

Hijacking Bitcoin: Large-scale Network Attacks on Cryptocurrencies

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Abstract

Bitcoin is without a doubt the most successful cryptocurrency in circulation today, making it an extremely valuable target for attackers. Indeed, many studies have highlighted ways to compromise one or several Bitcoin nodes. In this paper, we take a different perspective and study the effect of *large-scale network-level* attacks such as the ones that may be launched by Autonomous Systems (ASes).

We show that attacks that are commonly believed to be hard, such as isolating 50% of the mining power, are actually within the reach of *anyone* with access to a BGP-enabled network and hijacking *less than 900 prefixes*. Once on path, AS-level adversaries can then partition the Bitcoin network or delay block propagation significantly. The key factors that enable these attacks are the extreme centralization of Bitcoin, both from a routing and a mining perspective, along with the fact that Bitcoin messages are sent unencrypted, without integrity guarantees.

We demonstrate the feasibility of large-scale attacks in practice against the deployed Bitcoin software and quantify their disruptive network-wide impact. The potential damage to Bitcoin is severe. By isolating a part of the network or delaying the propagation of blocks, network-level attackers can cause a significant amount of mining power to be wasted, leading to revenue losses and enabling a wide range of attacks such as double spending. We provide several suggestions on approaches to mitigate such attacks employing both short-term and long-term measures.

1. INTRODUCTION

With more than 15 million bitcoins valued over 6.8 billion USD and up to 240,000 transactions per day, Bitcoin is *by far* the most successful cryptocurrency to date. Remarkably, it has achieved this as an open and fully decentralized monetary system. Instead of relying on a central entity, Bitcoin depends on a large distributed set of nodes that use consensus mechanisms to agree on the set of transactions within its core data structure: the blockchain. Anyone is free to partic-

ipate in the Bitcoin network (which boasts more than 6,000 nodes [2]) and can usually connect to any other node using a simple TCP connection.

While Bitcoin is an overlay network, the underlying network is key to its efficient and secure operation. As Bitcoin communications are not encrypted, any third party on the path between nodes can easily eavesdrop on all Bitcoin traffic and, if malicious, drop, modify, inject, or delay various messages.

While attacking a single node can already be problematic (e.g., if the node has a considerable amount of mining power), large autonomous systems (ASes) such as Internet Service Providers (ISPs) can be naturally on-path for many Bitcoin connections enabling them to perform network-wide attacks and to disrupt the entire system. Worse yet, even *individuals* with far fewer resources can perform well-known routing attacks (BGP hijacks) to place themselves on the forwarding path to many nodes. Such routing attacks are frequent and have targeted Bitcoin traffic in the past. BGP-Stream [1], a website monitoring BGP events worldwide, reported *1616* prefix hijacks between October 2015 and April 2016, i.e. *8.8 per day* on average. Some of these hijacks redirected Bitcoin traffic (for 90 nodes). In 2014, an attacker successfully managed to position herself between Bitcoin pools and their miners using BGP hijacks. Estimates place losses for the pools at over 80,000 USD [9].

This work We present the first comprehensive analysis of the impact of network attacks on Bitcoin. We consider both node-level as well as network-wide attacks, but focus more on the latter due to its greater impact on the currency itself.

Network-level attacks are composed of two general phases: *i*) intercepting Bitcoin traffic either naturally or via routing manipulation; and *ii*) “fiddling” with the Bitcoin messages by either dropping, modifying or delaying them.

We show that intercepting a large amount of Bitcoin traffic is relatively easy due to the *extreme* centralization of Bitcoin at the network level. Indeed, we find that only 13 ASes host over 30% of the network, while some networks such as Hurricane Electric can *passively* eavesdrop on more than 30% of *all* Bitcoin connections. Also, the fact that mining power is centralized in the hands of few pools [19] renders network attacks even easier. Based on actual routing data, we show that *any single AS* can effectively intercept enough Bitcoin connections to control 50% of the mining power by hijacking less than 900 well-chosen prefixes, i.e. only ~ 0.15 of all existing Internet prefixes.

We then explore the consequence of having access to Bitcoin traffic by considering two general exploits. First, we

show that, by severing connections, AS-level *attackers can effectively partition the Bitcoin network*, a feat which is commonly believed to be very hard. Second, we show that *attackers can significantly delay block propagation* in the network by simply delaying few key Bitcoin messages. For both exploits, we investigate the trade-off between detectability and effectiveness.

Impact on Bitcoin We verify the practicality of each attack against the reference Bitcoin implementation and evaluate their network-wide impact using a comprehensive set of measurements, simulations and experiments. We show that the damages caused to Bitcoin in case of a successful network attack is quite severe. By isolating a part of the network or delaying the propagation of blocks, attackers can force nodes to waste part of their mining power as some of the blocks they create are discarded. Partitioning further allows the attackers to filter the transactions nodes try to include in blocks. In both cases, miners lose potential revenue from mining and leave the network more susceptible to double spending attacks as well as selfish mining attacks [16]. Nodes that represent merchants, exchanges and other large entities that hold bitcoins are thus unable to secure their transactions, or may not be able to broadcast them to the network to begin with. The resulting longer-term loss of trust in Bitcoin’s security will most likely trigger a loss of value for Bitcoin (and similar crypto-currencies). Attackers may even short the currency and gain from the resulting devaluation (see the Goldfinger attack [25]).

Novelty While network-level adversaries have been studied in the context of anonymity systems such as Tor [15, 17, 29], we are not aware of any work, which has looked specifically at Bitcoin. Secure extensions to BGP would help, but only to an extent, as attackers can still be present on the path naturally. Such extensions are at best years away from being deployed.

Contributions Our main contributions are:

- The first comprehensive study of network attacks on Bitcoin (§3) ranging from one attacker attacking one node to AS-level attackers attacking many connections at once.
- A measurement study of the routing properties of Bitcoin using real-world routing data (§4). The key insight is that Bitcoin is *extremely* centralized, with few ASes (and prefixes) hosting most of the nodes. This centralization allows *any single* AS to intercept 50% of the mining power by hijacking less than 900 prefixes.
- An in-depth evaluation of the impact and duration of partition attacks by performing experiments in a large testbed containing 1050 Bitcoin nodes (§5). Our measurements show that while partitions attacks are extremely effective, Bitcoin recovers quickly once the attack ends.
- A fully-working implementation of a Bitcoin interception software (§6) that network-level adversary can use to delay the propagation of blocks; along with the implementation of a realistic event-driven Bitcoin simulator to measure the network-wide effect of delay attacks. We show that a single AS could increase the rate of discarded blocks (*orphans*) from 1% to 12%, while countries such as the US or Germany could increase it to 50% and 29%, respectively.
- A comprehensive set of countermeasures (§7) that do not harm the scalability or openness of the Bitcoin protocol.

Some of our measures can be applied today to counter the attack vectors presented in this paper.

To ensure reproducibility of our results, we will publicly release all our software, measurements scripts, and datasets.

2. BACKGROUND

We briefly provide background on the Bitcoin protocol and refer the reader to [30, 40] for a broader introduction.

Transactions Transaction validation requires nodes to be aware of the ownership of funds and the balance of each Bitcoin address. All this information is kept within Bitcoin’s blockchain: an authenticated data structure that effectively forms a ledger of all accepted transactions. Bitcoin’s main innovation lies in its ability to synchronize the blockchain in an asynchronous way, with attackers possibly attempting to disrupt the process. Synchronization is crucial: conflicting transactions attempting to transfer the exact same bitcoins to different destinations may otherwise be approved by miners that are unaware of each other.

Block creation Bitcoin’s blockchain is comprised of blocks, batches of transactions, that are appended to the ledger serially. Each block contains a cryptographic hash of its predecessor, which identifies its place in the chain, and a proof-of-work. The proof-of-work serves to make block creation difficult and reduces the conflicts in the system. Conflicts, which take the form of blocks that extend the same parent, represent alternative sets of accepted transactions. Nodes converge to a single agreed version by selecting the chain containing the highest amount of computational work as the valid version (usually the longest chain). The proof-of-work also serves to limit the ability of attackers to subvert the system: they cannot easily create many blocks, which would potentially allow them to create an alternative longer chain that will be adopted by nodes and thus reverse the transfer of funds (double spend). The difficulty of block creation is set so that one block is created in the network every 10 minutes in expectation, which is designed to allow sufficient time for blocks to propagate through the network. However, if delays are high compared to the block creation rate, many forks occur in the chain as blocks are created in parallel. The rate of discarded blocks (known as the *orphan rate* or the *fork rate*) increases and the security of the protocol deteriorates [14, 18, 36]. Newly created blocks are propagated through the network using a gossip protocol. In addition to the propagation of blocks, nodes also propagate transactions between them that await inclusion in the chain by whichever node creates the next block.

Network formation Bitcoin acts as a peer-to-peer network with each node maintaining a list of IP addresses of potential peers. The list is bootstrapped through a DNS server, and additional addresses are exchanged between peers. Each node randomly initiates a default of 8 *unencrypted* TCP connections to peers in different /16 prefixes. Nodes additionally accept connections initiated by others (by default on port 8333). The total number of connections nodes can make is 125 by default.

Nodes continually listen to block and transaction announcements from their peers. These are sent via an INV messages that contain the hash of the announced block. If a node determines that it does not hold the data its peers have announced it sends a GETDATA message to a single neighbor.

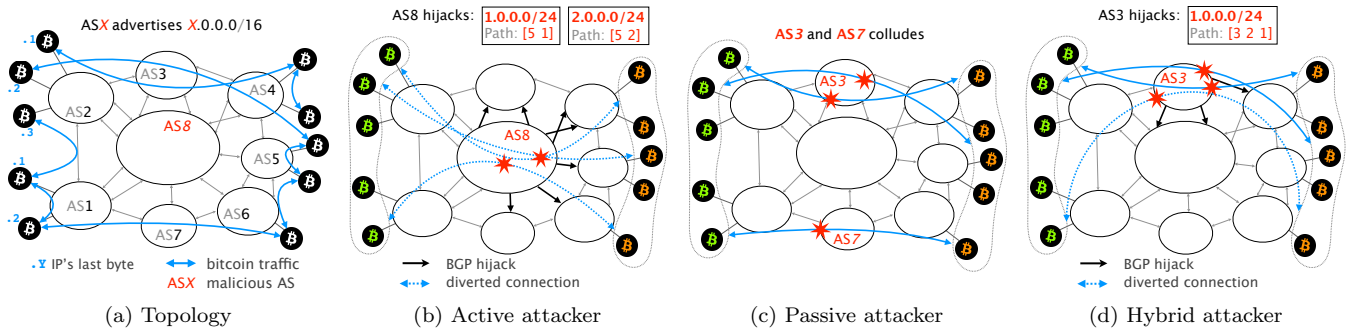


Figure 1: Illustration of how different types of AS-level adversaries can intercept Bitcoin traffic by: hijacking prefixes (b); leveraging natural connectivity and colluding with each other (c); or doing both (d).

The peer then responds by sending the requested information in a **BLOCK** message. Blocks that are requested and do not arrive within 20 minutes trigger a disconnection from the peer, and are requested from another. Transaction propagation occurs with a similar sequence of **INV**, **GETDATA**, and **TX** messages in which nodes announce, request, and share transactions that have yet to be included in blocks.

3. ROUTING ATTACKS ON BITCOIN

In this section we describe the various network attacks that we consider in this paper. We split an attack into two general phases: *i*) gaining access to Bitcoin traffic either naturally or via routing manipulation (§3.1); and *ii*) exploiting access to a large fraction of Bitcoin traffic to disrupt the system (§3.2). Table 1 provides a high-level overview of our results and their implications for Bitcoin (increased fork rate).

3.1 Phase I: Intercepting Bitcoin traffic

To intercept Bitcoin traffic at scale, adversaries either leverage or manipulate BGP routing. BGP is the de-facto routing protocol that regulates how IP packets are forwarded to their destination. Among other things, BGP is used to exchange routes pertaining to IP prefixes between neighboring networks or Autonomous Systems (AS). For any given IP prefix, one AS (the origin) is responsible for the original route advertisement, which is then propagated AS-by-AS, until all ASes learn about it. In the following, we consider three types of adversaries, which differ in how they intercept Bitcoin traffic. We illustrate these adversaries with a simple example (Fig. 1). Bitcoin nodes are connected to AS1, AS2, AS4, AS5 and AS6. Each ASX advertise one IPv4 prefix: $X.0.0.0/16$. For instance, AS1 advertises $1.0.0.0/16$, while AS2 advertises $2.0.0.0/16$ (Fig. 1a). We consider the problem of partitioning the Bitcoin network into two sets of Bitcoin nodes colored in green (left) and orange (right).

Active adversaries manipulate BGP routes to intercept Bitcoin traffic. By default, BGP does not check the validity of announcements. As such, any AS can inject forged information on how to reach one or more IP prefixes, leading other ASes to send traffic to the wrong location. These rogue advertisements are known as BGP “hijacks”. To attract some traffic for prefix p , an attacker can either announce p directly (in which case she will attract 50% of the traffic, on average [22]) or a more-specific (longer) prefix of p . In the latter case, the attacker will hijack traffic globally since routing in the Internet is based on the longest-match. Sending more-

specific prefixes has its limits though, as BGP operators will often filter prefixes longer than $/24$. Finally, an attacker hijacking prefixes acts as a sink for any intercepted traffic. Yet, an attacker can easily turn a hijack into an *interception* attack by making sure she leaves at least one path untouched to the destination [33]. In Fig. 1b, AS8 could gain visibility into Bitcoin traffic by hijacking AS1 and AS2 or AS4, AS5 and AS6. In this case AS8 would likely prefer the former, since hijacking two prefixes is less visible.

BGP hijacks are both hard to avoid and to protect from. There are also extremely slow to resolve. As BGP security extensions (BGPsec [10] or RPKI [26]) are seldom deployed [27], operators often simply rely on monitoring systems that report rogue announcements (*e.g.*, BGPmon [37]). When detected, solving a hijack can take hours as it is a human-driven process consisting of filtering or disconnecting the attacker. As an example, YouTube took close to 3 hours to resolve a hijack of its prefixes by a Pakistani ISP [5].

Passive adversaries only act on Bitcoin connections that are naturally crossing them. They do not manipulate routing announcements and, as such, are completely invisible. Obviously, only well-established ASes are likely to be traversed by a lot of Bitcoin connection naturally. As such, their main challenge is to avoid detection, as that would harm their reputation. Still, it is unlikely that well-known ASes will take the risk. What is more likely though is smaller, distinct passive adversaries colluding with each other and collectively acting on Bitcoin messages. Such coalition are most likely to occur among ASes of the same country, since they might share common interests, and are obliged to obey to the same government. In Fig. 1c, AS3 and AS7 can realize that by colluding with each other they can partition the Bitcoin graph.

Hybrid adversaries combine passive and active methods to increase their effectiveness and lower their footprint. They rely on active methods (hijacking) to increase the fraction of connections they naturally see, by biasing the selection of peers, or use passive behavior to prolong the effect of their attack after they have stopped hijacking. Their main challenge is to choose the right prefixes to hijack, and to maintain their influence as passive attackers in the future. In Fig. 1d, AS3 can reduce its footprint by leveraging the fact that it sees two Bitcoin connections naturally and only hijacking one prefix (from AS1) to create the partition.

Effectiveness Three factors make AS-level attackers particularly powerful (§4). First, the Bitcoin network is extremely

Routing attacks (§3)	Active # prefixes hijacked	Passive countries or AS	Fork rate
Partition (§5)			
- 50%	37/879	None	50%
- 20%	14/119	US/+CN	20%
Delay (§6)			
- >23% of intercepted traffic	100	US,DE,SE,GB/+CN,HK	> 15%
- >80% of intercepted traffic	300	US	> 50%

Table 1: Overview of feasibility of partition and delay attacks. The second column denotes the number of prefixes any AS should hijack to perform the corresponding attack. The lower and greater value correspond to an attacker, who is respectively aware and unaware of the exact location of the mining pools. The third column depicts which countries have the power to alone perform such attacks again. Left and right values again correspond to the awareness (or not) of the location of mining power. The effectiveness of the attack is shown in fourth column using fork rate, i.e. the total amount of wasted mining power.

centralized from a routing and mining viewpoint. Second, the vast majority of the network is vulnerable to global hijack. Third, discovering AS-level adversaries is hard as they can be anywhere on the path.

3.2 Phase II: Attacking Bitcoin consensus

Once on-path, AS-level adversaries can fiddle with Bitcoin connections by arbitrarily dropping, delaying or even modifying the messages exchanged. In the following, we consider two different attacks against Bitcoin consensus by either partitioning the Bitcoin network (§3.2.1) or by arbitrarily delaying the propagation of blocks (§3.2.2).

3.2.1 Attack#1: Partitioning Bitcoin

The goal of this attack is to partition the Bitcoin network into two disjoint components, such that there is no active connection between them. Partitioning the network would directly harm the consensus mechanism as the two parts will have different views of the blockchain and recent transactions. We define an X partition as a partition in which the smaller component contain $X\%$ of the total mining power.

Intuitively, an AS-level adversary can sever connections between nodes by simply dropping the packets of any TCP connection she is on-path for. As TCP connections are bidirectional, it is enough for the attacker to be present on a single direction of traffic.

While creating a 50% partition is extremely disruptive for Bitcoin, increasing the fork rate from 1% to 50%, we show that it is within the reach of *anyone* with access to a BGP-enabled network. Indeed, we show that such a partition can be formed by hijacking only 879 prefixes in the worst case (§4), and only 37 prefixes when taking the distribution of mining power into account. In contrast, passive attacks are relatively less effective. As illustrated in Table 1, no country in the world can cut the network into half. However, smaller partitions are feasible. In particular we show that a 20% partition can be created *passively* by American ASes as well as by Chinese ones, and actively by any AS by hijacking only 119 or 14 prefixes depending on the actual distribution of mining power.

We also show that a partition heals slowly once the attack is over: even 10 hours after the attack has stopped the partition is only 50% healed. This is due to the tendency of nodes to maintain their connections to neighbors over a long period of time. An attacker can use the traffic she naturally intercepts to partially continue enforcing the partition. For instance an attacker that intercepts less than 30% of the

traffic can prolong the partition by 58%. Despite the slow recovery in terms of connectivity, consensus in the system is very quickly regained.

Implications for Bitcoin If a full partition of the network is achieved, transactions from one side of the partition can be blocked from reaching the other side, effectively blocking payments from reaching across. Transactions mined into blocks on the side with less mining power will eventually be erased from the chain when the partition collapses. They can be included again, but this may take time if a significant backlog has formed and may result in transaction fee increases. Finally, the attacker can use the fact that blocks on both side of the partition are in conflict to send conflicting transactions to different sides that will allow it to double spend without requiring any mining power of his own.

3.2.2 Attack#2: Delaying Bitcoin traffic

The goal of this attack is to delay the propagation of blocks to weaken Bitcoin’s consensus mechanism. Indeed, the propagation delay in the network is the primary cause for blockchain forks [14]. To do so, the adversary can leverage its position and the way blocks are propagated to delay nodes from learning about recent blocks. Once it has requested a block from a peer, a node will indeed wait up to 20 minutes for the peer to deliver it [20] before requesting it from another peer. As such, a network adversary between the sender and the receiver of a block can delay its delivery, forcing the receiver to stay uniformed for 20 minutes.

Since Bitcoin is built atop of TCP, which guarantees message delivery, the adversary should ensure her activity is undetectable from the TCP layer. Intuitively, if the adversary simply drops messages, the connection will be reset due to the retransmission mechanism of TCP, and blocks will be requested from a different peer. Moreover, for a disconnection to be avoided, the block should be delivered before the 20 minutes timeout. We describe how an attacker can overcome these limitations (§6) and avoid disconnections. We also show how adversaries with a partial view of the connections (due to asymmetric routing and multi-homing) can still effectively delay block propagation.

As with partition attacks, we performed a delay attack in practice against a single node to investigate its effectiveness and simulated the network to estimate the cascading effect of delaying blocks at a network-wide scale. Regarding an attack on a single node, we found that an adversary intercepting 50% of the victim’s connections can keep it un-

informed for 63% of its uptime. With regards to attacking the network, we show that the US, as well as any AS hijacking 300 well-chosen prefixes, is able to increase the orphan rate from 1% to 50%. Germany, Sweden, and Great Britain could also increase the orphan rate to at least 15%. China is also very powerful when considering mining pools.

Implications for Bitcoin A significant slowdown of block transmission can be used to launch selfish mining attacks by adversaries with mining power (requiring less mining power than in situations without such delay [34]). Even without mining power, blocks that are lost as orphans deduct from the profits of miners (as off-chain blocks in Bitcoin yield no reward to their miner). The increased rate of lost blocks also makes it easier to double spend as the block chain grows at a slower pace and can be overtaken by weaker attackers.

4. INTERCEPTING BITCOIN TRAFFIC

In this section, we show how *any* AS-level adversary (independently of its size or position) can leverage the extreme centralization of Bitcoin regarding routing and mining power (§4.1) to intercept 50% of the Bitcoin connections (§4.2) by hijacking *less than 900 prefixes*.

4.1 Measurement analysis

Using routing and Bitcoin measurements (§4.1.1), we show that the Bitcoin network is extremely centralized (§4.1.2).

4.1.1 Datasets & Methodology

AS-level and Bitcoin topology We collected *2.5 million* BGP routes (covering all Internet prefixes) advertised on 182 BGP sessions maintained by 3 RIPE BGP collectors [7] (rrc00, rrc01 and rrc03). We collected these routes daily, for 4 months, between Oct 2015 and Jan 2016. We also collected inferred AS-level topologies computed by CAIDA [4]. An AS-level topology is an undirected graph, in which a node corresponds to an AS and a link represents an inter-domain connection between two neighboring ASes. Links are labeled with the business relationship linking the two ASes (customer, peer or provider).

In parallel, we collected around 6,000 IP addresses hosting Bitcoin nodes for each day between Oct 2015 and Jan 2016. The addresses are collected by a Bitcoin supernode, which continuously crawls the Bitcoin network to discover clients. The list of IP addresses is available online [2].

By combining these two datasets, we first identified which AS is hosting each Bitcoin node by mapping its IP address with the AS advertising the most-specific covering prefix. To protect our mapping from BGP hijacks and mapping a node to the wrong AS, we only consider prefixes that have been advertised consecutively for at least one day. We then computed the sequence of ASes traversed when any two Bitcoin nodes communicate. For this, we followed the routing tree algorithm described in [22], which takes into account the business relationships between ASes.

Mining power distribution Bitcoin mining power is not distributed uniformly across all Bitcoin nodes [6, 28]. To account for that fact, we consider two mining power distributions in the following: *uniform* and *centralized*.

In the *uniform* distribution, we attribute an equal share of the hash rate to each node. This constitutes the worst-case for the attacker as many nodes need to be quarantined to

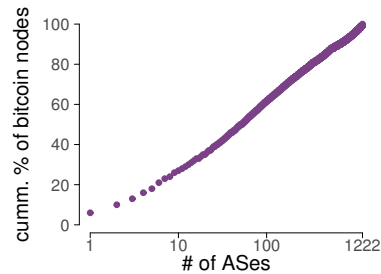


Figure 2: From a routing viewpoint, the Bitcoin network is extremely centralized. Only 13 ASes host 30% of the entire network, while 50 ASes host 50% of the network.

separate a substantial amount of computational power from the network. We therefore use this case as a baseline.

In the *centralized* distribution, we attribute most of the hash rate to few ASes. We attribute 92% of the mining power to pools and assume that the remaining 8% is equally distributed among all other nodes. We infer the distribution of mining power among pools from [6], which contains statistics sourced from the blockchain itself and refer to the first week of Nov 2015. We assign pools to ASes using the public IPs of the Stratum servers that are used by miners to connect to those pools. It is important to note that some pools are multi-homed. We decided to use this method instead of the alternative of locating the pools based on where the first INV messages is propagated from. Indeed, by analyzing the INV messages that a supernode connected to 2000 bitcoin nodes received from Dec 2015 to Apr 2016, we realized that this method would cause all pools to be homed in only 2–3 well-connected ASes.

4.1.2 Results

We now present our findings. As the results of our analysis do not change much through time, we focus on the results for Nov 15 2015 unless noted otherwise.

The Bitcoin network is extremely centralized Very few ASes host the majority of the nodes in the network. Fig. 2 depicts the cumulative fraction of Bitcoin nodes as a function of the number of hosting ASes. We see that only 13 (*resp.* 50) ASes host 30% (*resp.* 50%) of the entire Bitcoin network. These ASes pertain to broadband providers such as Comcast (US), Verizon (US) or Chinanet (CN) as well as to cloud providers such as Hetzner (DE), OVH (FR) and Amazon (US). We observe the same kind of concentration, at the distribution of Bitcoin nodes per IP prefix: only 63 prefixes (0.012% of the Internet) host 20% of the network.

Few ASes see a substantial part of Bitcoin traffic Fig. 3 depicts the cumulative percentage of connections that can be intercepted by an increasing number of ASes (*e.g.*, by colluding with each other). We see that only *three* ASes, namely, Hurricane Electric, Level3 and Telianet, can together intercept *more than 80% of all possible Bitcoin connections*, with Hurricane alone being on path for 32% of all connections. In general, large transit providers (*i.e.*, Tier-1s) are traversed by a large fraction of all Bitcoin connections.

>90% of the Bitcoin network is vulnerable to hijacks 93% of all prefixes hosting Bitcoin nodes are shorter

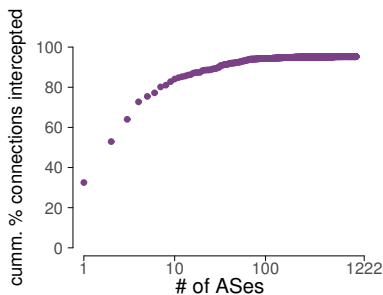


Figure 3: Few ASes intercepts a large percentage of Bitcoin traffic. Together, 3 (resp. 7) ASes (Hurricane, Level3 and Telianet) can intercept more than 60% (resp. 80%) of all possible Bitcoin connections.

than $/24$, making them vulnerable to a global IP hijack using more-specific announcements. Indeed, prefixes strictly longer than $/24$ are typically filtered by default by many ISPs. Note that the remaining 7% of nodes that are in $/24$ prefixes are *not* necessarily safe. These can still be hijacked by another AS performing a shortest-path attack, i.e., the attacker, who will advertise a $/24$ just like the victim will attract traffic from all ASes that are closer to it than they are to the victim (in terms of number of hops).

Bitcoin routing properties are stable While numerous nodes join and leave the Bitcoin network all the time, the routing properties highlighted in this section are stable. For validation, we ran our analysis daily over a 4 month period, during which the same IPs were present on average for 15.2 consecutive days (excluding IPs that were seen only once). Moreover, our observations regarding the network’s centralization are also extremely stable: 50 ASes hosted each day 49.5% of Bitcoin clients (standard deviation: 1.2%) while 24.7% of Bitcoin nodes are found daily in just 100 prefixes (standard deviation: 1.77%).

4.2 Interception attacks using centralization

We now evaluate how active, passive, and hybrid AS-level adversaries can leverage the centralization of the Bitcoin network to isolate 50% of Bitcoin’s mining power.

4.2.1 Active attackers

We start by considering an active AS-level attacker, whose goal is to intercept all traffic from nodes that hold 50% of the mining power using BGP hijacks, while lowering its footprint, i.e. the amount of prefixes hijacked. Table 2 summarizes the number of hijacks required to do so for *any single AS* considering the extreme case, in which the AS: *i*) does not see *any* traffic naturally; and *ii*) does not host any Bitcoin nodes. We further evaluate two attack strategies: *i*) a naive one (*random*), in which the attacker randomly constructs a partition intercepting 50% of the connections or; *ii*) a greedy optimized one (*greedy*), in which she aims to minimize the number of prefixes required. To compute *greedy*, we assign a score to each AS that equals to the ratio of mining power it contains over the number of prefixes with Bitcoin nodes it advertises. The attacker then hijacks the ASes with the higher scores first.

When considering a *uniform* distribution of mining power and an unoptimized choice of partition (both of which are

mining distribution strategy	uniform		centralized	
	random	greedy	random	greedy
Active attacker # prefixes hijacked	1394	870	67	31
Passive attacker # ASes colluding	202	50	7	3

Table 2: Due to centralization (§4.1.2), a *single* AS can intercept 50% of the Bitcoin connections by hijacking *only 870 prefixes* when mining power is uniformly distributed. *Only 31 prefixes* are enough when considering the centralization of mining power. Although less likely, only 7 ASes have to collude to intercept 50% of the connections.

highly unlikely assumptions in practice), we observe that *only 1394 prefixes* need to be hijacked. When considering the *greedy* partition, this number goes down to *870 prefixes*. We argue that these results are extremely worrying for the Bitcoin network. Indeed, large hijacks are often observed on the Internet. BGPStream [1], a website monitoring possible BGP hijacks, reported 1616 possible hijacks between October 2015 and April 2016—*more than eight per day on average*. When considering the mining pools and a skewed distribution of the mining power, the results are even worse, with less than *100 prefixes* needed in all cases.

4.2.2 Passive attackers

We now consider the case of passive AS-level attackers who similarly aim to intercept 50% of the mining power but, this time, naturally. Even though some ASes see a considerable fraction of the connections already (§4.1.2), passive AS-level attackers need to collude to intercept 50% of the mining power, making this attack less likely to happen in practice than an active one.

Table 2 summarizes the number of ASes that should collude to intercept 50% of the mining power. As before, we consider two attack strategies. The first one, *random*, corresponds to a random 50/50 partition, in which we randomly pick ASes and the connections crossing them until we manage to partition away 50% of the mining power. The second case, *greedy*, corresponds to an optimized partition, which optimizes the size of the coalition. We compute *greedy* as such: Given X , the set of edges to break to form the partition, we iteratively add to the coalition, C , the AS i , which appears on the path of the highest number of remaining uncut edges and remove all edges crossing i .

When considering a uniform distribution of mining power, we find that a coalition of 202 ASes is required to create a random partition, while a coalition of 50 ASes is enough to create the minimal 50 partition. Indeed, 50% of all Bitcoin clients are hosted in 50 ASes, which make up the best passive attackers. Overall, we believe that such a coalition is highly unlikely to form in practice. Yet, when considering a more skewed distribution of mining power (*centralized*), we observe that *only 3 ASes* are enough when considering the *greedy* partition and *only 7 ASes* when considering a random one. Still, these well-established ASes are unlikely to risk their reputation to attack Bitcoin. A more likely scenario though is the one of a government mandating all ASes under their jurisdiction to attack the currency. To evaluate this, we computed the “national power” of countries for which, na-

Country	Connections (%)	Partition size	
		<i>uniform</i>	<i>centralized</i>
US	89.8	37.0	28.5
DE	32.8	8.8	16.1
GB	31.4	5.4	0.0
SE	26.7	2.0	0.0
CN	12.2	5.4	32.3

Table 3: Cumulated power ASes in the same country have over Bitcoin measured in % of connections they intercept and the most disruptive partition they can achieve.

tional ASes intercept a lot of Bitcoin connections. Table 3 summarizes the results. While no country alone reaches 50% (independently of the mining power distribution), we see that US and CN can still create non-trivial partition. CN gets a lot more when considering the *centralized* distribution as it hosts almost 30% of the mining power.

4.2.3 Hybrid attackers

In practice, nothing prevents AS-level adversaries to combine active and passive attacks to reduce their footprint even further. While many hybrid strategies exist, we consider a generic yet efficient approach, which consists first of following the greedy strategy of an active attacker until the partition reaches 50%, and then colluding with the ASes that are harder to hijack (require more prefixes).

When considering a uniform distribution of mining power, 3 ASes and 736 prefixes are enough to intercept 50% of the mining power. As before, these numbers reduces considerably when considering a skewed mining distribution. Interestingly, a *single AS* can now perform a 50/50 partition by hijacking only 14 prefixes. This attack is possible because one Chinese AS hosts 29% of mining power in the *centralized* model. By hijacking 14 prefixes, this Chinese AS can attract the remaining 14% required to reach 50%.

5. PARTITIONING BITCOIN

In Section 4, we showed that any single AS can intercept 50% of the connections (and mining power) by hijacking few prefixes ($\sim 0.15\%$ of all prefixes). We now investigate the influence an attacker might have by simply dropping all messages on the intercepted connections, effectively partitioning the Bitcoin network.

We measure the effect of a partition in a large-scale virtualized environment composed of 1050 actual bitcoin nodes (§5.1). We describe two key findings. First, the network quickly goes down after connections are disrupted. Second, while connections crossing the partition slowly return as the partition heals (§5.2), the fork rate is quickly restored to normal. The latter result implies that imperfect partitions are not useful in disrupting the network, which makes partition attacks last only as long as the attacker successfully isolates the different parts of the network.

5.1 Methodology

We start by giving a high-level view of our experimental set-up and the incorporation of churn. Our testbed is composed of 1050 bitcoin clients running the default `bitcoind` core (v0.12.1) in testnet mode. Each node runs on a virtual machine connected to a virtual switch and is configured with

a different random IP address. To enforce a given partition, we simply install drop rules on the switch which discard any packets belonging to a connection crossing the partition. We measure the partition recovery time by collecting the percentage of connection going from one side to the other every 30 minutes.

Churn By design, Bitcoin TCP connections are kept alive for extended periods. As such, new connections are mostly formed when nodes reconnect or leave the network (churn). To simulate churn realistically, we collected the lists of all reachable Bitcoin nodes [3], every 5 minutes, from February 10 to March 10 2016. For every node i connected in the network on the first day, we measured t_i as the elapsed time until its first disappearance. To determine the probability of a node to reboot, we randomly associated every node in our testbed with a type t_i and assumed this node reboots after a period of time determined by an exponential distribution with parameter $\lambda = \frac{1}{t_i}$. The time for next reboot is again drawn according to the same distribution. This method produces churn with statistics identical to the empirical ones. We repeat each measurement at least 5 times with different sequences of reboots and report the median value found.

Validation We ensure the reliability of our results using three methods. Firstly, we avoid potential interference between consecutive experiment by rebooting each node before every experiment. Address books for the nodes (`peers.dat`) were generated through a random process of churn and are restored to their initial state in between different runs. All our nodes thus end up with ~ 800 addresses in their database. Secondly, before each experiment, we count and report the number of connection that cross the partition to ensure that there is no bias in the initialization process in favor of the partition. Thirdly, we made sure that the server running our testbed was moderately used during the entire experiment so that our results are not influenced by CPU spikes.

5.2 Results

We now measure how long it takes for a 50 partition to heal by measuring how many connections cross it, before, during and after its formation. We consider two different attack scenarios: *i*) the adversary does not see any bitcoin traffic before or after the attack; and *ii*) the adversary sees some connections naturally. Fig. 4 summarizes our findings. We stress that our experimental results serve as a generic study of partition recovery as they are independent of how the partition was formed.

In spite of the long healing time, the orphan rate of the network returned to normal even with 1% of all connections crossing the partition. This fact shows that partitions need to be perfect in order to affect the network significantly.

Case 1: no connection crosses the attacker(s) naturally As seen in Fig. 4, it takes 2 hours until one fifth of the initial number of connection crossing the partition are established, while after 10 hours only half of the connections has been recovered. The slow recovery is due to the fact that nodes on both sides do not actively change their connections unless they or their neighbors disconnect.

Case 2: some connections cross the attacker(s) naturally If an AS-level adversary is naturally on-path of some connection, she can significantly prolong the partitions healing. To do so, the attacker would just continue dropping

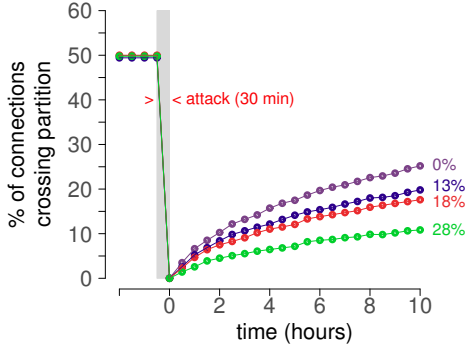


Figure 4: Bitcoin heals slowly after a 50 partition attack. After 10h, only 50% of the connections which crossed the partition initially cross it again. The healing is even slower if the attacker is on-path for some connections (13%, 18%, 28%) naturally.

packets on connections she is on-path for. We measured the effect of such attacks for attackers that are on-path for 14%, 18%, and 28% of the connections, respectively. The results appear in Fig. 4. We see that an AS-adversary who is initially on-path for 28% of the connections can prolong the already slow recovery of the partition by 58%.

To delay the recovery even further an adversary can pro-actively bias the connections the nodes will accept and initialize after the attack. Firstly, she can modify exchanged messages across the partition to cause nodes to ban each other, prohibiting the re-establishment of the same connections for 24 hours. Secondly, the attacker can flood the nodes in each partition with addresses of nodes belonging to the same partition [23] or modify the exchanged ADDR messages. This essentially increase the probability that future connections will be within the partition.

6. DELAYING BITCOIN TRAFFIC

While partitioning attacks are particularly effective and can be performed by any AS (§4 and §5), they are also highly visible. In this section, we explore another kind of attacks, *delay attacks*, which aim to hinder the propagation of blocks by fiddling with the Bitcoin messages of victim nodes. Delay attacks are almost invisible, yet very effective in disrupting Bitcoin’s consensus mechanism. This effectiveness is a consequence of the 20 minutes delay an attacker can cause to the delivery of a block. 20 minutes make up a large time interval for Bitcoin, given that the median propagation delay of blocks is around 7 seconds and the block creation rate is 10 minutes. During this time, the node mines on an obsolete branch, is uninformed of the latest authorized transactions and does not serve the P2P network by propagating a block.

We describe delay attacks in two steps. In the first step (§6.1), we describe how a network adversary can leverage some key features of the protocol to attack a single node she intercepts traffic from or towards. We evaluate the attack on actual Bitcoin nodes that we control and are connected to the live network. We show that a node can stay uninformed during 85% of the time it is under attack without detecting it. In the second step (§6.2), we investigate the damages

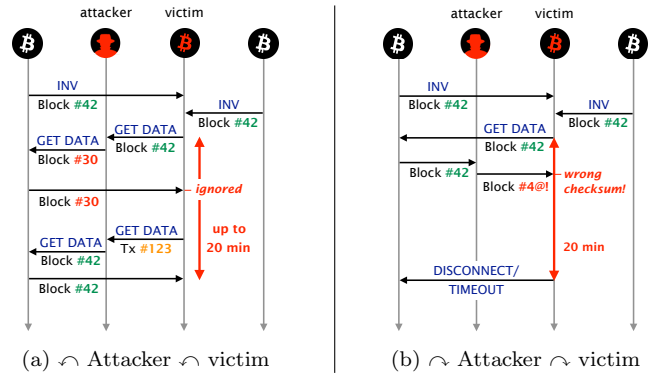


Figure 5: An attacker can perform different delay attack depending on the direction of traffic it intercepts. When on the path from the victim, it can modify the GETDATA message (a), while it can modify the BLOCK message when lying on the opposite path (b).

that an AS-level adversary can do at a network-wide scale. For this, we built a realistic Bitcoin simulator. Using it, we show that network-wide delay attacks are not only feasible but also adequate to increase the orphan rate to 50%.

6.1 Attacking a single node

We first consider the case of attacking a single node. We show how a network adversary, i.e. a Man-in-the-middle (MITM), can prevent it from learning about new blocks, by modifying Bitcoin messages on-the-fly.

In practice, the effectiveness of the attack depends on the direction and fraction of the victim’s traffic the MITM intercepts. Bitcoin nodes establish multiple (bi-directional) TCP connections, and the attacker can intercept one direction (e.g., if the victim is multi-homed), both or none at all.

We start by describing the most effective attack, which can be performed by an adversary that intercepts at least a fraction of the traffic that originates *from* the victim (§6.1.1). We then describe another attack that can be performed by a MITM observing at least a fraction of the traffic destined *to* the victim (§6.1.2). Both attacks allow an adversary to delay block by 20 minutes, but the former is less visible.

6.1.1 The MITM intercepts outgoing traffic

Once a node receives a notification that a new block is available via the INV message, it issues a download request to one of them using a GETDATA message (see Fig. 5a). As Bitcoin messages are not cryptographically protected against tampering, a MITM can easily modify the content of the GETDATA and recompute the TCP and Bitcoin checksums. One easy way to prevent the delivery of a requested block, is to modify the GETDATA message, such that it requests a block with an older hash, instead of the original one. The advantage of doing so is that the length of the message is left unchanged and as such does not require the TCP sequence numbers to be updated (*i.e.*, this does not require the MITM to be in both direction of the TCP connections). Also, the large majority of Bitcoin nodes uses the default TCP port (8333) to communicate, rendering the task of identifying Bitcoin traffic trivial.

A Bitcoin node asks for a block (Block 42 in Fig. 5a) from the first of its peers that advertised it, and sets a timer for

20 minutes. Once this period has elapsed, it will request the block from another peer. This practice was adopted by Bitcoin core as a scalability measure. To avoid a disconnection, which would deprive her from the MITM position, the attacker can simply use another `GETDATA`, sent within the 20 minutes window, to perform the reverse operation. Specifically, she modifies the hash back to the original one, requested from the victim. In practice, another `GETDATA` sent by the victim is almost always guaranteed to be found within 20 minutes of the original, as `GETDATA` messages for transactions, which are much more common in the Bitcoin network, can be also used.

Effectiveness Three reasons make this attack extremely effective. *Firstly*, it works even if the adversary does not intercept all of the victim’s connections. Even 50% of all connections is enough to eclipse the victim for 63% of its uptime. *Secondly*, the victim has no clear indication that it is under attack, since there is no error in its log files. *Thirdly*, by making sure that the victim receives the block within 20 minutes, the attacker avoids disconnection and maintains her influence over time. This matters especially when she intercepts only a relatively small fraction of the victim’s connections. Without doing so, the attacker loses one connection per delayed block, as the victim will likely pick connections the attacker cannot influence. Observe that the attacker could increase its effectiveness even more using hijacks or Eclipsing methods [23] so as to bias the selection of peers and intercept more of the victim’s connections.

6.1.2 The MITM intercepts incoming traffic

We now describe a corresponding attack that a MITM can perform when she is on the path towards the victim, *i.e.* she can see the messages (for the connection she is on-path) received by the victim, but not the messages sent. This attack is less effective compared to the attack of the opposite direction, as it will eventually result in the connection being dropped after the first delayed block delay. Yet, this attack still allows a MITM intercepting only this direction to effectively delay the delivery of a block to a node for 20 minutes.

Given that the MITM sees messages sent to the victim, the attack focuses on the `BLOCK` messages rather than on the `GETDATA`. A naive attack would be for the MITM to simply drop any `BLOCK` message she sees. As Bitcoin relies on TCP though, doing so would quickly kill the TCP connection. A smarter, yet still simple attack, is for the MITM to corrupt the content of a `BLOCK` message, while preserving the length of the packet. This simple operation causes the `BLOCK` to be discarded when it reaches the victim, because of a checksum mismatch. Surprisingly though, we discovered (and verified) that the victim will *not* request the block again, be it from the same or any other peer. After the 20 minutes timeout has elapsed, the victim simply disconnects because the requested block did not arrive in time.

An alternative for the adversary, is to replace the hash of the most recent Block with a hash of an older one, in all the `INV` messages the victim receives. This attack however would fail if the attacker intercepts only a fraction of the connections, as the victim will be informed via other connections. As such, this practice is only useful when the attacker hijacks and thus intercepts all traffic to the victim.

<i>intercepted connections</i>	<i>proportion of time victim is uninformed</i>	<i>attack duration</i>
100.0%	85.45%	191.61h
80.0%	81.38%	254.79h
50.0%	63.21	190.08

Table 4: Using our interception software, we show that when intercepting only 50% of the victim connections, she ends up lagging behind a reference node 63.21% of the time.

6.1.3 Experimental results

Prototype implementation To show that delay attacks work in practice, we implemented a fully-working prototype of the interception software that a MITM would run, and used it to test the effectiveness of the above attacks. Our prototype is built on top of Scapy [8], a Python-based packet manipulation software. Our prototype is efficient both in terms of state maintained and processing time, by leveraging parallelism. Regarding computation, we use pre-compiled regular expression to distinguish critical packets (such as those with `BLOCK` messages) from regular ones. Critical packets are then processed by dedicated threads. Regarding state, only 32B (hash size) per connections per 10 minutes per client, are required.

Methodology We use our prototype to attack one of our own Bitcoin nodes (running “/Satoshi:0.12.0/” on an Ubuntu 14.04 machine). We simulate a MITM by running our prototype on a different machine acting as a gateway to the victim node. Using this setup, we measure the effectiveness of a MITM in delaying the delivery of blocks, by varying the percentage of connections it can act on. To that end, we measured the fraction of time, during which the victim was uninformed of the most recently mined block. We consider our victim node to be uninformed when its view of the main chain is shorter than that of a reference node. The reference node, is another Bitcoin client running the exact same software version and same number of peers as our victim, but without any MITM fiddling with its messages.

Results Table 4 summarizes the time, during which our victim is uninformed with respect to a reference (non-attacked) node, considering the MITM can intercept 100%, 80%, and 50% of its connections. Each value is the mean of an attack period of ~ 200 hours. Recall that blocks an uninformed node mines, are destined to be rejected by the rest of the network. As such the node will not collect payments, and will not contribute to the overall security of the chain. Our results reflect the major strength of the attack, which is its effectiveness even when the adversary intercepts only a fraction of the victim’s connections. Particularly, we see that a MITM can waste 63% of a node’s mining power by intercepting half of its connections. On the one hand, even if the attacker is in all connections, the victim is still not always uninformed as all blocks are eventually delivered after 20 minutes.

6.2 Attacking the network as a whole

Having practically shown that network-level attacker can significantly delay block propagation, we now show the damages an AS-level adversary can do by attacking many nodes simultaneously. Unlike a 50 partition, the implications of introducing delay to specific connections on the network can-

not be quantified using only control-plane data; one would need to actually slow down the network to evaluate the cascading effect of delaying blocks. As such, we built a (realistic) event-driven simulator following the principles in [31]. Our simulator enables us to evaluate the effect of increased network-wide delays. We show that a single AS could increase the orphan rate by a factor of 10 with respect to that of the current Bitcoin network, while the US could increase orphan rate up to 50% and Germany up to 29%.

We start by describing the design of our simulator (§6.2.1) before presenting the results (§6.2.2).

6.2.1 Simulating the Bitcoin Network

Since we are interested in AS-level adversaries, our simulator focuses on accurately modeling block propagation in the Bitcoin network, excluding any cryptographic operations. This also enables our simulator to scale to a full Bitcoin topology composed of around 6000 nodes. The simulator takes as input the AS-level topology (along with the forwarding paths), the list of IP addresses running Bitcoin nodes as well as the percentage of mining power associated to each node. As before, we consider two possible distributions of mining power: *i) uniform*, in which all nodes have the same power; and; *ii) centralized*, in which a few nodes hold most of the mining power (see §4 for a description of the dataset).

The simulator models each Bitcoin node as an independent thread, which reacts to events according to the Bitcoin protocol. Whenever a node communicates with another, the simulator adds delay, which is proportional to the number of ASes on the path between the nodes. Blocks are generated at intervals drawn from an exponential distribution, with an expected rate of one block every 10 minutes. The probability that a specific node succeeds in mining a block directly depends on its mining power. The number of connections that each node initializes depends on its type. Regular nodes initialize 8 random connections (Bitcoin’s default), while nodes representing mining pools (with higher mining power) initialize 150 random connections following the same node degree distribution inferred in [28].

We verified our simulator by comparing the orphan rate as well as the median propagation delay computed with those of the real network. We found that both of them are within the limits of the actual Bitcoin network [14].

Methodology We evaluated the impact of delay attacks considering three kinds of adversaries: *i) Active*; *ii) Country*; *iii) Single*. In the simulation, an AS can effectively delay the delivery of a block between two nodes if and only if she intercepts the traffic from the potential recipient to the sender, essentially if she is able to perform the attack depicted in Fig. 5a. An adversary that intercepts the opposite direction is considered unable to delay blocks, during the simulation. Although this choice makes the attacker less effective, it avoids a dependency of the orphan rate on the time the simulation runs. These attackers lose their power through time, as the connections they intercept are dropped after the first effective block delay, and possibly replaced with connections that are not intercepted by the attacker.

6.2.2 Results

We run the simulation 20 times for each set of parameters and consider a new random Bitcoin topology during each run. In each run, 144 blocks are created, which is equivalent to a day’s worth of block production (assuming an average

<i>Country</i>	<i>uniform</i>	<i>centralized</i>
US	55.94	52.45
CN	8.39	33.22
DE	18.18	29.37
NL	12.59	4.55
GB	15.38	8.39
SE	14.69	15.38
HK	7.69	16.08
AS6939	14.69	11.89
<i># prefixes</i>	<i>uniform</i>	<i>centralized</i>
100	30.77	14.69
200	39.16	18.88
300	41.26	20.63

Table 5: Orphan rate achieved by different attackers performing delay attack: countries or AS6939 (passively), any single AS hijacking a given number of prefixes n . The baseline orphan rate is around 1%.

creation rate of one block per 10 minutes). We evaluated the impact of delay attacks by measuring the orphan rate, different adversaries can cause. As adversaries, we consider 8 different countries, Single ASes, and active attackers that intercept no Bitcoin traffic naturally. The criteria for picking these attackers is their effectiveness as measured by the percentage of traffic they intercept. Especially for the case of active attackers we consider three scenarios that differ in the amount of prefixes hijacked. In particular we consider attackers that hijack the 100, 200, 300 prefixes, that host the most Bitcoin nodes, excluding prefixes that host pools. The latter restriction was undertaken to avoid strong dependency of the results on the exact location of the pools. To ensure our results are not strongly dependent on the pool location, we have also run each set of parameters in a simulation with randomly located mining pools.

The results Fig. 5 highlight the effectiveness of delay attacks in the Bitcoin network. Recall that none of the attackers we consider is able to achieve a 50 partition the network, yet the orphan rates reach extremely high values, given that the baseline is around 1%.

Even a single can be disruptive A single AS (Hurricane Electric) can multiply the orphan rate by a factor of ten compared to the baseline, independently of the distribution of mining power. This outcome is a direct consequence of Bitcoin’s centralization (§4).

Coalitions within countries are extremely powerful

We show that many countries have considerable power over the currency. As an illustration, the US can clearly introduce chaos by increasing the fork rate to 50%, essentially wasting half of the network’s mining power. As far as European countries are concerned, Germany, England and the Netherlands are also quite powerful. Germany, for example, can force 18% to 30% of the mined blocks to be discarded. Well-known for the mining power within its borders, China can be very disruptive increasing the fork rate to 33% when we consider centralized mining power.

Hijacking prefixes can introduce chaos

With less than 300 prefixes an attacker can induce a 40% fork rate in case of the uniform distribution of mining power. The effect in the case of centralized mining power is lower because we

assumed that the attacker cannot hijack the actual prefixes of a pool. This choice was made to decrease the dependency of our results on the exact pool locations. Even so, the results are extremely troubling given that any AS can hijack.

7. COUNTERMEASURES

In this section, we present a set of countermeasures against routing attacks. We start by presenting measures that do not require any protocol change and can be partially deployed (§7.1) so that early adopters can benefit from higher protection. We then describe longer-term suggestions for both detecting and preventing routing attacks (§7.2).

7.1 Short-term measures

Host all Bitcoin nodes in /24 prefixes Our analysis indicates that 93% of Bitcoin nodes are located in prefixes whose length is strictly shorter than /24. This allows any single AS to launch a global BGP hijack by advertising a more specific prefix. Hosting all Bitcoin nodes in /24 would prevent such attacks at the cost of a marginal increase (~1%) of the total number of Internet prefixes.

Increase the diversity of node connections The more connected an AS is, the harder it is to attack it. We therefore advocate Bitcoin node owners to ensure they are multi-homed. Observe that even single-homed Bitcoin nodes could benefit from extra connectivity by using one or more VPN services through encrypted tunnels so that Bitcoin traffic to and from the node go through multiple and distinct ASes. Attackers that wish to deny connectivity through the tunnel would need to either know both associated IP addresses or, alternatively, disrupt all encrypted traffic to and from nodes—making the attack highly noticeable.

Select Bitcoin peers while taking routing into account Bitcoin nodes randomly establish 8 outgoing connections. While randomness is important to avoid biased decisions, we advocate that Bitcoin nodes should establish a few *extra* connections that take routing into consideration. For this, nodes could either issue a **traceroute** to each of their peers and analyze how often the same AS appears in the path, or alternatively, tap into the BGP feed of networks they are connected to to pick their peers based on the AS-PATH. In both cases, if the same AS appears in all paths, extra random connections should be established.

Monitor round-trip time (RTT) The RTT towards hijacked destinations increases upon hijack. By monitoring the RTT towards its peers, a node could detect sudden changes, which might be caused by an active attack against it.

Monitor additional statistics This includes the distribution of connections, the lag between request and delivery of information, sudden simultaneous disconnections of peers, and other lower-level connection anomalies. In general, nodes should deploy anomaly detection mechanisms to recognize sudden changes and alert operators.

7.2 Longer-term measures

Encrypt Bitcoin Communication and/or adopt MAC While encrypting Bitcoin connections would not prevent AS-level adversaries from dropping packets, it would prevent them from being able to “peek” into connections and selectively drop messages based on their content. Alternatively,

using a Message Authentication Code (MAC) to validate that the content of each message has not been changed would make delay attacks much more difficult.

Use distinct control and data channels A key problem of Bitcoin is that its traffic is easily identifiable by filtering on the default port (8333). Assuming connection encryption (above), the two ends of a connection could negotiate a set of random TCP ports upon connecting to each other using the well-known port and use them to establish the actual TCP connection, on which they will exchange Bitcoin data. This would force the AS-level adversary to look at *all the traffic*, which would be too costly. A simple (but poorer) solution, in which Bitcoin clients use randomized TCP port (encoded in clear with the ADDR message) would already improve the situation as it will force the AS-level adversary to maintain state to keep track of these ports.

Use UDP heartbeats A TCP connection between two Bitcoin nodes may take different forward and backward paths due to asymmetric routing, making AS-level adversaries more powerful (as it only need to see one direction, see §6). In addition to TCP connections, Bitcoin clients could periodically send UDP messages with corroborating data (*e.g.*, with several recent block headers). These UDP messages can be used as a heartbeat that will allow nodes to discover that their connection was partially intercepted. As UDP messages do not rely on return traffic, this would enable node to realize that they are out-of-sync and establish new connections.

Request a block on multiple connections Bitcoin clients could ask multiple peers for pieces of the block. This measure would prevent misbehaving nodes from deliberately delaying the delivery of a block, simply because in such a case the client will only miss one fraction of the block, which can request from one of the other seeders.

8. RELATED WORK

AS-level adversaries The concept of AS-level adversaries has been studied before in the context of Tor [17, 29, 15]. These works also illustrated the problems caused by centralization and routing attack on a distributed system running atop the Internet. Yet, Tor and Bitcoin differ vastly in their behavior with one routing messages in an Onion-like fashion, while the other used *random* connections to flood messages throughout the entire network. While random graphs are usually robust to attacks, this paper shows that it is *not* the case when the network is centralized at the routing-level.

Bitcoin attacks The security of Bitcoin to network-based attacks has been relatively less unexplored compared to other attack scenarios. One previous study examines the eclipse attack on a single node in the context of Bitcoin’s P2P network [23]. In contrast, our work focuses on larger scale disruptions. Gervais *et. al.* consider other aspects of the centralization of Bitcoin and their consequences to the security of the protocol in [19]. We refer the reader to a survey describing research perspectives on the Bitcoin protocol [13].

BGP security issues Measuring and detecting routing attacks has seen extensive research on BGP hijack [35, 38, 39] and interception attacks [11]. Similarly, there has been much work on proposing secure routing protocols that can prevent the above attacks [12, 21, 24, 32]. In contrast, our work is

the first one to show the *consequences* of these attacks on crypto currencies.

9. CONCLUSION

We presented the first analysis of the vulnerabilities of Bitcoin network from the networking viewpoint. Based on real-world data, we show that Bitcoin is heavily centralized. Leveraging this fact, we then demonstrated and quantified the disruptive impact that AS-level adversaries can have on the currency. We show that AS-level adversaries can partition the Bitcoin network by either colluding with each other or, when acting alone, by hijacking less than 900 prefixes (worst-case). We also show how AS-level adversaries can increase significantly the fraction of discarded blocks by arbitrarily delaying messages. While these attacks are worrying, we also explain how Bitcoin can counter them thanks to both short-term and long-term measures.

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