Technische Universität München

Fakultät für Informatik

Master's Thesis in Information Systems

Bitcoin-like Blockchain Simulation System

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Bitcoin-ähnliches Blockchain Simulationssystem

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I confirm that this master's thesis is my own work and I have documented all sources and material used.

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(Fabian Schüssler)

Abstract

Despite the recent $600 billion crash and the high volatility of the whole cryptocurrency market, interest in development and research on blockchains is growing. Reaching the scalability of more traditional payment processors like PayPal or VISA is still a hard problem for decentralized peer-to-peer networks like bitcoin. Heated debates about scalability solutions led to the creation of hardforks like bitcoin cash. For users to better understand the impact of changes to the bitcoin protocol on scalability and security and to find optimal solutions, we propose Bitcoin-like Blockchain Simulation System (BBSS). BBSS is a configurable bitcoin-like blockchain simulator. Its focus is on the visualisation of the simulation results to make every blockchain detail easy to understand. With block size limits, transaction fees, Segregated Witness and other features the Scalability Problem can be analysed. The optional attacks double-spending and transaction spam allow examination of security properties. The design and architecture allow large-scale simulations in a comparatively short amount of time.

Inhaltsangabe

Trotz des kürzlichen 600 Milliarden US-Dollar Kursabsturz und der hohen Volatilität des gesamten Kryptowährungsmarkt wächst das Interesse in Entwicklung und Forschung von Blockketten. Die Skalierbarkeit von eher traditionellen Zahlungsabwicklern wie PayPal oder VISA zu erreichen ist immer noch ein schwieriges Problem für dezentralisierte Rechner-zu-Rechner Netzwerke wie Bitcoin. Lebhafte Debatten über Verbesserungen der Skalierbarkeit haben zu Hardforks wie Bitcoin Cash geführt. Damit Benutzer die Auswirkungen von Veränderungen am Bitcoin Protokoll besser verstehen können und um optimale Lösungen zu finden, schlagen wir das Bitcoin-ähnliche Blockchain Simulationssystem vor (BBSS). BBSS ist ein konfigurierbarer Bitcoin-ähnlicher Blockchain Simulator. Der Fokus liegt auf die Visualisierung der Simulationsergebnisse, um jedes Detail der Blockchain einfach verständlich zu machen. Mit Beschränkungen der Blockgröße, Transaktionsgebühren, SegWit und anderen Erweiterungen kann das Problem der Skalierbarkeit analysiert werden. Die optionalen Angriffe wie doppelte Ausgabe und Transaktionsmüll erlaubt die Untersuchung von Sicherheitseigenschaften. Das Design und die Architektur erlauben Simulationen mit vielen Netzwerkteilnehmern in einer im Vergleich mit anderen Lösungen kurzen Zeit.

Acknowledgment

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Abbreviations

ASIC	application-specific integrated circuit.
AWS	Amazon Web Services, a Cloud-Computing-Provider.
BBSS	Bitcoin-like Blockchain Simulation System.
BTC	unit of the cryptocurrency bitcoin.
non-SegWit	legacy/before Segregated Witness.
SegWit	Segregated Witness.
tpb	transactions per block.
tps	transactions per second.
VIBES	Visualizations of Interactive, Blockchain, Extended Simulations.

Chapter 1

Introduction

There are papers describing blockchain technology as a disruptive innovation [8]. The *Harvard Business Review* argues blockchain technology is not a disruptive, but a foundational technology [9]. Whether blockchain is a disruptive technology or not, it is largely agreed upon that blockchain technology has immense potential and can revolutionize business and redefine companies and economies. But there are still lots of barriers. Currently and in the last years, blockchain technologies such as Bitcoin [10], Ethereum [11], IOTA [12] or Hyperledger fabric [13] are a very hot topic. According to the Gartner Hype Cycle Blockchain technology was undergoing the peak of inflated expectation in 2017 [14]. Price and market capitalization changes of cryptocurrencies are widely covered by the media. This shows Blockchain technologies are believed to have a great potential and a big variety of new use cases.

Blockchain technology enables decentralized consensus and can be used for record keeping. Bitcoin is the first digital currency to solve the double-spending problem without the need of a trusted authority. One of the main problems of Bitcoin or in general of blockchains is the low maximum amount of possible processed transactions per second. Additionally, the Bitcoin community disagrees about how to solve this scalability problem. It already split into multiple communities with different approaches and Bitcoin forks.

VIBES (Visualizations of Interactive, Blockchain, Extended Simulations) is a blockchain simulator, which allows fast, scalable and configurable network simulations on a single computer without any additional resources. It was developed in a master thesis by Lyubomir Stoykov [15] and is the foundation of this master thesis.

1.1 Motivation

The implications of blockchain protocol changes on key figures like scalability or security are difficult to predict. The reasons are complex relationships between the different parameter of the blockchain network, which can change the way nodes interact with each other or how blocks are handled. This may lead to getting the impression, the blockchain network is a black box. A configurable simulator can help to answer questions about scalability or security.

The goal of this master thesis is to improve VIBES to make more realistic bitcoin-like blockchain simulations possible. In the future, BBSS could be used by developers or heavy blockchain users to simulate changes to different blockchains, so it can help the bitcoin community to agree on bitcoin improvement proposals (BIP).

1.2 Problem Statement

Ideally, the users of VIBES could specify their Bitcoin-like Blockchain Simulation. VIBES then presents the results of the simulation in a very detailed and still easily understandable way.

In reality, VIBES does not yet support Bitcoin-like Blockchain Simulations. The Generic Simulations lack defining traits of Bitcoin like maximum block size, SegWit, transaction incentives or attack scenarios. Also, other important metrics are not yet displayed.

To achieve our goals VIBES needs to be changed in a way to allow multiple strategies in the front- and backend, while still having good maintainability of the code. A Bitcoin-like Blockchain Simulation needs to be implemented next to the existing Generic Simulation.

These extensions can improve the quality of the simulations and the use cases of VIBES. For example, the implications of Segwit2x could be analysed. Maybe these extensions could also make it possible to realistically simulate the current bitcoin blockchain with an as similar as possible configuration.

The focus of this master thesis is to implement a Bitcoin-like Blockchain Simulation with all important features to make the simulations as realistic as possible, to make it possible to simulate attacks like double-spending and to visualise all important outputs.

The approach is evaluated by six key figures: correctness, speed, scalability, flexibility, extensibility and powerful visuals.

1.3 Approach

The presented goals should be achieved while maintaining and extending the design and architecture of the existing VIBES framework, which are described in Chapter 3. The Bitcoin-like Blockchain Simulation fast-forwards the whole network ahead of time and skips heavy computations such as solving a block. The actor model is used to achieve simulation at the event level. The Coordinator or also called MasterActor takes the role of an application-level scheduler to make fast-forwarding possible. The Coordinator and other actors need to be adjusted for the Bitcoin-like Blockchain Simulation and attack scenarios. For the visual side, the pattern of Atomic Design [6] is maintained to add new visualisations to a high-quality and composable user interface.

1.4 Contribution

Before BBSS, there was no multi-purpose bitcoin simulator with good visualisations. BBSS makes bitcoin-like blockchains easy to understand and allows the optimization of bitcoin-like blockchains in scalability and security. Different scalability related changes like block size limit, SegWit or transaction incentives can be analysed. BBSS also allows the simulation of attacks like double-spending and transaction spam. The changes were implemented in a way to enable good maintainability to adjust the simulation to future changes of the bitcoin protocol or to add new attacks.

1.5 Organization

The structure of the thesis begins with this chapter as an introduction. The second chapter describes the background and the theoretical foundations which are necessary for the understanding of this thesis. The Chapter 3: Related Work presents related research papers and the architecture and design of VIBES on which this thesis builds on. And it also shows other related works and puts this work into perspective. Chapter 4 describes the approach and implementation details are explained. Developers or users of the simulator can use Chapter 4 as documentation to explain questions about the behaviour of the simulations. Chapter 5: Evaluation uses empirical and theoretical analysis to test the implementation according to our predefined criteria. In the last chapter, the status, conclusions and, suggestions for future work are summarised.

Chapter 2

Background

This chapter will give an overview over the background concepts necessary to understand the following chapters. The nature of a simulator, the concepts of blockchain, bitcoin and various attacks are explained. Unnecessary information for this thesis may be omitted.

2.1 Simulation and Simulator

A simulation is the imitation of the operation of a real-world process or system [16]. This requires a model representing the key characteristics, behaviours, and functions of the selected system [17].

A simulator is a tool that can be manipulated to observe the outcomes of different assumptions or actions. It models the behaviour of a real system with minimum information loss, less used resources and ideally faster than real-time. Simulators are often used for the optimization of systems, studying and gaining insights into the functioning of simulation models.

2.2 Bitcoin

Bitcoin is a purely peer-to-peer electronic currency published in the paper *Bitcoin: A Peer-to-Peer Electronic Cash System* and as open-source software in 2009 by an unknown person or a group of people under the name Satoshi Nakamoto [10]. It allows online payments to be sent directly from one party to another without going through a financial institution or the need to trust a third party. Bitcoin not only refers to the currency but is also a currency unit and can be shortened to BTC. Bitcoin uses digital signatures and proof-of-work to prevent double-spending.

2.2.1 Double-Spending Problem

The double-spending problem refers to the problem of electronic cash to prevent some money being spent more than once. Malicious actors can try a double-spending attack to commit fraud. Merchants or users of bitcoin can reduce their double-spending fraud risk by increasing the number of confirmations which they are waiting for [18].

In Chapter 2.2.8 the double-spending attack is explained and in 4.11.2 the maximal safe transaction value is calculated.

2.2.2 Proof-of-work and Blockchain

Digital signatures and proof-of-work provide the main benefit of not requiring a trusted third party to prevent double-spending. The peer-to-peer network timestamps transactions by hashing them into an ongoing chain of hash-based proof-of-work, also called blockchain. This process is called mining. The blockchain can't be changed without redoing the proof-of-work. One single part of this ongoing chain of proof-of-work is called a block. The longest blockchain serves as a proof of the history of transactions and blocks generated by the largest pool of CPU power [10].

VIBES already follows partly bitcoin's protocol [15]. This thesis's goal is to implement more features of the protocol.

2.2.3 Block

In the bitcoin protocol, the blockchain is implemented as a directed tree consisting of blocks [15]. As shown in Figure 2.1 each block has certain data like the hash of the previous block, the block timestamp, the transaction root, and the nonce.

The hash references to the block that came immediately before it. It is necessary to establish a chain of blocks.

Each block contains a block timestamp. This timestamp serves as a source of variation for the block hash and makes it also more difficult for an adversary to manipulate the blockchain [19].

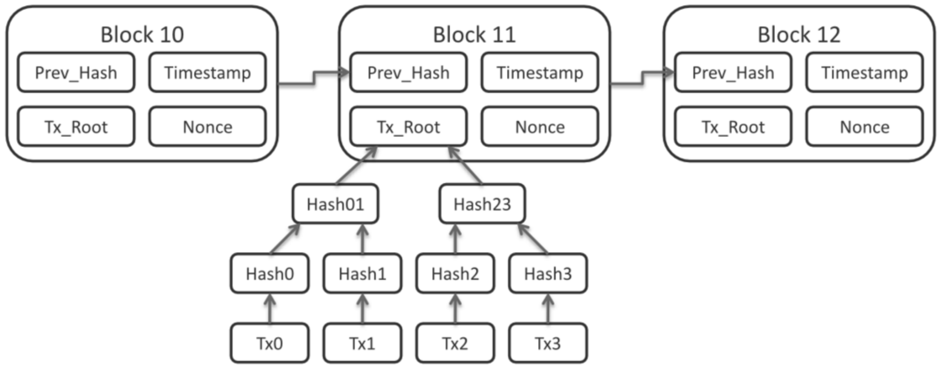


Figure 2.1: Bitcoin Block Data [1]

The transaction root is a Merkle root, it is the hash of all the hashes of all the transactions in the block. With this transaction root, it is possible to securely verify that a transaction has been accepted by the network and get the number of confirmations by downloading just the tiny block headers and Merkle tree, downloading the entire blockchain is unnecessary [2].

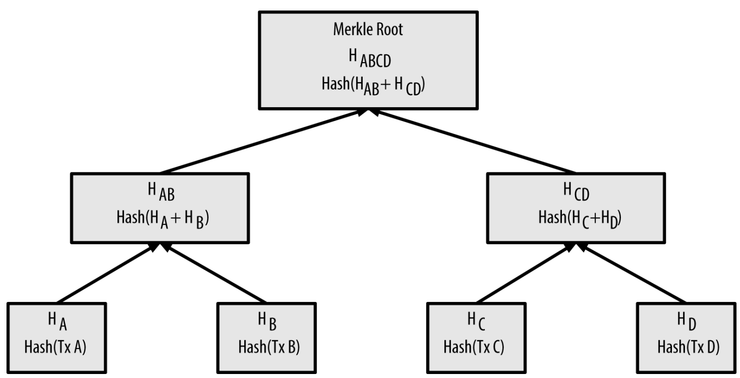


Figure 2.2: Merkle Tree [2]

The nonce is like the block hash a 32-bit field and this value is adjusted by miners to make the hash of the block less than or equal to the current target of the network [20]. This is often called a difficult-to-solve mathematical puzzle, the nonce is unique to each block.

Block Time and Difficulty

The current target of the network is related to the difficulty, the difficulty is a measure of how difficult it is to find a hash below a given target [21]. The difficulty adjustment is necessary for the average block time to be close to the target block time. Deviations of the average block time from the target block time have an effect on the stale block rate.

A block in the bitcoin protocol is supposed to be mined every ten minutes. This block time depends on the difficulty and the hash power. If the hash power is increasing, then the block time is lower than ten minutes because the difficulty adjustment is delayed. It is supposed to happen every 2016 blocks or approximately every 14 days.

Genesis Block

The first block of a blockchain is called genesis block [22]. Genesis is Ancient Greek and means creation or birth. Of course, the genesis block can't contain a hash reference to a previous block.

Orphan Block and Stale Block

An orphan block is a block which has no known parent in the currently-longest blockchain. This means a node received a block before its parent block, which could be part of the blockchain. An orphan block is not to be confused with a stale block. A stale block has a known parent but is no longer part of the longest chain [23]. Figure 2.3 visualizes these definitions.

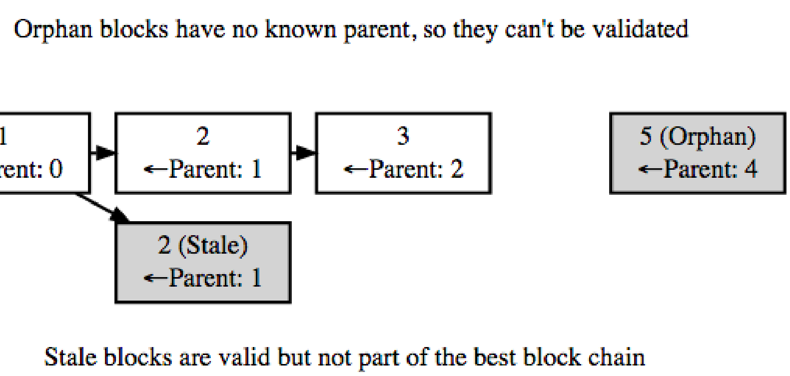


Figure 2.3: Stale and Orphan Blocks [3]

Block Size Limit

Blockchain protocols can have a block size limit which rejects all blocks with a higher block size [24]. This limits the number of transactions per block depending on the average transaction size.

In the original open-source software, the block size was limited to 32 MiB [25]. In 2010 Satoshi Nakamoto secretly introduced a block size limit of 1 MB. The reason for this secret introduction is assumed to be the protection of the bitcoin network from a DoS attack using blocks of unlimited size. Some nodes would not be willing to accept big blocks and then the chain would split [26]. Until the introduction of SegWit, the maximum size of a Bitcoin block was 1 MB.

2.2.4 Transaction

A transaction is a transfer of BTC that is broadcast to the network and committed into one block [27]. If too many transactions are sent, then the non-processed transactions are saved in the transaction pools of the miners. A sender of a transaction has to pay a transaction fee to the miner for him to include the transaction into a block. Otherwise there would be no financial incentive for the miner to include transactions, instead, it would only cost him computation and a miner that ignores transactions would be faster and earn more BTC. Transaction fees are the second financial incentive for miners next to block rewards. A miner can optimize his earned transaction fees by ordering the transactions in his transaction pool by transaction fee divided through transaction size.

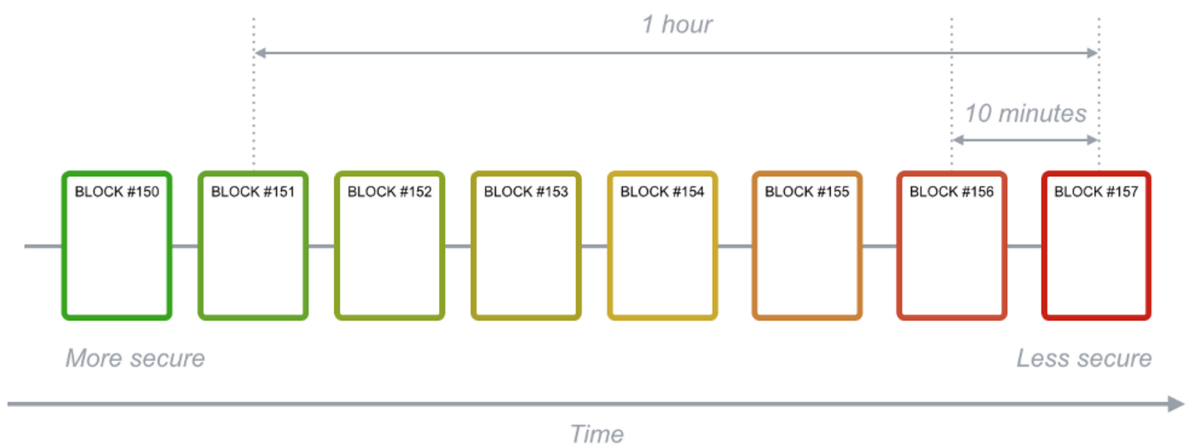


Figure 2.4: Transaction Security [4]

Confirmations

A transaction is confirmed as soon as the transaction is part of a block of the blockchain. A transaction confirmed in the most recent blocks can still be removed from the blockchain by creating another longer blockchain. This longer blockchain replaces then the original one. For this reason, merchants wait for a certain number of confirmations. As illustrated in Figure 2.5, confirmations are the number of blocks that were created after the block with a transaction. Figure 2.4 shows requiring more confirmations reduces this risk. Six confirmations is a widespread recommendation and require you to wait on average for one hour to be certain about receiving a transaction. Six transactions mean that even if an attacker owns 20% of the hash power, he would only have a chance of 2.3% for a successful double-spending attack.

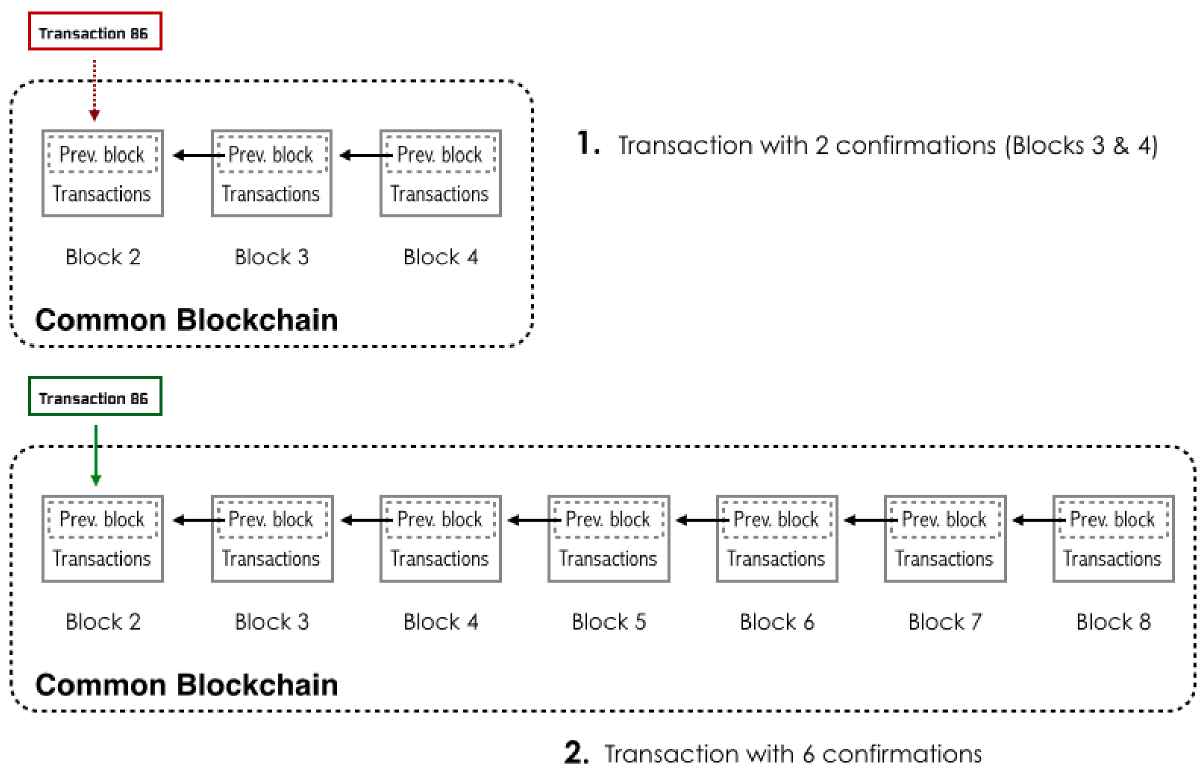


Figure 2.5: Confirmations [5]

Satoshi

Satoshi is currently the smallest unit of the bitcoin cryptocurrency named after the original creator [28]. One satoshi equals 0.00000001 BTC, 100.000.000 satoshi equals one bitcoin. Transaction fees are most commonly denominated in satoshi.

2.2.5 Full Node and Miner

Full nodes are clients that have validated the whole blockchain self-sufficiently. They enforce all of bitcoin's rules on any received data and can't be cheated through invalid blocks or transactions.

A full node does not need to keep all blockchain data, it can also run in pruning mode [29] [30]. Pruning mode allows the deletion of all data to make the blockchain size stay under a specified target size.

Also, a miner does not necessarily need the complete blockchain, the miner only needs to have the latest valid block. For example, members of mining pools only need to receive work from the mining pool. A miner is a provider of hash power for proof-of-work. Miners want to earn block rewards and transactions fees by adding blocks to the blockchain.

Block Rewards and Mining Pools

Miners are incentivized by block rewards to provide their hashing power. Mining is possible with CPUs, GPUs, application-specific integrated circuits (ASIC) or even a sheet of paper and a pencil, although mining with an ASIC is most profitable [31]. Since it can take years for miners to generate a block, mining pools were created to pool resources of miners together. The reward is then split equally according to their share of contributed work [32].

2.2.6 Segregated Witness

Segregated Witness (SegWit) is a bitcoin softfork activated on 24^{th} August 2017 as a solution to the scalability problem. After the activation of SegWit, the 1 MB block size limit was replaced with an almost 4 MB big block weight limit [33]. This block weight of almost 4 MB is more of theoretical nature, to fill a block with 4 MB it requires all transactions to be very weirdly formatted. The softfork was intended to increase the block capacity, increase the tps and therefore increase scalability. This is achieved by defining a new structure called the witness, which is used to check transaction validity and is committed to a block separately from the transaction Merkle tree. The witness structure is not required to determine transaction effects. This approach achieves great backward compatibility, SegWit-enabled and Non-SegWit bitcoin nodes can work on the same blockchain. One of the points of concern is that SegWit is expected to increase the tps only by a factor between 1.8 to 2.3. The average transaction make-up in 2017 would lead to a block size of 2.3 MB if all transactions were SegWit transactions. But SegWit does not only increase the tps, it also allows other scalability solutions like the Lightning Network to work by adding transaction malleability. Transaction malleability means the signature doesn't encompass all transaction data and a user could potentially change a transaction ID. Another point of concern is the necessary complex software update [34].

2.2.7 Fork

There are mainly four distinct meanings for fork [35]:

There is the chain fork, it occurs when multiple blocks are mined at the same height. Usually, this results in one of the blocks winning and the other blocks are stale blocks.

The softfork is a change to the protocol wherein only previously valid blocks or transactions are made invalid. Softforks are backward compatible, SegWit is an example of a softfork.

Thirdly, there is the hardfork. It makes previously invalid blocks or transactions valid. Hardforks are not backward compatible, Bitcoin Cash is an example.

The (source) code fork is an altcoin that is a derivative of Bitcoin. For example, Litecoin is a code fork of Bitcoin, but neither is a hardfork nor a softfork. The reason for this is Litecoin and Bitcoin do share the same genesis block.

2.2.8 Double-Spending Attacks

The entirety of bitcoin's system of blockchain, mining, proof-of-work, difficulty etc. exist to make the history of transactions irreversible and to solve the double-spending problem. When bitcoin is used correctly, the transactions on the blockchain are irreversible and final [18]. There are still scenarios to successfully spend bitcoin twice. These double-spending attacks depend on the number of confirmations a merchant/transaction receiver is waiting for and the hash power of the attacker. By redoing the proof-of-work and creating the longest blockchain an attacker can attempt a double-spending attack. An attacker can also abuse low-security confirmation and network settings.

Race Attack

A merchant or a transaction receiver operating his own bitcoin node who accepts a payment on seeing the transaction status ”0/unconfirmed” is at risk of a race attack and double-spending fraud. A malicious actor could send a transaction directly to the node of the transaction receiver and a conflicting transaction with a higher transaction fee to the rest of the bitcoin network with a different transaction receiver. The transaction with the higher transaction fee is more likely to be mined into a block, this also depends on the number of pending transactions.

According to the research paper *Two Bitcoins at the Price of One* [36] an attacker has a high degree of success in performing a race attack

As precautions, a transaction receiver can disable incoming connections and can connect to only well-connected nodes to lessen the risk of a race attack, but the risk can't be eliminated. This is another reason why waiting for six confirmations is recommended. There is a theoretical solution to enable fast and secure bitcoin transactions, alerts in case of double-spending fraud suspicions [36]. But there is no adaptation yet and making fast and secure bitcoin transactions are still very difficult.

Finney Attack

The Finney attack is another attack on transaction receivers who accept payments on the transaction status ”0/unconfirmed”. The Finney attack requires hash power. The attacker mines a block and includes a transaction from address A to address B, which he both controls. Now he sends a transaction from address A to transaction receiver's address C, the transaction receiver thinks the transaction is final after receiving the transaction status ”0/unconfirmed”. But the attacker broadcasts his mined block afterwards. His transaction to address B takes precedence over the transaction to address C.

Vector76 Attack

The Vector76 attack is a complex attack combining the race and the Finney attack, which can even reverse transactions included in the latest block. The malicious miner has to find an opportunity worth more than the current block reward to make the attack profitable, because the attack requires the miner to intentionally let a mined block become a stale block.

The malicious miner solves a block and includes transaction A sending BTC to a victim. Instead of broadcasting the solved block, the miner broadcasts the transaction A via node A (connected directly to the victim) and a second transaction B (via a well-connected) node B. Transaction B does not send money to the victim but to the malicious miner. Eventually, another miner will solve a block and include either transaction A or transaction B. The connectivity of node B and the transaction fees of transaction B make it more likely to take precedence over transaction A. The malicious miner sends his own solved block with transaction A via node A to the victim after seeing the solved block with transaction B via node B. At this moment the victim only sees transaction A in the block mined by the malicious miner, assumes everything is correct and does a beneficial action for the malicious actor. Now there are effectively two branches of the blockchain since it is likely that the majority of the hashing power has the block with transaction B, it will create a new child block and therefore be the longest blockchain and erase the other branch with transaction A. If transaction A gets propagated faster, there should be no/minimal loss for the malicious actor, except for the costs to produce a stale block. In case the block with transaction A gets propagated faster, the malicious actor earns the block reward and transaction fees.

A Vector 76 attack has a very high chance to be profitable, but it is very unlikely to find such an opportunity.

Alternative History Attack

Figure 2.6 visualises the concept behind the alternative history and the majority attack. In contrast to the previous attacks, the concept behind these attacks is more well-known.

Comparable to the Finney and Vector76 attacks, the attacker needs a significantly higher hashrate. The alternative history attack can even work if the transaction receiver waits for some confirmations. The higher the attacker's percentage of the network's total hashrate, the more confirmations are needed to prevent double-spending.

Like the name alternative history attack implies, the miner starts working on an alternative history, his own private blockchain after his transactions were included in a block A. Multiple transactions and double-spending attempts targeting different victims at the same time make the attack more profitable. The private blockchain has the same parent block as block A and the first block includes the fraudulent double-spending transactions. After the victims waited for their number of confirmations, accepted the transactions and did something beneficial for the attacker, the attacker makes his private blockchain public as soon as it is longer than the original blockchain and creates hereby an alternative

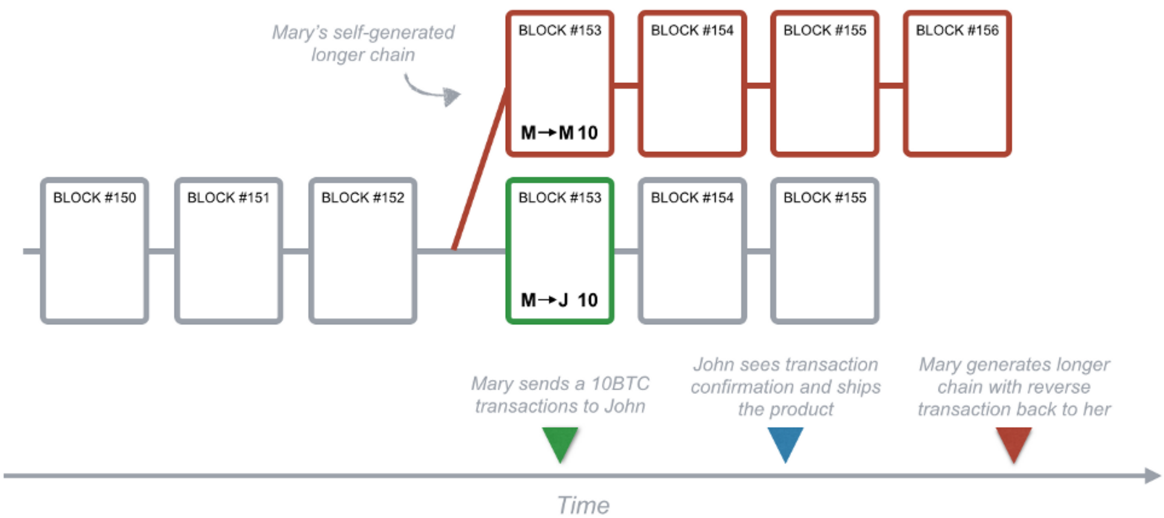


Figure 2.6: Double-Spending Attack [4]

history. In case of success, the attacker regains his spent bitcoins and receives beneficial actions from the victims. In case of failure, the attacker has to bear the hashrate costs and pay for the bought goods or services.

The success probabilities of an alternative history attack depending on the attacker's hashrate and the transaction receiver's number of confirmations are displayed in the Table A.1.

Maximal Safe Transaction Value

The maximal safe transaction value is the value a participant of the bitcoin network can send safely depending on the success probability of the double-spending attack and other variables like the block reward as can be seen in the Formula (4.4). The maximal safe transaction values are shown in Table A.2.

Majority Attack

The majority attack is also called 51% attack. The concept behind the alternative history attack and the majority attack is the same, the difference is the attacker's percentage of the total hash power of the network. For a majority attack equal to or more than 50% of the total network's hashrate is necessary. A majority attack has a probability of 100% to succeed, no amount of confirmations can prevent this attack. With at least 50% of the hashrate the attacker can work secretly until his private blockchain is longer.

Economic Majority

For an attacker, a majority attack on bitcoin can be catastrophic due to the effects on the market and the attacker's very high commitment to ASIC mining hardware [37]. A miner with more than 50% of the hashrate is therefore incentivized to calm down the market and to reduce his mining power and abstain from attacking to protect the mining hardware.

Altcoins of bitcoin or cryptocurrencies, for which a cryptocurrency with a similar algorithm and higher hashrate exists, are at risk from majority attacks.

2.2.9 Transaction Spam Attack

In July 2018 the Ethereum Network was affected by transaction spam or also called flood attack. In such a flood attack, the attacker, in principle, trades their own cryptocurrency for increased transaction costs for everyone by only using intended functionality and valid transactions. Vitalik Buterin tweeted about this attack [38], the tweet can be seen in Figure 2.7. This transaction spam is also possible in the bitcoin network. Interesting research questions arise about the costs which a malicious actor has to pay to make the bitcoin network unusable or too uneconomical to use for certain use-cases. Such an attack is only limited on the attacker's number of bitcoin and depends on the target transaction fee, the duration of the attack and the scalability of the network. An attacker with a certain amount of money can make blockchains for other users for a certain time unusable.

There are also other definitions for transaction spam or flood attacks. In this thesis, we assume a transaction spam attack only uses valid transactions.

Figure 2.7: Screenshot Tweet from Vitalik Buterin about Transaction Spam

Chapter 3

Related Work

Different related works were already presented in VIBES. The most similar related work is the Bitcoin-Simulator, its architecture and design are different, it can only simulate maximal 6000 nodes and has no transactions. In contrast, VIBES has transactions and unlimited nodes. The two other presented related works are the bitcoin testnet and the back of the envelope approach. Testing and analyzing metrics on the bitcoin testnet is essentially the same as on the public bitcoin network and is almost as resource-intensive. The back of the envelope approach using empirical data to infer certain properties of the network is also impractical due to the very expensive, time-consuming and non-configurable nature [15].

Despite numerous bitcoin simulators existing, since the release of VIBES until the writing of this thesis nothing has been published as similar to VIBES as the Bitcoin-Simulator.

There are some single purpose bitcoin simulators in the research fields of mining [39] or network [40] [41]. The main difference between these simulators and VIBES is the attachment of importance to the user interface. The designs and architectures are also completely different.

To understand the approach of this thesis, an overview over the existing classes and concepts of VIBES is necessary.

For the double-spending attack the research paper *Analysis of hash rate-based double-spending* is presented and for the flood attack the research paper *Stressing Out: Bitcoin "Stress Testing"*.

3.1 VIBES: Fast Blockchain Simulations for Large-scale Peer-to-Peer Networks

The architecture and design lend itself to being split up into the frontend and the backend. The communication channel between both is HTTP.

3.1.1 Frontend

As JavaScript framework React was chosen for the frontend [42]. The most interesting part of the frontend is the Atomic Design [6]. This approach makes it easy to add new components to the user interface or to remove components from pages. The modularity makes the maintainability easy. Atomic design is a philosophy that encourages the composition of entities. There are four of these entities, the smallest components like buttons and inputs are called atoms. Atoms, in turn, assemble molecules, several molecules make up an organism. Finally, several organisms create a page. Actually, several organisms create templates which then create pages, but templates are not used in VIBES. The reason for not using templates could be that this abstraction layer was not needed.

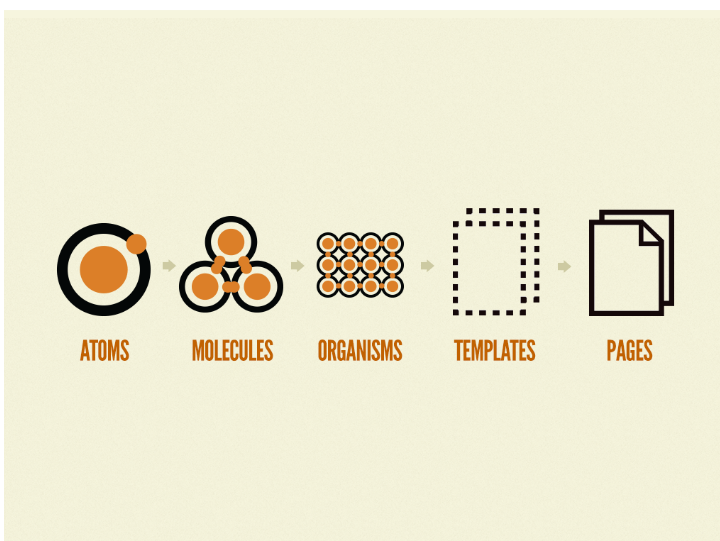


Figure 3.1: Atomic Design [6]

3.1.2 Backend

The backend of VIBES has in principle four main types of classes: actions, actors, models, and utils. The following sub-chapters explain them and the Main object.

Actors and Actions

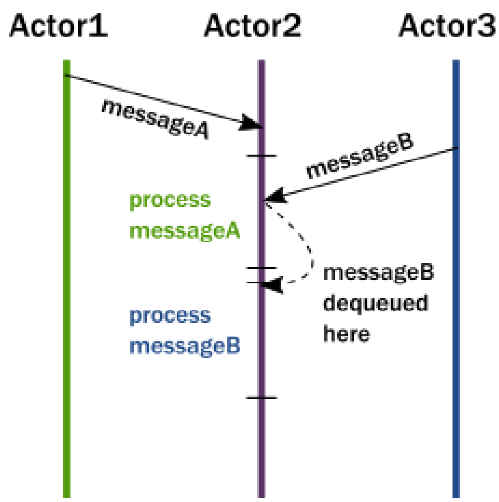


Figure 3.2: The Actor Model - Usage of message passing avoids locking and blocking

VIBES uses the Actor Model [43]. An Actor is a computational entity, the primary unit of concurrency and actors communicate via messages. There is no shared state and message-first communication, therefore no locks and no blocking exist as shown in Figures 3.2 and 3.3. This is very important to make sure the simulator is fast.

The implementation in Scala and Akka has five actors with their corresponding actions. Actions describe the methods of Actors. Figure 3.4 shows this architecture.

MasterActor & MasterActions: The MasterActor is also called Coordinator, controls the nodes and the execution order in the network. The MasterActor grants permission to nodes to work on a work request. A **work request** is a piece of computational unit for whose execution the node needs permission, for example, mining a block. If the MasterActor wants to execute a work request with a timestamp in the future, it can **fast-forward** the entire system to this point in the future.

DiscoveryActor & DiscoveryActions: The DiscoveryActor is responsible for assigning and updating the neighbours of nodes.

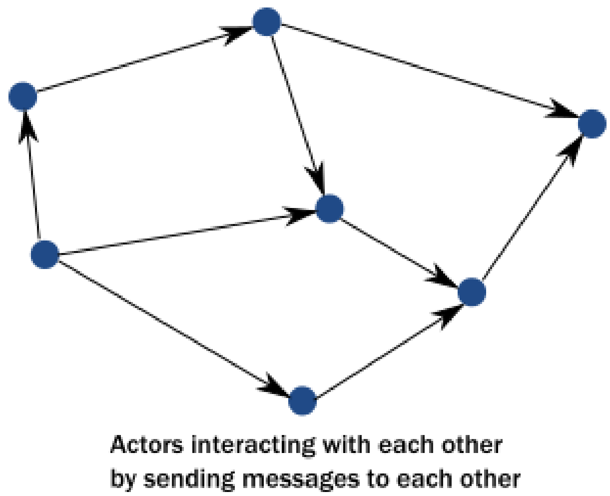


Figure 3.3: The Actor Model - Usage of message passing avoids locking and blocking

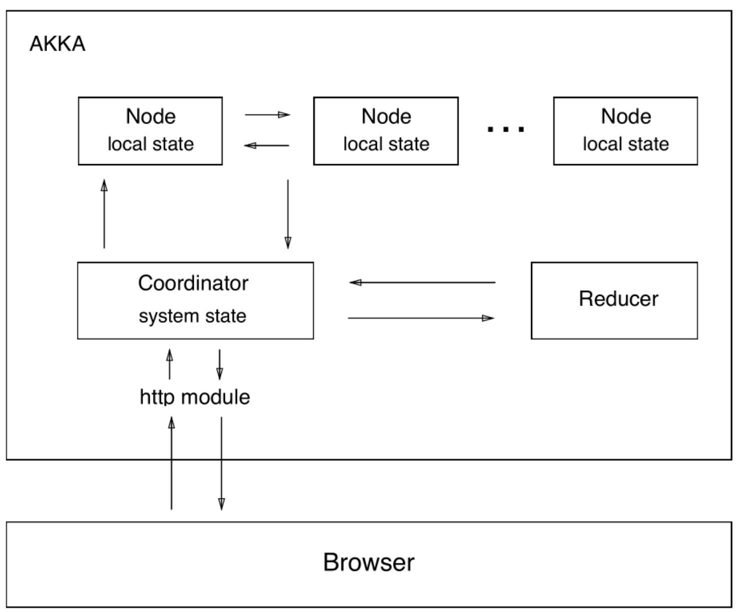


Figure 3.4: VIBES' Architecture

NodeActor & NodeActions: The NodeActor is the equivalent to a miner in the bitcoin network, interacts with other nodes, blocks, and transactions. The NodeActor is also responsible for the generation of the best guess of a work request. The **best guess** is, for example, the time in the future when a node wants to mine a block.

NodeRepoActor & NodeRepoActions: The NodeRepoActor helps the MasterActor, is the repository for all nodes, starts and ends the simulation.

ReducerActor & ReducerActions: The ReducerActor is called after the simulation to calculate, summarize and prepare the simulation results for the transfer to the user interface.

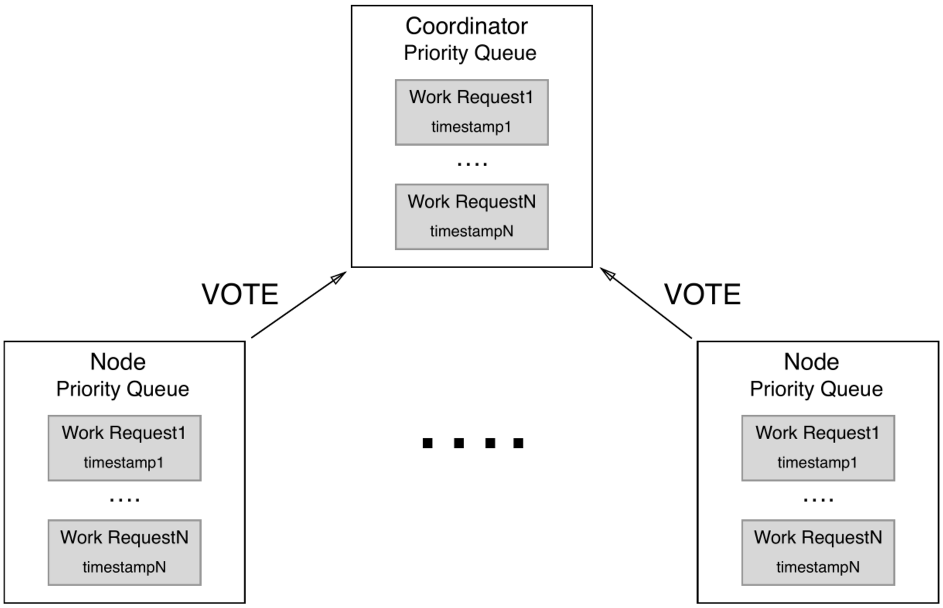


Figure 3.5: Nodes voting to fast-forward

Models

There are five data structures called models.

VNode: VNode is the model of a node in the bitcoin network. It has methods to interact with blocks, transactions, nodes, and the blockchain.

VBlock: VBlock is the model of a block in the bitcoin network, it also has a method to calculate the propagation times of a block.

VTransaction: VTransaction is the model of a transaction in the bitcoin network.

VEventTypes: VEventTypes is a special model to provide the frontend with information about the simulation and events. There are three types: *MinedBlock*, *TransferBlock* and *ReducerResult*.

VRecipient: VRecipient is a very simple model of a event receiver consisting only out of two nodes and a timestamp.

Utils

VExecution: Each work request has a **type**, there are four types which are defined in VExecution.

- *MineBlock* is a node's work request to solve the current block.
- *IssueTransaction* is a node's work request to create a transaction.
- *PropagateTransaction* is a node's work request to propagate transactions.
- *PropagateOwnBlock/PropagateExternalBlock* is a node's work request to propagate a block to its neighbours.

VConf: The **configuration parameters** from the user interface are saved in the VConf which can be accessed globally.

Joda: An object for ordering the timestamps.

Main

The Main object starts the backend. It gets the configuration parameters from the frontend, saves them in the VConf and prepares the simulation. Then it starts the simulation. After the end of the simulation the Main object provides the simulation results to the frontend.

3.2 Analysis of hash rate-based double-spending

The research paper *Analysis of hash rate-based double-spending* focuses on the quantitative aspects of bitcoin's double-spending prevention and how they relate to attack vectors and their countermeasures. It takes a look at the stochastic processes underlying typical attacks and their resulting probabilities of success. It provides a formula to calculate the success probability of a double-spending attack depending on the attacker's percentage of the network's total hashrate and the confirmations the merchants are waiting for. A formula to calculate the maximal safe transaction value is also provided. Both of these formulas are used in this thesis and the models with their configuration parameters are implemented.

3.3 Stressing Out: Bitcoin "Stress Testing"

The research paper *Stressing Out: Bitcoin "Stress Testing"* is an empirical study of a spam campaign in the summer 2015 that resulted in a DoS attack on bitcoin [44]. The attacker tested several different attack vectors with valid and invalid transactions and even managed to crash over 10% of all bitcoin nodes at one point. The impacts were measured, for example, the total costs of the attack and the average price increase for transactions are calculated.

Chapter 4

Approach

In this chapter, the changes to the existing VIBES framework are presented one by one. The reasons for each improvement are described. The prerequisites for every change and the design and architecture are shown. The implementation details are explained.

The implementation is split into frontend and backend. Since the frontend is only displaying the information from the backend, the focus of this thesis is on the backend where the changes to the actual behaviour of the simulation are done. The frontend, the console output, and the log file show the results of the backend and can be used for the evaluation.

4.1 Bitcoin-like Blockchain Simulation

Extending the previous *Generic Simulation* to *Bitcoin-like Blockchain Simulation* made lots of changes necessary, especially in the frontend. More abstract ways to implement different strategies in the backend in Scala were researched. The backend differentiates between the currently only two strategies mainly with If-clauses. This seemed to be the best option, which avoids creating unnecessary complexity. It was also recommended by the author of VIBES. Bloated methods due to having multiple strategies in one method can be avoided by outsourcing strategy-specific parts into their own methods.

4.2 Time-outs and Configuration

Previously the frontend could only display the information from the backend if the simulation results were sent within 60 seconds. After checking the existing time-outs in the project and researching the default time-outs of the used frameworks, the problem was found in the akka.http.server.idle-timeout default setting. This default setting of 60 seconds was changed in *\vibes\server\src\main\resources\application.conf* to infinite.

Listing 4.1: application.conf

```
akka.http {

  server {
    idle-timeout = infinite
  }
}
```

Currently, the time-out for providing the information to the frontend is set to 24 hours in *Main.scala*.

4.3 Lazy Logging

Previously logging only occurred in the console. This made debugging of long simulations difficult. Especially for the evaluation of any implementations, a log file is necessary. For this reason, the Scala modules *logback* and *scala-logging* were integrated into the project. Every important event is logged into */logfile.log*.

4.4 Time between Blocks

The time between the blocks or also called block time is a very important metric. It can be used to check the overall system health. Due to the nature of the bitcoin protocol, a new block can immediately be found after the last one. Very short block times can lead to unusual behaviour, as nodes might not have enough time to send transactions, synchronise their transactions pools or the blockchain. Therefore the block time can explain unusual behaviour. The user interface needs the corresponding data to display the time between blocks chart in Figure 4.1. To calculate the duration of the first block, a new timestamp was introduced to save the start time of the simulation.

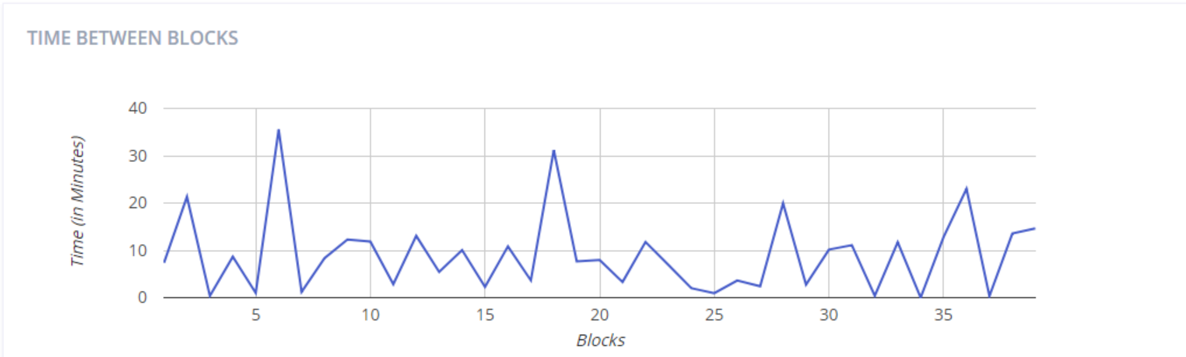


Figure 4.1: Screenshot Time between Blocks

4.5 Block Size Limit

Previously VIBES had no block size limit. This means infinite transactions can be processed and changing input parameters has no effect on the scalability. To be able to investigate the effects of different input parameters on the scalability, the introduction of a block size limit is necessary. This allows a more accurate simulation of bitcoin. The block size limit is, for example, necessary to analyse the implications of Segwit2x according to VIBES [15].

The only prerequisite is to add an additional **configuration parameter** *maxBlockSize*: the maximal block size in B, the current default value is 50.000 B.

The design and architecture changes of the backend mainly happen in the model VBlock. All generated blocks obey the block size limit depending on if the simulation is a Bitcoin-like Blockchain Simulation. If the block size limit is set to zero, the simulator assumes the block size is unlimited and the maximum number of transactions per block is infinite.

Listing 4.2: VBlock with focus on block size limit

```
object VBlock extends LazyLogging {
  def createWinnerBlock(node: VNode, timestamp: DateTime): VBlock = {
    var maxTransactionsPerBlock : Int = 0
    var processedTransactionsInBlock: Set[VTransaction] = Set.empty

    if (VConf.strategy == "BITCOIN_LIKE_BLOCKCHAIN" && VConf.maxBlockWeight !=
        ↪ 0) {
      maxTransactionsPerBlock = Math.floor(VConf.maxBlockSize /
          ↪ VConf.transactionSize).toInt

      // takes the amount of maxTransactionsPerBlock out of the transaction
          ↪ pool into the winner block
      processedTransactionsInBlock =
          ↪ node.transactionPool.toSeq.take(maxTransactionsPerBlock).toSet
    } else {
      maxTransactionsPerBlock = node.transactionPool.size
      processedTransactionsInBlock = node.transactionPool
    }

    VBlock(
      id = UUID.randomUUID().toString,
      origin = node,
      transactions = processedTransactionsInBlock,
      level = node.blockchain.size,
      timestamp = timestamp,
      recipients = ListBuffer.empty,
      transactionPoolSize = node.transactionPool.size
    )
  }
}
```

The Listing 4.2 shows only the essential lines of code. First, the maximum number of transactions per block is calculated via the maximum block size and the transaction size. For simplicity VIBES chose to have a constant transaction size, therefore this calculation is simple and it could also be done only once. It was a conscious decision to implement it in this way to make the implementation of variable transaction sizes in the future easier. Rounding down the maximal transactions per block makes sure the actual block size is smaller than the limit. Finally, the transactions are taken out of the transaction pool and later this set of transactions is used in the creation of the winner block.

4.6 Segregated Witness

In Chapter 4.5 the block size limit was implemented to make the simulation more accurate and similar to the actual bitcoin network. In this subchapter, one step further is taken. To accurately simulate the bitcoin network the block size limit needs to replaced by a block weight limit like the actual bitcoin network did with the softfork SegWit.

For a very simple implementation of SegWit, one could maybe just introduce a boolean segWitEnabled and replace the already existing block size limit with a block weight limit and the transaction size with a transaction weight. Since the comparison between non-SegWit und SegWit key figures could be a very interesting use-case, new **configuration parameters** are introduced instead.

- *blockWeightLimit*: maximal block weight limit in weight unit
- *transactionWeight*: witness data per transaction in weight unit

As can be seen in Listing 4.3 a new condition for SegWit is added to the VBlock object.

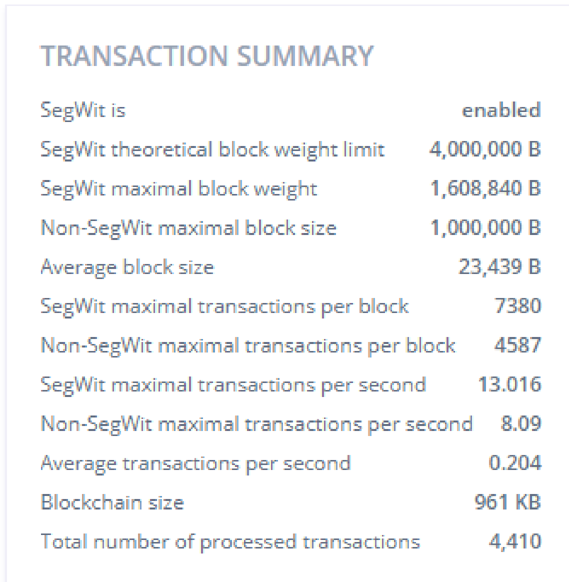
Listing 4.3: VBlock with focus on block weight limit

```
if (VConf.strategy == "BITCOIN_LIKE_BLOCKCHAIN" && VConf.transactionSize
  ↪ != 0) {
  // this part could be moved to Main for constant transaction weight and
    ↪ size to save calculations, but is necessary here for non-constant
    ↪ transaction weight and size
  if (VConf.maxBlockWeight != 0 && VConf.transactionWeight != 0) {
    // SegWit is enabled
    maxTransactionsPerBlock = Math.floor(VConf.maxBlockWeight /
      ↪ VConf.transactionWeight).toInt
  } else if (VConf.maxBlockSize != 0) {
    // SegWit is disabled
    maxTransactionsPerBlock = Math.floor(VConf.maxBlockSize /
      ↪ VConf.transactionSize).toInt
  } else {
    // any number of transactions is accepted
    maxTransactionsPerBlock = node.transactionPool.size
  }

  // sorts the transaction pool by the transaction fee and takes the
    ↪ amount of maxTransactionsPerBlock out of the transaction pool into
    ↪ the winner block
  processedTransactionsInBlock =
    ↪ node.transactionPool.toSeq.sortWith(_.transactionFee >
    ↪ _.transactionFee).take(maxTransactionsPerBlock).toSet

  // sets confirmation status of transaction true
  processedTransactionsInBlock.foreach { _.confirmation = true }

  // sets confirmation level of transaction
  processedTransactionsInBlock.foreach { _.confirmationLevel =
    ↪ node.blockchain.size }
} else {
  maxTransactionsPerBlock = node.transactionPool.size
  processedTransactionsInBlock = node.transactionPool
} ... }
```

Comparisons between the SegWit vs Non-SegWit metrics are provided in the frontend. These are calculated in the ReducerActor as can be seen in Listing 4.4. The SegWit theoretical block weight limit and the Non-SegWit maximal block size are given input values. The SegWit maximal block weight considers the transaction size and is more realistic than the theoretical block weight limit. Additionally, both maximal transactions per block and transactions per second values show the differences between SegWit and Non-SegWit while the actual simulation values are also shown in Figure 4.2.

Listing 4.4: Calculations for the comparisons in the ReducerActor

```
// works only for constant transaction size and weight, otherwise an array is
    ↪ necessary
    var segWitMaxBlockWeight = 0 // nonSegWitMaxBlockSize = VConf.maxBlockSize
    var segWitMaxTransactionsPerBlock = 0
    var nonSegWitMaxTransactionsPerBlock = 2147483647
    var maxTransactionsPerBlock = 0
    var segWitMaxTPS: Double = 0
    var nonSegWitMaxTPS: Double = 0
    if (VConf.transactionSize != 0) {
      // multiplies by 1000 because maxBlockSize is in KB and transaction size
          ↪ is in B
      nonSegWitMaxTransactionsPerBlock = Math.floor(VConf.maxBlockSize * 1000
          ↪ / VConf.transactionSize).toInt
      maxTransactionsPerBlock = nonSegWitMaxTransactionsPerBlock
      nonSegWitMaxTPS = nonSegWitMaxTransactionsPerBlock.toDouble /
          ↪ VConf.blockTime.toDouble
      nonSegWitMaxTPS = (math rint nonSegWitMaxTPS * 1000) / 1000
    }
    if (VConf.maxBlockWeight != 0 && VConf.transactionWeight != 0) {
      segWitMaxTransactionsPerBlock = Math.floor(VConf.maxBlockWeight /
          ↪ VConf.transactionWeight).toInt
      segWitMaxBlockWeight = segWitMaxTransactionsPerBlock *
          ↪ VConf.transactionSize
      maxTransactionsPerBlock = segWitMaxTransactionsPerBlock
      segWitMaxTPS = segWitMaxTransactionsPerBlock.toDouble /
          ↪ VConf.blockTime.toDouble
      segWitMaxTPS = (math rint segWitMaxTPS * 1000) / 1000
    }
```



TRANSACTION SUMMARY

SegWit is	enabled
SegWit theoretical block weight limit	4,000,000 B
SegWit maximal block weight	1,608,840 B
Non-SegWit maximal block size	1,000,000 B
Average block size	23,439 B
SegWit maximal transactions per block	7380
Non-SegWit maximal transactions per block	4587
SegWit maximal transactions per second	13.016
Non-SegWit maximal transactions per second	8.09
Average transactions per second	0.204
Blockchain size	961 KB
Total number of processed transactions	4,410

Figure 4.2: Screenshot Transaction Summary

4.7 Transactions per Second

One of the biggest unresolved issues of bitcoin-like blockchains is scalability. The main metric to measure scalability is transactions per second (*tps*). One drawback of this metric is that it contains no information about the transaction size or the usefulness of the transaction.

According to the research paper Bitcoin-NG the *tps* of bitcoin pre-SegWit was limited to only 1 to 3.5 *tps* for typical transaction sizes due to the block size at 1 MB [45]. For bitcoin heavy transaction loads are an obstacle for a more widespread usage [46]. A payment processor like VISA handles 4,000 transactions per second on average and has been stress-tested in 2013 to handle 47,000 transactions per second. In comparison, bitcoin can only handle 7 transactions per second, due to the fact that block sizes are restricted to have a maximum size of 1 MB.

Of course, SegWit increased those numbers.

The transactions per second (*tps*) is also called throughput or transaction rate, Figure 4.2 also shows the average *tps*. The average *tps* is - as the Listing 4.5 shows - calculated over the duration of the whole simulation and then given to the frontend.

Listing 4.5: Calculations for the tps in the ReducerActor

```
var actualTPS: Double = longestChainNumberTransactions.toDouble /
  ↪ secondsBetween(VConf.simulationStart,
  ↪ VConf.simulateUntil).getSeconds.toDouble
actualTPS = (math rint actualTPS * 1000) / 1000
```

In our tool the *average transactions per second* can be higher than the *SegWit maximal transactions per second* or the *non-SegWit maximal transactions per second*. This should happen when the simulated block time is shorter than the input simulation time and the blocks are full. The *average transactions per second* is based on the simulated block time, the maximal tps values are based on the input simulation time.

4.8 Processed and Pending Transactions per Block

After introducing the block size limit in Chapter 4.5 and SegWit in Chapter 4.6 it would be very insightful to have visualisations about how many transactions are actually included in blocks and how many transactions are pending. This would also be very helpful for the evaluation of correctness.

Changes in the models VBlock and VEventTypes and the ReducterActor were done for the pending transactions per block chart in Figure 4.3. As a new attribute, every block has the transaction pool size minus the included number of transactions at the time of the block creation.

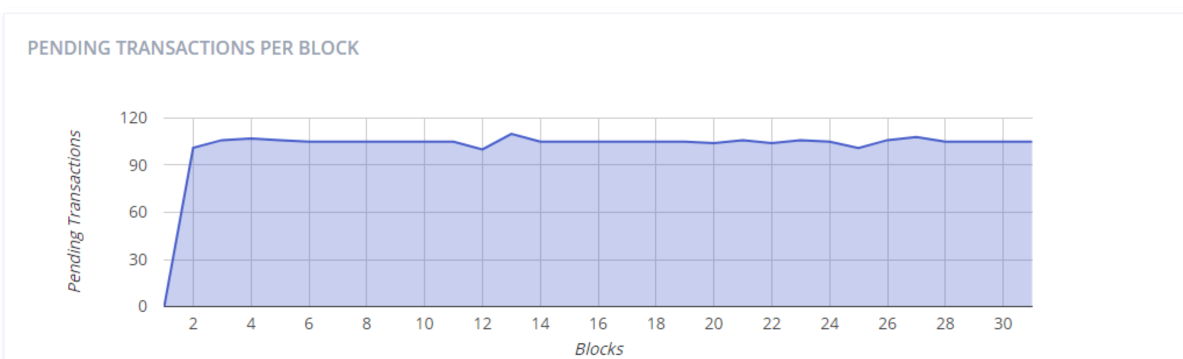


Figure 4.3: Screenshot Pending Transactions per Block

Changes to the same classes and additionally the Main object were done for the processed transactions per block chart in Figure 4.4. The new attribute processed transactions of a block describes the transactions which were included by the winning miner. This is shown as the blue line, the red line shows the maximal possible transactions depending on if there is a block size limit or if SegWit is enabled. If the block size limit and SegWit are disabled (equal to zero), then the transaction limit per block is unlimited and the red line isn't shown.

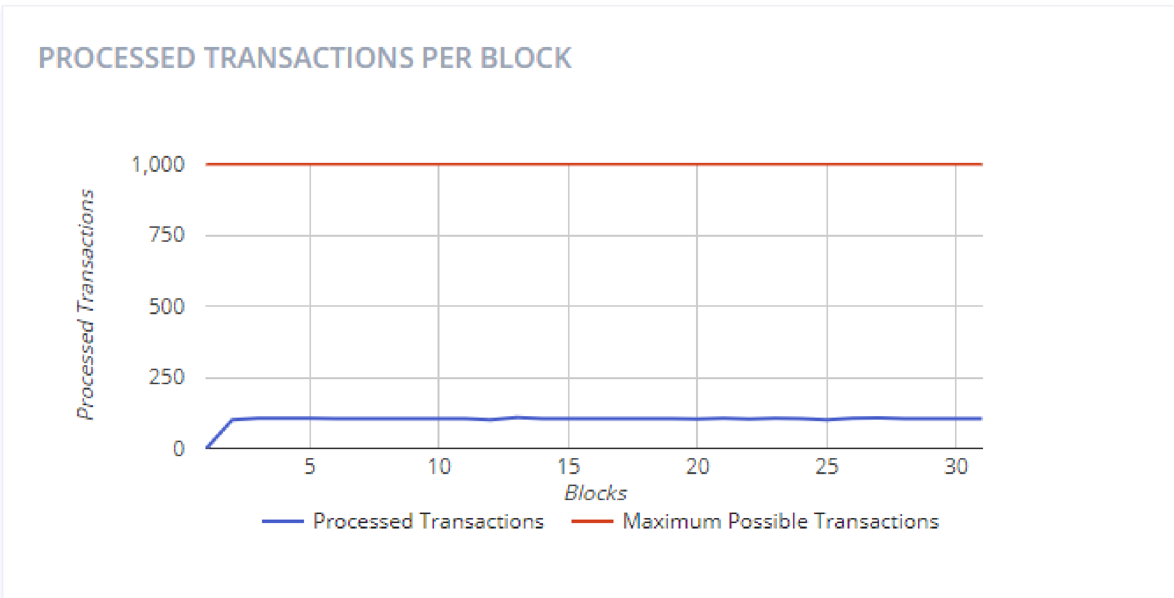


Figure 4.4: Screenshot Processed Transactions Per Block

Both Figures 4.3 and 4.4 show that the first block contains no pending and no processed transactions. The reason for this is that no transactions are received before the genesis block is mined. One reason for having an empty genesis block is the fact that no bitcoin exists before the first block, so no transaction fees can be paid and no bitcoin can be sent (assuming no premine like in Ethereum). But also transactions with zero transactions fees and zero bitcoin sent can be valid and included in blocks. These transactions would be considered transaction spam. The miners have no financial incentive to include zero fee transactions. Bitcoin's genesis block contains one transaction [47]. In the end, this question about having zero, one or lots of transactions in the genesis block seems to be a question of personal preference. One disadvantage of having only zero or one transaction in the genesis block is that it distorts transactions metrics like *tps* for a very small number of blocks or transactions.

4.9 Transaction Incentives and Confirmation Status

In bitcoin there are two types of incentives for miners, block rewards and transaction incentives or also called transaction fees. Previously these mining incentives were not considered in VIBES. To make a more realistic simulation, transaction incentives are added to the simulation. This allows analysis, for example, for determining the necessary price to include a transaction in a block within a certain time. It can also be used in future work about mining pools. Since research questions about transaction incentives are closely linked to the confirmation status, new data structures are needed to easily access information about the creation time and confirmation time of transactions.

New variables for the transaction incentives and confirmation status are added to the VTransaction model.

- *transactionFee*: transaction fee in Satoshi
- *confirmation*: confirmation status as a boolean
- *creationLevel*: block level when the transaction was created
- *confirmationLevel*: block level when the transaction was included in a block

Transactions are assigned a random integer between 0 and 124 as the transaction fee in Satoshi. This is about the same range as in reality, but the distribution is different. The real distribution can change from one moment to the next and is difficult to model. When a transaction gets included in a block, its transaction status changes from *false* to *true*.

Two charts were created to show the results of this implementation. For these charts a slightly higher transaction throughput than block transaction capacity was chosen because this shows an interesting case. In this case, the miners can prefer transactions with high transaction fees over transactions with low fees.

Figure 4.5 shows the transaction confirmation status per transaction fee. The abscissa shows the transaction fees from 0 to 124 in Satoshi, the ordinate shows the number of transactions. The red area shows the unconfirmed and the green area shows the confirmed transactions. It can be clearly seen, the red area is only really big from 0 to 7 Satoshi. This means most of the pending transactions are the ones with the lowest transaction incentives.

The red area exists even if the block size limit or block weight limit is smaller than the actual transaction throughput because the nodes are sending transactions even after the last block of the simulation was mined.

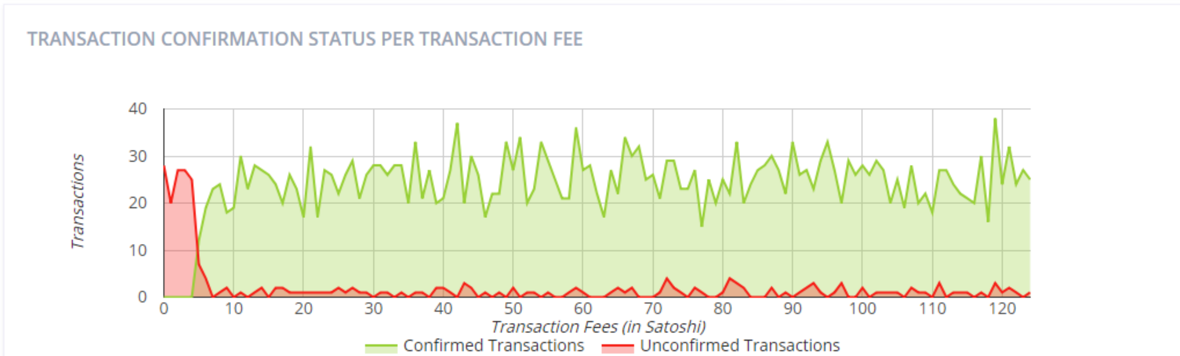


Figure 4.5: Screenshot Transaction Confirmation Status per Transaction Fee

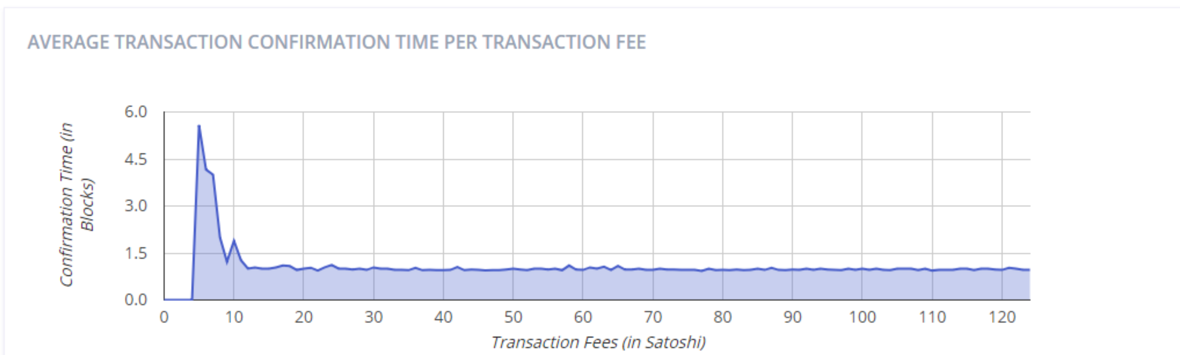


Figure 4.6: Screenshot Average Transaction Confirmation Time per Transaction Fee

The next Figure 4.6 shows the average transaction confirmation time per transaction fee. The abscissa shows again the transaction fee, the ordinate shows the confirmation time in blocks. Both Figures are from the same simulation. Therefore we can see that the average confirmation time for transaction fees 0 to 3 is zero blocks. The reason is that there are no confirmed transactions in this range. Maybe this visualisation is not perfect, since it may lead to the conclusion that transactions with fees from 0 to 3 are instantly included in a block. But infinite confirmation time in blocks is hard to visualise and taking the first nonzero confirmation time would also be misleading. The highest confirmation time is the point where the transactions barely get included into blocks. After this bottleneck, all transactions get included in about the same time.

For the generation of both charts, all created transactions are sent from the backend to the frontend. The frontend then summarizes the transactions per transaction fee, this could also be done by the backend. Sending all transactions ever created to the frontend is very likely a bottleneck for simulations with a very large number of transactions. The reason for this design decision is the flexibility to create or change charts to analyse different aspects of transactions. So far no issues were found during development. Parts of the previously created frontend are also a bottleneck for simulations with a very large number of blocks or nodes since every created block and every node is sent to the frontend. A solution for this issue could be a database.

VIBES offers the possibility to change the parameters sent to the frontend fast and easily. For simulations with a very large number of transactions and/or a very large number of blocks the frontend could be changed, or the sought after data can also be output via log file or console.

4.10 Transaction Spam

The transaction spam or also called flood attack has one configuration parameter in the frontend, which is the target transaction fee. The target transaction fee is the minimal fee that the attacker wants everyone in the network to pay for transactions.

Main

In the *Main* class changes were made to set up the flood attack. Currently the implementation only allows one attack at a time, either double-spending or flood attack. If both attacks have a valid input, the implementation prefers the double-spending attack.

The flood attack transaction buffer is also set up in the *Main*. Very short block times can lead to no regular transactions being sent, therefore a buffer is needed. The size of the buffer is two times the maximal tpb.

NodeActions

NodeActions implements a new case class to issue transactions in a flood attack.

VTransaction

VTransaction implements a new transaction attribute to enable analysis about how many flood attack transactions were pending or processed at a certain time.

VConf

VConf implements *transactionFee* as the target transaction fee and *floodTransactionPool* as an easy way to access the current number of flood attack transactions.

MasterActor

If a flood attack is active, the *MasterActor* is responsible to make the flood attack transaction happen by assigning random nodes to send these transactions. In future work the nodes could be configurable. The number of sent transactions depends on the number of confirmed flood attack transactions in the last block. In reality the attacker might not have the time to always check the number of confirmed flood attack transactions, the attacker could mitigate this by a larger buffer.

Listing 4.6: caption text

```
// checks if flood attack is active
if (VConf.floodAttackTransactionFee > 0) {
  logger.debug(s"VConf.floodTransactionPool...
    ↪ ${VConf.floodAttackTransactionPool}")

  (1 to VConf.floodAttackTransactionPool).foreach { _ =>
    val randomActorFrom =
      ↪ actorsVector(Random.nextInt(actorsVector.size))
    val randomActorTo =
      ↪ actorsVector(Random.nextInt(actorsVector.size))
    val now = priorityWorkRequest.timestamp
    randomActorFrom ! NodeActions.IssueTransactionFloodAttack(
      randomActorTo,
      now.plusMillis(50)
    )
  }
}
```

NodeActor

The *NodeActor* needed a new method and a new case for the flood attack.

ReducerActor

The *ReducerActor* calculates how many Satoshi were spent by the attacker on transaction fees, it checks how many transactions were confirmed below the target transaction fee and how many flood attack transactions are in the blockchain.

VEventTypes

The *VEventTypes* had to be adjusted to export the data to the user interface.

Frontend

Figure 4.7 shows the changes to the user interface in case of a flood attack. The number of pending flood attack transactions is added to the pending transactions per block chart, this number should stay constant at about two times maximal tpb.

The green line in the processed transactions per block chart shows the processed flood attack transactions per block. It can be seen at block 11, very short block times can lead to a block full of flood attack transactions.

The flood attack summary shows us the number of confirmed flood attack transactions, the number of bitcoin spent and the confirmed transactions below the target transaction fee.

The next two charts are also interesting, they confirm no transaction below the target transaction fee was confirmed. The target transaction fee in this simulation was 30 Satoshi, as can be seen.

4.11 Alternative History Attack

A 51% attack is one of the most commonly discussed attacks on the bitcoin protocol. It belongs to the group of alternative history attacks. Complex changes are required due how it works which is explained in Chapter 2.2.8.

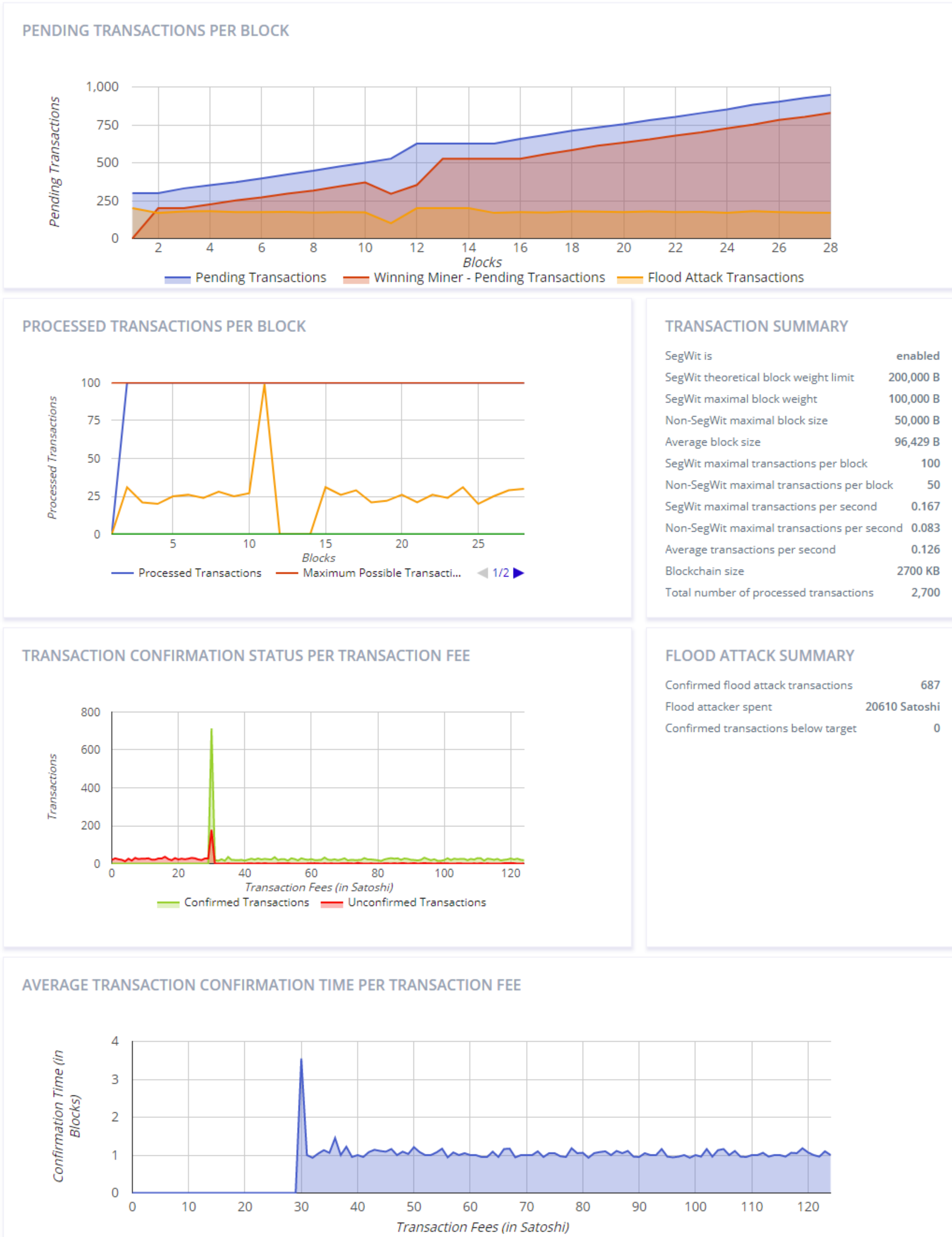


Figure 4.7: Screenshot Transaction Spam

4.11.1 Prerequisites

To simulate an alternative history attack additional **configuration parameters** are necessary. These parameters are used for the actual simulation of the attack, the calculation of the success probability of the attack and the maximal safe transaction value.

- *isAlternativeHistoryAttack*: if an alternative history attack is simulated as a boolean
- *hashRate*: attacker's hashRate as a percentage of the total hashRate of the bitcoin network
- *confirmations*: the amount of confirmations the attacked merchants are waiting for to accept a transaction
- *attackDuration*: the attacker gives up after mining a certain number of blocks and not succeeding or if it is not possible anymore to surpass the level of the honest blockchain
- *discountOnStolenGoods*: discount of the stolen goods by the attacker, a value from 0 (= full discount) to 1 (= no discount)
- *amountOfAttackedMerchants*: the attack is carried out against a certain amount of merchants at the same time
- *blockReward*: current block reward in BTC

4.11.2 Design and Architecture

Simulating the Attack

In the following the attacker's nodes, blockchain or blocks are interchangeably described as evil, private or malicious and the honest networks' nodes as good or public.

The solution for the simulation of an alternative history attack selects nodes as attacking nodes according to the attacker's hash rate as a percentage of the total bitcoin network. The good and the evil nodes both can mine the genesis block. The genesis block is then the first block in both the good and the evil blockchain. For simplicity, we assume that the attacker successfully sent the transactions to the attacked merchants in the second block of the honest blockchain. Immediately after the genesis block is mined, the evil nodes start mining together on their own evil blockchain. It is necessary for all nodes to update their neighbour nodes to only have their corresponding nodes as neighbours. The synchronising of the blockchain is only possible for the same type of node. As a counterexample, the attacker's hash rate would suffer if the evil nodes could not synchronise their blocks properly if a high percentage of their neighbours are honest nodes.

Finally, the success of the simulated attack is decided if the attacker's blockchain level can surpass the honest blockchain's block level after waiting for the Merchants confirmation and before the attack duration ends. The attack can succeed, fail or be undecided. For example, if a huge percentage of the network is malicious, then the honest network is likely to need a long time to reach the needed block level for the Merchants confirmation.

In the case of success or failure, the two networks need to merge back together by updating their neighbours, allowing the synchronising of all blocks and taking the winning blockchain.

Calculating the Success Probability

To be able to validate the results of the Bitcoin-like Blockchain Simulation with an Alternative History Attack a correct reference value for the success probability is required. Therefore the success probability of an Alternative History Attack needs to be calculated.

Before the formula to calculate the success probability of an alternative history attack is shown, the variables need to be explained. q is *hashRate*, the attacker's percentage of the hash rate of the total network. p is $1 - q$ and the percentage of the honest network [7].

$$p + q = 1 \tag{4.1}$$

It is the goal to calculate the success probability r. If the attacker's hash rate q is equal or bigger than p, then the success probability of the attacker is 100%. Due to the implementation the behaviour of the implementation can deviate from the 100%. For example, the variables *attackDuration*, *confirmations* or the simulation duration can have an impact. If $q < p$, then the upper complex formula with binomial coefficients needs to be calculated.

$$r = \begin{cases} 1 - \sum_{m=0}^{n} \binom{m+n-1}{m} (p^n q^m - p^m q^n), & \text{if } q < p \\ 1, & \text{if } q \geq p \end{cases} \tag{4.2}$$

The formula for $q < p$ is transformed for the implementation. This allows the usage of factorial functions instead of binomial coefficients.

One difference between this formula and the implementation is the attack duration. The formula is not limited by an attack duration, while the implementation has one. We assume the difference is negligible. The default value of the attack duration is 20 blocks. The probability of an attacker winning despite being behind 20 blocks is in most cases very small.

$$r = \begin{cases} 1 - \sum_{m=0}^{n} \frac{(m+n-1)!}{m!\,(n-1)!}(p^n q^m - p^m q^n), & \text{if } q < p \\ 1, & \text{if } q \geq p \end{cases} \tag{4.3}$$

Calculating the Maximal Safe Transaction Value

Using the success probability from Equation (4.3) we can calculate the maximal safe transaction value [7]. B is the block reward, o is the attack duration, α is the discount on stolen goods, and k is the number of attacked merchants.

$$\frac{(1-r)oB}{k(\alpha + r - 1)} \tag{4.4}$$

4.11.3 Implementation

The implementation of double-spending is complex due to the need of splitting up the nodes and having two separate blockchains running at the same time and after the double-spending attack the two networks are merging back together to work on one blockchain.

VConf

The VConf implements the new parameters for the alternative history attack which are mentioned in the Prerequisites (Chapter 4.11.1).

Main

The simulation and also the attack starts in Main. Main checks if an alternative history attack happens and sets up the configuration. After the end of the simulation, Main also sends the results back to the frontend.

VNode

The VNode Model needs a new parameter *isMalicious* as Option[Boolean].

NodeRepoActor

In case of an attack, NodeRepoActor creates/registers nodes with their corresponding type Option[Boolean] in the predefined ratio according to the attacker's hash rate. Malicious nodes are set to Some(true).

DiscoveryActor

The DiscoveryActor updates the neighbours according to the defined Neighbours Discovery Interval. In the case of an active attack, the nodes are only allowed to receive neighbours of the same type (malicious/non-malicious).

NodeActor

The node with the smallest timestamp is allowed to add his block in the NodeActor. Here several conditions are checked to make sure that only in valid cases the blocks are added. In the case of an attack also the status of the attack is determined in the *addBlockIfAlternativeHistoryAttack* function. In the case of a preRestart, the configuration is reset. NodeActor has new property *isEvil*.

VBlock

Robustness increased by considering that in an attack the recipients of a block can be null.

ReducerActor

The ReducerActor calculates the maximal safe transaction value and the success probability of the alternative history attack. It also prepares the other values connected to the attack.

VEventTypes

VEventTypes provides the new figures to the Main.

Frontend

The block tree and branch selection visualization of the frontend was inspired by the double-spending paper [7].

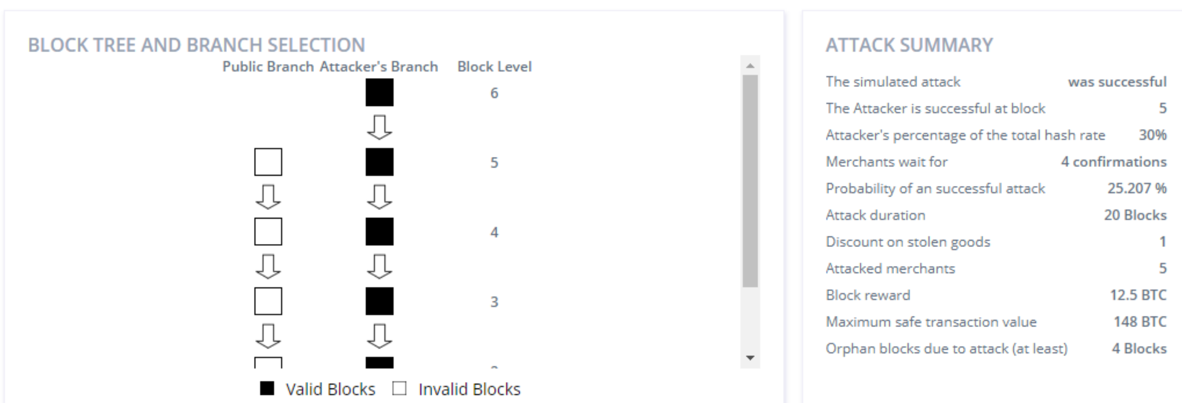


Figure 4.8: Screenshot Block Tree, Branch Selection, and Attack Summary - Attacker wins

Figure 4.8 shows a successful attack. In this case, the attack was successful immediately after the public branch reached the merchants' confirmation requirement. The blocks of the winning branch are shown as black squares and the losing branch's blocks are white. The public branch is always on the left side, the attacker's branch in the middle and the right column shows the block level. In case of a successful attack, only the necessary valid blocks are shown for better visibility.

Figure 4.9 shows a failed attack. As can be seen, the attack failed due to the public branch reaching the end of the attack duration without the attacker's branch overtaking once. The attack duration limit is the reason even attacks with 100% success probability

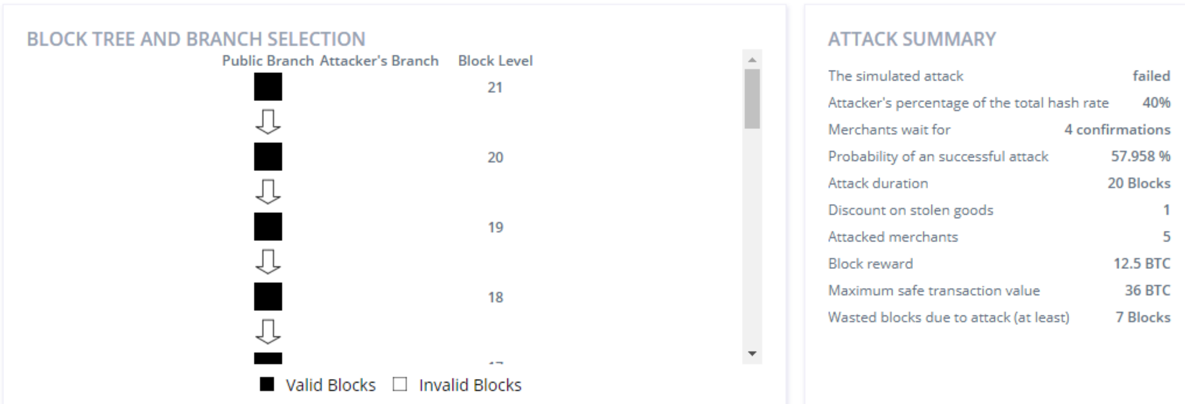


Figure 4.9: Screenshot Block Tree, Branch Selection, and Attack Summary - Attacker loses

can fail, since the attack duration is only considered in the formula for the maximal safe transaction value (4.4) but not in the formula for the success probability (4.3).

Figure A.3 shows an undecided attack. The outcome "ATTACK NEITHER SUCCESSFUL NOR FAILED" can happen if the simulation time was too short.

Zero Confirmations: Race or Finney Attack

In the case of zero confirmations the simulation assumes the attack was successful because of a race or Finney attack.

4.12 Frontend

The React Google Charts package was used for all the charts [48]. During development, some error messages appeared about *loader.js* which is working correctly now [49] [50].

One of the main focuses of this paper is the frontend. Previously not everything captured by VIBES was visualised. This paper added lots of interesting graphics like block tree and branch selection, block time, pending transactions, processed transactions, transaction status and transactions fees and also new figures about double-spending, transactions and staleBlocks to the frontend. But there may still very interesting information that has not yet been analysed or visualized. These graphics and figures were chosen to validate the correctness of the changes to the backend and can also be used for research questions about double-spending, transaction fees, transaction status, tps etc.

Chapter 5

Evaluation

For the evaluation of the approach the same six criteria from VIBES are taken: correctness, speed, scalability, flexibility, extensibility and powerful visuals. These criteria must be at least maintained or improved. Additionally, new use cases are showcased.

5.1 Correctness

The evaluation of the correctness of the simulator's frontend output is essential. By validating the output of the frontend we also validate the output of the backend.

Some parts of the evaluations are sample testing for consistency between the input parameters, expected and simulated or calculated output. Other parts are empirically tested.

For the calculation of the probability of a successful double spend and the maximal safe transaction value sample testing is used. For validating the success probability of simulated double spends empirical testing is applied.

5.1.1 Block Size Limit

Average block size =¡ Non-SegWit maximal block size

Total number of processed transactions =¡ Non-SegWit maximal transactions per block * Blocks

5.1.2 Segregated Witness

Average block size =¡ SegWit maximal block weight =¡ SegWit theoretical block weight limit

Total number of processed transactions =¡ SegWit maximal transactions per block * Blocks

5.1.3 Simulated and Expected Transaction Incentives

If the number of process transactions per block is smaller than the maximum number of transactions per block, then the transaction incentives have no impact. For the evaluation of transaction incentives we take a look at the Figures 4.5, 4.6 and 4.7 which are all based on scenarios with full blocks.

Transactions with higher fees should have a better confirmation status

The first expectation is transaction with higher transaction fees should have preference over transaction with lower transaction fees, therefore in the transaction confirmation status chart the lower transaction fees should have a higher percentage of unconfirmed transactions. The simulated results confirm this expectation.

Transactions with higher fees should have a shorter average transaction confirmation time

The second expectation is transactions with higher transaction fees should have a shorter average transaction confirmation time. The simulated results confirm this expectation.

5.1.4 Transaction Spam

The Screenshot Transaction Spam 4.7 shows the simulated results which match the following expected results.

No transaction confirmed with transaction fee below the target

No transaction below the target transaction fee is expected. The charts about the transaction confirmation status and the average transaction confirmation time and the flood attack summary show that no confirmed transaction has a transaction fee below the target.

All blocks are full

One of the requirements of a transaction spam attack is that the blocks need to be full to block the transactions with fees below the target. All blocks in Figure 4.7 are full, except for the genesis block. There are 28 blocks, the maximum number of transactions per block is 100, so 2.700 transactions are expected and simulated.

Flood attack transaction buffer is not shrinking

To guarantee that no transaction below the target is confirmed, the flood attack transaction buffer should not decrease and stay constant. The number of pending flood attack transactions stays constant in the pending transaction chart.

5.1.5 Expected and Simulated Transactions per Second

For the evaluation of correctness of the transactions per second (tps) of our simulation, the formula for the calculation of *tps* is compared to the implementation.

$$\text{tps} = \text{transactions per block}/\text{block time} \tag{5.1}$$

Since the *tps* for the whole simulation is an important key metric, the division is not done for one block, but instead for all blocks.

```
var tps: Double = longestChainNumberTransactions.toDouble /
    ↪ secondsBetween(VConf.simulationStart,
    ↪ VConf.simulateUntil).getSeconds.toDouble
```

As can be seen, the formulas are identical and therefore the result should be correct. Sample testing is done to check for implementation errors.

Sample with a Simulation Duration of Six Hours

For the first sample a short simulation of six hours is chosen. The chosen block time is 567 seconds and the chosen throughput is 105 transactions per block (*tpb*).

Calculation of the expected total processed transactions *pt*:

$$pt = 6\text{h}/567\text{sec} * 105\text{tpb} = 6 * 60 * 60/567 * 105 = 4000 \tag{5.2}$$

Calculation of the expected *tps*:

$$\text{tps} = 4000\text{transactions}/6\text{h} = 0.185 \tag{5.3}$$

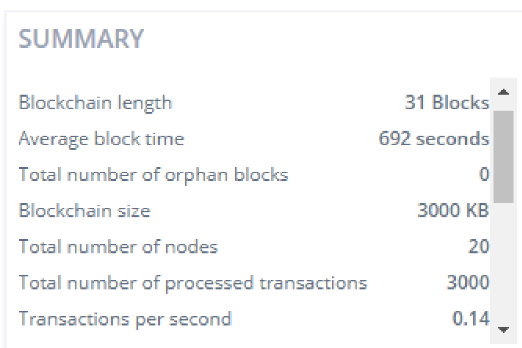


Figure 5.1: Screenshot Transactions per Second - 6h Simulation Duration

As can be seen in Table 5.1, for such a short simulation the tps is off by about 30%. One reason for this significant difference is the difference in the block time between the simulated and expected values. This can be due to variance. To reduce block time variance a longer simulation time is chosen as a second sample.

The parameters for reproduction can be found in Chapter A.3.

Table 5.1: Simulated and expected results of transactions per second: Sample with 6h simulation duration

Metric	**Simulation**	**Expectation**
Block time	692	567
Total number of processed transactions	3000	4000
Transactions per second	0.14	0.185

Sample with a Duration of 48 Hours

For the second sample a longer simulation of 48 hours is chosen. The chosen block time is still 567 seconds and the chosen throughput is also still 105 transactions per block (*tpb*).

Calculation of the expected total processed transactions:

$$\text{pt} = 48h/567\text{sec} * 105\text{tpb} = 48 * 60 * 60/567 * 105 = 32000 \tag{5.4}$$

Of course the expected tps stays the same, since only the simulation duration parameter has been changed.

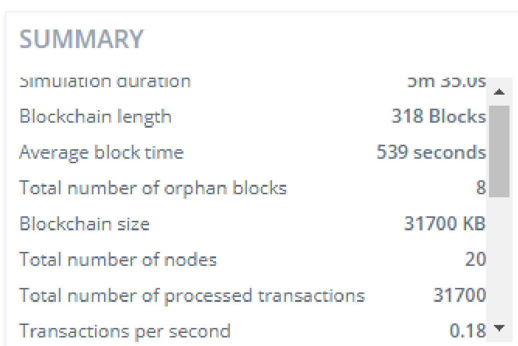


Figure 5.2: Screenshot Transactions per Second - 48h Simulation Duration

It can be observed in the second comparative table 5.2, that a longer simulation duration leads the simulated block time to be closer to the expected block time. As a result the simulated *tps* is close to the expected value.

The parameters for reproduction can be found in Chapter A.3.

Table 5.2: Simulated and expected results of transactions per second: Sample with 48h simulation duration

Metric	Simulation	Expectation
Block time	539	567
Total number of processed transactions	31700	32000
Transactions per second	0.18	0.185

5.1.6 Expected and Calculated Probability of a Successful Double-Spending Attack

The probability of a successful double-spending attack is tested with five samples and the results are compared to the Figure A.1 from the research paper *Analysis of Hashrate-Based Double Spending* [7].

The variable q stands for the hashrate, the variable n is the number of confirmations. The edge cases q = 2% and n = 1, q = 2% and n = 10, q = 50% and n = 1 and q = 50% and n = 10 are tested as well as the common case of q = 30% and n = 6.

Table 5.3: Expected and Calculated Probabilities of a Successful Double-Spending Attack

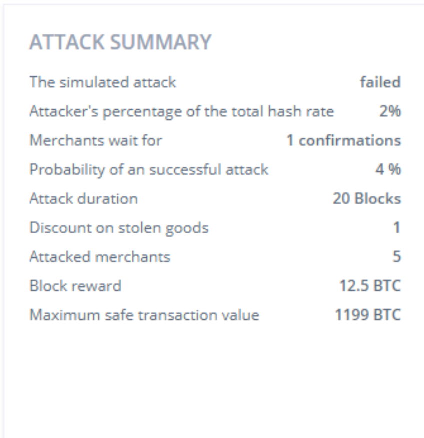
Sample	n	q	Calculated Probability	Expected Probability
a	2	1	4%	4%
b	2	10	0%	0%
c	50	1	100%	100%
d	50	10	100%	100%
e	30	6	15.645%	15.645%

All mentioned test cases in Figure 5.3 match the expected result.

5.1.7 Expected and Calculated Maximal Safe Transaction Value

For the test of the maximal safe transaction value the samples from the evaluation of the successful double spend probability are reused and compared to Figure A.2.

The additional input parameters were:



ATTACK SUMMARY

The simulated attack	failed
Attacker's percentage of the total hash rate	2%
Merchants wait for	1 confirmations
Probability of an successful attack	4 %
Attack duration	20 Blocks
Discount on stolen goods	1
Attacked merchants	5
Block reward	12.5 BTC
Maximum safe transaction value	1199 BTC

(a) Sample with input: q = 2% and n = 1

ATTACK SUMMARY

The simulated attack	failed
Attacker's percentage of the total hash rate	2%
Merchants wait for	10 confirmations
Probability of an successful attack	0 %
Attack duration	20 Blocks
Discount on stolen goods	1
Attacked merchants	5
Block reward	12.5 BTC
Maximal safe transaction value	∞ BTC
Wasted blocks due to attack (at least)	1 Blocks

(b) Sample with input: q = 2% and n = 10

ATTACK SUMMARY

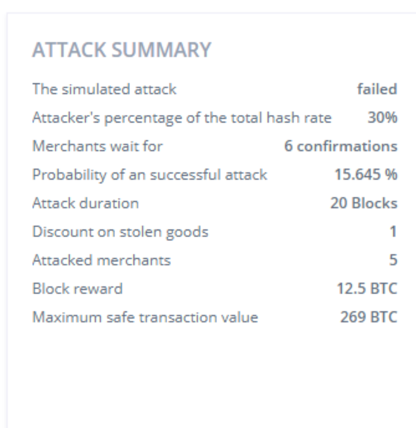
The simulated attack	was successful
The Attacker is successful at block	2
Attacker's percentage of the total hash rate	50%
Merchants wait for	1 confirmations
Probability of an successful attack	100 %
Attack duration	20 Blocks
Discount on stolen goods	1
Attacked merchants	5
Block reward	12.5 BTC
Maximum safe transaction value	0 BTC

(c) Sample with input: q = 50% and n = 1

ATTACK SUMMARY

The simulated attack	was successful
The Attacker is successful at block	11
Attacker's percentage of the total hash rate	50%
Merchants wait for	10 confirmations
Probability of an successful attack	100 %
Attack duration	20 Blocks
Discount on stolen goods	1
Attacked merchants	5
Block reward	12.5 BTC
Maximum safe transaction value	0 BTC

(d) Sample with input: q = 50% and n = 10



ATTACK SUMMARY

The simulated attack	failed
Attacker's percentage of the total hash rate	30%
Merchants wait for	6 confirmations
Probability of an successful attack	15.645 %
Attack duration	20 Blocks
Discount on stolen goods	1
Attacked merchants	5
Block reward	12.5 BTC
Maximum safe transaction value	269 BTC

(e) Sample with input: q = 30% and n = 6

Figure 5.3: Screenshots Success Probability of Double-Spending

- Attack duration: 20 Blocks
- Discount on stolen goods: 1
- Attacked merchants: 5
- Block reward: 12.5 BTC

Compared to the *Analysis of Hashrate-Based Double Spending* paper the block reward was updated from 25 BTC to the current block reward of 12.5 BTC. This means the maximal safe transaction values need to be doubled to compare them with the correct values.

Table 5.4: Expected and Calculated Maximal Safe Transaction Values (MSTV)

Sample	**n**	**q**	**Calculated MSTV**	**Expected MSTV**
a	2	1	1199 BTC	1200 BTC
b	2	10	∞ BTC	∞ BTC
c	50	1	0 BTC	0 BTC
d	50	10	0 BTC	0 BTC
e	30	6	269 BTC	269.5 BTC

Ignoring minor rounding differences in samples (a) and (e), all test cases in Figure 5.3 match the expected result. The sample with ∞ BTC is a special case, the frontend displays ∞ BTC in the case of receiving 2,147,483,647 BTC which is the maximal possible 32-bit signed integer value. 2,147,483,647 BTC is much more than the hard supply limit of 21 million BTC.

5.1.8 Expected and Simulated Success Probability of Double Spending

The success probability for the scenario with q = 30% and n = 6 is reused from Chapter 5.1.6.

For the empirical testing of double-spending a script was used, it can be found in Chapter A.3 for reproduction. It starts the simulation, waits for a certain time to let the simulation finish and repeats this for a total of 100 times.

Table 5.5: Double-spending outcomes and their simulated and expected probabilities

Outcome	**Occurrences**	**Simulated probability**	**Expected probability**
Attack neither successful nor failed	45	-	-
Attack successful	8	15.09%	15.645%
Attack failed	47	84.91%	84.355%
TOTAL	**100**	**100%**	**100%**

After counting the occurrences of the outcomes in the logfile, they were summarized in Table 5.5. All simulations were finished in the specified time. The undecided attacks are ignored for the calculation of the probabilities. It is assumed that the unfinished simulations have a similar probability distribution like the finished ones. The simulated probability of the double-spending attack is with 15.09% very close to the expected probability of 15.645%, which was calculated in Chapter 5.1.6. Hereby is shown that the simulation of double-spending has the correct success probability.

5.2 Speed

To make sure there are no significant performance losses introduced by the implementation of bitcoin, we compare the simulation results from BBSS with VIBES.

5.3 Scalability

The block size limit, the block weight limit and the target transaction fee in the case of a flood attack are in $O(1)$ and do not effect the performance, except for requiring increasing memory if the throughput is higher than the maximal transactions per block.

For examining the effect of the hashrate in case of a double-spending attack on the scalability, multiple simulations were executed. Figure 5.4 show there is no significant difference in simulation duration because of a varying hashrate.

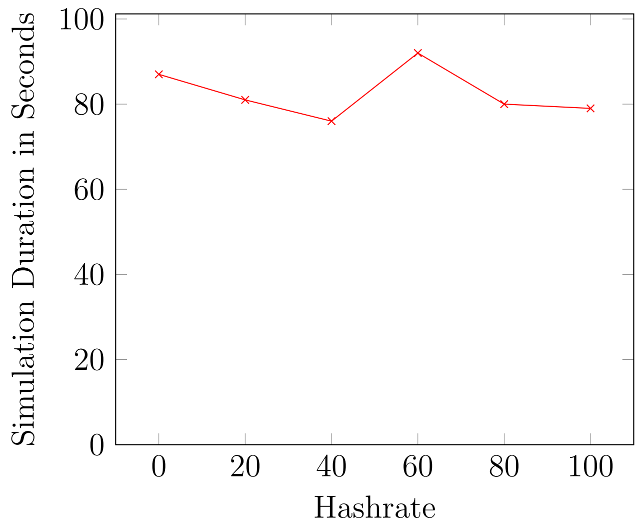


Figure 5.4: Effect of Hashrate on Simulation Duration

5.4 Limitations of Speed and Scalability

There are certain limitations on the simulator. One of the goals of the simulator is that the execution time of the simulation is shorter than the simulated duration. With increasing nodes and transactions, there is a point when the execution time equals the simulation time. In this chapter we want to examine this relationship and the resulting speedup ratio. The speedup ratio is the simulated duration divided by the execution duration.

All computations were done on a Home PC with Windows Ultimate 64-bit, Intel i7-4770 CPU @ 3.40 GHz and 16.0 GB 1600 MHz DD3.

The simulations were done with an equal number of nodes and transactions. This seems to be a good ratio for the simulator, which allows lots of parallel computation.

The Table 5.6 and the Figure 5.5 shows the results of the simulations and the declining speedup ratio with increasing nodes and transactions. The values in the table should be considered as approximations, since only one simulation per number of nodes and transactions was done and the block time deviations can have an impact on the speedup ratio. One of the consequences deriving from this table is that it is not feasible to do a simulation with the configuration of the real-world bitcoin network with ten thousand nodes and one thousand tpb on a Home PC.

Of course, other configuration parameters than nodes and transactions like block size limit or block weight limit have a limiting impact due to the increasing memory requirement.

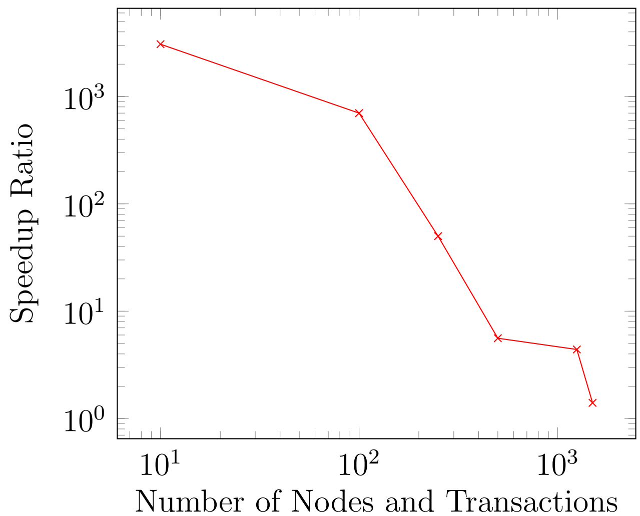


Figure 5.5: Effect of Hashrate on Simulation Duration

Table 5.6: Effect of Number of Nodes and Transactions on the Speedup Ratio

Number of Nodes and Transactions	Simulation Duration in Seconds	Execution Duration in Seconds	Speedup Ratio
10	21480	7	3070
100	21120	30	700
250	19140	373	50
500	6900	1228	5.6
1250	3045	697	4.4
1500	3060	2188	1.4

5.4.1 Realistic Bitcoin Network Simulation with AWS

Amazon Web Service (AWS) is used to find out if it is actually possible to simulate a bitcoin network with ten thousand nodes and thousand tpb. The instance typ t2.2xlarge has a similar performance to the used Home PC and therefore doesn't have the required performance. The instance type p3.2xlarge was chosen, since it is advertised as "high performance computing" and as "ideal platform for technical simulations".

Instance-Größe	GPUs – Tesla V100	GPU-Peer-to-Peer	GPU-Speicher (GB)	vCPUs	Speicher (GB)	Netzwerkbandbreite	EBS-Bandbreite	On-Demand-Preis/Std.*	1 Jahr lang Reserved Instance pro Stunde*	3 Jahre lang Reserved Instance pro Stunde*
p3.2xlarge	1	–	16	8	61	Bis zu 10 GBit/s	1,5 GBit/s	3,06 USD	1,99 USD	1,23 USD

Figure 5.6: Screenshot AWS p3.2xlarge

Using various tools we asumme the following configuration parameters:

- strategy=BITCOIN_LIKE_BLOCKCHAIN
- simulateUntil=1 hour
- blockTime=600
- numberOfNeighbours=15
- numberOfNodes=10000 [51]
- neighboursDiscoveryInterval=3000
- latency=900
- transactionSize=700 [52]
- maxBlockSize=0
- throughput=1300 [53]
- transactionWeight=1400
- maxBlockWeight=4000000
- networkBandwidth=1
- transactionPropagationDelay=150
- hashRate=0
- confirmations=0
- transactionFee=0

With these configuration parameters the simulator uses only about 20% CPU. This means realistic parameters do not allow lots of parallel computing.

5.5 Flexibility

asdf

5.6 Extensibility

asdf

5.7 Powerful Visuals

5.8 Use Cases

This thesis made new use cases possible, some of which are presented in the following chapter.

5.8.1 Optimising Transactions per Second

Scalability is one of the biggest issues of bitcoin-like blockchains. The simulator could be used to optimised the tps of bitcoin.

[54]

for example block size increase like in research paper..

5.8.2 Securing a Blockchain Merchant

5.8.3 Choosing Transaction Fees

5.8.4 Flood Attack

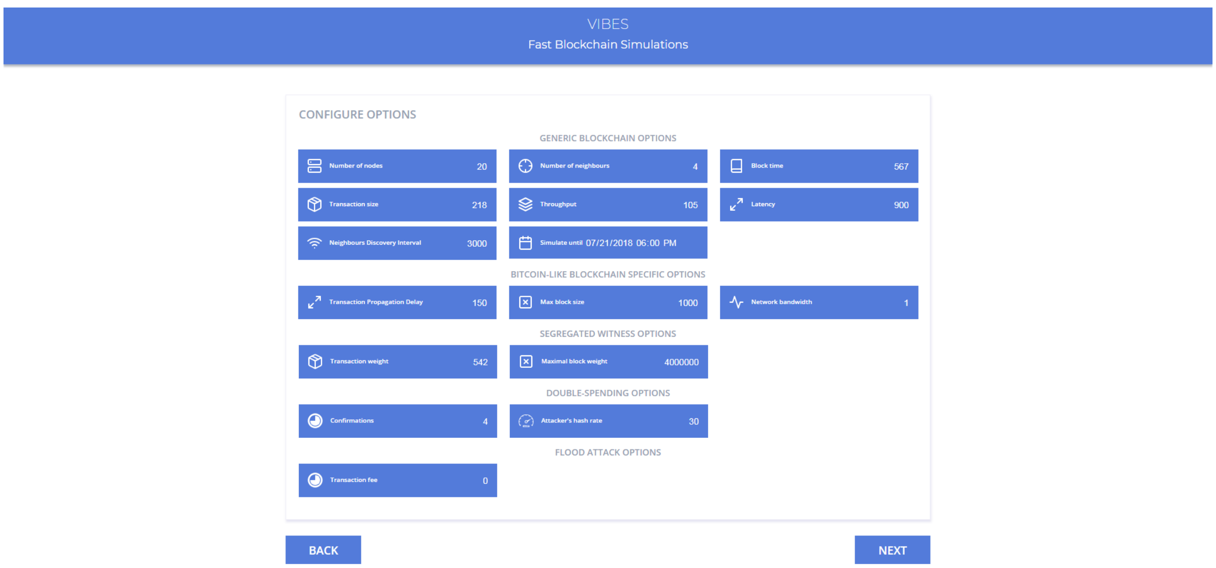


Figure 5.7: Screenshot Configuration

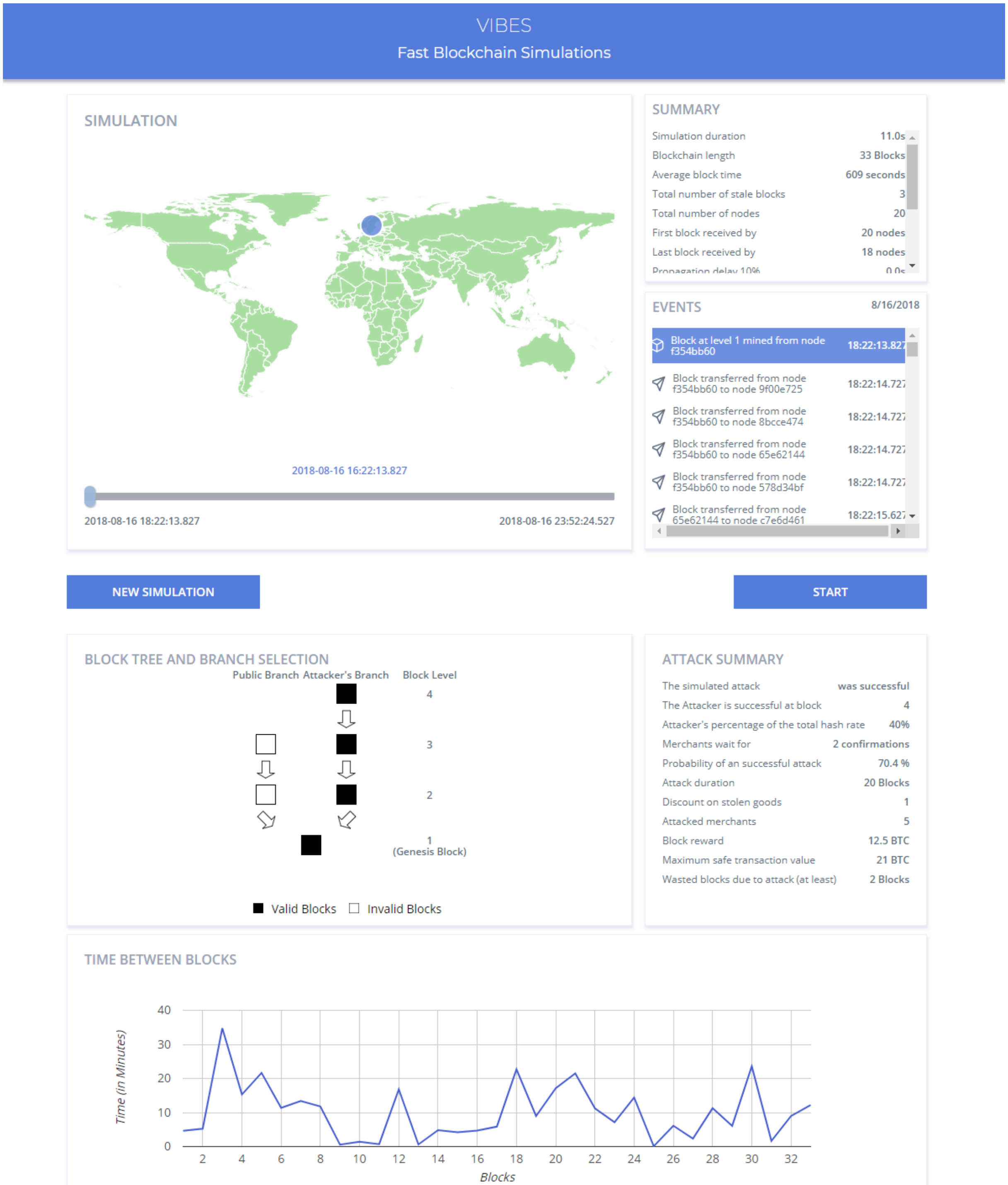


Figure 5.8: Screenshot Simulation - Part 1

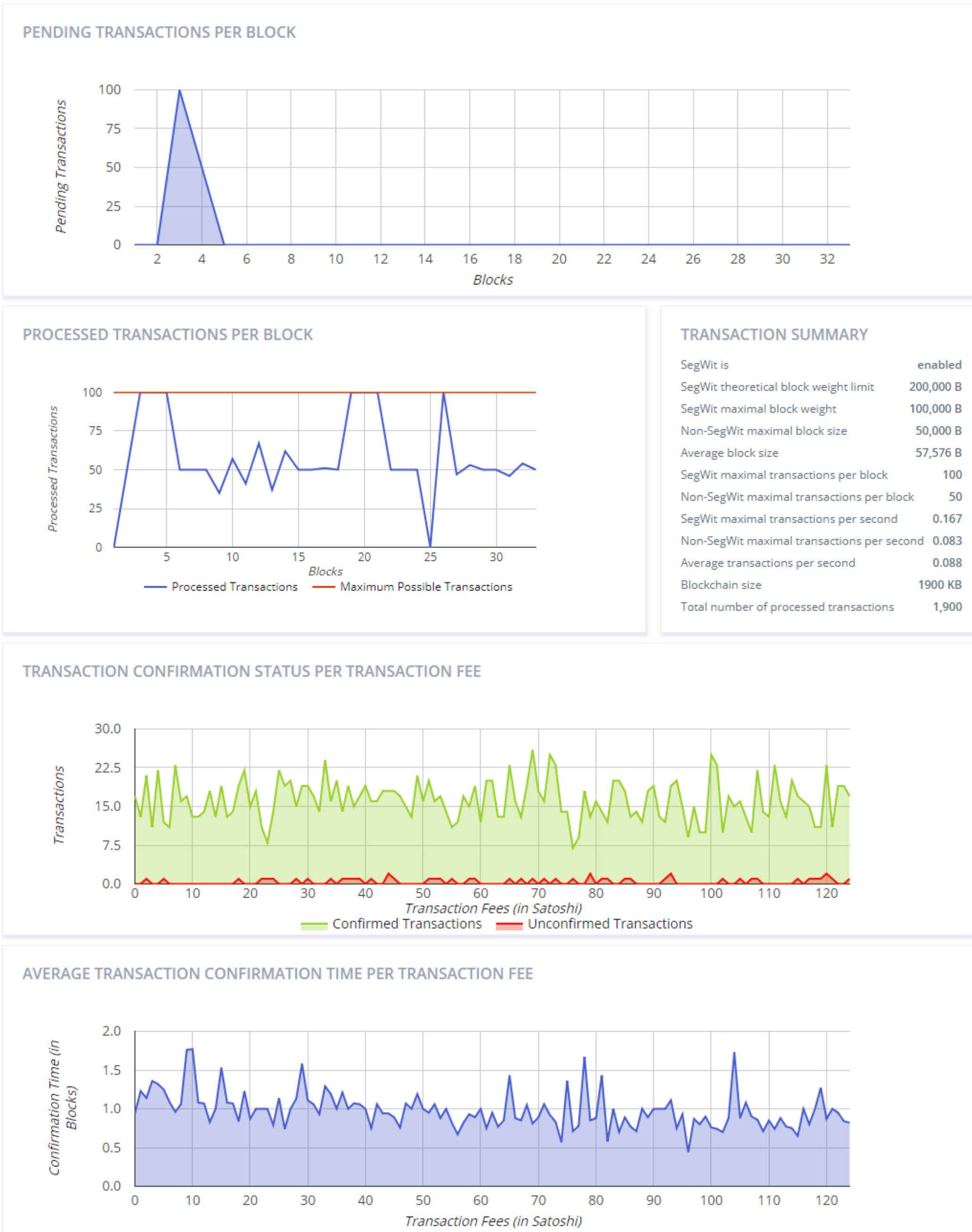


Figure 5.9: Screenshot Simulation - Part 2

Chapter 6

Summary

Summary

6.1 Status

Final Status of the Thesis

6.2 Conclusions

Concluding remarks of Thesis

6.3 Future Work

Future Work

for bitcoin related stuff

node != miner selfish mining mining pools

transaction sizes differ

difficulty adjustment for long simulations ¿2 weeks, flexible hashpower, flexible nodes

Appendices

Appendix A

Appendix

A.1 Installation and Usage Instructions

A.1.1 Installation Frontend

Install npm

You need to install the npm package manager as documented: `https://www.npmjs.com/`

Install yarn

Then install yarn: `https://yarnpkg.com/lang/en/docs/install/`

Install package.json dependencies

After the installation is done you can navigate to the frontend folder of the project and run *yarn install*.

A.1.2 Installation Backend

SBT

The only thing you need to install is SBT (interactive scala build tool) as documented: `https://www.scala-sbt.org/`

A.1.3 Run

Windows

Navigate to the root folder and run *start frontend and backend.bat* to start the frontend and backend server. Go to `http://localhost:8080/` with your browser.

Linux

Run *yarn dev* to start the frontend, run *sbt server/run* to start the backend.

A.1.4 Inspecting the output of the backend

Start your backend. Then enter the following URL into the browser of your choice after you have adjusted the timestamp of the simulateUntil parameter.

```
http://localhost:8082/vibe?strategy=BITCOIN_LIKE_BLOCKCHAIN&simulateUntil
    ↪ =1534457813308&blockTime=600&numberOfNeighbours=4&numberOfNodes=20&
    ↪ neighboursDiscoveryInterval=3000&latency=900&transactionSize=1000&
    ↪ maxBlockSize=50&throughput=50&transactionWeight=2000&maxBlockWeight
    ↪ =200000&networkBandwidth=1&transactionPropagationDelay=150&hashRate
    ↪ =40&confirmations=2&transactionFee=0
```

The browser shows the simulation results that are fetched by the frontend from the backend.

A.2 Source code

Available at `https://github.com/i13-msrg/vibes/tree/FabianSchuessler`.

A.3 Simulations

The simulateUntil parameter of the following URLs to reproduce the evaluation results has to be adjusted. New features might make additional parameters necessary.

Expected and Simulated Success Probability of Double Spending

```
ECHO Start of Loop

FOR /L %%i IN (1,1,100) DO (
  ECHO %%i
  start chrome "http://localhost:8082/vibe?blockTime=567&
      ↪ numberOfNeighbours=4&numberOfNodes=20&simulateUntil
      ↪ =1531411943382&transactionSize=1&throughput=105&latency=900&
      ↪ neighboursDiscoveryInterval=3000&maxBlockSize=100&maxBlockWeight
      ↪ =4000&networkBandwidth=1&strategy=BITCOIN_LIKE_BLOCKCHAIN&
      ↪ transactionPropagationDelay=150&hashRate=30&confirmations=6"
  timeout /t 40
)
```

Expected and Simulated Transactions per Second - 6 hours

```
http://localhost:8082/vibe?blockTime=567&numberOfNeighbours=4&
    ↪ numberOfNodes=20&simulateUntil=1531752759474&transactionSize=1&
    ↪ throughput=105&latency=900&neighboursDiscoveryInterval=3000&
    ↪ maxBlockSize=100&maxBlockWeight=4000&networkBandwidth=1&strategy=
    ↪ BITCOIN_LIKE_BLOCKCHAIN&transactionPropagationDelay=150&hashRate=0&
    ↪ confirmations=4
```

Expected and Simulated Transactions per Second - 48 hours

```
http://localhost:8082/vibe?blockTime=567&numberOfNeighbours=4&
    ↪ numberOfNodes=20&simulateUntil=1531905360000&transactionSize=1&
    ↪ throughput=105&latency=900&neighboursDiscoveryInterval=3000&
    ↪ maxBlockSize=100&maxBlockWeight=4000&networkBandwidth=1&strategy=
    ↪ BITCOIN_LIKE_BLOCKCHAIN&transactionPropagationDelay=150&hashRate=0&
    ↪ confirmations=4
```

A.4 Tables

q	1	2	3	4	5	6	7	8	9	10
2%	4%	0.237%	0.016%	0.001%	≈ 0	≈ 0	≈ 0	≈ 0	≈ 0	≈ 0
4%	8%	0.934%	0.120%	0.016%	0.002%	≈ 0	≈ 0	≈ 0	≈ 0	≈ 0
6%	12%	2.074%	0.394%	0.078%	0.016%	0.003%	0.001%	≈ 0	≈ 0	≈ 0
8%	16%	3.635%	0.905%	0.235%	0.063%	0.017%	0.005%	0.001%	≈ 0	≈ 0
10%	20%	5.600%	1.712%	0.546%	0.178%	0.059%	0.020%	0.007%	0.002%	0.001%
12%	24%	7.949%	2.864%	1.074%	0.412%	0.161%	0.063%	0.025%	0.010%	0.004%
14%	28%	10.662%	4.400%	1.887%	0.828%	0.369%	0.166%	0.075%	0.034%	0.016%
16%	32%	13.722%	6.352%	3.050%	1.497%	0.745%	0.375%	0.190%	0.097%	0.050%
18%	36%	17.107%	8.741%	4.626%	2.499%	1.369%	0.758%	0.423%	0.237%	0.134%
20%	40%	20.800%	11.584%	6.669%	3.916%	2.331%	1.401%	0.848%	0.516%	0.316%
22%	44%	24.781%	14.887%	9.227%	5.828%	3.729%	2.407%	1.565%	1.023%	0.672%
24%	48%	29.030%	18.650%	12.339%	8.310%	5.664%	3.895%	2.696%	1.876%	1.311%
26%	52%	33.530%	22.868%	16.031%	11.427%	8.238%	5.988%	4.380%	3.220%	2.377%
28%	56%	38.259%	27.530%	20.319%	15.232%	11.539%	8.810%	6.766%	5.221%	4.044%
30%	60%	43.200%	32.616%	25.207%	19.762%	15.645%	12.475%	10.003%	8.055%	6.511%
32%	64%	48.333%	38.105%	30.687%	25.037%	20.611%	17.080%	14.226%	11.897%	9.983%
34%	68%	53.638%	43.970%	36.738%	31.058%	26.470%	22.695%	19.548%	16.900%	14.655%
36%	72%	59.098%	50.179%	43.330%	37.807%	33.226%	29.356%	26.044%	23.182%	20.692%
38%	76%	64.691%	56.698%	50.421%	45.245%	40.854%	37.062%	33.743%	30.811%	28.201%
40%	80%	70.400%	63.488%	57.958%	53.314%	49.300%	45.769%	42.621%	39.787%	37.218%
42%	84%	76.205%	70.508%	65.882%	61.938%	58.480%	55.390%	52.595%	50.042%	47.692%
44%	88%	82.086%	77.715%	74.125%	71.028%	68.282%	65.801%	63.530%	61.431%	59.478%
46%	92%	88.026%	85.064%	82.612%	80.480%	78.573%	76.836%	75.234%	73.742%	72.342%
48%	96%	94.003%	92.508%	91.264%	90.177%	89.201%	88.307%	87.478%	86.703%	85.972%
50%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Figure A.1: The probability of a successful double spend, as a function of the attacker's hashrate q and the number of confirmations n. The abscissa shows the confirmations n and the ordinate shows the attacker's hashrate q. [7]

q	1	2	3	4	5	6	7	8	9	10
2%	2400	42K	644K	9370K	$\approx\infty$	$\approx\infty$	$\approx\infty$	$\approx\infty$	$\approx\infty$	$\approx\infty$
4%	1150	10K	82K	615K	4437K	$\approx\infty$	$\approx\infty$	$\approx\infty$	$\approx\infty$	$\approx\infty$
6%	733	4722	25K	127K	626K	3018K	14M	$\approx\infty$	$\approx\infty$	$\approx\infty$
8%	525	2650	10K	42K	159K	588K	2144K	7749K	$\approx\infty$	$\approx\infty$
10%	400	1685	5741	18K	56K	168K	503K	1486K	4361K	12M
12%	316	1158	3391	9212	24K	62K	157K	396K	990K	2460K
14%	257	837	2172	5200	11K	27K	60K	132K	290K	632K
16%	212	628	1474	3178	6580	13K	26K	52K	102K	200K
18%	177	484	1043	2061	3901	7202	13K	23K	42K	74K
20%	150	380	763	1399	2453	4190	7039	11K	19K	31K
22%	127	303	571	983	1615	2582	4053	6288	9671	14K
24%	108	244	436	710	1103	1665	2467	3608	5229	7525
26%	92	198	337	523	775	1113	1570	2182	3005	4106
28%	78	161	263	392	556	766	1035	1377	1815	2372
30%	66	131	206	296	406	539	701	899	1141	1435
32%	56	106	162	225	299	385	485	602	740	901
34%	47	86	127	172	221	277	340	411	491	582
36%	38	69	99	130	164	200	240	283	331	383
38%	31	54	76	98	121	144	169	196	224	254
40%	25	42	57	72	87	102	118	134	151	168
42%	19	31	41	51	61	70	80	90	99	109
44%	13	21	28	34	40	46	51	57	62	68
46%	8	13	17	21	24	27	30	32	35	38
48%	4	6	8	9	10	12	13	14	15	16
50%	0	0	0	0	0	0	0	0	0	0

Figure A.2: The maximal safe transaction value, in BTC, as a function of the attacker's hashrate q and the number of confirmations n. The abscissa shows the confirmations n and the ordinate shows the attacker's hashrate q. [7]

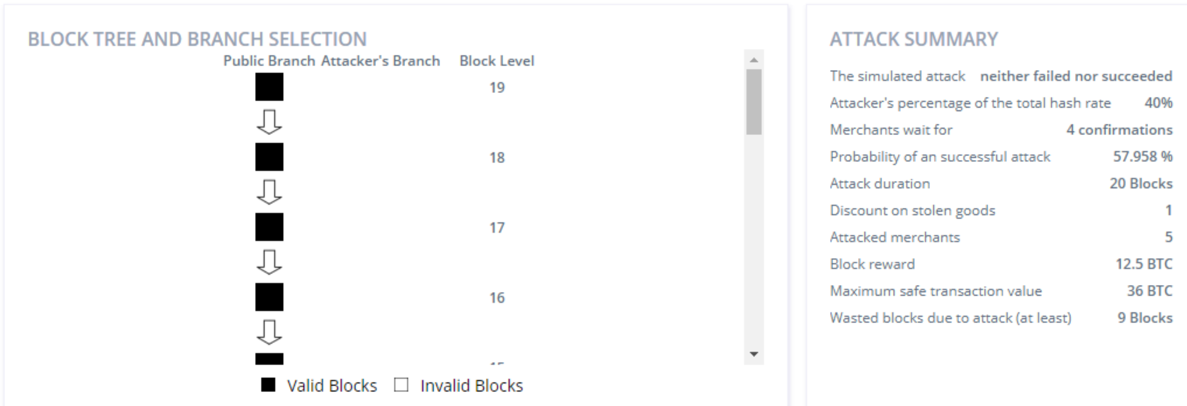


Figure A.3: Screenshot Block Tree, Branch Selection, and Attack Summary - Attack undecided

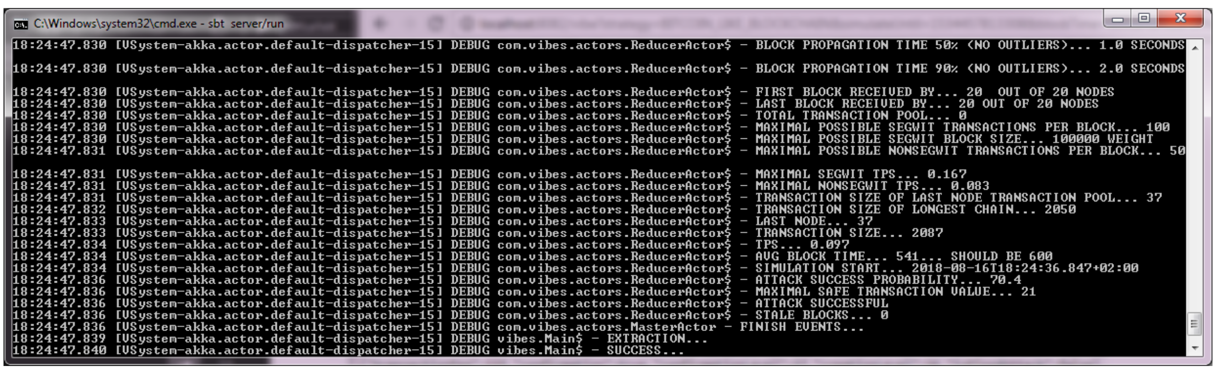


Figure A.4: Screenshot Backend Console

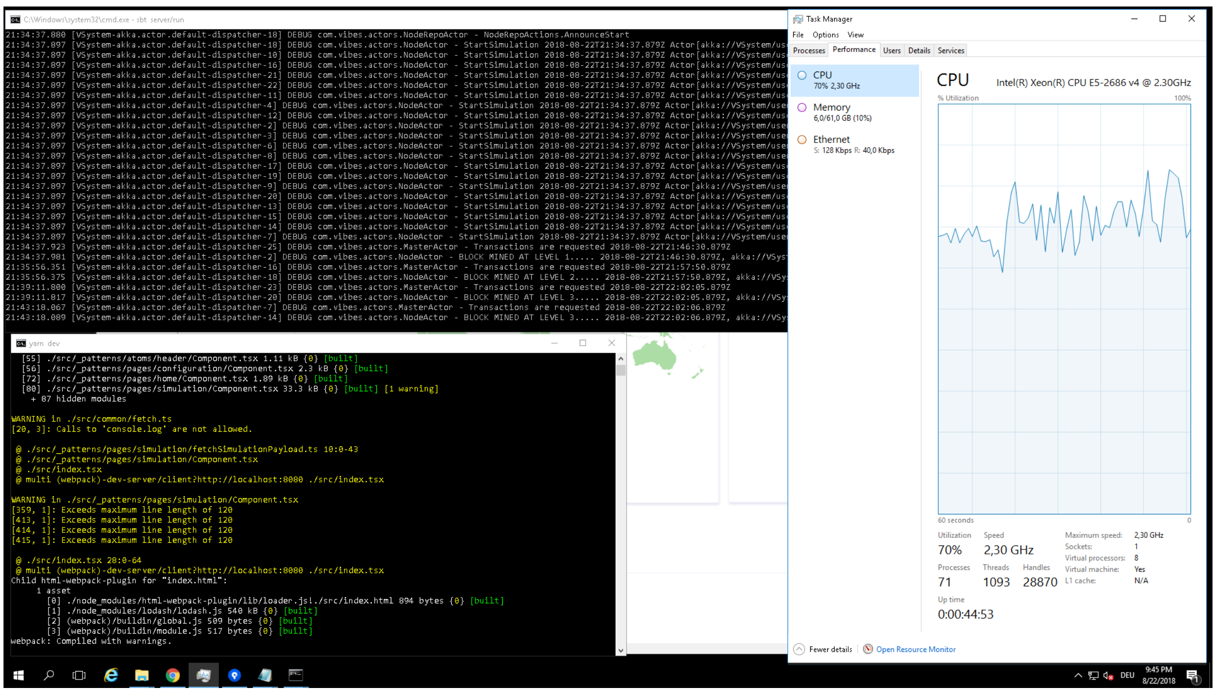


Figure A.5: Screenshot BBSS on AWS

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