Holding all the ASes: Identifying and Circumventing the Pitfalls of AS-aware Tor Client Design

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ABSTRACT
Traffic correlation attacks to de-anonymize Tor users are possible when an adversary is in a position to observe traffic entering and exiting the Tor network. Recent work has brought attention to the threat of these attacks by network-level adversaries (e.g., Autonomous Systems). We perform a historical analysis to understand how the threat from AS-level traffic correlation attacks has evolved over the past five years. We find that despite a large number of new relays added to the Tor network, the threat has grown. This points to the importance of increasing AS-level diversity in addition to capacity of the Tor network.

We identify and elaborate on common pitfalls of AS-aware Tor client design and construction. We find that succumbing to these pitfalls can negatively impact three major aspects of an AS-aware Tor client – (1) security against AS-level adversaries, (2) security against relay-level adversaries, and (3) performance. Finally, we propose and evaluate a Tor client – Cipollino– which avoids these pitfalls using state-of-the-art in network-measurement. Our evaluation shows that Cipollino is able to achieve better security against network-level adversaries while maintaining security against relay-level adversaries and performance characteristics comparable to the current Tor client.

1. INTRODUCTION
As governments and organizations increase their commitment to mass surveillance and online tracking, the Tor anonymity network has become the de facto technology for preserving anonymity and privacy on the Internet with nearly two million daily users [1]. Tor’s popularity has made it a prime target for attacks and also increases the importance of improving its defenses. In this paper, we focus on a long-standing class of attacks known as traffic-correlation attacks. In a traffic-correlation attack, an adversary correlates the characteristics of traffic (e.g., packet sizes, inter-packet timings, etc.) entering and exiting the Tor network. Successfully correlating these flows results in the de-anonymization of Tor users – i.e., it becomes possible to identify the destination server being contacted by a Tor user.

Traffic correlation attacks have been known about for over a decade [2] but as our study shows, Tor is still incredibly vulnerable. Worse yet, the recent Snowden leaks have confirmed that the NSA and GCHQ, in collusion with several Internet Service Providers (ISPs), have actively been working to implement network-level attacks in the wild [3][4][5]. In order to launch a traffic correlation attack, an adversary needs to be able to observe network traffic on (1) the path between the Tor user and the entry (relay) to the Tor network and (2) the path between the exit (relay) from the Tor network to the destination server. Such attacks have been shown to be feasible for both, relay-level adversaries [6][7][8] and network-level adversaries such as Autonomous Systems (ASes) [2][9][10][11][12][13].

While the problem of relay-level traffic-correlation attacks have been mitigated and solutions have been integrated into the current Tor client [14][15], the problem of defending against network-level traffic-correlation attacks remains unsolved. While numerous defenses have been proposed [2][16][17][18], none have been successfully adopted in practice. We identify five pitfalls that render existing AS-aware Tor clients insecure, impractical, or both. We characterize the impact of these pitfalls and propose a modified Tor client that is able to mitigate them.

In this paper we make three major contributions.

Measuring the threat (Section 3). We perform a current and a historical analysis to understand how the threat from AS-level adversaries has evolved over the past five years. From these measurements, we make the following observations:

- When considering Tor clients used specifically for the purpose of loading webpages, 31% of the circuits constructed by the Tor client in our experiments were found to be vulnerable to AS-level correlation attacks. However, due to aggressive circuit re-use by the Tor client, 58% of the websites loaded in our experiments were vulnerable to de-anonymization. When considering Tor clients used for a mix of applications (Web, BitTorrent, IRC, email, etc.), 30% of the circuits were found
to be vulnerable.

- From our historical analysis, we find that the threat faced by Tor clients has grown. In the context of clients used for loading webpages, we found the number of vulnerable circuits used by the client increased from 38% (2010) to 41% (2015). In the context of clients used for a mix of applications, we found the number of vulnerable circuits increased more drastically - from 21% (2010) to 35% (2015). These results show that the threat has been increasing in spite of a massive growth in the size of the Tor network.

Evaluating existing defenses (Section 4). We identify five pitfalls in the design of AS-aware Tor clients: (1) a lack of accurate Internet path data, and not considering (2) the impact of asymmetric routing on the Internet, (3) the impact of BGP hijack and interception vulnerabilities, (4) relay-level adversaries, or (5) capacity of Tor relays. We characterize how these pitfalls impact the security and performance of existing AS-aware solutions.

Improving security and performance of AS-aware Tor (Section 5). Based on our evaluation, we design and construct Cipollino, an AS-aware Tor client which carefully avoids previous pitfalls while improving security and performance, compared to the current state-of-the-art. In particular, we show that only 1.4% of all the webpages loaded by the Cipollino client were vulnerable to AS-level attacks, compared to 55% with the vanilla Tor client. Further, Cipollino reduces the attack surface for relay-based adversaries by 80% relative to the state-of-the-art AS-aware Tor client (Astoria). Finally, in terms of performance, the Cipollino client achieves median page-load times that are seven seconds faster than the Astoria Tor client and only 1.6 seconds slower than the vanilla Tor client.

2. BACKGROUND

In this section, we overview the current state of Tor relay selection and circuit construction algorithms. Then we present our adversary model which considers active and passive network-level traffic correlation attacks.

2.1 The Tor anonymity network

Tor is a low-latency onion routing network that currently consists of 7.1K relays and has nearly two million daily users [1]. When a user connects to a destination server via the Tor client, the client typically establishes the connection using a nested and encrypted three relay circuit. The first relay, called the entry-relay, communicates directly with the Tor user. The last-relay, called the exit-relay, communicates directly with the destination server. The key idea is that no single relay is simultaneously aware of the identities of both, the source (Tor user) and destination of the circuit.

**Tor relay selection.** The three relays in a Tor circuit are selected according to the following constraints [19]: (1) no relay may be selected twice in the same circuit, (2) no two relays belonging to the same family (advertised by the relays) may be selected as part of the same circuit, and (3) no two relays belonging to the same /16 subnet may be chosen as part of the same circuit.

In addition to the above constraints, Tor is (by default) configured to select an entry-relay from a restricted set of guard relays that are stable and have good performance metrics. When the Tor client is configured to use guards as entry-relays, it maintains an ordered list of guards and selects the first usable (online) relay in this list to serve as its entry-relay [15]. Guards help mitigate the threat of relay-level attacks such as the predecessor attack [20], selective denial-of-service attacks [21], and relay-level correlation attacks [8]. For the middle- and exit-relay positions in the circuit, relays are selected based on their available bandwidths. While the middle-relay is selected from the set of all available relays, exit-relays are chosen from a smaller subset of relays which have an exit flag. Since relays are chosen with probability proportional to their available bandwidths, the problem of overloading small sets of relays is avoided.

**Circuit construction and usage.** Since relays willing to serve as Tor exits have the ability to specify which ports and IP addresses they are not willing to establish connections to, not all circuits constructed by a Tor client are usable for incoming connection requests. To deal with this, the Tor client pre-emptively constructs circuits so that at least two are available for every destination port seen in the past hour. This allows connection requests to be served by existing circuits as soon as they are received. In the event that the client receives a request that cannot be satisfied by any available circuit, it constructs a new circuit using an exit-relay that can serve the IP and port specific to that request.

2.2 Adversary model

As a pre-condition to launch network-level correlation attacks, an attacker (e.g., an Autonomous System (AS)) needs to be present on one of the paths entering the Tor network and one of the paths exiting it. Figure 1 illustrates this condition. Here, to de-anonymize a Tor client, an AS needs to be present on one of the solid path segments and on one of the dashed path segments.

More formally, if \( P_{SRC\rightarrow EN} \) is the set of ASes on the forward and reverse paths between the Tor client (source) and the selected Tor entry-relay and similarly, \( P_{EX\rightarrow DST} \) is the set of ASes on the paths between the selected Tor exit-relay and the destination, then we say that a Tor circuit is vulnerable to de-anonymization via...
Figure 1: Condition required for launching traffic-correlation attacks: An AS needs to be present on one of the two solid path segments – i.e., path segment A or B – and on one of the two dashed path segments – i.e., path segment C or D.

traffic-correlation if there is some AS $A$ such that:

$$A \in \{P_{SRC\rightarrow EN} \cap P_{EX\rightarrow DST}\}$$  \hspace{1cm} (1)

An adversarial AS may satisfy Equation ?? through passive or active means.

**Passive adversaries.** An AS may find itself in a position to launch a traffic-correlation attack simply as a result of the AS-level topology and the relationships (i.e., customer-provider or peer-peer) it shares with other ASes. In order to defend against attacks from passive adversaries, it is sufficient to have an accurate snapshot of the ASes that occur in the sets $P_{SRC\rightarrow EN}$ and $P_{EX\rightarrow DST}$ for each choice of $EN$ and $EX$. Given this information, a correlation attack can be avoided by simply selecting an entry- and exit-relay for which there is no AS $A$ which satisfies Equation ?? (if such an entry- and exit-relay combination exists).

**Active adversaries.** Due to the dynamics and insecurities of the BGP protocol, ASes may also actively seek to place themselves in a position to launch traffic-correlation attacks. For example, an AS may hijack or intercept traffic sent to the prefix associated with the client, entry-relay, exit-relay, or destination server. Such targeted hijacks and interceptions potentially allow adversaries to place themselves on any of the four paths illustrated in Figure 1. Defending against such adversaries is more challenging due to need for access to real-time control-plane data to identify AS that are likely to be hijacking or intercepting traffic. This is in addition to the snapshots of AS-level paths required for defending against passive adversaries.

### 3. MEASURING THE THREAT

In this section we describe our methodology for measuring the potential threat from AS-level adversaries. We use a combination of live experiments on the current Tor network and simulations that capture a variety of user workloads on snapshots of the Tor network from 2010 to 2016. Table 1 summarizes our experimental setup.

| Period     | Setting       | Workload     | Streams Tested |
|------------|---------------|--------------|----------------|
| 2016       | Live          | Web model    | 215K           |
| 2016       | Simulated     | mixed model  | 12M            |
| 2010 - 15  | Simulated     | Web model    | 145M           |
| 2010 - 15  | Simulated     | mixed model  | 1.9B           |

Table 1: Summary of our experiments to study the threat posed by AS-level adversaries.
3.2 Workload models

When the Tor client selects relays for a circuit, it may only select exit relays that have agreed to transport the type of traffic to be sent over the circuit (e.g., some exits restrict commonly abused ports such as port 25 – SMTP). As a result, the vulnerability of the Tor client can depend on the applications used by the Tor user. We consider two different client workloads described below.

Web model. For each experiment using the web user model, 200 websites were loaded by the Tor client. The list of 200 websites were dependent on the client location – i.e., comprised of the local Alexa Top 100 sites [26] and 100 country-specific sensitive (likely to be blocked or monitored) webpages obtained from the Citizen Lab testing list repository. In the case of simulated Tor clients, streams that were used as input to the TorPS simulator were constructed using the IPs and ports observed in the live experiments.

Mixed (application) model. For each experiment considering a mixed user model, we considered clients that used Tor for a mix of Web, P2P (BitTorrent), e-mail and IRC chat for an hour long period. The purpose of these experiments was to understand if the security of the Tor client was affected when users required connections to non-HTTP(S) ports.

3.3 Identifying vulnerable circuits

To measure the threat posed by network-level attackers, we need to be able to identify the different networks (i.e., ASes) traversed by packets sent between the Tor entry- / exit-relay and client / destination server. However, ISPs generally treat their routing information and relationships as trade secrets, making predictions based on simulations inaccurate. To mitigate this problem, we use a novel path prediction tool – PathCache [27]. The main idea behind PathCache is to perform AS-level path prediction by utilizing existing publicly available measurements obtained from data-plane measurement platforms such as RIPE Atlas [28], iPlane [29], CAIDA Ark [30], and control-plane measurement platforms such as RouteViews [31], RIPE RIS [32], and many others.

In the remainder of our experiments, we consider a circuit constructed by a Tor client to be vulnerable if the set of ASes $A$ in Equation ?? is non-empty. Here, we use the PathCache framework to identify the ASes on $P_{SRC\leftrightarrow EN}$ and $P_{EX\leftrightarrow DST}$.

3.4 How vulnerable is the Tor client to AS-level adversaries?

M1: Measuring vanilla Tor’s vulnerability to AS-level adversaries (web model). In this experiment we measured the fraction of vulnerable circuits constructed by the vanilla Tor client and the fraction of websites that use one of these vulnerable circuits. The results, for each of the ten countries, are illustrated in Figure 2. The experiments were conducted using a VPN vantage point in each of the ten countries, while loading 200 webpages (from each).

Observation: While only 31% of the circuits constructed by the Tor client are vulnerable to AS-level adversaries, we find that due to aggressive circuit reuse and concentration of websites in a few ASes, that a larger fraction (58%) of all websites loaded by the clients end up using a vulnerable circuit.

M2: Measuring current vulnerability to AS-level adversaries (mixed model). In this experiment we measured the fraction of vulnerable circuits constructed by the vanilla Tor client when it was used for a mix of loading webpages, sending email, communicating via IRC chat, and downloading files using BitTorrent. The results for each of the ten countries are illustrated in Figure 3. The experiments were simulated using the TorPS simulator and a user model based on streams generated by the above applications. 100 of the most populous (in terms of end-users) ASes [24] in each of the ten countries were selected as Tor client locations.

Observation: We find that although the average vulnerability of mixed application clients (30%) in the countries is similar to web-only clients (31%), the average vulnerability of clients in DE, FR, and UA are most affected by considering mixed application traffic. This
implies that the few exit-relays that allow communication over non-HTTP(S) ports enable at-least one AS to perform a traffic correlation attack, given clients located in these countries.

3.5 How has the vulnerability evolved as the Tor network has grown?

M3: Measuring historical vulnerability to AS-level adversaries (web model). In this experiment we measured the fraction of vulnerable circuits constructed by the vanilla Tor client when loading 200 webpages from each of our ten countries, while considering the changing landscape of the Tor ecosystem between 2010 and 2015. In each country we consider clients located in the 100 most populous ASes [24]. Figure 4 illustrates our results. Here, we show the average fraction of vulnerable circuits for clients in all 1000 ASes, the country whose 100 ASes had the least average vulnerability (FR), and the country whose 100 ASes had the highest average vulnerability (CN).

Observation: Most countries have an average of 25-45% of their circuits remaining vulnerable to AS-level attackers. China is an exception with an average of 50-60% of their circuits remaining vulnerable. Further, in spite of the addition of nearly 6K new relays in the Tor network (since 2010), the average threat from AS-level adversaries has grown – from 38% of all circuits being vulnerable in 2010 to 41% in 2015.

M4: Measuring historical vulnerability to AS-level adversaries (mixed model). Here, we use the same settings as experiment M3, only changing the user model – i.e., while M3 calculated the fraction of vulnerable circuits for users loading 200 webpages in each country, here we consider users who perform a variety of non-htp(s) related communication via Tor – e.g., IRC, email, BitTorrent, etc.. The results are illustrated in Figure 5.

Observation: We find that the threat faced by clients that use Tor for a mix of non-Web applications is currently slightly lower than web-only Tor clients, in general. However, the threat has been growing at a significantly faster rate. We see in the last five years that the average threat (in terms of vulnerable circuits constructed in the course of our experiments) has increased from 21% to 35%.

Discussion. Our results indicate that the threat from de-anonymization by AS-level adversaries is significant, regardless of client location and what the Tor client is used for (web or mixed models). Although the threat faced by clients used for non-Web purposes is slightly lower, we find that it is growing at a faster rate than Web-only clients. This is due to the small number of new non-Web supporting exit-relays being added to the Tor network.

Investigating further into the reason for the growth of the threat from AS-level adversaries in spite of the massive growth of the Tor network, we find that while the network has grown, the diversity of the ASes in the network has not increased. This is illustrated in Figure 6. Here, we see that while the number of relays in the network has grown to nearly 250% and the capacity of the network has grown to over 3000% of their 2010 values, the number of ASes in the network has lagged behind (growing to only 160% of its 2010 value).

Take-away: The Tor network faces a fundamental problem when dealing with AS-level attackers: the lack
of AS-level diversity in the network. In the absence of a specific client-based solution for constructing AS-aware circuits, the threat from AS-level attackers is only expected to increase.

4. PITFALLS OF AS-AWARE TOR CLIENTS

In this section we survey previous work to identify five common pitfalls (P1 - P5) in the design and construction of AS-aware Tor clients. We empirically demonstrate the negative consequences of each.

4.1 Inaccurate path predictions (P1)

The core component of any AS-aware Tor client is its path-prediction toolkit. The Tor client must accurately identify ASes on the paths from and to the selected entry- and exit-relays to build circuits that avoid network-level correlation attacks. Designers of AS-aware clients have three main options for predicting paths between pairs of ASes:

Data-plane measurements: Data-plane measurement tools such as traceroute allow measurement of exact paths between a source and destination host. However, this requires control of the source host, which may not always be possible (e.g., it is not possible to traceroute between the exit-relay and destination server) and has a high latency cost, making it infeasible for clients to perform on-demand.

Control-plane measurements: Paths may also be obtained via control-plane measurement infrastructure such as BGP monitors (e.g., RIPE [32], Routeviews [31]). However, they (like data-plane infrastructure) are limited by the location and peers of the BGP monitors.

Algorithmic simulations: This approach relies on several simplified assumptions about Internet routing. Typically, algorithmic simulators use empirically derived AS-level topologies, inferred inter-AS relationships (e.g., customer-provider or peer-peer), and a simplified model of Internet routing policies (e.g., [33, 34]). While algorithmic simulators are able to predict AS-level paths between any pair of ASes, their accuracy compares unfavorably with paths obtained from data- and control-plane measurements. This is due to the incompleteness of AS-level topologies and the absence of ground-truth while inferring AS relationships.

Table 2 illustrates the design choices of previous efforts to measure and defend against threats from AS-level attackers. Here, we see that all previous work, with the exception of LASTor [17] and Juen et al. [12] relied solely on algorithmic path simulators to identify threatening ASes.

To understand the impact of inaccurate path predictions, we test the accuracy of the state-of-the-art simulator [P1].

Figure 7: Number of ASes over or under-estimated by the state-of-the-art algorithmic simulator [P1].

1The client was not made available by the authors after multiple requests. We try to objectively evaluate the paper based on descriptions in the text.
| Country | Asymmetric model | Symmetric model |
|---------|-----------------|-----------------|
| BR | X | √ |
| CN | X | √ |
| DE | X | √ |
| ES | X | √ |
| FR | X | √ |
| GB | X | √ |
| IT | X | √ |
| RU | X | √ |
| UA | X | √ |
| US | X | √ |
| All | X | √ |

Table 2: Comparison of the measurement methodologies and defense contributions of the state-of-the-art. X indicates the corresponding criteria was not considered and √ indicates that it was. (P1-P5)

Figure 8: Fraction of websites using vulnerable circuits against a symmetric and asymmetric adversary [P2].

repeat experiment M1, but this time we only consider an attacker that can exploit only forward paths – i.e., we say that a circuit is vulnerable to de-anonymization if there is some AS A such that: A ∈ {P_{SRC→EN} ∩ P_{EX→DST}}. Figure 8 compares the fraction of websites marked as vulnerable against a forward-path exploiting (symmetric) adversary model with our (asymmetric) adversary model. We find that operating under the assumption of symmetric routing (i.e., considering only forward-path exploiting adversaries) results in significant threat under-estimation, with circuits to 17% of all websites identified as safe when they were in fact vulnerable.

4.3 Ignoring active BGP attacks (P3)

The potential for BGP hijacks and interceptions to compromise Tor traffic was highlighted by Sun et al. [13]. In this section, we measure how vulnerable Tor relays are to BGP hijacks and interceptions by sets of malicious ASes. For this experiment, we considered 10K pairs of (source, entry) ASes and 10K pairs of (exit, destination) ASes. The source ASes were randomly selected from the 1000 popular ASes (100 in each of ten countries) used in experiments M2-M4 while the entry and exit ASes were selected from the set of all Tor entry and exit relays, respectively. Destination ASes were randomly chosen from the set of all destination ASes seen in experiment M1 (when loading 200 webpages in each of ten countries). For our adversary (i.e., ASes attempting to launch hijack and interception attacks), we selected the 16 malicious ASes identified in previous work [38] as popular ASes for hosting illegal content, botnet C&C servers, and other malicious resources.

For each pair of ASes we use heuristics from Goldberg et al. [39] to check which of the 16 malicious ASes is capable of hijacking or intercepting traffic between the pair of ASes.

We first characterize the ability of the malicious ASes to hijack traffic for a chosen path. Figure 9a demonstrates the hijack and interception success rates of each of the 16 ASes considered in this experiment. Here we see that two ASes – ASN 9002: RETN (UA), ASN 29131: RapidSwitch (GB) – achieve high hijack and interception success rate of nearly 50%. The case of ASN 29131 can be explained by its high customer cone size (3271 customer ASes). On the other hand ASN 29131 is a smaller AS with only one customer AS, however, it peers with seven other large ASes having an AS rank under 1K (based on customer cone sizes).

Next we wanted to understand how vulnerable given Tor relays are to attack. Specifically, Figure 9a shows the fraction of hijack/interception attempts were successful for the relays in ascending order. Each one of the relays we consider is susceptible to at least 20% of hijacks and 12% of interception attempts.

4.4 Increasing risk of relay adversaries (P4)

We argue that a client which utilizes a smaller number of relays to serve connection requests, over a period of time, is less likely to encounter a malicious relay in the Tor network. Thus, a Tor client that uses a smaller number of relays is more secure against adversarial relays.

We observe that many proposed defenses [2, 16, 17, 18] do not consider the impact of AS-aware relay sele-
4.5 Overloading relays in the Tor network (P5)

We find that much of previous work [2, 16, 17] does not consider the capacities of relays chosen as part of AS-aware circuits. We argue that relay capacity is important to consider to prevent custom relay selection schemes from overloading low-capacity relays and reducing performance across the population of Tor users.

As an example of the impact of ignoring relay capacities, Wacek et al. [40] performed a study to analyze the throughput of various Tor relay selection strategies and found that: (1) strategies that ignored relay capacities had significant drops in both, client and network throughput and (2) while LASTor had better performance than vanilla Tor when considering round-trip times on established circuits, the throughput of the client when used for page loads was 70% less than the Tor client (compared to 25% more than Tor as demonstrated in original work by Akhoondi et al.).

The reason for this large disparity in performance reported in the two evaluations is due to Akhoondi et al. only sending HTTP HEAD requests in their experiments (as opposed to downloading complete web-pages or documents). In addition to being unrepresentative of typical web traffic, such evaluations do not sufficiently stress all the relays chosen as part of a circuit and as a result do not reveal the issues associated with capacity-agnostic relay selection.

5. THE CIPOLLINO TOR CLIENT

Based on the pitfalls we identified in the prior section, we design Cipollino, an AS-aware Tor client that uses state-of-the-art network measurements and optimizations to mitigate the pitfalls. Table 3 summarizes how Cipollino addresses each of the pitfalls described in Section 4. We elaborate on each in the following sections.

5.1 Improving path prediction (P1)

We reduce our dependence on algorithmic simulators by using PathCache – a system that aggregates existing data and control plane measurements to predict paths. We fall back to simulations only when a path query cannot be answered using measurement data. Repeated querying of the PathCache server every time a circuit needs to be built is (1) time consuming and (2) reveals destinations of interest to a third party (e.g., PathCache server). To avoid this, the Cipollino client subscribes to daily updates of the routing graphs maintained by the PathCache server and locally computes paths between ASes. This is beneficial for two other

| Pitfall                       | Solution                                      |
|------------------------------|-----------------------------------------------|
| P1. Simulated network paths  | PathCache empirical data                      |
| P2. Ignoring route asymmetry  | Including reverse paths in decision making    |
| P3. Ignoring BGP hijacks     | Realtime BGP data                              |
| P4. Increasing risk of relay adversaries | Reuse safe circuits between destinations      |
| P5. Overloading Tor relays   | Load balance across safe circuits              |

Table 3: Overview of how Cipollino mitigates the pitfalls of prior AS-aware Tor clients.
Figure 10: Number of ASes over or under-estimated by PathCache, when compared to exact AS-level paths obtained by traceroutes [P1].

To understand how often PathCache is able to predict paths using empirical data, we queried PathCache for paths between (1) 1,000 source ASes (100 of the most populous ASes in each of the ten countries) and the ASes of all entry-relays in the Tor network (265K path queries) and (2) between the ASes of all exit-relays in the Tor network and all the destination ASes seen in our 2,000 web-page loads (312K path queries). Table 4 shows the percentage of paths that were predicted by PathCache using empirical data. Here we see that PathCache is able to achieve reasonable coverage when considering high capacity entry- and exit-relays (34-36%). This implies a higher accuracy of paths predicted for organically generated Tor circuits, as the Tor client will tend to use these higher capacity relays.

In Figure 11 we see the per-country breakdown of the fraction of path requests satisfied by PathCache. Interestingly, we see BR and CN in particular having a very small fraction of paths between their 100 AS sources and the Tor entry-relays. We speculate that this is due to blocking of communication with Tor entry-relays in these countries. This prevents traceroutes (that PathCache uses as a basis for path prediction) from successfully traversing paths from client ASes in these countries to Tor entry relay ASes.

Depending on client location, PathCache is able to answer between 15-50% of all queries issued to it by the Tor client. Importantly, the paths returned for these queries are unlikely to under-estimate the presence of an AS. Additionally, coverage increases significantly when considering higher capacity Tor relays. These factors make it a good alternative to relying on simulations for path prediction.

5.2 Considering active adversaries that can exploit asymmetric routes (P2-P3)

Cipollino considers an adversary model that includes the possibility of ASes exploiting (1) asymmetric routes and (2) BGP insecurities. To explain how we deal with such adversaries, we describe how Cipollino verifies the safety of a given circuit below.

- Mapping destination IP addresses to ASNs and prefixes: Given a circuit and a destination IP address,
the Cipollino client first uses an up-to-date offline IP to ASN database (based off of BGP announcements) to obtain the AS numbers associated with the network of the client, entry-relay, exit-relay, and requested destination IP. This database (sourced and updated by CAIDA) is supplied and updated by the PathCache daily updates.

Following this, Cipollino generates two pairs of ASes and two pairs of prefixes – \((\text{AS}_{\text{EN}}, \text{AS}_{\text{SRC}}), (\text{AS}_{\text{EX}}, \text{AS}_{\text{DST}}), (\text{Pre}_{\text{EN}}, \text{Pre}_{\text{SRC}}), \) and \((\text{Pre}_{\text{EX}}, \text{Pre}_{\text{DST}})\).

- **BGP anomaly detection:** In order to detect hijacks and interceptions in near-real-time, Cipollino receives hourly (customizable in the client configuration) feeds from BGPStream \([11]\) of current BGP routing anomalies. In particular, BGPStream produces a live stream of ongoing Multiple Origin AS (MOAS) anomalies. MOAS anomalies, which occur when a prefix is being announced by multiple origin ASes. We use MOAS as an indicator of potentially anomalous routing behavior as a proof of concept. Beyond the scope of this paper we are working to develop more accurate detection methods for hijacks and interceptions which could be incorporated into Cipollino \([12]\). This feed of ASes is used to identify ASes that are likely to be hijacking or intercepting traffic to any of the prefixes in the previously generated pairs – \((\text{Pre}_{\text{EN}}, \text{Pre}_{\text{SRC}})\) and \((\text{Pre}_{\text{EX}}, \text{Pre}_{\text{DST}})\).

Any AS \(X\) that is suspected to be hijacking or intercepting traffic with the entry-relay is added to the set \(H_{\text{EN}}\). Similarly, the sets \(H_{\text{EX}}, H_{\text{SRC}},\) and \(H_{\text{DST}}\) are populated.

- **Path prediction:** The Cipollino client uses the locally stored PathCache destination based graphs to obtain the set of ASes on the SRC ↔ EN and EX ↔ DST paths. Additionally, the ASes occurring on the paths between \(H_{\text{EN}} ↔ \text{SRC}\) and \(EN ↔ H_{\text{EN}}\) are added to SRC ↔ EN. This accounts for all ASes that are able to view traffic characteristics in the event of a successful interception (and hijack) of traffic to EN. The same process is repeated for \(H_{\text{EX}}, H_{\text{SRC}},\) and \(H_{\text{DST}}\).

- **Circuit safety marking:** After the paths are computed, a circuit is marked as safe iff the sets SRC ↔ EN and EX ↔ DST have no intersection.

The circuit safety verification procedure shows that Cipollino does not mark a circuit as safe to serve a given destination unless there are no ASes that are in a position to view traffic characteristics at either end of a circuit, after accounting for route asymmetry and potential hijacks.

### 5.3 Pre-building and re-using circuits (P4)

To reduce the number of relays it uses, Cipollino employs a circuit pre-building strategy similar to the vanilla Tor client. Cipollino pre-emptively constructs a fixed (and configurable) number of circuits. In addition to the benefit of reduced utilization of relays, two other arguments for pre-emptive circuit construction come from the following observations drawn from previous work by Nithyanand et al. \([18]\):

- For over 50% of all client locations and destination ASes considered, at least 50% of all possible entry- and exit-relay combinations were safe from correlation attacks by AS-level adversaries. Therefore, by pre-building a number of circuits, we are very likely to find at least one safe circuit for a given destination AS.

- Constructing a new circuit is significantly more expensive than verifying the safety of an existing circuit – i.e., due to the need for estimating the paths between all possible (source, entry-relay) and (exit-relay, destination) pairs. Therefore, by pre-emptively constructing circuits, Cipollino reduces the need to construct on-demand destination-aware circuits. To understand how circuit pre-building affects the number of relays used by Cipollino, we consider the 200 Web pages loaded in the Web user model with Cipollino configured to pre-build and always maintain 4, 16, and 64 live and usable circuits. Figure \([12]\) compares the number of relays used in each setting with the vanilla Tor client and Astoria. When Cipollino is configured to only pre-build and maintain 4 active circuits, it utilizes 786 relays (compared to the 623 relays used by Tor). This is significantly lower than Astoria (3104 relays).

Figure \([13]\) also illustrates that pre-building circuits results in the need for constructing fewer on-demand and destination-aware circuits. In this experiment, 1,000 Cipollino clients were simulated (with locations in the 100 most populous ASes in each of ten countries) and issued connection requests for destinations associated with 200 country-specific webpages. Here we see that 50% of the clients were able avoid on-demand circuit construction for at least 86% of the connection requests, when just four circuits were prebuilt.
Figure 13: Distribution of the fraction of connection requests that were able to find a safe and usable circuit from 4, 16, and 64 circuits pre-built be the Cipollino client [P4].

Figure 14: Distribution of circuit allocation times [P4].

Reusing circuits, when possible, also improves the performance of Cipollino as compared with other AS-aware Tor clients. Figure 14 shows the elapsed time between the arrival of a connection request and the allocation of a circuit to satisfy the request. As expected, since the vanilla Tor client always uses an existing circuit, it is significantly faster than Astoria and Cipollino, requiring under .1 seconds to allocate a circuit to over 99% of incoming connection requests. Within the same time constraints we see that the Cipollino Tor client is able to satisfy 60% of its requests, while the Astoria client can only satisfy 21%. Pre-emptive circuit construction yields two primary benefits. First, it is responsible for a nearly 80% reduction in number of relays utilized by the AS-aware client (compared to AS-aware clients that do not do pre-emptive construction), resulting in improved security against relay-level adversaries. Second, it results in reduced circuit allocation times when an existing circuit is reused.

5.4 Load-balance like Tor when possible (P5)

Load balancing is explicitly performed in two cases: (1) when constructing and replenishing Cipollino’s reserve of pre-built circuits and (2) when there are multiple safe circuits available for a connection request.

In the first case, Cipollino exactly mimics the load-balancing approach utilized by the vanilla Tor client – i.e., relays are selected in a circuit with probability proportional to their bandwidth capacity. The second case, however, is more nuanced. When there are multiple safe entry- and exit-relay options – \((en_1, ex_1), \ldots, (en_n, ex_n)\) – Cipollino selects the \(i\)th entry and exit-relay combination with probability \(Pr_i\), where:

\[
Pr_i = \frac{BW_{en_i} \times BW_{ex_i}}{\sum_{j=1}^{n} BW_{en_j} \times BW_{ex_j}}
\]

Here \(BW_{en_i}\) and \(BW_{ex_j}\) are the advertised bandwidths of the entry- and exit-relay associated with the \(j\)th safe relay combination. This weighting of combinations works to ensure that each entry- and exit-relay is selected with the probability proportional to its advertised bandwidth (when only considering safe relay options).

Figure 15 compares the effect of the load-balancing approaches used by the vanilla Tor client, Astoria, and Cipollino. We find that they are all able to effectively ensure that relays do not get overloaded. Further, Cipollino does not perform any worse than Astoria, despite its reuse of existing safe circuits.

5.5 Putting it all together

In this section we describe the complete architecture of Cipollino. Finally, we complete our evaluation of the security and performance of the complete Cipollino client.

Cipollino architecture. Cipollino consists of three main components: (1) an AS-level path aggregation toolkit (PathCache), (2) a circuit allocator, and (3) a circuit builder. The interaction between each of these components is illustrated in Figure 16.

The Cipollino client maintains a compact local repository of destination-based routing graphs. These are updated by the PathCache servers on a daily (or, configurable) basis. The PathCache path-stitching algorithms are used on these graphs to identify ASes that are in a position to observe traffic flowing between a given source and destination AS.

When the Cipollino client receives a request for a connection to a destination IP and port, the circuit allocator uses the PathCache stitching algorithms and graphs
to identify if there are any pre-built circuits that are not vulnerable to traffic correlation attacks by ASes. If exactly one of the safe circuits is able to serve the requested IP and port of the destination, then the circuit is used to satisfy the connection request. If there are multiple such circuits, then one of them is chosen in accordance with our load-balancing scheme described in the previous section.

In the event that none of the pre-built circuits is able to satisfy the connection, the circuit builder constructs a circuit specifically for the requested connection. The constructed circuit performs also relay selection in a way that achieves load-balancing across all relays in the Tor network. Additionally, the circuit builder also handles the worst-case scenario — when there are no safe circuits that may be built. In this case, the circuit builder borrows the linear program proposed by the Astoria Tor client to ensure that no single adversary is able to de-anonymize a large number of circuits.

**Cipollino security against AS-level adversaries.** We compare the security of the circuits constructed by Cipollino, Astoria, and the vanilla Tor client while performing 200 page-loads performed in each of ten different client locations (same settings as M1). The results are shown in Figure 17. From these results we see that the Cipollino client circuits provide more security against AS-level traffic-correlation adversaries. Only 1.4% of all webpages loaded by the Cipollino client utilized a vulnerable circuit, when compared to 11% and 57% for the Astoria and vanilla Tor clients, respectively.

**Cipollino page-load times.** To give a complete picture of the performance of the Cipollino client we consider the time required to load a complete web-page (including third-party content). Figure 18 shows the cumulative distribution of page-load times of 2000 webpages in ten client locations for the Cipollino, Astoria, and Tor clients. We find that the time required for loading pages using the Cipollino and Tor client are quite closely matched with the median page-load time differing by only 1.6 seconds, while the Astoria Tor client is nearly 7 seconds slower.

6. CONCLUSIONS

In this paper we analyzed the threat faced by Tor clients from AS-level adversaries from a current and historical perspective. We found that the current threat is high, with around 30% of all Tor circuits created in our experiments remaining vulnerable to de-anonymization by AS-level correlation attacks, regardless of whether the Tor client is used for web browsing or other applications. Further, our historical analysis points to a fundamental problem with the Tor network – the lack of growth of AS-level diversity. Without specific efforts from the Tor project to increase diversity of relays or incorporate AS-awareness in the Tor client, our study shows that the threat is bound to increase.

Our survey of previous work identified five common pitfalls associated with the design and construction of AS-aware Tor clients. We show how each of these pitfalls results in high under-estimation of the threat from AS-level adversaries, or increased vulnerability to active (AS-level) and passive (relay-level) adversaries, or poor performance characteristics.

We find that our AS-aware Tor client – Cipollino, designed specifically to address these pitfalls improves the current state-of-the-art by achieving better security.
against network-level adversaries. Specifically, by using a data- and control-plane measurement infrastructure whenever possible, Cipollino reduces the fraction of vulnerable webpage loads from 57% (vanilla Tor) and 11% (Astoria) to 1.4%. Additionally, by incorporating the concept of circuit pre-building and circuit re-use, the Cipollino client significantly reduces the threat faced from malicious relays. As a consequence of circuit pre-building and re-use, the Cipollino client is also able achieve performance characteristics comparable with the vanilla Tor client.

Data and source-code release: In an effort to enable reproducibility and ease future comparative evaluation efforts, the following resources will be made available on acceptance of this work: the Cipollino Tor client, the destination-based graphs provided by PathCache during the time of this study, and the Web and mixed-application user-models used in our simulations.

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