, an Autonomous System in BGP terms, to their destination based on a shortest path computation. These computations however, are influenced by policy decisions and peering

agreements, making it difficult to get a complete picture of routes from users to anycast instances. This means for example, that a user from one network might not be routed via the topologically shortest path across a certain intermediate network because the user’s network prefers to send its traffic over another intermediate network (or series of networks) resulting in a longer path. Adding to the complexity is the fact that routes in BGP can change frequently, causing the catchment to change over time.

IP-anycast brings several advantages over a traditional single site service. The main advantage is reduced latency caused by localization of traffic [26] [15], although this requires careful configuration and planning and is not automatically provided. Resiliency and scalability are other benefits of using IP-anycast which stem from the replication of the service.

IP-anycast may be unsuitable for services that require state-full sessions such as TCP based services, since in subsequent messages from a client to an anycast service might suddenly be routed to different instances if the routing topology changes in between these messages. This phenomenon is called route flapping, although it appears that this does not occur frequently and only for small subsets of users [11], which means affinity of clients to anycast instances is usually stable. Other drawbacks may include a long failover time due to BGP route convergence if one of the anycast sites fails, but failover times were found to be less than a minute in most cases and might not be very relevant if anycast sites host multiple load-balanced servers.

One example of the use of IP-anycast is in the domain name system (DNS) [22][9]. The DNS protocol is very suitable as it stateless and usually requires only one request message and a response. Out of the 13 root DNS operators (named after the letters A through M), 12 use IP-anycast [4] [9]. Other examples are Content Delivery Networks (CDN) an DDoS mitigation services [12] [1] [27].

2.2.1 Catchment measurement

When analyzing anycast infrastructures one of the most important aspects is discovering the catchment of the anycast infrastructure. Several methods to determine anycast catchment have been used in previous works. The methods to determine the catchment of an anycast service can be roughly divided in two categories: active and passive. Passive methods register all source IP-addresses reaching each site at the site itself. This results in the catchment among all IP-addresses that connected to the anycast service and is almost always incomplete or biased towards the user population of the anycast service. Active methods use some kind of vantage points (VPs) to actively send some message to the anycast prefix and infer the anycast site reached from the response. The catchment among the VP IP-addresses is determined from the combined data from all VPs. The completeness of these kind of methods depends on the number of VPs and their location, but the catchment representation tends to be better as VPs can be selected to represent whole networks and spread evenly across the globe. A variation on these kind of methods use VPs to send probes to the anycast prefix and records source IP-addresses of the probes at each anycast instance.

Catchment measurements have been performed before in various studies, mainly focused on the DNS root servers. Most of these studies [26][16][15] employed DNS CHAOS class queries [33] to identify anycast instances of some

of the root DNS servers from different numbers of vantage points. Some DNS servers are configured according to a common convention to respond to a DNS CHAOS class, TXT type query for the hostname `hostname.bind` or `id.server` with a text record identifying the responding DNS server.

In [26] a combination of four root and TLD DNS servers were evaluated using this method with 400 vantage points from PlanetLab. They targeted four root DNS servers and found that the majority of clients did not reach the closest anycast instance.

PlanetLab vantage points in combination with CHAOS queries were also used in [16] complemented with traceroutes measurements and another set of 64000 Netalyzr vantage points to measure the catchment of F-root and Packet Clearing House anycast services. This study also proposes a different type of DNS query to identify DNS servers to allow catchment measurements with open recursive DNS resolvers, potentially further increasing the number of vantage points.

CHAOS queries were also combined with 7000 RIPE Atlas vantage points in [15] to study four of the DNS root servers. This work focused on major factors influencing the performance of anycast and found that the location and debugging BGP routing of anycast instances was more important for optimal catchments in terms of latency than the number of sites.

Another method to measure the catchment of an anycast service was introduced by [30] and is used in this work. This method involves sending ICMP Echo requests (ping) with the anycast prefix as the source and listening for the responses on the anycast instances. The source IP-addresses of all received responses at each site constitutes the measured catchment for that site. A lot of hosts on the Internet respond to ping requests, allowing measurements with a large number of vantage points. In order to generate a complete picture of the catchments, ping requests are sent to one known responding IP-address of each /24 subnet of the IPv4 address space.

2.2.2 Controlling catchment

Anycast operators have limited options to influence the catchment of anycast instances with BGP. The catchment can be influenced by choosing the upstream AS and making peering agreements. Or by using for example AS-path prepending, artificially increasing the length of the path to a certain instance. These methods however, often have unpredictable results and are applied on a trial-and-error basis [24] [31].

In [11] the effectiveness of AS-path prepending was evaluated using a custom anycast deployment with 20000 vantage points. They found that if multiple anycast instances have the same upstream AS all of them need to use the same level of AS-path prepending to divert traffic away from these servers to instances with other upstream ASes. In their work AS-path prepending did not succeed to manipulate the amount of traffic between sites that use the same upstream provider. Sites with the same upstream provider will need an equal-length AS-path or the site with shortest path will receive all the traffic.

Chapter 3

Methodology & Measurements

To answer the main research question on how to configure anycast deployments for DDoS mitigation we test different anycast deployment scenarios on the anycast testbed and simulate traffic from real DDoS attacks for each scenario.

First we introduce the anycast testbed and how we determine the catchment of the anycast testbed. Next we describe the available DDoS attack data and how they are combined with the catchment data from the anycast testbed. In §3.2.1 we explain which anycast deployment scenarios we use in our measurements and the reasoning behind them.

3.1 Mapping attack traffic to anycast instances

In order to determine the effect of a DDoS attack on a certain anycast deployment configuration we map the attack traffic on anycast instances. We combine the catchment of each instance, which contains a mapping of a large part of the IPv4 address space to instances, with the source IP-addresses found in the DDoS attack data. This results in a share of attack traffic for each instance and allows us to calculate the load on each anycast instance if the DDoS attack would have been directed at the anycast deployment.

3.1.1 Anycast Testbed

The anycast testbed, as introduced by [30], is an anycast service which allows measuring the catchment of each of its instances. The testbed consists of 9 instances, which are shown in Table 3.1.

The testbed can determine the catchment of each of its instances by using ICMP Echo requests and replies ("ping"). When one of the instances sends an ICMP Echo request to a certain IP-address the source IP-address will be the anycast prefix. The response will be addressed to the anycast prefix and will be routed by BGP to the "closest" anycast instance. The closest instance will receive the ICMP Echo response and the source IP-address of the response is determined to belong the catchment of this instance.

To determine the complete catchment of each instance among all IPv4 addresses, each /24 IP-address prefix with a known responding host receives an ICMP Echo request from the anycast testbed. Each anycast instance collects all source IP-addresses from the ICMP Echo responses it receives and all the collected IP-addresses form the catchment for this instance. This method sends ICMP Echo requests to 6.4 million IP-addresses and covers 90% of all ASes.

The testbed can be configured with local and global nodes and nodes can be disabled. AS path-prependings can also be used to change the route to an instance, which makes the route to the instance appear longer to BGP and therefore decreases the chance of the instance being selected as the closest instance. After each configuration change the catchment is determined again to reflect the changes in the configuration.

For a more detailed description of the anycast testbed, see [30].

3.1.2 DDoS Attack data

The DDoS attacks used in this research are captured from so called Booter or Stresser services [25]. These DDoS for hire services can provide large DDoS attacks without requiring any form of technical knowledge on DDoS attacks.

Selecting some of these Booter services to attack a controlled target which captures all the DDoS traffic resulted in a dataset of several DDoS attack captures. The largest of these attacks generated an average attack traffic rate of 5.48 Gbps, while the rest managed to generate around 1 Gbps or below.

3.2 Measurements

The goal of the measurements is to find the best mitigation strategies using AS-path prepending for different combinations of DDoS attacks and anycast deployment scenarios. For each combination we try different AS path-prependings strategies, evaluate the effects and extract the strategies that have a positive effect and possibly refine them.

3.2.1 Anycast deployments

To determine which configuration manipulations are best suited for DDoS mitigation we define several deployment scenarios to simulate on the anycast testbed and evaluate the prepending strategies against. The anycast deployments are defined with the following properties in mind: the goals/policies of the anycast service, the number of anycast sites and the capacity of each site.

The policies of the anycast service can differ per type of service. Some services require maximum availability to all users. Other services require a certain minimum performance possibly at the cost of availability to some users. These policies, which can also be seen as constraints, determine which anycast manipulations are acceptable solutions for DDoS mitigation.

We define two different types of policies for anycast services:

1. Maximum availability for all, users are never discriminated against and the service should be available to as much users as possible

2. Minimum required performance, a certain level of performance is deemed more important than availability to all users

Anycast comes in many different configurations depending on the number of instances, capacity of each instance, local or global BGP configuration and other BGP route adjustments. The configuration variables we use to define our initial deployment configurations are as follows:

1. Number of instances and instance location
2. Capacity per node

The number of instances is limited to the number of anycast sites available in the testbed. The capacity is not however, because the DDoS attacks are not actually executed against the testbed but simulated based on the mapping of source IP-addresses on the catchment of the anycast testbed.

These variables combined determine our initial configuration and function as constraints when we evaluate each mitigation strategy.

Anycast configurations

Here we give a short overview of the different IP-anycast configurations used for evaluation and modeled on the testbed.

Description	Number of sites	Sites
All sites	9	Washington (US) Miami (US) Enschede (NL) Sydney (AU) Paris (FR) Sao Paulo (BR) Copenhagen (DK) Tokyo (JP) London (UK)
Europe	4	Enschede (NL) Paris (FR) Copenhagen (DK) London (UK)
No big 3	6	Miami (US) Enschede (NL) Sydney (AU) Sao Paulo (BR) Copenhagen (DK) Tokyo (JP)

Table 3.1: Anycast testbed configuration used

3.2.2 DDoS attacks

Another aspect to take into account when evaluating the effect of mitigation strategies is the type of DDoS attack. DDoS attacks come in many flavours.

Table 3.2: Overview of the DDoS attacks used

Short name	Full name	Protocol	Nr. of IPs	Nr. of ASes	Date
CONS-NTP-01	Connection-stresser NTP-01	NTP	1200	191	2014-12-22 15:45
CONS-NTP-02	Connection-stresser NTP-02	NTP	1013	187	2014-12-23 23:28
DEJA-DNS	Deja-booter DNS	DNS	2762	803	2013-08-14 23:04
GRIM-DNS	Grim-booter DNS	DNS	66	18	2013-08-14 22:41
IPSTR-SNMP-02	IP-stresser SNMP-02	SNMP	1249	303	2014-12-25 17:38
IPSTR-CHARGEN-02	IP-stresser Chargen-02	Chargen	1487	220	2014-12-25 15:12
IPSTR-NTP-01	IP-stresser NTP-01	NTP	1223	201	2014-12-22 23:12
IPSTR-NTP-02	IP-stresser NTP-02	NTP	1227	194	2014-12-25 15:54
KRYPT-NTP-02	Kryptonic NTP-02	NTP	3025	810	2015-01-06 23:58
REBEL-CHARGEN	Rebel-security Char-gen	Chargen	258	123	2013-08-14 22:09
REST-DNS-01	Restricted DNS-01	DNS	2092	375	2014-12-22 10:05
REST-DNS-02	Restricted DNS-02	DNS	1089	240	2014-12-25 19:09

They differ in the types of protocols used, amplification techniques used (or not used), number of attack sources and their location. Since we are only interested in the volume of traffic the attacks would generate for instances of an anycast service, we define two types of attacks:

1. Many different locations with (roughly) evenly distributed traffic
2. Fewer locations, with a significant amount of traffic originating from a single location or area

Most attacks use some kind of amplification to achieve a greater attack traffic volume. With this type of attack, the source of the traffic, as observed from the target, becomes the point where the traffic is amplified. We consider these amplification points, such as open DNS resolvers, as the sources of attack in our scenarios, because there is often no easy way to find the real sources of the attack traffic. Another reason is that the real origin of the traffic does not matter for mitigation at the target, since the traffic originates from the amplification points from the perspective of the target.

All DDoS attacks taken into account are real DDoS attacks from previous captures, so the distribution of traffic over the different anycast sites is realistic. The DDoS attacks used are listed in [Table 3.2](#) and are all reflected DDoS attacks and therefore do not have spoofed source-IPs from the targets point of view.

3.3 Prepending strategies

In order to evaluate the effects of AS-prepend for DDoS mitigation, we have to define certain goals that the prepending should aim to achieve. Whether AS-path prepending yields a positive result for DDoS mitigation largely depends on how effective AS-path prepending is in redistributing attack traffic over the anycast sites and on the specific properties of the anycast service. An example can be an anycast service which sees a large spike of DDoS traffic at one site which is successfully redistributed to two other sites using AS-path prepending. If these two other sites together have a smaller capacity than the site previously

under attack, then the end result would not have been positive for the anycast service. If it were the other way around it would be. Furthermore, anycast service specific properties such as the server capacity and network bandwidth per site will vary per deployment and over time. Therefore we will not take into account anycast service specific parameters, but instead focus on the ability of AS-path prepending to effectively redistribute attack traffic.

To evaluate whether AS-path prepending can be used to redistribute attack traffic we developed three strategies which each define a goal as to how the attack traffic should be redistributed. Each strategy is applied with different combinations of testbed configuration and DDoS attack. The AS-path prepending strategies used are described in the following subsections.

3.3.1 Vacuum cleaner

Goal This strategy aims to divert all attack traffic to one of the anycast sites, ideally with minimal impact on non-attack traffic.

How Path prepend all sites except the blackhole site until most of the attack traffic reaches the blackhole site.

Situation/conditions Works best if the DDoS traffic mainly comes from one topological location and the blackhole site has additional anti-DDoS measures such as a scrubbing service in place to further mitigate the attack.

Benefits Further mitigation efforts can be focused on one anycast sites while the other sites remain in normal operation. Clients routed to the remaining sites are not affected by the DDoS attack

Downsides Clients from the same network as the attack traffic will be routed to the blackhole site and will experience degraded or no service.

3.3.2 Redistribute to large sites/ Save the children

Goal Take the load of small sites that cannot handle the load the DDoS attack traffic by redistributing the attack traffic to the larger capacity sites in the anycast deployment until the larger capacity sites are at capacity.

How Path prepend all smaller sites until either the smaller sites can handle the traffic load or the larger sites are at capacity.

Situation/conditions DDoS attack has many topologically spread out source locations. Larger sites have sufficiently more capacity than smaller ones.

Benefits The capacity of the anycast deployment is used efficiently to handle the load of attack traffic.

Downsides Does not work if the attack traffic volume is larger than the total capacity of the anycast deployment.

3.3.3 Dynamic redistribution/ Breakwaters

Goal Distribute all attack traffic from nodes that are overloaded by the DDoS traffic to sites with spare capacity. Traffic can also be offloaded from the sites over capacity without redirecting to a specific instance.

How Path-prepend all sites that receive a larger traffic share than they can handle at the same time in steps until the traffic share for all of them becomes smaller.

Situation/conditions DDoS attack traffic has topologically distributed source locations. Does not work if the total capacity is smaller than the total attack volume.

Benefits Most efficient way of traffic redistribution. Prevents one site from absorbing all attack traffic (which means this site does not need the capacity to do so)

Downsides Requires constant updates on the load per instance. Depends heavily on the actual DDoS traffic and is hard to generalize. Traffic from one overloaded site may end up tipping other sites over the edge and overload them as well.

3.4 Prepending method

AS-path prepending increases the AS-path length as seen by routers in the Internet for a particular site. When a router has to choose between two routes to the same site, it will choose the shortest path unless overridden by explicit configuration. Since all sites share the same IP-address and are the same destination for a router, a site with a longer path is less likely to be chosen as the path to the IP-address for the anycast service and is expected to receive less traffic. For each prepending strategy/testbed configuration/DDoS attack combination, prepending will be applied in an iterative manner to achieve the desired result (e.g. redistribute traffic from attack X to all sites equally). In each iteration the sites that should receive less traffic according to the current goal are prepended at most once. An exception to this rule can be made when one site continues to receive unwanted traffic after several iterations of prepending and in this case only that site will be prepended multiple times. After each iteration the effect on the catchment is measured and the DDoS attack under investigation is mapped onto the catchment to evaluate the effects on the normal (as defined by the catchment) and attack traffic. The prepending iterations continue until either the goal of the prepending strategy is achieved or the results of the mapping show no positive change in the catchment or mapping (e.g. the catchment does not change anymore or traffic bounces forth between two sites).

Chapter 4

Results

In this chapter we present and discuss our findings on path-prepend strategies under different conditions. We first look at what we call the *vacuum cleaner* strategy (§4.1), in which (attack) traffic is shifted to a single anycast site. We then move to the *save the children* strategy (§4.2), where the goal is to spare the low-resource, low-capacity sites from receiving large amounts of (attack) traffic. And finally, we look at *dynamic redistribution* strategy (§4.3), focused on redistributing (attack) traffic equally across the anycast deployment.

4.1 Vacuum cleaner

The first evaluated prepending strategy is the vacuum cleaner. This strategy aims at creating a blackhole site to which all attack traffic, and ideally *only* attack traffic, is redirected. The blackhole site should preferably be a site which, *a)* can handle large traffic volumes, *b)* is equipped to deal with DDoS traffic using some form of mitigation and *c)* is the only site that possesses the previously listed properties, because it does not make sense to move traffic around otherwise. Which sites are suitable to receive the attack traffic also heavily depends on the anycast operators and the specific characteristic of each site (agreements with upstream providers etc.) The anycast testbed does not have DDoS protection and none of the sites has special properties or more capacity than another site and generally does not receive much traffic at all. Therefore we chose the blackhole site at random.

We validated different scenarios, varying the blackhole site, anycast configurations and DDoS attacks. The blackhole sites vary across anycast configurations because in some configurations a previously chosen blackhole is not included. The attacks were chosen based on the traffic distribution without any path prepending per anycast configuration and blackhole combination. In §4.1.1 and §4.1.1 we use a global anycast configuration with Washington and London as blackhole sites respectively. In §4.1.2 we use the anycast configuration with European sites only, with Copenhagen and Paris as blackhole sites. And in §4.1.3 we configure the anycast testbed without the 3 big sites and Copenhagen as the blackhole.

Attacks used in this validation.

The attack selection only took into account whether not all attack traffic was already sent to the blackhole site.

- Deja-booter DNS
- Grim-booter DNS
- Rebel-security Chargen
- Restricted DNS-01
- IP-stresser SNMP-02
- IP-stresser Chargen-02
- IP-stresser NTP-02

See [Table 3.2](#) for more details on the attacks.

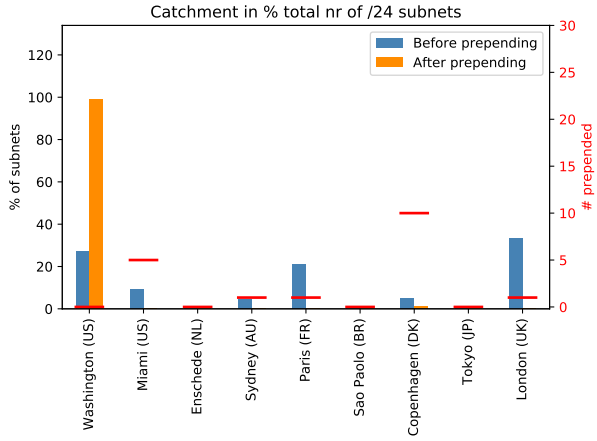
4.1.1.1 Measurements with global anycast configuration

All measurements in this section were performed using the global anycast configuration with all 9 available sites enabled.

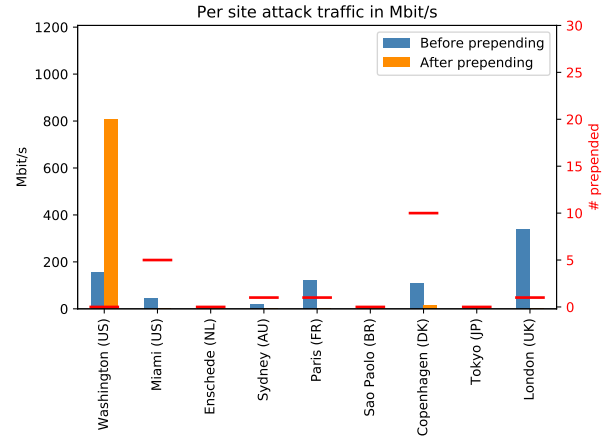
Washington blackhole

We applied this prepending strategy with the Deja-booter and Grim-booter DDoS attacks as a starting point. Each of these attacks have a different distribution of traffic sources, from wide-spread globally to localized. The Deja-booter attack's traffic is very much distributed around the world and the initial mapping of the traffic onto the catchment reflects that, as shown in [Figure 4.1a](#). The blue columns show the percentage of subnets going the each site before the prepending attempt and the orange columns after. The red bars show the amount of prepending applied after all the last iteration of the prepending attempt. In the scenario all sites are active and the goal is to move all traffic to one large site for scrubbing or other purposes, in this case the site chosen was the one in Washington, US (US-WAS). The Grim-booter attack traffic mainly targets the Miami site when the catchment is measured without any prepending.

In the Dejabooter case, the goal was achieved fairly easy, and all attack traffic was routed to the Washington site as can be seen in [Figure 4.1b](#). The catchment, however, as seen in the orange columns of [Figure 4.1a](#) went along with it, resulting in a blackhole that does not only absorb all attack traffic but nearly all legitimate traffic as well. Prepending for the Grim-booter attack shows similar results and similar effect on the catchment ([Figure 4.2](#)). An important difference between the Grim-booter attack and the Deja-booter attack is the number of attacker IP-addresses (50 vs. 2000). One might expect that when the prepending targets this small set of subnets from the Grim-booter attack, the attack traffic is shifted to the blackhole site with a relatively low amount of prepending and without a large change to the catchment. But even with a relatively low amount of prepending the effect on the global catchment was high. So although the attacks used were quite different the results and the effects on the catchment are the same in this case.



(a) Catchment of the anycast testbed before and after prepending



(b) Mapping of attack traffic on anycast testbed before and after prepending

Figure 4.1: Catchment and traffic mapping before and after prepending for the Deja-booter attack on the global anycast configuration

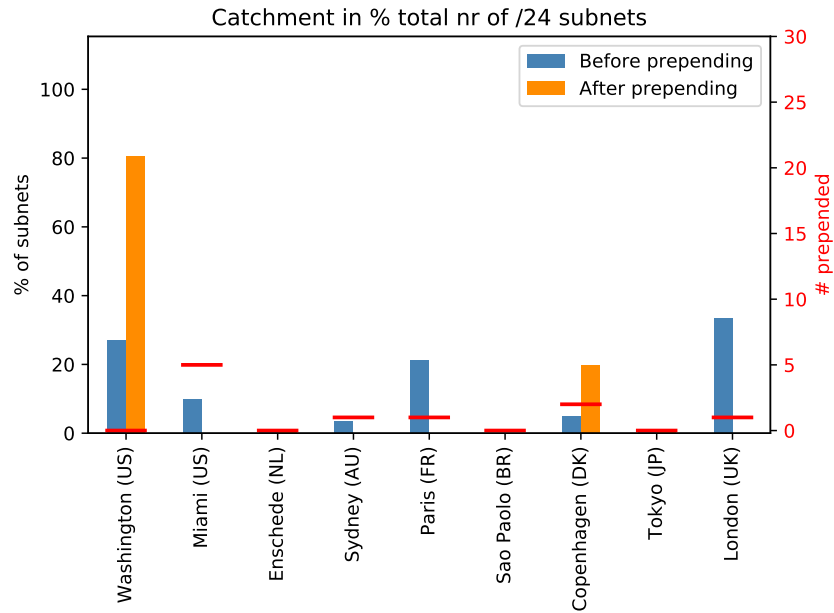


Figure 4.2: Catchment of the anycast testbed before and after prepending for the Grim-booter attack on the global anycast configuration

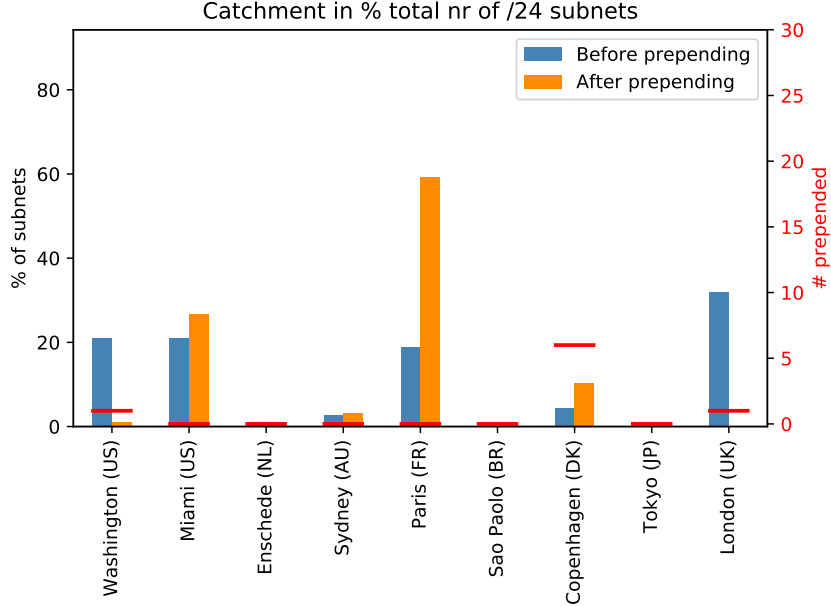


Figure 4.3: Catchment before and after prepending for the Vacuum strategy on the global anycast configuration with the IP-stresser SNMP-02 attack

London, Copenhagen and Paris blackhole

Switching to a different blackhole site and suitable DDoS attacks yielded the same results. We applied the strategy with the London site as the blackhole site and Rebel-stresser as the attack, Copenhagen as blackhole and the Restricted DNS-01 attack and Paris as blackhole combined with the Restricted DNS-01 and IP-stresser SNMP-02 attacks. The goal of the prepending strategy, moving all attack to the blackhole site is achieved in all 4 cases. The original catchment however, is also disturbed and moved almost completely to the blackhole site. The only case which showed a slightly different result was Paris as a blackhole with the IP-stresser SNMP-02 attack. The global catchment seems to be less affected with this combination, because 4 out of 6 sites still have the same share of the catchment after prepending, as can be seen when comparing the blue and orange columns in figure [Figure 4.3](#).

4.1.2 European anycast configuration: Copenhagen and Paris blackhole

All measurements in this section used the anycast testbed configured with only sites in Europe enabled. In this configuration we performed the prepending strategy with both Copenhagen as the blackhole site combined with the Restricted DNS-01 and IP-stresser CHARGEN-02 attacks, as well as Paris as the blackhole site combined with the Restricted DNS-01 and IP-stresser NTP-02 attacks. Two attempts, Copenhagen with IPSTR-CHARGEN-02 and Paris with IPSTR-NTP-02, failed, The combination Copenhagen and IPSTR-CHARGEN-

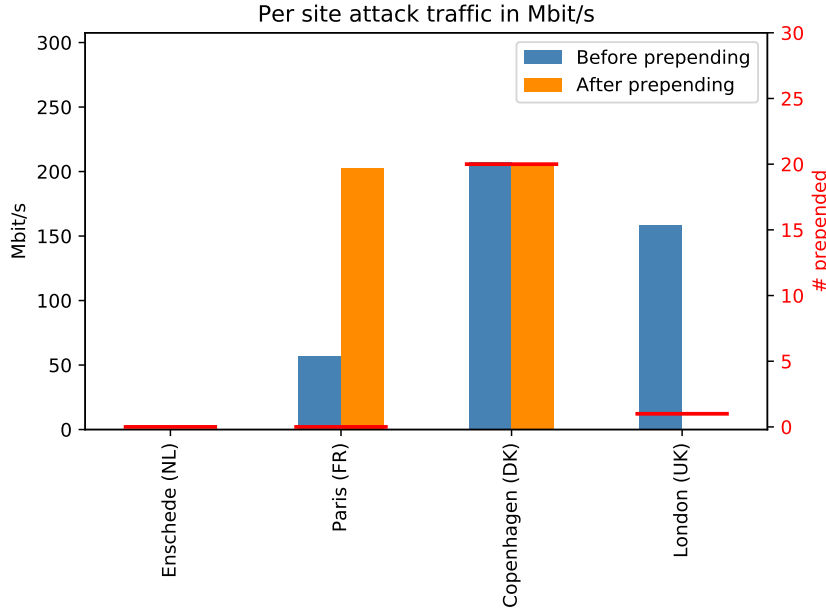


Figure 4.4: Mapping of attack traffic on the testbed before and after prepending for the Vacuum strategy on the European anycast configuration with the IP-stresser NTP-02 attack

02 failed due to missing attack traffic after prepending which could not be explained. In the case of the IPSTR-NTP-02 attack with Paris as the black-hole, the attack traffic could not be moved away from the Copenhagen site towards the Paris site, even after prepending the Copenhagen site 20 times (see Figure 4.4).

When looking into this specific attack we see in Figure 4.5 the attack traffic is unequally distributed over the ASes that were part of the attack. This leads us to speculate that one of these ASes responsible for a large part of the attack traffic sent traffic to the Copenhagen instance because of for instance a routing policy or other factor which could not be influenced by AS-path prepending.

4.1.3 No big 3 anycast configuration: Copenhagen black-hole

The measurement in this section were performed on the testbed without the largest sites enabled in terms of catchment. We applied the vacuum cleaner strategy successfully with Copenhagen as blackhole site with the Restricted DNS-01 attack, with the same adverse effects as in the attempts discussed in the previous sections. Other attacks could not be easily paired with Copenhagen(or other sites) as a blackhole site in this anycast testbed configuration because in most cases either the mapping failed or the attacks already sent all traffic to the blackhole site.

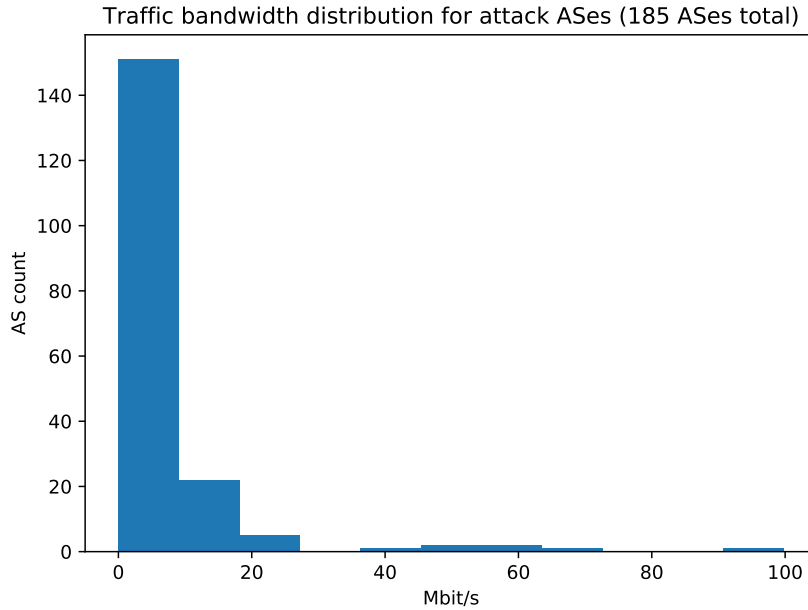


Figure 4.5: Attack traffic distribution over ASes for the Vacuum strategy on the European anycast configuration with the IP-stresser NTP-02 attack

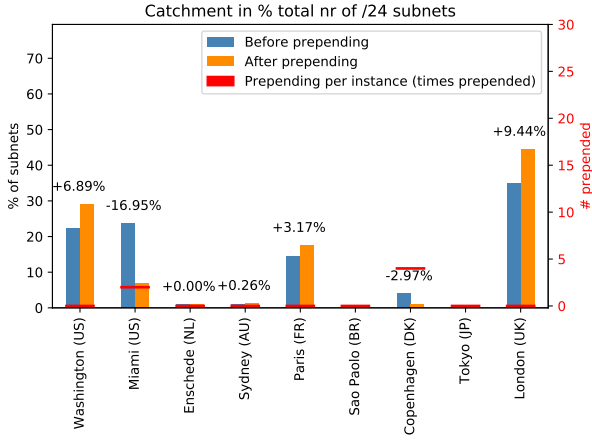
4.1.4 Summary

The overall results for the vacuum cleaner strategy show that attack traffic can be diverted to one specific site successfully with different target blackhole sites, anycast site configurations and attacks. The main downside of this strategy is the disruption of the catchment of the anycast service, most likely causing all legitimate traffic to shift to the blackhole site as well. In this case, disabling all sites would but the blackhole site would yield the same result quicker. Other disadvantages can include the potential overloading of the blackhole site or the collateral damage caused at the site were the blackhole is hosted. Despite these disadvantages this strategy can still be useful in an anycast configuration with one main large site with almost all of the server capacity/bandwidth and many smaller sites.

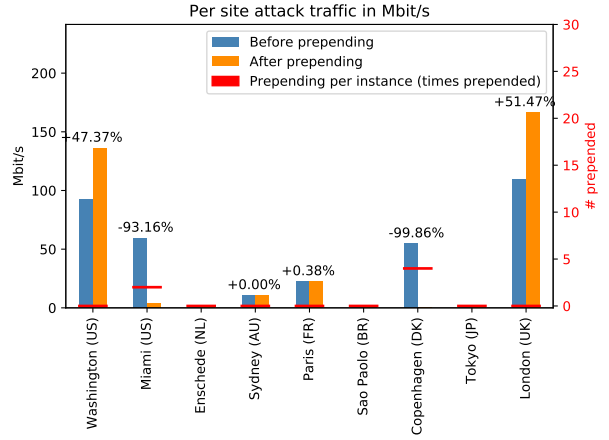
All omitted prepending results for the different combinations of blackhole sites and DDoS attacks can be found in [Appendix A](#).

4.2 Save the children

This prepending strategy focused on diverting traffic from certain instances designated as “smaller” to “large” instances. In our work the selection of larger and smaller instances is arbitrary and under normal circumstances would depend on the actual capacity of the anycast site and/or its operational practices and policies.



(a) Catchment of the anycast testbed before and after prepending



(b) Mapping of attack traffic on anycast testbed before and after prepending

Figure 4.6: Catchment and mapping of attack traffic from the IP Stresser NTP-01 attack on the global anycast testbed configuration before and after prepending for the Save the children strategy

Attacks used in this validation

For the tests we selected combinations of anycast configurations and DDoS attacks where the DDoS traffic would not already select the larger sites, since in those situations the goal is already achieved without any prepending.

- Connection-stresser NTP-01
- IP-stresser NTP-01
- Restricted DNS-02
- Connection-stresser NTP-02
- IP-stresser NTP-02

See [Table 3.2](#) for more details on the attacks.

4.2.1 Measurement with a global anycast configuration

In the first set of measurements we used an anycast configuration with all 9 sites and the 3 sites with the largest catchment (London, Paris, Washington) were also designated as the largest sites; this follows the scenarios we see in real world deployments, where higher capacity sites are typically those there most of the traffic goes (either legitimate or attack traffic). We performed prepending on this configuration to attempt redistributing traffic from three DDoS attacks, two NTP-based attacks from Connection-stresser and IP-stresser and one DNS based attack from Restricted-stresser. All of these attacks send a share of their traffic to the designated smaller sites in Miami and Copenhagen.

After 4 iterations of prepending we see in [Figure 4.6b](#) that for the IP-stresser attack the majority of DDoS traffic moved from Copenhagen and Miami to Washington and London. The results for Connection-stresser and Restricted-stresser attacks are the same, except for a higher amount of prepending needed at the Miami site for the Restricted-stresser attack. So the goal of moving the attack traffic away from the smaller sites has been achieved.

The difference in the catchment for the IP-stresser attack before and after the prepending is shown in [Figure 4.6a](#). The Miami site loses more than half of the subnets in its catchment, as does the Copenhagen site. Some of the smaller variations in the catchment are caused by a different number of responding sites for each catchment measurements. The large change in catchment at the Miami site however, is caused by the prepending.

The difference in catchment before and after prepending for the Connection-stresser attack are very similar. The catchment after prepending for the Restricted-stresser did not have any subnets in the catchment for the Miami and Copenhagen sites. In this case disabling the Copenhagen and Miami sites would have had the same effect as prepending.

When comparing the catchment changes for all subnets versus subnets that send attack traffic, we can see in [Figure 4.7](#) that attacker subnets were not targeted specifically by the path prepending. Only in one case, the Restricted stresser traffic at the Copenhagen site, did the attack subnets shift significantly more than the other traffic. Because in all cases the attack traffic did shift away from the prepended sites, the prepending caused the relatively small amount of subnets that generated the most attack traffic to shift away from these sites. This also means that the collateral damage of the path prepending in these specific three cases is low in terms of total non-attacker subnets shifted, but can be expected to be higher in general because attacker subnets shift away from sites at the same rate as normal sites. Compared to other prepending strategies the impact on the catchment for normal users is relatively low, because the aim is to divert traffic away from smaller sites in terms of user traffic.

4.2.2 Measurement with Europe based anycast configuration

We applied the the same strategy with an anycast configuration which only has sites in Europe (Enschede, Paris, Denmark, and London). The Paris and London sites where designated as the larger sites, since they normally have the largest catchment and therefore are expected to receive most of the traffic. We applied the strategy with two NTP based DDoS attacks, from IP- and Connections-stresser, which direct a larger share of their traffic to the Enschede and Copenhagen sites under normal circumstances.

As can be seen in [Figure 4.8a](#) the prepending strategy did not work with this testbed configuration. Even after prepending the Copenhagen site 20 times the traffic did not move to either Paris or London which was the goal. When comparing the number of attack subnets and normal subnets that shifted (or did not), moving any traffic away from Copenhagen was impossible and not just attack traffic (see [Figure 4.8b](#)). This suggests that, for example, either the path to Copenhagen was somehow favored by the subnets in its catchment, possibly due to overriding the path length propagated by the instance (filtering) or the Copenhagen site's AS lying on the path to the other instances.

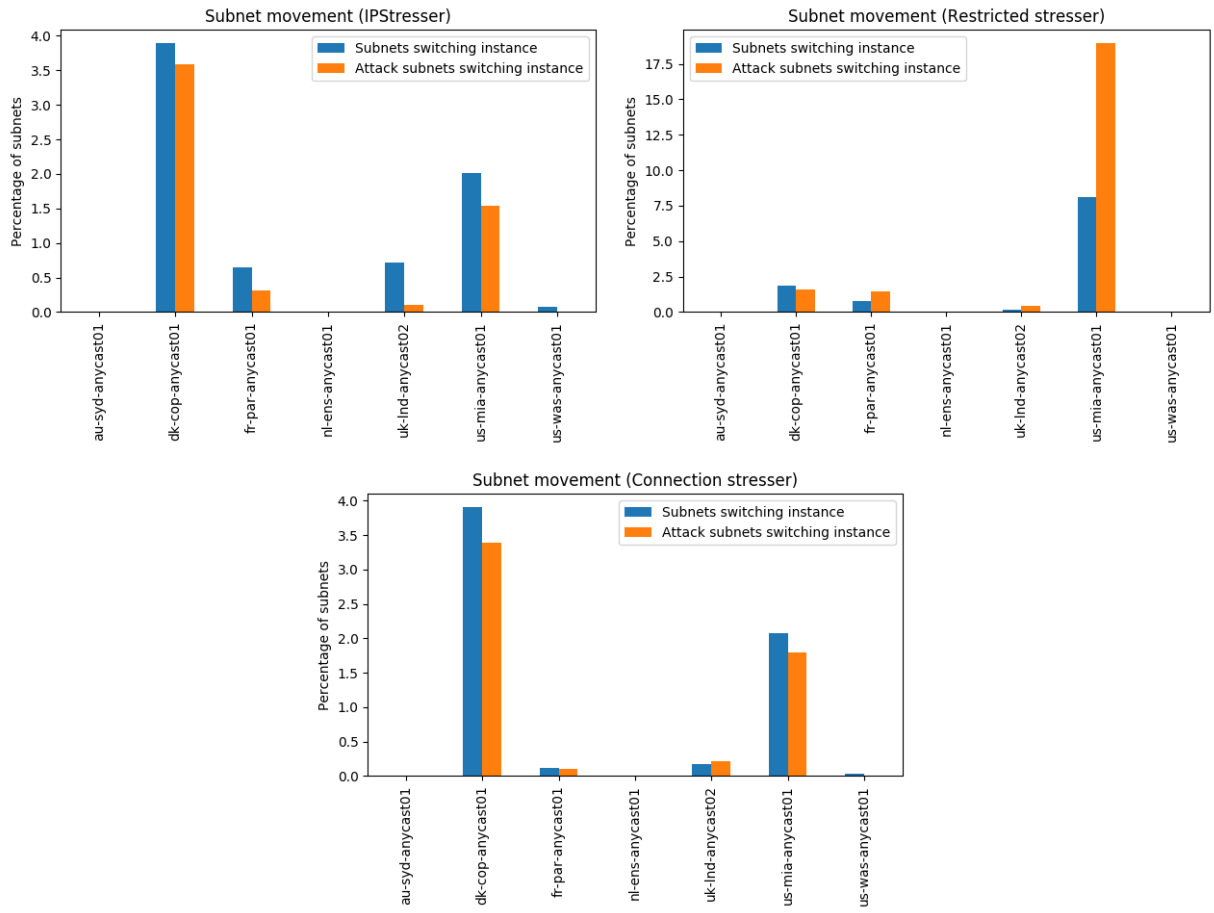
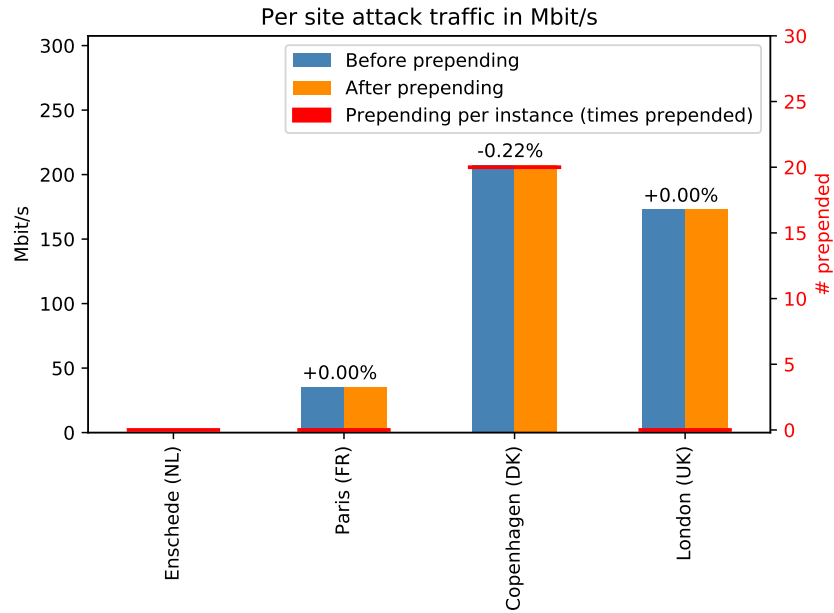
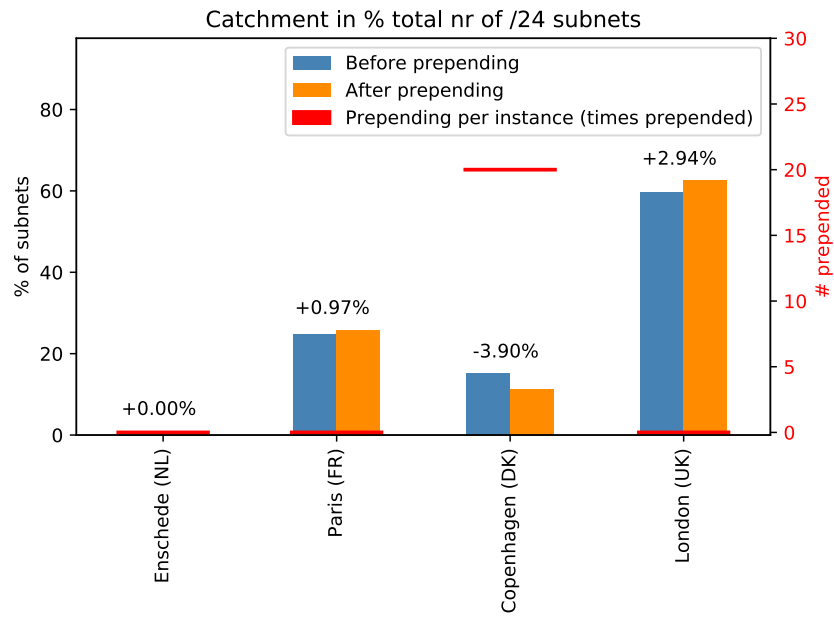


Figure 4.7: Relative shift of all subnets after prepending per instance and for attack subnets with the Save the Children strategy (IP-, Restricted- and Connection stresser attacks)



(a) Mapping of attack traffic on European testbed configuration before and after prepending



(b) Catchment of the European testbed configuration before and after prepending

Figure 4.8: Catchment and mapping of attack traffic on anycast testbed in Europe based configuration before and after prepending for the IP Stresser NTP-02 attack

4.3 Dynamic redistribution

The dynamic distribution strategy is focused on redistributing DDoS traffic as equally as possible among all available anycast sites through the use of prepending. The sites that should be prepended depend on the initial attack traffic distribution and on the total volume of attack traffic. The goal is that any large peak of attack traffic that was visible before the strategy took place, is no longer present and the attack traffic is “more equally” distributed across the anycast sites. As with the other strategies normal traffic, i.e. the original catchment should be disturbed as little as possible.

Attacks used in this validation

The selected DDoS attacks for the measurements all showed large traffic peaks at at least one of the sites.

- Connection-stresser NTP-01
- IP-stresser SNMP-02
- Restricted DNS-01
- IP-stresser Chargen-02
- Kryptonic NTP-02

See [Table 3.2](#) for more details on the attacks.

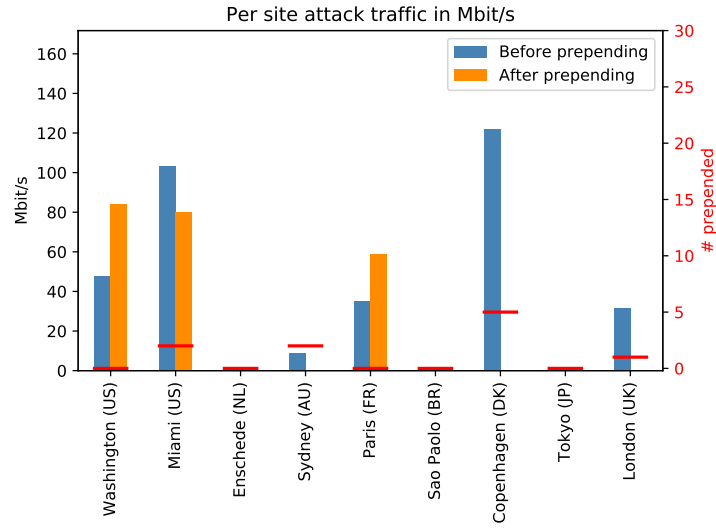
4.3.1 Measurements with global anycast configuration

The first testbed configuration tested had all sites enabled. For all three different DDoS attacks the prepending strategy failed. The attempts to remove attack peaks from sites by prepending them did not cause the traffic to split up and distribute to other sites, instead the traffic moved around as a whole to another site. Examples of this behaviour can be seen in [Figure 4.9a](#) and [Figure 4.9b](#), where a blue column at one site representing attack traffic before prepending, shows up as an orange column at another site representing traffic after prepending. Sometimes the traffic moved from one site to another and back again after a new iteration and the end results sometimes even show more large peaks than in the starting situation, as shown in [Figure 4.9c](#).

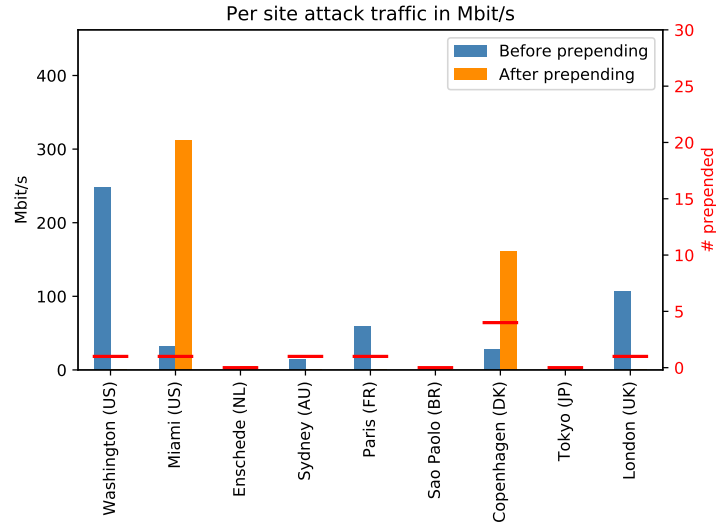
Looking at the attack traffic distribution per ASN in [Figure 4.10](#) we can see that there is one ASN that is responsible for a relatively large peak of around 100 Mbit/s. Prepending could never redistribute this traffic because path prepending works on the AS level. This peak however, does at most represent 1/4th of the total attack traffic and is therefore not an explanation as to why the rest of the traffic could not be redistributed equally across all sites.

4.3.2 Measurements with Europe based and without 3 largest site configurations

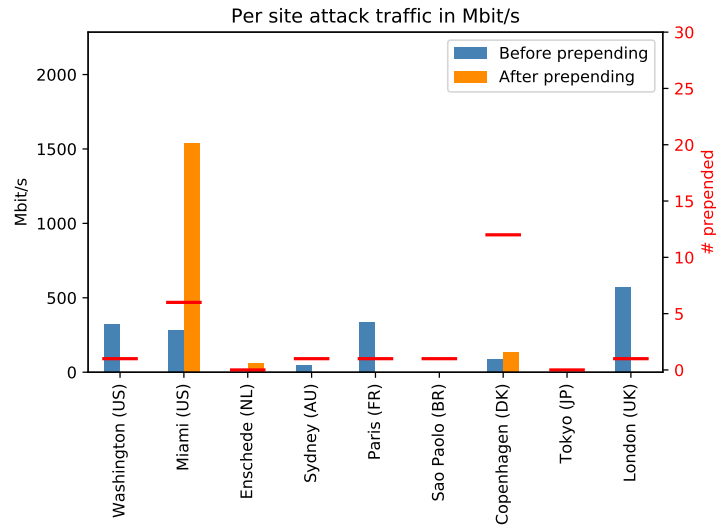
Changing the anycast configuration to an Europe-based set-up, or without the 3 largest sites (Washington, Paris and London) did not yield different results



(a) Mapping of attack traffic on global testbed configuration before and after prepending (Connection stresser NTP-01)



(b) Mapping of attack traffic on global testbed configuration before and after prepending (IP-stresser SNMP-02)



(c) Mapping of attack traffic on global testbed configuration before and after prepending (Restricted DNS-01)

Figure 4.9: Mapping of attack traffic on global testbed configuration after applying the Dynamic Redistribution strategy for 3 attacks.

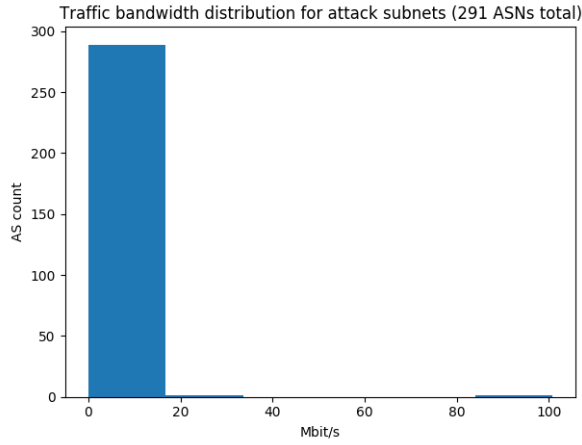
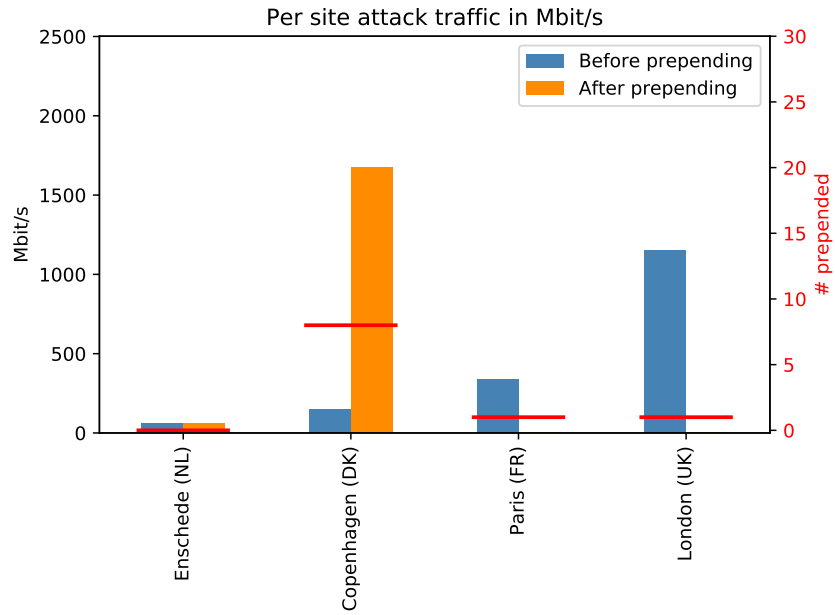


Figure 4.10: AS attack traffic distribution for the IP-stresser SNMP-02 attack (all sites enabled)

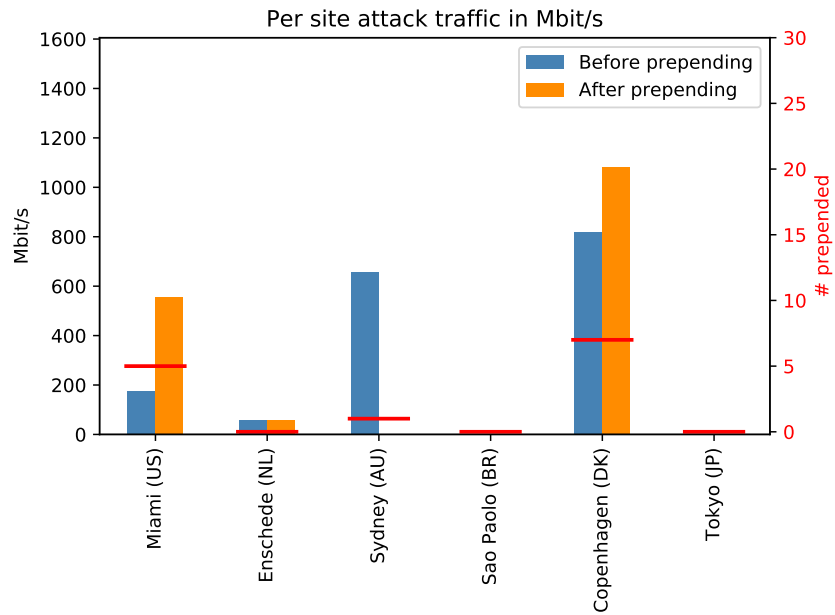
for this prepending strategy. [Figure 4.11a](#) and [Figure 4.11b](#) show the result for prepending with the Restricted DNS based DDoS attack for both different testbed configurations. Both attempts failed to redistribute the traffic evenly across all sites.

4.4 Summary

An overview of the measurements performed is given in [Table 4.1](#). The overall success rate is around fifty percent, which is by most standards too low. A measurement was marked successful if the primary goal of the prepending was achieved and unwanted side effects were not taken into account. When these side effects are taken into account, the value of the 50% success cases is lowered even further as sometimes the catchment was disturbed so much the normal traffic would be shifted around unacceptably. Taking a closer look at the individual prepending strategies, the vacuum cleaner is the winner among the three, while the dynamic redistribution strategy was the least successful. The vacuum cleaner strategy however, also showed the most disturbance to the catchment, which makes the save the children strategy a closer second than might appear from the table.



(a) Mapping of attack traffic on Europe based testbed configuration before and after prepending



(b) Mapping of attack traffic on testbed configuration without 3 largest sites before and after prepending (Restricted DNS-01)

Figure 4.11: Mapping of attack traffic from the Restricted DNS-01 attack before and after prepending on the global and European anycast configuration for Dynamic Redistribution strategy

Table 4.1: Overview of the measurements performed

Strategy	Testbed config	DDoS attack	Success?	Iterations	Max prepend count
Vacuum Cleaner (§4.1)	All	Deja-booter (Washington blackhole)	Yes	7	10
		Grim-booter (Washington blackhole)	Yes	6	5
		Rebel (London blackhole)	Yes	7	7
		Restricted DNS-01 (Copenhagen blackhole)	Yes	3	3
		Restricted DNS-01 (Paris blackhole)	Yes	5	5
		IP-stresser SNMP-02 (Paris blackhole)	Yes	7	6
	Europe	Restricted DNS-01 (Copenhagen blackhole)	Yes	1	1
		Restricted DNS-01 (Paris blackhole)	Yes	4	4
		IP-stresser Chargen-02 (Copenhagen blackhole)	(mapping error)	1	1
		IP-stresser NTP-02 (Paris blackhole)	No	7	20
	No big 3	Restricted DNS-01 (Copenhagen blackhole)	Yes	4	4
Save the children (§4.2)	All	Connection NTP-01	Yes	4	4
		IP-stresser NTP-01	Yes	4	4
		Restricted DNS-02	Yes	5	5
	Europe	Connection NTP-02	No	10	10
		IP-stresser NTP-02	No	5	20
Dynamic redistribution (§4.3)	All	Connection NTP-01	No	5	5
		IP-stresser SNMP-02	No	8	4
		Restricted DNS-01	No	12	12
	Europe	Restricted DNS-01	No	6	8
		IP-stresser CHARGEN-02			
	Without big 3	Connection NTP-01	No	12	12
		Kryptonic NTP-02	No	2	2
		Restricted DNS-01	No	7	7

Chapter 5

Discussion & Conclusion

5.1 Discussion

In this section, based on our methodology and results from previous chapters we make considerations related to pros and cons of proposed strategies for using anycast against DDoS (§5.1.1); reliability of proposed approaches (§5.1.2); ethics on shifting traffic by means of anycast manipulation (§5.1.3); and finally the effectiveness of proposed strategies (§5.1.4).

5.1.1 Side effects, collateral damage and precision

The main goal of applying prepending is to reroute DDoS traffic while minimizing the impact on normal traffic. In the results from the previous section we see that the main goal is often achieved but the impact on normal traffic, .i.e. the global catchment, is high. The results for the vacuum cleaner strategy show this most clearly. After prepending the catchment of the blackhole site includes nearly all subnets, effectively disabling all other sites for both attack traffic and normal sites. The problem here is that, although the blackhole site might be able to handle all traffic and employ anti DDoS measures such as scrubbing etc., the same could be achieved by simply disabling all other sites except for the blackhole. Prepending does not have much additional value, except that the other sites remain available to local clients.

The other prepending strategies do not perform much better in this regard. As discussed in §4.2.1, Figure 4.7, the rate at which subnets sending attack traffic switch site in response to prepending is lower on average than that of a normal subnet which does not send any attack traffic. This means that for every attack subnet that switches site because of prepending at least one other subnet is also expected to switch site, which is not in line with the goals of the prepending strategies and means the collateral damage to the catchment is high.

The main cause for the high collateral damage among prepending measurements is a lack of precision. The DDoS attacks used in the experiments send traffic from around 1000 subnets or more from around the world. Prepending targets ASes, and when only one subnet from an AS sends attack traffic, the amount of normal subnets that switch site along with the attack traffic is high when the AS is moved site after a successful prepending step. Furthermore,

prepending never targets only the ASes that send attack traffic, because when the AS path length to one site increases enough for the attacker AS (AS sending attack traffic) to switch site, this will happen for many normal ASes at that same level of prepending as well. So in two different ways the prepending strategies do not have enough precision to target attack traffic from the evaluated DDoS attacks to limit the collateral damage to a level that most operators would deem acceptable.

5.1.2 Reliability

Prepending sites to reroute traffic proved to be rather unpredictable. One example are the results with a European testbed configuration when applying the "Save the Children" strategy, where after prepending the Copenhagen site 20 times the catchment for this site would not change. In other occasions the catchment also appeared to be "stuck" at one site, where simply applying more prepending to this site did not further decrease the size of its catchment noticeably.

Another frequently occurring event is site catchments jumping from one site to another (usually a site which does not normally receive a large share of traffic) in subsequent iterations of prepending. So before the end goal of the prepending is reached, these catchment jump from one site to the other and back might negatively impact the reachability or stability of the anycast service during the process of iteratively prepending.

A final aspect covering the reliability of prepending for DDoS mitigation is the varying number of iterations needed when prepending. The number of prepending iterations necessary to get to the same result for different DDoS attacks varies from 4 to 8 iterations with outliers for (partially) failed attempts. In the experiments the longest prepending attempt had 12 iterations after which prepending the same site no longer seemed to have any effect, as might be expected as this site probably had a longer AS-path than any other conceivable path to the same prefix. In this case stopping the process was based on a straightforward decision (prepending was expected to not have any effect anymore), but in some cases after twelve iterations the longest amount of prepending might still be in the range of what is considered normal and then this decision becomes harder.

5.1.3 Ethics

While moving around DDoS traffic can be beneficial for an anycast service in some way or another, other network service providers might not be prepared to deal with a sudden increase in DDoS traffic. Moving DDoS traffic to another site might cause serious problems for a transit provider now suddenly in the path of large amounts of DDoS traffic caused by for instance blackholing all DDoS traffic from a large attack to one site. On the one hand the anycast service operator might directly cause problems for other network providers. On the other hand the DDoS traffic is caused by a malicious third party over which the anycast operator has no control. Usually intermediate transit providers have more network capacity than the anycast operator and will take measures to protect themselves. Nonetheless, caution is still advised when redirecting exceptionally large amounts of DDoS traffic around through prepending.

5.1.4 Effectiveness

For all prepending strategies, the primary goal, i.e. moving the DDoS traffic to a predefined site, was reached in 12 out of 24 cases. This means that for most prepending strategies the success rate was not very high. Moreover, even when the goals are achieved the collateral damage in terms of legitimate traffic shifted and large catchment changes is medium to high in all cases. Other side effects also have to be taken into account when considering prepending, such as seemingly random shifts of traffic among sites. The amount of iterations of prepending it took to reach the predefined goals also varied, meaning that the time needed to apply a prepending strategy is also uncertain and might be quite long if applying the same step by step algorithm as used here. Time is an important factor when considering the effectiveness of AS-path prepending as a first-line defense system, because it is supposed to be a quick defense against the effects of a DDoS attack until actual mitigation of the DDoS traffic can be started. All these factors combined suggest that the effectiveness of AS-path prepending is not very high as a first-line DDoS defense system.

5.2 Challenges & Future work

In this section we outline the challenges and possible future work related to our methodology and approaches.

5.2.1 Mapping method

The technique used to map DDoS traffic on anycast sites can be improved in several ways. The catchment of the anycast testbed was measured using the method as described in [30]. Measuring the catchment using this method yields a good but not complete picture of the anycast testbeds catchment. Not every IPv4 subnet has a responding host to answer pings and the number of responding hosts from the known responding hosts varies. Therefore, when mapping DDoS attack traffic on sites, some traffic will not be mapped because the catchment picture is not complete. The mapping percentage of DDoS traffic is on average around 90 % and this is usually sufficient to give an accurate view of the amount of attack traffic each site would receive from the DDoS traffic.

There is a chance however that some of the attack traffic that could not be mapped due to an incomplete catchment measurement contains a disproportionate share of the attack traffic in which case the calculated mapping of DDoS attack traffic might be less accurate than desired. Furthermore, IP version 6 traffic is excluded as a whole, since it is unfeasible to find a host in a small enough subnet responding to pings in a significant share of the huge IPv6 address space. Therefore, although we believe the current method for determining catchment is the best currently available and sufficient for showing the impact of almost entirely IPv4 based DDoS traffic on an anycast service, it is still a challenge to find a better catchment measurement method, especially since more and more traffic is moving towards IPv6.

Another area of improvement concerns the mapping of past DDoS attacks using catchment measurements for the current situation in the Internet. Differences in IP-addresses of the hosts sending the attack traffic, hosts since being

disconnected from the Internet and a different routing situation cause the mapping of attack traffic on sites to be different than if the mapping was performed at the time the DDoS occurred. Again we do not believe this is a problem for the goals of this research as the goal is not to create a 100% accurate mapping of DDoS traffic on anycast sites, but show the general DDoS traffic behaviour when mapped on anycast services. A more ideal situation would be when the anycast service continuously measures its catchment and keeps a historical record of its catchment.

Another aspect that is not covered in the DDoS mapping methodology is the attackers response to the prepending. Actual DDoS attacks can adapt to the mitigations of the defenders. Switching tactics after a short period might cause the prepending to fail because the attacker now uses different attack source hosts or another reflection technique with different amplification points. The prepending strategies only consider a relatively static set of attack sources, at least for a certain while. Changing attack sources during prepending would make it difficult to assess whether a shift in traffic from one site to another is due to the effect of prepending or the attacker changing attack sources or tactics.

5.2.2 Testbed

The anycast testbed has 9 sites, with 4 in Europe and 5 spread around the world. Comparing this configuration with other anycast configuration such as the DNS root servers [9], the number of sites is at the low end of the spectrum. B-root still has fewer sites but most other root servers that use anycast, and large CDN's as well, have more sites; deployments with more than 100 sites are not uncommon nowadays. The ongoing trend among anycast operators is to add more and more sites. This begs the question whether an anycast testbed of 9 sites represents anycast services in general. Anycast services with significantly more sites might react differently to prepending. The challenge here lies in increasing the size of the anycast testbed that would allow for more and better testing in the future with more possible configurations to better model anycast services used in the wild. The conclusions on path prepending remain valid however, because a larger testbed would make path prepending more complex and not more likely to yield better results.

Another difference from larger commercial anycast operations is the type of sites the testbed uses. The testbed uses a combination of donated and rented sites at different locations, while commercial anycast sites are hosted in large datacenters with probably better peering. Commercial anycast operators likely opt for peering in datacenters close to large Internet exchanges. Running the same experiments on an actual large scale anycast service would provide more insight into these differences and may be considered as future work; although with the obvious challenge of running such experiments in large scale or even within production networks.

5.3 Conclusion

In this report we evaluated AS path-prepend as a first line of defense for anycast services against DDoS attacks. The goal of the research is to deter-

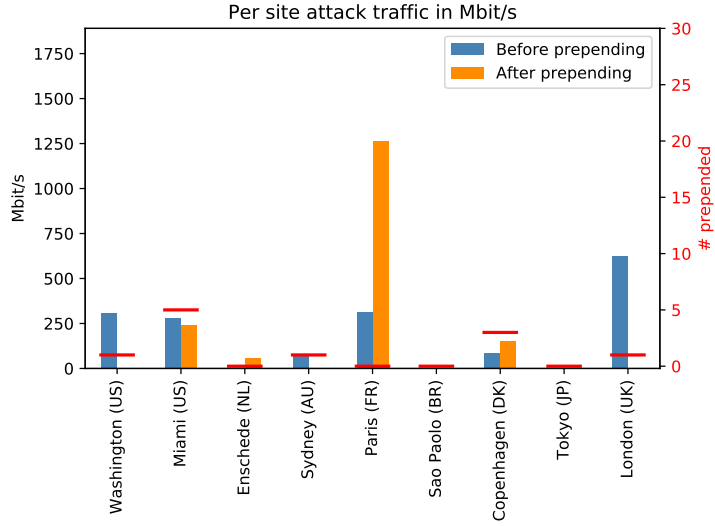
mine if the effects of a DDoS attack on an anycast service can be mitigated by redistributing traffic among the anycast sites by prepending the AS path announcements for the anycast service. This kind of DDoS defense technique falls under the category of network reconfiguration and is meant as a first response before other mitigation tactics focusing on stopping the DDoS traffic can come into effect.

For all evaluated prepending strategies with different DDoS attacks the results were mixed at best. In some cases the prepending achieved the primary goal of redirecting attack to certain instances as part of a mitigation strategy. In some cases the prepending failed to reach the targets set in advance. Therefore the results show that this method is not reliable for shaping (DDoS attack) traffic directed at anycast services. In the cases where the attack traffic could be diverted it could not be sufficiently targeted and the collateral damage in terms of normal traffic was high and often the complete catchment was overturned. The number of prepending iterations to reshape the traffic varies greatly which makes it uncertain if it is fast enough to be used as a first line defense technique.

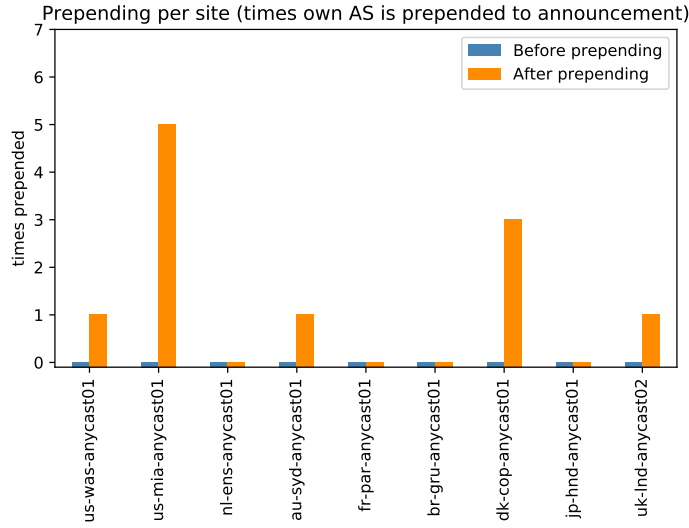
The first research question, whether the AS-path prepending strategies might achieve positive effects as DDoS traffic mitigation, can be answered affirmatively by considering the partially successful prepending attempts for two of the prepending strategies. The "save the children" and "vacuum cleaner" strategies yielded positive results in some cases albeit at a cost and not reliably. Automating the prepending process to move DDoS traffic can not be expected to yield positive results as a large part of the experiments using the previously outlined prepending steps did not achieve their goal. The goal of this research was to evaluate AS-path prepending as first line DDoS mitigation method and the results indicate that it does not work when performed as described in this report. More research which addresses some of the limitations in this work might find a more reliable way to use AS-path prepending as traffic redistribution mechanism in the event of a DDoS attack.

Appendix A

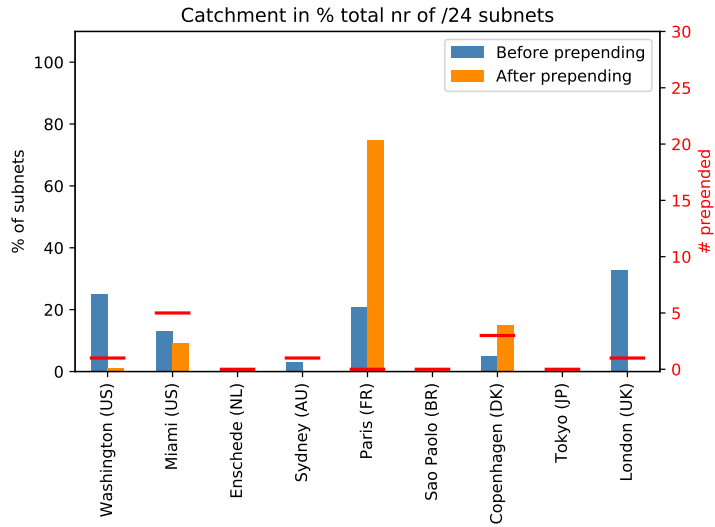
All prepending results



(a) Attack traffic mapping

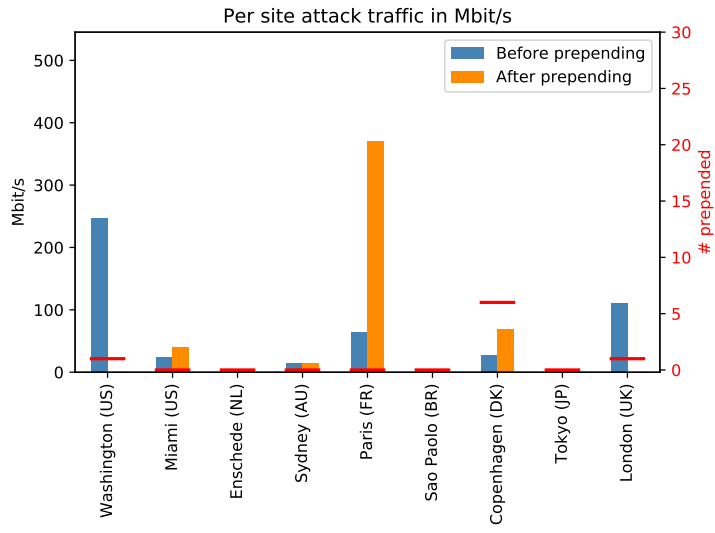


(b) Amount of prepending

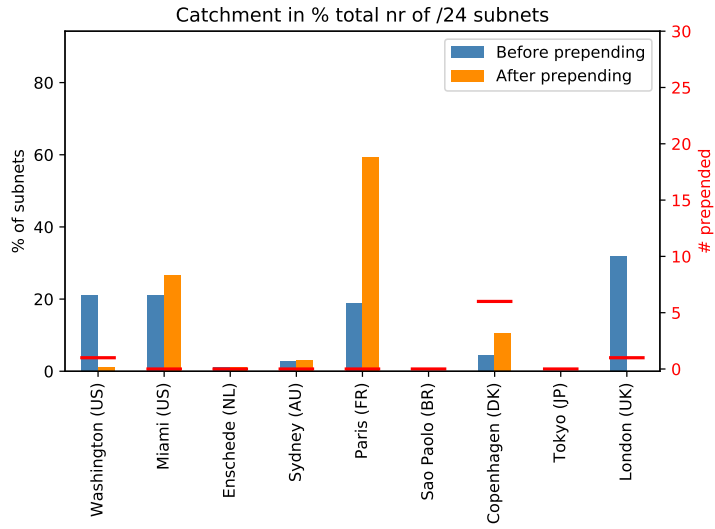


(c) Catchment

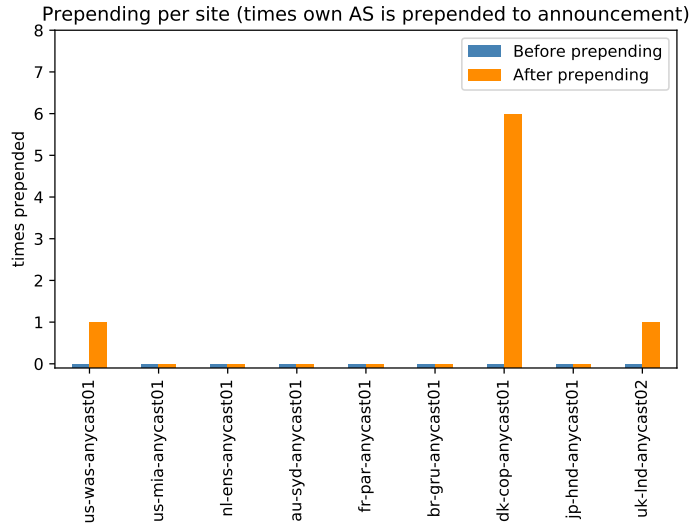
Figure A.1: Catchment, attack traffic mapping and amount of prepending before and after applying the Vacuum cleaner prepending strategy on the global anycast configuration (Paris as blackhole) for the Restricted DNS-01 attack (5 iterations of prepending)



(a) Attack traffic mapping

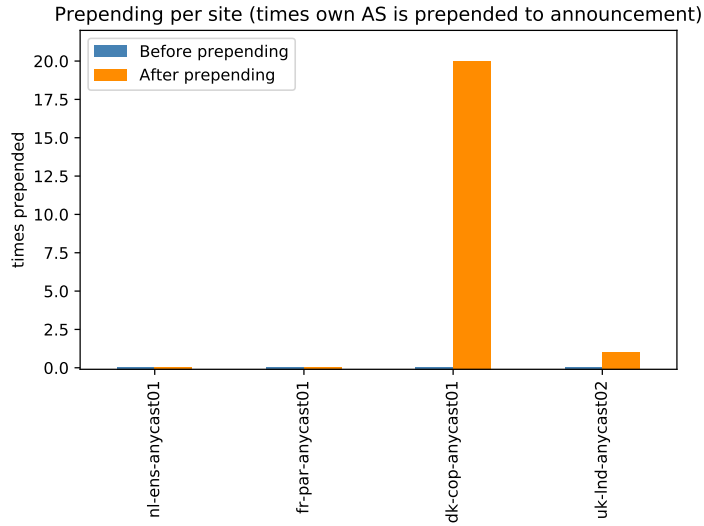


(b) Catchment

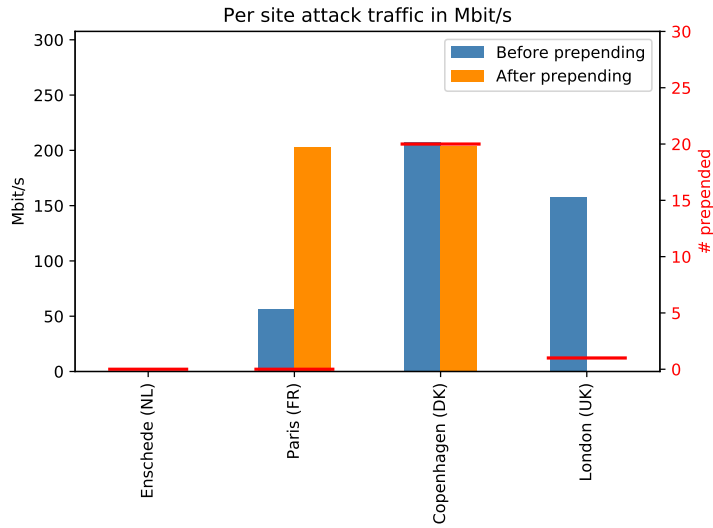


(c) Amount of prepending

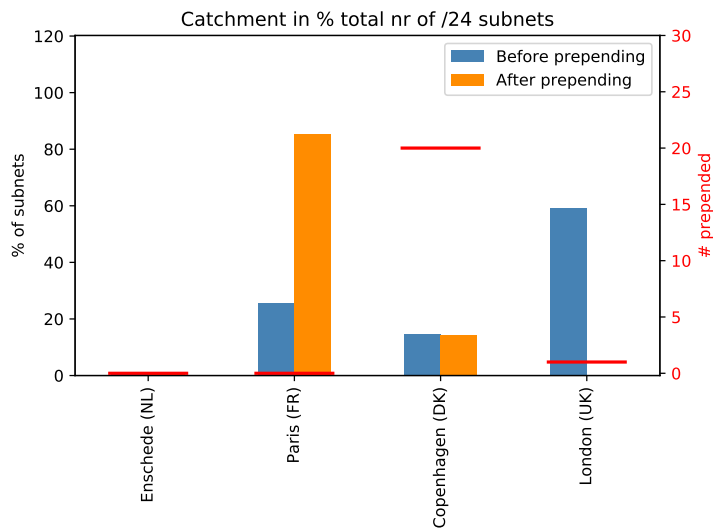
Figure A.2: Catchment, attack traffic mapping and amount of prepending before and after applying the Vacuum cleaner prepending strategy on the global anycast configuration (Paris as blackhole) for the IP-stresser SNMP-02 attack (7 iterations of prepending)



(a) Amount of prepending

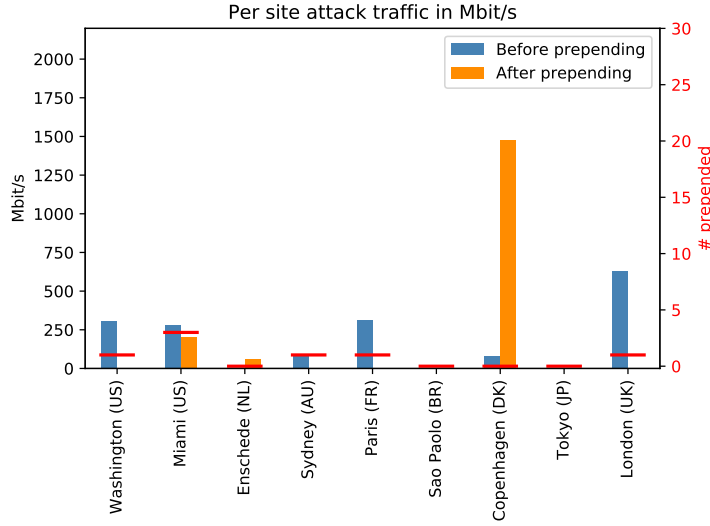


(b) Attack traffic mapping

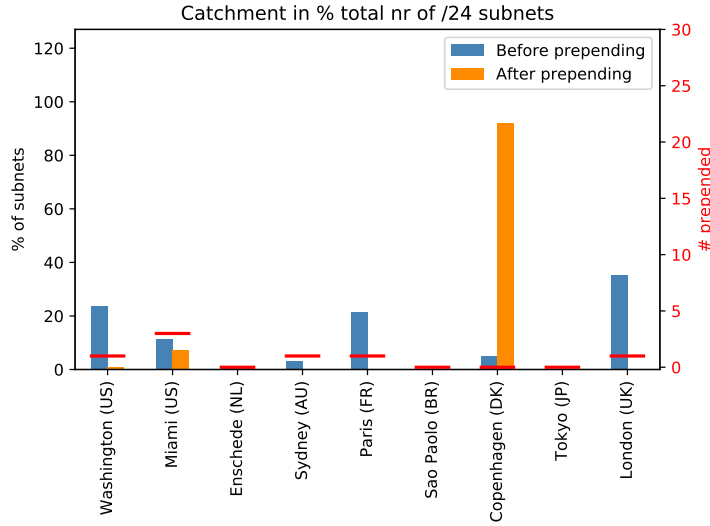


(c) Catchment

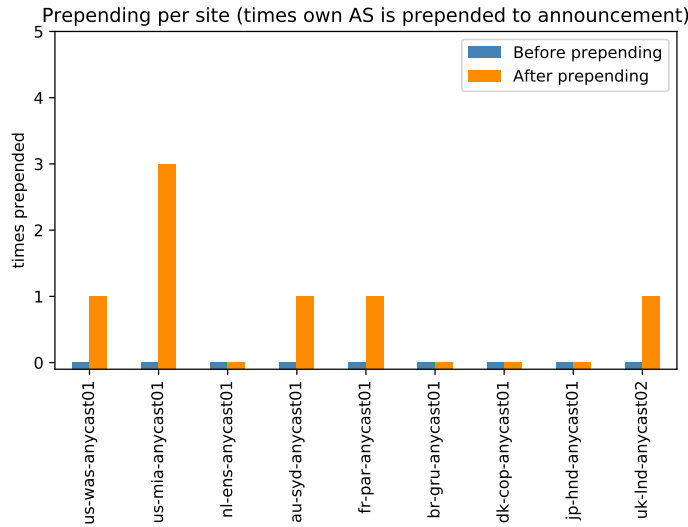
Figure A.3: Catchment, attack traffic mapping and amount of prepending before and after applying the Vacuum cleaner prepending strategy on the European anycast configuration (Paris as blackhole) for the IP-stresser NTP-02 attack (7 iterations of prepending)



(a) Attack traffic mapping

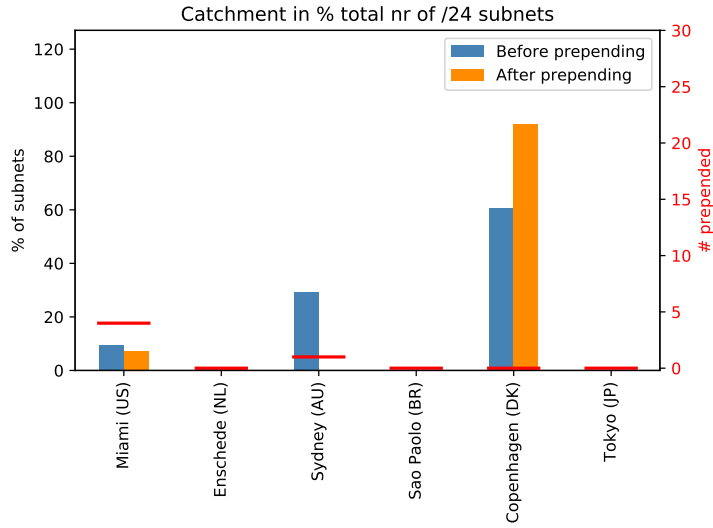


(b) Catchment

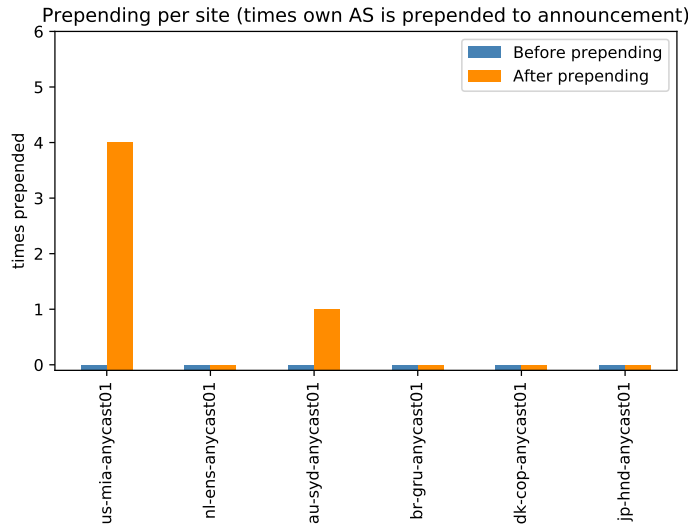


(c) Amount of prepending

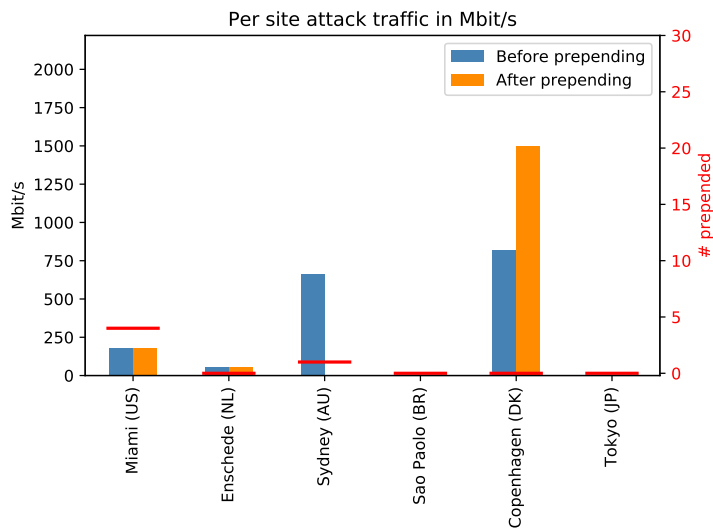
Figure A.4: Catchment, attack traffic mapping and amount of prepending before and after applying the Vacuum cleaner prepending strategy on the global anycast configuration (Copenhagen as blackhole) for the Restricted DNS-01 attack (3 iterations of prepending)



(a) Catchment

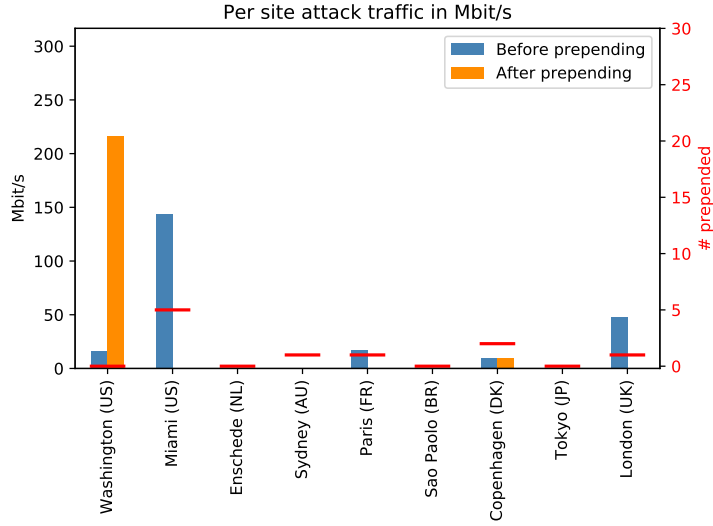


(b) Amount of prepending

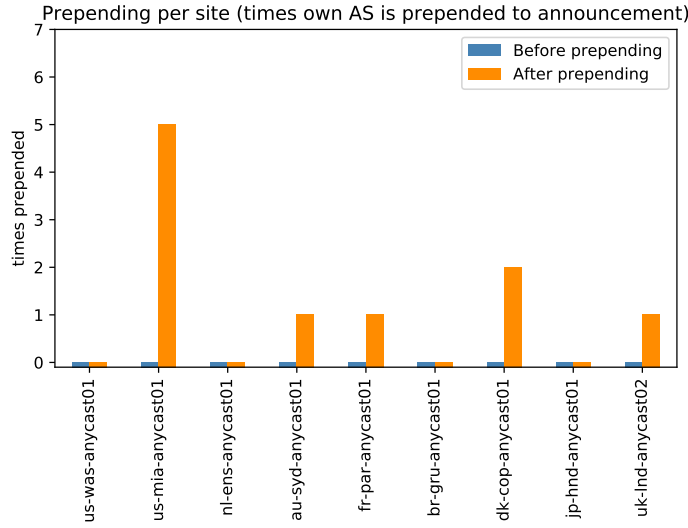


(c) Attack traffic mapping

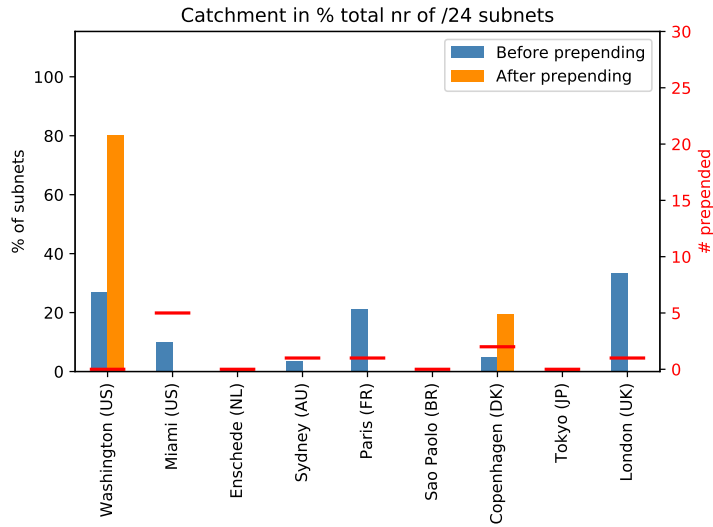
Figure A.5: Catchment, attack traffic mapping and amount of prepending before and after applying the Vacuum cleaner prepending strategy on the "No big 3" anycast configuration (Copenhagen as blackhole) for the Restricted DNS-01 attack (4 iterations of prepending)



(a) Attack traffic mapping

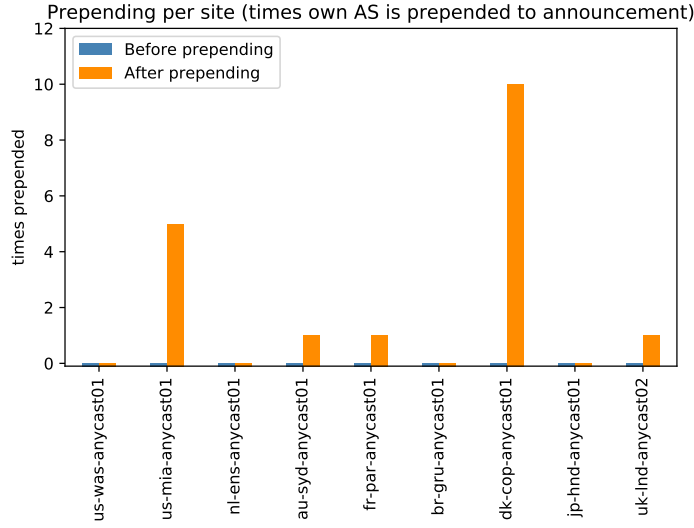


(b) Amount of prepending

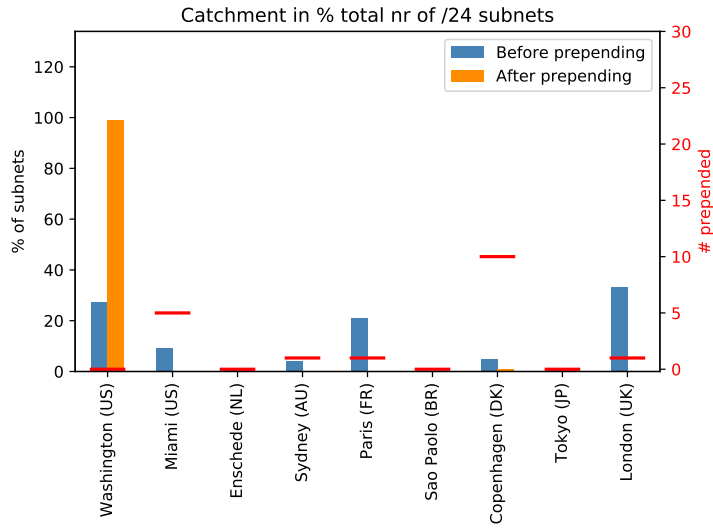


(c) Catchment

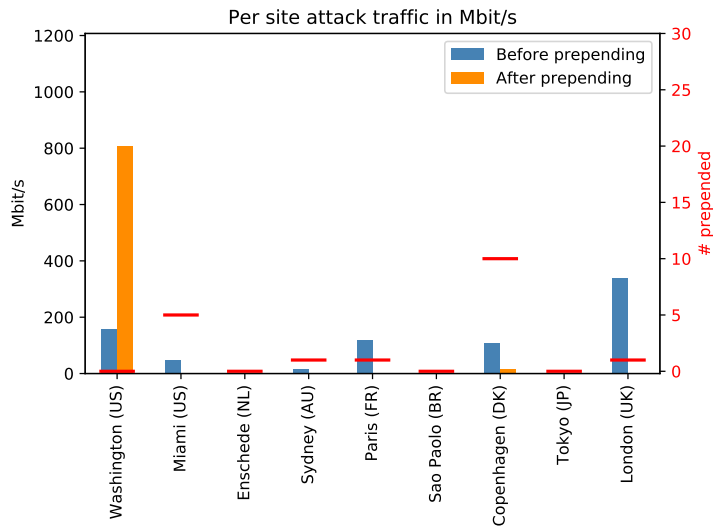
Figure A.6: Catchment, attack traffic mapping and amount of prepending before and after applying the Vacuum cleaner prepending strategy on the global anycast configuration (Washington as blackhole) for the Grim-booter DNS attack (6 iterations of prepending)



(a) Amount of prepending

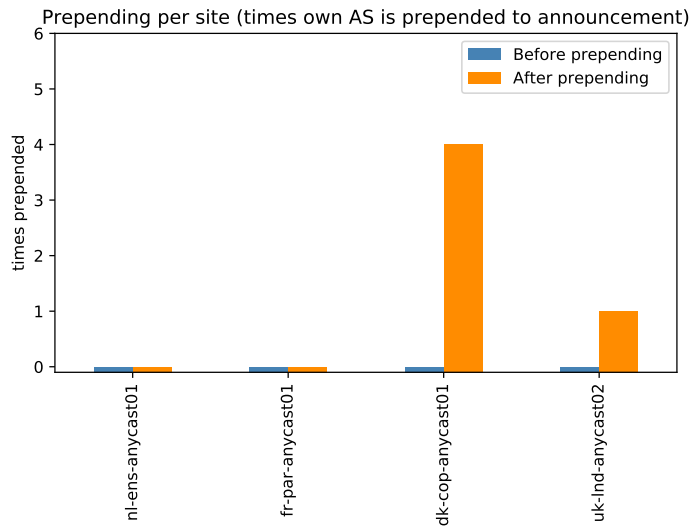


(b) Catchment

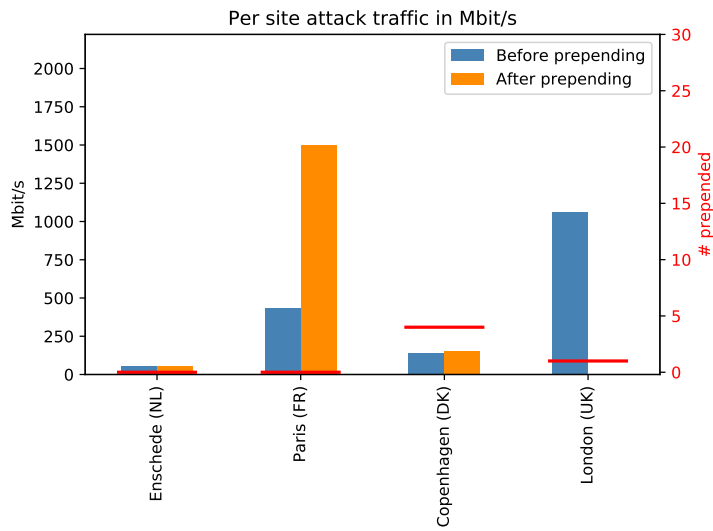


(c) Attack traffic mapping

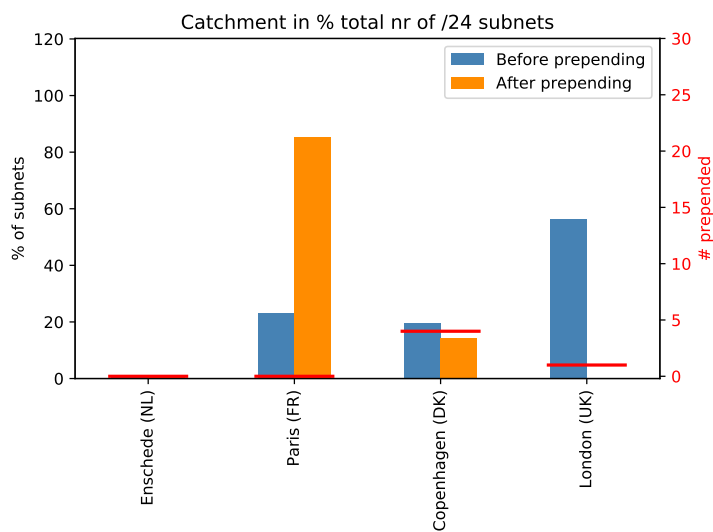
Figure A.7: Catchment, attack traffic mapping and amount of prepending before and after applying the Vacuum cleaner prepending strategy on the global anycast configuration (Washington as blackhole) for the Deja-booter DNS attack (6 iterations of prepending)



(a) Amount of prepending

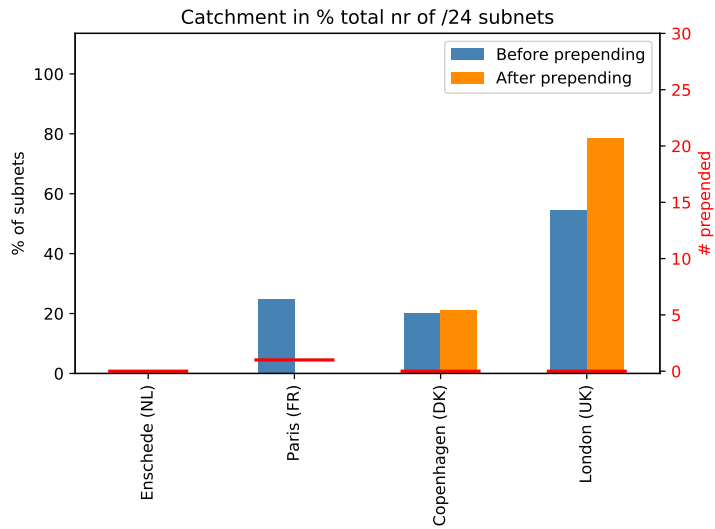


(b) Attack traffic mapping

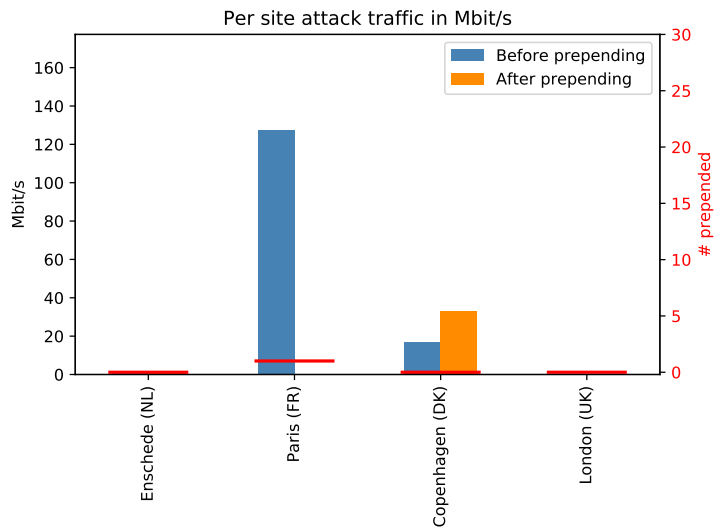


(c) Catchment

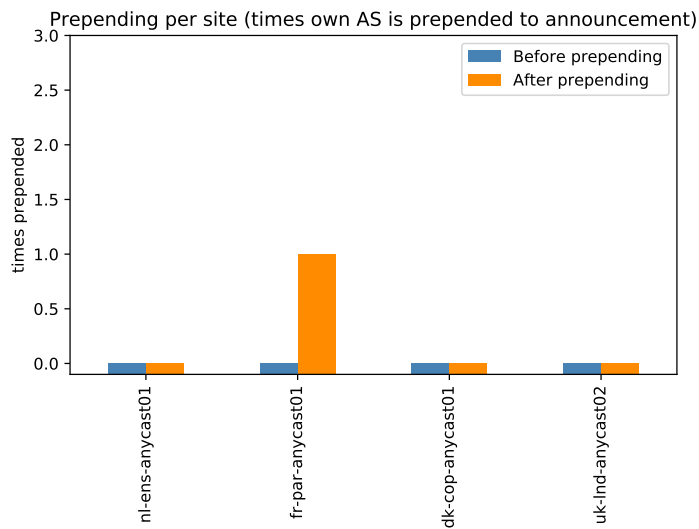
Figure A.8: Catchment, attack traffic mapping and amount of prepending before and after applying the Vacuum cleaner prepending strategy on the European anycast configuration (Paris as blackhole) for the Restricted DNS-01 attack (4 iterations of prepending)



(a) Catchment

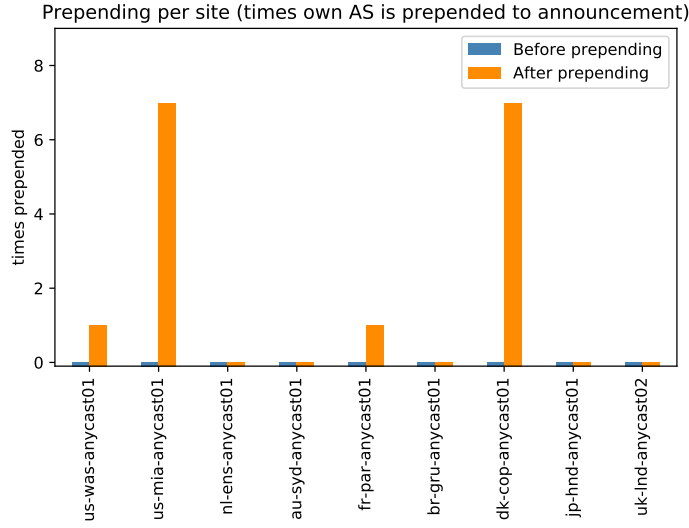


(b) Attack traffic mapping

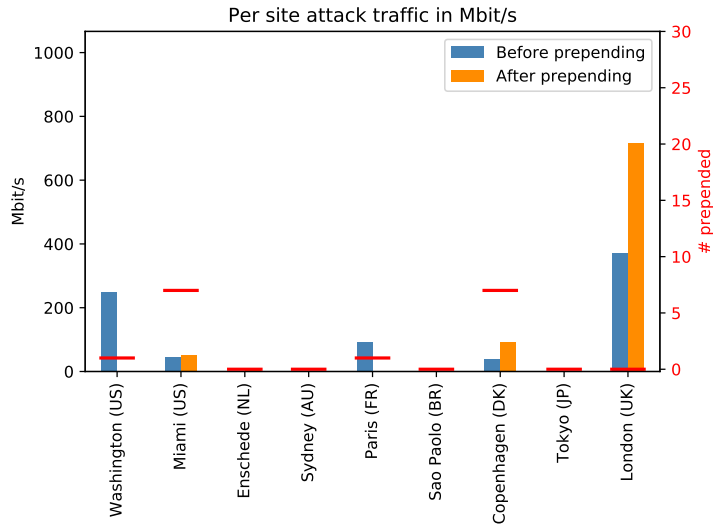


(c) Amount of prepending

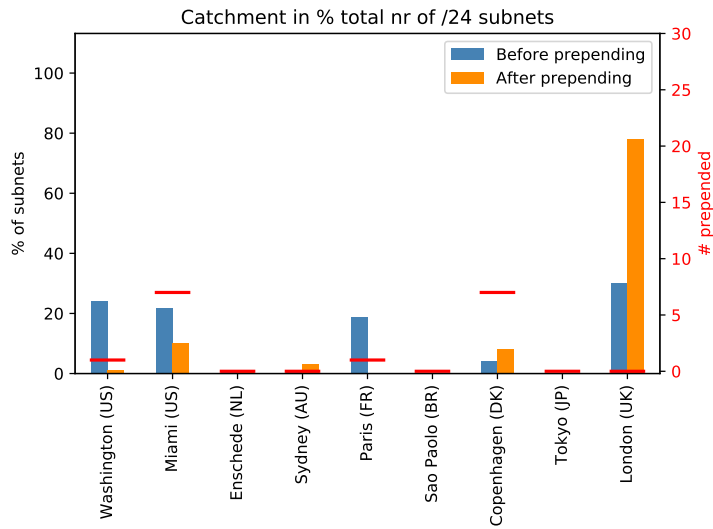
Figure A.9: Catchment, attack traffic mapping and amount of prepending before and after applying the Vacuum cleaner prepending strategy on the European anycast configuration (Copenhagen as blackhole) for the IP-stresser Chargen-02 attack (1 iteration of prepending)



(a) Amount of prepending

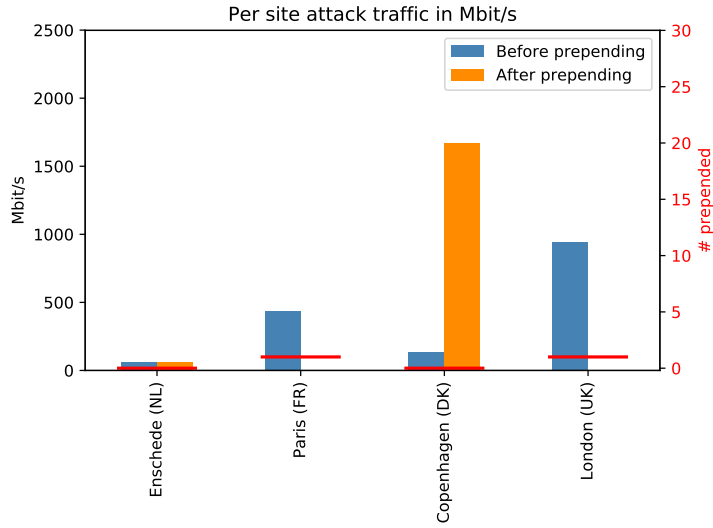


(b) Attack traffic mapping

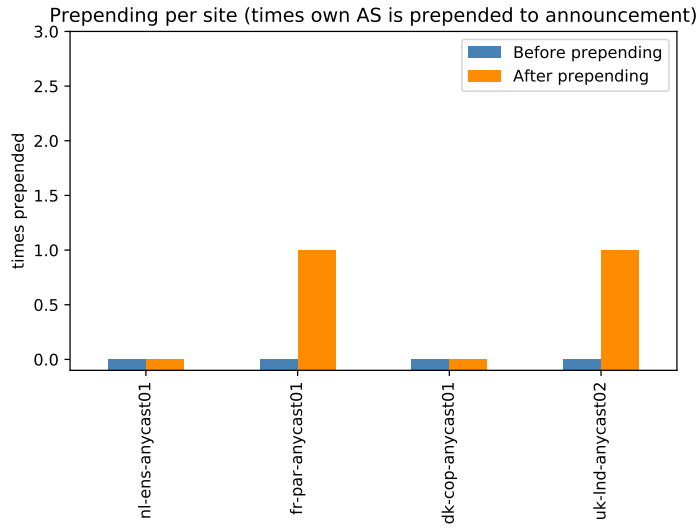


(c) Catchment

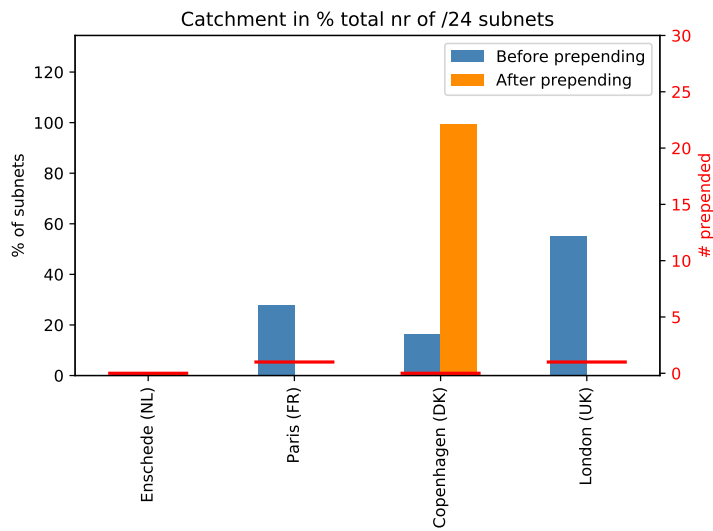
Figure A.10: Catchment, attack traffic mapping and amount of prepending before and after applying the Vacuum cleaner prepending strategy on the global anycast configuration (London as blackhole) for the Rebel-stresser DNS attack (7 iterations of prepending)



(a) Attack traffic mapping

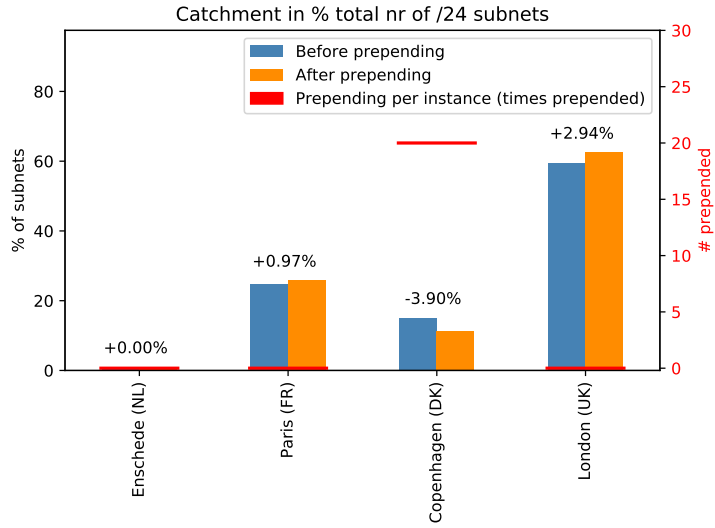


(b) Amount of prepending

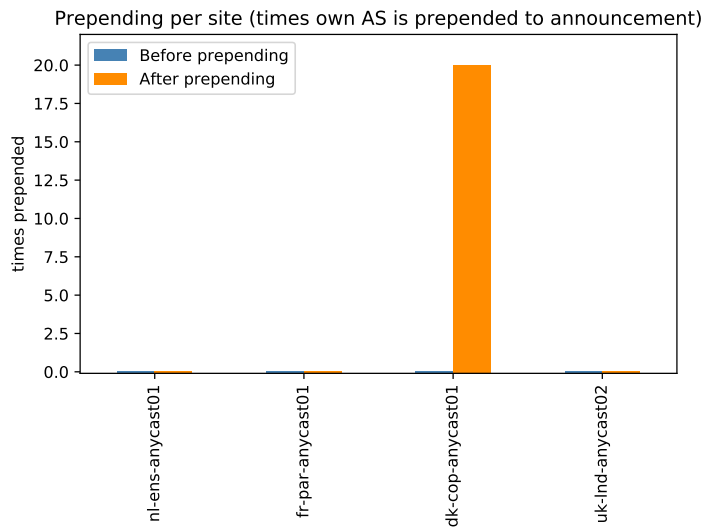


(c) Catchment

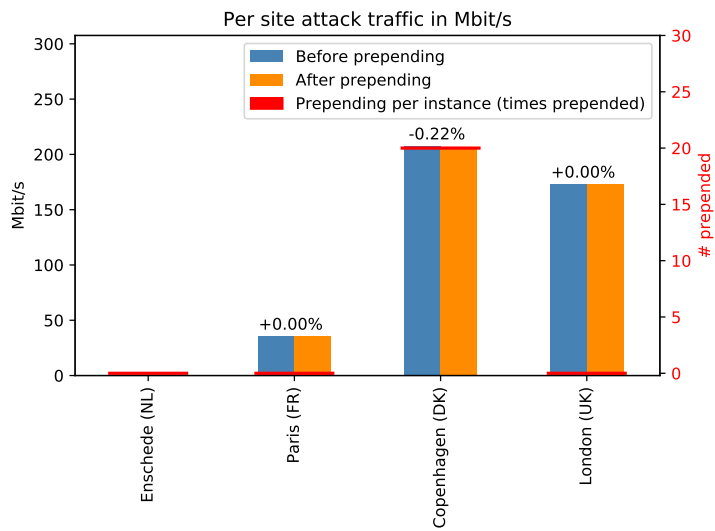
Figure A.11: Catchment, attack traffic mapping and amount of prepending before and after applying the Vacuum cleaner prepending strategy on the European anycast configuration (Copenhagen as blackhole) for the Restricted DNS-01 attack (1 iteration of prepending)



(a) Catchment

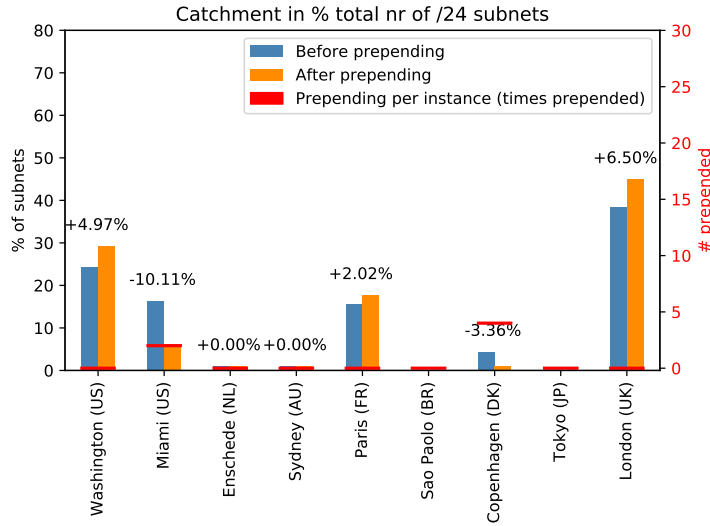


(b) Amount of prepending

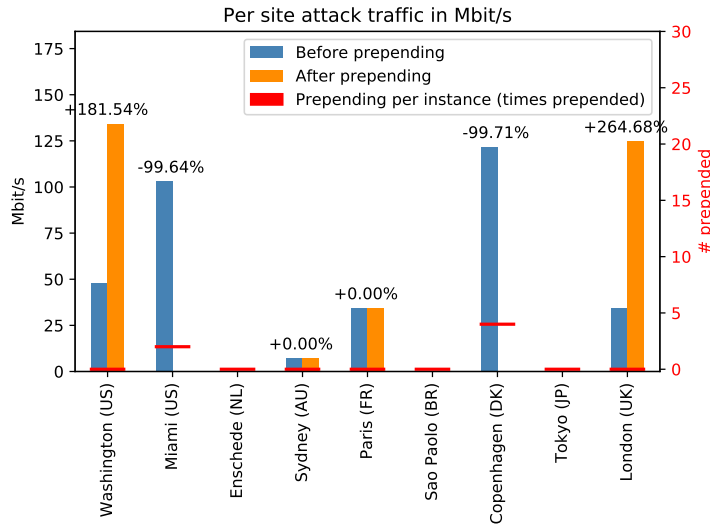


(c) Attack traffic mapping

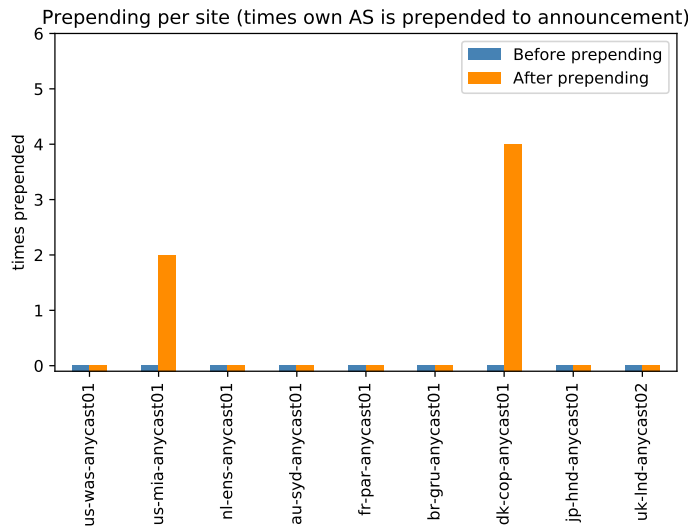
Figure A.12: Catchment, attack traffic mapping and amount of prepending before and after applying the Save the children prepending strategy on the global anycast configuration for the IP-stresser NTP-02 attack (5 iterations of prepending)



(a) Catchment

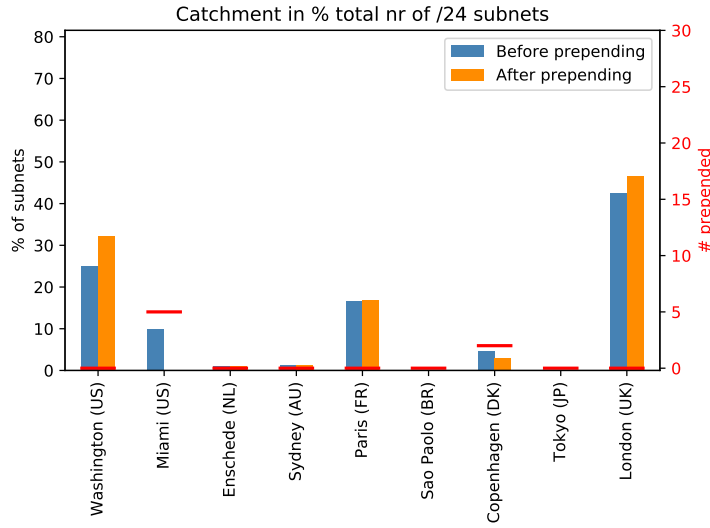


(b) Attack traffic mapping

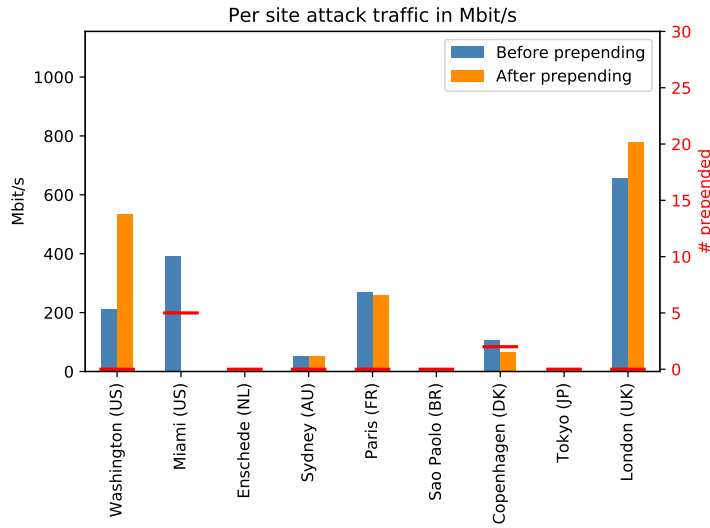


(c) Amount of prepending

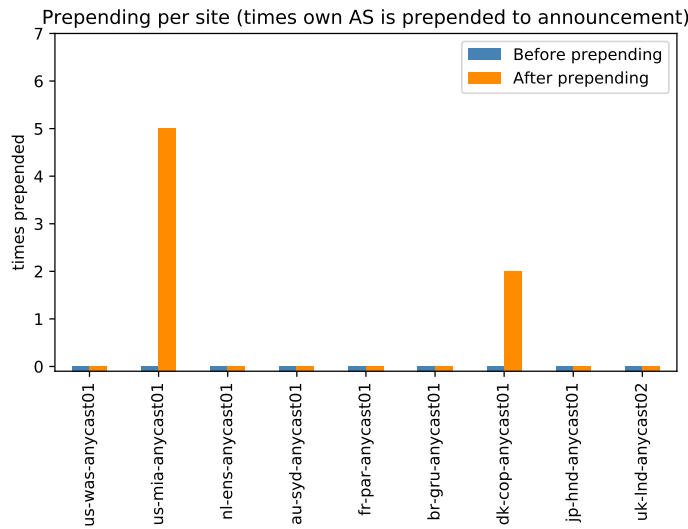
Figure A.13: Catchment, attack traffic mapping and amount of prepending before and after applying the Save the children prepending strategy on the global anycast configuration for the Connection NTP-01 attack (4 iterations of prepending)



(a) Catchment

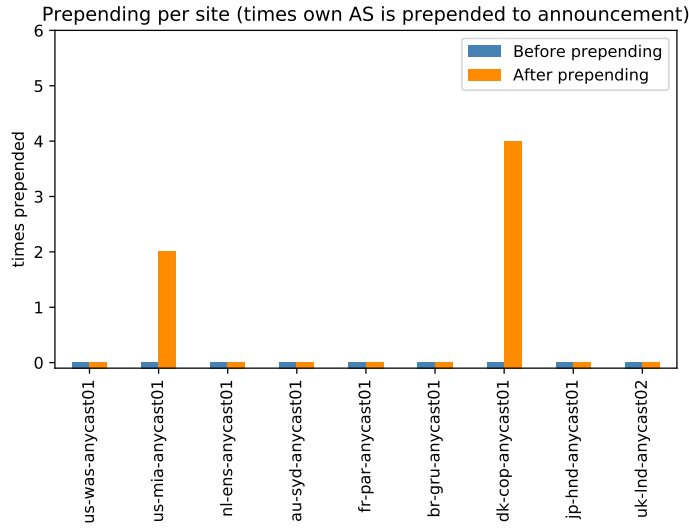


(b) Attack traffic mapping

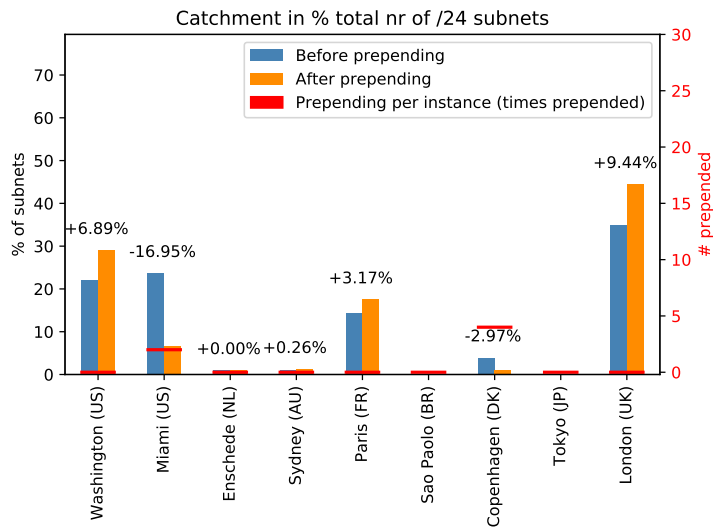


(c) Amount of prepending

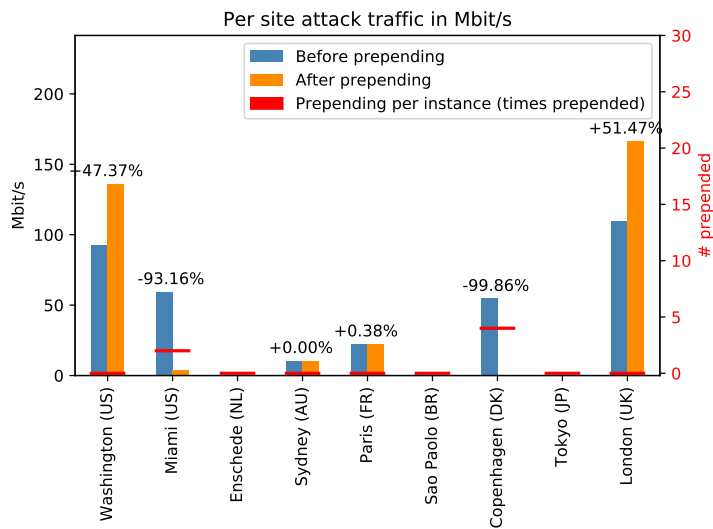
Figure A.14: Catchment, attack traffic mapping and amount of prepending before and after applying the Save the children prepending strategy on the global anycast configuration for the Restricted DNS-02 attack (5 iterations of prepending)



(a) Amount of prepending

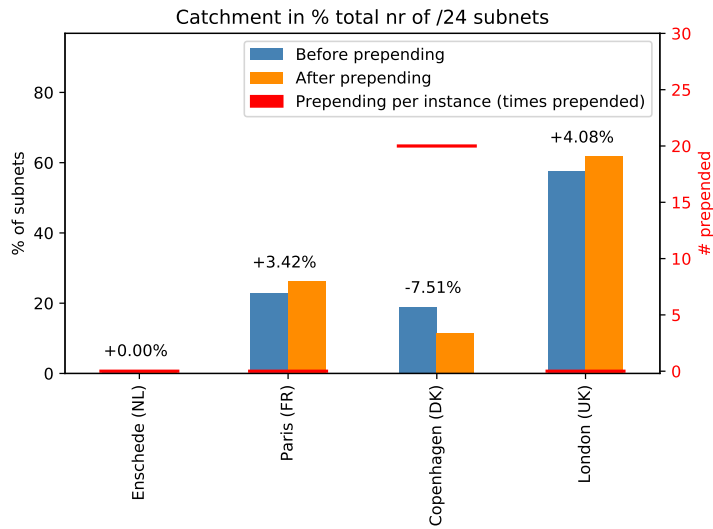


(b) Catchment

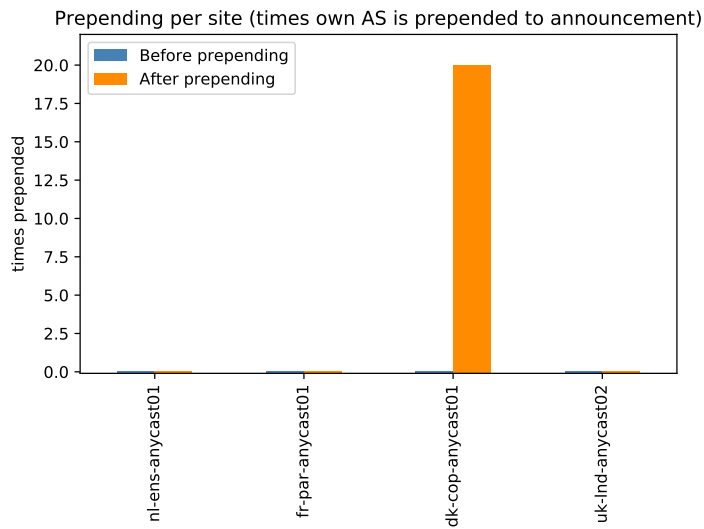


(c) Attack traffic mapping

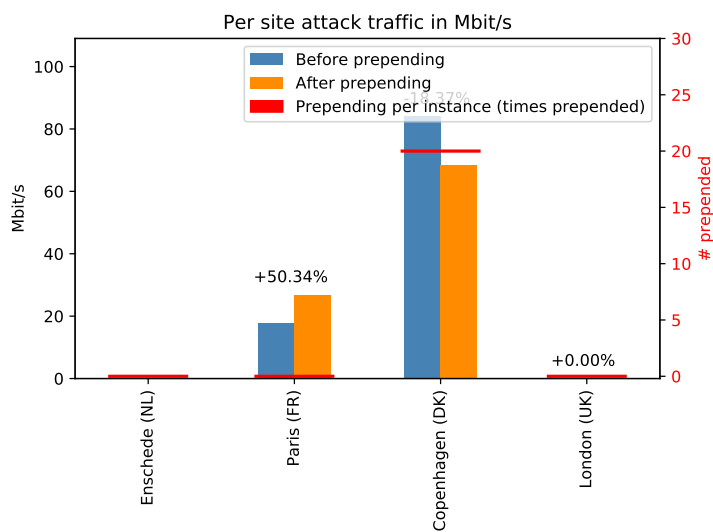
Figure A.15: Catchment, attack traffic mapping and amount of prepending before and after applying the Save the children prepending strategy on the global anycast configuration for the IP-stresser NTP-01 attack (4 iterations of prepending)



(a) Catchment

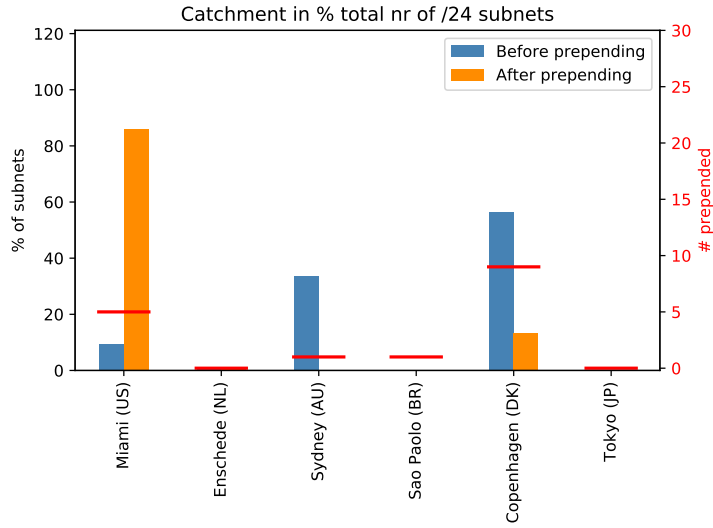


(b) Amount of prepending

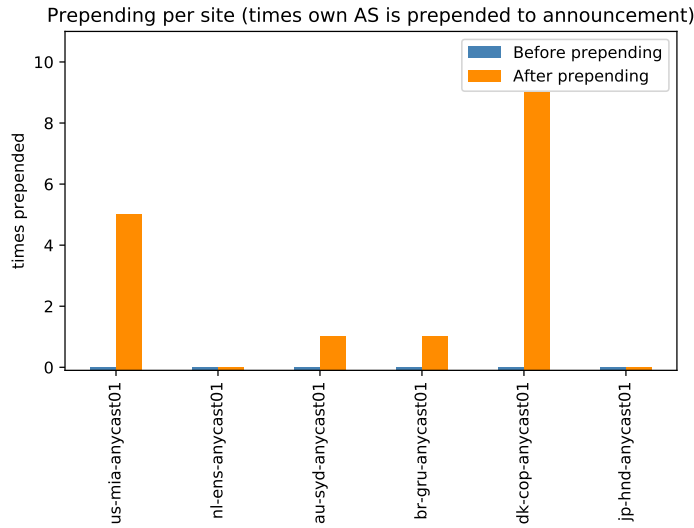


(c) Attack traffic mapping

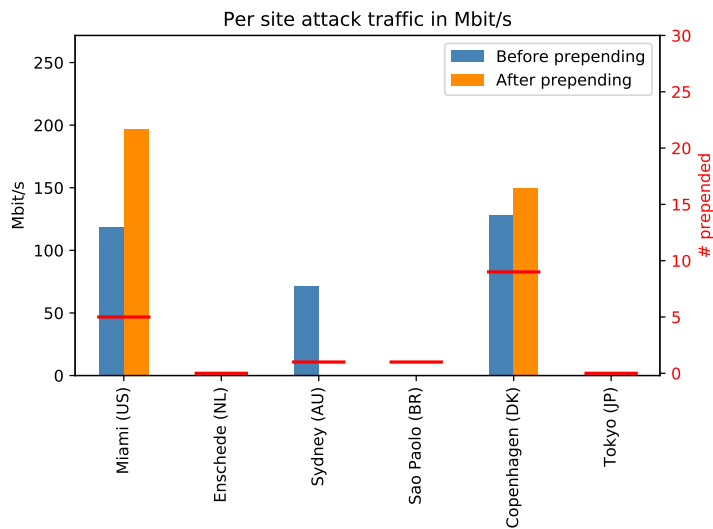
Figure A.16: Catchment, attack traffic mapping and amount of prepending before and after applying the Save the children prepending strategy on the European anycast configuration for the Connection NTP-02 attack (4 iterations of prepending)



(a) Catchment

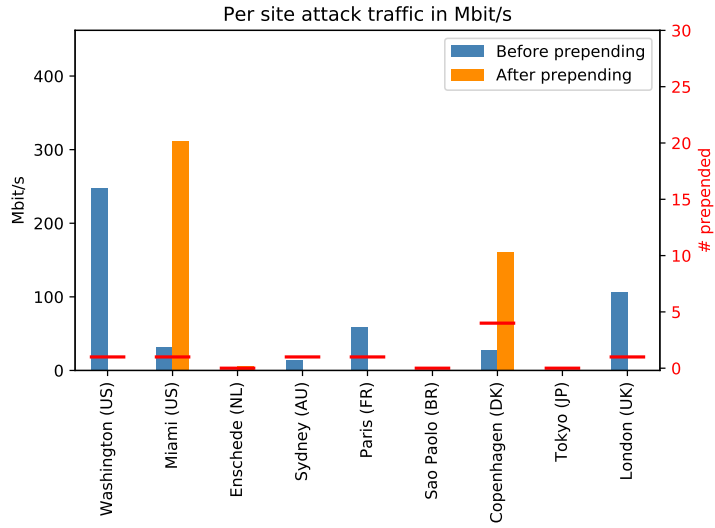


(b) Amount of prepending

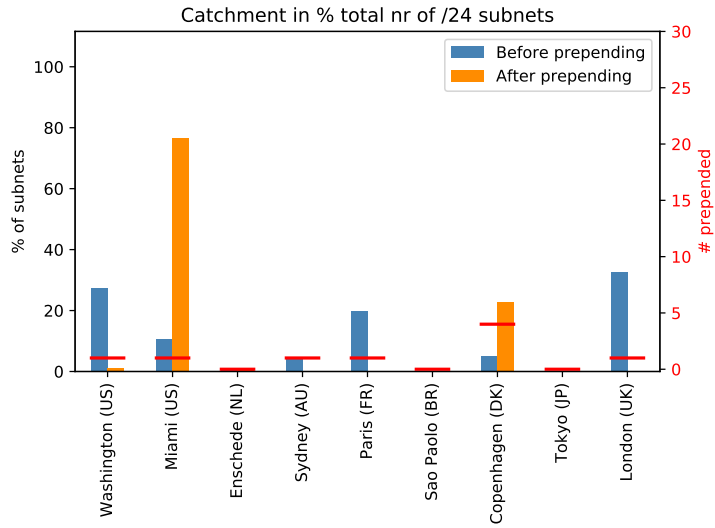


(c) Attack traffic mapping

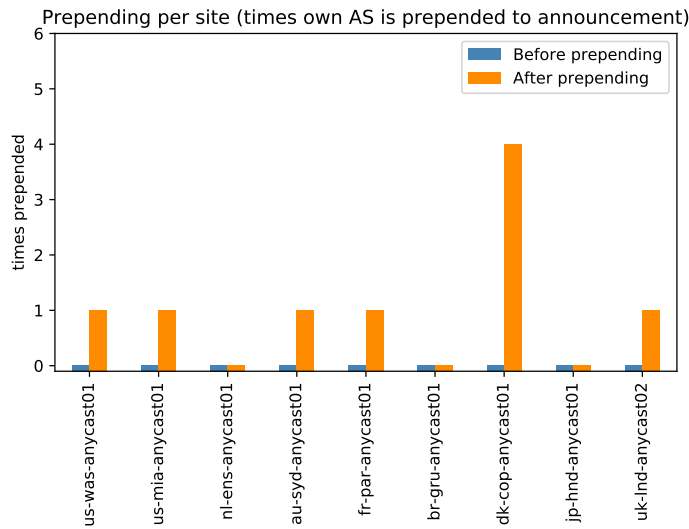
Figure A.17: Catchment, attack traffic mapping and amount of prepending before and after applying the Dynamic redistribution prepending strategy on the "No big 3" anycast configuration for the Connection NTP-01 attack (9 iterations of prepending)



(a) Attack traffic mapping

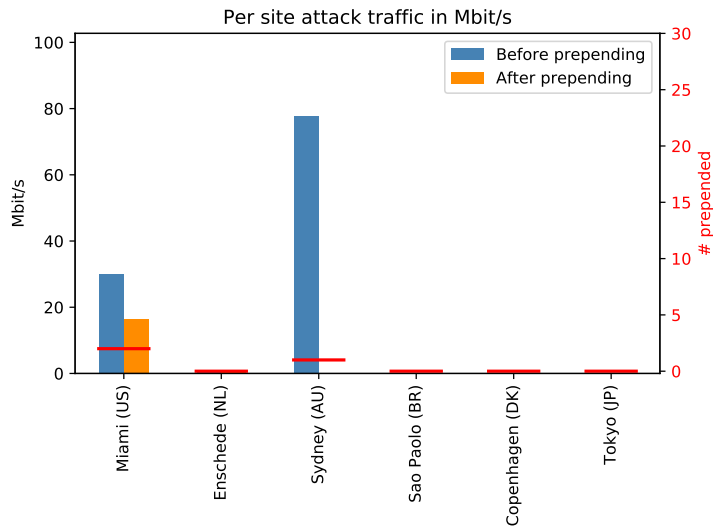


(b) Catchment

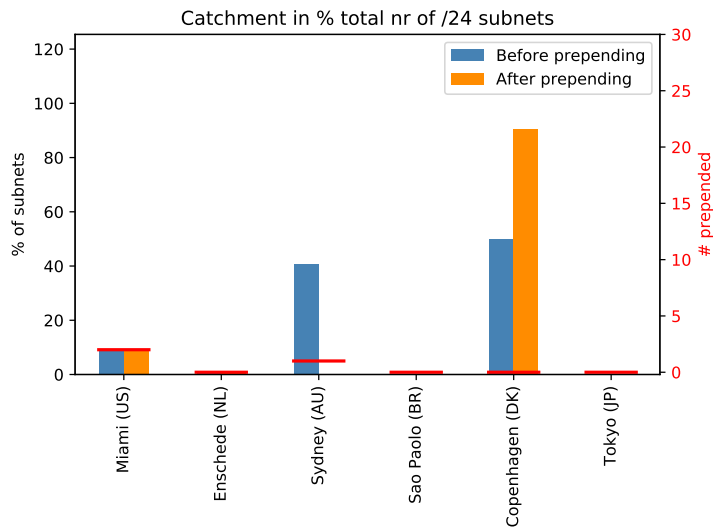


(c) Amount of prepending

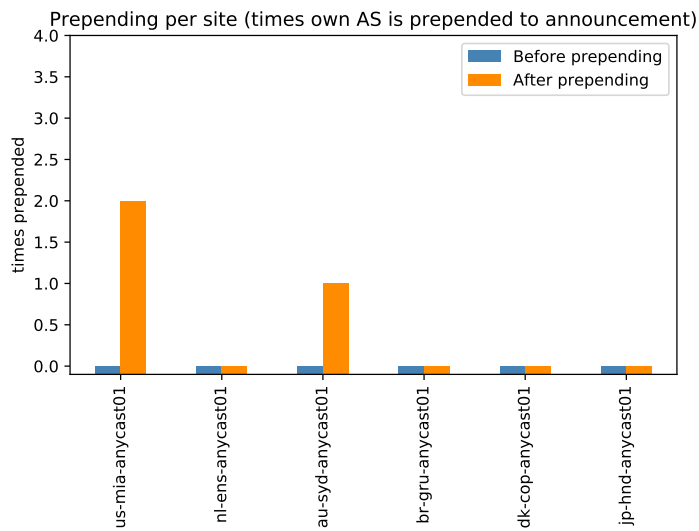
Figure A.18: Catchment, attack traffic mapping and amount of prepending before and after applying the Dynamic redistribution prepending strategy on the global anycast configuration for the IP-stresser SNMP-02 attack (8 iterations of prepending)



(a) Attack traffic mapping

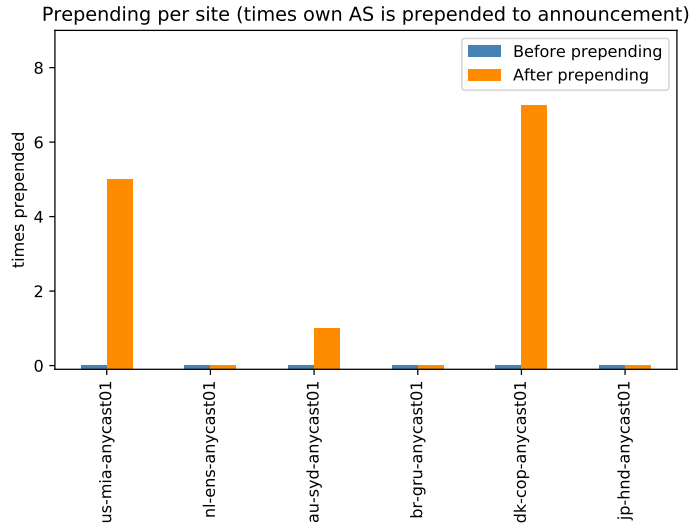


(b) Catchment

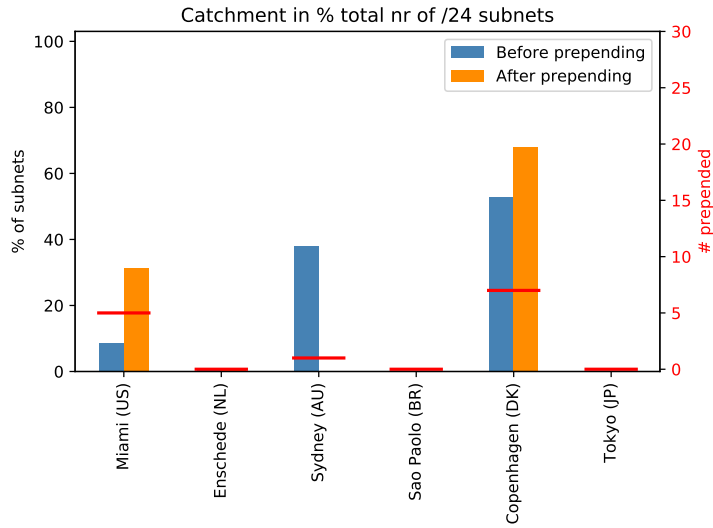


(c) Amount of prepending

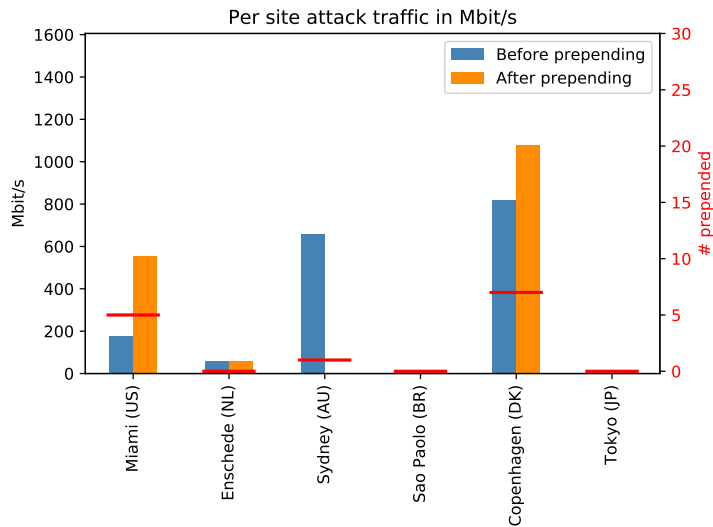
Figure A.19: Catchment, attack traffic mapping and amount of prepending before and after applying the Dynamic redistribution prepending strategy on the "No big 3" anycast configuration for the Krypton NTP-02 attack (2 iterations of prepending)



(a) Amount of prepending

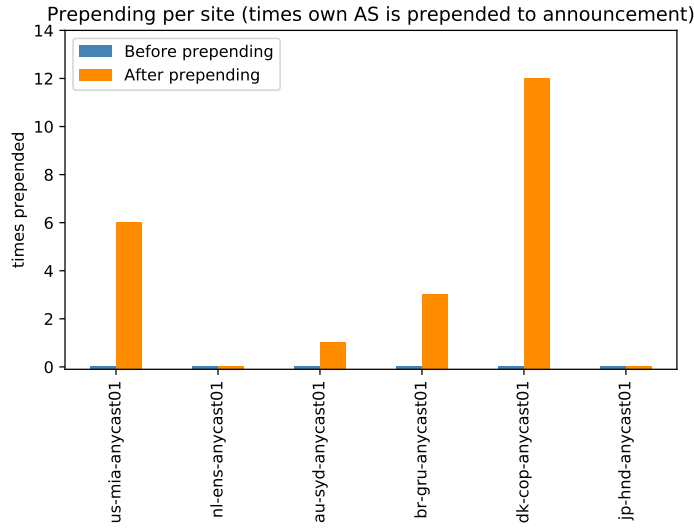


(b) Catchment

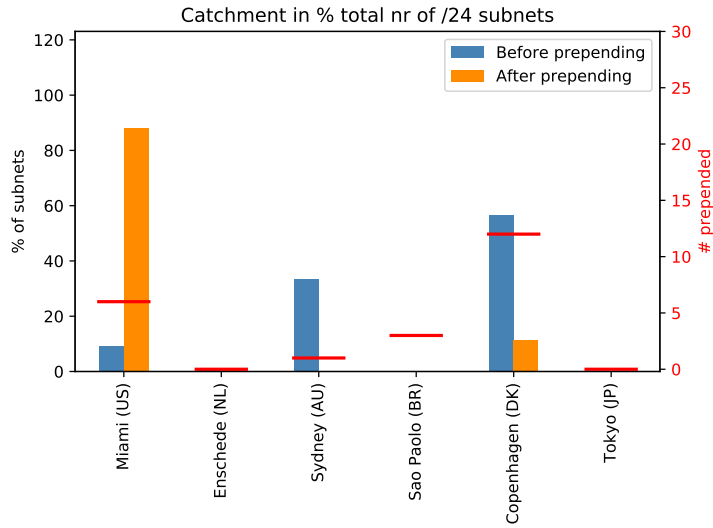


(c) Attack traffic mapping

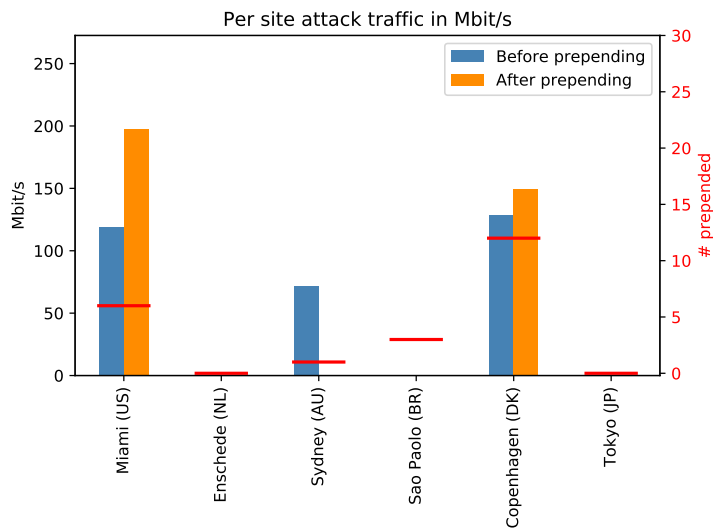
Figure A.20: Catchment, attack traffic mapping and amount of prepending before and after applying the Dynamic redistribution prepending strategy on the "No big 3" anycast configuration for the Restricted DNS-01 attack (7 iterations of prepending)



(a) Amount of prepending

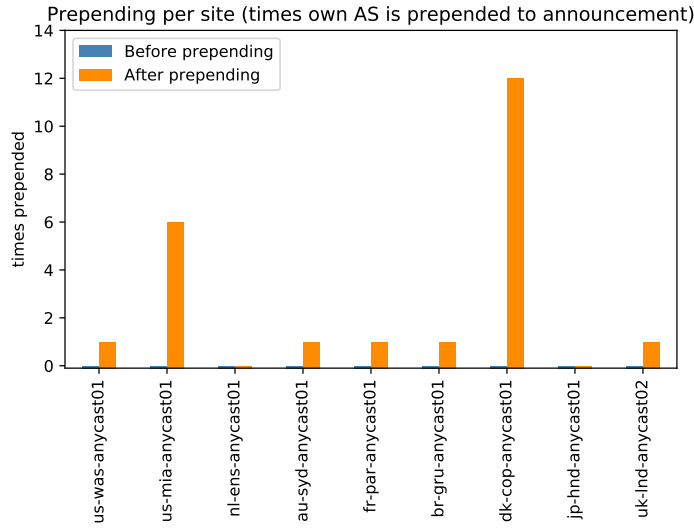


(b) Catchment

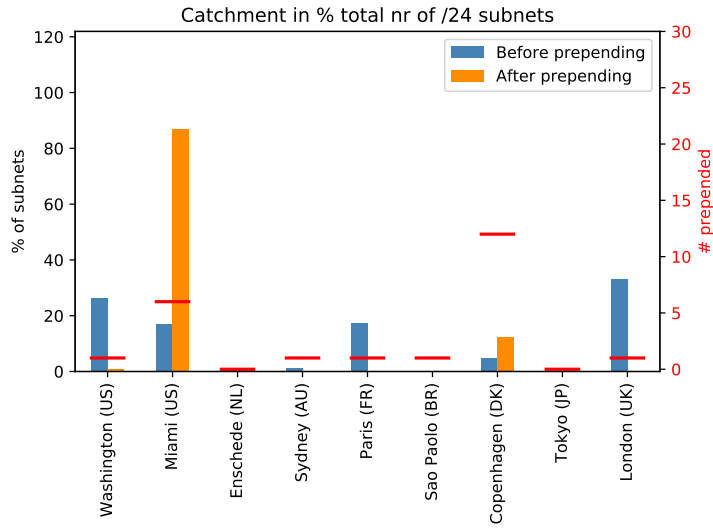


(c) Attack traffic mapping

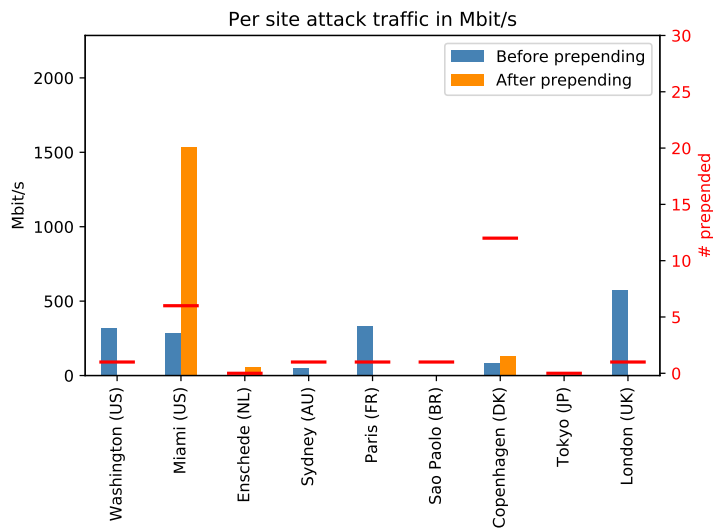
Figure A.21: Catchment, attack traffic mapping and amount of prepending before and after applying the Dynamic redistribution prepending strategy on the "No big 3" anycast configuration for the Connection NTP-01 attack (9 iterations of prepending)



(a) Amount of prepending

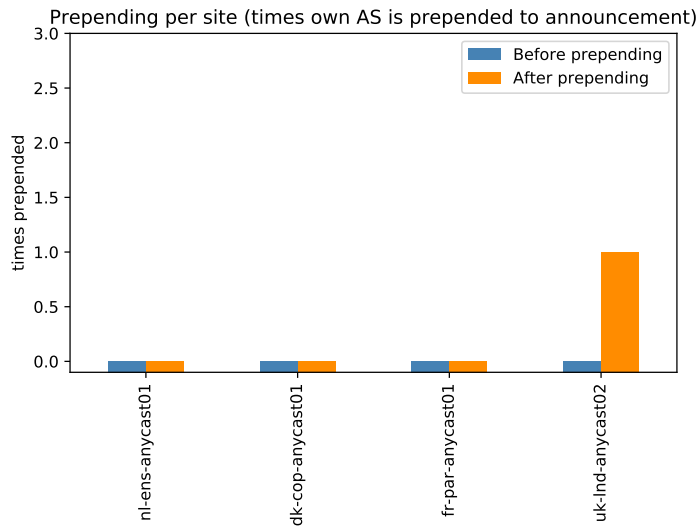


(b) Catchment

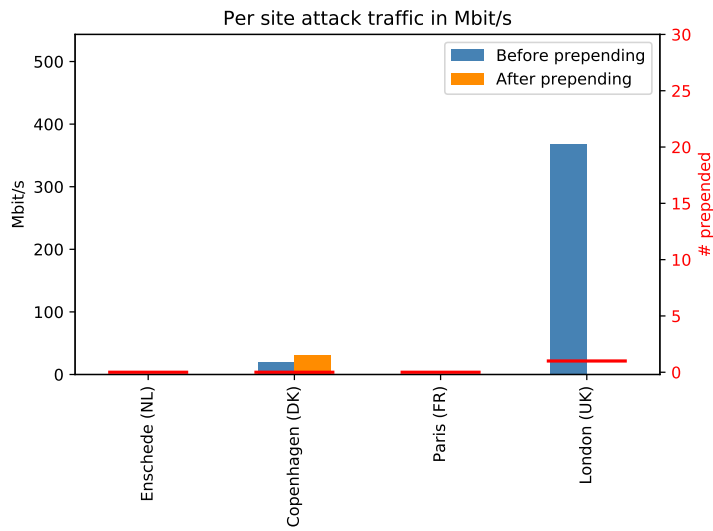


(c) Attack traffic mapping

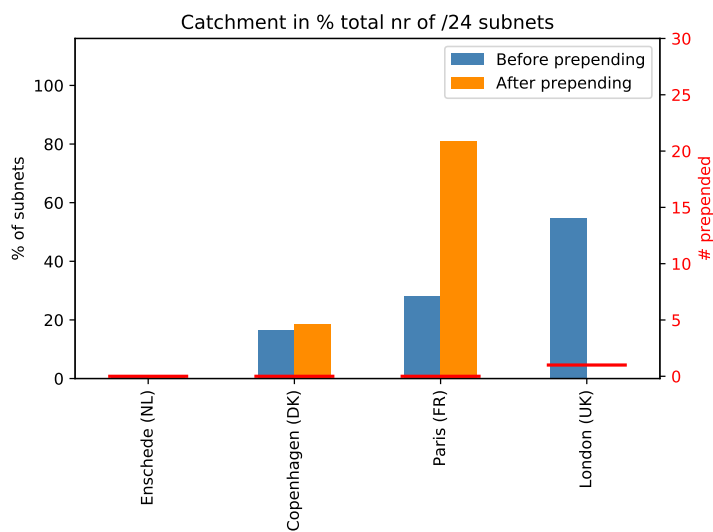
Figure A.22: Catchment, attack traffic mapping and amount of prepending before and after applying the Dynamic redistribution prepending strategy on the global anycast configuration for the Restricted DNS-1 attack (9 iterations of prepending)



(a) Amount of prepending

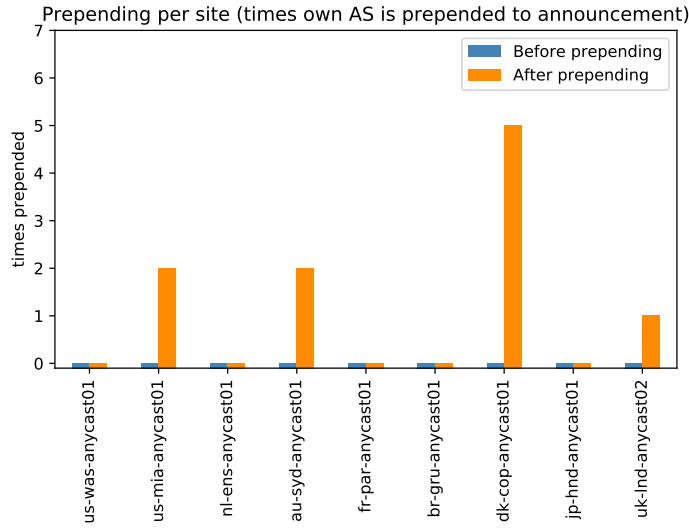


(b) Attack traffic mapping

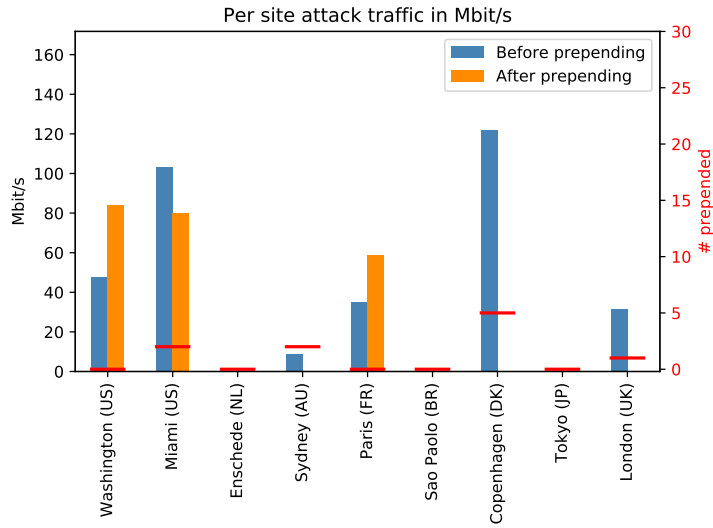


(c) Catchment

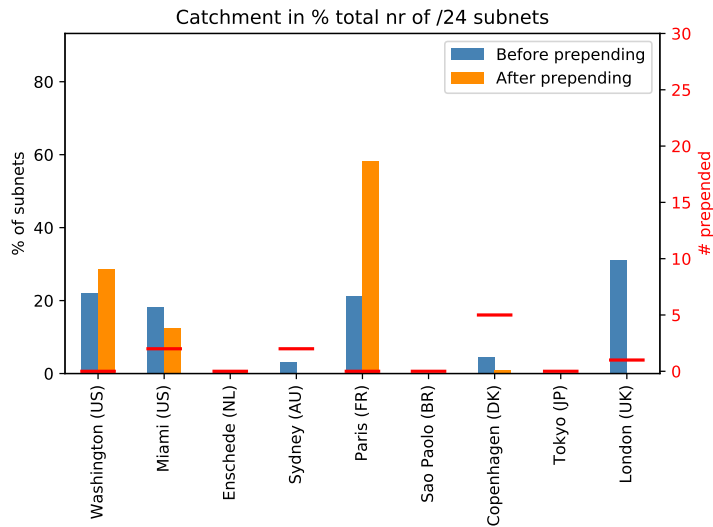
Figure A.23: Catchment, attack traffic mapping and amount of prepending before and after applying the Dynamic redistribution prepending strategy on the European anycast configuration for the IP-stresser Chargen-02 attack (1 iteration of prepending)



(a) Amount of prepending

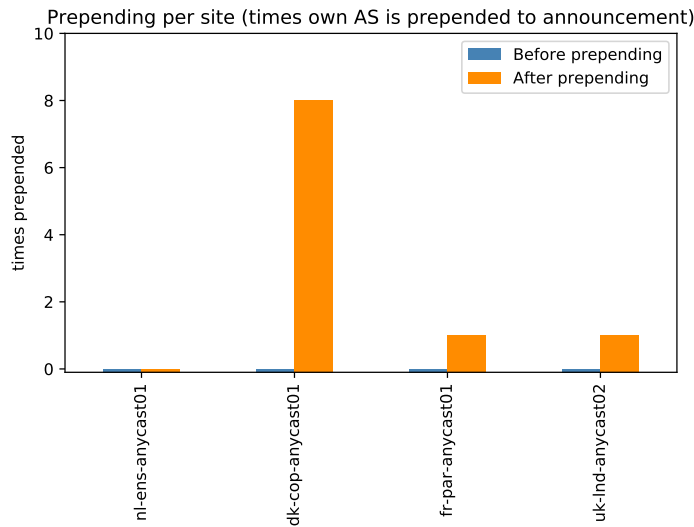


(b) Attack traffic mapping

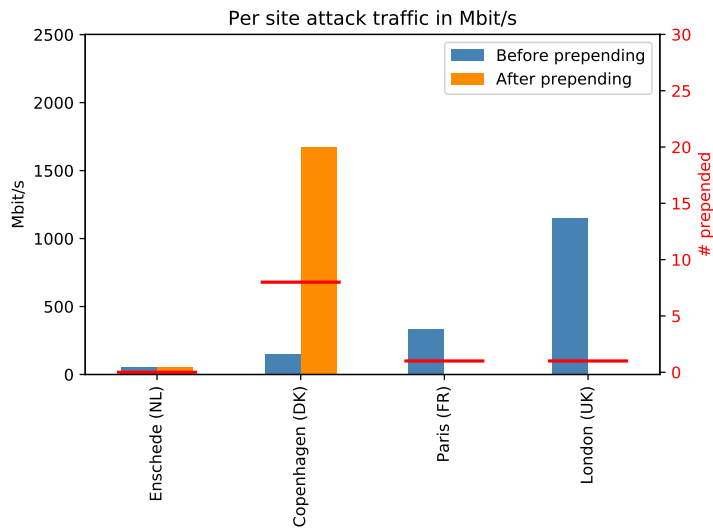


(c) Catchment

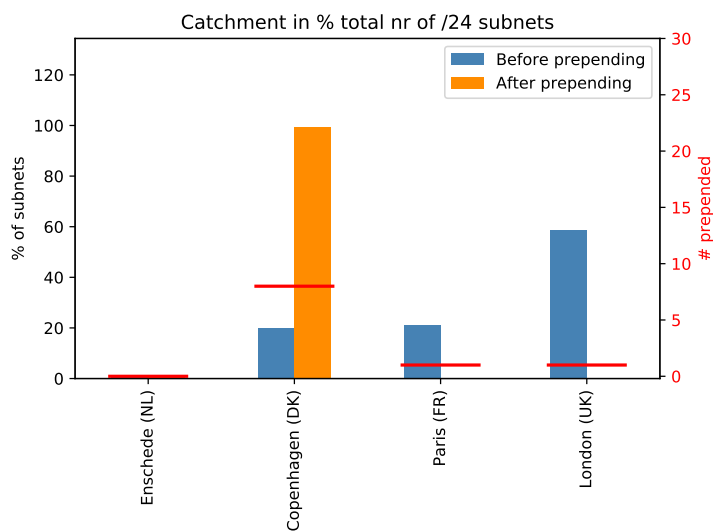
Figure A.24: Catchment, attack traffic mapping and amount of prepending before and after applying the Dynamic redistribution prepending strategy on the global anycast configuration for the Connection NTP-01 attack (5 iterations of prepending)



(a) Amount of prepending



(b) Attack traffic mapping



(c) Catchment

Figure A.25: Catchment, attack traffic mapping and amount of prepending before and after applying the Dynamic redistribution prepending strategy on the European anycast configuration for the Restricted DNS-01 attack (6 iterations of prepending)

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