Anonymity on QuickSand: Using BGP to Compromise Tor

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ABSTRACT

Anonymity systems like Tor are known to be vulnerable to malicious relay nodes. Another serious threat comes from the Autonomous Systems (ASes) that carry Tor traffic due to their powerful eavesdropping capabilities. Indeed, an AS (or set of colluding ASes) that lies between the client and the first relay, and between the last relay and the destination, can perform timing analysis to compromise user anonymity. In this paper, we show that AS-level adversaries are much more powerful than previously thought. First, routine BGP routing changes can significantly increase the number of ASes that can analyze a user's traffic successfully. Second, ASes can actively manipulate BGP announcements to put themselves on the paths to and from relay nodes. Third, an AS can perform timing analysis even when it sees only one direction of the traffic at both communication ends. Actually, asymmetric routing *increases* the fraction of ASes able to analyze a user's traffic. We present a preliminary evaluation of our attacks using measurements of BGP and Tor. Our findings motivate the design of approaches for anonymous communication that are resilient to AS-level adversaries.

Categories and Subject Descriptors

C.2.0 [**Computer-communication Networks**]: General—*Security and protection*; C.2.3 [**Computer-communication Networks**]: Network Operations—*Network Management*

General Terms

Management, Measurement, Security

Keywords

BGP, Tor, anonymity system, routing dynamic, IP hijack, man-in-the-middle, MITM

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1. INTRODUCTION

Due to increased surveillance of online communications, *anonymity* systems have become a key privacy-enhancing technology. Anonymity systems enable users to communicate privately by hiding their identities from the recipient or third parties on the Internet. For example, the Tor network [14] is a popular anonymity system that serves millions of users every day using over 5000 volunteer relays [1]. Tor is used today by journalists, whistle-blowers, political dissidents, military, intelligence agencies, law enforcement, and businesses, as well as ordinary citizens [2].

Although Tor traffic is encrypted, an adversary that controls both the first and last relays in the path can deanonymize a user by correlating the timing and size of the packets. However, we argue that the large Autonomous Systems (ASes) that carry the traffic are also a serious threat. An AS, like an Internet Service Provider (ISP), can easily eavesdrop on a portion of all links, and observe any unencrypted information, packet headers, packet timing, and packet size. Recent revelations by Edward Snowden have confirmed that ASes pose a realistic threat: the NSA's Marina program stores vast amounts of metadata for up to a year [10], while the GCHQ's Tempora program buffers data for three days and metadata for 30 days [24]. In particular, Tor has been specifically targeted by such adversaries in collusion with ASes [4, 6, 7].

Tor's vulnerability to AS-level adversaries has received relatively little attention [15, 17, 21, 27]. Prior work has focused on: *(a)* inferring the *static* AS-level paths to compute the chance of a single AS observing traffic between the client and the first relay, and the last relay and the destination, *(b)* selecting paths to minimize the risk of timing-analysis attacks. But this is just the tip of the iceberg. Interdomain (BGP) routes *change* over time, placing more ASes in a good position to perform timing analysis. These routing changes happen naturally due to equipment failures and changes in routing policies. The problem grows more serious if we consider ASes that actively manipulate BGP [11, 34] to gain strategic visibility into remote communications of Tor relays. For example, an active adversary could launch a prefix hijack attack to take ownership of a Tor relay's IP prefix, or launch a prefix interception attack to become an intermediate AS for traffic destined to a Tor relay.

Interception attacks are especially dangerous, because the traffic continues to flow between the communicating hosts. BGP interceptions have become increasing common in recent years [5]. In one high-profile example, China Telecom intercepted traffic for tens of thousands of IP prefixes all over the world for around 18 minutes [3]. During this time, China Telecom would have seen packets destined to any Tor relay nodes in these address blocks. Naturally, China Telecom can always see the traffic its own customers exchange with Tor guard nodes. By putting this information together, an AS has sufficient data for an accurate timing analysis on that traffic. Of course, it is not easy to know whether BGP interceptions are intentional or accidental; the more important point is that interceptions substantially increase an AS's ability to determine what sites Tor users are accessing.

While BGP churn and BGP attacks are well known in the networking community, their impact on the security of anonymity systems like Tor is not well understood. We show that BGP routing changes, whether incidental or intentional, decreases user anonymity. In addition, we show that the adversarial AS (or set of ASes) needs only see one direction of the traffic at each end of the communication. For example, an adversary could correlate data packets from the client to the first relay with TCP acknowledgments from the server to the last relay. As such, these attacks are effective even under asymmetric routing. In fact, asymmetric routing only *increases* the security risk, by increasing the number of ASes that lie on some path (either forward or reverse) at each end of the communication.

We quantify the threat of AS-level adversaries based on a preliminary analysis from real-world Tor and BGP data, and also propose countermeasures for our traffic-analysis attacks. Overall, our work motivates the design of new approaches for anonymous communication that account for the powerful capabilities of AS-level adversaries.

2. TOR BACKGROUND

This work focuses on low-latency anonymity systems such as the Tor network [14]. Low-latency systems are suitable for interactive communications on the Internet, as they do not inject any timing delays, but are also vulnerable to timing analysis attacks. The Tor network is a popular deployed system for low-latency anonymous communication that serves millions of clients a day, and carries 8 GBps traffic. As of July 2014, the Tor network comprises more than 5000 volunteer relays all over the world [1]. Tor clients first download information about Tor relays (called network consensus) from directory servers. Tor clients then select three relays for anonymously forwarding users' traffic to the destination (source routing). Layered encryption is used to ensure that each relay learns the identity of only the previous hop and the next hop in the communications, and no single relay can link the client to the destination. To load balance the network, clients select relays with a probability that is proportional to their network capacity.

Threat model and conventional attacks: *End-to-end Timing Analysis*: It is well known that if an attacker observes encrypted traffic from a client to the first relay as well as from the final relay to the destination (or traffic from the destination to the final relay and from the first relay to the client), then it can leverage correlation between packet timing and sizes to infer the identities of clients and destinations. Typical security analysis of Tor mostly considers the threat of end-to-end timing analysis due to malicious relays. Note that this attack requires the adversary to insert a large number of malicious relays in the Tor network, and has some fundamental limitations discussed below. In this work, we focus on the threat posed by AS-level adversaries. In particular, an AS-level adversary can launch passive attacks, and is also capable of certain types of active attacks.

Long-term anonymity: When users communicate with recipients over multiple time instances, then there is a potential for compromise of anonymity at every communication instance [28, 30]. Therefore, the anonymity protection received by users degrades over time. Prior work considered this threat from the perspective of malicious relays: to defend against such long-term attacks, Tor clients choose their first hop relay from a small set of three relays (called *guards*). The set of three guard relays per client is kept fixed for about a month[1]. Without the use of guard relays, the probability of user deanonymization approaches 1 over time. With the use of guard relays, if the chosen guards are honest, then the user cannot be deanonymized for the lifetime of guards. Some of our attacks rely on the observation that even if the set of guard relays for a client stay the same across communication instances, the set of ASes on the paths between the client and the guard relays does change.

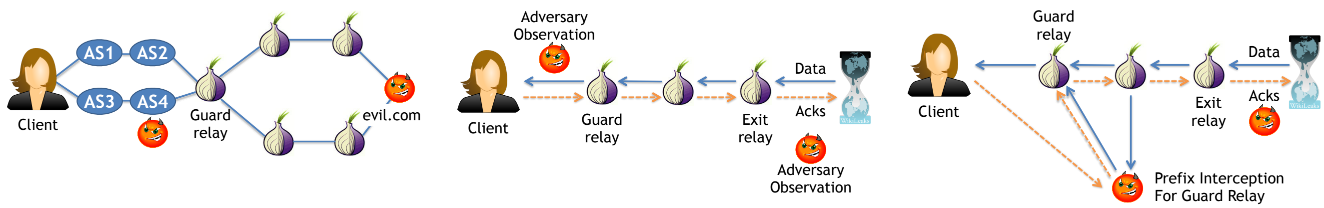
3. AS-LEVEL TRAFFIC ANALYSIS

In this section, we show how ASes can exploit natural BGP dynamics, or even launch active attacks, to compromise the anonymity of Tor users. We then discuss how seeing just one direction of the traffic for each segment (between the sender and the guard, and between the last relay and the destination) is sufficient for the adversary.

3.1 Exploiting Natural Temporal Dynamics

When communicating with recipients multiple times, a user's traffic is susceptible to adversarial analysis at each communication instance. Thus, anonymity can degrade over time. Tor's use of guard relays defends against this threat with respect to adversarial relays, but *not* against AS-level adversaries. The underlying Internet paths between a client and guard relay vary over time due to changes in the physical topology (*e.g.*, failures, recoveries, and the rollout of new routers and links) and AS-level routing policies (*e.g.*, traffic engineering and new business relationships). These changes give a malicious AS surveillance power that increases over

[1]The Tor Project is considering increasing the duration of the time period to 9 months [13].



(a) Path changes degrade anonymity (b) Asymmetric traffic analysis (c) Active BGP manipulations

Figure 1: AS-level Traffic Analysis. We show that (a) natural routing changes and (c) malicious BGP manipulations increase AS surveillance capabilities, enabling it to deanonymize Tor clients using timing/traffic analysis and (b) it suffices for an adversary to observe communication at both ends in *any* direction.

time. For example, AS 4 in Figure 1(a) does not lie on the original path from the client to the guard, but a BGP routing change can put AS 4 on the path for some period of time.

Let us suppose that the probability of any AS being malicious is f, and that the set of malicious ASes collude. Also, let us suppose that there are n AS-level paths between a client and a particular guard relay comprising x distinct ASes. Then, over time, the adversary's probability of observing the client's communication with the guard approaches $1-(1-f)^x$, *i.e.*, the probability that at least one of out of the x ASes is malicious. Observe that this probability increases *exponentially* with the number of ASes (x). Thus the adversary can deanonymize the client over time by correlating observed traffic at both communication ends.

Moreover, the Tor network uses multiple guard relays for improved availability (set to three guard relays in the current implementation). The average probability of an adversary observing communications between a client and any of the l guard relays is computed as $1-(1-f)^{l \cdot x}$. Thus, we can see that the impact of temporal dynamics (which increases the value of x) is further amplified due to the use of multiple guard relays. The severity of the problem depends on the frequency of routing changes—and the diversity of ASes on these paths. Our preliminary measurement study in Section 4 shows that routing changes do, in fact, give ASes greater power.

Effect of BGP convergence on user anonymity: The convergence process—where BGP explores multiple options before settling on a new stable path—allows even more far-flung ASes to get a (temporary) look at the client's traffic. BGP convergence, while notoriously slow, is probably fast enough to prevent these ASes from performing a successful traffic-analysis attack. Still, these ASes can learn about a client's use of the Tor network (and a particular guard)—information that can be combined with other data to implicate the client. As an example, the suspect in the recent bomb scandal at Harvard University was implicated purely due to the use of the Tor network from the Harvard campus [12]. While in this case, FBI had direct visibility into the suspect's communications, route convergence enables remote (off-path) attackers to draw similar inferences.

3.2 Manipulating Interdomain Routing

Internet routing is vulnerable to well-known attacks which enable a malicious router or AS to manipulate routing by advertising incorrect BGP control messages. Any AS could hijack a prefix [32] by advertising a particular IP prefix as its own, in which case, a fraction of Internet traffic destined to that prefix would be captured by the AS. Adversaries can exploit these vulnerabilities in several ways to compromise user anonymity:

Traffic analysis via prefix hijack: To deanonymize the user associated with a target connection (say an observed connection to the WikiLeaks website), the adversary can first use existing attacks on Tor to infer what guard relay the connection uses [19, 25, 26, 28]. Next, the adversary can learn the identity of the client by launching a prefix-hijack attack against the prefix corresponding to the discovered guard relay. The attack allows a malicious AS to see the traffic destined to the guard relay. It works by essentially blackholing all traffic destined to the guard relay, so the client's connection only remains active for a limited amount of time, after which it will be dropped. *The malicious AS can therefore learn the set of clients associated with the guard relay for the duration of the connection* (anonymity set) by inspecting the IP headers. In the Harvard example, this reduced anonymity set would already have been incriminating for the user.

Prefix hijack only enables a limited form of traffic analysis since the connection is eventually dropped. Also, a malicious AS cannot perform a man-in-the-middle attack pretending to be the guard since the Tor software is shipped with cryptographic keys of trusted directory authorities.

Traffic analysis via prefix interception: To perform exact deanonymization of the user via end-to-end traffic analysis, malicious ASes could launch a variant of the prefix hijacking attack, known as a prefix interception attack [11]. A prefix interception attack allows the malicious AS to become an intermediate AS in the path towards the guard relay, *i.e.*, after interception, the traffic is routed back to the actual destination. Such an interception attack allows the connection to be kept alive, enabling *the malicious AS to exactly deanonymize the client via timing analysis.* For example, if the flow of traffic is from the user towards the destination website (say, a file upload to WikiLeaks), then the adversary can correlate users' traffic to the guard with the target flow at the destination, and fully deanonymize the user. In case the flow of traffic is towards the client (file download from WikiLeaks), then correlation can be performed using the asymmetric traffic analysis mechanism discussed next. The latter scenario is illustrated in Figure 1(c).

In addition to prefix hijack and prefix interception, Renesys [35] recently shed light on a man-in-the-middle attack using BGP communities. Using communities, an attacker can limit the propagation of a hijacked prefix to a few ASes, in a predictable way, making the attack very hard to detect.

These attacks enable malicious ASes to deanonymize user identity corresponding to a monitored target connection. Similarly, ASes that act as the Tor client's own ISP already see the client's traffic to the guard, so they only need to intercept traffic from the exit relay to the destination. Furthermore, our attacks can be extended to perform general surveillance of the Tor network by intercepting traffic at *both* guard and exit relays. Since Tor clients select relays with a probability proportional to their bandwidth, high bandwidth relays observe a significant fraction of Tor traffic. Thus, an adversary could intercept traffic towards high bandwidth guard relays and exit relays (last hop), and perform traffic correlation to break user anonymity in Tor.

3.3 Asymmetric Traffic Analysis

In this section, we present a novel traffic-analysis attack that AS-level adversaries can use to compromise user anonymity. In particular, this attack can be used in conjunction with the previously discussed interception attacks to increase adversaries' surveillance capabilities.

Let us suppose that a Web server is sending a large file to a client. Conventional end-to-end timing analysis considers that a malicious AS observes traffic from the Web server to the last relay, as well as from the first guard relay to the client[2]. However, Internet paths are often asymmetric. The path between the Web server and the last relay may therefore differ from the opposite one. This observation has interesting consequences for traffic analysis. Given the asymmetric nature of Internet paths, we can view the conventional end-to-end attack scenario as a setting in which the adversary is able to observe traffic at both ends of the anonymous path, and in *the same direction as the flow of traffic*.

In our new traffic-analysis attack, the adversary may observe traffic at both ends of the anonymity path, but *in opposite directions to each other*. For example, our attack is applicable to the scenario where an adversary observes traffic from: *(a)* the last relay to the Web server, and first relay to the client (illustrated in Figure 1(b)), *(b)* the Web server to the last relay and client to the first relay. Note that, in scenario (b), both paths have destinations that are Tor relay nodes, meaning that an adversary can easily attack a large number of users simply by launching an interception attack on destination prefixes that include Tor relay nodes.

We call such an attack an *asymmetric traffic analysis*. In this new setting, the adversary might not be able to observe data traffic at one end of the anonymity circuit, but it can still observe TCP acknowledgement traffic. In most deployed anonymity systems, SSL/TLS encryption is used, which leaves the TCP header unencrypted. Our attack inspects TCP headers to infer the number of bytes being acknowledged using the TCP sequence number field. Our traffic-analysis attack considers the number of bytes seen in data packets at one end, the number of bytes acknowledged by TCP at the other end, and analyzes correlation between these fields over time. Note that a new correlation analysis is required here since TCP acknowledgements are cumulative, and there is not a one-to-one correspondence between packets seen at both ends of the communication.

In a more extreme variant of the attack, an adversary observes only the acknowledgment traffic at both ends of the connection. In this case, our attack correlates the number of acknowledged bytes at both ends of the path over time. Our preliminary evaluation in Section 4 shows the feasibility of such asymmetric traffic analysis.

4. PRELIMINARY RESULTS

In this section, we show that BGP temporal dynamics significantly increases AS-level surveillance capabilities and should therefore be considered during Tor relay selection. We also show the feasibility of asymmetric traffic analysis.

Methodology and datasets. We collected all the BGP updates received by 4 RIPE collectors (*rrc00*, *rrc01*, *rrc03* and *rrc04*) over more than 70 eBGP sessions during May 2014. To ensure meaningful results, we removed any artificial updates caused by BGP session resets [31]. We also collected data (IP address, flags and bandwidth) about 4586 Tor relays [1]. 1918 (resp. 891) of them were listed as *guards* (resp. *exits*) and 442 relays were listed as both guard and exit. We consider that a malicious AS aims at intercepting traffic from the destination to the last relay and from the client to the first relay as this attack only requires to intercept traffic for 2 prefixes (see Section 3.2). For each guard and exit relay, we identified the most specific BGP prefix that contained it. We refer to those as *Tor prefixes*. Overall, we identified 1251 Tor prefixes, announced by 650 distinct ASes. The distribution of the number of guard/exit relays per Tor prefix is skewed, with a median number of relay per prefix of 1, a 75th percentile of 2, and maximum of 33 (`78.46.0.0/15`[3] announced by Hetzner Online AG). All Tor prefixes were not received on all the sessions. On average, each Tor prefix was received on 40% of them with a maximum of 60%. All sessions learned at least one Tor prefix though, with a median value of 438 Tor prefixes learned (35% of total) and a maximum of 1242 (99% of total).

[2] If the traffic is flowing from the client to the server, then end-to-end timing analysis considers a scenario where the adversary observes traffic from the client to the first relay and from the last relay to the server.

[3] The prefix also hosted 22 middle nodes, for a total of 55 relays.

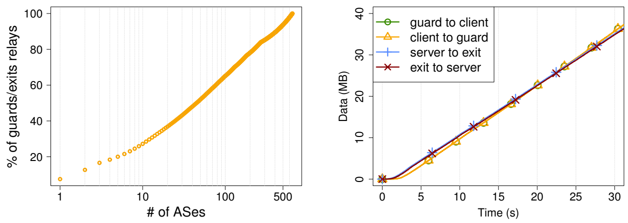


Figure 2: Tor guards and exit relays are concentrated in a handful of ASes, with just 5 ASes hosting 20% of them (left). ASes can deanonymize clients by observing traffic at both communication ends in *any* direction. The data sent from server to exit is nearly identical to the data acknowledged by the client to the guard across time (right).

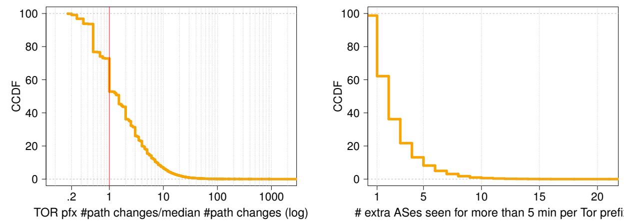


Figure 3: The BGP prefixes hosting a guard or an exit relay (Tor pfx) received on a session tend to see more path changes than other BGP prefixes, with more than 50% of them seeing more changes than the median amount (left). In more than 50% of the cases, this instability increases the surveillance capability of AS-level adversaries by increasing the amount of ASes seeing Tor traffic by at least 2 over 1 month (right).

Tor guard and exit relays are concentrated in a handful of ASes. Figure 2 (left) illustrates the lack of AS diversity among Tor guard and exit relays. A point (x, y) on the curve means that x number of ASes are hosting $y\%$ of Tor relays. Only 5 ASes host 20% of Tor guards and exit relays: Hetzner Online AG, OVH SAS, Abovenet Communications, Fiberring and Online.net. These few ASes have therefore a significant visibility into Tor communications. They also constitute a very attractive target for active BGP attacks.

Tor prefixes (hosting guards or exit relays) tend to see *more* path changes than normal BGP prefixes. We computed the number of path changes seen by each BGP prefix on each session. We define a path change as a change in the set of ASes crossed to reach a BGP prefix (as indicated by the AS-PATH) between two subsequent BGP UPDATEs. Figure 3 (left) plots the number of path changes seen by Tor prefixes on a session divided by the median number of changes seen by any BGP prefix on the same session. Results are presented as Complementary Cumulative Distribution Functions (CCDFs).

More than 50% of the time Tor prefixes saw more changes than any BGP prefix (ratio greater than one) on a session. One Tor prefix (`178.239.176.0/20`), hosting one guard relay (`178.239.177.19`), saw more than 2000 times more path changes than the median case on a session. Over the month, that session saw not less than 36 distinct paths, defined over 30 ASes, for that particular Tor prefix. Interestingly, 90% of the Tor prefixes saw more changes than the median case on at least one session, meaning they experienced at least some local disturbance over the month.

BGP temporal dynamics significantly increase AS-level surveillance capabilities. As a second step, we computed how many additional ASes were seeing traffic directed to a Tor prefix as a result of BGP temporal dynamics. As baseline, we considered the first path that was used at the beginning of the month and computed the number of extra ASes that were crossed over the month. To be fair, we did not consider an AS if it was crossed for less than 5 minutes as it is anyway unlikely that an attack can be performed on such a short timescale. The right part of Figure 3 describes the results as a CCDF. In 50% of the cases, the number of ASes seeing Tor traffic increased by 2 over the month. In 8% of the cases, the number of ASes increased by more than 5. Such increases are actually significant as the number of ASes crossed in the Internet is around 4, on average [23].

Asymmetric traffic analysis is feasible. We performed a wide-area experiment over the Tor network using a Tor client and an Apache web server. The Tor client and server were chosen in different geographical locations. We used the `torsocks` program at the client to tunnel wget requests over Tor, and downloaded a large file from the web server. We used `tcpdump` to collect data at the server and the client, and show the number of MBs sent or acknowledged (computed by inspecting TCP headers) at various segments of the path in Figure 2 (right). We can see that data sent or acknowledged at all 4 segments is nearly identical across time. Thus, it suffices for an AS-level adversary to observe traffic at both ends of the communication in *any* direction.

5. COUNTERMEASURES

Limiting impact of BGP dynamics: To minimize opportunities for AS-level traffic analysis, the Tor network can monitor the path dynamics between the clients and the guard relays, and between the exit relays and the destinations. Information about path dynamics can be obtained using data-plane (*e.g.*, `traceroute`) or control-plane (*e.g.*, BGP feed) tools. For instance, each relay could publish the list of any ASes it used to reach each destination prefix in the last month. This information can be distributed to all Tor clients as part of the Tor network consensus data. Tor clients can use this data in relay selection, perhaps in combination with their own traceroute measurements of the forward path to each guard relay. For example, Tor clients should select relays such that the same AS does not appear in both the first and the last segments, after *taking path dynamics into account*.

Detecting and reacting to routing manipulations: We can extend the data-plane and control-plane based monitoring framework to perform *real-time* monitoring of prefixes corresponding to the Tor relays. For that, the monitoring framework can leverage classical techniques for detecting prefix hijacks and interception attacks [11, 22, 29, 32–34]. For anonymity systems, false positives are much more acceptable than false negatives, so we can afford to be aggressive in classifying anomalies as attacks, rather than risking compromising anonymity. If the monitoring system has a suspicion that a relay might be under attack, this information can be broadcasted through the Tor network, so clients can avoid selecting this relay.

Favoring relays with shorter AS-PATHs: BGP control-plane monitoring is particularly effective at detecting attacks in which the adversary advertises a more-specific prefix for the victim relay, as all ASes would eventually see the bogus announcement. However, the adversary could use stealthier attacks, such as advertising an existing prefix or using recent BGP community attacks [35]. These attacks affect only ASes that have relatively long paths to the legitimate destination AS, since other ASes will tend to favor the (shorter) route to the real destination. Thus, Tor clients can mitigate such routing manipulations by preferring guard relays with shorter AS-PATHs. Still, the client should balance this strategy with the need to limit the number of guard relays, to protect against conventional attacks on long-term anonymity.

Mitigating asymmetric traffic analysis: Using IP-layer encryption (*e.g.*, IPsec) rather than SSL/TLS would thwart our asymmetric traffic-analysis attack, by hiding the TCP sequence numbers from the adversarial ASes. However, using IPsec would come at a significant cost; because IPsec is not widely used, it makes Tor traffic much easier to identify, and limits its applicability for important applications such as censorship-resilient communications.

6. RELATED WORK

AS-level adversaries: Most security analysis of anonymity systems focuses on the threat of end-to-end timing analysis by malicious or compromised relays/proxies. The existing literature on AS-level adversaries is more limited. Feamster and Dingledine [17], and later Edman and Syverson [15] explored this aspect, and considered the probability of a single AS being on the path between a client and the first relay as well as on the path between the last relay and the destination, using the AS-level path simulator of Gao *et al*. [18]. Recently, Johnson *et al*. [21] analyzed the impact of such attacks using user-understandable metrics for anonymity, and Akhoondi *et al*. [8] considered path selection algorithms that minimize opportunities for AS-level end-to-end traffic analysis. Finally, Murdoch *et al*. [27] considered the analogous analysis with respect to Internet exchange level adversaries, which are also in a position to observe significant fraction of Internet traffic. We build upon prior work in this domain, and show increased surveillance capabilities of AS-level adversaries, due to BGP path changes, active routing attacks, and asymmetric traffic analysis.

Tor traffic analysis: There is an exciting thread of research that aims to investigate the traffic analysis attacks on anonymity systems such as Tor. For example, Murdoch and Danezis [26] showed how a remote adversary could congest a Tor relay by sending traffic, and observe the impact of the impact of congestion on other flows to infer the relay's membership in an anonymity channel (also known as a circuit). Evans *et al*. [16] and Jansen *et al*. [20] show how an adversary could exploit protocol level details to cause similar relay congestion (and even shutdown) with minimal resources. The work of Mittal *et al*. [25] and Hopper *et al*. [19] further studies the impact of leveraging network level characteristics such as circuit throughput and latency to make probabilistic inferences about Tor relays and clients that are part of a target anonymity circuit. Most of the above attacks are only able to provide probabilistic information about Tor relays, and do not fully de-anonymize the actual clients. In contrast, we show that a remote adversary can fully de-anonymize Tor clients by actively manipulating inter-domain routing.

Other work: There has been a lot of work on prefix hijack attacks [29,32–34], and prefix interception attacks [11], but we are the first to analyze the implications of these attacks on privacy technologies such as anonymous communication. Recent work by Arnbak and Goldberg [9] discusses surveillance possibilities by AS-level adversaries from a legal perspective, but does not focus on anonymity systems.

7. CONCLUSION

The security of privacy technologies like Tor depends on how the underlying Internet infrastructure delivers traffic. In this paper, we show that normal BGP routing changes greatly increase the likelihood that an AS (or set of colluding ASes) can perform traffic-analysis attacks, and ASes can easily manipulate BGP to gain even wider visibility into user traffic. In fact, the adversary need only lie on one direction of each path, between the client and guard and between the last relay and the server. Our initial experiments illustrate that these vulnerabilities can be easily exploited in practice.

Improvements in BGP security can go a long way toward addressing the most serious concerns. However, deployment of BGP security solutions—and particularly techniques that prevent interception attacks—has proven challenging. We hope that the concerns we raise about compromises of user anonymity help build much-needed momentum for improving BGP security in the long term, and real-time detection of BGP anomalies in the short term. In our future work, we plan to (a) conduct a more extensive measurement study, including an analysis of recent BGP interception attacks on Tor prefixes, and (b) study the design of a real time monitoring framework for secure path selection in Tor.

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8. REFERENCES

[1] Tor metrics portal. https://metrics.torproject.org. Accessed, July 2014.

[2] Who uses Tor? https://www.torproject.org/about/torusers.html.en. Accessed, July 2014.

[3] Chinas 18-minute mystery, Nov. 2010. Renesys Blog Posting, http://www.renesys.com/2010/11/chinas-18-minute-mystery/.

[4] How the NSA attacks Tor/Firefox users with QUANTUM and FOXACID. https://www.schneier.com/blog/archives/2013/10/how_the_nsa_att.html, Oct. 2013.

[5] The new threat: Targeted Internet traffic misdirection, Nov. 2013. Renesys Blog Posting, http://www.renesys.com/2013/11/mitm-internet-hijacking/.

[6] Peeling back the layers of Tor with EgotisticalGiraffe. http://www.theguardian.com/world/interactive/2013/oct/04/egotistical-giraffe-nsa-tor-document, Oct. 2013.

[7] Tor stinks. http://www.theguardian.com/world/interactive/2013/oct/04/tor-stinks-nsa-presentation-document, Oct. 2013.

[8] M. Akhoondi, C. Yu, and H. V. Madhyastha. Lastor: A low-latency AS-aware Tor client. In *Proceedings of the 2012 IEEE Symposium on Security and Privacy*, SP '12, pages 476–490, Washington, DC, USA, 2012. IEEE Computer Society.

[9] A. Arnbak and S. Goldberg. Loopholes for circumventing the constitution: Warrantless bulk surveillance on americans by collecting network traffic abroad. In *HotPETs*, 2014. Available at http://ssrn.com/abstract=2460462.

[10] J. Ball. NSA stores metadata of millions of web users for up to a year, secret files show. http://www.theguardian.com/world/2013/sep/30/nsa-americans-metadata-year-documents, Sep. 2013.

[11] H. Ballani, P. Francis, and X. Zhang. A study of prefix hijacking and interception in the Internet. In *Proceedings of the 2007 Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications*, SIGCOMM '07, pages 265–276, New York, NY, USA, 2007. ACM.

[12] R. Brandom. FBI agents tracked harvard bomb threats despite Tor. http://www.theverge.com/2013/12/18/5224130/fbi-agents-tracked-harvard-bomb-threats-across-tor. Accessed, July 2014.

[13] R. Dingledine, N. Hopper, G. Kadianakis, and N. Mathewson. One fast guard for life (or 9 months). In *HotPETs*, 2014.

[14] R. Dingledine, N. Mathewson, and P. Syverson. Tor: The second-generation onion router. In *Proceedings of the 13th Conference on USENIX Security Symposium - Volume 13*, SSYM'04, Berkeley, CA, USA, 2004. USENIX Association.

[15] M. Edman and P. Syverson. AS-awareness in Tor path selection. In *Proceedings of the 16th ACM Conference on Computer and Communications Security*, CCS '09, pages 380–389, New York, NY, USA, 2009. ACM.

[16] N. S. Evans, R. Dingledine, and C. Grothoff. A practical congestion attack on Tor using long paths. In *Proceedings of the 18th Conference on USENIX Security Symposium*, SSYM'09, pages 33–50, Berkeley, CA, USA, 2009. USENIX Association.

[17] N. Feamster and R. Dingledine. Location diversity in anonymity networks. In *Proceedings of the 2004 ACM Workshop on Privacy in the Electronic Society*, WPES '04, pages 66–76, New York, NY, USA, 2004. ACM.

[18] L. Gao. On inferring autonomous system relationships in the Internet. *IEEE/ACM Trans. Netw.*, 9(6):733–745, Dec. 2001.

[19] N. Hopper, E. Y. Vasserman, and E. Chan-TIN. How much anonymity does network latency leak? *ACM Trans. Inf. Syst. Secur.*, 13(2):13:1–13:28, Mar. 2010.

[20] R. Jansen, F. Tschorsch, A. Johnson, and B. Scheuermann. The sniper attack: Anonymously deanonymizing and disabling the Tor network. In *Proceedings of the 21st Annual Network and Distributed System Security Symposium (NDSS '14)*. Internet Society, 2014.

[21] A. Johnson, C. Wacek, R. Jansen, M. Sherr, and P. Syverson. Users get routed: Traffic correlation on Tor by realistic adversaries. In *Proceedings of the 2013 ACM SIGSAC Conference on Computer and Communications Security*, CCS '13, pages 337–348, New York, NY, USA, 2013. ACM.

[22] J. Karlin, S. Forrest, and J. Rexford. Autonomous security for autonomous systems. *Computer Networks*, Oct. 2008.

[23] M. Khne and V. Asturiano. Update on as path lengths over time. https://labs.ripe.net/Members/mirjam/update-on-as-path-lengths-over-time.

[24] E. MacAskill, J. Borger, N. Hopkins, N. Davies, and J. Ball. GCHQ taps fibre-optic cables for secret access to world's communications. http://www.theguardian.com/uk/2013/jun/21/gchq-cables-secret-world-communications-nsa, June 2013.

[25] P. Mittal, A. Khurshid, J. Juen, M. Caesar, and N. Borisov. Stealthy traffic analysis of low-latency anonymous communication using throughput fingerprinting. In *Proceedings of the 18th ACM Conference on Computer and Communications Security*, CCS '11, pages 215–226, New York, NY, USA, 2011. ACM.

[26] S. J. Murdoch and G. Danezis. Low-cost traffic analysis of Tor. In *Proceedings of the 2005 IEEE Symposium on Security and Privacy*, SP '05, pages 183–195, Washington, DC, USA, 2005. IEEE Computer Society.

[27] S. J. Murdoch and P. Zieliński. Sampled traffic analysis by Internet-exchange-level adversaries. In *Proceedings of the 7th International Conference on Privacy Enhancing Technologies*, PET'07, pages 167–183, Berlin, Heidelberg, 2007. Springer-Verlag.

[28] L. Overlier and P. Syverson. Locating hidden servers. In *Security and Privacy, 2006 IEEE Symposium on*, pages 100–114, May 2006.

[29] X. Shi, Y. Xiang, Z. Wang, X. Yin, and J. Wu. Detecting prefix hijackings in the Internet with Argus. In *Proceedings of the 2012 ACM Conference on Internet Measurement Conference*, IMC '12, pages 15–28, New York, NY, USA, 2012. ACM.

[30] M. Wright, M. Adler, B. N. Levine, and C. Shields. Defending anonymous communications against passive logging attacks. In *Proceedings of the 2003 IEEE Symposium on Security and Privacy*, SP '03, Washington, DC, USA, 2003. IEEE Computer Society.

[31] B. Zhang, V. Kambhampati, M. Lad, D. Massey, and L. Zhang. Identifying BGP routing table transfer. *SIGCOMM 2005 MineNet Workshop*, August 2005.

[32] Z. Zhang, Y. Zhang, Y. C. Hu, and Z. M. Mao. Practical defenses against BGP prefix hijacking. In *Proceedings of the 2007 ACM CoNEXT Conference*, CoNEXT '07, New York, NY, USA, 2007. ACM.

[33] Z. Zhang, Y. Zhang, Y. C. Hu, Z. M. Mao, and R. Bush. iSPY: Detecting IP prefix hijacking on my own. *IEEE/ACM Trans. Netw.*, 18(6):1815–1828, Dec. 2010.

[34] C. Zheng, L. Ji, D. Pei, J. Wang, and P. Francis. A light-weight distributed scheme for detecting IP prefix hijacks in real-time. In *Proceedings of the 2007 Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications*, SIGCOMM '07, pages 277–288, New York, NY, USA, 2007. ACM.

[35] E. Zmijewski. The end of undetected BGP route hijacking. http://www.renesys.com/wp-content/uploads/2014/05/Linx851.pdf, May 2014.