The Balance Attack or Why Forkable Blockchains Are Ill-Suited for Consortium

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Abstract—Most blockchain systems are forkable in that they require participants to agree on a chain out of multiple possible branches of blocks. In this paper, we identify a new form of attack, called the Balance attack, against these forkable blockchain systems. The novelty of this attack consists of delaying network communications between multiple subgroups of nodes with balanced mining power. Our theoretical analysis captures the tradeoff between the network delay and the mining power of the attacker needed to double-spend in the Ghost protocol with high probability.

We quantify our analysis in the settings of the Ethereum testnet of the R3 consortium where we show that a single machine needs to delay messages for 20 minutes to double spend while a coalition with a third of the mining power would simply need 4 minutes to double spend with 94% of success. We experiment the attack in our private Ethereum chain before arguing for a non-forkable blockchain design to protect against Balance attacks.

Keywords—Ethereum, forks, GHOST, consortium blockchain, private blockchain, Bitcoin, Byzantine, Casper

I. INTRODUCTION

Blockchain systems are distributed implementations of a chain of blocks. Each node can issue a cryptographically signed transaction to transfer digital assets to another node or can create a new block of transactions, and append this block to its current view of the chain. Due to the distributed nature of this task, multiple nodes may append distinct blocks at the same index of the chain before learning about the presence of other blocks, hence leading to a forked chain or a tree. For nodes to eventually agree on a unique state of the system, nodes apply a common strategy that selects a unique branch of blocks in this tree.

Bitcoin [32], one of the most popular blockchain systems, selects the longest branch. This strategy has however shown its limitation as it simply wastes all blocks not present in this branch [11], [36], [38], [20], [35]. If an attacker can solve crypto-puzzles fast enough to grow a local branch of the blockchain faster than the rest of the system, then it will eventually impose its own branch to all participants. In particular, by delaying the propagation of blocks in the system, one can increase the amount of wasted blocks and proportionally slow down the growth of the longest branch of the system. This delay presents a serious risk to the integrity of the blockchain, as the attacker does not even need a large fraction of the computational power to exceed the length of the chain, allowing her to double spend in new transactions the coins that she already spent in earlier transactions [37].

Ethereum [40] proposes another selection strategy that copes with this problem. Each node uses an algorithm, called GHOST, that starts from the first block, also called the genesis block, and iteratively selects the root of the heaviest subtree to construct the common branch. Even if nodes create many blocks at the same index of the blockchain, their computational power is not wasted but counted in the selection strategy [38]. In particular, the number of these “sibling” blocks increase the chance that their common ancestor block be selected in favor of another candidate block mined by the attacker. Although it clearly alleviates the Bitcoin limitation discussed above [11], [36], [20], [35] it remains unclear how long an attacker with a low mining power should delay messages to discard previous transactions in Ethereum.

In this paper, we answer this question by demonstrating theoretically and experimentally that an attacker can compensate a low mining power by delaying selected messages in Ethereum. To this end, we propose a simple attack, called the Balance attack: an attacker transiently disrupts communications between subgroups of similar mining power. During this time, the attacker issues transactions in one subgroup, say the transaction subgroup, and mines blocks in another subgroup, say the block subgroup, up to the point where the tree of the block subgroup outweighs, with high probability, the tree of the transaction subgroup. The novelty of the Balance attack is to leverage the Ghost protocol that accounts for sibling or uncle blocks to select a chain of blocks. This strategy allows the attacker to mine a branch possibly in isolation of the rest of the network before merging its branch to one of the competing blockchain to influence the branch selection process.

We experimented a distributed system running Ethereum in similar settings as R3, a consortium of more than 70 world-wide financial institutions. In January, R3 consisted of eleven banks and successfully collaborated in deploying an
Ethereum private chain to perform transactions.\footnote{http://www.ibtimes.co.uk/r3-connects-11-banks-distributed-ledger-using-ethereum-microsoft-azure-1539044.} Since then, R3 has grown and kept using Ethereum\footnote{http://www.coindesk.com/r3-ethereum-report-banks/.} while the concept of consortium private chain gained traction for its ability to offer a blockchain system among multiple companies in a not necessarily private but controlled environment. R3 has experimented with various blockchains and has recently released a distributed ledger implementation that does not use any blockchain [5]. As opposed to a fully private chain scenario, the consortium private chain involves different institutions, possibly competitors. As they can be located at different places around the world, they typically use Internet to communicate. We illustrate the Balance attack in the R3 network setting as of June 2016 that consisted of a testnet of 50 machines among which 15 were actively mining, by deploying Ethereum on own private testnet.

One can exploit the Balance attack to corrupt or violate the persistence of the main branch, hence rewriting previously committed transactions, and allowing the attacker to double spend. As opposed to previous attacks against Bitcoin where the attacker has to expand the longest chain faster than correct miners to obtain this result [37], the novelty of our attack lies in the contribution of the attacker to one of the correct miner chain in order to outweigh another correct miner chain. We generalize our contribution to forkable blockchains, i.e., blockchains that experience forks, by proposing a simple model for forkable blockchains and specifying Nakamoto’s and GHOST consensus algorithmic differences. More precisely, we make the four following contributions:

1) We show that the GHOST consensus protocol is corruptible or vulnerable to double spending attacks with high probability when an attacker can delay communications. We introduce the Balance attack that influences the branch selection rather than trying to solo-mine heavier or longer branches.

2) We illustrate the problem in the context of the R3 Ethereum testnet if a single node can delay communications for 20 minutes or when a coalition delay communications during 4 minutes. This vulnerability stems from the heterogeneous nature of participants that is exacerbated in small consortium blockchains.

3) We argue for a non-forkable blockchain design that protects against Balance attacks. The idea is to design fork-free blockchains so that no adversary can exploit forks to influence the decision in favor of a particular branch. This design may find applications in critical sectors where the loss of digital assets cannot be tolerated.

As of today, mainstream blockchains have implicitly assumed synchrony [17] to be able to predict an upper-bound on the delay of messages. While strong guarantees can clearly be proved under this assumption, the guarantees to expect if this assumption is violated remain unclear. The problem is that mainstream blockchains, whether they are fully public or involve a consortium of institutions, relies on large network, like the internet, in which one cannot predict the delay of messages. More dramatically, multiple results demonstrated recently how one can simply delay messages in blockchain networks [25], [22], [1]. The Balance attack reveals that delaying messages can be dramatic for blockchains, leading to double-spending even with a small portion of the mining power and raises interesting challenges in the design of safe consortium blockchains.

Section II defines the problem. In Section III, we present the algorithm to run the attack. In Section IV, we show how the analysis affects GHOST. In Section V, we analyze the success of the Balance attack in the context of the R3 consortium network. In Section VI, we present our experiments run in an Ethereum private chain. In Section VII, we propose some blockchain design solutions immune to the Balance attack. Section VIII presents the related work. And Section IX concludes.

II. Preliminaries

In this section we model a simple distributed system that implements a blockchain abstraction as a directed acyclic graph. We propose a high-level pseudocode representation of proof-of-work blockchain protocols in this model that allows us to illustrate an important difference between Bitcoin and Ethereum in the selection of a main branch with a persistent prefix.

A. A simple distributed model for blockchains

We consider a communication graph $G = (V, E)$ with nodes $V$ connected to each other through fixed communication links $E$. Nodes are part of a blockchain system $S \in \{bitcoin, ethereum\}$ and can act as clients by issuing transactions to the system and/or servers by mining, the action of trying to combine transactions into a block. For the sake of simplicity, we consider that each node possesses a single account and that a transaction issued by node $p_i$ is a transfer of digital assets or coins from the account of the source node $p_i$ to the account of a destination node $p_j \neq p_i$. Each transaction is uniquely identified and broadcast to all nodes in a best-effort manner. We assume that a node reissuing the same transfer multiple times creates as many distinct transactions.

Nodes that mine are called miners. We refer to the computational power of a miner as its mining power and we denote the total mining power $t$ as the sum of the mining powers of all miners in $V$. Each miner tries to group a set $T$ of transactions it heard about into a block $b \supseteq T$ as long as transactions of $T$ do not conflict and that the account balances remain non-negative. For the sake of simplicity in
Figure 1: The global state $\ell_0$ of a blockchain results from the union of the distributed local views $\ell_1$, $\ell_2$ and $\ell_3$ of the blockchain.

Algorithm 1 describes the progressive construction of a forkable blockchain at a particular node $p_i$ upon reception of blocks from other nodes by simply aggregating the newly received blocks to the known blocks (lines 3–5). As every added block contains a hash to a previous block that eventually leads back to the genesis block, each block is associated with a fixed index. By convention we consider the genesis block at index 0, and the blocks at $j$ hops away from the genesis block as the blocks at index $j$. As an example, consider the simple blockchain $\ell_1 = \langle B_1, P_1 \rangle$ depicted in Figure 1(a) where $B_1 = \{g, b_1\}$ and $P_1 = \{(b_1, g)\}$. The genesis block $g$ has index 0 and the block $b_1$ has index 1.

4) Forks as disagreements on the blocks at a given index: As depicted by views $\ell_1$, $\ell_2$ and $\ell_3$ in Figures 1(a), 1(b) and 1(c), respectively, nodes may have a different views of the current state of the blockchain. In particular, it is possible for two miners $p_1$ and $p_2$ to mine almost simultaneously two different blocks, say $b_1$ and $b_2$. If neither block $b_1$ nor $b_2$ was propagated early enough to nodes $p_2$ and $p_1$, respectively, then both blocks would point to the same previous block $g$ as depicted in Figures 1(a) and 1(b). Because network delays are not predictable, a third node $p_3$ may receive the block $b_1$ and mine a new block without hearing about $b_2$. The three nodes $p_1$, $p_2$ and $p_3$ thus end up having three different local views of the same blockchain, denoted $\ell_1 = \langle B_1, P_1 \rangle$, $\ell_2 = \langle B_2, P_2 \rangle$ and $\ell_3 = \langle B_3, P_3 \rangle$.

We refer to the global blockchain as the directed acyclic graph $\ell_0 = \langle B_0, P_0 \rangle$ representing the union of these local blockchain views, denoted by $\ell_1 \cup \ell_2 \cup \ell_3$ for short, as depicted in Figure 1, and more formally defined as follows:

$$\begin{align*}
B_0 &= \bigcup_{i} B_i, \\
P_0 &= \bigcup_{i} P_i.
\end{align*}$$

The point where distinct blocks of the global blockchain DAG have the same predecessor block is called a fork. As an example Figure 1(d) depicts a fork with two branches pointing to the same block: $g$ in this example.

In the remainder of this paper, we refer to the DAG as a tree rooted in $g$ with upward pointers, where children blocks point to their parent block.

5) Main branch in Bitcoin and Ethereum: To resolve the forks and define a deterministic state agreed upon by all nodes, a blockchain system must select a main branch, as a unique sequence of blocks, based on the tree. Building upon the generic construction (Alg. 1), we present two
Algorithm 2 Nakamoto’s consensus protocol at node $p_i$

6: $m = 5$, the number of blocks to be appended after the one containing $tx$, for $tx$ to be committed in Bitcoin
7: \hfill $tx$, for $tx$ to be committed in Bitcoin
8: get-main-branch(); \hfill $\triangleright$ select the longest branch
9: $b$ ← genesis-block($B_i$) \hfill $\triangleright$ start from the blockchain root
10: while $b$.next $\neq \perp$ do \hfill $\triangleright$ prune shortest branches
11: block ← $\arg\max_{c\in$children($b$)}{\{\text{depth}(c)\}} \hfill $\triangleright$ deepest subtree
12: $B$ ← $B \cup \{\text{block}\}$ \hfill $\triangleright$ update vertices of main branch
13: $P$ ← $P \cup \{\text{block}, b\}$ \hfill $\triangleright$ update edges of main branch
14: $b$ ← block \hfill $\triangleright$ move to next block
15: return $(B, P)$ \hfill $\triangleright$ returning the Bitcoin main branch
16: \hfill $\triangleright$ depth of tree rooted in $b$
17: if children($b$) = $\emptyset$ then return 1 \hfill $\triangleright$ stop at leaves
18: return $1 + \max_{c\in$children($b$)}{\text{depth}(c)} \hfill $\triangleright$ recurse at children

Algorithm 2 depicts the Bitcoin-specific pseudocode that includes Nakamoto’s consensus protocol to decide on a particular block at index $i$ (lines 8–18) and the choice of parameter $m$ (line 6) explained later in Section II-B. When a fork occurs, Nakamoto’s protocol resolves it by selecting the longest branch as the main branch (lines 8–15) by iteratively selecting the root of the deepest subtree (line 11). When process $p_i$ is done with this pruning, the resulting branch becomes the main branch $(B_i, P_i)$ as observed by the local process $p_i$. Note that the pseudocode for checking whether a block is decided and a transaction committed based on this parameter $m$ is common to Bitcoin and Ethereum, it is thus deferred to Alg. 4.

6) The GHOST consensus algorithm: As opposed to the Bitcoin protocol, Ethereum generates one block every 12–15 seconds. While it improves the throughput (transactions per second) it also favors transient forks as miners are more likely to propose new blocks without having heard about the latest mined blocks yet. To avoid wasting large mining efforts while resolving forks, Ethereum uses the GHOST (Greedy Heaviest Observed Subtree) consensus algorithm that accounts for the, so called uncles, blocks of discarded branches. In contrast with Nakamoto’s protocol, the GHOST protocol iteratively selects, as the successor block, the root of the subtree that contains the largest number of nodes (cf. Algorithm 3).

The main difference between Nakamoto’s consensus protocol and GHOST is depicted in Figure 2, where the black blocks represent the main branch selected by Nakamoto’s consensus protocol and the grey blocks represent the main branch selected by GHOST. Note that Ethereum adapted GHOST to account for the difficulties of blocks in the choice of the deepest subtree [38].

B. Decided blocks and committed transactions

A blockchain system $S$ must define when the block at an index is agreed upon. To this end, it has to define a point in its execution where a prefix of the main branch can be “reasonably” considered as persistent.\footnote{In theory, there cannot be consensus on a block at a particular index [16], hence preventing persistence, however, applications have successfully used Ethereum to transfer digital assets based on parameter $m_{ethereum} = 11$ [34].} More precisely, there must exist a parameter $m$ provided by $S$ for an application to consider a block as decided and its transactions as committed. This parameter is typically $m_{bitcoin} = 5$ in Bitcoin (Alg. 2, line 6) and $m_{ethereum} = 11$ in Ethereum (Alg. 3, line 6). Note that these two choices do not lead to the same probability of success [18] and different numbers are used by different applications [34].

Definition 1 (Transaction commit). Let $\ell_i = \langle B_i, P_i \rangle$ be the blockchain view at node $p_i$ in system $S$. For a transaction

Figure 2: Nakamoto’s consensus protocol at the heart of Bitcoin selects the main branch as the longest branch (in black) whereas the GHOST consensus protocol at the heart of Ethereum follows the heaviest subtree (in grey)
tx to be locally committed at $p$, the conjunction of the following properties must hold in $p$’s view $\ell$:

1) Transaction $tx$ has to be in a block $b_0 \in B_i$ of the main branch of system $S$. Formally, $tx \in b_0 \land b_0 \in B_i : \langle B_i', P_i' \rangle = \text{get-main-branch}(\ell)$.

2) There should be a subsequence of $m$ blocks $b_1, ..., b_m$ appended after block $b$. Formally, $\exists b_1, ..., b_m \in B_i : \langle b_1, b_0 \rangle, \langle b_2, b_1 \rangle, ..., \langle b_m, b_{m-1} \rangle \in P_i$. (In short, we say that $b_0$ is decided.)

A transaction $tx$ is committed if there exists a node $p_i$ such that $tx$ is locally committed.

Property (1) is needed because nodes eventually agree on the main branch that defines the current state of accounts in the system—blocks that are not part of the main branch are ignored. Property (2) is necessary to guarantee that the blocks and transactions currently in the main branch will persist and remain in the main branch. Before these additional blocks are created, nodes may not have reached consensus regarding the unique blocks $b$ at index $j$ in the chain. This is illustrated by the fork of Figure 1 where nodes consider, respectively, the pointer $\langle b_1, g \rangle$ and the pointer $\langle b_2, g \rangle$ in their local blockchain view. By waiting for $m$ blocks were $m_i$ is given by the blockchain system, the system guarantees with a reasonably high probability that nodes will agree on the same block $b$. Note that the property is not prefix-closed in the sense that get-main-branch may return a chain that is not necessarily a prefix of another branch returned later.

Algorithm 4 Checking transaction commit at node $p_i$

19: $\text{is-committed}(tx)$; ▷ check whether transaction is committed
20: $\langle B_i', P_i' \rangle$ ← get-main-branch(); ▷ pick main branch with Alg. 2 or 3
21: if $\exists b_0 \in B_i' : tx \in b_0 \land \exists b_1, ..., b_m \in B_i' : b_0 \in b_1 \land ... \land b_m$ then ▷ is in main branch
22: $\langle b_1, b_0 \rangle, \langle b_2, b_1 \rangle, ..., \langle b_m, b_{m-1} \rangle \in P_i$ then ▷ enough blocks
23: return true
24: else return false

For example, consider a fictive blockchain system with $m_{\text{prefix}} = 2$ that selects the heaviest branch (Alg. 3, lines 8–15) as its main branch. If the blockchain state was the one depicted in Figure 2, then blocks $b_2$ and $b_3$ would be decided and all their transactions would be committed. This is because they are both part of the main branch and they are followed by at least 2 blocks, $b_8$ and $b_{13}$. (Note that we omit the genesis block as it is always considered decided but does not include any transaction.)

III. THE BALANCE ATTACK

In this section, we present the Balance attack, a novel form of attacks that affect proof-of-work blockchains, especially Ethereum. Its novelty lies in identifying subgroups of miners of equivalent mining power and delaying messages between them rather than entering a race to mine blocks faster than others.

The Balance attack demonstrates a fundamental limitation of main proof-of-work systems in that they are not immutable.

**Definition 2** (Corruptibility). A blockchain system is corruptible if an adversary can:

1) make the recipient of a transaction $tx$ observe that $tx$ is committed and
2) later remove the transaction $tx$ from the main branch, with probability $1 - \varepsilon$.

The Balance attack is simple: while the attacker disrupts communications between correct subgroups of equivalent mining power, it simply issues transactions in one subgroup. The attacker then mines sufficiently many blocks in another subgroup to ensure with high probability that the subtree of another subgroup outweighs the transaction subgroup’s. Even though the transactions are committed, the attacker can rewrite with high probability the blocks that contain these transactions by outweighing the subtree containing this transaction.

Note that one could benefit from delaying messages only between the merchant and the rest of the network by applying the eclipse attack [22] to Ethereum. Eclipsing one node of Bitcoin appeared, however, sufficiently difficult: it requires to restart the node’s protocol in order to control all the logical neighbors the node will eventually try to connect to. While a Bitcoin node typically connects to 8 logical neighbors, an Ethereum node typically connects to 25 nodes, making the problem even harder. Another option would be to isolate a subgroup of smaller mining power than another subgroup, however, it would make the attack only possible if the recipients of the transactions are located in the subgroup of smaller mining power. Although possible this would limit the generality of the attack, because the attacker would be constrained on the transactions it can override.

Note that the Balance attack inherently violates the persistence of the main branch prefix and is enough for the attacker to double spend. The attacker has simply to identify the subgroup that contains merchants and create transactions to buy goods from these merchants. After that, it can issue the transactions to this subgroup while propagating its mined blocks to at least one of the other subgroups. Once the merchant shipped goods, the attacker stops delaying messages. Based on the high probability that the tree seen by the merchant is outweighed by another subtree, the attacker could reissue another transaction transferring the exact same coin again.

A. Executing a Balance Attack

For the sake of simplicity, let us fix $k = 2$ and postpone the general analysis for any $k \geq 2$ to the companion technical report [33]. We consider subgraphs $G_1 = (V_1, E_1)$ and $G_2 = (V_2, E_2)$ of the communication graph $G = (V, E)$ so that each subgraph has half of the mining power of
the system as depicted in Figure 3(a) whereas Figure 3(b) illustrates the variant when \( k = 4 \). Let \( E_0 = E \setminus (E_1 \cup E_2) \) be the set of edges that connects nodes of \( V_1 \) to nodes of \( V_2 \) in the original graph \( G \). Let \( \tau \) be the communication delay introduced by the attacker on the edges of \( E_0 \).

As indicated in Algorithm 5, the attacker can introduce a sufficiently long delay \( \tau \) during which the miners of \( G_1 \) mine in isolation of the miners of \( G_2 \) (line 13). As a consequence, different transactions get committed in different subgraphs of 25 units of mining power each. Let \( b_2 \) be a block present only in the blockchain viewed by \( G_2 \) but absent from the blockchain viewed by \( G_1 \). In the meantime, the attacker issues transactions spending coins \( C \) in \( G_1 \) (line 14) and mines a blockchain starting from the block \( b_2 \) (line 16). Before the delay expires the attacker sends his blockchain to \( G_2 \). After the delay expires, the two local views of the blockchain are exchanged. Once the heaviest branch that the attacker contributed to is adopted, the attacker can simply reuse the coins \( C \) in new transactions (line 19).

### Algorithm 5 The Balance attack initiated by attacker \( p_i \)

```plaintext
1: State:
2: \( G = (V, E) \), the communication graph
3: \( \text{pow} \), a mapping from a node in \( V \) to its mining power in \( \mathbb{R} \)
4: \( \ell_i = (B_i, P_i) \), the local blockchain at node \( p_i \) is a directed acyclic graph of blocks \( B_i \) and pointers \( P_i \)
5: \( \rho \in (0; 1) \), the portion of the mining power of the system owned by the attacker \( p_i \), with \( 0 < \rho < 0.5 \)
6: \( d \), the difficulty of the crypto-puzzle currently used by the system

9: balance-attack((\( V, E \))): \( \triangleright \) starts the attack
10: Select \( k \geq 2 \) subgraphs \( G_1 = (V_1, E_1), \ldots, G_k = (V_k, E_k) \):
11: \( \sum_{v \in V_i} \text{pow}(v) \approx \ldots \approx \sum_{v \in V_k} \text{pow}(v) \)
12: Let \( E_0 = E \setminus \bigcup_{0 \leq i < k} E_i \) \( \triangleright \) attack communication channels
13: Stop communications on \( E_0 \) during \( \tau \geq (1-\rho)\text{td} \log(\frac{1}{\epsilon}) \) seconds
14: Issue \( tx \) crediting a merchant in graph \( G_i \) with coins \( C \)
15: Let \( b_2 \) be a block appearing in \( G_i \) but not in \( G_j \)
16: Start mining on \( \ell_i \) immediately after \( b_2 \triangleright \text{contributed to correct chain} \)
17: Send blockchain view \( \ell_i \) to some subgraph \( G_j \) where \( j \neq i \)
18: When \( \tau \) seconds have elapsed, stop delaying messages on \( E_0 \)
19: Issue transaction \( tx' \) that double spends coins \( C \)
```

### C. Delaying networking communications

While disrupting the communication between subgroups of a blockchain system may look difficult, there have been multiple attacks successfully delaying blockchains messages in the past.

In 2014, a BGP hijacker exploited access to an ISP to steal $83,000 worth of bitcoins by positioning itself between Bitcoin pools and their miners [25]. Some known attacks against Bitcoin involved partitioning the communication graph at the network level [1] and at the application level [22]. At the network level, a study indicated the simplicity for autonomous systems to intercept a large amount of bitcoins and evaluated the impact of these network attacks on the Bitcoin protocol [1]. At the application level, some work showed that an attacker controlling 32 IP addresses can “eclipse” a Bitcoin node with 85% probability [22].

Starting in September 2016, Ethereum experienced a denial-of-service attacks that forced miners to spend a long time accessing memory while executing smart contracts. While it did not lead to double-spending as far as we know it as the current difficulty of the crypto-puzzle can be found at https://ethstats.net/.

It is more difficult, however, to gather information regarding the communication network. Note that some tools exist to retrieve information regarding the communication topology of blockchain systems. The interesting aspects of the Balance attack is that it can apply to the logical overlay used by the peer-to-peer network of the blockchain system or to the physical overlay. While there exist tools to retrieve the logical overlay topology, like AddressProbe [28] to find some information regarding the peer-to-peer overlay of Bitcoin, it can be easier for an attacker of Ethereum to run a man-in-the-middle attack rather than a BGP hijacking [25], [1].
slowed down the entire network.\footnote{https://blog.ethereum.org/2016/09/22/ethereum-network-currently-undergoing-dos-attack/} More generally, there are varieties of network attacks, known as man-in-the-middle attacks and spoofing attacks, that can be exploited to lead to similar results by relaying the traffic between two nodes through the attacker.

IV. VULNERABILITY OF THE GHOST PROTOCOL

In this Section, we show that the Balance attack makes a blockchain system based on \textsc{Ghost} (depicted in Alg. 3) corruptible. A malicious user can issue a Balance attack with less than half of the mining power by delaying the network. Let us first summarize previous and new notations in Table I.

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Table I: Notations of the analysis

For the sake of simplicity, we assume that \( k = 2 \) and \( \sum_{v_e \in V_1} \text{pow}(v) = \sum_{v_e \in V_2} \text{pow}(v) \) so that the communication is delayed between only two communication subgraphs of equal mining power. We defer the proofs to the companion technical report \cite{33}.

As there is no better strategy for solving the crypto-puzzles than random trials, we consider that subgraphs \( G_1 \) and \( G_2 \) mine blocks during delay \( \tau \). During that time, each of \( G_1 \) and \( G_2 \) performs a series of \( n = \frac{1-\rho}{\rho} t \tau \) independent and identically distributed Bernoulli trials, each returning one in case of success with probability \( p = \frac{1}{2} \) and 0 otherwise. Let the sum of these outcomes for subgraphs \( G_1 \) and \( G_2 \) be the random variables \( X_1 \) and \( X_2 \), respectively, each with a binomial distribution and mean:

\[
\mu_c = np = \frac{(1-\rho)t\tau}{2d}.
\]

Similarly, the mean of the number of blocks mined by the malicious miner during time \( \tau \) is

\[
\mu_m = \rho t \frac{\tau}{d}.
\]

The Balance attack relies on the adversary outnumbering the difference in blocks mined by each subgraph \( G_1 \) and \( G_2 \). Thus, we first lower-bound the probability \( \text{Pr}[\mu_m > \Delta] \) that the expected number of blocks \( \mu_m \) mined by the attacker is greater than the difference \( \Delta = |X_1 - X_2| \) in blocks mined by the two subgraphs \( G_1 \) and \( G_2 \). Theorem 3. At time \( \tau \), the probability \( \text{Pr}[\mu_m > \Delta] \) that the expected number of blocks \( \mu_m \) mined by the attacker

\[
1 - 4e^{-\frac{\rho^2}{(1-\rho)^2} \mu_c}.
\]

Corollary 4. A blockchain system that selects a main branch based on the \textsc{Ghost} protocol (Alg. 3) is corruptible.

\textbf{Proof.} By lines 17–18 of Alg. 3, we know that \textsc{Ghost} counts the mined blocks to compute the weight of a subtree, and to select one blockchain view and discard the other.

Since by Theorem 3, the expected number of blocks mined by the attacker at time \( \tau \) is greater than the difference \( \Delta \) with probability larger than \( 1 - 4e^{-\frac{\rho^2}{(1-\rho)^2} \mu_c} \geq 1 - \varepsilon \), we know that when the timer expires at line 18 of Alg. 5, the attacker can make the system discard the blockchain view of either \( G_1 \) or \( G_2 \) with probability larger than \( 1 - \varepsilon \) by sending its blockchain view to the other subgraph, hence making the blockchain system corruptible.

V. ANALYSIS OF THE R3 NETWORK

The statistics of the R3 network were gathered through the \texttt{eth-netstat} applications at the end of June 2016. R3 is a consortium of more than 50 banks that has tested blockchain systems and in particular Ethereum in a consortium private chain context over 2016.\footnote{http://www.coindesk.com/r3-ethereum-report-banks} The network consisted at that time of \( |V| = 50 \) nodes among which only 15 were mining.

The mining power of the system was about 20 MH/s, the most powerful miner mined at 2.4 MH/s or 12\% of the total mining power while the difficulty of the crypto-puzzle was observed close to 30 MH.

First, let assume that the attacker is the r3 node with \( \rho = 12\% \) of the mining power as depicted in Figure 4 and that it delays communication between subgraphs \( G_1 \) and \( G_2 \), each with mining power \( \frac{1-\rho}{2} t \tau = 8.8 \text{MH/s} \). The probability \( \rho \) of solving the crypto-puzzle per hash tested is \( \frac{1}{30 \times 10^6} \) so that the mean is \( \mu_c = \frac{(1-\rho)t\tau}{2d} = \frac{8.8 \times 10^6 \times 1180}{2 \times 30 \times 10^6} = 346.13 \) if we wait for 19 minutes and 40 seconds, i.e., 1180 seconds. The attacker creates, in expectation, a block every \( \frac{30}{2} \) seconds or \( \frac{1180}{12.5} \approx 94 \) blocks during the 19 minutes and 40 seconds. Hence let \( \delta = \rho/(1-\rho) = 0.136 \). The probability that the attack is a success is 53\%.

Second, let assume that the adversary controls \( \rho = \frac{1}{4} \) of the total mining power, which represents \( pt = 6.7 \text{MH/s} \). In this case the adversary delay communications between two subgraphs \( G_1 \) and \( G_2 \) with mining power \( \frac{1-\rho}{2} t \tau = 6.7 \text{MH/s} \) each. If we wait for 4 minutes, i.e., 240 seconds, then each isolated graph and adversary would mine \( 6.67 \times 10^6 \times 240/(30 \times 10^6) = 53.4 \) blocks. The probability that the attack succeeds would become \( 1 - e^{-\frac{\rho^2}{(1-\rho)^2} \mu_c} \) which is around 94\%.
VI. EXPERIMENTING THE BALANCE ATTACK ON A PRIVATE ETHEREUM BLOCKCHAIN

In this section, we experimentally produce the attack on an Ethereum private chain involving up to 18 physical distributed machines. To this end, we configure a realistic network with 15 machines dedicated to mining as in the R3 Ethereum testnet and 3 dedicated network switches.

All experiments were run on 18 physical machines of the Emulab environment where a network topology was configured using ns/2. The topology consists of three local area networks configured through a ns/2 configuration file with 20 ms latency and 100 Mbps bandwidth. All miners run the geth Ethereum client v.1.3.6 and the initial difficulty of the crypto-puzzle is set to 40 KH. The communication graph comprises the subgraph $G_1$ of 8 miners that includes the attacker and 7 correct miners and a subgraph $G_2$ of 7 correct miners.

A. Favoring one blockchain view over another

We run our first experiment during 2 minutes. We delayed the link $E_0$ during 60 seconds so that both subgraphs mine in isolation from each other during that time and end up with distinct blockchain views. After the delay we take a snapshot, at time $t_1$, of the blocks mined by each subgraphs and the two subgraphs start exchanging information normally leading to a consensus regarding the current state of the blockchain. At the end of the experiment, after 2 minutes, we take another snapshot $t_2$ of the blocks mined by each subgraph.

<table>
<thead>
<tr>
<th>Subgraph</th>
<th>Blocks at $t_1$</th>
<th>Blocks discarded at $t_2$</th>
<th>Blocks kept at $t_2$</th>
<th>Retention</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_1$</td>
<td>52</td>
<td>39</td>
<td>13</td>
<td>25%</td>
</tr>
<tr>
<td>$G_2$</td>
<td>58</td>
<td>58</td>
<td>0</td>
<td>0%</td>
</tr>
</tbody>
</table>

Table II: Number of blocks in the main branch (excluding uncles) mined by the subgraphs $G_1$ and $G_2$; the adversary influences the selection of branches and keeps blocks from $G_1$ but discards blocks from $G_2$.

Table II lists the number of blocks (excluding uncles) of the blockchain views of $G_1$ and $G_2$ at times $t_1$, while the two subgraphs did not exchange their view, and at time $t_2$, after the subgraphs exchanged their blocks. Note that we did not represent the uncle blocks to focus on the main branches. We observe that the blockchain view of the subgraph $G_1$ was adopted as the valid chain while the other blockchain view of the subgraph $G_2$ was not. In particular, we retrieved 13 blocks of the main branch of $G_1$ at time $t_1$ in the main branch selected at $t_2$. As expected, all the blocks of $G_2$ at time $t_1$ were discarded from the main branch by time $t_2$.

B. Blocks mined by an attacker and two subgraphs

We now report the total number of blocks mined, especially focusing on the creation of uncle blocks. More precisely, we compare the number of blocks mined by the attacker against the difference of the number of blocks $\Delta$ mined by each subgraph. We know from the analysis that it is sufficient for the attacker to mine at least $\Delta + 1$ blocks in order to be able to discard one of the $k$ blockchain views, allowing for double spending. The experiment is similar to the previous experiment in that we also used Emulab with the same ns/2 topology, however, we did not introduce delays and averaged results over 10 runs of 4 minutes each.

Figure 5(a) depicts the minimum, maximum and average blocks obtained over the 10 runs. The vertical bars indicate minimum and maximum. First, we can observe that the average difference $\Delta$ is usually close to its minimum value observed during the 10 runs. This is due to having a similar total number of blocks mined by each subgraph in most cases with few rare cases where the difference is larger. As we can see, the total number of blocks (including uncles) mined during the experiment by the attacker is way larger than the difference in blocks $\Delta$ mined by the two subgraphs. This explains the success of the Balance attack as was observed in Section VI-A.

C. The role of uncle blocks in Ethereum

In the previous experiment, we focused on the total number of blocks without differentiating the blocks that are adopted in the main branch and the uncle blocks that are only part of the local blockchain views. The GHOST protocol accounts for these uncle blocks to decide the current state of the blockchain as we explained previously in Section II.
blocks (excluding uncle blocks) over time for subgraphs
may mine blocks concurrently at the same indices. We
note several uncle blocks in the subgraphs, as correct miners
utively to the latest block of its current blockchain view. We
delay messages between this subgraph and another,
because he mines the block in isolation of the rest of the
network, successfully appending each mined block consec-
tively to the latest block of its current blockchain view. We
we note several uncle blocks in the subgraphs, as correct miners
may mine blocks concurrently at the same indices.

Figure 5(c) depicts the creation of the number of mined
blocks (excluding uncle blocks) over time for subgraphs $G_1$
and $G_2$, and the attacker (referred to as ‘Malicious’). As we
can see the difference between the number of blocks mined
on the subgraphs is significantly smaller than the number of
blocks mined by the attacker. This explains why the Balance
attack was observed in this setting.

D. Relating connectivity to known blocks

Figure 5(d) illustrates the execution of two subgraphs
resolving connectivity issues and adopting a chain. This
experiment outlines one of the fundamental aspects of the
balance attack, in which the chosen subgraph resolves the
network delay and attempts reconnection with another sub-
graph. At this point, the subgraphs will initiate the consensus
protocol and select the branch to adopt as the main branch.
The experiment was set up with two subgraphs $G_1$ and $G_2$
where $|V_1| = |V_2| = 7$. The attacker selects a subgraph
and delays messages between this subgraph and another,
enforcing an isolated mining environment. Once the delay
is set, the attacker joins one of the subgraphs and begins
to mine onto the current chain. The attacker then delays
the messages until there is a sufficient amount of blocks
mined onto the isolated blockchain for it to be adopted as
the correct chain by the other subgraph. In this experiment,
at $t = 60$ s, the delay between subgraphs is resolved, and
the subgraphs maintain a connection. Upon reconnection, the
subgraphs invoke the consensus protocol to select and adopt
the correct chain. In this case, using the GHOST protocol,
the heaviest chain is selected for both subgraphs, meaning
the chain mined by $G_1$ is chosen, to which the attacker
corributed.

This result reveals that the adoption of a chosen
blockchain is plausible, given that the attacker is able to
sufficiently delay messages between subgraphs.

VII. SOLUTION WITH NON-FORKABLE BLOCKCHAINS

Corruptibility is a general problem that may affect other
forkable blockchains, especially if they require messages
to be propagated within a time bound, or may experience
disagreement with a non-null probability [27], [13].

A. Other forkable blockchains

First, it is important to note that the corruptibility problem
is not restricted to the GHOST algorithm or to the proof-of-
work mechanism underlying Ethereum but could also apply
to other forkable algorithms as well.

For example, we can slightly change the Balance attack to
work in Bitcoin as well. While in Ethereum it was sufficient
for the attacker to mine on any branch of the blockchains
view of $G_j$ after the block $b_j$ (Alg. 5, line 15), in Bitcoin
the attacker has to mine at the top of the blockchain view
of $G_j$. By doing so, the attacker increases the length of
the Nakamoto’s main branch in graph $G_j$. Considering that
each correct miner mines at the top of the longest branch
of their subgroup with the same probability $q$, the mean of
the number of blocks added to the main branch will become
$\mu_{\text{bitcoin}} = \frac{(1-p)t}{2dq}$. We can then define two binomial random
variables $X_i'$ and $X_j'$ for the expected number of blocks in
the main branch of $G_i$ and $G_j$, respectively, and apply a
similar argument as in Section IV.

The absence of proof-of-work does not imply immunity
against the Balance attack. Casper [6] has been proposed
as a proof-of-stake alternative to GHOST for the Ethereum
blockchain. Even with Casper, the Ethereum blockchain would remain forkable. Validators are incentivized to bet some coin amount, called value-at-loss, on the block that they believe will be decided first among multiple ones. Once the aggregated value-at-loss bet by all validators for a particular block reaches a threshold, then the block gets decided and the winning gambler gets rewarded. For the sake of availability, this threshold has to be adjusted depending on the responding participants. Like in the Balance attack, an adversary could delay communication between groups of nodes to alter the responsiveness of the participants and the threshold definition. By contrast with proof-of-work, the adversary would have to exploit some value-at-loss rather than its computational power to outweigh the bets and influence the selection of the main branch.

B. Non-forkable Blockchains

The crux of the problem of corruptible blockchains is that they favor availability over consistency. The well-known CAP theorem, initially mentioned by Brewer at PODC [4] and proved by Gilbert and Lynch [19], stating the impossibility for a distributed service to provide (i) consistency: returning the right response to a request; (ii) availability: returning a response to each request; and (iii) partition-tolerance: supporting message delays and losses. Intuitively, it appears natural for a distributed system to stop working as soon as communication is no longer ensured between the distributed participants. What is less clear is the consequence of communication being delayed. As we presented here, the consequence for forkable blockchains can be asset losses.

There exist a large body of solutions in the distributed computing literature favoring consistency over availability. As consortium and private blockchains involve a typically known number of participants, Byzantine consensus algorithms could be used to cope with the Balance attack provided that strictly less than \(\frac{n}{3}\) processes are under the control of the adversary. Several blockchains tried to build upon the classic Byzantine consensus implementation PBFT [8]. This is the case of Hyperledger\(^7\), Tendermint [23] and Corda [5]. Unfortunately, PBFT does not perform well with a growing set of participants [10]. Hierarchical approaches were proposed to improve the performance of PBFT [26], but assume synchrony. Another tentative [29] improved performance by building upon a more recent Byzantine consensus algorithm [30], however, this algorithm is probabilistic [31]. A new deterministic Byzantine algorithm designed especially for blockchains has just been proposed [9]. Although it appears efficient and is guaranteed to terminate, to our knowledge it has not been evaluated empirically.

VIII. RELATED WORK

Traditional attacks against Bitcoin consist of waiting for some external action, like shipping goods, in response to a transaction before discarding the transaction from the main branch. As the transaction is revoked, the issuer of the transaction can reuse the coins of the transaction in another transaction. As the side effects of the external action cannot be revoked, the second transaction appears as a “double spending”.

Perhaps the most basic form of such an attack assumes that an application takes an external action as soon as a transaction is included in a block [15], [24], [2]. The first attack of this kind is called Finney’s attack and consists of solo-mining a block with a transaction that sends coins to itself without broadcasting it before issuing a transaction that double-sends the same coin to a merchant. When the goods are delivered in exchange of the coins, the attacker broadcasts its block to override the payment of the merchant. The vector76 attack [39] consists of an attacker solo-mining after block \(b_0\) a new block \(b_1\) containing a transaction to a merchant to purchase goods. Once another block \(b'_1\) is mined after \(b_0\), the attacker quickly sends \(b_1\) to the merchant for an external action to be taken. If \(b'_1\) is accepted by the system, the attacker can issue another transaction with the coins spent in the discarded block \(b_1\).

The attacks become harder if the external action is taken after the transaction is committed by the blockchain. Rosenfeld’s attack [37] consists of issuing a transaction to a merchant. The attacker then starts solo-mining a longer branch while waiting for \(m\) blocks to be appended so that the merchant takes an external action in response to the commit. The attack success probability depends on the number \(m\) of blocks the merchant waits before taking an external action and the attacker mining power [18]. However, when the attacker has more mining power than the rest of the system, the attack, also called majority hashrate attack or 51-percent attack, is guaranteed successful, regardless of the value \(m\). To make the attack successful when the attacker owns only a quarter of the mining power, the attacker can incentivize other miners to form a coalition [14] until the coalition owns more than half of the total mining power.

Without a quarter of the mining power, discarding a committed transaction in Bitcoin requires additional power, like the control over the network. It is well known that delaying network messages can impact Bitcoin [11], [36], [38], [20], [35]. Decker and Wattenhoffer already observed that Bitcoin suffered from block propagation delays [11]. Godel et al. [20] analyzed the effect of propagation delays on Bitcoin using a Markov process. Garay et al. [17] investigated Bitcoin in the synchronous communication setting, however, this setting is often considered too restrictive [7]. Pass et al. extended the analysis for when the bound on message delivery is unknown and showed in their model that the difficulty of Bitcoin’s crypto-difficulty has to be adapted depending on the bound on the communication delays [36]. This series of work reveal an important limitation of Bitcoin: delaying propagation of blocks can waste the computational

\[^7\]http://www.hyperledger.org.
effort of correct nodes by letting them mine blocks unnecessarily at the same index of the chain. In this case, the attacker does not need more mining power than the correct miners, but simply needs to expand its local blockchain faster than the growth of the longest branch of the correct blockchain.

Ethereum proposed the GHOST protocol to cope with this issue [38]. The idea is simply to account for the blocks proposed by correct miners in the multiple branches of the correct blockchain to select the main branch. As a result, growing a branch the fastest is not sufficient for an attacker of Ethereum to be able to double spend. Even though the propagation strategy of Ethereum differs from the pull strategy of Bitcoin, some network attacks against Bitcoin could affect Ethereum. In the Eclipse attack [22] against Bitcoin, the attacker forces the victim to connect to 8 of its 25 clients as the default number of clients is 25. Apostolaki et al. [1] proposed a BGP hijacking attack and showed that the number of Internet prefixes that need to be hijacked for the attack to succeed depends on the distribution of the mining power. BGP-hijacking typically requires the control of network operators but is independent from Bitcoin and could potentially be exploited to delay network messages and execute a Balance attack in Ethereum.

Some work already evoked the danger of using proof-of-work techniques in a consortium context [21]. In particular, experiments demonstrated the impossibility of ordering even committed transactions in an Ethereum private chain without exploring the impact of the network delay [34]. We go further by showing that forkable blockchains may suffer from corruptibility.

IX. Conclusion

In this paper, we propose the Balance attack a new attack that combines mining power with communication delay to affect prominent forkable blockchain protocols like Ethereum and Bitcoin. This attack simply consists of convincing correct nodes to disregard particular proposed series of blocks to lead to a double spending. We analyzed the tradeoff inherent to Ethereum between communication delay and mining power, hence confirming that forkable designs are ill-suited for consortium and private blockchains.

There are several ways to extend this work. First, the context is highly dependent on medium-scale settings where statistics about all participants can be easily collected. It would be interesting to extend these results when the mining power of participants is unknown. Second, the success of the Balance attack despite a low mining power requires communication delay between communication subgraphs. The next step is to compare denial-of-service and man-in-the-middle attacks and evaluate their effectiveness in introducing this delay.

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