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PROCESSING OF THE BLOCKCHAIN EMPLOYING IPFS

VYUŽITÍ IPFS PRO ZPRACOVÁNÍ BLOCKCHAINU

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Abstract

This work aims to design a system for processing blockchain data of selected cryptocurrencies for further exploring using IPFS. In this thesis, we created a proprietary decentralized and distributed database system that supports simple queries. The solution provides a well-arranged graphical user interface for data visualization as well as REST API, which makes it easy to connect to other systems. The benefit of this work is a new view of blockchain processing which opens up new possibilities in its exploring.

Abstrakt

Cieľom tejto práce je navrhnuť systém na spracovanie a preskúmavanie blockchainu vybraných kryptomien pri použití IPFS. Na riešenie tohoto problému bolo potrebné navrhnuť vlastný decentralizovaný a distribuovaný databázový systém, ktorý podporuje jednoduché dotazy. Vytvorené riešenie poskytuje prehľadné grafické užívateľské rozhranie, ktoré slúži na vizualizáciu dát a taktiež RestAPI, vďaka ktorému sa dá systém jednoducho napojiť na iné systémy. Prínosom tejto práce je nový pohľad na zpracovávanie blockchainu čo otvára nové možnosti v jeho prehľadávaní.

Keywords

IPFS, decentralization, blockchain, cryptocurrecny

Klíčové slová

IPFS, decentralizácia, blockchain, cryptocurrecny

Reference

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Processing of the Blockchain Employing IPFS

Declaration

I declare that this semester project was prepared as an original author's work under the supervision of Mr. Ing. Vladimír Veselý, PhD. All the relevant information sources, which were used during the preparation of this project, are cited and included in the list of references.

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Matúš Múčka

April 20, 2020

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Chapter 1

Introduction

HTTP is “good enough” for the most use cases of distributing files over the network. However, when we want to stream lots of data to multiple connected clients at once, we are starting to hit its limits. When two clients are requesting the same data, there is no mechanism in HTTP that would allow sending the data only once. Sending duplicate data has become a problem in large companies because of bandwidth capacity. Blizzard¹ started to distribute video game content via a distributed solution because it was cheaper for the company and faster for players[7]. Linux distributions use BitTorrent to transmit disk images².

The Bitcoin blockchain has now 242 gigabytes³. When blockchain is processed (all its data are parsed), the size can grow twice as much. If there are multiple blockchains, then data can have few terabytes. When we are sharing blockchains data from the server for several clients, there is a big chance that multiple clients want the same data. They may be working on the same case and investigating the same wallets. So in standard solution with relational database and some HTTP server, the server has to search in all data (that can have a size of few terabytes) and transmits selected data to the client for every request. This problem happens even if a different client asks for the same data in a few minutes ago. Behaviour mentioned above dramatically limits the scalability of the server.

Services that are using HTTP, often have client-server architecture, so there is also a problem with a single point of failure. If the server for some reason stops working, the client can not receive data. In distributed file system such as IPFS, there is no such problem as one point of failure because all data are duplicated on multiple clients.

This Semestral project is divided into six chapters. Chapter 2 describes the differences between cryptocurrencies used in this project. Chapter 3 describes IPFS and all its layers. Design of the system created in this thesis is in Chapter 4. The implementation of all applications that are provided with this project is in chapter 5. Finally, summarization of results achieved in this work is in chapter 7.

¹Game company - <https://www.blizzard.com/>

²Image of Debian downloadable by BitTorrent <https://www.debian.org/CD/torrent-cd/>

³Current size of bitcoin blockchain can be seen at <https://www.statista.com/statistics/647523/worldwide-bitcoin-blockchain-size/>

Chapter 2

Cryptocurrencies

There were hundreds of failed attempts of creating cryptographic payment systems before cryptocurrencies like Bitcoin and Ethereum came into existence. Some of these systems are listed in Figure 2.1. All of them were created before Bitcoin. Despite that, only a few of them survived to these days. Some of these attempts were only academic proposals while others were deployed and tested systems. One of the survival is PayPal. It is only because it quickly gave up its original idea of hand-held devices for cryptographic payments.[11]

So there is a question, what makes cryptocurrencies successful nowadays? It may be easy to use principle and no need for external hardware. Another critical component of cryptocurrencies discussed in this work is Blockchain. Generally, it is a ledger in which all transactions are securely stored. The idea behind blockchains is pretty old, and it was originally used for timestamping digital documents.[5]

| | | | | |
|---------------|-----------------------|----------------|------------------|-------------------|
| ACC | CyberCents | iKP | MPTP | Proton |
| Agora | CyberCoin | IMB-MP | Net900 | Redi-Charge |
| AlIMP | CyberGold | InterCoin | NetBill | S/PAY |
| Allopass | DigiGold | Ipin | NetCard | Sandia Lab E-Cash |
| b-money | Digital Silk Road | Javien | NetCash | Secure Courier |
| BankNet | e-Comm | Karma | NetCheque | Semopo |
| Bitbit | E-Gold | LotteryTickets | NetFare | SET |
| Bitgold | Ecash | Lucre | No3rd | SET2Go |
| Bitpass | eCharge | MagicMoney | One Click Charge | SubScrip |
| C-SET | eCoin | Mandate | PayMe | Trivnet |
| CAFÉ | Edd | MicroMint | PayNet | TUB |
| CheckFree | eVend | Micromoney | PayPal | Twitpay |
| ClickandBuy | First Virtual | MilliCent | PaySafeCard | VeriFone |
| ClickShare | FSTC Electronic Check | Mini-Pay | PayTrust | VisaCash |
| CommerceNet | Geldkarte | Minitix | PayWord | Wallie |
| CommercePOINT | Globe Left | MobileMoney | Peppercoin | Way2Pay |
| CommerceSTAGE | Hashcash | Mojo | PhoneTicks | WorldPay |
| Cybank | HINDE | Mollie | Playspan | X-Pay |
| CyberCash | iBill | Mondex | Polling | |

Figure 2.1: Electronic payment systems before cryptocurrencies[9]

2.1 Bitcoin

Bitcoin is probably the most famous cryptocurrency. On 3 January 2009, Satoshi Nakamoto (an alias for a person or group persons authored the bitcoin white paper) mined the genesis block of bitcoin (block with height 0). Satoshi gets the reward of 50 bitcoins (half a million US dollars in the time of writing). This text was embedded in the block (see Figure 2.2): *The Times 03/Jan/2009 Chancellor on brink of second bailout for banks.*¹[3].

| | | | |
|----------|-------------------------|-------------------------|--------------------------|
| 00000000 | 01 00 00 00 00 00 00 00 | 00 00 00 00 00 00 00 00 | |
| 00000010 | 00 00 00 00 00 00 00 00 | 00 00 00 00 00 00 00 00 | |
| 00000020 | 00 00 00 00 3B A3 ED FD | 7A 7B 12 B2 7A C7 2C 3E |;Łiýz{.²zÇ,> |
| 00000030 | 67 76 8F 61 7F C8 1B C3 | 88 8A 51 32 3A 9F B8 AA | gv.a.È.Ã~ŠQ2:Ÿ,ª |
| 00000040 | 4B 1E 5E 4A 29 AB 5F 49 | FF FF 00 1D 1D AC 2B 7C | K.^J)«_IŸŸ...¬+ |
| 00000050 | 01 01 00 00 00 01 00 00 | 00 00 00 00 00 00 00 00 | |
| 00000060 | 00 00 00 00 00 00 00 00 | 00 00 00 00 00 00 00 00 | |
| 00000070 | 00 00 00 00 00 00 FF FF | FF FF 4D 04 FF FF 00 1D |ŸŸŸŸM.ŸŸ.. |
| 00000080 | 01 04 45 54 68 65 20 54 | 69 6D 65 73 20 30 33 2F | ..E The Times 03/ |
| 00000090 | 4A 61 6E 2F 32 30 30 39 | 20 43 68 61 6E 63 65 6C | Jan/2009 Chancel |
| 000000A0 | 6C 6F 72 20 6F 6E 20 62 | 72 69 6E 6B 20 6F 66 20 | lor on brink of |
| 000000B0 | 73 65 63 6F 6E 64 20 62 | 61 69 6C 6F 75 74 20 66 | second bailout f |
| 000000C0 | 6F 72 20 62 61 6E 6B 73 | FF FF FF FF 01 00 F2 05 | or banks ŸŸŸŸ..ò. |
| 000000D0 | 2A 01 00 00 00 43 41 04 | 67 8A FD B0 FE 55 48 27 | *....CA.gŠŸ°pUH' |
| 000000E0 | 19 67 F1 A6 71 30 B7 10 | 5C D6 A8 28 E0 39 09 A6 | .gñ q0·.\Ö"(à9.! |
| 000000F0 | 79 62 E0 EA 1F 61 DE B6 | 49 F6 BC 3F 4C EF 38 C4 | ybaê.aB¶IÖª?Li8Ã |
| 00000100 | F3 55 04 E5 1E C1 12 DE | 5C 38 4D F7 BA 0B 8D 57 | óU.â.Á.Ð\8M÷°..W |
| 00000110 | 8A 4C 70 2B 6B F1 1D 5F | AC 00 00 00 00 | ŠLp+kñ._¬.... |

Figure 2.2: Genesis bitcoin block

First documents purchase happened in 22nd May 2010, when Laszlo Hanyecz bought two pizzas for 10 000 bitcoins (\$41 then, now about \$80 000 000)². This transactions hash is `a1075db55d416d3ca199f55b6084e2115b9345e16c5cf302fc80e9d5fbf5d48d` and will be stored in bitcoin blockchain forever³.

2.2 DigiByte

DigiByte was developed and released in 2013. It is based on Bitcoin with some adjustment in the code to improving functionality. In late 2017 there was 200 000 pending transaction in Bitcoin. Miners preferred transaction with a bigger fee, so to confirm a transaction, user needed to pay \$50. Digibyte solved this problem by adding a new block every 15 seconds (new block in Bitcoin is mined every 10 minutes). Average transaction occupies 570 bytes of data. One block can contain approximately 3 500 transactions given the 2 MB limit. This means that in DigiByte, 230 transactions can be confirmed in one second compared

¹https://en.bitcoin.it/wiki/Genesis_block

²<https://bitcointalk.org/index.php?topic=137.0>

³Actual photos of \$80 000 000 pizza are on <http://heliacal.net/~solar/bitcoin/pizza/>

to Bitcoin 4-7 transaction per second. DigiByte also has 1000:1 DigiByte to Bitcoin ratio, so for every Bitcoin there will be 1000 DigiByte.[2]

2.3 Ethereum

While both the Bitcoin and Ethereum networks are powered by the principle of distributed ledgers and cryptography, the two differ technically in many ways. For example, transactions on the Ethereum network may contain executable code, while data affixed to Bitcoin network transactions are generally only for keeping notes. Other differences include block time (an ether transaction is confirmed in seconds compared to minutes for bitcoin) and the algorithms that they run on (Ethereum uses ethash while Bitcoin uses SHA-256).[12]

2.4 Decred

Decred is cryptocurrency build from Bitcoin. Main difference from Bitcoin is the rewarding system from mining. In Bitcoin, the miner gets full reward for a mined block. Sometimes, the Bitcoin blockchain splits when two or more miners found a block at nearly the same time. The fork is resolved when the subsequent block(s) are added, and one of the chains becomes longer than the alternative(s). In Decred the chance of blockchain forks is minimized by hybrid proof of work and proof of state system. Each time a block is created (by a miner), it is not automatically part of the blockchain. Block needs to be approved by ticket holders. Then miner receives a block reward (newly created DCR). If the block is rejected by ticket holders, the miner does not receive a reward. Tickets holders for a new block are chosen randomly. The ticket validates the previous block. A block needs at least three of the five votes chosen to approve it for it to be validated. This hybrid system has many implications, including making a 51% hashpower attack very difficult, and making a minority fork very difficult as well.[6]

2.5 Monero

Three years after Bitcoin, in 2012, the competing Bytecoin cryptocurrency entered the market. The problem with this cryptocurrency, however, was that 80% of all coins were mined in advance by its authors. The chances of mining were, therefore, not balanced. This led to the decision that this cryptocurrency would start again. New cryptocurrency starts on 18 April 2014 and was called BitMonero, a composite of the word coin in Esperanto (Monero) and Bitcoin according to Bitcoin. However, after five days, the community decided to use only Monero for short. Monero's significant advantage is the dynamic size of the mined blocks. Bitcoin has one block size limited to 1 MB, while Monero adapts the block size to the network load. If the number of transactions increases, so does the block size to accommodate all transactions. Thus, unlike Bitcoin, the more transactions users make, the lower the transaction fee. Monero's main benefit is its full anonymity and interchangeability. Monero hides recipient and sender addresses.[10]

2.6 Analyze of current blockchain explorers

[[vela z nich je NoSql. Ziadne filtrovanie a pod.]]

Chapter 3

IPFS

IPFS¹ stands for InterPlanetary File System and is a peer-to-peer distributed filesystem designed to make the Web faster, safer, and more open. In contrast with a standard filesystem, objects in IPFS are content-addressed by the cryptographic hash of their contents. In the case of the standard Web, when user wants some file, he needs to know on which server is a file located and the full path to the file (see Figure 3.1). In IPFS user needs only to know the hash of the requested file. He does not care about the location of the file (see Figure 3.2). Let us take an MIT license text, and add it to IPFS. If somebody tries to add this license as a file to IPFS, it will return `QmWpvK4bYR7k9b1feM48fskt2XsZfMaPfNnFxdbhJHw7QJ` every time. That is now and will be in the future, the *content address* of that file. Later, when user try to get this file by its hash, he can get it from a random person that added it into IPFS in the past.

IPFS can easily represent a file system consisting of files and directories. A small file (less than 256 kB) is represented by an IPFS object with data being the file contents (plus a small header and footer). Note that the file name is not part of the IPFS object, so two files with different names and the same content will have the same IPFS object representation and hence the same hash. A large file (more than 256 kB) is represented by a list of links to file chunks that are less than 256 kB, and only minimal information specifying that this object represents a large file. Currently, there is no known size limitations uploaded file or directory. There are already some big datasets hosted on IPFS such as Geocities archive² (704TB) or Project Apollo Archives³ (61GB).

IPFS provides API for manipulation with objects in several levels of abstraction. Two most used APIs are Files and Graph API. The files API⁴ enables users to use the File System abstraction of IPFS. Currently it has `add`, `cat`, `get` and `ls` methods. In the future, there should be MFS (Mutable File System), that would add methods `chmod`, `cp`, `mv`, `rm`, `stat` and `touch`⁵. Graph API⁶ is used in lower level of abstraction for manipulating with any IPFS object and creating links between objects. There are `put` and `get` methods available.

¹<https://ipfs.io/>

²<https://ipfs.io/ipfs/QmVCjhoEFC9vwvaa8bKyJgwABYP4MXSogcyDGoZ4Lkc3ox>

³<https://ipfs.io/ipfs/QmSnuWmxptJZdLJpKRarxBMS2Ju2oANVrgbr2xWbie9b2D>

⁴<https://github.com/ipfs/interface-js-ipfs-core/blob/master/SPEC/FILES.md>

⁵<https://docs.ipfs.io/guides/concepts/mfs/>

⁶<https://github.com/ipfs/interface-js-ipfs-core/blob/master/SPEC/DAG.md>

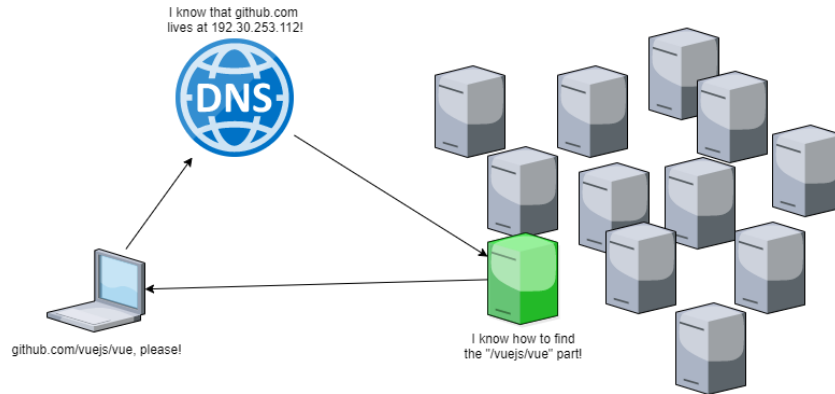


Figure 3.1: Classic web addressing

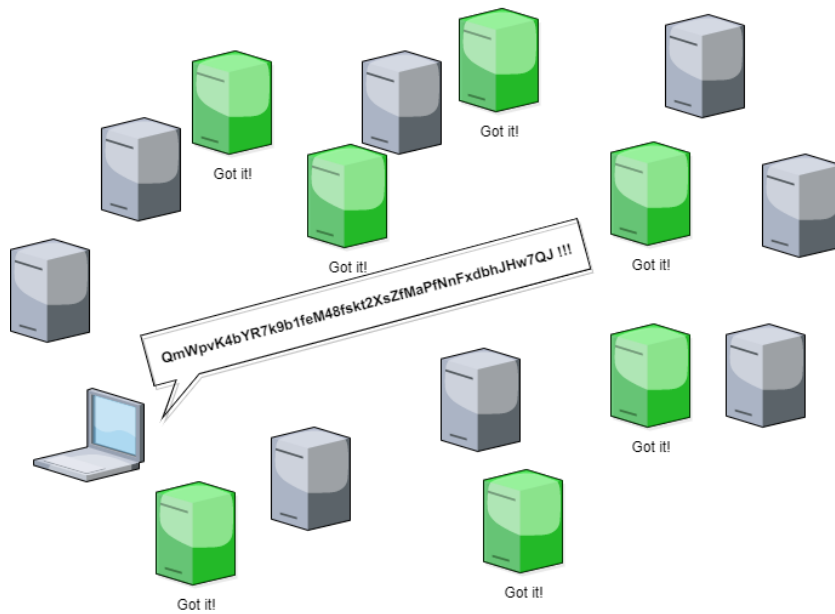


Figure 3.2: Content-based addressing

3.1 IPFS stack

We can split IPFS into layers (see Figure 3.3). *Libp2p*⁷ is at the bottom, which is a peer-to-peer networking module, that handles peer and content discovery, transport, security, identity, peer routing, and messaging. *IPLD* is the data model of the content-addressable web. It is providing linking between objects and multihash computing. On the top is *IPFS* which allows to publish and share files (or any data).[1]

3.2 libp2p

Libp2p is a modular system of protocols, specifications and libraries that enable the development of peer-to-peer network applications. It provides NAT Traversal, Peer Discovery, Routing, Stream Multiplexing, Protocol Multiplexing, Encryption, Authentication and

⁷<https://libp2p.io/>

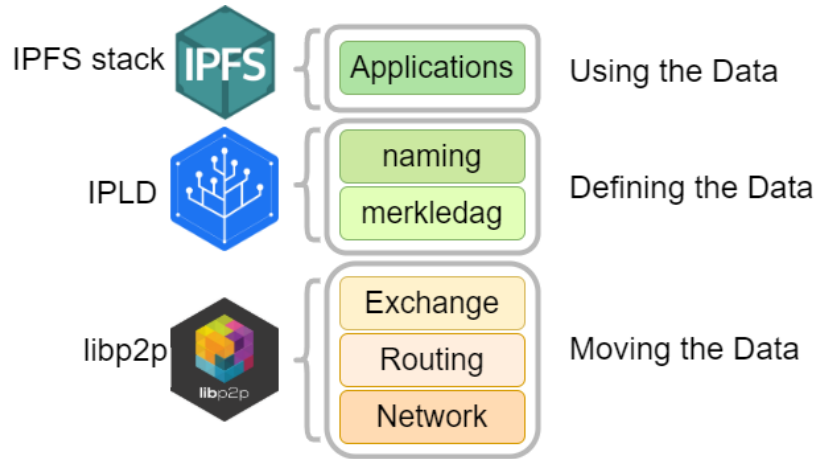


Figure 3.3: IPFS stack

| Property | | Value |
|------------|-------------|-------------------------|
| Multibase | | base58btc |
| Version | | cidv0 |
| Multicodec | | dag-pb |
| Multihash | Hash Type | sha2-256 |
| | Hash Length | 256 |
| | Hash | 7e1b666c0327...3dc3022f |

Table 3.1: Example of human redable version of CID

more. It grew out of IPFS to solve networking problems in p2p networks, but now it does not require or depend on IPFS. Today many projects use libp2p as their network transporting layer, which is responsible for the actual transmission and receipt of data from one peer to another. For both content discovery and peer routing, libp2p uses Kademlia-based distributed hash table. With Kademlia, libp2p iteratively routes requests closer to the desired peer or content using Kademlia routing algorithm[8]. In the future, Kademlia might be changed easily to some other solutions that implements a simple interface for publishing and requesting data and finding a peer.[4]

3.3 IPLD

IPLD is providing linking and addressing objects with CID (Content ID). CID is hash-based self-describing content identifier (usually encoded to base58⁸ format) which includes codec and multihash. Multihash is then further composed of hashtype and hash value. Let us look closer on the MIT license file, that we add to IPFS at the beginning of this chapter (see Figure 3). It's CID is `QmWpvK4bYR7k9b1feM48fskt2XsZfMaPfNnFxdbhJHw7QJ`. It can be converted to human-readable format as can be seen in Figure 3.1, thanks to multicodec table⁹. We can see that this CID is encoded in base58 format and the file was stored using protobuf¹⁰ codec (this information is necessary to decode file correctly).

⁸<https://en.wikipedia.org/wiki/Base58>

⁹<https://github.com/multiformats/multicodec/blob/master/table.csv>

¹⁰<https://en.wikipedia.org/wiki/Protocol Buffers>

3.4 IPFS

IPFS is the top layer from the IPFS stack. It is used for pinning objects and files, naming system (see IPNS¹¹) and keys management. File or object is automatically pinned when a user adds it (but other IPFS commands do not include automatic pinning). Pinning a CID tells an IPFS server that the data is important and must not be thrown away. When garbage collection is triggered on a node, any pinned content is automatically exempt from deletion. Non-pinned data may be deleted. The InterPlanetary Name System (IPNS) is a system for creating and updating mutable links to IPFS content. Since objects in IPFS are content addressed, an object address changes every time an object's content changes. A name in IPNS is the hash of a public key. It is associated with a record containing information about the hash it links to that is signed by the corresponding private key.

3.5 IPNS

Naming inside IPFS is governed by IPNS¹², the InterPlanetary Naming System. IPNS takes ideas from SFS¹³ to enable the creation of cryptographically signed mutable pointers, which can be used to the creation of name records inside the network.

3.6 Existing blockchain explorers in IPFS

There are already stored a few blockchains of cryptocurrencies in IPFS. For browsing them we can use dedicated applications^{14 15} or IPLD explorer¹⁶. Blockchains in IPFS are stored in raw binary format, so custom IPLD codec has to be created for every type of object. Using custom codecs for cryptocurrencies allows explorers to request blocks and transactions by its hash very fast, but there are also limitations.

- Existing IPLD codecs for cryptocurrencies are very limited. Only a few of cryptocurrency codecs are currently available in IPLD (namely Leofcoin, Ethereum, Bitcoin, Zcash, Steller, Decred and Dash)¹⁷.
- Addresses are not stored in IPFS, because they are not part of a blockchain. This means the explorer needs to go through the entire blockchain for computing address balance or to find address transactions.
- No additional information (for example transaction value in US dollars) can be stored with objects because it would change content, and therefore hash of the object.
- There is no sorting or filtering. Explorer can only show the object (block or transaction) by its hash.

3.7 IPFS cluster

¹¹<https://docs.ipfs.io/guides/concepts/ipns/>

¹²<https://docs.ipfs.io/guides/concepts/ipns/>

¹³https://en.wikipedia.org/wiki/Self-certifying_File_System

¹⁴<https://github.com/arcalineia/IPFS-Zcash-Explorer>

¹⁵<https://github.com/whyrusleeping/zcash-explorer>

¹⁶<https://explore.ipld.io/#/explore/z43AaGEvwdfzjrCZ3Sq7DKxdDhrwoaPQDtqF4jfdkNEVTiqGVFW>

¹⁷<https://github.com/multiformats/multicodec/blob/master/table.csv>

Chapter 4

Design

This chapter describes the proposed design of the whole system for storing and exploring blockchains in IPFS that is to be created as a result of this thesis. All parts of the system are described in this chapter.

4.1 Database system

We need a database in our system to store and index data. Database system needs to be decentralized and distributed. There are several databases build on top of IPFS already implemented. The two most known are OrbitDB and Textile.

4.1.1 OrbitDB

OrbitDB is a serverless, distributed, peer-to-peer database build on top of IPFS, developed by HAJA networks. OrbitDB is a decent solution for small user's databases, but it is still in the alpha stage of developing, and it is not well optimized to store hundreds of gigabytes of data. The biggest problem is that OrbitDB performs all queries locally. To perform a query that selects transactions that are more valuable than 1BTC, OrbitDB needs to load the whole database locally and then perform a cycle on all transactions to select only those transactions that meet the criteria. So every client ends up with a full copy of the database. This limitation is not usable for our case when we have a database that has hundreds of gigabytes of data.

4.1.2 Textile

Textile is a set of open-source tools that provide a distributed peer-to-peer database, remote storage, user management, and more, over the IPFS network. Textile already created applications for storing photos, notes or anything else (Anytype). Textile provides a high abstraction on top of the IPFS and provides simple API to store and index files securely. It uses Cafe peers to provide backups and indexing. Data are duplicated on several Cafe peers. When a client is performing some query, it contacts one of the Cafe peers to resolve the query for the client. Neither of these solutions fits our use case to store a large amount of data distributed on several nodes and performs queries that can be resolved by downloading only necessary parts of the database. Therefore, we need to create a new database system based on IPFS that would be decentralized and distributed.

4.1.3 Database system design

After some research, we concluded that currently for storing and indexing data in IPFS without large harddisk memory consumption, there is no solution. We created our own indexing system that currently supports three types of indexes. A database system that fits our needs is distributed and decentralized. That brings us lots of synchronization problems to solve. This database system consists of tables that contain records. For faster searching, tables have indexes. Relations between tables are represented via foreign keys. Also, this database system supports fluent query language, used for performing complex queries.

Record

Every record in our database system is stored in an append-only log that contains the whole history of the record. Every update of a record adds a new entry to its log which points to the previous entry.

In centralized systems such as git, conflicts are detected on write (for example, when two git users push changes to the server at the same time, one of them gets an error and needs to pull repository). This approach is impossible in a decentralized system. When we update some record in our database, we can not know if somebody does not update it before (and we do not receive changes yet). For this reason, we need to solve conflicts while reading. Record with conflict has more than one head in a record log, and users need to solve them in application logic. Look at the example in Figure 4.1. There is a record that is updated by every country in the World when they have new statistics about a pandemic. If two countries update data at the same time (their updates pointing to the same previous version of the entry) they create conflict. Luckily, this specific conflict is easy to solve. We just need to look at the previous entry and compute increment for both country. Then update the record with final increment.

Indexes

An index is B-tree optimized for IPFS (no cycled references and node size less than 256kB). Each table has at least one primary index. We use the primary index to reference record in foreign keys. A primary key is automatically created when a user does not specify it and has type of Guid. Value of the primary key for an entity can not be changed (because we would need to scan all tables where the entity is referenced and change the referenced value to a new one). Also, when we execute a query without any condition or sorting, we use a primary key to obtain records. Every index has several components:

- **Comparator** - is a function that has two parameters (two keys of B-tree) and outputs a number. An index is using a comparator to search records and insert record to the right place in B-tree.
- **Key-getter** - is a function that returns a comparable object from the record (a comparable object is an object that can be compared using index comparator). Every index has key-getter that is using to obtain keys for B-tree.

Table

A table contains indexes and table name. Also it implements operations like **insert**, **update** and **delete**.

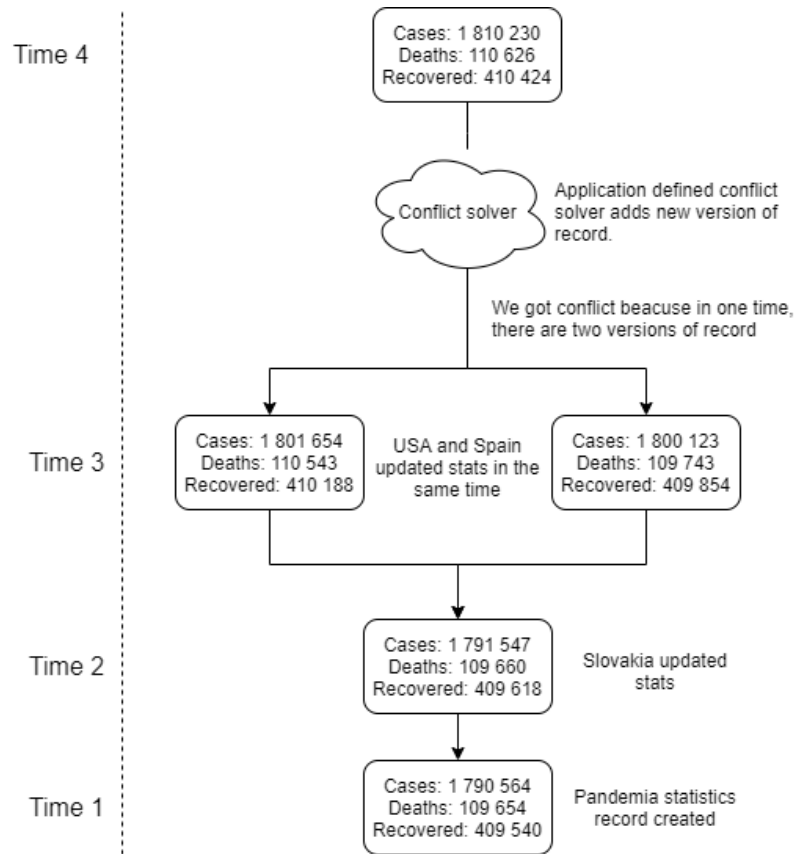


Figure 4.1: Record conflict

Foreign keys

We use foreign keys to represent relationships between tables. A foreign key is simply a table name and a value of a primary key of a referenced record.

Transactions

When we commit a transaction, it is inserted to the transactions queue. If there are more transactions in the queue, a database performs it one by one. We can not execute more transactions in one moment, because it could cause data inconsistency. There are five types of transactions:

- **read** - transaction for reading data from table. It is not logged in a database log (other peers don't have to know what we are reading from database).
- **sync** - when some peer publishes a new version of the database, all other peers have to migrate to it. This transaction has the biggest priority, and therefore it is inserted at the beginning of the transactions queue. After a migration is done, transactions queue can continue working normally.
- **insert, update, delete** - other types of transactions are written to database logs, because they are modifying the database.

Synchronization

Every time a transaction queue is empty (all pending transactions has been applied), a new version of a database is broadcasted to all connected users. When we receive information about the new database version, we load its root. Each database version has information from which version was created. Database versions create an append-only log called database log. Database log is an immutable, operation-based conflict-free replicated data structure (CRDT¹) for storing database versions. Every version in the log is saved in IPFS and each points to a hash of previous version(s) forming a graph. Database logs can be forked and joined back together.[?]

If more than one peer publishes a new version of the database that has been created from the same database version, other peers need to decide which version they would accept. Opposite to records conflicts, we need to solve database versions conflict fast and automatically. There are multiple ways to solve them. For example:

- **The biggest hash wins** - if there is more than one database version at the same (discrete) time, the one with the biggest hash wins. This strategy is present in Figure 4.2.
- **The longest connecting time wins** - a user who is connected to the database for the longest time wins.

Lots of more strategies can be implemented. But they need to be deterministic and as fair as possible. If we have access to geolocation, we can implement a strategy based on a distance to the North pole (the closest node to the North pole wins).

Queries

A Database system provides query language for performing selects. A query consists of:

- **conditions** - query may contain multiple conditions. There are logical operators (and - conjunction, or - disjunction) between conditions. When it is possible (an index is available on condition property), we use indexes for evaluating conditions. If there are more than one conditions, we use an intersection between and's conditions and union between or's a disjunction. These types of conditions are supported:
 - **equal** - record property equals to specified value,
 - **greater than** - record property is greater than specified value,
 - **less than** - record property is less than specified value,
 - **between** - record property is greater than specified minimal value, and less than specified maximal value.
- **filters** - filters are similar to conditions, but they can be more complicated. They are functions returning boolean that are being applied to query results. If any filter return **false** for the query result, the query result is ignored. A query can contain several filters.
- **offset** - offset saying how many query results should be ignored from the beginning.
- **evaluator** - we use evaluator for accessing results of the query.

¹https://en.wikipedia.org/wiki/Conflict-free_replicated_data_type

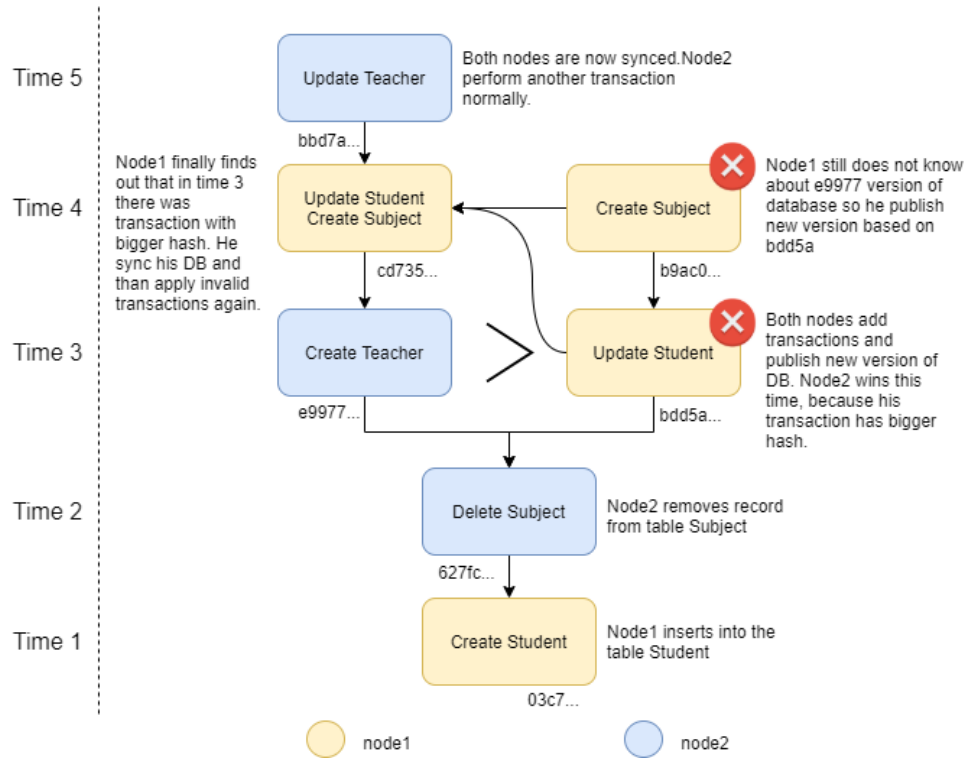


Figure 4.2: Synchronization of a database. Note that in time 4, Node1 add two transactions in one DB version.

- **all** - returns array of all results of the query,
- **first** - returns only first result,
- **take** - returns N number of results where N is an argument,
- **paginate** - returns page of results. Accept two arguments. **perPage** specifies the number of results in one page. **page** is number of requested page.
- **iterate** - returns iterator that can be used in cycles such as **for** or **while**.

4.2 System components

The system consists of one or more Feeders and Explorers. Feeders are connected to data sources and provide synchronization with cryptocurrency blockchains. Explorer can request data from the system network and display them to a user (see Figure 4.3).

4.2.1 Database design

[[Describe used indexes and database structure that is present in the Feeder, ER-diagram]]

4.2.2 Feeder

A Feeder is a service that stores data in IPFS and indexes them in our database system. Once all blocks are indexed, Feeder waits for new blocks and is periodically publishing most

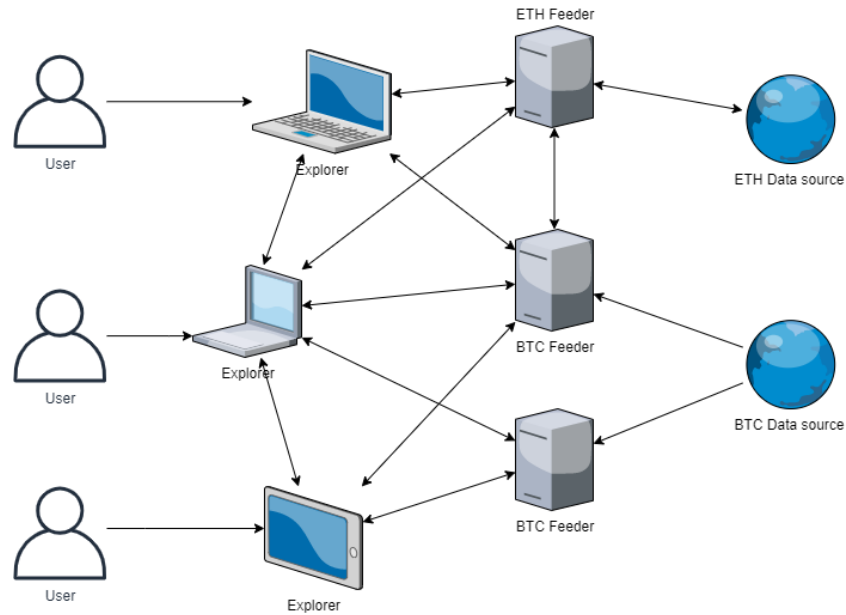


Figure 4.3: System architecture

updated database version. This way new clients synchronize database more quickly. For optimization purposes, Feeder is performing transactions in bulks. This means that Feeder is not publishing new version of the database every time it parsed block or transaction, but rather after it parsed transactions bulk which can consists of hundreds of transactions.

A Feeder can use different sources for obtaining blockchains data. It can be connected directly to the blockchain as a full node or to some other data source providing blockchain data as Blockbook² or Insight³.

4.2.3 Explorer

Explorer can perform basic queries like a search for block by its height or hash and search address and transaction by hash. Nevertheless, Explorer can also make more complex queries for example, get the first 20 transaction where the sum of inputs is more than some value, or get transactions between some time interval. Explorer is an application that can be used in two environments. In browser with graphical user interface, or in node.js⁴ as a RestAPI.

ExplorerGUI

ExplorerGUI is browser version of Explorer. It is implemented as a SPA⁵ to prevent restarting connection with IPFS after each time a user visit different page. It has separated views for block, transaction and address details. Also paginating, filtering and sorting objects by all its properties that has index is supported. UI of ExplorerGUI needs to be

[[Add mockups]]

²<https://github.com/trezor/blockbook>

³<https://insight.is>

⁴<https://nodejs.org/>

⁵https://en.wikipedia.org/wiki/Single-page_application

ExplorerAPI

ExplorerAPI is a node.js application provides several endpoints for obtaining the data:

- GET /tx - get collection of transaction,
- GET /tx/[:txHash] - get transaction by hash,
- GET /block - get block collection,
- GET /block/[:blockHeightOrHash] - get block by height or hash,
- GET /address - get address collection,
- GET /address/[:hash] - get address by hash.

All endpoints support more detailed path specification by providing multiple parameters at the end of the path (for example, it is possible to request only a block hash by calling /block/42/hash). Also, every endpoint supports query parameters

- **filter** where value of this parameter can be simple arithmetic expression like **height>50**,
- **limit** parameter for pagination with default value set to 20,
- **orderBy** sorts results of a sequence in ascending order.

Chapter 5

Implementation

This chapter describes the implementation details of the system, shows the internal architecture. As mentioned in the previous chapter, the program was created in Typescript, and they are using js-ipfs¹ implementation of IPFS node. This selection of tools enables code sharing between these two separated applications.

5.1 Explorer-core implementation

Explorer-core is the most complex module of a whole system with more than 5000 lines of code. The database is a main part of the explorer-core module. Database system consists of a query system, indexes and a database abstract layer.

5.1.1 Indexes

For indexing there is currently implemented only B-tree, but different structures such as tries² can be implemented easily. They only need to implement index's interface (function such as `insert`, `delete`, `update`, `find`). We can create indexes on database entities with decorators³, which are part of ECMAScript 6 standard. Every database entity has to have `PrimaryKey` decorator on property that is used as a primary index. Index has three parameters:

- **comparator** - is a function that accepts two arguments and returns number that is less than zero if first arguments is greater than second, zero if arguments are the same, more then zero if a second argument is greater than first. If a user has not set any custom comparator default one $((a, b) \Rightarrow a < b ? -1 : +(a > b))$ is used. This default comparator works on atomic keys such as string or numbers.
- **keyGetter** - is another function that accepts a whole entity as arguments and returns key, that is used in an index. A default key getter is function that returns property of the entity (for example default key getter for property `height` is $(e) \Rightarrow e["height"]$).
- **branching** - the branching factor is the number of children at each node, the out-degree. Default branching factor is 16.

¹<https://github.com/ipfs/js-ipfs>

²<https://en.wikipedia.org/wiki/Trie>

³<https://www.typescriptlang.org/docs/handbook/decorators.html>

The B-tree structure (see Figure 5.1) is optimized for IPFS. Unlike PostgreSQL B-tree⁴, leaf nodes have not got left and right sibling references due to cyclic reference this is not possible in IPFS. Cyclic references are not possible, because links are changing CID of an object. Therefore if we store object A with a link to the object B, CID of A will change. Then if we add backlink from B to A, CID of B will be changed and so A has now link to an old version of B. If we update link of object A to point on the new version of object B, CID of object A will change and therefore object B is now pointing to the old version of object A. From this example, it appears that there is no way of making cyclic references in IPFS. Without siblings references we don't have to store data only in leaves, but we can store data in nodes itself. This approach lead to better performance when executing queries. In insert queries, statistically fewer nodes needs to be updated. Also in search queries, there is a chance that we found a key in some non-leaf node, and therefore we would need fewer node visits.

All search queries (equal, less, greater, between) has two steps:

- **Find subtree** - First, we need to find minimal subtree that contains all results. We start in a root node of the B-tree. Then, we use an index's **comparator** function to determine if we can visit some child node and still have all the result in it. If not, we found a minimal subtree for the query.
- **Traverse** - To get results of the query we can traverse minimal subtree in two direction. In-order for **greater than** and **between**. For **less than** reversed in-order. With **equal** it does not matter.

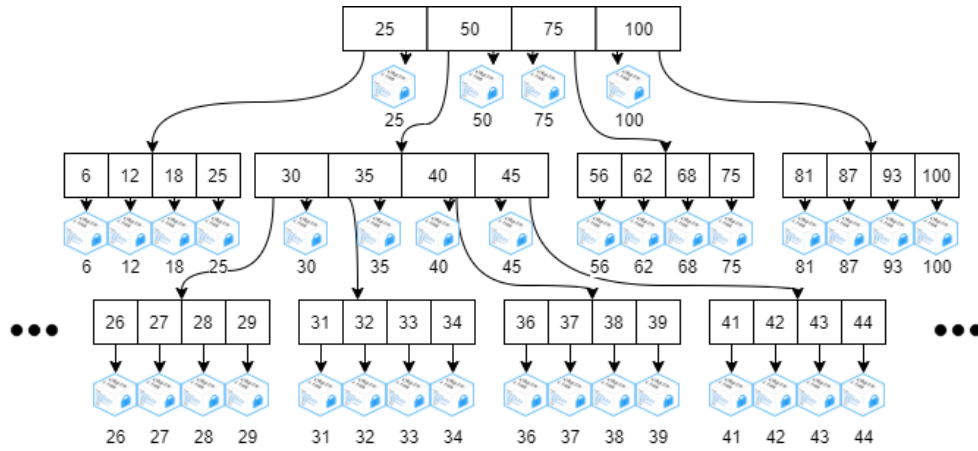


Figure 5.1: Btree indexing first 100 block by their height

5.1.2 Query system

Database system offers a complex query system. A query can consist of multiple conditions and the **Query Planner** is responsible for resolving them. It decides which indexes are used for query and choose a strategy. If there is no condition, a primary key is used for query execution. In the case of a single condition, **Query Planner** checks if there is an index on the condition's property. If yes, then this index is used to perform the query. Else condition

⁴<https://github.com/postgres/postgres/tree/master/src/backend/access/nbtree>

is transformed to filter and a primary key is used to obtain results which are then filtered. For multiple conditions connected with logical operators AND or OR, **Query Planner** creates **OR-hashset** and **AND-hashset**. **AND-hashset** is initialized with the results of a condition which has the smallest number of results and uses AND operator. Then we check for each result hash for all other AND conditions if **AND-hashset** contains it. If no, a hash is deleted from **AND-hashset**. This creates intersection between all AND conditions. The **OR-hashset** is created empty. Then, we add a hash of every result of all OR conditions to it. This creates union between OR conditions. At the end, we perform union between **AND-hashset** and **OR-hashset**. This creates final hashset which is used later to obtain actual data with resolvers such as **all**, **first**, **paginate** etc. If one of the AND conditions has great selectivity (it has less than a hundred results), **Query Planner** can decide to don't use other indexes, but transform condition to filter and cycle over the results. Example query returning blocks between 38 and 42 is shown in Figure 5.2. A peer needs to download only data that are highlighted in green. After downloading them, they are stored on peer's filesystem and are offered to other peers.

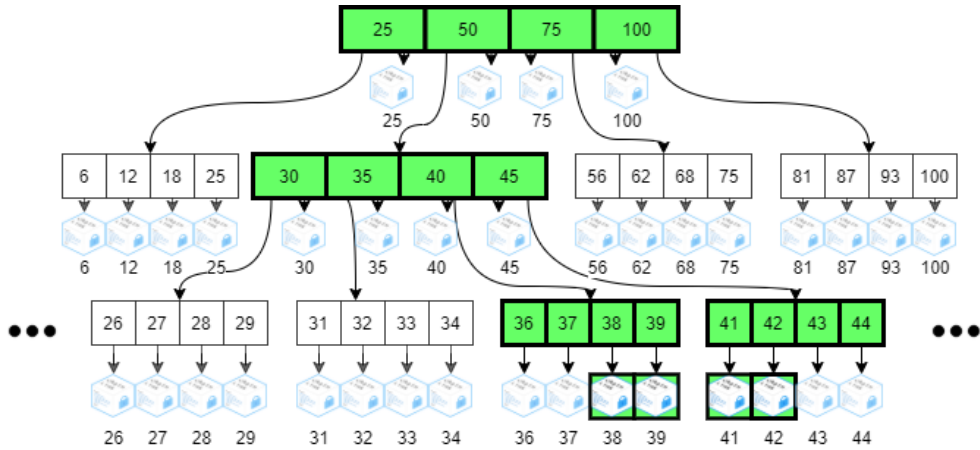


Figure 5.2: Data access for performing query that returns blocks that have a height between 38 and 42.

5.1.3 Database

The most important part of the explorer-core module is a Database system which connects query system with indexes. When we make a query, it translates to the database, and data are obtained from the indexes.

Tables

A database contains tables. A table contains indexes and table name and implements operations that modifies its state:

- **insert** - creates history log for entity with first entity version. Then adds it to every table index.
- **update** - adds new version of the entity to its history log. Than update every index of the table.

- **delete** - removes entity from every table index. From now, an entity can not be find in this table.

Example of the class `User` is in Figure 5.3. It has two indexes. One primary on property **name** and one normal index on property **age**. The second index has also specified **comparator** that is a bit faster than default one, but works only on numbers, and **keygetter** that returns a year when a user has born.

```
class User extends Queriable<User> {
  @PrimaryKey()
  name: string;

  @Index(
    (a, b) => a - b,
    u => new Date().getFullYear() - u.age,
  )
  age: number;
}
```

Figure 5.3: Example of database table abstraction

Transactions

A database can be executing only a single transaction at the time to prevent data inconsistency. For that reason, we implemented a transaction queue where transactions are stored before executing in the order in which they came. Executing more transactions in a row is significantly more effective than executing them one by one. If a transactions queue has only one transaction, it will wait 100ms for more transactions to come.

Synchronization

There are two types of transactions. Those that changes the database state (**create**, **update**, **delete**) and those that don't (**read**). Every transaction that changes database state need to be synchronized with other peers. We created Database log for that. It is an append-only log with a discrete time. There can be only one valid database transaction in every point in time. There are several strategies to choose which transaction is globally accepted and which transactions need to rollbacks (described in design [\[\[add link\]\]](#)).

5.2 Feeder implementation

A Feeder is a simple program (less than a hundred lines of code) written in Typescript (see Algorithm 1). It strongly depends on the Explorer-core module. Currently, we support only Blockbook connector as a source of blockchain's data, but Feeder can be simply expanded to support more data source such as InsightAPI or direct connection to a blockchain as a full node. Each Feeder has configuration file (usually called `.env`) with Feeder's settings. Main Feeder settings are URL of the source for the blockchain's data and `DB_NAME` which is a name of the database where Feeder inserts new blocks. A Feeder can be connected to

only one blockchain. We can create multiple Feeders for single blockchain, but we need to provide some deterministic algorithm, that insures that each block is parsed by only one Feeder. This can be done by providing **FeederId** and **FeedersCount** in **.env** config file. If those values are provided, Feeder parses only blocks that have height modulo **FeedersCount** equals to **FeederId**.

Algorithm 1: Simplified Feeder algorithm

```

load configuration;
while there is new block do
    fetch block;
    for transaction in block do
        | save transaction;
    end
    save block;
end

```

5.3 Explorer implementation

We can split Explorer to several modules. The central part is ExplorerCore which communicates with IPFS and provides an interface to explore blockchain and to perform queries. There can be ExplorerGUI or ExplorerAPI on the top of the ExplorerCore. These modules are providing communication with user or other systems. This architecture is shown in Figure 5.4.

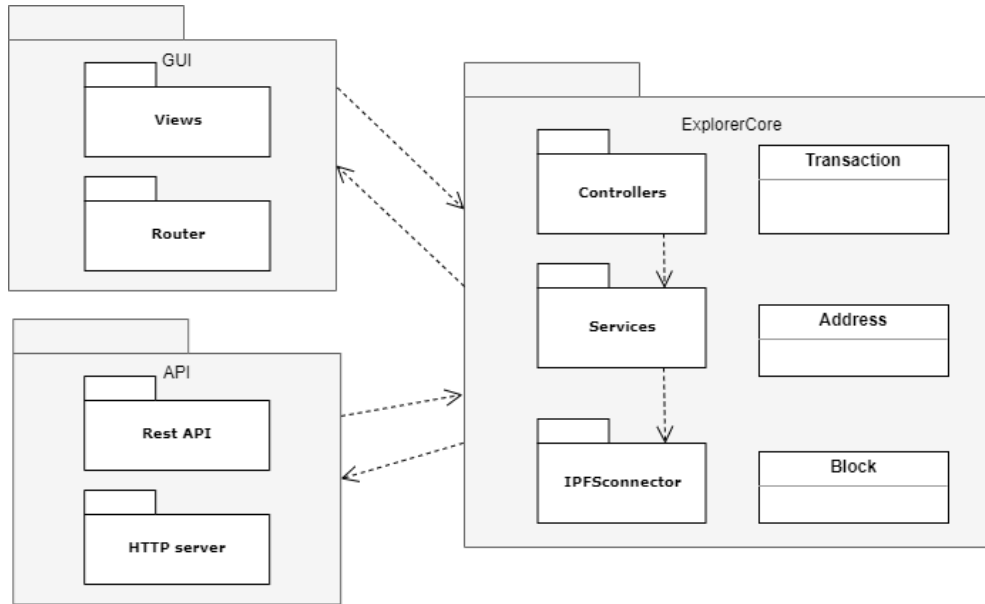


Figure 5.4: Explorer architecture

5.3.1 ExplorerCore

ExplorerCore is main module of the Explorer. It is responsible for obtaining and resolving data from IPFS and performing queries. It has simple interface:

- `getObject(CID[, path])` - gets object from IPFS with optional path,
- `getTx(txHash)` - gets transaction by its hash,
- `getBlock(blockHash)` - gets block by its hash,
- `getBlock(blockHeight)` - gets block by its height,
- `getAddress(addressHash)` - gets address by its hash.

All ExplorerCore methods except `getObject` are returning `QueryObject`.

Query system

Explorer supports a simple query system. Every queriable object (address, transaction, block) has methods:

- `where(propertyName)` - create a condition on the property. There can be multiple conditions in one query. A condition has to be followed by one of the functions:
 - `gt(value)` - property is greater or equal than `value`. The query finds in an index first object that has property (set by `propertyName` in condition) equal or greater than `value`, and traverse index to the right (to bigger objects).
 - `lt(value)` - property is less or equal than `value`. Similar as in the `gt` function, the query finds the closest object that has property equal or less than `value`. Then, the query traverses index to the smaller objects with smaller index value (to the left).
 - `between(min, max)` - property is greater or equal than `min` and less or equal than `max`.
- `offset(offsetValue)` - query will skip `offsetValue` number of results,
- `limit(limitValue)` - set maximum number of results. After query has `limitValue` count of matched objects it will stop browsing the index,
- `all()` - return all objects that matched query,
- `first()` - return the first object that matched a query,
- `and(childQuery)` - logical and between two queries. Parent query resolves `childQuery` (call `all()` function) and makes a hashtable from its results. Later, when parent query being resolved, query checks if the result exists in the hashtable for every result.
- `or(childQuery)` - logical or between two queries. `childQuery` will be resolved by parent query, and its results stores in hashtable. When the parent query is resolved, its results will be added to the hashtable. This will remove duplicates in the final results.
- `[Symbol.iterator]()` - iterator that is used in cycle for (result of query).

The data obtaining will happen only when we access the data inside the `Query` object (for example, in for-loop) or by calling `all()` or `first()` method. Index is used only for the first condition in a query, that is on the property, that has created index. Other conditions are performed client-side.

5.3.2 ExplorerGUI

ExplorerGUI is a single page application with simple user interface that runs in browser implemented with Vue.js⁵. Browser's implementation of IndexedDB is used as a storage for IPFS as can be seen in Figure 5.5. Communication with other peers is provided though WebRTC⁶ or WebSockets. Every tab opened in the browser is the same IPFS node. Opening a new tab in Incognito mode or different browser will spawn different IPFS node.

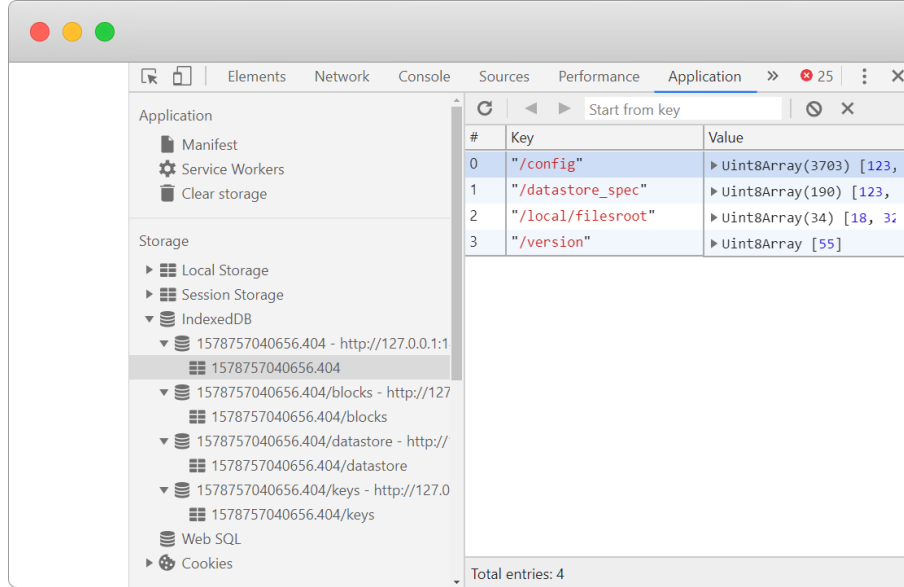


Figure 5.5: IPFS storage in browser

5.3.3 ExplorerAPI

Node.js⁷ implementation of IPFS uses filesystem to store data (see Figure 5.6). On the top of ExplorerCore, there is a simple web framework Express⁸, where are routes (endpoints) defined. Currently available routes are described in Section 4.2.3. Every route supports query parameters **filter** (used for filtering results) and **limit** (which reduces number of results). Pagination can be made by setting **filter** to be greater/smaller (depending on ordering) as key of the last displayed object and **limit** to page size. For example, if a user is looking at page of transactions ordered by time (ordered from the newest transactions to the oldest), the next page of transactions are first N transactions that happened before last displayed transaction (where N is page size).

Rest API supports optional path param **path** that is useful for traversing objects in IPFS. If we want to get fifth transaction of the block with height 1000 one of the way is request URL `/block/998/next_block/next_block/txs/5` (get block with height 998, get next block two times, get transaction, a get fifth item from array of transactions). This approach allows the user to explore IPFS storage as graph very quickly by objects links.

⁵<https://vuejs.org/>

⁶<https://webrtc.org/>

⁷<https://nodejs.org/>

⁸<http://expressjs.com/>

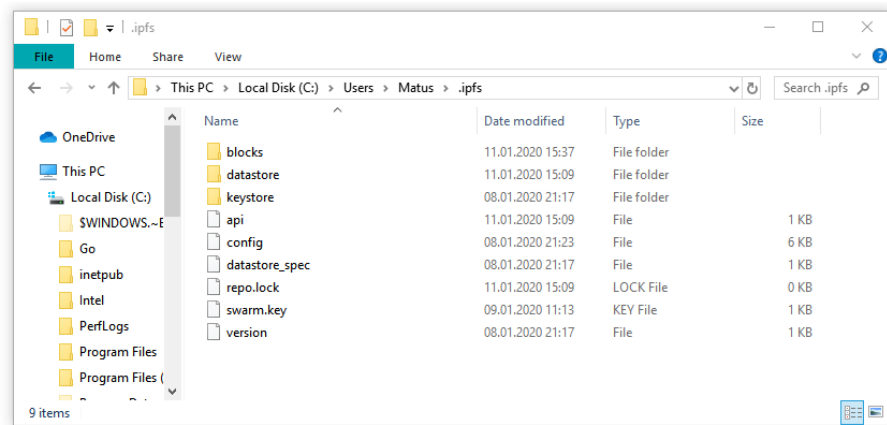


Figure 5.6: IPFS storage in node.js

Chapter 6

Benchmarking

6.1 Comparing to other database systems

Comparing our database system with typical database systems is very difficult. We need to prepare same environment.

6.1.1 MySQL

MySQL is free and open-source software under the terms of the GNU General Public License, and is also available under a variety of proprietary licenses. MySQL was owned and sponsored by the Swedish company MySQL AB, which was bought by Sun Microsystems (now Oracle Corporation). MySQL is used by many database-driven web applications, including Drupal, Joomla, phpBB, and WordPress. MySQL is also used by many popular websites, including Facebook, Flickr, MediaWiki, Twitter, and YouTube.

6.1.2 PostgreSQL

PostgreSQL also known as Postgres, is a free and open-source relational database management system emphasizing extensibility and SQL compliance. It was originally named POSTGRES, referring to its origins as a successor to the Ingres database developed at the University of California, Berkeley. In 1996, the project was renamed to PostgreSQL to reflect its support for SQL. After a review in 2007, the development team decided to keep the name PostgreSQL. PostgreSQL features transactions with Atomicity, Consistency, Isolation, Durability (ACID) properties, automatically updatable views, materialized views, triggers, foreign keys, and stored procedures. It is designed to handle a range of workloads, from single machines to data warehouses or Web services with many concurrent users. It is the default database for macOS Server, and is also available for Linux, FreeBSD, OpenBSD, and Windows.

6.1.3 Environment

We compare MySQL and PostgreSQL with our p2p database system. These database systems run virtualized in Docker containers on hardware with 4 core's processor Intel Pentium G4560 3.50GHz and 16GB of RAM. On another hardware we starts clients, that connects to these database systems a preforms queries. Than we measure average queries per seconds that clients execute. Clients are written in javascript with official node.js

connectors for MySQL¹ and PostgreSQL² and are connected in the LAN with database systems over 1Gb ethernet. Database structure that is used in benchmarks can be seen in Figure 6.1. Table **authors** contains 10000 records and table **posts** contains 50000 records (each author has 5 posts). Test query for each database system can be seen in Figure 6.2.

| | | |
|--|---|---|
| <pre>CREATE TABLE 'authors' ('id' int(11) PRIMARY KEY, 'first_name' varchar(50), 'last_name' varchar(50), 'email' varchar(100), 'birthdate' date, 'added' timestamp, PRIMARY KEY ('id'), UNIQUE KEY 'email' ('email')); CREATE TABLE 'posts' ('id' int(11) PRIMARY KEY, 'author_id' int(11), 'title' varchar(255), 'description' varchar(500), 'content' text, 'date' date, PRIMARY KEY ('id'));</pre> <p>(a) MySQL</p> | <pre>CREATE TABLE authors (id serial PRIMARY KEY, first_name varchar(50), last_name varchar(50), email varchar(100), birthdate date, added timestamp); CREATE TABLE posts (id serial PRIMARY KEY, author_id integer, title varchar(255), description varchar(500), content text, date date);</pre> <p>(b) PostgreSQL</p> | <pre>class Author { @PrimaryKey() id: number; first_name: string; last_name: string; email: string; @Index() birthdate: Date; added: Date; } class Post { @PrimaryKey() id: number; author_id: number; title: string; description: string; content: string; date: Date; }</pre> <p>(c) Our database system</p> |
|--|---|---|

Figure 6.1: Database structures for benchmarking

| | | |
|--|--|---|
| <pre>SELECT * FROM authors JOIN posts ON posts.author_id=authors.id WHERE authors.id= (SELECT FLOOR(RAND() * 10001 + 1));</pre> <p>(a) MySQL</p> | <pre>SELECT * FROM authors JOIN posts ON posts.author_id=authors.id WHERE authors.id= (SELECT floor(random() * 10001 + 1)) ;</pre> <p>(b) PostgreSQL</p> | <pre>new Author() .where("id") .equal(Math.floor(Math.random() * 10001 + 1)).first();</pre> <p>(c) Our database system</p> |
|--|--|---|

Figure 6.2: Test query

6.1.4 Single connected client

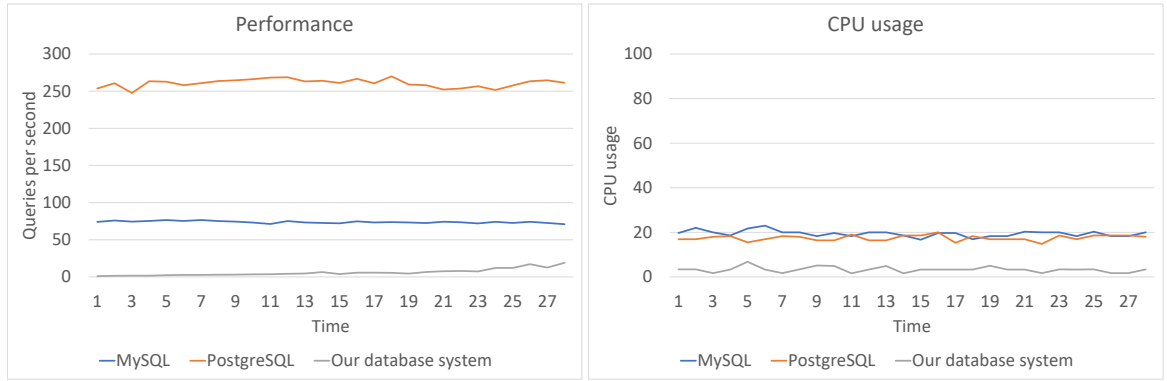
With a single connected client PostgreSQL can make more than 250 queries per second and MySQL 70 queries per second. Our database system is far behind with up to 20 queries per second (see Figure 6.3a). We can see that our database system builds cache, and performance increases by time. With only a single connected client there is no advantage of p2p network. CPU usage with a single connected client is for MySQL and PostgreSQL same - about 20% (see Figure 6.3b). For our database system it is only 3% due to lots of IO operations.

6.1.5 20 connected clients

With 20 connected clients, PostgreSQL performance dropped to 50 queries per seconds and MySQL to 10 queries per seconds. At the end of benchmarking, our database system is more powerful than PostgreSQL and MySQL, because data gets distributed to clients (see 6.4a). Our database system also requires less processor time thanks to p2p network. Data are not obtained only from the server (as opposed to MySQL and PostgreSQL) but also

¹<https://www.npmjs.com/package/mysql>

²<https://www.npmjs.com/package/postgres>

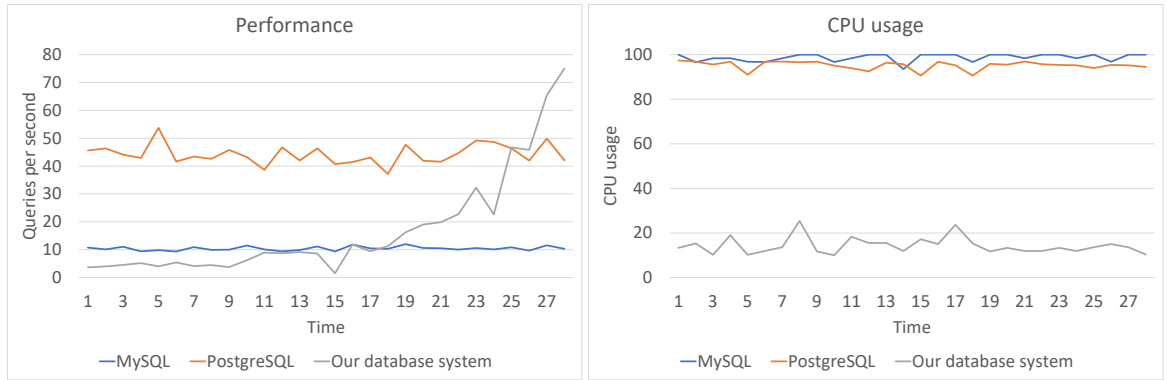


(a) Performance

(b) CPU usage with

Figure 6.3: Single connected client benchmark plots

from other clients. Thanks to this our system only using less than 20% CPU power (see Figure 6.4b).



(a) Performance

(b) CPU usage with

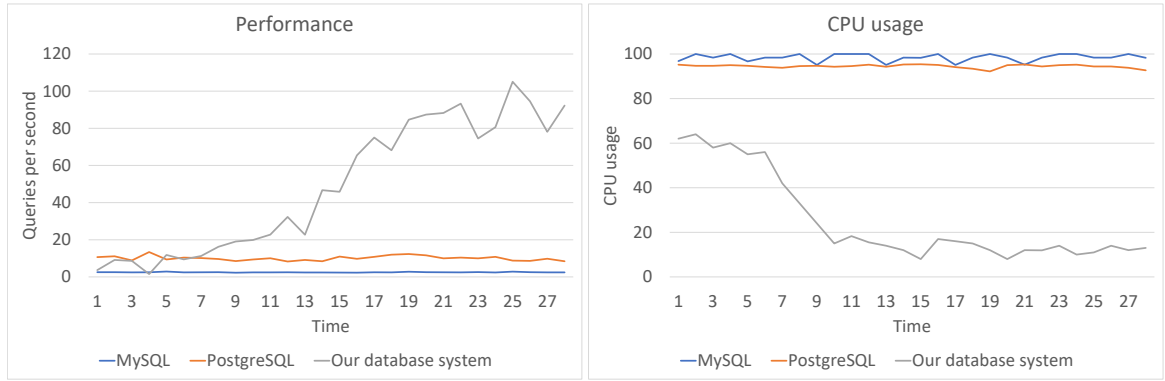
Figure 6.4: 20 connected clients benchmark plots

6.1.6 80 connected clients

With 80 connected clients, our database system outperforms MySQL and PostgreSQL after few seconds. Every client of our database system performs 100 queries per second. PostgreSQL client performs only 10 queries per second and MySQL only 2 queries per second (see 6.5a). CPU usage is in our database system also very low. At the beginning, when content is not distributed on the clients, the central node uses 60 percents of CPU but it decreases over time (see 6.5b).

6.1.7 150 connected clients

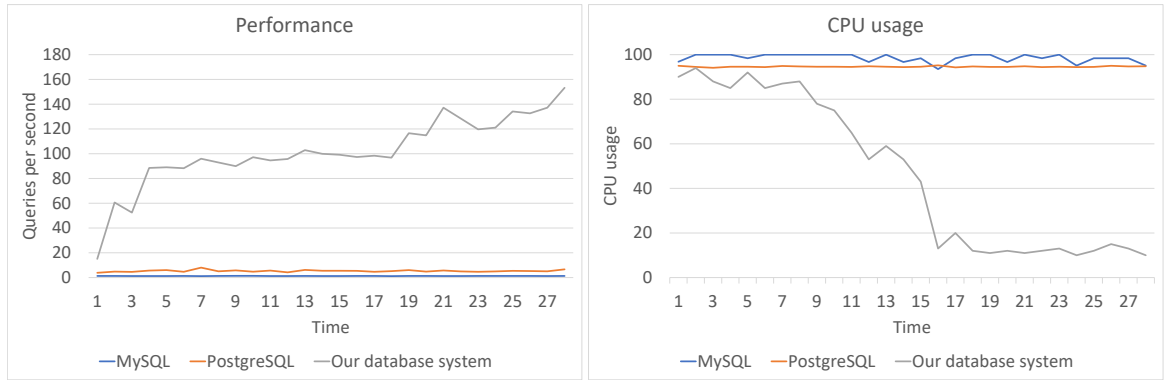
To connects more than 100 clients to the PostgreSQL, we need to change default PostgreSQL setting for maximum connections. Our system can handle 150 clients very well (opposite to MySQL and PostgreSQL). Each client connected to our database system can make up to



(a) Performance (b) CPU usage with

Figure 6.5: 80 connected clients benchmark plots

150 queries per second, and it increases by the time (see 6.6a). For the first seconds, CPU usage on the central node is high (near 100%), but it decreases over the time (see 6.6b).



(a) Performance (b) CPU usage with

Figure 6.6: 150 connected clients benchmark plots

6.1.8 Benchmark conclusion

We can see that with more than 20 connected clients, our database system became more effective than traditional ones. Thanks to IPFS and its p2p network, a content of the database is distributed on the clients. This reduces load on central node.

6.2 Comparing with blockchain explorers

6.2.1 Blockbook

Blockbook³ is a blockchain indexer for Trezor Wallet⁴, developed by SatoshiLabs⁵. It currently supports more than 30 coins (and the community implemented some others). For data storage Blockbook is using RocksDB⁶ developed by Facebook, which is a NoSQL database that stores only key-value pairs. Blockbook is providing fast API for accessing blocks, addresses and transactions. Main limitations of blockbook:

- **Not distributed** (client-server architecture) - problem with scaling for more users.
- **Not a SQL database** - it does not have a relational data model, it does not support SQL queries, and it has no support for indexes.
- **Single-Process** - only a single process (possibly multi-threaded) can access a particular database at a time.

[[Najprv je potrebne synchronizovat cely blockchain aby som mohol uskutočnit merania]]

6.2.2 Writing

6.2.3 Reading

6.2.4 Filtering

³<https://github.com/trezor/blockbook>

⁴<https://wallet.trezor.io/>

⁵<https://satoshilabs.com/>

⁶<https://github.com/facebook/rocksdb/wiki>

Chapter 7

Conclusion

The goal of this project was to create a system that uses IPFS to explore blockchain. To achieve this, we needed to create our own decentralized and distributed database system that supports queries and indexes on top of the IPFS. Feeder and ExplorerCore communicate with this database system to store (Feeder) or retrieve data (ExplorerCore). To visualize data in GUI, ExplorerGUI can be used, and for obtaining data with RestAPI there is ExplorerAPI.

The research section of this project focuses mainly on the IPFS principles (content-based addressing, nodes linking, and others). Selected cryptocurrencies for exploring are also briefly discussed. Great effort was devoted to designing the whole system and creating a functional prototype.

In the next semester, we want to highly improve database system by support more operators (`like`, `groupBy`). We want to research and compare more indexing strategies and make performance testing and profiling. Also, comparison with Blockbook in the same conditions would be interesting. There is high potential by using IPFS in this system to create new use cases that no other system for exploring cryptocurrencies blockchain supports. For example, with some heuristic, we believe, that with this system, we can follow crypto coins after exchange for another crypto coins (thanks to linking between objects in the IPLD layer).

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