Detection of BGP routing misbehavior against Cyber-Terrorism

Georgos Siganos, Michalis Faloutsos

***Abstract*— Attacks at the control and routing plane may be the next generation of threats for the Internet. Manipulation of the routing layer could originate from profiteering, malice, or simply human error. The community has recognized this danger and several promising approaches have been proposed to capture and block routing anomalies. In practice, the difficulty of deploying such approaches limits their usefulness. Our goal is to develop a scheme that can have immediate impact today. In this light, we propose a reactive approach that can help reduce the extent and impact of routing misbehaviors.**

We develop an approach and a tool to act as an expert advisor that will flag suspicious updates. Our main motivation is that problems spread quickly, so quick reaction is imperative. Additionally, the volume of routing updates makes it impossible for humans operators to manually identify malicious updates. Our approach uses the policies that Autonomous Systems register in the Internet Routing Registries. We use the policy of an AS as found in these registries to detect deviations between the intended policy and the actual policy seen in BGP. As a proof of concept, we use the RIPE registry to monitor the European Internet routing for ten days. With our approach, we are able to confirm the validity of the origin AS of 97% of the updates, while suggesting the need for further analysis of the remaining 3% of the updates.

I. INTRODUCTION

In this work, we propose a reactive approach and present a tool to identify BGP routing misbehaviors in the Internet in order to reduce their extent and impact. The Internet has revolutionized the way people work and communicate to the extent that, in some countries, it is considered to be just another utility like electricity and water. Therefore, it is important to ensure that the Internet continues to function reliably, even in the face of attacks, exploits, and errors. A fundamental component of the Internet functionality is Internet routing and therefore, it is critical to ensure its correctness and reliability. In this paper, we investigate what is the best we can do today to improve the security of Internet routing, and propose mechanisms to reduce the extent and impact of such errors. We use the term *routing security* [1] to denote the loose concepts of correctness in BGP routing according to the intended policy as defined by the network operators. We are interested in the part of the policy that specifies which operator can originate a specific IP prefix.

G. Siganos and M. Faloutsos are with the Dept. of Computer Science & Engineering,University of California, Riverside, Email:{siganos,michalis}@cs.ucr.edu

BGP [2] has evolved in an incremental way [3] [4] [5] [6] in order to address the security requirements that threatened its robust operation, and has overcome a number of problems since its original deployment. One of the problems in BGP is the unauthorized advertisement of IP prefixes. For example, in 1997, AS7007 [7] deaggregated and advertised a large portion of the Internet, thus creating a black-hole for Internet traffic. Another abnormal routing behavior can happen with illegal traffic engineering [8]. These problems can happen either because of compromised routers, or by human error. It has been documented that BGP is especially vulnerable to human errors [9]. Configuring the routers is a difficult and tedious procedure. The tools used are usually low-level with no static checking of the correctness of the configuration and no immediate feedback control on possible errors. It is difficult to predict what will happen with a configuration change [10]. As a result, it is often done using a trial and error approach.

The incremental improvements have allowed BGP to evolve and become a very complex network. But with the significance of the network ever increasing, there is a need for more security [11] [12] [13]. A number of approaches have been proposed and IETF has established a working group, RPsec [1], to address the threats and possible solutions to secure Internet routing. The most well-known and advanced proposal is S-BGP [14], [15], which is proposed by BBN and has been in development for many years. They use Public Key Infrastructure (PKI) to authenticate every aspect of a routing message. SoBGP [16] is a new proposal by engineers that work for CISCO, a company with huge influence on the Internet. Its original goal was to allow only the authorized networks to advertise their address space. Currently, they are extending it to cover various other scenarios and threats. Other more lightweight proposals include

IRV [17], SPV [18], whisper [19], and moas [20].

Securing Internet routing is a daunting task. We need a flexible and scalable protocol and most importantly, a deployment strategy, since the Internet consists today of hundreds of thousands of routers and tens of thousands of independent networks. The current proposals have four main problems. First, in most of the cases we need significant changes in the routing protocol, i.e., BGP. Any implementation will go through an infant period with new bugs and new problems to solve. Second, most require a significant amount of processing power, and the current routers may not able to keep up. For example S-BGP increases the resources needed by 800% [15]. Third, none of the current approaches has been fully approved by the community (IETF). Additionally, there exist serious considerations [21] in determining whether the path of any path vector protocol can be verified, since a network can advertise one thing to its peers and another internally. Last, but not least these proposals focus solely on how to prevent the routing misbehaviors while completely ignore the human usability. Complex solutions can steer away operators from some very useful and probably needed approaches.

In this paper, we are interested in investigating the potential for improving the security of Internet routing today. We want to develop a tool to automate the identification of routing errors. We propose to use a reactive approach based on IRR. Our approach could alleviate easy attacks, before they become widely spread, for example AS number and IP hijackings [22]. Our approach is based on the knowledge of the intended Internet routing. If we know what Internet routing should be, we can detect abnormal routing behavior. Two components are needed to achieve this: 1) accurate information on the policy and configuration of an AS, 2) a way to detect deviations from the expected routing. The policy of an AS can be described using the RPSL language, and there exist public repositories that networks can use to publish their policy. Additionally, we need a way to monitor Internet routing. There exist a number of monitors like Routeviews [23] and the RIS [24] project in Ripe, that exist for the sole purpose of recording Internet routing for operational and research purposes. In our previous work [25], we showed how we can extract useful information from the registries. Here, we will use part of the information for the purpose of validating Internet routing.

Our contributions can be summarized as follows:

- We propose a new approach to improve the security and robustness of BGP by monitoring its operation.
- We demonstrate the efficacy of our approach by applying it to RIPE to validate the European Internet Routing.
- We analyze for 10 days the European Internet routing and examine over 4 million updates. This allow us to check the sanity of $23,210$ distinct European IP prefixes. We find that for 97% of these prefixes we can validate their origin AS in the RIPE registry.

The rest of this paper is structured as follows. In section II we present some definitions and background work. In section III we describe our framework. In section IV, we present how RIPE can use our approach to improve the security of the European Internet routing. In section V we discuss the necessary steps to make our approach even more effective and discuss about the practical potential of our tool. In section VI we present our conclusions.

II. BACKGROUND AND PREVIOUS WORK

In this section, we briefly describe an overview of Internet routing. Then, we briefly present the Internet Routing Registries and the language used to describe the routing policy.

A. Internet and BGP-4

Internet is structured into a number of routing domains that have independent administrations, called **Autonomous Systems (AS)**. Each autonomous system is identified by a number, **asn**, which is assigned to it by an Internet registry. An Autonomous System uses an intra-domain routing protocol, like OSPF or IS-IS, inside its domain, and an inter-domain protocol to exchange routing information with other Autonomous Systems. The defacto standard for inter-domain routing is **BGP-4** [2]. The primary difference between the intra-domain and the inter-domain protocol is that the first one is optimized for performance, solely based on operational requirements, while the second is used to enforce the **policy** of the Autonomous System, which corresponds to the **business relations** with its neighboring ASes.

An Autonomous System given its policy, will advertise to its neighbors a list of **IP Prefixes**, or **routes** that are reachable through it. Each route is tagged with a number of **attributes**. The most important attribute is the **AS_PATH**. The AS_PATH is the list of ASes that packets towards that route will traverse.

An AS uses **filters** to describe what it will import from and export to a neighboring AS. The filter can include a list of routes, a list of regular expressions on the AS_PATH, a list of communities, or any possible combination of these three. Filters can have both positive and negative members. For example we can explicitly reject routes that are either private [26], or reserved [27].

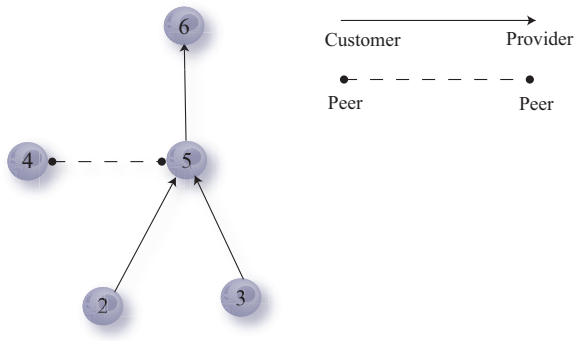

Fig. 1. A simple AS level topology.

```
as-set:     AS-5
members:    AS5, AS5:AS-CUSTOMERS
mnt-by:     AS5-MNT

as-set:     AS5:AS-CUSTOMERS
members:    AS2,AS3
mnt-by:     AS5-MNT

route:      199.237.0.0/16
origin:     AS5
mnt-by:     AS5-MNT

aut-num:    AS5
import:     from AS6 action pref = 100; accept ANY
import:     from AS4 action pref = 90;
                 accept <^AS4+ AS4:AS-CUSTOMERS*$>
import:     from AS2 action pref = 80;  accept AS2
import:     from AS3 action pref = 80;  accept AS3
export:     to AS6 announce AS-5
export:     to AS4 announce AS-5
export:     to AS2 announce ANY
export:     to AS3 announce ANY
mnt-by:     AS5-MNT
```

Fig. 2. Example of RPSL policy for Autonomous System 5

B. Internet Routing Registries and RPSL

The need for cooperation between Autonomous Systems is fulfilled today by the **Internet Routing Registries (IRR)** [28]. ASes use the **Routing Policy Specification Language (RPSL)** [29] [30] to describe their routing policy, and router configuration files can be produced from it. At present, there exist 62 registries, which form a global database to obtain a view of the global routing policy. Some of these registries are regional, like RIPE or APNIC, other registries describe the policies of an Autonomous System and its customers, for example, cable and wireless CW or LEVEL3. The main uses of the IRR registries are to provide an easy way for consistent configuration of filters, and a mean to facilitate the debugging of Internet routing problems.

The design goal of RPSL is twofold. First, RPSL provides a standard, vendor independent language, so that the policy of an AS can be published in an easy to understand format. Second, RPSL provides high level structures for a more convenient and compact policy specification. RPSL provides an abstract representation of policy, but still the policy described is based on filters on routes, on regular expressions on the AS_PATH, and on communities. There exist 12 different classes of records, that either describe portion of a policy, or describe who is administering this policy. In figures 1 and 2, we have an example topology and the corresponding RPSL records for an Autonomous System. The route class is used to register the IP prefixes or routes an AS owns and originates. The as-set and route-set classes are high level structures that can be used to group routes. For example an AS can create a route-set that will contain the routes of its customers. Finally, the aut-num class contains the import and the export policies for every neighbor of the AS. Note that every class has a mnt-by attribute that specifies the maintainer of the record. This is done for security reasons so that only the maintainer can update that record. There exist additional attributes, not shown in the figure, like the source attribute that specifies in which registry the record exists, and the changed attribute that provides the date that the record was either last updated or created. In our previous work [25], we have developed a methodology to analyze the policy register in the registries. Using our tool we can reverse engineer the policy of an Autonomous System, and check for possible errors.

III. Framework for security

We develop a framework to detect abnormal routing behavior by using the Internet Routing Registries. We first present an overview of our framework and then discuss in detail its two main components. The first component is how we process the registered policy in IRR. The second component is how we discover abnormal routing using the registered policy.

A. Problem overview

The problem we are trying to solve is the following. Assume that a router receives an update from a peer for the prefix $62.1.0.0/16$ with path $\{15623\ 702\ 1241\ 8573\}$. We want to check if the destination AS have the authorization to advertise the IP prefix? In our case is $AS8573$ authorized to advertise the prefix $62.1.0.0/16$? There can be three different valid cases. First, the AS was assigned the IP space directly from an authority like RIPE. Second, the AS is using the space that is owned by one of its providers. Third, the AS that originates the IP prefix has aggregated many shorter IP prefixes, usually of its customers, and appears to be the origin AS.

B. Detect abnormal routing behavior

To describe the intended policy of an AS, we will use the following definitions. For every AS A given its policy as described in the route, aut-num and set records, we collect the following information.

- $Origin[A]$: The list of IP prefixes AS A registers, by using the route records.
- $Links[A]$: The list of neighbors AS A registers.

Given a router C and its routing table, and the IRR that describes the policies, we want to find whether an update for prefix I and path $P_I = \{a_1, a_2, ..., a_n\}$ is valid. To test that a_n can be the origin of I either of the following should hold:

- $Origin[a_n]$ contains I.
- If $Origin[i]$ contains I, then $Links[a_n]$ contains i
- If $Origin[i]$ contains I, $Links[i]$ contains a_n.

IV. Case study: European Internet Routing(RIPE)

In this section, we show how our approach can be used to check the consistency of the European Internet routing. We study the European Internet routing since RIPE is the best maintained registry.

We start with presenting the data sets that we use and an overview of the data we process. Next, we check the origin AS of the updates, and show that RIPE contains accurate information. Finally, we check the validity of the path and we present our results.

A. Data and Methodology

We process the RIPE registry and the RIS [24] router rrc03 at AMS-IX in Amsterdam for a period of 10 days starting at June, 03, 2004. The rrc03 router had 86 active peers during that time period, and it is the best connected router among all other routers that are part of the RIS project. We start with the routing table of rrc03 collected at June, 03, 2004, and we apply the updates that the router received for the next 10 days. Additionally, during these 10 days, we download and process the IRR registries daily so that changes in IRR reflect back to our model of the intended policy. For our analysis, we are only interested for the prefixes that are assigned to RIPE by IANA [27]. The address space chunks we monitor are the following: 62/8, 80/5, 88/8, 193/8, 194/7, 212/7, 217/8. In order to analyze the prefix and path tuple, we check if the prefix is part of the prefixes administered by RIPE. We analyze the tuple only if the prefix is part of the RIPE prefixes, given that we are interested on the European Internet routing.

Using this methodology, we observe $23,210$ distinct prefixes during the time period of 10 days. In figure 3,

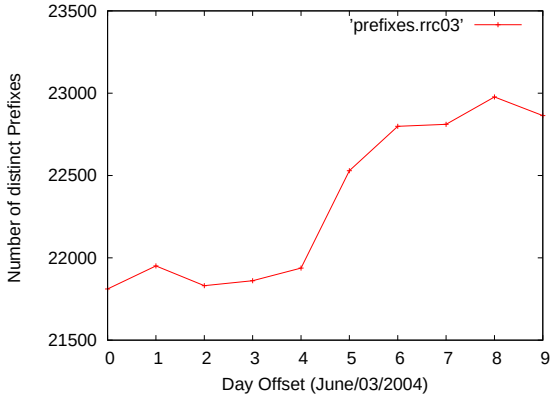

Fig. 3. The number of RIPE prefixes found in rrc03 per day.

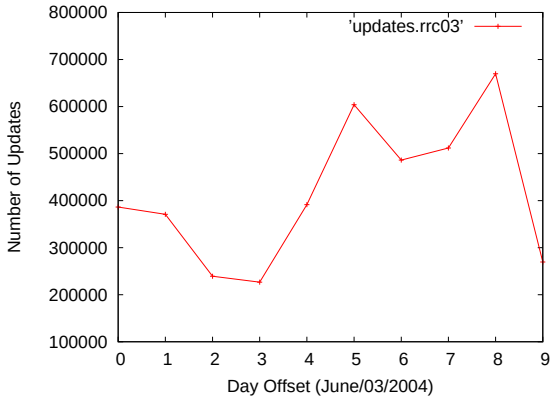

Fig. 4. The number of updates for the RIPE prefixes that we analyze.

we plot the number of prefixes that appear in the routing table of rrc03[1]. It is worth noting the difference after the 5th day, where in the duration of the next two days almost $1,000$ new prefixes were added to the routing table. The reason for this increase is that a number of ASes started advertising more specific prefixes together with the less specific one. When we started our experiment, the routing table had $21,811$ distinct prefixes during the first day, and $22,864$ during the last one. In figure 4, we plot the number of updates the router at rrc03 receives per day that are relevant to the RIPE prefixes. The peak is on the 9th day with close to $670,000$ updates, while the lowest number of updates is on the 4th day with a little over $226,000$ updates. In total, during these 10 days we processed $4,156,340$ updates plus the original $400,025$ prefix-path tuples of the routing table.

B. Origin validation

Next, we study whether we can verify with our intended policy model, the origin AS of every prefix-path tuple. In figure 5, we have the evolution of the

[1]Note that we compute the routing table by applying the updates

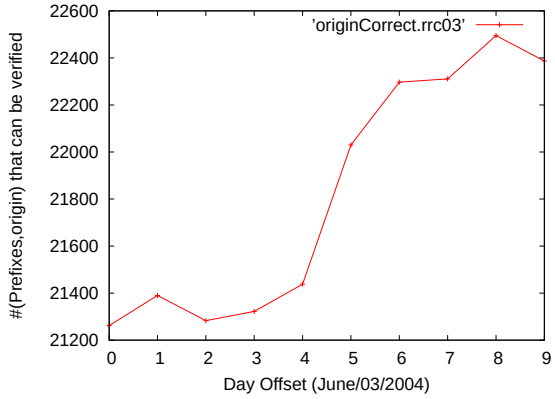

Fig. 5. The evolution of the number of prefix,origin that can be verified in RIPE.

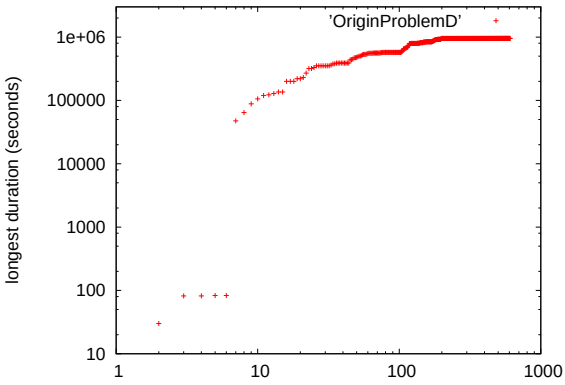

Fig. 7. The longest duration in seconds of the prefix,origin tuple that can not be verified in RIPE.

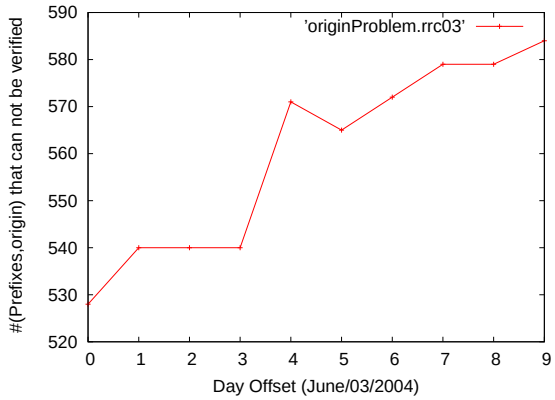

Fig. 6. The evolution of the number of prefix,origin that can not be verified in RIPE.

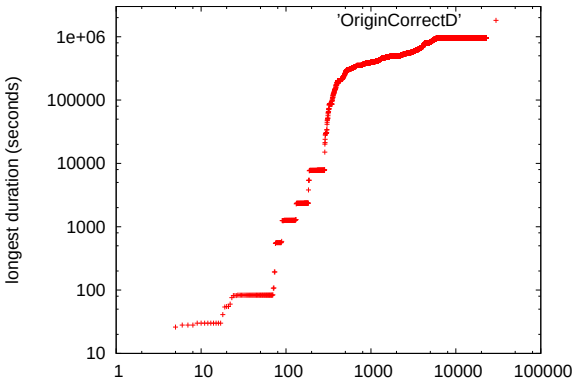

Fig. 8. The longest duration in seconds of the prefix,origin tuple that can be verified in RIPE.

number of prefix-origin tuples where the origin can be validated. The total number of the tuples that their origin can be validated is $22,791$. This means that over 97% of the tuples can be validated using the RIPE registry. As we can see in the figure, the number of tuples that we can validate is increasing with time. This is happening because in the same time period the number of prefixes we observe is increasing.

In figure 6, we have the evolution of the number of prefix-path tuples that we can not validate their origin AS. The total number of these cases is 612. As with the previous figure, we see that the number of tuples is increasing with time, again this is happening because we have more prefixes. Additionally, it seems that the problems seems to be persistant, something that indicates that we can not validate them because the registry doesn't contain the appropriate route records.

Next, we want to understand better the persistence of the errors. In figure 7, we plot the maximum continuous time we observe a prefix-path tuple with an origin mismatch. We find that only 5 cases can be classified as short-lived, something that can classify them as possible errors. These five instances appear in the routing table for less than two minutes. The next problematic origin appears continuously for over 13 hours. In figure 8, we plot the maximum continuous time we observe the prefix-path tuple for the cases where we can validate the origin AS. Again as with the previous figure, we can see that some prefix-path tuples last for an extremely small amount of time. We have 70 cases where the prefix is observed for less that 100 seconds. Currently, we don't have any explanation, but it could be interesting to try to understand why this phenomenon is happening.

To summarize our results on the origin validation phase, the percentage of 97% of the prefixes that can be validated, shows that the route records in the RIPE registry are meticulously maintained. There exist records that contain inaccurate information, but the vast majority of the records are kept accurate. One of the reasons is that the European operators use the RIPE registry to automate the generation of filters. Usually, one of the requirements for peering is to maintain route records in RIPE. Another reason is that RIPE requires the ASes to publish their route records. Additionally, they have

a number of projects to check the consistency of their registry.

V. Discussion

In this section, we discuss the vision that we have on how our approach can be deployed. In addition, we mention the advantages and benefits of our approach.

Deploying our approach: the vision. First, we need to clarify that our approach encourages and relies to some extent on collaboration between ASes, but it does not need a centrally controlled Internet. Clearly, a centrally managed Internet could be made secure if it could overcome scalability issues. However, the Internet is distributedly run for a variety of civil, business and operational reasons. Our approach is aligned with this requirement.

In our vision, IRR could become a more sophisticated database, where multiple views and various levels of access to information could be provided. For example, an AS operator could be allowed to retrieve more information about a neighbor AS and less information about a distant unrelated AS. Similarly, a network operator could have more clearance and access to details than a researcher. In other words, we can shift the security and privacy issues to the access of the IRR registry, which is something that falls into the database security and information access category.

Our approach could significantly benefit from the addition of automated consistency checking in the registries. The more accurate information the better we can detect routing problems. To this effect, the registries can have automated tools for consistency checks. For example, when one AS registers a link, while the neighbor AS does not. Note that many such checks are easy to automate [31] [32] and they can even generate notifications in a web-log or email form.

In a nutshell, the point of this work is to show the power of information sharing and collaboration. Having this, and the appropriate tools, we could automate and speed up the detection of routing errors. Implementing a secure and privacy-aware IRR infrastructure is a separate and technically feasible issue.

The advantages of our approach. We list several advantages that our approach provides. First, by automating the update validation, we decrease the window of opportunity for malicious users. If we can detect abnormal routing fast enough, we can limit the profits from illegal routing. After that, it is up to the community to find ways to act or enforce a solution through recovery mechanisms or business practices. For example, today, a spammer can hijack a route, or an AS number to send spam for a number of days or weeks, until either he is discovered, or the routes he uses are blacklisted. At that point it just hijacks another route. Second, it can limit human errors indirectly by encouraging the use of IRR and the related tools that come with it. Finally, our approach can offer limited protection against malicious users, for example terrorists, which may attempt a massive routing attack. Again, our approach could provide a quick detection of the problem and a potentially fast response, even in the form of a shutdown of affected parties.

VI. Conclusions

We develop an approach to improve the security and robustness of Internet routing with the information that exist today. Our approach has a large number of benefits. First, no changes are required in the routing protocol and therefore it can be used with minimal disruption. Second, there is no need for global cooperation, and conformance. Any number of networks that publish their policies can use our approach. Third, we increase the accountability of Internet routing and automate the discovery of routing anomalies. Fourth, monitoring of Internet routing can help us separate hype from reality. Which problems are real, how often do they appear? Convery et.al. [33], showed that even though theoretically it is possible for an external attacker to create problems like BGP spoofing, in reality it is extremely difficult to make a succesful attack.

Other practitioners have been interested in similar approaches. For example RIPE has developed a prototype, myAS [34], for a similar purpose. Their tool allows administrators to manually register the routes they want to safeguard, and their upstream providers. They use the RIS monitors to detect deviations from the registered policy, and inform the network administrator of the problems. Our approach is much more ambitious and is motivated by this question: why not use the actual RPSL records described in the RIPE registry for route validation?

We believe that our approach can be used *today* towards a more secure Internet routing. The different elements needed by our approach already exist. In conclusion, our approach can be used to protect Internet routing and automatically evaluate, with little or no human intervention, the extent of the problem before deciding to take extra steps to add security within the Internet infastructure.

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