Securing Internet Applications from Routing Attacks

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ABSTRACT

Attacks on Internet routing are typically viewed through the lens of availability and confidentiality, assuming an adversary that either discards traffic or performs eavesdropping. Yet, a strategic adversary can use routing attacks to compromise the security of critical Internet applications like Tor, certificate authorities, and the bitcoin network.

In this paper, we survey such application-specific routing attacks and argue that both application-layer and network-layer defenses are essential and urgently needed. The good news is that, while deployment challenges have hindered the adoption of network-layer defenses (i.e. secure routing protocols) thus far, application-layer defenses are much easier to deploy in the short term.

1. INTRODUCTION

The Internet is a “network of networks” that interconnects tens of thousands of separately administered networks. The Border Gateway Protocol (BGP) is the glue that holds the Internet together by propagating information about how to reach destinations in remote networks. However, BGP is notoriously vulnerable to misconfiguration and attack. The consequences range from making destinations unreachable (e.g., Google’s routing incident caused widespread Internet outage in Japan [7]), to misdirecting traffic through unexpected intermediaries (e.g., European mobile traffic routed through China Telecom due to improper routing announcements from a Swiss datacenter [9]), to impersonating legitimate services (e.g., traffic to an Amazon DNS server rerouted to attackers who answered DNS queries with fraudulent IP addresses [8]). Efforts to secure the Internet routing system have been underway for many years [20–22,26,28,29], but the pace of progress is slow since many parties must agree on solutions and cooperate in their deployment.

In the meantime, more and more users rely on the Internet to access a wide range of services, including applications with security and privacy concerns of their own. Applications such as Tor (the onion router) allow users to browse anonymously, certificate authorities provide certificates for secure access to web services, and blockchain supports secure cryptocurrencies. However, the privacy and security properties of these applications depend on the network to deliver traffic; Figure 1 illustrates the cross-layer interaction between Tor and the underlying network. Application developers abstract away the details of Internet routing, but BGP does not provide a sufficiently secure scaffolding for these applications. This gap leaves the vulnerabilities due to routing insecurity significantly underestimated. Traditionally, routing attacks have been viewed primarily as causing availability problems (when misdirected traffic is dropped) and affecting confidentiality (when data is not encrypted). However, routing attacks on Internet applications can have even more devastating consequences for users—including uncovering users (such as political dissidents) trying to communicate anonymously, impersonating websites even if the traffic uses HTTPS, and stealing cryptocurrency.

The paper argues that the security of Internet applications and the network infrastructure should be considered together, as vulnerabilities in one layer lead to broken assumptions (and new vectors for attacks) in the other. We first give an overview of Internet routing security, reviewing BGP, possible attacks, and proposed defenses. Then, we discuss how cross-layer interactions enable routing attacks to compromise popular applications like Tor, certificate authorities, and the bitcoin network. Given the slow adoption of secure routing defenses, we then discuss how application-specific defenses can be used in the near-term to mitigate routing attacks without requiring global coordination. We believe that application-layer and network-layer solutions are interconnected and both are essential to secure Internet applications. Furthermore, by demonstrating the disastrous consequences for users, we hope to motivate the community to redouble efforts to tackle BGP’s many security problems once and for all.

2. ROUTING ATTACKS

Routing attacks occur in the wild, and are getting increasingly prevalent and more sophisticated. An attacker can launch carefully-crafted attacks to achieve desired goals,
ranging from causing outages to impersonating services, and affecting targeted regions of users. We dissect routing attacks from the perspective of an attacker, and review existing defenses against routing attacks. This section serves as the “building block” for Sections 3, 4, and 5, where we show how routing attacks can compromise Internet applications and discuss application-specific defenses.

2.1 How BGP Works

The Internet consists of around 67,000 Autonomous Systems (ASes) [11], each with an AS number (ASN) and a set of IP prefixes—a sequence of bits that describe the IP address space. For instance, the 140.180.0.0/24 prefix contains 256 IP addresses ranging from 140.180.0.0 to 140.180.0.255. Neighboring ASes exchange traffic in a variety of bilateral relationships that specify which traffic should be sent and how it is paid for. Such agreements can generally be classified in two types: a customer-provider relationship, in which the customer pays the provider to send and receive traffic to and from the rest of the Internet, and a peer-to-peer relationship, in which no money is exchanged but traffic must be destined for the peer or one of its customers.

Routing among the ASes is governed by the Border Gateway Protocol (BGP), which computes paths to destination IP prefixes. Upon receiving multiple BGP routes for the same prefix (i.e., equally-specific prefix), an AS chooses one “best” route based on a list of factors, with the top two generally being: (1) Local Preference: a path via a customer is preferred over path via a peer, which is preferred over a provider; (2) Shortest Path: among paths with the highest local preference, paths with the fewest AS hops will be preferred. The AS will then add the route into its local Routing Information Base, and further propagate the route to its neighbors after prepending itself in the path.

When forwarding a packet with a given destination IP address, an AS uses the path for the longest matching destination prefix. For instance, in Figure 2, AS1 announces 140.180.0.0/22 via neighbor AS2, and 140.180.0.0/24 via neighbor AS3 for traffic engineering purpose. Upon receiving the two announcements, AS4 will forward packets destined for IP addresses within 140.180.0.0/22 via the path through AS3 based on the longest prefix match. Note that, in general, the longest prefix that can be propagated out is /24; many ASes filter prefixes that are longer than /24 by default.

2.2 Goals of Routing Attacks

Routing attacks happen when an AS announces an incorrect path to an IP prefix. By default, ASes trust routing announcements sent from other ASes. This causes the data packets to traverse through and/or arrive at the attacker AS. The attacker can use routing attacks to achieve various goals. We discuss the goals from two perspectives: whom to affect and what to achieve.

2.2.1 Whom to Affect

Routing attacks affect two groups of victims: (1) destinations, whose address spaces are announced by the attacker, and (2) senders, who send packets to IP addresses within the attacked prefixes.

Destinations. The attacker may target specific destinations. For instance, YouTube was the target of a hijacking incident in 2008, where Pakistan authorities tried to block access to YouTube. Pakistan Telecom (AS17557) announced the prefix 208.65.153.0/24, which was a subnet of 208.65.152.0/22 announced by YouTube (AS36561).

Senders. The attacker may want to affect global traffic from all senders on the Internet, or selectively target only traffic from certain senders without affecting the rest of the Internet traffic. In the 2008 YouTube routing attack example above, the goal was to target only senders within Pakistan; however, the attack unintentionally affected all senders around the globe.

2.2.2 What to Achieve

Historically, the most visible effect of routing attacks is availability issues, where the destinations cannot be reached by the senders any more. However, the attacker’s goals can be more sophisticated.

Availability. The attacker’s goal could be to make the services hosted at the destinations become unreachable to the senders. The packets from senders arrive at the attacker, who subsequently drops the packets (i.e., the traffic is “blackholed”). This type of attack is also characterized as a hijack attack where traffic is blackholed.

Surveillance. Authorities may use routing attacks to perform surveillance and target traffic from senders in certain regions. Intelligence agencies such as NSA could launch routing attacks to make certain traffic easier to intercept for surveillance. Traffic from the targeted region would be rerouted to the authorities, who keep forwarding the traffic to the destinations but record the activities at the same time. This type of attack is usually characterized as an interception attack, where the attacker forwards the packets to the legitimate destinations and keeps the communication alive. Interception attacks are much harder to notice than hijack attacks since they do not interrupt the communications, though performance may degrade due to more circuitous paths. Furthermore, authorities could exploit routing attacks to surpass legal restrictions by diverting domestic traffic (e.g., emails between Americans) to foreign jurisdictions to conduct surveillance.

Impersonation. The attacker can impersonate the destinations to deceive the senders. The attacker may intercept the packets and reply with forged responses by performing either hijack attacks or interception attacks. These attacks can have damaging consequences. For instance, in 2018, attackers used routing attacks to impersonate Amazon’s authoritative DNS service, where the attackers answered the DNS queries for a cryptocurrency website with Russian IP addresses and subsequently directed the users to a fraudulent site which the users believed to be their real cryptocurrency service. As a result, cryptocurrency was stolen.

In this paper, we show that attacker’s goals can also include traffic analysis of encrypted communications in Tor, obtaining digital certificates for web servers, and preventing...
blockchain systems from reaching consensus.

2.3 Attack Methodology

To achieve its goals, the attacker needs to decide (1) which prefix to announce, (2) which path to announce, and (3) which ASes should receive the announcement.

2.3.1 Which Prefix to Announce

The attacker can announce either (1) a sub-prefix (i.e., more-specific prefix) of the destination AS’s prefix, or (2) an equally-specific prefix as the destination AS’s prefix. Note that a less-specific prefix would not be preferred and hence would not constitute a successful attack.

Affecting global traffic by announcing sub-prefixes. The attacker announces a more-specific (i.e., longer) prefix than the destination AS’s prefix. Since forwarding is based on longest prefix match, a sub-prefix attack is highly effective at hijacking traffic from all senders. However, since most ASes filter announcements for prefixes longer than /24, sub-prefix attacks on /24 prefixes would not be effective.

Targeting selective traffic by announcing equally-specific prefixes. The attacker announces the exact same prefix that the destination AS is announcing. An AS that receives both announcements, would pick between the two paths based on local preferences and shortest path. Note that some ASes may only receive one of the two announcements. For instance, in Figure 3, the attacker AS2 announces the same /24 prefix as the destination AS1, and AS4 prefers the path to the attacker AS2 while AS3 still prefers the path to the destination AS1. As we can see, this attack will generally affect only certain parts of the Internet and not have global impact. On the other hand, this attack is stealthier due to its local impact and enables targeted attacks on certain senders.

2.3.2 Which Path to Announce

The most straightforward attack is for the attacker to announce itself as the origin of the prefix. This naturally constitutes a hijack attack, where the attacker receives and drops the packets. Yet, a more sophisticated attacker has a range of other options.

Evading detection by forging the victim AS. The attacker can add the legitimate destination AS to the end of its path, so the announcement has the same “last hop” (or “origin”) AS as a legitimate announcement. This increases the stealthiness of the attack since some countermeasures only check the origin AS of the announcement. Note that the path now appears one hop longer, which may reduce the number of ASes that pick the attacker’s route over the legitimate route.

Limiting attack propagation through AS path poisoning. A sophisticated attacker can append a set of carefully-selected ASes at the end of the path. These ASes should constitute a legitimate path from the attacker to the destination AS. The appended ASes will ignore the attacker’s announcement because of BGP loop prevention, which consequently helps preserve legitimate routes from the attacker AS to the destination AS. This attack is known as the “AS path poisoning attack”, as illustrated in Figure 4. This attack can be performed by any multi-homed AS (having more than one provider) so at least one provider can deliver the sender’s traffic to the attacker while another provider forwards the traffic to the legitimate destination. This attack is very stealthy and effective at performing interception attacks while announcing a sub-prefix.

2.3.3 Which ASes Should Receive the Announcement

By default, the attacker makes the announcement to all of its neighbors, who further propagate the announcement. However, a strategic attacker may attempt to limit the propagation of the announcement to increase attack stealthiness, perform an interception attack, or target certain senders. We discuss two scenarios where limiting announcement propagation is used to perform interception attacks.

Limiting attack propagation by announcing to certain neighbors. Attackers may exploit routing policies to control attack propagation by only announcing to certain peers and customers. Announcements that are sent to a peer or a customer will only be propagated “down” to the neighbor’s customers. Thus, the attacker can selectively launch interception attacks on a small portion of the Internet by preserving a valid path to the legitimate destination.

Limiting attack propagation through BGP communities. BGP communities are optional attributes that can be added to an announcement to control the routing policy in upstream ASes, for purposes such as traffic engineering. Attackers may exploit BGP communities to strategically control attack propagation and increase the effectiveness and viability of interception attacks [15]. For example, if the attacker is a stub network (i.e., an AS with no customers) and learns the victim’s route through a provider, there are potentially no neighbors the attacker can safely make its malicious announcement to while retaining a valid
route to the victim. However, an attacker can leverage BGP communities to manipulate the local preferences and announcement exporting behaviors of upstream routers in other ASes. As a result, selected ASes will never hear or will not prefer the bogus announcements, and thus maintain a valid path to forward traffic to the victim.

2.4 Proposed Defenses

Defending against routing attacks is challenging due to the lack of “ground truth” to inform whether a path is “correct” or not. Seemingly suspicious announcements could be legitimate paths used by ASes to optimize network performance. Over the years, many BGP security solutions have been proposed. They range from deployed solutions such as BGP monitoring systems that rely on historical data and defensive filtering that relies on preset information from customers and peers, to more ambitious solutions that use cryptographic primitives to verify routes.

**Anomaly detection via BGP monitoring.** BGP monitoring systems detect anomalous routing announcements by relying on historical routing data to infer the “expected” origin ASes or paths for prefixes. Monitoring systems typically do not require changes to the routing protocol and hence are highly deployable. However, many early efforts on monitoring systems focused on catching “easy” attacks (e.g., mismatched origin ASes), but fail to detect more sophisticated attacks such as interception attacks. Furthermore, relying on historical data to infer ground truth is prone to false positives (flagging legitimate routes) and false negatives (missing real attacks).

**Defensive filtering via preset knowledge.** ASes often perform prefix filtering on announcements received from direct customers. This solution is effective against attacks launched by customer ASes, since provider ASes have prior knowledge about their customers’ allowed prefixes. However, prefix filtering does not prevent ASes from attacking their direct or indirect customers. A more advanced filtering technique is AS path filtering, which uses a whitelist of paths for announcements received from peering ASes based on prior information exchange among peers. This technique extends the knowledge base further from the sole knowledge of an individual provider on its customers (as in prefix filtering), to a collective knowledge base exchanged and built among a network of trusted peers. The Internet Society’s MANRS project has outlined best practices for using filtering techniques to protect the routing infrastructure.

**Origin validation via RPKI.** The Resource Public Key Infrastructure (RPKI) is a public key infrastructure that stores cryptographic attestations, known as Route Origin Authorizations (ROAs), about which ASes are authorized to originate which prefixes. Upon receiving an announcement, ASes may perform Route Origin Validations (ROV) to filter routes originated from invalid ASes. RPKI utilizes cryptographic primitives to make the knowledge base available to all ASes as opposed to only direct neighbors in defensive filtering. Even though ROV only validates the origin AS instead of the full path, it can already be effective at preventing many attacks. However, RPKI has been struggling with deployment issues for many years, where currently less than 20% of the prefixes have valid ROAs and even fewer ASes are correctly performing ROV.

**Path validation via BGPsec.** BGPsec uses cryptographic primitives to validate the whole AS path, but it differs from ROV in the sense that BGPsec is an online process and integral part of the routing protocol, as opposed to a separate offline lookup. In BGPsec, as an AS prepends its ASN to a path and propagates it to each neighbor, it generates a cryptographic signature which is added to the path. Thus, each AS in the path becomes protected with a signature. While BGPsec provides validation of the full path, it places a heavy overhead on BGP routers. Furthermore, incremental deployment is challenging—it requires all ASes along a path to participate. We have yet to see real-world deployment of BGPsec.

In the following sections, we demonstrate how adversaries can exploit routings attacks to compromise critical Internet applications like Tor, certificate authorities, and the bitcoin network. In addition, we discuss near-term application-layer defenses to protect end users even with the insecure underlying routing infrastructure.

3. THE TOR NETWORK

As the most widely used anonymity system, Tor carries terabytes of traffic every day and serves millions of users. However, a network-level adversary can deanonymize Tor users by launching routing attacks to observe user traffic and subsequently performing correlation analysis. Routing attacks have significantly increased the attack surface of anonymity systems, jeopardizing user anonymity now more than ever. Furthermore, the attacks also have broad applicability to low-latency anonymous communication systems beyond Tor.

3.1 How Tor Works

To prevent an adversary from associating a client with a destination server, Tor encrypts the network traffic and sends it through a sequence of relays (proxies) before going to the destination. The client selects a sequence of three relays, namely, entry (also known as guard), middle, and exit, as shown in Figure 5. The client then constructs a circuit through them with layered encryption by repeatedly encrypting the next hop with the keys of the current hops. Thus, each relay only learns the previous and next hops, and no relay or local network observer can identify both the source and destination.

However, Tor is known to be vulnerable to network-level adversaries who can observe traffic at both ends of the communication, i.e., between client and entry, and between exit and server. By default, Tor does not obfuscate packet timings, so the traffic entering and leaving Tor are highly correlated. An adversary on the path at both ends can then perform traffic correlation analysis on the packet traces to deanonymize the clients.
3.2 Routing Attacks on Anonymity Systems

Traditional attacks from network-level adversaries focus on passive adversaries who are already on the communication paths to observe Tor traffic. However, adversaries can exploit active routing attacks to strategically intercept Tor traffic, enabling on-demand and targeted attacks on Tor users [37].

We illustrate the attack in Figure 6. The adversary AS3 only sees traffic between the exit and the web server, and needs to intercept the traffic between the client and the entry relay. The adversary also needs to keep the connection alive in order to capture sufficient traffic for the correlation analysis, or in other words, perform an interception attack. The adversary can first uncover the identity of the entry relay using existing attacks [19]. Then, the adversary announces an equally-specific prefix that AS1 is announcing which covers the entry relay, while maintaining a valid path (via AS5) to the victim AS1. Consequently, traffic from the client gets routed to the adversary AS3, which forwards the traffic to AS1 to keep the connection alive. Similar attacks can be performed to intercept the exit-server connection as well, if the adversary is not already on the path.

Furthermore, the attacks become more effective with asymmetric traffic analysis, which enables traffic correlation analysis on either direction of the traffic (i.e., from the client to the entry relay), which are mostly TCP ACK packets. Asymmetric traffic analysis uses the sequence and acknowledgment numbers from the TCP packet header (which is not encrypted) to determine the sizes of the data packets traveling in the other direction.

The attack was successfully demonstrated on the live Tor network (ethically). Routing announcements were propagated through the PEERING testbed [33], and 50 Tor clients were configured to download files from 50 web servers. The attack deanonymized 90% of the clients in less than five minutes.

3.3 Defenses to Protect Anonymity

Building countermeasures to protect Tor users against routing attacks is challenging due to the underlying insecure routing protocol. Application-layer defenses can mitigate the attacks on Tor even with the insecure routing protocol at the network-layer [36].

**Proactive defense via relay selection algorithm.** Sun et. al. [36] proposed a Tor entry relay selection algorithm to protect the connection between a Tor client and the entry relay. This algorithm aims to defend against equally-specific attacks on entry relays, where the adversary announces the same prefix as the victim AS. Equally-specific attacks tend to be stealthier given the localized effect, and are effective for performing interception attacks where the connections need to be maintained to capture traffic. The localized effect opens up the possibility for Tor users to stay unaffected during such attacks on the entry relay by choosing the relay wisely and proactively before any attack happens. The new relay selection algorithm helps Tor users choose an entry relay that maximizes the probability of being unaffected by attacks based on the topological locations of the users and the relays. The algorithm successfully improves the probability by 96% on average (up to 166% for certain Tor user locations).

**Reactive defense via BGP monitoring.** To complement the proactive defense, Sun et. al. also proposed a monitoring system on routing activities for Tor relays. The monitoring system includes novel analytics-based detection methods such as time-based and frequency-based analytics, specifically tuned for Tor. The authors showed that most BGP updates involving a Tor relay are only announced by a single AS (across all updates), effectively differentiating
the announcements made by adversary ASes who never announced the prefix in the past. Tan et al. [38] also proposed a data-plane detection approach that periodically runs traceroute to detect longest-prefix attacks and update Tor relay descriptors upon anomaly detection, so that Tor users can pick entry relays correspondingly.

3.4 Broader Impact

The attacks on Tor have broad applicability to low-latency anonymous communication systems (e.g., I2P anonymous network or even VPNs) that are vulnerable to traffic correlation analysis and fingerprinting attacks. The adversary can exploit routing attacks to observe user traffic and subsequently deanonymize the users. The defense strategy of choosing Tor entry nodes based on user location to minimize the probability of being affected by routing attacks is broadly applicable too. Both users and applications can take the network topology into account when deciding which node to connect to.

4. CERTIFICATE AUTHORITIES

The Public Key Infrastructure is the foundation for securing online communications. Digital certificates are issued by trusted certificate authorities (CAs) to domain owners, verifying the ownership of a domain. Internet users trust a domain with encrypted communications, such as bank websites, only if a valid certificate signed by a CA is presented. This mechanism effectively prevents Man-In-The-Middle (MITM) attacks that can have disastrous consequences, such as stealing users’ financial information.

However, the certificate issuance process is itself vulnerable to routing attacks, allowing a network-level adversary to obtain trusted digital certificates for any victim domain [17]. These attacks have significant consequences for the integrity and privacy of our online communications, as adversaries can use fraudulently obtained digital certificates to bypass the protection offered by encryption and launch man-in-the-middle attacks against critical communications.

4.1 How Certificate Authority Works

Domain control verification is a crucial process for domain owners to obtain digital certificates from CAs. Domain owners approach a CA to request a digital certificate, and the CA responds with a challenge that requires the owners to demonstrate control of an important network resource (e.g., a website or email address) associated with the domain. For example, in the case of verification over HTTP, the CA requires the domain owner to upload a document to a well-known directory on its web server. Upon completion of the challenge, the CA will issue the digital certificate to the domain owner. This process is illustrated in Figure 8.

4.2 Routing Attacks on Digital Certificates

The domain control verification process creates a vulnerability to adversaries who can fake control of the network resources. A network-level adversary can use BGP attacks to hijack or intercept the traffic to the victim’s domain such that the CA’s request is routed to the adversary instead (step (5) in Figure 8). The adversary can then answer the CA’s HTTP request in step (6) and subsequently obtain a signed digital certificate from the CA for the victim domain. The attacks were successfully demonstrated in the real world, ethically [17]. The adversary obtained certificates for victim domains via routing attacks from five top CAs (Let’s Encrypt, GoDaddy, Comodo, Symantec, and GlobalSign) in as little as 35 seconds (see Table 1 for details). This work highlights the significant damage that routing attacks can cause to compromise the foundation of secure online communications, and shows the urgent need for practical defenses.

4.3 Defenses to Protect Digital Certificates

Many currently deployed defenses against routing attacks do not sufficiently protect digital certificates. Given the relatively short time required to obtain a fraudulent certificate, an adversary can get a certificate before its attack is mitigated even if the attack is detected by BGP monitoring. In addition, an adversary can potentially obtain a malicious certificate using only a localized routing attack that does not affect a large portion of the Internet. The adversary only needs to affect routes from one (of several hundred) commercial CAs to obtain a malicious certificate.

A recent work by Birge-Lee et al. [17] proposed two practical application-layer defenses. (1) Multiple Vantage Point Verification: building on the key insight that many routing attacks (e.g., equally-specific attacks) are localized, CAs can significantly decrease their vulnerability to attacks by performing domain verification from multiple vantage points and subsequently suspend certificate issuance in the case

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Table 1: Five CAs were attacked and obtained certificates from. All were automated and none had any defenses against BGP attacks.

| Method Attacked       | Let’s Encrypt | GoDaddy | Comodo | Symantec | GlobalSign |
|-----------------------|--------------|---------|--------|----------|------------|
| Time to issue certificate | 35s          | <10min | 51s    | 6min     | 4min       |
| Human Interaction     | No           | No      | No     | No       | No         |
| Multiple Vantage Points | No           | No      | No     | No       | No         |
| Validation Points     | HTTP         | HTTP    | Email  | Email    | Email      |

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No vantage points were deployed at time of attack. Let’s Encrypt has since deployed multiple vantage point verification [13].
of inconsistent validation results. By adding only one additional vantage point, the probability of catching a localized routing attack on a domain increases from 61% to 84%. By having two additional vantage points, the probability of catching the attack reaches over 90% for 74% of the 1.8 million domains in the study. (2) BGP monitoring with route age heuristics: building on the key insight that anomalous and suspicious routing announcements are usually short-lived, CAs can require the routes to the domains to be active for a minimum time threshold before signing a certificate. This defense would force sub-prefix BGP attacks to be active for over 30 hours before the routes can be used to obtain a bogus certificate. Both of these countermeasures only require minimal deployment effort by the CAs with no change needed from domain owners or the Internet infrastructure.

Multiple vantage point verification has gained significant traction. Let’s Encrypt, the world’s largest CA, has deployed multiple vantage point verification [13]. In addition, the prominent CDN CloudFlare has developed an API for CAs to perform multiple vantage point verification using its network [10]. We urge all CAs to immediately adopt the multiple vantage point based defense to enhance the resilience of domain control verification against routing attacks.

4.4 Broader Impact

The attacks on digital certificates apply to other systems that require demonstration of control on certain resources via verification requests. For instance, registering an account or changing its password usually involves verifying the activity through the email address associated with the account (as is the case with Facebook and Google accounts), where the communication with the mail server can be hijacked or intercepted. If the email message is unencrypted, the security of online accounts can be jeopardized. The multiple vantage point verification also generalizes to a broad set of such verification processes, where verifications from multiple sources would help lower the success of an attack and significantly increase the cost to an adversary.

5. THE BITCOIN NETWORK

Bitcoin is the most widely-used cryptocurrency to date, with over 42 million users in September 2019 [14]. A network-level adversary can partition the network, effectively preventing the system from reaching consensus [16]. This attack is applicable to any public blockchain system running on top of the Internet.

5.1 How Bitcoin Works

Bitcoin is a peer-to-peer network in which nodes use consensus mechanisms to jointly agree on a (distributed) log of all the transactions that ever happened. This log is called the blockchain because it is composed of an ordered list (chain) of grouped transactions (blocks).

Special nodes, known as wallets, are responsible for originating transactions and propagating them in the network using a gossip protocol. A different set of nodes, known as miners, are responsible for verifying the most recent transactions, grouping them in a block, and appending this block to the blockchain. To do so, the miners need to solve a periodic puzzle whose complexity is automatically adapted to the computational power of the miners in the network.

Every time a miner creates a block, it broadcasts it to all the nodes in the network and receives freshly-mined bitcoins. Besides the most recent transactions, the block contains a proof-of-work (a solution to the puzzle) that each node can independently verify before propagating the block further. As an illustration, in Figure 9a, node n “mines” a block which is then broadcasted hop-by-hop in the network.

As miners work concurrently, several of them may find a block at nearly the same time. These blocks effectively create “forks” in the blockchain, i.e., different versions of the blockchain. The conflicts are eventually resolved as subsequent blocks are appended to each chain and one of them becomes longer. In this case, the network automatically discards the shorter chains, effectively discarding the corresponding blocks together with the miner’s revenues.

5.2 Routing Attacks on Consensus

A network-level adversary can perform several attacks on bitcoin including partitioning the set of nodes into two (or more) disjoint components [16]. Consequently, these attacks disrupt the ability of the entire network to reach consensus.

To partition the network into disjoint components, the adversary must divert and cut all the connections connecting the various components together. To do so, the adversary can perform an interception attack by hijacking the IP prefixes pertaining to each component and selectively dropping the connections crossing the components, while leaving the internal connections (within a component) untouched.

As an illustration, in Figure 10, the adversary creates a partition by hijacking all prefixes pertaining to bitcoin nodes in the gray zone. Having gained control over the traffic towards these nodes (red lines), the adversary drops the connections between the clients that are within the gray zone and outside it, effectively creating a partition.

For cryptocurrencies, the impact of partition attacks is worrying. First, a partition attack can act as a denial-of-service attack: clients can neither properly propagate the corresponding transactions, nor verify the ownership of funds. Second, a partition attack can lead to high revenue loss for the miners: once the network reconnects, the shortest chain(s) will be discarded, permanently depriving miners of their rewards.

5.3 Defenses to Protect the Bitcoin Consensus

A recent work [15] proposed SABRE to protect the bitcoin system against partition attacks. SABRE is a relay network, composed of a small set of special bitcoin clients (relays) that receive, verify, and propagate blocks. Regular bitcoin clients can connect to one or more relays in addition to their regular connections. During a partition attack, the SABRE relays stay connected to each other and to many bitcoin clients, allowing block propagation among the otherwise disconnected components. As an illustration, in Figure 11, while clients in the gray zone are isolated from the rest of the network, a block mined by node n is propagated via the relay nodes (colored in orange) to the rest of the network.

SABRE achieves this by strategically choosing the ASes in which to host relay nodes. SABRE’s placement algorithm is based on the key insight that some ASes, such as those without customers, are naturally protected against routing attacks. By hosting relays in these ASes, SABRE can therefore maintain its connectivity and its ability to propagate blocks on behalf of bitcoin clients, even in the presence of routing attacks. Note that a bitcoin client only requires one
unhindered connection to a SABRE relay to be protected.

For instance, in the SABRE network shown in Figure 10a, the algorithm selects three ASes, namely ASB, ASC, ASD, to host the relay nodes. Observe that during a partition attack, the relay network stays connected. Indeed, if the adversary is the provider of ASC and she advertises the prefix of the relay hosted in ASB to ASC, the latter will not use it, as it would prefer the direct route via its peer, namely ASB. Additionally, all bitcoin clients keep at least one connection to the relay network during the attack. Indeed, even nodes such as node q which lose one of their connections to the relay network due to the attack, stay connected to SABRE via another node.

5.4 Broader Impact

Besides Bitcoin, routing attacks targeting consensus mechanisms are generally applicable to many peer-to-peer networks and are particularly dangerous against blockchain systems such as Ethereum [2], Litecoin [3], and ZCash [32]. The good news though is that application-specific relay networks, such as SABRE [15] for Bitcoin (see above), are also generally applicable and can be used to protect other peer-to-peer networks. Among others, the relay placement algorithm presented in [15] is general and can be used for designing relay networks that protect other peer-to-peer networks.

6. CONCLUSION

Often times, we focus on the security of individual layers of the network in isolation. The adversaries do quite the opposite—they look for opportunities to exploit the interactions between layers. In neglecting the insecurity of the routing infrastructure, application developers underestimate the security risks for their users. In focusing on availability and confidentiality threats, network operators underestimate the security risks to Internet applications. This gap leaves the security and privacy of billions of users at risk.

While application-layer defenses can provide immediate protections, we should also push for large-scale deployment of general defenses against sophisticated routing attacks. We recommend that ASes (i) adopt best practices outlined in the MANRS [12] project, (ii) accelerate the adoption of RPKI by publishing ROAs and performing Route Origin Validation (ROV), and (iii) build consensus on a pathway to solving routing security issues (including full path security) once and for all.

Securing all 800K prefixes and 67K ASes [11] seems like an impossible task. However, only a small portion of the prefixes play a heavy role in each application. For instance, only around 1100 ASes have Tor relays hosted on their prefixes, and one AS alone carries 23% of all Tor traffic. Furthermore, in digital certificate issuance, a handful of certificate authorities issue the vast majority of certificates, and the domains are largely hosted on a few cloud and CDN providers (e.g., five ASes including SquareSpace and Amazon host nearly half of the domains [17]). Finally, only 5 ASes host one third of all Bitcoin clients [1], while 50% of all mining power is hosted in less that 100 prefixes [16]. If a few thousand ASes can take major steps to deploy routing security, the applications will receive tremendous benefits.

In addition, popular applications—and their users—can help incentivize the deployment of routing security solutions by the actions they take. For instance, Tor could favor certain relays that are hosted on authenticated prefixes, and domain owners could favor cloud hosting services that provide origin validations and favor certificate authorities hosted on authenticated prefixes. Similarly, miners could prefer hosting their infrastructure in ASes that provide origin validation, while regular client could prefer to connect to peers hosted on authenticated prefixes. These steps would help motivate network operators to validate their prefixes to offer better service to their customers, and eventually lead to a more secure routing infrastructure.

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(a) SABRE nodes are hosted in ASes that have no customer ASes and compose connected graph of direct peering links. Clients connect to at least one SABRE node.

(b) Blocks mined in the gray zone are propagated further via the SABRE network.

Figure 10

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