Defending Tor from Network Adversaries: A Case Study of Network Path Prediction

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Abstract. The Tor anonymity network has been shown vulnerable to traffic analysis attacks by Autonomous Systems and Internet Exchanges who can observe different overlay hops belonging to the same circuit. We perform a case study to determine whether network path prediction techniques are suitable for avoiding such adversaries. We perform a measurement study by running traceroutes from Tor relays to destinations around the Internet. We use the data to evaluate the accuracy of the Autonomous Systems and Internet Exchanges that are predicted to appear on the path using state-of-the-art path inference techniques. We also consider to what extent overestimation can improve prediction accuracy.

Keywords: Autonomous Systems; Internet Exchanges; Tor

1 Introduction
Over the years, many efforts have sought to map and study the routing of Internet traffic. One application of such mapping is studying the threats to the Tor anonymity network. An adversary who monitors Tor traffic as it flows over the Internet can potentially violate some of the security guarantees of Tor. Previous work has studied the vulnerability of the Tor network to adversaries who may control an autonomous system (AS) or Internet exchange (IX), but has generally relied on Internet path predictions in its analysis.

We perform a measurement study to obtain a new perspective on this vulnerability and potential defenses by collecting traceroute probes performed by relays participating in the Tor network. We find that state-of-the-art AS path prediction generally performs poorly at identifying all ASes that are discovered by traceroutes, and over-approximation that considers several top predicted paths provides only limited improvement. Notably, path prediction performs significantly worse than in previous analyses, despite our simpler criteria of determining the set of ASes on a path, rather than their exact sequence, and tolerance for overestimates. We also find that techniques for predicting Internet exchanges on a path tend to grossly overestimate the number of IXes as compared to what is observed in the traceroute data.

We next analyze the impact of these prediction errors on the vulnerability of Tor to AS- and IX-level adversaries, with the help of a simulator that faithfully reconstructs Tor paths that may have been chosen by a Tor user. We find that AS and IX path prediction significantly overestimates the threat of vulnerability to such adversaries; at the same time, most users do run a significant risk of compromise by an AS-level adversary

³ https://www.torproject.org/
as determined from the traceroute data, whereas IX-level adversaries affect only a small fraction of paths.

We then modify our simulator to specifically avoid selecting paths that are vulnerable to AS or IX adversaries based on predictions; we show that this significantly limits the choice of paths and frequently results in no paths being available for use while following the Tor practice of maintaining a long-term fixed set of entries into the network. We find that many of these failures are a consequence of over-prediction, as we are often able to find suitable non-vulnerable paths in our traceroute data set despite covering only a fraction of the Tor relays. Our results strongly motivate the use of active path measurement, rather than AS path models, in further study of Tor vulnerability to AS- and IX-level adversaries and development of practical defenses.

2 Background

2.1 Tor

Tor is a popular system for anonymous communication online. Tor consists of a network of volunteer relays that form an overlay network and forward traffic sent by users running Tor clients. As of September 2014, it contains over 6,000 relays and transfers over 43 Gbps of data for over 2,000,000 users.\(^4\)

Tor uses onion routing\(^5\) to achieve anonymity. A client sets up a connection to a destination by choosing a sequence of three relays, conventionally called guard, middle, and exit, and establishing a circuit through the sequence. The client encrypts a message once for each circuit relay (a process called onion encryption) then sends it through the circuit, and each relay removes one layer of encryption before forwarding. The final relay sends unencrypted messages to the destination. The reverse process happens for messages from the destination to the client. As a result of this process, the client identity is only directly observable in traffic between the client and the guard relay, and the destination identity is only directly observable in traffic between the exit relay and the destination.

In order to be real-time and efficient, Tor does not mix, pad or delay traffic. Therefore it is vulnerable to attacks based on traffic analysis. For example, an adversary that can observe a circuit between the client and guard and also between the exit and destination can correlate the traffic patterns and deanonymize the connection\(^6\). Thus entities that can observe parts the underlying network infrastructure, such as Internet Service Providers or Internet Exchanges, are a serious threat to Tor. Previous work has shown that individual Autonomous Systems and Internet Exchanges are in fact frequently in a position to break Tor's security\(^8,9,11,12,17\). However, almost all of this analysis uses heuristic route-inference techniques whose accuracy may not be satisfactory. Murdoch and Zieliński\(^17\) do study Tor security against IXes using traceroutes from Tor relays, but that analysis is from the UK only and does not consider how IX inference can be used for global Tor security.

2.2 Internet routing

Internet routing at the highest level is performed among Autonomous Systems using the Border Gateway Protocol (BGP). An AS is a network with an opaque internal routing

\(^4\) https://metrics.torproject.org/
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policy (e.g., using OSPF, IS-IS, RIP, or iBGP) that routes traffic to and from other networks. BGP is a path-vector routing protocol, that is, neighboring networks advertise the whole AS path that they will use to send traffic to a given destination. A path is advertised for an IP prefix and represents the path used for all IP addresses sharing that prefix. Path-vector routing enables each AS to make complex routing decisions based on factors such as individual contracts with other ASes.

Understanding the behavior of such complex routing policies on the Internet is a challenging problem. Routers just propagate the routes that they provide for a given neighbor to use, and so different Internet vantage points reveal different subsets of global routing behavior. Sources of routing data include the Route Views Project\(^5\), which provides BGP routing information from many large ASes, and CAIDA Archipelago\(^6\), which provides and analyzes traceroute data from three teams of 17–18 monitors distributed worldwide. Gao describes how to use such data to infer Internet routes [10]. Gao’s method uses heuristics to classify the observed connections between ASes by their economic relationship (viz. customer-to-provider, provider-to-customer, peer-to-peer, or sibling), and then shortest-path valley-free routing is used to infer the route between two hosts. Qiu and Gao improve the accuracy of this technique by incorporating the observed advertised BGP paths [18]. In addition, they describe how to infer a set of possible paths rather than just one. Their results show that these techniques can infer the exact correct AS path for 60% of evaluation ASes; furthermore, the exact path is found within the top 5 predicted possible paths for 83% ASes and within the top 14 paths for 86% ASes.

Many links between ASes occur at Internet Exchanges. These are facilities that provide space and infrastructure for ASes to locate routers and establish connections. Ager et al. [3] describe how the largest IXes may provide links among hundreds of ASes and carry petabytes of traffic per day. Augustin et al. [5] describe how IXes on Internet routes can be detected using traceroutes and an index of known IXes and their IP prefixes. They identify 44 000 peering relationships between ASes at IXes. Each peering between two ASes indicates that some traceroute passed directly from one AS to another through an IX. Discovering such links can improve the accuracy of AS path inference techniques. However, as we will observe, it doesn’t discern among different router-level paths taken between the same two ASes, which may pass through different IXes.

The traceroute tool is extraordinarily useful in measuring routing behavior on the Internet. There are many variations of the basic algorithm [15] which provide different levels of success depending on the traffic engineering (e.g. filtering and load balancing) that occurs en route. In addition to such problems with traceroute itself, it is not always straightforward to make inferences about Internet paths from a traceroute. For example, Mao et al. [16] describe the difficulties of inferring an AS-level path from traceroutes, which include that different iterations of a single traceroute might take different paths, that reported IP addresses may be from a network interface other than the one that actually received it, and that mapping from IP address to AS number is non-trivial due

\(^5\) http://www.routeviews.org/
\(^6\) http://www.caida.org/projects/ark/
to inaccurate WHOIS information. Augustin et al. [5] discuss similar issues in inferring the presence of IXes from traceroutes.

3 Internet Path Measurement

3.1 Generating Traceroutes

Our measurement study consists of running traceroutes from Tor relays to various destinations in the Internet. We use the scamper\(^7\) network tool, which probes multiple destinations in parallel, and uses techniques to accurately discover the Internet path traversed by packets in the presence of multi-path load balancing [4, 13].

For our measurements, we extracted the set advertised destination IP prefixes from the September 2013 RIB dumps from Route Views. Each relay running the measurements picks a random IP address within each of the \(\sim 500K\) prefixes and performs a traceroute to that destination. We also collected traceroutes to Tor relay destinations as well as a scan of all /24 IPv4 subnets, but this data was not used for the analysis in this paper. We focus on advertised prefixes to make analysis more tractable. We expect addresses within a prefix to use the same or similar routes, and our analysis of CAIDA’s traceroutes to all /24 IPv4 subnets [2] found that 81% of the time traceroutes destined to the same routable prefix traversed the same set of ASes. Our measurement scripts are available for public review.\(^8\)

3.2 Processing Traceroutes

We next process the traceroutes to determine which ASes and ISPs an Internet path has traversed. First, we filter out traceroutes that do not successfully reach the destination. Note that because we use randomized destinations, in many cases the destination may not exist or may be down; indeed, only a small fraction (8%) of probes reaches their target. However, 49% reach the AS of the destination, as determined by the MaxMind GeoIP database [1].

We further find that 94% of the traceroutes are missing some hops from the path. In some cases, we believe this is caused by routers close to the probe source rate limiting their ICMP responses. To address this, we perform route stitching, where gaps in a traceroute are filled by path segments observed in other traceroutes. For example, if we see a path “A B C D E” and another path “A B * D F,” where “*” denotes a missing hop, we can repair the second path by inferring that the third hop must have also been C in this case. To minimize inaccuracies introduced by this repair mechanism, we only consider path segments that originate from the same host, and which are contained within the same batch of 64K traceroutes, which typically occur within an hour or two of each other. We validated this approach on complete paths and found that stitching would have given us the correct AS path result 96% of the time.

We then compute the ASes corresponding to each IP in the path using the GeoIP database. Similar to Mao et al. [16], we consider the corresponding AS path complete if the traceroute reached the AS of the destination and there are no missing hops in the path on the boundary between ASes. For example, an AS path “AS1 AS1 * AS1 AS2

\(^7\) [http://www.caida.org/tools/measurement/scamper/](http://www.caida.org/tools/measurement/scamper/)

\(^8\) [https://bitbucket.org/anupam_das/traceroute-from-tor-relays](https://bitbucket.org/anupam_das/traceroute-from-tor-relays)
AS3” is considered complete, because the missing hop is contained entirely within AS1, whereas “AS1 AS1 * AS2 AS3” is considered incomplete. Overall, 28% of the traceroutes yield a complete AS path. We discard the other traceroutes from our analysis.

4 Predicting Path ASes and IXes

We predict AS paths from source to destination using Gao’s algorithm [10] to classify relationships and Qiu and Gao’s algorithm [18] to infer paths. While advances have been made in classifying AS link relationships [14], we find that matching route information broadcasts is more accurate than using graph based methods based solely on AS relationships [12]. It is known that AS relationships are difficult to classify especially at the highly interconnected core of the AS graph. Violations in the valley free principle from advertised routes often indicate erroneous AS relationship classification especially through top tier ASes. Therefore Qiu and Gao’s method of pre-pending advertised routes to complete paths yields accurate results even with incorrectly classified AS relationships at the core of the internet. Since the pre-pended hops are almost entirely easily classified customer-to-provider hops at the bottom of the AS graph, improving the AS relationship classification of the top level ASes does little to improve overall AS path prediction accuracy.

The analysis of path prediction accuracy is conducted on traceroutes collected during January 19–26, 2014. We divide the traceroute data into 24-hour windows. Routing table dumps are downloaded from each server from the Route Views project from the time closest to the 12th hour of the window. Each day window contains an average of 15 prefix table dumps with between four to six gigabytes of route information broadcasts. Every unique AS source and destination pair is selected and the top five paths are predicted using Qiu and Gao’s algorithm. The top five paths are then saved and used for further analysis.

To predict the presence of IXes, we recreate the work of Augustin et al. [5]. We scraped Packet Clearing House\(^9\) and the Peering Database\(^10\) in February of 2014 creating a list of 732 Internet exchange points and their known prefixes. We parsed over 200 million traceroutes from February and March 2014 collected from both the CAIDA routed IPv4 database [2] and the iPlane project\(^11\) to map roughly 130 000 Internet exchange point peerings for our subsequent test data. This number is roughly twice the number of links found by Augustin et al. in 2009, which is unsurprising considering the trend for ASes to peer at IX points. This list of source AS, destination AS, and IX number is used to identify potential IX points on AS-level paths throughout our experiment. The list of IXes and prefixes is used to positively identify IX points in the IP traces.

5 Experimental Results

5.1 Measurement Results

We conduct analysis on 17 million traceroutes obtained from 28 Tor relay servers from January 19th to January 26th 2014 as summarized in Table 1\(^12\). Our 28 servers included

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9 http://www.pch.net
10 https://www.peeringdb.com
11 http://iplane.cs.washington.edu/
12 We extend sincere thanks to the volunteer Tor relay operators who assisted us with this study.
many of the largest Tor relays and cover a portion of the Tor network which includes 23.2% of guard node capacity and 25.55% of exit node capacity. Thus, their measurements can give us good insight into how traffic is routed in and out of Tor. Of these 17 million traces, only about 1 million reached the target IP address with roughly 250,000 complete paths with no missing IP hops. We find that roughly 9 million paths can have some hops filled in by using the repair techniques presented in section 3. We map each IP address to AS numbers using the MaxMind GeoLite ASN database taken from January 15th 2014 [1]. The AS-level paths are then parsed to remove routing loops, duplicate hops, and missing hops directly proceeded by and followed by the same AS. After processing, we attain 5.3 million complete AS-level routes.

5.2 Overall Path Prediction

For security in Tor, we are interested in the accuracy of identifying potential AS and IX adversaries. Our 5.3 million traces contain 450,000 unique AS source and destination pairs. Using Qiu and Gao’s model we predict paths for roughly 400,000 of these pairs with the rest failing due to either the source or destination AS missing from the Route-Views routing tables. The 400,000 successful path inferences cover 4.5 million of our 5.3 million traces with AS paths. Figure 2 is a CDF showing the number of ASes seen in the traceroute but missed by the top k predicted paths. Zero missing ASes correspond with a correct path prediction. Using only the top path from the prediction,
yields roughly 20% prediction accuracy with a decreasing return for higher levels of k and a maximum accuracy of 48% when considering the top 5 paths. This accuracy is far lower than the 83% accuracy for the top 5 paths attained by Qiu and Gao; however, their validation was conducted using Route-Views data as the ground truth and not traceroute data [10]. We surmise the lower accuracy is due to a combination of known error sources both from the increase in prevalence of IX peering [3] and inherent errors in traceroute measurements from actual AS-level paths [19]. We finally note that the overall accuracy of prediction is similar to our extensive analysis of accuracy against Caida traceroutes demonstrating that the Tor network would benefit from improvements to path prediction in the general case [12].

At the AS level, IX paths can only be inferred by identifying any AS-AS peering known to occur at an exchange point. Traceroutes provide better ground truth since we can identify IP hops with prefixes known to belong to IX points. Figure 1 shows the number of IXes identified in the path by finding a known IX IP prefix versus the number of IXes found by identifying known IX AS-AS peerings over the observed AS traces per each of our 28 hosts. We find that identifying IX points from AS paths provides far more false positives than correct identifications. We surmise that large ASes have multiple points of presence at many IX points, but individual traffic often takes different paths. Thus, while our list of potential IX AS-AS peerings can provide 1-5 possible IX points that could transit traffic between the ASes, in a majority of our traces, the actual traffic does not traverse that particular IX point. This is problematic for identifying IX adversaries and motivates the need for better IX identification in AS paths.

Figures 3 4 show the missing AS/IXes and extra AS/IXes seen by the path prediction algorithms for the k top paths from k = 1 to 5. We see diminishing returns for missing ASes for larger values of k. In most hosts, IX identification is helped very little by increasing the top paths. Overall, the average attainable missing AS accuracy is 1 and the average missing IX is .2 per hop; however, the low average missing IX point is due to so few IX points being seen in the traceroute traffic. False positive seem to increase linearly for ASes. False positives for IX points are problematic with averages ranging from 10-25 for our hosts illustrating the need for better methods in identifying IX points.

5.3 Specific Analysis for Tor
These errors in path prediction call into question previous work that has used path prediction to evaluate the security of Tor and that has proposed changes to Tor’s path
selection based on path prediction. Understanding the effect of the errors uncovered by our traceroute measurements requires taking into account the specific properties of Tor.

We accomplish such an analysis by simulating the Tor protocol and network at a high level. We use and adapt the Tor Path Simulator 13 (TorPS) to perform Monte Carlo simulation of Tor path selection by a single client. By using the hourly network “consensuses” and server “descriptors” archived by CollecTor 14, we can recreate the state of the Tor network over the period we run our simulations, including features such as the number, bandwidths, and addresses of Tor relays available in any given hour. We simulate “typical” user activity using the recorded volunteer trace of Johnson et al. [11], which includes user behaviors such as web search and webmail on a plausible daily schedule. Over the course of a week, this schedule results in 2632 streams (i.e. TCP connections over Tor) to one of 205 distinct IP addresses. Finally, we run simulations using the most common client ASes as measured by Juen in Fall 2011 [12].

Simulating path selection in Tor allows us to estimate which Internet hosts a user’s traffic is likely to flow over in a typical use case. Then we can use our traceroute data to determine the specific Internet routes that traffic would take and evaluate the resulting security. Specifically, we provide new estimates for how often a Tor stream flows through the same AS or IX between the client and the guard and between the destination and the exit. When this happens, the AS or IX is in a position to deanonymize the client. This issue was previously studied only using inferred AS paths and IX sets. In addition, using this method we provide an improved evaluation of the repeatedly-proposed [8, 9] modification to Tor to use AS/IX path inference to choose relays that are path independent, that is, that result in paths for which the same AS or IX cannot observe both the client and the destination. We modify TorPS to produce the first simulator for path-independent Tor (to our knowledge) that reproduces how path selection occurs over time, including features that have the potential to significantly alter the effectiveness of the path independence requirement, such as guard lists and circuit reuse. We apply our traceroute measurements to the results of these simulations to evaluate the effectiveness of path inference as a basis for path independence in Tor.

All of our Tor simulations run over the week of January 19–25, 2014. When producing and analyzing these simulations, we generally use the same data sources and inference algorithms as in Sec. 4 to produce AS paths inferences, AS-level IX inferences, and traceroute IX inferences. However instead of daily AS-path inferences, we produce inferences for 1/15/14 and 1/22/14 and use them for the first half and second half, respectively, of the simulation week. We also use the daily Route Views prefix-to-AS datasets to determine routed prefixes and to map IPs to ASes. When analyzing our simulations using traceroutes, we use all of the measurements gathered during the week of 1/19/14. In our analysis we match a traceroute to a pair of communicating hosts in Tor of the source prefix and destination prefix match. We consider clients coming from 189 of the top 200 most common client ASes (cf. [12]), because 11 of these ASes did not appear on the AS topology map inferred from Route Views data.

13 https://github.com/torps
14 https://collector.torproject.org/
AS and IX adversaries with Default Path Selection  We first conduct a simulation using the default Tor path selection algorithm. The simulator runs 800 repetitions of simulated traffic using input data from the week of January 19th-26th 2014 yielding over 2 million traffic streams per client prefix. We identify the presence of AS and IX adversaries using AS-path inference with the top three paths and our collected traceroute data from January 19th-January 26th. In total, we have inferred path information for an average of 1.7 million streams per client and traceroute information for an average of 14,280 streams per client.

Figure 5 shows the path compromise rates for AS and IX adversaries according to the traceroutes and AS-Path inference. Overall, the actual adversary threat seen from the traceroutes is significantly lower than the adversaries present through the AS-Path inference. While AS-Path inference predicts the presence of an AS adversary on anywhere from 28.7%-87.9% of the streams, actual traceroute data shows the rate to be much lower ranging from 0%-51.1%. Likewise, identifying IX points using AS-Path inference yields a compromise rate of 44.1%-94.0% but traceroute data yields a much smaller range of 0%-4.6%. Thus, AS inference significantly over-estimates the threat of both AS and IX adversaries to a Tor user.

Path-independent Tor  In order to avoid deanonymization by an AS or IX, Tor clients could attempt to choose Tor relays such that the forward and reverse paths between the client and guard are independent of the forward and reverse paths between the exit and destination, in terms of the ASes and IXes that appear. However, it is non-trivial to design a system that allows the client to do so, because he must preserve his anonymity while making this decision, and Tor should be usable even by users with little bandwidth and low-powered devices. Edman and Syverson [8] presented the first detailed proposal for solving this problem with a system that provides enough data for clients to build an AS Internet map on which to run AS-path inference (in fact, they propose a slightly less
accurate algorithm than Qiu and Gao’s for efficiency). Juen added IX inference to this idea [12].

However, using inference techniques to achieve path independence has two potential drawbacks that our simulation methodology and traceroute measurements allow us to accurately explore: (i) errors in path inference can accumulate, leading to an increasing risk of deanonymization of a given client, and (ii) each client limits himself to a small set (2–3) of guards for security against an adversary running relays, which can result in stream failure when all Tor exits violate path independence with a client’s guards. These problems are somewhat in tension, in that false negatives make (i) worse, and false positives makes (ii) worse.

Table 1(a) provides estimates for the effects on the security of path-independent Tor of path inference errors. Our traceroute data provided path information (i.e. matched both guard/client and exit/destination host pairs in either the forward or reverse direction) for nearly 9% of the simulations’ streams. Of these, between 0.16% and 0.25% were revealed to violate path independence (depending on whether the top 3 or the top 1 inferred paths were used to determine independence). While this may seem acceptably low, even one Tor deanonymization is potentially serious, and over the course of the simulated week, a client had between 3% and 10% probability of experiencing at least one path-independence violation, averaged over client locations. At one location, path independence was violated with a probability as high as 20%!

Table 1(b) shows that this insecurity cannot simply be handled by increasing the number of top possible paths from which the inferred ASes and IXes are taken. It shows that already by using the top 3 paths, 25% of requested streams failed to be constructed because exit relays could not be found that satisfied path independence with one of the client’s guards. Note that stream failures never occurred in simulation with Tor’s default path selection, and are particularly bad because the stream will not succeed until

| (a) Stream compromise | (b) Stream failures |
|-----------------------|---------------------|
|                       | Top 1 Path | Top 3 Paths | Top 1 Path | Top 3 Paths |
| Mean fraction of streams that have traceroutes | 0.0894 | 0.0897 | 0.0146 | 0.2480 |
| Mean fraction of streams with traceroutes that are w/o independence | 0.0025 | 0.016 | 0.0580 | 0.2206 |
| Min prob of at least one stream w/o independence | 0.004 | 0 | 0.7304 | 0.9829 |
| Mean prob of at least one stream w/o independence | 0.0952 | 0.0346 | 0.14 |
| Max prob of at least one stream w/o independence | 0.196 | 0.14 | 1 | 1 |

Table 2: Path-independent Tor traceroute analysis over client ASes
the Tor relay population changes sufficiently. Thus a 25% failure rate effectively makes Tor unusable for general Internet use. Moreover, we can see that every simulated client experienced at least one stream failure. By looking at our traceroute measurements, however, it appears that most of these failures are in fact not necessary. Among the failed streams for which we had traceroutes matching between the client and at least one guard and between the destination and at least one potential exit relay, 73% to 99% did not appear to share an AS or IX between the client and destination sides. Generally, our traceroutes measured only one direction on either side, and so it is possible that a common AS or IX appeared in a missing direction. However, these results strongly suggest that a better method of predicting Internet routing than current route inference techniques could support a usable path-independent Tor.

6 Limitations and Future Work

Our first round of traceroutes demonstrate the inherent errors in predicting what AS and IXes are present on a path. While the current study covers roughly 25% of the Tor network by selection probability, it still only contains 28 hosts. We plan on continuing recruitment to expand the analysis. We surmise there may be bias in the paths that do not yield AS predictions due to missing IP hops, missing IP to AS mappings, and missing advertisements from the routeviews routers, but need further analysis to determine the causes. All path inferences were done on paths from Tor relays to destinations leaving us without symmetric path information. We plan to investigate this using looking glass servers to run reverse traceroutes in real time. We plan to collect repeated measurements of successful traceroutes allowing us to measure the variability of ASes and IXes on a given path over time. Another major limitation to this work is the lack of known IX prefix spaces. We hope the research community can continue to investigate this issue.

7 Conclusions

We have presented a measurement study to evaluate the suitability of Internet path prediction algorithms to assess and mitigate the threats from network-level adversaries to the Tor network. We have found that AS-path prediction techniques significantly over-estimate ASes and IXes traversed by Tor traffic, calling into question the results of previous evaluations of the network-level adversary threat. To evaluate this threat with our new data and to evaluate the effectiveness of proposed modifications to Tor’s path selection to avoid network-level adversaries, we perform Monte Carlo simulations of both default and proposed Tor path selection. When we examine the results, we observe that Tor may currently be less vulnerable to an AS or IXP adversary than has been previously found. We also find that proposed path-selection algorithms to avoid a network adversary still leave a significant chance for users to be deanonymized over time due to the errors in path prediction, and we find that these algorithms lead to significant rates of connection failures, even though in the large majority of cases the failures could be avoided with better measurement. Thus our results suggest the importance of accurate measurement both for understanding Tor security and for improving it.
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