BDoS: Blockchain Denial-of-Service Attacks

Michael Mirkin* Technion and IC3 smirkin@campus.technion.ac.il

Ariah Klages-Mundt Cornell University aak228@cornell.edu Yan Ji* Cornell Tech and IC3 yj348@cornell.edu

Ittay Eyal
Technion and IC3
ittay@technion.ac.il

Jonathan Pang Cornell University jp2268@cornell.edu

Ari Juels Cornell Tech and IC3 juels@cornell.edu

ABSTRACT

Proof-of-work (PoW) cryptocurrency blockchains like Bitcoin secure vast amounts of money. Their operators, called *miners*, expend resources to generate blocks and receive monetary rewards for their effort. Blockchains are, in principle, attractive targets for Denial-of-Service (DoS) attacks: There is fierce competition among coins, as well as potential gains from short selling. Classical DoS attacks, however, typically target a few servers and cannot scale to systems with many nodes. There have been no successful DoS attacks to date against prominent cryptocurrencies.

We present *Blockchain DoS* (*BDoS*), the first *incentive-based DoS attack* that targets PoW cryptocurrencies. Unlike classical DoS, BDoS targets the system's *mechanism design*: It exploits the reward mechanism to discourage miner participation. Previous DoS attacks against PoW blockchains require an adversary's mining power to match that of all other miners. In contrast, BDoS can cause a blockchain to grind to a halt with significantly less resources, e.g., 17% as of Feb 2019 in Bitcoin according to our empirical study.

BDoS differs from known attacks like Selfish Mining in its aim not to increase an adversary's revenue, but to disrupt the system. Although it bears some algorithmic similarity to those attacks, it introduces a new adversarial model, goals, algorithm, and gametheoretic analysis. Beyond its direct implications for operational blockchains, BDoS introduces the novel idea that an adversary can manipulate miners' incentives by *proving the existence of a secret longest chain* without actually publishing blocks.

1 INTRODUCTION

Cryptocurrencies such as Bitcoin, implemented with blockchain protocols based on Nakamoto [69], have a current market capitalization of about \$180B [20]. Like classical state machine replication protocols, blockchains allow participants to agree on a state, in their case – the client balances of a cryptocurrency. Unlike those classical protocols, however, public blockchains are decentralized and allow anyone to join the system at will.

To deter Sybil attacks [28], where an attacker masquerades as multiple entities, Nakamoto relies on *incentives*. Participants, called *miners*, expend resources and generate Proofs of Work (PoW) [29, 45]. They are rewarded with cryptocurrency for their efforts. Miners aggregate cryptocurrency *transactions* into so-called *blocks*, each containing PoW, and form a tree data structure. A path in the tree is called a *blockchain*. The path representing the most work is called the *main chain*; its contents define the system's state.

An extensive line of work (§2) explores revenue-driven attacks against blockchains [32, 33, 53, 70, 78]. DoS attacks, where the attacker is driven by exogenous incentives to stop a cryptocurrency blockchain, have received less attention. This may be because classical, network-based DoS attacks [27] do not scale to large decentralized systems and known mining-based DoS attacks [9, 10, 52] are prohibitively costly, as they require the attacker's mining resources to be at least equal to those of all other miners combined.

In this work, we present a new type of sabotage attack called *Blockchain Denial of Service (BDoS)*. BDoS is incentive-based – the attacker targets the system's mechanism design and violates its incentive compatibility. Specifically, the attacker invests resources in order to incentivize rational miners to stop mining. A BDoS adversary can cause a blockchain to cease functioning with only a fraction of the resources of the other miners. It is the first formally studied mechanism-based DoS attack of which we are aware.

The key element that enables BDoS is the consideration of miner behavior §3 that is typically overlooked in previous work. First, miners can stop mining intermittently if it benefits them, as demonstrated in the wild [19, 30, 54]. The majority of previous work assumes a constant number of miners, i.e., miners always mine. Secondly, an attacker can signal the miners that the system is in a state that reduces their revenue. Specifically, an attacker can generate a block and publish only its *header*, proving that she has spent the necessary resources, but without exposing the block's content. Although this option is technically practical, it was not considered in prior work to the best of our knowledge. Finally, like prior work [15, 30, 91], we consider miners that do not venture with more elaborate strategic behavior [33, 70, 78], which indeed has not been observed in the wild.

The crux of the attack (§4) is as follows. The attacker generates a block $B_{\mathcal{A}}$ and publishes only its header (fig. 1b); we then say the attack is *active*. A miner can ignore the existence of the header of $B_{\mathcal{A}}$ and generate a block following its parent, resulting in a *fork* (fig. 1c). In this case, the attacker publishes the contents of $B_{\mathcal{A}}$, resulting in a *race* with two branches (fig. 1d). The miner's block might or might not end up in the main chain, depending on the parameters of the system. The implication is that the expected profitability of the rational miners decreases, and if it is low enough, then pausing mining becomes a better option than mining. If the profitability decrease is significant enough so that all miners stop mining, the attacker can cease mining as well, while she has an advantage of one block ($B_{\mathcal{A}}$). The blockchain thus grinds to a complete halt.

We formulate the behavior of the miners as a game and look for a dominant strategy (§5). The attack is successful when not mining is the best response of the miners, and it depends on several

^{*}Both authors contributed equally to the paper

factors, mainly the sizes of the attacker and rational miners, and the baseline profitability of mining. One might think that non-myopic miners invested in the success of the system would be willing to suffer a temporary profitability decline to overcome an attack and keep the blockchain running. However, we find that their dilemma is even more difficult if this is the case – if other miners behave altruistically and ignore the attack, a rational miner has a stronger incentive to stop mining until the attack becomes inactive.

We consider several extensions of the action space. First, in practice, miners can mine on block headers, performing so-called *SPV Mining*. This action behavior is common, performed by otherwise benign miners to slightly reduce latencies [75]. SPV mining leads to an updated attack, as follows. If a rational miner successfully mines a block that extends the attacker's published header, the attacker abandons this header and never publishes its content, effectively invalidating the rational miner's block. We analyze the new game (§6) using Iterated elimination of strictly dominated strategies (IESDS) [34], and show that stop mining remains an equilibrium under the same parameters.

Secondly, we observe that the situation becomes significantly worse if miners have the option to use their resources in another blockchain rather than stop (§7). If two cryptocurrencies have similar initial profitability, even a small BDoS attacker can tip the scale and lead rational miners to defect from the attacked coin to the now-more-profitable one.

Thirdly, we propose techniques for the attacker to prove she has a hidden block without exposing its header, making mitigation even harder (§8).

To empirically validate the practicality of BDoS, we calculate profitability in the longest-running cryptocurrency, Bitcoin (§8). We combine mining difficulty data with mining hardware consumption and power, historical Bitcoin price fluctuation, and electricity costs. For example, as of today, given that the miners in Bitcoin have a \$1.50 expected return on every \$1 of electricity investment, an attacker with 22% of the mining power can successfully induce a complete shutdown. The instantaneous drop in block reward (and thus profitability) that is expected to take place in 2020 will put Bitcoin's security at further risk. Moreover, since the profitability of Bitcoin and Bitcoin Cash are almost identical, the two-coin model implies that BDoS poses an imminent threat for both coins.

Constructively, we propose some possible mitigations to BDoS (§9). First, honest miners can prefer non-attacker blocks on a fork with a heuristic time-based detector. Secondly, alternative reward mechanisms [14, 98] compensates miners on lost races, making BDoS ineffective (though similar attacks might apply).

The discovery of BDoS adds another consideration for the evaluation of blockchain systems and raises questions on the existence of similar attacks against different blockchain designs (§10).

In summary:

- We introduce and explore new, practical actions in the action space of adversaries and miners (§3).
- We initiate the first formal study of a mechanism-based DoS attack on PoW blockchains called Blockchain Denial-of-Service (§4).
- We formalize a game between rational miners and a BDoS adversary and show when the dominant strategy is to stop mining (§5).

- We consider several extensions to the basic BDoS action / strategy space, including SPV mining, mining on other blockchains, and proofs of hidden blocks. We show that SPV mining doesn't help, and the other two hurt (§6,§7,§8).
- We empirically study BDoS attacks in Bitcoin, showing that under reasonable assumptions a BDoS attacker can succeed with roughly 17% mining power as of Feb 2019 (§8).
- We propose mitigations that can reduce the effectiveness of BDoS (§9).

Responsible disclosure We have completed a disclosure process with prominent blockchain development groups.

2 RELATED WORK

To the best of our knowledge, this work is the first to study incentive-based denial of service attacks against blockchains. We present an overview here of previous work on denial-of-service attacks in the context of blockchains, incentive-related behavior, and other related work.

DoS Denial-of-Service (DoS) attacks [27] aim to prevent a system from serving clients, and are often mounted from multiple machines as *Distributed DoS* (*DDoS*) attacks. In blockchain networks, however, such techniques can only successfully target isolated system elements [46, 68, 93] like cryptocurrency exchanges or mining coordinators in *pools*. In eclipse attacks [16, 81, 82] an adversary monopolizes all connections of a target node and isolates it from the network. When applied to blockchain systems [40, 59], the victim's local view is no longer in sync with the network, disrupting the victim and amplifying other blockchain attacks [70]. Similar effects can be achieved with routing attacks, chiefly BGP hijacking [2, 3, 89]. However, due to the decentralized structure of the system, nodes outside the effect of the attack can continue to interact with the blockchain as usual, apart from the possible reduction of attacked mining power. In contrast, BDoS stops all blockchain progress.

Other attacks [56, 66, 67] saturate the blockchain to prevent transactions from being placed. Such attacks, however, result in graceful degradation, as the attacker simply raises the cost of transaction writes. Clients can still place transactions, albeit with a higher fee, thus also increasing the attacker's cost. Additionally, unlike BDoS, such attacks require continuous resource expenditure for the duration of the attack.

Majority (51%) attacks A 51% attack allows a miner that controls the majority of the mining power in the system to fork any section of the chain. She can mine on an old block and eventually build a longer chain than any minority competitors (even if the competitors have a significant head start). An attacker controlling a majority of the mining power violates the assumptions of PoW protocols and can perform a full-fledged DoS attack by simply generating empty blocks and ignoring other blocks. Since this is a majority attacker, her chain will extend faster than any other chain, making it the main chain, despite its empty content. An attacker with such power can also perform other attacks violating the system's safety properties. Goldfinger and bribery attacks [9, 10, 52, 57, 61, 90] utilize miner bribery to achieve similar effects, only without requiring the attacker to acquire mining power directly. Majority attacks have

been observed happening on smaller cryptocurrencies [11, 26, 41], but not on major ones, possibly due to their high continuous cost. In contrast to this family of attacks, BDoS requires significantly lower than 50% mining-power budget, and no continuous expenditure.

Revenue-seeking deviations Nakamoto blockchains' security relies on incentive mechanisms that aim to reward miners that follow the rules. One line of study [6, 50, 60, 70, 72, 76, 78] considers the incentive compatibility of blockchain protocols. It analyzes mining as a game, showing when the correct behavior is an equilibrium, and when deviations allow the miners to increase their revenue, and correct behavior is not an equilibrium. Such attacks may bias the mining power structure, leading to centralization, or affect other desired blockchain properties like censorship resistance. However, their goal and analysis consider only the internal system revenue, they do not consider exogenous malicious motivations, and they cannot be directly applied to achieve complete denial of service.

Goren and Spiegelman [38] show that a miner can increase her revenue by mining intermittently. Unlike BDoS, this is a revenue seeking attack, only the attacker stops mining, and she is not manipulating the behavior of other miners.

Several incentive attacks can affect individual mining pools [32, 53, 55, 58, 77], but do not directly lead to macro effects on the blockchain.

Incentive-based attacks Another line of work explores attacks that use incentives to affect blockchain properties, using a form of bribery. Judmayer et al. [48] categorize incentives attacks by their goals into three groups: transaction revision, transaction ordering, and transaction exclusion. These attacks may not violate protocol safety directly, but can be used to force a particular order of transactions [21, 31, 79], or transaction omission [47, 61, 63, 97]. They do not affect the system liveness.

Non-Nakamoto blockchains The BDoS attack is explicitly designed for a Nakamoto-like blockchain. Nakamoto-like protocols with alternatives to PoW [17, 18, 95, 96, 99] are equally vulnerable. On the other hand, it does not directly apply to the Ethereum blockchain (that is more vulnerable to other attacks [72, 76], though), where blocks receive partial reward even if they are off the main chain, and so in case of a BDoS header publication, a participant is indeed better off mining, getting at least a partial reward. Blockchain operators should be aware of this new type of attack and evaluate the resilience of their individual designs.

PoW alternatives such as Proof of Stake (PoS) [5, 22, 24, 37, 51] typically do not require participants to waste significant resources to approve transactions. Therefore, BDoS is not relevant to PoS in general. However, Buterin [13] introduced the so-called Discouragement Attack on PoS, where an attacker reduces the profit of other participants by censoring victims' messages, leading to a temporary DoS.

3 MODEL

We describe the system model (§3.1), namely the participants, their interaction, and network assumptions, and the resultant game model (§3.2), namely the miners' action space and utility function.

3.1 Mining Model

We model the system in a similar way to that of previous works [35, 64, 73] using common network assumptions [33, 70, 78]. However, we define an additional capability of the attacker. Rather than releasing a regular block, the attacker can release a partial block data that serves as proof that the block was mined.

Blockchain data structures The system constructs a data structure called the blockchain, which is a collection of *blocks*. A block B contains *block data* or payload, denoted by D, and the metadata called *block header*, denoted by H. Thus, a block is a pair B = (H, D). Each block contains a hash reference to another block, except the so-called *genesis block* which we denote by B_0 .

The linked blocks form a tree. The longest chain of blocks in the tree is called *the blockchain*. The blockchain is the main data structure in the system, and it defines the state of the cryptocurrency. Each block B in the blockchain is either a *full block* containing the entire block information (H, D), or a block header without the block data (H, \bot) where \bot denotes the lack of data. The fact that the blockchain can consist of partial block information is a refinement of our model compared to previous work [6, 33, 35, 64, 70, 72, 73, 76, 78], where a blockchain consists only of full blocks.

Participants We consider a system that comprises n participants called miners, we denote them by $\mathcal{P}_1, \mathcal{P}_2, \ldots, \mathcal{P}_n$, and an adversary \mathcal{A} . Each miner \mathcal{P}_i has an associated value α_i called its *mining power*, and the adversary \mathcal{A} has mining power $\alpha_{\mathcal{A}}$. The total mining power is normalized to 1, $\alpha_{\mathcal{A}} + \sum_{i=1}^n \alpha_i = 1$. Each miner has a *public key* known to all that allows her to prove her identity to other miners using a secret called *private key*.

Each rational miner \mathcal{P}_i possesses a view of the blockchain L_i locally. L_i^{Full} is the subset of L_i that consists only of the full blocks in L_i – i.e. blocks of the form (H, D). As mentioned before, each block B in L_i can either be a block header if \mathcal{P}_i does not receive the block data or a full block otherwise.

 \mathcal{P}_i also has a local order function $O_i:L_i^{Full}\to\{0,1,\ldots,\left|L_i^{Full}\right|\}$. This function indicates the order of full blocks in L_i observed by miner \mathcal{P}_i . Note that O_i is not defined for blocks that are not in L_i^{Full} – i.e. partial blocks of the form (H,\bot) . For all $\mathcal{P}_i\in\{\mathcal{P}_1,\mathcal{P}_2,\ldots,\mathcal{P}_n\}$ it holds that $O_i(0)=0$, that is all miners agree that the genesis block is the first block. Different miners may have different order functions on their full blocks depending on the order they receive blocks locally.

We call path in the block tree consisting of *full* blocks a *chain*. The longest chain of full blocks in L_i represents the state of the system for a miner \mathcal{P}_i and is called the *main chain*. When multiple chains are the longest, \mathcal{P}_i prefers the chain she observes first to be the main chain, i.e., the chain whose $O_i(B)$ value of the last block B in the chain is the minimal among that of other chains.

Rushing We denote by γ the strength of \mathcal{A} 's rushing ability [33, 70, 78]. Formally, γ is the expected ratio of rational miners that adopt \mathcal{A} 's block when \mathcal{A} publishes it to compete with a newly published block by some other miner \mathcal{P}_i at the same *height*, i.e., having the same sequential index in chains that contain them. The remaining $(1 - \gamma)$ are the miners that adopt \mathcal{P}_i 's new block.

Scheduler The system progresses in *rounds*, orchestrated by so called *scheduler*. During each round, the scheduler selects a miner to generate a new block. Additionally, the scheduler acts as an intermediate for the blocks propagation. All the messages are delivered immediately, and the system is synchronous.

Each round has a duration. We denote with λ a system constant called the *round rate constant*. It corresponds to the desired round rate (average number of rounds per second) in the blockchain. For instance, in Bitcoin $\lambda = \frac{1}{10\cdot 60}~\text{s}^{-1}$, thus a block is created on average every 10 minutes.

At the beginning of each round r, the scheduler asks each miner whether she participates as a candidate to find a new block during this round. We say that a participating miner is active in this round. The scheduler also records the so-called block template of each active miner, which is the scaffolding of the block consisting of miner's identity (using her private key) and the hash of the block it extends. Then the scheduler chooses a miner to mine the next block, from the set of active miners by a weighted random distribution. Each miner's probability to be chosen is proportional to her mining power. The selected miner can create a block in round rand is called the *winner* of the round, we denote it by w_r . We index the blocks $\mathbb{B} = \{B_0, B_1, B_2, \dots\}$ by the order of their issuance, i.e., w_r creates the block B_r . We denote with $\alpha_{\sf active}^r$ the total mining power of active miners in round r. The scheduler then simulates the duration of the round, which is determined using an exponential distribution with the rate $\lambda \cdot \alpha_{\mathrm{active}}^r$. The only purpose of block generation time is to determine the cost of active miners (further details are given in §3.2). If all the miners are mining during a round (i.e., $\alpha_{\text{active}}^r = 1$) and $L_i^{Full} = L_i$, which we call the *honest setting*, it holds that the exponential distribution of the duration of round r has a rate of $\lambda \cdot \alpha^r_{\rm active}$. In the general case, the exponential distribution has a rate of λ Note that we do not consider difficulty adjustment unless otherwise stated; thus, the expected block generation time in a round is always $\frac{1}{\lambda \cdot \alpha_{\text{active}}^r}$.

Next, the scheduler is responsible for adding the partial or full block to the private ledgers of all other miners. It treats the cases of an adversarial winner and a rational winner separately. If the adversary \mathcal{A} is chosen by the scheduler to mine a block, she decides whether to publish the full block of B_r or only the block header. She then announces her decision to the scheduler. Receiving the adversary's decisions, the scheduler adds to the private ledgers of the other miners either the full block or the block header of B_r depending on \mathcal{A} 's decision.

If a rational miner \mathcal{P}_i is chosen by the scheduler to mine a block, the scheduler notifies the adversary \mathcal{A} of B_r before sending it to any rational miner. The adversary decides whether to race against B_r . In case she decides to race, she sends the full block that corresponds to the previously withheld block. Otherwise, the adversary sends an empty message. If the message is empty, the scheduler simply broadcasts B_r to all miners. Otherwise, the scheduler sends B_r and \mathcal{A} 's competing blocks in different orders to different miners, to simulate the connectivity factor γ : For each miner $p \in \{\mathcal{P}_1, ..., \mathcal{P}_n\} \setminus \{w_r\}$, with probability $\frac{\gamma(1-\alpha_{\mathcal{A}})}{1-\alpha_{\mathcal{A}}-\alpha_{w_r}}$ the scheduler sends \mathcal{A} 's competing blocks first and then B_r to p, and with probability $1-\frac{\gamma(1-\alpha_{\mathcal{A}})}{1-\alpha_{\mathcal{A}}-\alpha_{w_r}}$ sends B_r first and then \mathcal{A} 's blocks. Naturally, \mathcal{A} sees her block first.

We assume that the scheduler can add blocks to the private ledgers in an atomic way. This implies that the local blockchains L_i are equal for all miners. The pseudo-code of the scheduler is in Appendix E.

3.2 Game-Theoretic Model

The system model gives rise to a game played among the rational miners given the adversary's behavior.

Miners As before, a rational miner \mathcal{P}_i possess a mining power α_i . Each miner knows the adversary's strategy and participates in a game with a finite number of actions: {mine, stop}, which are defined later. The sole purpose of the rational miners in this game is to maximize their utility.

Utility For each rational miner \mathcal{P}_i we denote by $\Pi_i(t)$, $R_i(t)$, and $C_i(t)$ her expected profit, revenue, and cost until time t, respectively. It holds that: $\Pi_i(t) = R_i(t) - C_i(t)$. We denote the average revenue and cost per time unit, for \mathcal{P}_i by $\hat{R}_i \triangleq \lim_{t \to \infty} \frac{R_i(t)}{t}$ and $\hat{C}_i \triangleq \lim_{t \to \infty} \frac{C_i(t)}{t}$ respectively. Consequently, the average profit per time unit, for \mathcal{P}_i , is: $\hat{\Pi}_i \triangleq \hat{R}_i - \hat{C}_i$. Notice that any constant cost is neglected when we discuss about per second values of profit and cost, therefore from now on we ignore the constant cost (or initial cost) and assume there is only varying cost.

For simplicity, we assume that the coin price is constant during the entire game, and thus we denote the block reward by K. Different miners may mine at different costs per mining power. The cost of miner \mathcal{P}_i per one second of mining is $\alpha_i c_i$, where c_i is the normalized mining cost per second for \mathcal{P}_i . We assume that c_i is constant throughout the game. When there is no attack, the expected profit per time unit is $\hat{\Pi}_i^b = \alpha_i (\lambda K - c_i)$.

In order to define the utility function, we normalize the expected profit by the miner's mining power. The utility function U of \mathcal{P}_i is thus: $U_i \triangleq \frac{\hat{\Pi}_i}{\alpha_i}$. We conclude that the utility of the rational miner \mathcal{P}_i during an honest game (with no attack) is:

$$U_i^b \triangleq \lambda K - c_i. \tag{1}$$

We also define the *profitability factor* ω_i^b for miner \mathcal{P}_i participating in an honest game. Intuitively, the profitability factor is the return per dollar investment for a miner in an honest game. Formally it is defined as:

$$\omega_i^b \stackrel{\triangle}{=} \lim_{t \to \infty} \frac{R_i(t)}{C_i(t)} = \frac{\lambda K}{c_i}.$$
 (2)

We note that when $U_i^b>0$ it implies $\omega_i^b>1$ and $U_i^b<0$ implies $\omega_i^b<1$.

Actions We consider miners that are rational, meaning that they do not participate in the game when it is not profitable. The miners are trying to maximize their profit within the protocol rules, with the ability to exit the game – i.e. stop mining. Specifically, each rational miner has two possible actions:

- (1) mine Mine on the main chain, or
- (2) stop Stop mining.

A miner chooses an action at the beginning of a round and commits to it until the end of the round. Changing the action within the

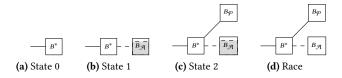


Figure 1: States

round does not increase \mathcal{P}_i 's utility since no new information is available to \mathcal{P}_i during a round. The elapsed time does not provide any new information due to the memorylessness property [78, 91]. This is formally justified in Appendix A.

Notice that if $\omega_i^b > 1$, the rational miner always chooses mine if there is no attack and if $\omega_i^b < 1$ she chooses stop.

In case the adversary releases a block header, a rational miner has to choose one of the two actions. The pseudocode that describes the rational miner's possible actions is in Appendix E.

4 THE BDOS ATTACK

The BDoS attack aims to incentivize rational miners to stop mining. The crux is that an attacker (\mathcal{A}) can bring the system to a state where if a rational miner \mathcal{P}_i chooses mine and finds a block $\mathcal{B}_{\mathcal{P}}$, \mathcal{A} can invalidate $\mathcal{B}_{\mathcal{P}}$ —with some probability. Thus, while \mathcal{P}_i incurs the same cost for performing mining (e.g., the cost of electricity) as in the honest game, there is significantly larger profitability it would be in vain.

We now describe the strategy, which is illustrated in fig. 1. Let B^* denote the latest block on the main chain. \mathcal{A} 's attack algorithm is to mine on B^* (fig. 1a). If she successfully appends a new block $B_{\mathcal{A}} = (H_{\mathcal{A}}, D_{\mathcal{A}})$ to B^* rather than publishing $B_{\mathcal{A}}$ in full, she publishes only its header $(H_{\mathcal{A}}, \bot)$. She withholds the rest of the block, namely its associated transactions. At this point, we refer to the state of the attack as active. We refer to $B_{\mathcal{A}}$ as the leading block in the attack. $B_{\mathcal{A}}$ is not part of the main chain, as it has not been published in full (fig. 1b).

The header of $B_{\mathcal{A}}$ serves as a proof that \mathcal{A} has successfully mined $B_{\mathcal{A}}$ and is currently withholding the full block. Until a rational miner produces a new block, \mathcal{A} stops mining completely. Next, two things can happen:

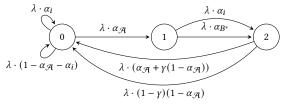
Block generated via mine: If at lease one miner performs mine and successfully generates a block $B_{\mathcal{P}}$ appended to B^* (fig. 1c), \mathcal{A} immediately publishes $B_{\mathcal{A}}$ in full, i.e., attempts to add it to the main chain. A race ensues as describe in §3: Mining power is now divided between $B_{\mathcal{P}}$ and $B_{\mathcal{A}}$ (fig. 1d). The first block to be extended "wins" the race in the sense of becoming part of the main chain.

Rational miners stop mining: \mathcal{A} stops mining as longs as there no new block generated by rational miners.

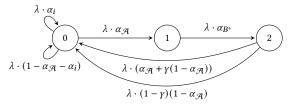
The effect of the attack on \mathcal{P}_i 's actions depends on the values of the system parameters ω_i^b , α_i and $\alpha_{\mathcal{A}}$. The pseudocode for BDoS is in Appendix E.

5 ANALYSIS

If stop is the best response for all miners, we say the attack is successful as it achieves a *complete shutdown* of the system. If



(a) S_{mine} : \mathcal{P}_i mines on B^* in state 1



(b) S_{stop} : \mathcal{P}_i stops mining in state 1

Figure 2: Markov chain.

stop is the best response for some miners, there is only a *partial shutdown* and we say BDoS is *partially successful*.

5.1 Game-Theoretic Analysis

We now derive the possible strategy space for a rational miner. We analyze the game as an infinite-horizon game where the miners play indefinitely [33, 85]. This applies although the cryptography in the Nakamoto consensus breaks in an infinite game - as we analyze an ergodic process, the average utility over infinite time is similar to the average utility of finite games. Therefore, we are interested in the expected profit per second of the miners that would allow us to compare different strategies. In order to calculate it, we construct a Continuous-Time Markov Chain for every strategy. Unlike previous analysis of similar games [33], the block creation rate varies when the attack is active/inactive, and therefore our system cannot be described with a discrete-time Markov chain. The Markov chains allow us to compute the utility function for each strategy as a function of other players' strategies. We analyze the conditions for a specific strategy (that corresponds to stop mining) to be a *dominant strategy* by comparison of the utility functions given the same choice of the other players.

Strategies We evaluate the strategies from the perspective of a rational miner \mathcal{P}_i . We define with Λ_{B^*} the set of miners actively mining on B^* while the attack is active. Next, we define: $\alpha_{B^*} \stackrel{\triangle}{=} \sum_{j \in \Lambda_{B^*}} \alpha_j$.

Given the attack algorithm BDoS and honest game profitability ω_i^b , our goal is to find an optimal strategy for \mathcal{P}_i which she chooses at the beginning of the game, i.e., a map from the private ledger L_i and the order function O_i to an optimal action. We say that strategy S^1 is more beneficial than strategy S^2 , for a rational \mathcal{P}_i , if the utility by playing S^1 is larger than the utility by playing S^2 . Consequently, we consider only two strategies: S_{mine} and S_{stop} that differ only by the actions of \mathcal{P}_i during the attack: mine and stop respectively. We describe the game for each strategy with three-state Markov

chains. Strategy S_{mine} appears in fig. 2a and S_{stop} in fig. 2b. In both chains, state 0 represents the initial state where everyone mines on B^* fig. 1a. State 1 represents the state where the adversary managed to find a block fig. 1b. State 2 represents the race condition, where the miners are divided between \mathcal{A} 's block and the block generated by a rational miner fig. 1c. In both strategies, \mathcal{P}_i chooses the action mine when not in state 1 (when the attack is not active). We prove this intuitive assumption in Appendix B. Therefore, each Markov chain matches a strategy that differs only by the actions of the miner in state 1.

State Probabilities We denote \mathcal{P}_i 's strategy by S and with $\alpha_{B^*}(S)$ the total mining power of miners that mine on B^* in state 1, i.e., the portion of miners who keep mining on B^* during the attack:

$$\alpha_{B^*}(S) \stackrel{\triangle}{=} \begin{cases} \alpha_{B^*} + \alpha_i, & \text{if } S = S_{\text{mine}} \\ \alpha_{B^*}, & \text{otherwise.} \end{cases}$$
 (3)

We proceed to calculating the state probabilities of the two Markov chains in fig. 2:

$$p_0^S = \frac{\alpha_{B^*}(S)}{\alpha_{\mathcal{A}} \cdot \alpha_{B^*}(S) + \alpha_{\mathcal{A}} + \alpha_{B^*}(S)},$$

$$p_1^S = \frac{\alpha_{\mathcal{A}}}{\alpha_{\mathcal{A}} \cdot \alpha_{B^*}(S) + \alpha_{\mathcal{A}} + \alpha_{B^*}(S)},$$

$$p_2^S = \frac{\alpha_{\mathcal{A}} \cdot \alpha_{B^*}(S)}{\alpha_{\mathcal{A}} \cdot \alpha_{B^*}(S) + \alpha_{\mathcal{A}} + \alpha_{B^*}(S)}.$$
(4)

Notice that miner \mathcal{P}_i changes the state probabilities depending on which strategy she chooses, as $\alpha_{B^*}(S)$ depends on \mathcal{P}_i 's strategy.

Utility For Each Strategy As the first step in calculating the utility, we calculate the cost and the revenue of \mathcal{P}_i . While a rational miner is mining, her cost per second is constant. However, when she stops mining, her cost per second is zero. Therefore for S_{stop} it holds that the average cost per time unit $\hat{C}_i^{S_{\text{stop}}}$ for \mathcal{P}_i is:

$$\hat{C}_{i}^{S_{\text{stop}}} = \lim_{t \to \infty} \frac{C_{i}^{S_{\text{stop}}}(t)}{t} = \alpha_{i}(1 - p_{1}^{S_{\text{stop}}}) \cdot c_{i}.$$

On the other hand when \mathcal{P}_i chooses strategy S_{\min} and therefore keeps mining all the time, her cost $\hat{C}_i^{S_{\min}}$ is constant:

$$\hat{C}_{i}^{S_{\text{mine}}} = \lim_{t \to \infty} \frac{C_{i}^{S_{\text{mine}}}(t)}{t} = \alpha_{i} \cdot c_{i}.$$

Therefore, it is left find the average revenues $\hat{R}_i^{S_{\text{stop}}}$ and $\hat{R}_i^{S_{\text{mine}}}$ for S_{stop} and S_{mine} respectively, in order to find the more beneficial strategy.

We now analyze the Markov chain: For both strategies the rational miner \mathcal{P}_i receives profit K every time she passes from state 0 back to state 0 with the rate $\alpha_i\lambda$ and from state 2 to 0 with rate $\alpha_i\lambda$. For strategy S_{mine} , \mathcal{P}_i receives profit $(1-\gamma)(1-\alpha_{\mathcal{A}})\cdot K$ when she passes from state 1 to state 2 with rate $\alpha_i\lambda$. Therefore the expected utility for strategy S_{stop} is:

$$\begin{split} U_i^{S_{\text{stop}}} &= \frac{1}{\alpha_i} (\hat{R}_i^{S_{\text{stop}}} - \hat{C}_i^{S_{\text{stop}}}) \\ &= \frac{1}{\alpha_i} \cdot ((p_0^{S_{\text{stop}}} + p_2^{S_{\text{stop}}}) \cdot \alpha_i \lambda K - (1 - p_1^{S_{\text{stop}}}) \cdot \alpha_i c_i) \\ &= (p_0^{S_{\text{stop}}} + p_2^{S_{\text{stop}}}) \cdot \lambda K - (1 - p_1^{S_{\text{stop}}}) \cdot c_i. \end{split} \tag{5}$$

Similarly the expected utility for strategy S_{mine} is:

$$U_i^{S_{\text{mine}}} = \frac{1}{\alpha_i} (\hat{R}_i^{S_{\text{mine}}} - \hat{C}_i^{S_{\text{mine}}})$$

$$= (p_0^{S_{\text{mine}}} + p_2^{S_{\text{mine}}} + (1 - \gamma)(1 - \alpha_{\mathcal{A}}) \cdot p_1^{S_{\text{mine}}}) \lambda K - c_i.$$
(6)

Conditions for Successful Attack We intend to calculate for what values of ω_i^b (defined in eq. (2)) the attack would be successful given $\alpha_{\mathcal{A}}$ and α_i , i.e., the mining power of the attacker and a certain rational miner \mathcal{P}_i . Note that in order for this attack to enforce complete shutdown, we have to examine the miner with the largest mining power. Using eq. (5) and eq. (6) we define $D(\alpha_{B^*})$ to be the normalized difference between $U_i^{S_{\text{stop}}}$ and $U_i^{S_{\text{mine}}}$:

$$\begin{split} D(\alpha_{B^*}) &\triangleq \frac{U_i^{S_{\text{stop}}} - U_i^{S_{\text{mine}}}}{c_i} \\ &= (p_0^{S_{\text{stop}}} + p_2^{S_{\text{stop}}} - p_0^{S_{\text{mine}}} - p_2^{S_{\text{mine}}} \\ &- (1 - \gamma)(1 - \alpha_{\mathcal{A}}) \cdot p_1^{S_{\text{mine}}}) \cdot \omega_i^b + p_1^{S_{\text{stop}}}. \end{split} \tag{7}$$

Our goal is to find when the attack is successful and all miners stop, that is, what are the ω_i^b values for which for all possible α_{B^*} values it holds that $D(\alpha_{B^*}) < 0$. We therefore calculate the condition on ω_i^b so that $D(\alpha_{B^*}) < 0$ using eq. (7):

$$\omega_{i}^{b} < \underbrace{\frac{p_{1}^{S_{\text{stop}}}}{p_{0}^{S_{\text{mine}}} + p_{2}^{S_{\text{mine}}} + (1 - \gamma)(1 - \alpha_{\mathcal{A}}) \cdot p_{1}^{S_{\text{mine}}} - (p_{0}^{S_{\text{stop}}} + p_{2}^{S_{\text{stop}}})}^{S_{\text{stop}}}}_{Q(\alpha_{B^{*}})}$$
(8)

We use calculus to find the tight condition, and we get that $Q(\alpha_{B^*})$ receives minimal value when $\alpha_{B^*}=0$, regardless of the parameters' values.

This result implies that the motivation for a miner to keep mining during the attack decreases when other miners keep mining, as the minimum is achieved when all other miners are following S_{stop} . By assigning $\alpha_{B^*}=0$ to eq. (8) and using the probabilities calculated in eq. (4), the tight condition on ω_i^b is:

$$\omega_i^b < \frac{\alpha_{\mathcal{A}} + \alpha_i + \alpha_{\mathcal{A}}\alpha_i}{\alpha_i + \alpha_{\mathcal{A}}\alpha_i + (1 - \gamma)\alpha_{\mathcal{A}}(1 - \alpha_{\mathcal{A}})}.$$
 (9)

This is the condition that ensures that S_{stop} is dominant strategy for \mathcal{P}_i . In other words, S_{stop} is always the best strategy for \mathcal{P}_i regardless of other payers' actions. Notice that the dominant strategy is S_{stop} for all miners if the condition in eq. (9) holds for all miners in the system.

5.2 Threshold Values

We consider specific system parameter values and the resulting threshold on ω_i^b for a successful attack.

First we use the condition on ω_i^b that was obtained in eq. (9). Figure 3 shows the highest ω_i^b that allows the attack for different values of $\alpha_{\mathcal{A}}$, α_i and γ . Unlike previous attacks, even an attacker with a relatively small computational power (e.g., $\alpha_{\mathcal{A}} < 0.1$) can successfully mount an attack to stop all other miners from mining. The mining power of the rational miner α_i is also important to the

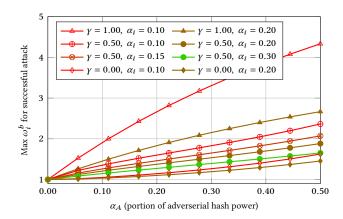


Figure 3: ω_i^b that will allow an attack for different α_A , γ and α_i (Notice that γ can't reach 1 in real setting).

success of the attack. For example, with $\alpha_{\mathcal{A}}=0.2$ and $\alpha_i=0.05$, the threshold ω_i^b is almost 1.9. Note that even if all the rational miners have similar profitability, a small attacker would be able to stop only smaller miners. This shows that large mining pools have stronger protection against BDoS.

Moreover, fig. 3 shows that when $\gamma=0$ and $\alpha_{\mathcal{A}}=0.2$, the attacker needs ω_i^b to be smaller than 1.15 in order to attack a rational miner with $\alpha_i=0.1$, compared to $\omega_i^b<1.6$ when $\gamma=\frac{1}{2}$ and $\omega_i^b<2.7$ when $\gamma=1$. This highlights the importance of the rushing ability for the attacker. Note that $\gamma=\frac{1}{2}$ is a conservative assumption primarily since an adversary can control a relay network [36] and therefore potentially achieve γ even closer to 1. In §8, we further show that even if the rational miners are deviating from Nakamoto's protocol by boycotting \mathcal{A} 's blocks (and therefore decreasing γ), she can use smart contracts (on external cryptocurrency) to make her blocks indistinguishable from rational miners' blocks.

Fixing α_{B^*} We found the borderline ω_i^b for the worst case, i.e., for all possible chosen strategies of other miners. But we saw that if the portion of rational miners that keep mining α_{B^*} increases, the motivation for \mathcal{P}_i to stop mining also increases. We now consider a scenario where \mathcal{P}_i can accurately estimate α_{B^*} . In practice, this can be done by spying on other pools [32, 87] or by monitoring the recent inter-block time. As before, we assume that $\alpha_{\mathcal{A}}=0$. Using eq. (8), we conclude that the bound on ω_i^b is $Q(\alpha_{B^*})$ (eq. (8)). We define: $\alpha_r = \frac{\alpha_{B^*}}{1-\alpha_{\mathcal{A}}-\alpha_i}$, which is the absolute portion of rational miners other than \mathcal{P}_i that continue mining. We plot the borderline ω_i^b , $\alpha_{\mathcal{A}}$ and α_i for different α_r values in fig. 4.

We can see that if all other rational miners chose S_{\min} ($\alpha_r = 1$), then for $\alpha_{\mathcal{A}} = 0.2$ and $\alpha_i = 0.16$, \mathcal{P}_i stops mining for $\omega_i^b < 2$ which is significantly higher than $\omega_i^b < 1.45$ for the case with $\alpha_r = 0$. As expected, the threshold for a partial shutdown is significantly higher than the threshold for a complete shutdown.

6 BDOS ATTACK WITH SPV MINING

So far, we assumed that no rational miner would mine on the block header. We note that publishing the header allows miners to

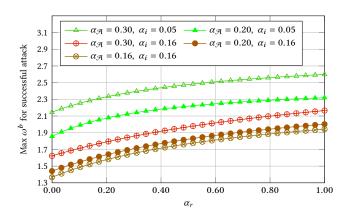


Figure 4: ω_1^b that will allow an attack for different α_r , $\alpha_{\mathcal{A}}$ and α_i while $\gamma = \frac{1}{2}$.

try to extend it in an optimistic manner, as a block can be extended using only its hash. In practice, this type of mining is common and called *SPV mining* [75]. According to Nakamoto consensus, no miner considers a block that references a header as part of her main chain, as the state is undefined without the content of the block. It is also impossible to validate the transactions of the next block (even if it is a full block). Therefore, when engaging in *SPV mining*, a miner assumes that the full block corresponding to the header would be published in the future.

6.1 Model Updates

To assume miners can SPV mine, we have to extend our definition for miners' behavior and assume that they can digress from the protocol with small deviations. Like Carlseten et al. [15] we say that the miners are petty-compliant, that is, they only take steps that almost follow the protocol, namely extending the longest chain, leave the protocol or engage in SPV mining. As SPV mining is a common behavior in practice, we are still considering benign miners, but expand the model to include a third action mineSPV where the miner tries to extend the attacker's block $B_{\mathcal{A}}$. Consequently, we add a third strategy to the rational miners' strategy space, mining on the attacker's header during the attack. We denote it with S_{SPV} .

In addition, we assume that the \mathcal{A} is aware of when a rational miner \mathcal{P}_i finds a block that extends \mathcal{A} 's header. More formally, if \mathcal{P}_i won the round, the scheduler adds her block to all other miners' ledgers, including \mathcal{A} 's. On a practical note, this can be done by spying on other mining pools. Thus, \mathcal{A} can join all major mining pools as a miner and be warned when the mining pool manages to find a block that extends her block header.

Therefore we change \mathcal{A} 's strategy slightly so that when a rational miner successfully finds block $B_{\mathcal{P}}$ that extends $B_{\mathcal{A}}$, \mathcal{A} abandons $B_{\mathcal{A}}$ and return mining on B^* . \mathcal{A} commits never to publish the data that corresponds to $B_{\mathcal{A}}$, practically invalidating $B_{\mathcal{P}}$.

Note If we consider a setting where \mathcal{A} can ignore or be unaware of a new block mined by \mathcal{P}_i that extends her header, the attack, in fact, becomes stronger. This is because the new block would be withheld until \mathcal{A} publishes the content of the header. But \mathcal{A}

would only publish it in case of a race condition. By releasing the header, \mathcal{P}_i immediately causes \mathcal{A} to win in the race. So if miners chose S_{SPV} in such a setting, they only decrease the motivation for other miners to choose S_{mine} . Moreover, the blocks mined with SPV are likely to be empty, as a miner who does not possess all the transactions in the current state would not risk invalidating her block by causing conflicts. We, therefore, leave the analysis of this case outside the scope of this paper.

6.2 Analysis Changes

As before we denote with $\Lambda_{B_{\mathcal{A}}}$ the set of miners actively mining on $B_{\mathcal{A}}$ while the attack is active. We define: $\alpha_{B_{\mathcal{A}}} \triangleq \sum_{j \in \Lambda_{B_{\mathcal{A}}}} \alpha_j$. Next, in the same way as in eq. (2) we denote with $\alpha \in \{0\}$ the mining

in the same way as in eq. (3) we denote with $\alpha_{B_{\mathcal{A}}}(S)$ the mining power of miners that mine on $B_{\mathcal{A}}$ in state 1:

$$\alpha_{B_{\mathcal{A}}}(S) \stackrel{\triangle}{=} \begin{cases} \alpha_{B_{\mathcal{A}}} + \alpha_i, & \text{if } S = S_{\text{SPV}} \\ \alpha_{B_{\mathcal{A}}}, & \text{otherwise.} \end{cases}$$

To analyze the dominant strategy, we construct Markov chains for each strategy in the new strategy space $\{S_{\rm stop}, S_{\rm mine}, S_{\rm SPV}\}$, similarly to what was done in §5. First, we calculate the state probabilities for each strategy. We denote the states probabilities with p_0^S, p_1^S and p_2^S for states 0, 1 and 2 respectively (as in §5). Recall that states 0, 1 and 2 correspond to the initial, attack is progress and race states respectively. We denote the utility functions by $U_i^{S_{\rm stop}}$, $U_i^{S_{\rm mine}}$ and $U_i^{S_{\rm SPV}}$ for $S_{\rm stop}$, $S_{\rm mine}$ and $S_{\rm SPV}$ respectively. The Markov chains for $S_{\rm mine}$ and $S_{\rm stop}$ are almost identical to the ones described in fig. 2, with a new edge from state 1 to state 0 that corresponds to a portion $\alpha_{B,\pi}$ of other miners that mine on \mathcal{A} 's block. The Markov chain for $S_{\rm SPV}$ is similar to the new Markov chain for $S_{\rm stop}$ but with an edge from state 1 to state 0 that corresponds to \mathcal{P}_i 's efforts to extend $B_{\mathcal{B}}$. The full Markov chains are described in Appendix D.

Next we calculate the state probabilities for each state depending on the strategy using basic Markov chains analytical analysis:

$$\begin{split} p_0^S &= \frac{\alpha_{B^*}(S) + \alpha_{B_{\mathcal{A}}}(S)}{\alpha_{\mathcal{A}} \cdot \alpha_{B^*}(S) + \alpha_{\mathcal{A}} + \alpha_{B_{\mathcal{A}}}(S) + \alpha_{B^*}(S)} \,, \\ p_1^S &= \frac{\alpha_{\mathcal{A}}}{\alpha_{\mathcal{A}} \cdot \alpha_{B^*}(S) + \alpha_{\mathcal{A}} + \alpha_{B_{\mathcal{A}}}(S) + \alpha_{B^*}(S)} \,, \\ p_2^S &= \frac{\alpha_{\mathcal{A}} \cdot \alpha_{B^*}(S)}{\alpha_{\mathcal{A}} \cdot \alpha_{B^*}(S) + \alpha_{\mathcal{A}} + \alpha_{B_{\mathcal{A}}}(S) + \alpha_{B^*}(S)} \,. \end{split} \tag{10}$$

The utilities for S_{stop} and S_{mine} are identical to the ones in 5 and 6 in respect to state probabilities, as non of the original edges where \mathcal{P}_i gets a reward have changed. Finally, we calculate the utility for playing S_{SPV} :

$$U_i^{S_{\text{SPV}}} = \frac{1}{\alpha_i} (\hat{R}_i^{S_{\text{SPV}}} - \hat{C}_i^{S_{\text{SPV}}})$$

$$= (p_0^{S_{\text{SPV}}} + p_2^{S_{\text{SPV}}}) \cdot \lambda K - c_i.$$
(11)

6.3 Narrowing down the possible number of strategies

In order to simplify the analysis, we spot a dominated strategy, i.e., a strategy that is always less beneficial compared to another strategy.

Claim 6.1. S_{SPV} is strictly dominated by S_{mine} .

PROOF. We calculate the difference Δ between the utility of playing S_{mine} (defined in eq. (6)) and the utility of playing S_{SPV} (defined in eq. (11)):

$$\Delta \stackrel{\triangle}{=} U_i^{S_{\text{mine}}} - U_i^{S_{\text{SPV}}}$$

$$= p_0^{S_{\text{mine}}} + p_2^{S_{\text{mine}}} + (1 - \gamma)(1 - \alpha_{\mathcal{A}}) \cdot p_1^{S_{\text{mine}}}$$

$$- (p_0^{S_{\text{SPV}}} + p_2^{S_{\text{SPV}}})) \cdot \lambda K.$$
(12)

We notice that the probability p_1^S (eq. (10)) decreases when \mathcal{P}_i chooses S_{mine} instead of S_{SPV} , the numerator stays the same while the denominator increases. We conclude that $p_1^{S_{\text{mine}}} < p_1^{S_{\text{SPV}}}$ and therefore:

$$\begin{split} &(p_0^{S_{\text{mine}}} + p_2^{S_{\text{mine}}}) - (p_0^{S_{\text{SPV}}} + p_2^{S_{\text{SPV}}}) \\ = &(1 - p_1^{S_{\text{mine}}}) - (1 - p_1^{S_{\text{SPV}}}) = p_1^{S_{\text{SPV}}} - p_1^{S_{\text{mine}}} > 0. \end{split} \tag{13}$$

From eq. (12) and eq. (13) we conclude that $\Delta > 0$. Therefore by playing S_{mine} , \mathcal{P}_i always has a strictly larger profit than she would have if she would play S_{SPV} .

From now on we consider only two strategies for \mathcal{P}_i in our analysis: S_{mine} and S_{stop} , as we proved that \mathcal{P}_i never chooses strategy S_{SPV} . Notice that we still have to consider S_{SPV} for other miners in order to find conditions for S_{stop} to be dominant strategy (§6.4). In §6.5 we relax this in order to argue about the more practical setting where no rational miner chooses a dominated strategy.

6.4 Conditions for Successful Attack

As in §5.1 we calculate for what values of ω_i^b the attack would be successful given $\alpha_{\mathcal{A}}$ and α_i . We define $D(\alpha_{B^*}, \alpha_{B_{\mathcal{A}}})$ to be the normalized difference between $U_i^{S_{\text{stop}}}$ and $U_i^{S_{\text{mine}}}$:

$$\begin{split} D(\alpha_{B^*}, \alpha_{B_{\mathcal{A}}}) &\triangleq \frac{U_i^{S_{\text{stop}}} - U_i^{S_{\text{mine}}}}{c_i} \\ &= (p_0^{S_{\text{stop}}} + p_2^{S_{\text{stop}}} - p_0^{S_{\text{mine}}} - p_2^{S_{\text{mine}}} \\ &- (1 - \gamma)(1 - \alpha_{\mathcal{A}}) \cdot p_1^{S_{\text{mine}}}) \cdot \omega_i^b + p_1^{S_{\text{stop}}}. \end{split} \tag{14}$$

As before we find for values of ω_i^b for all possible α_{B^*} and $\alpha_{B_{\mathcal{A}}}$ it holds that $D(\alpha_{B^*}, \alpha_{B_{\mathcal{A}}}) < 0$. We therefore calculate the condition on ω_i^b so that $D(\alpha_{B^*}, \alpha_{B_{\mathcal{A}}}) < 0$ using eq. (14):

$$\omega_{i}^{b} < \underbrace{\frac{p_{1}^{S_{\text{stop}}}}{p_{0}^{S_{\text{mine}}} + p_{2}^{S_{\text{mine}}} + (1 - \gamma)(1 - \alpha_{\mathcal{A}}) \cdot p_{1}^{S_{\text{mine}}} - (p_{0}^{S_{\text{stop}}} + p_{2}^{S_{\text{stop}}})}^{S_{\text{stop}}}}_{Q(\alpha_{B^{*}}, \alpha_{B_{\mathcal{A}}})}.$$

$$(15)$$

This is the general bound on ω_i^b that makes S_{stop} the dominant strategy for \mathcal{P}_i . This can be solved for specific values of γ , $\alpha_{\mathcal{A}}$ and α_i and otherwise it's not analytically solvable for the parametric case.

6.5 Iterated Elimination of Weakly Dominated Strategies

The result in eq. (15) is the condition for S_{stop} to be strictly dominating strategy among the three strategies: $\{S_{\text{stop}}, S_{\text{mine}}, S_{\text{SPV}}\}$.

We use a technique called iterated elimination of strictly dominated strategies (IESDS) [34] and show that our game is dominance-solvable game. We assume that no rational miner chooses to mine on $B_{\mathcal{A}}$ and that this is a common knowledge that no other miner would mine on it [4], as this is a strictly dominated strategy as we showed in §6.3. This elimination would leave us with the only Nash equilibrium in the game. Therefore, we analyze the case where $\alpha_{B_{\mathcal{A}}}=0$. This implies that if the result in eq. (9) holds for all rational miners, S_{stop} is the only Nash equilibrium in the game [52]. This equilibrium is conceptually stronger than general equilibrium, as it implies that S_{stop} is the best strategy regardless of other miners' rational strategies.

7 TWO-COIN MODEL

So far, we used a model where the attacker initiates an attack on coin *C*, and the rational miners can either mine on this coin or not mine at all.

We now consider a *two-coin model* where miners can choose to mine between two coins alternately. This requires the two coins to share similar mining algorithm so that miners could mine on both coins with similar efficiency. The main conceptual difference from the previous model is that miners have less to lose by ceasing mining activity on one coin. If the profitability of the coins is similar, even if the attacker lowers the expected profit even slightly, the miners would still be motivated to quit mining and switch to the other coin.

Due to the large number of coins in the blockchain world and the fact that some of them use the same or similar mining schemes, the mentioned above alternative model is more realistic [39, 42, 54, 62, 74, 80, 84, 88].

When there is a profitability difference, miners are expected to switch coins to the more profitable coin. By doing that, they cause the profitability to decrease in the long term (due to difficulty adjustment) and bring the coins' profitability to equilibrium. We describe a way to create artificial profitability differences between the coins, consequently causing all rational miners to abandon one of the coins for the other(s).

7.1 Model Changes

In our two-coin model, we assume a rational miner can choose between mining on C or a competing coin C' with the same mining mechanism. We denote the profitability and utility of \mathcal{P}_i for coin C with ω_i^b and U_i respectively, and the profitability and utility of \mathcal{P}_i for coin C' with $\omega_i^{b'}$ and U_i' respectively. In case the initial mining profitability for the miner with the largest mining power \mathcal{P}_i , on both coins, is equal, thus $\omega_i^b = \omega_i^{b'}$, the attacker has no longer an upper bound on ω_i^b , that would be a threshold for an attack on coin C. This is because any attack always decreases the mining utility U_i for \mathcal{P}_i (mining on coin C) and therefore every miner would choose to mine on C' instead (as $U_i^{b'} > U_i$).

7.2 Analysis

The model is almost the same as the one described in §3.2, and the analysis would be similar to the analysis in §5. The main difference is that we no longer consider a choice between mine on B^* and stop but between mining on B^* in the attacked coin C and mining on

another coin C'. The utility $U_i^{S_{mine}}$ for \mathcal{P}_i for the first strategy S_{mine}^1 (mining on B^* in coin C) is the same as $U_i^{S_{\min}}$ in eq. (6), thus $U_i^{S_{\min}} = U_i^{S_{\min}}$.

While the utility $U_i^{S_2}$ for \mathcal{P}_i for the second strategy S_{mine}^2 (mining in the honest setting in coin C') is similar to U_i^b in eq. (1). We use different λ , c_i and K parameters for the second coin (λ', c_i') and K' respectively), as they are not necessary the same for both coins. Thus: $U_i^{S_{mine}^2} = U_i^{b'} = \lambda' K' - c_i'$. To compare the two utilities in two different coins, we can no longer use the normalized utility, as the mining power constants α_i and α_i' of coin C and C' respectively, are not necessarily the same. Notice that the mining cost per second of \mathcal{P}_i is equal for both coins, so that $\alpha_i c_i = \alpha_i' c_i'$. We define D as the difference between the two utilities $U_i^{S_{mine}}$ and $U_i^{S_{mine}^2}$, when each utility is multiplied by the respective hashrate:

$$\begin{split} D(\alpha_{B^*}) &\triangleq \frac{\alpha_i U_i^{S_{mine}^1} - \alpha_i' U_i^{S_{mine}^2}}{\alpha_i c_i} \\ &= \frac{\alpha_i U_i^{S_{mine}^1}}{\alpha_i c_i} - \frac{\alpha_i' U_i^{S_{mine}^2}}{\alpha_i' c_i'} \\ &= (p_0^{S_{mine}} + p_2^{S_{mine}} + (1 - \gamma)(1 - \alpha_{\mathcal{A}}) \cdot p_1^{S_{mine}}) \cdot \omega_i^b - \omega_i^{b'}. \end{split}$$

As before we ask when it holds that $D(\alpha_{B^*}) < 0$. Therefore we are looking for the ratio r s.t:

$$r \triangleq \frac{\omega_i^{b'}}{\omega_i^b} > \underbrace{(p_0^{S_{\min}e} + p_2^{S_{\min}e} + (1 - \gamma)(1 - \alpha_{\mathcal{A}}) \cdot p_1^{S_{\min}e})}_{W(\alpha_{\mathcal{B}^*})}.$$

We now need to calculate the maximal value $W(\alpha_{B^*})$ can get. Using calculus we derive that it attains maximum for $\alpha_{B^*} = 1 - \alpha_{\mathcal{A}} - \alpha_i$ which holds when all other miners do not switch coins (as this is the maximum utility they can get):

$$\begin{split} r &> W(\alpha_{B^*} = 1 - \alpha_{\mathcal{A}} - \alpha_i) \\ &= \frac{(1 - \alpha_{\mathcal{A}})(\alpha_{\mathcal{A}}(\gamma - 2) - 1)}{\alpha_{\mathcal{A}}^2 - \alpha_{\mathcal{A}} - 1} = r^*. \end{split}$$

An interesting fact is that the minimal r that allows the attack, which we denote with r^* , does not depend on the mining power of \mathcal{P}_i .

We plot r^* that allows the attack for different γ and $\alpha_{\mathcal{A}}$ in fig. 5. When $\gamma=\frac{1}{2}$ and $\alpha_{\mathcal{A}}=0.2$, it holds that $r^*=0.9$. This means such an attacker can attack as long as C profitability is less than 11% more profitable than C'. Notice that the attack is always possible when the profitability of C' is equal to the one of C, i.e. r=1. In §8 we show such conditions exist currently between Bitcoin ABC and Bitcoin.

8 PRACTICAL CONCERNS

8.1 Attack Cost

We investigate the cost of attack for different attacker sizes. Note that in the previous sections, we assumed that an *existing* miner aims to disable the coin, ignoring the hardware cost. We first recall that portion of time spent in state 1 of fig. 2 is p_1 . It immediately follows that the attacker's cost is: $\alpha_{\mathcal{A}} c_{\mathcal{A}} (1 - p_1)$ as the attacker

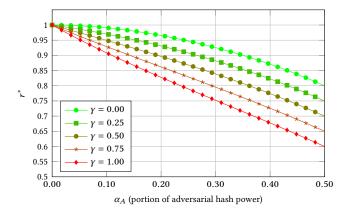


Figure 5: r^* that will allow the attack

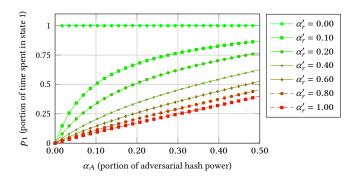


Figure 6: Fraction of time spent in state of active attack (p_1) for varying α_A , α'_r . Here, $\alpha_{B_{\mathcal{A}}} = 0$.

mines at a constant rate in all states but 1. In Appendix C we calculate the cost per day of achieving hash power equivalent to that of the entire Bitcoin network. This is \$7,104,000 given the use of Antminer S9 SE rigs and \$3,508,438 for Antminer S17 Pro. For majority hashpower, an attacker needs only $\alpha_{\mathcal{A}}(1-p_1)$ of these costs.

We plot the graph of p_1 vs. $\alpha_{\mathcal{A}}$ in fig. 6. We denote by $\alpha_r' = \frac{\alpha_{B^*} + \alpha_i}{1 - \alpha_{\mathcal{A}}}$ the total fraction of rational miners who keep mining. The results of the graph are not surprising for $\alpha_r' = 0$, as in such case \mathcal{A} takes complete control of the system, and the Markov chain stays in state 1 forever at cost 0. Notice that for a complete failed attack $(\alpha_r' = 0)$, the system still spends 0.17 of the time in state 1 and pays a total 0.165 of the mining cost (\$580k a day for the Antminer S17 Pro).

For $\alpha_{\mathcal{A}} = 0.2$ and given a small fraction of altruistic miners, for example, $\alpha'_r = 0.1$, we will spend 6.5% of the entire mining cost (\$65k a day for the Antminer S17 Pro). We showed that the attack would be less costly than regular mining with α_i , and significantly cheaper if only a small portion of the miners are altruistic.

8.2 Publication Method

The BDoS attack requires the adversary to announce a block header without revealing a full block. We first describe practical methods for propagating a block header. In the rest of the subsection, we describe few alternative methods for proving that the adversary found a block, without revealing identifying details about the block.

In order to propagate the block header, the attacker can announce that she is committing to an attack, and attach a web link to her private web page. The webpage would be then used to publish her block headers. Rational miners have the incentive to poll this external website, as more information means larger long-term revenue. It is important to stress that by ignoring the website and therefore, the attack, miners are necessarily decreasing their profit.

Instead of sending a block header, the adversary can use a smart contract (potentially on external coin) to demonstrate the discovery of a block without revealing its header.

The idea is to use an *economic mechanism* to demonstrate knowledge of a valid block header H. Briefly, the attacker places large collateral in the contract, along with a cryptographic commitment Comm to H, and with the previous block. If, at some predetermined (distant) future time, she de-commits a valid H for the contract, i.e., one that points to the previous block, she recovers the collateral. Otherwise, she forfeits the collateral to miners. Thus, the attacker is incentivized to claim and commit only to a valid header, but *need not reveal any information about* H (until H is no longer useful to miners).

To ensure that the attacker has the incentive to commit to a valid H, the collateral should be significantly larger than the cost of mining blocks during the commitment period. The collateral, if forfeited, can be split among a predefined list of mining pools (weighted by their mining power). For example, this list might include miners of the last, e.g., 1,000 blocks.

This approach has one key advantage over the block header approach: until H is de-committed (again, in the far future), no rational miner can distinguish the attacker's block from an honest block as, during the race, the other miners only posses a commitment for the block rather than a block header or hash. This approach prevents rational miners from forming a coalition that would ignore the attacker's block. When the attacker reveals the block after a long time, it would be impractical to ignore it as it would require to reorg a block located deep in the main chain.

It is possible to build the smart contract in a way that when an attacker finds a block, instead of sending the commitment to the smart contract, an action that can delay the attack significantly, she can publish an *undeniable* commitment to the network.

Another method that can achieve a similar effect is Zero-Knowledge proof. An attacker can publish a non-interactive Zero-Knowledge proof on her website and prove she found a block header without exposing identifying information like the block hash. Like in the case of smart contracts, rational miners would not be able to distinguish the attacker's block from an honest block in case of a race.

Exact details for both methods are beyond the scope of this paper.

8.3 Practical ω^b

The success of the attack relies critically on the baseline profitability ω^b . To estimate realistic values for ω^b , we study the properties of Bitcoin, as the archetypal PoW cryptocurrency. We would like to understand the costs that affect ω^b . Next, we would like to find out, how and when ω^b changes, this is important due to the

attacker's liberty to choose the moment of the attack. Finally, we are interested in estimating real values for ω^b , using both previous work and our own estimation.

CAPEX and OPEX First, we can separate the miner's cost into two categories: Operating expense (OPEX or ongoing cost) and capital expense (CAPEX or sunk cost). A similar separation of costs can be found in [39, 49]. The OPEX would include costs like Electricity cost of mining equipment, electricity cost of hardware cooling. The CAPEX would include costs like buying/renting facilities and buying mining. As we compare $S_{\rm stop}$ to other strategies, we can ignore the CAPEX cost because all strategies have an identical initial cost. Moreover, in §5 we showed that the CAPEX is not relevant in our infinite-horizon game, as it does not change the profit per second.

Nevertheless, high CAPEX keeps ω^b high, as miners have to return their initial investment. Lower CAPEX can cause ω^b to decrease as more potential miners would join the game, bringing the system closer to equilibrium [7, 38, 43, 92] – i.e. ω^b close to 1. As we showed in §5 this would hurt the security of the system as small attackers would be able to mount a successful BDoS attack.

 ω^b **Fluctuations** More than 50% of the hash power in Bitcoin is originated from Sichuan, China [100]. The reason for that is that the price of electricity in this region is extremely low during the wet season (as low as \$0.04 per kWh, which may vary by hydropower plants). Moreover, at the end of the wet season or in unexpected dry periods, the difficulty would remain high, but with the rise of electricity prices, the profitability of most miners is expected to be at its lowest point. This would be the ideal moment to attack.

Another essential factor that can make the system vulnerable to the attack is the block reward adjustment that is estimated to happen in the year 2020 [1]. The block reward will then drop from 12.5BTC to 6.25BTC. The transition would be immediate; therefore, this will cause a significant drop in ω^b . An attacker can prepare for such an event and launch her attack at the exact moment of the drop.

Estimating Upper Bound for ω^b Estimating ω^b is based on several parameters. Mining hardware rates and electricity consumption of different mining hardware are available in *ASIC Miner Value* [65]. We analyzed Bitcoin blocks 471744 to 602784 (June 17, 2017 – Nov 7, 2019) using the Google BigQuery [25] Bitcoin dataset to collect mining difficulty data and compute the expected number of hashes needed to find a block [94]. We consider an electricity price of \$0.05 per kWh [7] and Bitcoin prices from [44]. fig. 7 shows the profitability of mining Bitcoin with the best mining hardware at each time, as well as with S9.

Eghbali and Wattenhofer [30] estimate that at the beginning of 2019 almost all miners used S9 machines (or similar). Based on this data with conservative \$0.04 [7] per kWh electricity price, assuming largest rational miner is 16% and $\gamma=\frac{1}{2}$, an attacker with 17% mining power could have successfully launched a BDoS attack in Feb 2019. According to the same assumptions, if the Bitcoin price would have dropped extra 22% to \$2950, even an adversary with 5% of the mining power could have successfully launched the attack.

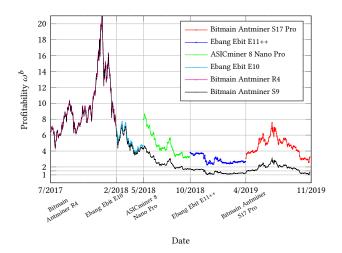


Figure 7: Profitability of mining Bitcoin using different mining hardware.

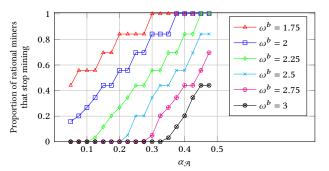


Figure 8: Proportion of rational miners that stop mining in the Nash equilibrium.

8.4 Simulation of Realistic Mining Pools

Even if the mining profitability is not low enough for a complete shutdown, a BDoS attacker can still discourage some small miners from mining. This is because, the upper bound on ω_i^b that drives a rational miner out of mining increases with the mining power of \mathcal{P}_i , as shown in fig. 3. Assuming all miners have the same profitability factor ω^b , consider an adapting process in which rational miners are always aware of the total mining power of active miners in the network, and choose between S_{\min} and S_{stop} adaptively. A rational miner \mathcal{P}_i chooses to mine if the real-world ω^b is higher than the upper bound for \mathcal{P}_i , and stops mining otherwise. The process starts with the state in which everyone mines and ends when no rational miner changes her strategy anymore. Thus at the end of the process, rational miners reach a Nash equilibrium. We simulate the process to find an equilibrium where all rational miners may fall in. In the simulation, we assume \mathcal{A} 's rushing ability factor γ is 0.5. We use the mining power of real pools collected from [12] on Oct 25, 2019, which is estimated as the block generation rate of each mining pool during the past week. We view each mining pool as an individual miner. To be conservative, we assume all the hash power from unknown sources form a single entity. Note that we introduce the

adversary as a new miner entering the game with existing mining pools, so the actual mining power of each rational miners in the simulation is scaled with a factor $1-\alpha_{\mathcal{A}}$. We plot the proportion of rational miners that stop mining in the Nash Equilibrium with different mining profitability ω^b in separate curves in fig. 8. The simulation indicates that for an adversary with only 20% of mining power, she may stop more than half of rational miners even when the real-life profitability is 2.

8.5 Estimating Practical r

To justify the analysis in §7, we are interested in finding whether miners tend to switch between coins, with identical mining algorithms, according to their profitability. Besides, we are interested to see if this causes the profitability of coins to be close to each other over time.

In [54], the authors collect data from inside mining pools and show that such migrations between coins happen frequently. In [88], the authors found a correlation between profitability changes of Bitcoin and Bitcoin Cash with the changes in the hash rate of the two coins, concluding that miners migrate between coins according to profitability.

The ratio between profitabilities of Bitcoin and Bitcoin Cash, presented in [23], is equivalent to r that was defined in §7. We can see that r is close to 1 and often is within 5% error range. Such realistic values for r would allow an attacker with 10% (and even less) of the mining power to mount a successful attack.

9 MITIGATION

We now describe possible mitigations for BDoS attacks.

Uncle blocks The attack described in this work designed to attack Bitcoin and similar coins. However, it is not practical in Ethereum [14, 98]. The main property of Ethereum that might prevent the BDoS attacks is the uncle block mechanism [98]. This mechanism rewards miners who mined blocks that are directly connected to the main chain, but their block was excluded as a result of a longer sequence of blocks. This imposes a significant challenge on our attack, as now, in case a rational miner loses the "race", her reward is almost as the original block reward. Therefore, by publishing a block header, the attacker no longer reduces the expected profit of rational miners significantly. Notice that the mechanism does not grant a reward for blocks that are not directly connected to the main chain. Consequently, there are likely similar attacks to the one described in this paper that still allow the attacker to decrease the expected reward, e.g., by publishing two-block headers that fork the most recent block in the chain. However, the design for such an attack is beyond the scope of this work.

Another work suggests an alternative to Nakamoto blockchain, where blocks always included in the data structure [83]. This eliminates the risk for a miner to lose her block and therefore turns BDoS to ineffective

Ignoring attacker's block during race Another possible way to weaken the attack is to change miner behavior so that if there is a fork, a miner should prefer blocks not generated by an attacker. The challenge is to identify attack blocks. A third party service for this goal is out of the question as it violates the decentralized nature of

the system and allows false incrimination. Instead, we propose to classify according to the time interval between the reception of the header and the reception of the block. We can safely assume that for a non-attack block, this interval is bounded by, e.g., one minute, and blocks with a longer interval are suspect.

Notice that this mitigation is possible only when the adversary chooses to prove that she mined a block using a block header. This solution does not work with other methods like smart contracts and ZK proofs, as we described in §8.2.

10 CONCLUSION

We present BDoS, the first Blockchain denial-of-service attack that uses incentive manipulation. BDoS sabotages the incentive mechanism behind Nakamoto's consensus by proving the attacker has achieved an advantage in mining without releasing her complete block. Such proof reduces miners' incentive to mine to be less profitable than not mining. Thus, rational profit-driven miners would cease mining. We show that cryptocurrencies based on Nakamoto's blockchain are vulnerable to BDoS under realistic settings, and propose mitigations.

The header-only publication capability we present is a realistic extension of the standard model under which blockchain protocols typically analyzed. This could open the door to study new equilibria and strategies where a miner manipulates the system to increase her revenue rather than sabotage the system. Secondly, BDoS applies to heaviest-chain PoW blockchains such as Bitcoin, Litecoin, Bitcoin-Cash, Zcash, and others. It is necessary to understand whether there are similar attacks against other protocols like Ethereum and whether our heuristic mitigation applies there as well.

Additionally, alternative incentive-based DoS attacks may exist, possibly more efficient than BDoS. General bounds and mitigations are necessary to ensure the security of blockchain protocols.

A CHANGING ACTION IN THE MIDDLE OF THE ROUND

In the model, we assumed that no rational miner changes her action in the middle of the round. We now justify this assumption. As mentioned earlier, the coin price is assumed to be constant during the entire game. Therefore, the honest game profitability factor ω_i^b of \mathcal{P}_i keeps its value constant during the round. In addition, we assume that no miner withholds blocks. We define as Time_j the time when round j ends and round j+1 starts.

Claim A.1. If \mathcal{P}_i chooses an action a in the beginning of round j (Time j-1), she does not gain anything from changing her action for all t that hold Time j-1 < t < Time j.

PROOF. We know that the rational miner \mathcal{P}_i chose the most beneficial action a in the beginning of round r, assume by contradiction that it is beneficial for \mathcal{P}_i to change her action in time t_1 that holds $\mathrm{Time}_{j-1} < t_1 < \mathrm{Time}_j$ to a different action a' s.t $a \neq a'$. Previous works showed that new block appearance in the system can be described with Poisson distribution, with the time between blocks correspond to exponential distribution [86]. One of the properties of this distribution is that it is memoryless. Since \mathcal{P}_i has the same probability of finding a new block as she had at the beginning of the round (and so do other miners), she has the same expected revenue from each action. If changing action in the middle of a round is profitable, this implies that changing an action was also beneficial at the beginning of the round. This is a contradiction to the fact that \mathcal{P}_i is rational and chose the best action at the beginning of the round.

Note that for memorylessness, we had to assume that there is no block withholding in the system, i.e., in every point during the round, it is known by everyone that there was no new block mined, by any miner, since the beginning of the round. For example, this assumption does not hold when there is an active selfish mining attack [33]. Although, it is reasonable to assume that no miner is withholding blocks during the attack as there is no evidence of cases of selfish mining attacks in the wild.

B MINE IN STATE 0 AND STATE 2 ALWAYS BETTER ACTION THAN STOP

Throughout the paper, we assume that miners always play mine in State 0 and State 2. We now prove formally that mine is always better action than stop in these states. In other words, assume that there are two strategies that differ only by the action in state 0 (or state 2), namely strategy S_A uses action mine while strategy S_B uses stop. It necessary means that $U_{S_A} > U_{S_B}$.

Claim B.1. If $\omega_i^b > 1$ then mine in state 0 and state 2 is always more profitable than stop for \mathcal{P}_i .

PROOF. We show the claim for state 0. The proof for state 2 is the equivalent. As we did before we consider two strategies S_A and S_B that differ only by the action in state 0 (mine for S_A vs. stop for S_B). We need to compare the utilities of two strategies that differ only by the action of \mathcal{P}_i in state 0. First, we observe that p_1 does not change as a result of \mathcal{P}_i 's action in state 0. This is because the rate from state 0 to state 1 and the rate from state 1 to state 2 are

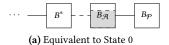


Figure 9: States

not affected by wether or not \mathcal{P}_i mines in state 0 (or state 2). We denote with ρ_s the normalized profit rate in state s, it is equal to the product of the expected block reward, and the normalized rate \mathcal{P}_i finds blocks. We denote with ρ_1 and ρ_2 the expected profit rates in states 1 and 2 respectively. With ρ_{mine} and ρ_{stop} the profit rates of playing mine and stop in state 0 respectively. We denote with p_0 and p_2 the state probabilities of state 0 and state 2, respectively, when playing mine in state 0. We denote with p_0 ' and p_2 ' the state probabilities of state 0 and state 2 respectively when playing stop in state 0. Therefore the utility of playing mine in state 0 is:

$$U_{\text{mine}} = \rho_{\text{mine}} \cdot p_0 + \rho_1 \cdot p_1 + \rho_2 \cdot p_2.$$

Similarly, the utility of playing stop in state 0 is:

$$U_{\text{stop}} = \rho_{\text{stop}} \cdot p_0' + \rho_1 \cdot p_1 + \rho_2 \cdot p_2'.$$

The profit rates in state 1 and state 2 (ρ_1 and ρ_2) can not be larger than the profit rate in state 0 (ρ_{mine}) as ρ_{mine} is the maximal possible profit rate. Therefore, it holds that $\rho_{\text{mine}} \geq \rho_1, \rho_2$ and $\rho_{\text{mine}} > 0$ (as $\omega_i^b > 1$). Additionally, there is no reward and cost when not mining, so $\rho_{\text{stop}} = 0$. Thus, the following inequality holds:

$$\begin{split} U_{\text{mine}} &= \rho_{\text{mine}} \cdot p_0 + \rho_1 \cdot p_1 + \rho_2 \cdot p_2 \geq \rho_1 \cdot p_1 + \rho_2 \cdot (p_0 + p_2) \\ &= \rho_1 \cdot p_1 + \rho_2 \cdot (p_0' + p_2') > \rho_1 \cdot p_1 + \rho_2 \cdot p_2' = U_{\text{Stop}}. \end{split}$$

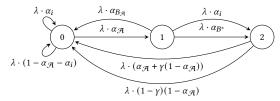
C COST OF 51% ATTACK

We show our calculation for the cost of 51% attack. At the moment of writing this paper, the total hash rate of Bitcoin is roughly 100,000,000 TH/s. The most advanced mining equipment is considered to be Bitmain S17 Pro which has hashrate of 53 TH/s and power consumption of 2.094 kWh [8]. The official cost of a unit is \$2128. Another widely used ASIC machine, which is significantly cheaper to acquire, is Bitmain S9 SE [71]. The hash rate of this machine is 16 TH/s; its power consumption is 1.280 kWh and unit price \$350. The number of S17 Pro rigs required to have the majority of mining power in the network is: $\lceil \frac{100,000,000}{53} \rceil = 1,886,793$. With total cost of 1,886,793 · 2128 = \$4B and power consumption of 1,886,793 · 2.094 = 94,822,669 kWh which with electricity price of 0.037 $\frac{\$}{kWh}$ would cost \$3.5M a day. Similarly, for S9 SE, the equipment cost would be \$2.2B, and the daily electricity cost would be \$7.1M.

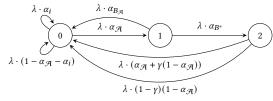
D BDOS WITH SPV - MARKOV CHAINS

In this section we describe the CTMC (Continuous Time Markov Chains) for a rational miner with the action space $\{S_{\text{stop}}, S_{\text{mine}}, S_{\text{SPV}}\}$.

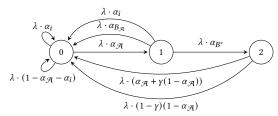
This Markov Chains (fig. 10) for S_{stop} and S_{mine} are similar to the ones shown in fig. 2. Although, the chains described in fig. 10 have an extra edge from state 1 to state 0 with rate $\lambda \cdot \alpha_{B,q}$ that



(a) S_{\min} : \mathcal{P}_i mines on B^* in state 1



(b) S_{stop} : \mathcal{P}_i stops mining in state 1



(c) S_{SPV} : \mathcal{P}_i mines on $B_{\mathcal{A}}$ in state 1

Figure 10: Markov chain.

corresponds to the portion of rational miners (excluding \mathcal{P}_i) that keep mining during the attack. In fig. 10c there is an additional edge from state 1 to state 0 with rate $\lambda \cdot \alpha_i$, as now \mathcal{P}_i also mines during the attack.

E PSEUDO-CODE FOR MODEL

In this section, we describe the pseudo-code for the scheduler (algorithm 1), adversary (algorithm 2) and the rational miner (algorithm 3) that were described in §3.1. Note that for simplicity of the pseudocode we denote the mining power of rational miner \mathcal{P}_i as $\alpha_{\mathcal{P}_i}$ as well, so $\alpha_{\mathcal{P}_i} := \alpha_i$.

Algorithm 1 Scheduler

```
1: r ← 0
 2:
     loop // The scheduler runs in an infinite loop.
 3:
 4:
        r \leftarrow r + 1
 5:
        active \leftarrow \emptyset
 6:
        for p \in \{\mathcal{A}, \mathcal{P}_1, \dots, \mathcal{P}_n\} do
  7:
           if p.Mine_This_Round = true then
              template_p \leftarrow p.Get\_Block\_Template
 8:
              active \leftarrow active \cup p
 9:
10:
           end if
        end for
11:
12:
        T \leftarrow \mathsf{Exp\_Distribution}(\lambda \cdot \textstyle\sum_{\mathsf{p} \in \mathsf{active}} \alpha_\mathsf{p})
13:
        sleep(T) // Simulate block time.
        w ← Sample by weight of hashrate from active
14:
        B_r \leftarrow \text{Generate\_Valid\_Block}(r, \text{template}_w)
15:
16:
        if w = \mathcal{A} then
17:
           \mathsf{publish} \leftarrow \mathcal{A}.\mathsf{Find\_New\_Block}(B_r)
18:
           if publish = "header" then
19:
              H = \text{Get\_Header}(B_r)
20:
21:
              for p \in \{P_1, \dots, P_n\} do p.Add_Header(H)
           else if publish = "full block" then
22:
23:
              for p \in \{\mathcal{A}, \mathcal{P}_1, \dots, \mathcal{P}_n\} do p.Add_Block(B_r)
24:
25:
         else
           competing \leftarrow \mathcal{A}.\mathsf{Get}\_\mathsf{Competing}\_\mathsf{Blocks}(B_r)
26:
27:
           if competing.empty = true then
28:
              for p \in \{\mathcal{A}, \mathcal{P}_1, \dots, \mathcal{P}_n\} do p.Add_Block(B_r)
29:
30:
              Send_Blocks(w, [B_r] + competing)
              Send_Blocks(\mathcal{A}, competing + [B_r])
31:
              for p \in \{\mathcal{P}_1, \ldots, \mathcal{P}_n\} \setminus \{w\} do
32:
                 with probability \frac{\gamma(1-\alpha_{\mathcal{A}})}{1-\alpha_{\mathcal{A}}-\alpha_{\mathsf{w}}}:
33:
                     Send_Blocks(p, competing + [B_r])
34:
                 with probability 1 - \frac{\gamma(1-\alpha_{\mathcal{A}})}{1-\alpha_{\mathcal{A}}-\alpha_{\mathsf{w}}}:
35:
                     Send_Blocks(p, [B_r] + competing)
36:
              end for
37:
38:
           end if
        end if
39:
40: end loop
41:
42: function Send_Blocks(p, blocks)
        for B \in \mathsf{blocks} \ \mathsf{do} \ \mathsf{p.Add\_Block}(B)
44: end function
```

Algorithm 2 Adversary A

39: end function

```
1: L_{\mathcal{A}} \leftarrow \{B_0\}, O_{\mathcal{A}}[B_0] \leftarrow 0, r \leftarrow 0
 2: B_{\text{withheld}} \leftarrow \bot, B_{\text{extend}} \leftarrow B_0
 4: function Mine_This_Round
 5:
      r \leftarrow r + 1
       if B_{\text{withheld}} = \bot then
 6:
 7:
          return true
 8:
        else
 9:
          return false
       end if
10:
11: end function
12:
13: function Get_Block_Template
       return Generate_Template(\mathcal{A}, Get_Header(B_{\text{extend}}))
15: end function
16:
17: function Find_New_Block(B)
18:
        B_{\mathsf{withheld}} \leftarrow B
       return "header"
19:
20: end function
21:
22: function Get_Competing_Blocks(B)
       \mathbf{if} \; \mathsf{Get\_Height}(B) = \mathsf{Get\_Height}(B_{\mathsf{withheld}}) \; \mathbf{then}
23:
24:
           B_{\mathsf{withheld}} \leftarrow \bot
          return [B_{withheld}]
25:
26:
          return []
27:
        end if
28:
29: end function
30:
31: function Add_Block(B)
       L_{\mathcal{A}} \leftarrow L_{\mathcal{A}} \cup \{B\}, O_{\mathcal{A}}[B] \leftarrow |L_{\mathcal{A}}|
32:
33:
       if B = B_{\text{withheld}} then
          B_{\mathsf{withheld}} \leftarrow \bot
34:
35:
       \textbf{if} \; \mathsf{Get\_Height}(B) > \mathsf{Get\_Height}(B_{\mathsf{extend}}) \; \textbf{then}
36:
          B_{\mathsf{extend}} \leftarrow B
37:
       end if
38:
```

Algorithm 3 Rational Player \mathcal{P}_i

```
1: L_i \leftarrow \{B_0\}, O_i[B_0] \leftarrow 0, r \leftarrow 0
 2: B_{\text{header}} \leftarrow \bot, B_{\text{extend}} \leftarrow B_0
 3: M \leftarrow \text{Get\_Best\_Strategy}(BDoS, \alpha_i, \omega_i^b)
 5: function Mine_This_Round
        r \leftarrow r + 1
 6:
        if M[L_i][O_i] = \text{stop then}
 7:
 8:
           return false
 9:
        else
           return true
10:
        end if
11:
12: end function
13:
14: function Get_Block_Template
        if M[L_i][O_i] = mineSPV then
15:
           \mathbf{return} \; \mathsf{Generate\_Template}(\mathcal{P}_i, \mathsf{Get\_Header}(B_{\mathsf{header}}))
16:
17:
        else if M[L_i][O_i] = mine then
           \mathbf{return} \; \mathsf{Generate\_Template}(\mathcal{P}_i, \mathsf{Get\_Header}(B_{\mathsf{extend}}))
18:
19:
        end if
20: end function
21:
22: function Add_Block(B)
        L_{\mathcal{A}} \leftarrow L_{\mathcal{A}} \bigcup \{B\}, O_{\mathcal{A}}[B] \leftarrow |L_{\mathcal{A}}|
        if Get_Header(B) = Get_Header(B_{header}) then
24:
25:
           B_{\text{header}} \leftarrow \bot
        \textbf{if} \ \mathsf{Get\_Height}(B) > \mathsf{Get\_Height}(B_{\mathsf{extend}}) \ \textbf{then}
27:
28:
           B_{\mathsf{extend}} \leftarrow B
        end if
29:
30: end function
31:
32: function Add_Header(H)
33:
      B_{\mathsf{header}} \leftarrow (H, \perp)
34: end function
```

REFERENCES

- Moe Adham. 2019. What Will The Next 'Halving' Mean For The Price Of Bitcoin? (May 2019). https://www.forbes.com/sites/forbesfinancecouncil/2019/05/10/what-will-the-next-halving-mean-for-the-price-of-bitcoin/
- Maria Apostolaki, Gian Marti, Jan Müller, and Laurent Vanbever. 2018. SABRE: Protecting Bitcoin against Routing Attacks. arXiv preprint arXiv:1808.06254 (2018).
- [3] Maria Apostolaki, Aviv Zohar, and Laurent Vanbever. 2017. Hijacking bitcoin: Routing attacks on cryptocurrencies. In 2017 IEEE Symposium on Security and Privacy (SP). IEEE, 375–392.
- [4] Robert J Aumann. 1976. Agreeing to disagree. The annals of statistics (1976), 1236–1239.
- [5] Christian Badertscher, Peter Gaži, Aggelos Kiayias, Alexander Russell, and Vassilis Zikas. 2018. Ouroboros genesis: Composable proof-of-stake blockchains with dynamic availability. In Proceedings of the 2018 ACM SIGSAC Conference on Computer and Communications Security. ACM, 913–930.
- [6] Qianlan Bai, Xinyan Zhou, Xing Wang, Yuedong Xu, Xin Wang, and Qingsheng Kong. 2018. A Deep Dive into Blockchain Selfish Mining. arXiv preprint arXiv:1811.08263 (2018).
- [7] Christopher Bendiksen, Samuel Gibbons, and E Lim. 2019. The Bitcoin Mining Network-Trends, Marginal Creation Cost, Electricity Consumption & Sources. CoinShares Research (2019).
- [8] Bitmain. 2019. (2019). https://shop.bitmain.com/product/detail?pid = 000201910231616554895rHmxLOT06C2
- [9] Joseph Bonneau. 2018. Hostile blockchain takeovers (short paper). In International Conference on Financial Cryptography and Data Security. Springer, 92–100.
- [10] Joseph Bonneau, Edward W Felten, Steven Goldfeder, Joshua A Kroll, and Arvind Narayanan. 2016. Why buy when you can rent? bribery attacks on bitcoin consensus. (2016).
- [11] Danny Bradbury. 2013. Feathercoin hit by massive attack. (Jun 2013). https://www.coindesk.com/feathercoin-hit-by-massive-attack
- [12] BTC.com. 2019. Pool Distribution. (Otc 2019). https://btc.com/stats/pool?pool_mode=week
- [13] Vitalik Buterin. 2018. Discouragement Attacks. (2018). https://github.com/ ethereum/research/blob/master/papers/discouragement/discouragement.pdf
- ethereum/research/blob/master/papers/discouragement/discouragement.pdf
 [14] Vitalik Buterin et al. 2014. A next-generation smart contract and decentralized application platform. white paper 3 (2014), 37.
- [15] Miles Carlsten, Harry Kalodner, S Matthew Weinberg, and Arvind Narayanan. 2016. On the instability of bitcoin without the block reward. In Proceedings of the 2016 ACM SIGSAC Conference on Computer and Communications Security. ACM, 154-167.
- [16] Miguel Castro, Peter Druschel, Ayalvadi Ganesh, Antony Rowstron, and Dan S Wallach. 2002. Secure routing for structured peer-to-peer overlay networks. ACM SIGOPS Operating Systems Review 36, SI (2002), 299–314.
- [17] Ethan Cecchetti, Ian Miers, and Ari Juels. 2018. PIEs: Public Incompressible Encodings for Decentralized Storage. IACR Cryptology ePrint Archive 2018 (2018), 684
- [18] Lin Chen, Lei Xu, Nolan Shah, Zhimin Gao, Yang Lu, and Weidong Shi. 2017. On security analysis of proof-of-elapsed-time (poet). In *International Symposium on Stabilization, Safety, and Security of Distributed Systems*. Springer, 282–297.
- [19] CoinDesk. 2019. Bitcoin Mining Power Sees Short-Term Drop as Rainy Season Ends in China. (Nov. 2019). https://www.coindesk.com/ bitcoin-mining-power-sees-short-term-fallback-as-rainy-season-ends-in-china
- [20] CoinMarketCap. 2019. Cryptocurrency Market Capitalizations. (2019). https://coinmarketcap.com/
- [21] Philip Daian, Steven Goldfeder, Tyler Kell, Yunqi Li, Xueyuan Zhao, Iddo Bentov, Lorenz Breidenbach, and Ari Juels. 2019. Flash Boys 2.0: Frontrunning, Transaction Reordering, and Consensus Instability in Decentralized Exchanges. arXiv preprint arXiv:1904.05234 (2019).
- [22] Phil Daian, Rafael Pass, and Elaine Shi. 2019. Snow White: Robustly Reconfigurable Consensus and Applications to Provably Secure Proof of Stake. In International Conference on Financial Cryptography and Data Security. Springer, 23–41.
- [23] Coin Dance. 2020. Daily Bitcoin Cash Profitability Against Bitcoin. (Jan 2020). https://cash.coin.dance/blocks/profitability
- [24] Bernardo David, Peter Gaži, Aggelos Kiayias, and Alexander Russell. 2018. Ouroboros praos: An adaptively-secure, semi-synchronous proof-of-stake blockchain. In Annual International Conference on the Theory and Applications of Cryptographic Techniques. Springer, 66–98.
- [25] Allen Day and Colin Bookman. 2018. Bitcoin in BigQuery: blockchain analytics on public data. (2018). https://cloud.google.com/blog/products/gcp/bitcoin-in-bigquery-blockchain-analytics-on-public-data
- [26] Matthew De Silva. 2019. Ethereum Classic is under attack. (Jan 2019). https://qz.com/1516994/ethereum-classic-got-hit-by-a-51-attack/
- [27] Department of Homeland Security. 2018. Understanding Denial-of-Service Attacks. (Jun 2018). https://www.us-cert.gov/ncas/tips/ST04-015

- [28] John R Douceur. 2002. The sybil attack. In International workshop on peer-to-peer systems. Springer, 251–260.
- [29] Cynthia Dwork and Moni Naor. 1992. Pricing via processing or combatting junk mail. In Annual International Cryptology Conference. Springer, 139–147.
- [30] Aryaz Eghbali and Roger Wattenhofer. 2019. 12 Angry Miners. In Data Privacy Management, Cryptocurrencies and Blockchain Technology. Springer, 391–398.
- [31] Shayan Eskandari, Seyedehmahsa Moosavi, and Jeremy Clark. 2019. SoK: Transparent Dishonesty: front-running attacks on Blockchain. (2019).
- [32] Ittay Eyal. 2015. The miner's dilemma. In 2015 IEEE Symposium on Security and Privacy. IEEE, 89–103.
- [33] Ittay Eyal and Emin Gün Sirer. 2018. Majority is not enough: Bitcoin mining is vulnerable. Commun. ACM 61, 7 (2018), 95–102.
- [34] Drew Fudenberg and Jean Tirole. 1991. Game theory, 1991. Cambridge, Massachusetts 393, 12 (1991), 80.
- [35] Juan Garay, Aggelos Kiayias, and Nikos Leonardos. 2015. The bitcoin backbone protocol: Analysis and applications. In Annual International Conference on the Theory and Applications of Cryptographic Techniques. Springer, 281–310.
- [36] Arthur Gervais, Ghassan O Karame, Karl Wüst, Vasileios Glykantzis, Hubert Ritzdorf, and Srdjan Capkun. 2016. On the security and performance of proof of work blockchains. In Proceedings of the 2016 ACM SIGSAC conference on computer and communications security. ACM, 3–16.
- [37] Yossi Gilad, Rotem Hemo, Silvio Micali, Georgios Vlachos, and Nickolai Zeldovich. 2017. Algorand: Scaling byzantine agreements for cryptocurrencies. In Proceedings of the 26th Symposium on Operating Systems Principles. ACM, 51–68.
- [38] Guy Goren and Alexander Spiegelman. 2019. Mind the Mining. arXiv preprint arXiv:1902.03899 (2019).
- [39] Adam S Hayes. 2017. Cryptocurrency value formation: An empirical study leading to a cost of production model for valuing bitcoin. *Telematics and Informatics* 34, 7 (2017), 1308–1321.
- [40] Ethan Heilman, Alison Kendler, Aviv Zohar, and Sharon Goldberg. 2015. Eclipse attacks on bitcoin's peer-to-peer network. In 24th {USENIX} Security Symposium ({USENIX} Security 15). 129–144.
- [41] Alyssa Hertig. 2019. Bitcoin Cash Miners Undo Attacker's Transactions With '51% Attack'. (May 2019). https://www.coindesk.com/bitcoin-cash-miners-undo-attackers-transactions-with-51-attack
- 42] MINING POOL HUB. 2019. MINING POOL HUB. (2019). https://miningpoolhub.
- [43] Gur Huberman, Jacob Leshno, and Ciamac C Moallemi. 2019. An economic analysis of the Bitcoin payment system. *Columbia Business School Research Paper* 17-92 (2019).
- [44] Investing.com. 2019. BTC USD Kraken Historical Data Investing.com. (Oct 2019). https://www.investing.com/crypto/bitcoin/btc-usd-historical-data
- [45] Markus Jakobsson and Ari Juels. 1999. Proofs of work and bread pudding protocols. In Secure Information Networks. Springer, 258–272.
- [46] Benjamin Johnson, Aron Laszka, Jens Grossklags, Marie Vasek, and Tyler Moore. 2014. Game-theoretic analysis of DDoS attacks against Bitcoin mining pools. In International Conference on Financial Cryptography and Data Security. Springer, 72–86.
- [47] Aljosha Judmayer, Nicholas Stifter, Philipp Schindler, and Edgar Weippl. 2018. Pitchforks in Cryptocurrencies: Enforcing rule changes through offensive forking-and. (2018).
- [48] Aljosha Judmayer, Nicholas Stifter, Alexei Zamyatin, Itay Tsabary, Ittay Eyal, Peter Gaži, Sarah Meiklejohn, and Edgar Weippl. 2019. Pay-To-Win: Incentive Attacks on Proof-of-Work Cryptocurrencies. (2019).
- [49] Dimitris Karakostas, Aggelos Kiayias, Christos Nasikas, and Dionysis Zindros. 2019. Cryptocurrency egalitarianism: a quantitative approach. arXiv preprint arXiv:1907.02434 (2019).
- [50] Aggelos Kiayias, Elias Koutsoupias, Maria Kyropoulou, and Yiannis Tselekounis. 2016. Blockchain mining games. In Proceedings of the 2016 ACM Conference on Economics and Computation. ACM, 365–382.
- [51] Aggelos Kiayias, Alexander Russell, Bernardo David, and Roman Oliynykov. 2017. Ouroboros: A provably secure proof-of-stake blockchain protocol. In Annual International Cryptology Conference. Springer, 357–388.
- [52] Joshua A Kroll, Ian C Davey, and Edward W Felten. 2013. The economics of Bitcoin mining, or Bitcoin in the presence of adversaries. In *Proceedings of WEIS*, Vol. 2013. 11
- [53] Yujin Kwon, Dohyun Kim, Yunmok Son, Eugene Vasserman, and Yongdae Kim. 2017. Be selfish and avoid dilemmas: Fork after withholding (faw) attacks on bitcoin. In Proceedings of the 2017 ACM SIGSAC Conference on Computer and Communications Security. ACM, 195–209.
- [54] Yujin Kwon, Hyoungshick Kim, Jinwoo Shin, and Yongdae Kim. 2019. Bitcoin vs. Bitcoin Cash: Coexistence or Downfall of Bitcoin Cash? arXiv preprint arXiv:1902.11064 (2019).
- [55] Aron Laszka, Benjamin Johnson, and Jens Grossklags. 2015. When bitcoin mining pools run dry. In *International Conference on Financial Cryptography and Data* Security. Springer, 63–77.

- [56] Xiaoqi Li, Peng Jiang, Ting Chen, Xiapu Luo, and Qiaoyan Wen. 2017. A survey on the security of blockchain systems. Future Generation Computer Systems (2017)
- [57] Kevin Liao and Jonathan Katz. 2017. Incentivizing blockchain forks via whale transactions. In *International Conference on Financial Cryptography and Data Security*. Springer, 264–279.
- [58] Loi Luu, Ratul Saha, Inian Parameshwaran, Prateek Saxena, and Aquinas Hobor. 2015. On power splitting games in distributed computation: The case of bitcoin pooled mining. In 2015 IEEE 28th Computer Security Foundations Symposium. IEEE, 397–411.
- [59] Yuval Marcus, Ethan Heilman, and Sharon Goldberg. 2018. Low-Resource Eclipse Attacks on Ethereum's Peer-to-Peer Network. IACR Cryptology ePrint Archive 2018 (2018), 236.
- [60] Francisco J. Marmolejo-Cossío, Eric Brigham, Benjamin Sela, and Jonathan Katz. 2019. Competing (Semi-)Selfish Miners in Bitcoin. In Proceedings of the 1st ACM Conference on Advances in Financial Technologies (AFT '19). ACM, New York, NY, USA, 89–109. https://doi.org/10.1145/3318041.3355471
- [61] Patrick McCorry, Alexander Hicks, and Sarah Meiklejohn. 2018. Smart contracts for bribing miners. In *International Conference on Financial Cryptography and Data Security*. Springer, 3–18.
- [62] Dmitry Meshkov, Alexander Chepurnoy, and Marc Jansen. 2017. Short paper: Revisiting difficulty control for blockchain systems. In *Data Privacy Management*, Cryptocurrencies and Blockchain Technology. Springer, 429–436.
- [63] Andrew Miller. 2013. Feather-forks: enforcing a blacklist with sub-50% hash power. (Oct 2013). https://bitcointalk.org/index.php?topic=312668.0
- [64] Andrew Miller and Joseph J LaViola Jr. 2014. Anonymous byzantine consensus from moderately-hard puzzles: A model for bitcoin. Available on line: http://nakamotoinstitute.org/research/anonymous-byzantine-consensus (2014).
- [65] ASIC miner value. 2019. Miners Profitability. (2019). https://www.asicminervalue.com/
- [66] Bernhard Mueller. 2018. DoS with Block Gas Limit. (Oct 2018). https://github.com/ethereum/wiki/wiki/Safety#dos-with-block-gas-limit
- [67] Bernhard Mueller. 2018. DoS with (Unexpected) Throw. (Oct 2018). https://github.com/ethereum/wiki/wiki/Safety#dos-with-unexpected-throw
- [68] Phil Muncaster. 2017. World's Largest Bitcoin Exchange Bitfinex Crippled by DDoS. (Jun 2017). https://www.infosecurity-magazine.com/news/ worlds-largest-bitcoin-exchange/
- [69] Satoshi Nakamoto et al. 2008. Bitcoin: A peer-to-peer electronic cash system. (2008).
- [70] Kartik Nayak, Srijan Kumar, Andrew Miller, and Elaine Shi. 2016. Stubborn mining: Generalizing selfish mining and combining with an eclipse attack. In 2016 IEEE European Symposium on Security and Privacy (EuroS&P). IEEE, 305–320.
- [71] Bitcoin News. 2019. Bitmain Launches Low-Cost Special Edition Antminer S9. (June 2019). https://news.bitcoin.com/bitmain-launches-low-cost-special-edition-antminer-s9/
- [72] Jianyu Niu and Chen Feng. 2019. Selfish Mining in Ethereum. arXiv preprint arXiv:1901.04620 (2019).
- [73] Rafael Pass, Lior Seeman, and Abhi Shelat. 2017. Analysis of the blockchain protocol in asynchronous networks. In Annual International Conference on the Theory and Applications of Cryptographic Techniques. Springer, 643–673.
- [74] A Hash Pool. 2017. A Hash Pool. (2017). https://www.ahashpool.com
- [75] Bitcoin Project. 2015. Some Miners Generating Invalid Blocks. (2015). https://bitcoin.org/en/alert/2015-07-04-spy-mining
- [76] Fabian Ritz and Alf Zugenmaier. 2018. The impact of uncle rewards on selfish mining in ethereum. In 2018 IEEE European Symposium on Security and Privacy Workshops (EuroS&PW). IEEE, 50–57.
- [77] Meni Rosenfeld. 2011. Analysis of bitcoin pooled mining reward systems. arXiv preprint arXiv:1112.4980 (2011).
- [78] Ayelet Sapirshtein, Yonatan Sompolinsky, and Aviv Zohar. 2016. Optimal selfish mining strategies in bitcoin. In *International Conference on Financial Cryptogra*phy and Data Security. Springer, 515–532.
- [79] SECBIT. 2018. How the winner got Fomo3D prize A Detailed Explanation. (Aug 2018). https://medium.com/coinmonks/ how-the-winner-got-fomo3d-prize-a-detailed-explanation-b30a69b7813f
- [80] SFOX. 2019. Bitcoin Cash vs. Bitcoin SV: Six Months after the Hash War. (June 2019). https://blog.sfox.com/bitcoin-cash-vs-bitcoin-sv-six-months-after-the-hash-war-e6d92a03b891
- [81] Atul Singh et al. 2006. Eclipse attacks on overlay networks: Threats and defenses. In In IEEE INFOCOM. Citeseer.
- [82] Emil Sit and Robert Morris. 2002. Security considerations for peer-to-peer distributed hash tables. In *International Workshop on Peer-to-Peer Systems*. Springer, 261–269.
- [83] Jakub Sliwinski and Roger Wattenhofer. Blockchains Cannot Rely on Honesty. In The 19th International Conference on Autonomous Agents and Multiagent Systems (AAMAS 2020)
- [84] SmartMine. 2019. SmartMine An intelligent way to mine cryptocurrency. (2019). https://www.smartmine.org/

- [85] Joel Sobel and Ichiro Takahashi. 1983. A multistage model of bargaining. The Review of Economic Studies 50, 3 (1983), 411–426.
- [86] Yonatan Sompolinsky and Aviv Zohar. 2015. Secure high-rate transaction processing in bitcoin. In *International Conference on Financial Cryptography and Data Security*. Springer, 507–527.
- [87] Yonatan Sompolinsky and Aviv Zohar. 2018. Bitcoin's underlying incentives. Commun. ACM 61, 3 (2018), 46–53.
- [88] Alexander Spiegelman, Idit Keidar, and Moshe Tennenholtz. 2018. Game of coins. arXiv preprint arXiv:1805.08979 (2018).
- [89] JOE STEWART. 2014. BGP Hijacking for Cryptocurrency Profit. (Aug 2014). https://www.secureworks.com/research/bgp-hijacking-for-cryptocurrency-profit
- [90] Jason Teutsch, Sanjay Jain, and Prateek Saxena. 2016. When cryptocurrencies mine their own business. In *International Conference on Financial Cryptography* and Data Security. Springer, 499–514.
- [91] Itay Tsabary and Ittay Eyal. 2018. The gap game. In Proceedings of the 2018 ACM SIGSAC Conference on Computer and Communications Security. ACM, 713–728.
- [92] Itay Tsabary, Alexander Spiegelman, and Ittay Eyal. 2019. Just Enough Security: Reducing Proof-of-Work Ecological Footprint. arXiv preprint arXiv:1911.04124 (2019).
- [93] Marie Vasek, Micah Thornton, and Tyler Moore. 2014. Empirical analysis of denial-of-service attacks in the Bitcoin ecosystem. In *International conference on financial cryptography and data security*. Springer, 57–71.
- [94] Bitcoin Wiki. 2017. Difficulty. (2017). https://en.bitcoin.it/wiki/Difficulty
- [95] Shawn Wilkinson, Tome Boshevski, Josh Brandoff, and Vitalik Buterin. 2014. Storj a peer-to-peer cloud storage network. (2014).
- [96] Shawn Wilkinson, Jim Lowry, and Tome Boshevski. 2014. Metadisk a blockchainbased decentralized file storage application. Tech. Rep. (2014).
- [97] Fredrik Winzer, Benjamin Herd, and Sebastian Faust. 2019. Temporary censorship attacks in the presence of rational miners. In 2019 IEEE European Symposium on Security and Privacy Workshops (EuroS&PW). IEEE, 357–366.
- [98] Gavin Wood et al. 2014. Ethereum: A secure decentralised generalised transaction ledger. Ethereum project yellow paper 151, 2014 (2014), 1–32.
- [99] Fan Zhang, Ittay Éyal, Robert Escriva, Ari Juels, and Robbert Van Renesse. 2017. {REM}: Resource-Efficient Mining for Blockchains. In 26th {USENIX} Security Symposium ({USENIX} Security 17). 1427–1444.
- [100] Wolfie Zhao. 2019. Bitcoin Miners Halt Operations as Rainstorm Triggers Mudslides in China. (Aug 2019). https://www.coindesk.com/bitcoin-miners-halt-operations-as-rainstorm-triggers-fatal-mudslide-in-china