Decentralized Metering and Billing of energy on Ethereum with respect to scalability and security

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Contents

1 Abstract

We leverage the power of Smart Contracts to create a pilot energy use-case on Ethereum. We propose a suite of Smart Contracts which can be utilized to trustlessly store and verify the kilowatthour readings of an arbitrary number of 'smart-meters' on the Ethereum network, while also applying accounting computations in order to properly bill that energy to the corresponding deparments of a company structure. Finally, contributions towards smart contract security and scalability are made.

2 Introduction

2.1 History

In 2009 Satoshi Nakamoto published the Bitcoin whitepaper [37]. There, Nakamoto describes 'a purely peer-to-peer version of electronic cash would allow online payments to be sent directly from one party to another without going through a financial institution.' In the beginning, Bitcoin was primarily used for fast and low-cost financial transactions. It was soon realized that its uses could be extended to more than just transfering value from A to B. The concept of colored coins, [10] was introduced, where users were able to embed extra data on a bitcoin which resulted in coins that could represent represent ownership over a land title or a domain name. In 2015, Vitalik Buterin authored the Ethereum Whitepaper [19] which was an alternative cryptocurrency to Bitcoin that enabled the creation of *smart Contracts*. smart Contracts as a term was first introduced by Nick Szabo in 1996 [39] as a model for verified trustless computation. The Ethereum Network acts as a world computer and smart contracts are code that gets executed trustlessly on every node that is part of the network.

2.2 Problem Statement

The problem this Master Thesis solves is: How an entity can manage the energy consumed by a complex system of energy meters. The system should be able to bill and perform accounting on the metering data, based on a pre-specified accounting model which can be changed at runtime. The system must be transparent, distributed, decentralized, easy-to-use and secure. Anyone in the network should be able to verify the validity transactions. It also needs to be scalable at reasonable cost.

2.3 Scope

The Master Thesis explores the fundamental terms needed to understand blockchain terminology. The contributions to scalability are limited to optimizing smart-contracts with respect to not stressing the network. Larger scale scalability solutions such as alternative consensus algorithms, payment channels or sidechains are out of scope. On security, the industry's best practices are applied, while also utilizing tools used by smart contract auditing firms, along with a proprietary tool that was provided for furter analysis.

2.4 Outline

Chapter X describes Y

3 Ethereum and Blockchain Basics

3.1 Overview

Before getting into the specifics of blockchains and Ethereum, the next section will be used to explain fundamental terms on cryptograpy and blockchain.

In non technical terms, a blockchain is a database that can be shared by non-trusting individuals without having a central party that maintains the state of the database. Namely, it is a growing list of *blocks* that grows over time. Each block contains various metadata (*blockheaders*) and a number of transactions. A block is chained to its previous one by referencing the previous block's hash. As more blocks get added to the chain, previous blocks and their contents are considered to be more secure.

Any future reference to blockchain terminology such as the contents of a block or a transaction will be referring to the implementations of the Ethereum Platform. The Ethereum Yellowpaper provides details on the formal definitions and contents of each entity [43].

3.1.1 Public Key Cryptography

Also refered to as Assymetric Cryptography, it is a system that uses a pair of keys to encrypt and decrypt data. The two keys are usually called **public** and **private**, due to the private key being known only to its owner while the public key is known to the public. The main advantage of Public Key Cryptography is the lack of need for a secure channel for the initial exchange of keys between any communicating parties.

The security Public Key Cryptography is based on cryptographic algorithms which are not solvable efficiently due to certain mathematical problems, such as the factorization of large integer numbers for RSA or the discrete logarithm problem for ECDSA, being hard.

When a person encrypts a message with one key, its pair can be used to decrypt the same message. If a message gets encrypted with the private key of the sender, any receiver can verify that the message was indeed sent by the sender as they are the only possible owners of the private key used to enrypt the message. This achieves authentication, and the process is often referred to as *signing* of a message.

3.1.2 Cryptographic Hash Functions

A hash function is any function that is used to map arbitrary size data to fixed size. The result of a hash function is often called the *hash* of its input. Cryptographic hash functions are hash functions that fullfil certain security properties and are used in cryptograpy

More specifically, a secure cryptographic hash function should satisfy the following properties ($H(x)$ refers to the hash of x):

1. **Collision Resistance**: It should be computationally infeasible to find x and y such that $H(x) = H(y)$.

2. **Pre-Image Resistance**: Given $H(x)$ it should be computationally infeasible to find x.

3. **Second Pre-Image Resistance**: Given $H(x)$ it should be computationally infeasible to find x' so that $H(x') = H(x)$.

Bitcoin uses the SHA-256 cryptographic hash function, while Ethereum uses KECCAK-256. Both functions' outputs are 256 bits long which is considered secure given the document's writing date standards.

It should be noted that although similar, a second preimage attack is significantly more difficult than a preimage attack due to the attacker being able to manipulate only one input in order to cause a collision.

3.2 Ethereum Blockchain

3.2.1 Transaction

The contents of a transaction in Ethereum are as follows:

```
1  > web3.eth.getTransaction("0
       x6a5d9e470bbff3eb476e20647fbe66e0cec7795291efd6301e6028865d0d4201
       ")
2  { blockHash: '0
       x61ff0118470fdda14815bdc26f6e4fb29effc55369f3d6985e1433f782686403
       ',
3    blockNumber: 5284738,
4    from: '0xbc7f7a5eb2039a3330665aa22b5d79485896bd11',
5    gas: 250000,
6    gasPrice: BigNumber { s: 1, e: 10, c: [
7        80000000000
8      ]
9    },
10   hash: '0
         x6a5d9e470bbff3eb476e20647fbe66e0cec7795291efd6301e6028865d0d4201
         ',
11   input: '0
         x0a19b14a0000000000000000000000000000000000000000000000000000000000000000
         ',
12   nonce: 9,
13   to: '0x8d12a197cb00d4747a1fe03395095ce2a5cc6819',
14   transactionIndex: 0,
15   value: BigNumber { s: 1, e: 0, c: [
```

```
16        0
17      ]
18    },
19    v: '0x1c',
20    r: '0
          xe7df9fee346ea3575dd541e120df7b154d46bba2bf859352b29a7f2c6dd5fab3
          ',
21    s: '0
          x68d266b140ac468ee328592ca6b4a461edace859d6837358bc3f8eeeb24ade63
          '
22  }
```

The fields blockHash, blockNumber, from, to, value, hash are all usual fields that can be found in blockchain transactions. Gas and gasPrice are used for performing computations on the Ethereum platform and will be analyzed in Section X. Ethereum uses an account model compared to Bitcoin's UTXO model [CITE]. In the account model, an attacker can replay a transaction by rebroadcasting it. This is mitigated by adding a nonce to each account's transactions which gets incremented after each transaction. The input field allows embedding extra data to a transaction. This can be used either to add a message or in the case of smart contracts, to have the contents of a function call. The v, r, s parameters are outputs from the Elliptic Curve Digital Signature Algorithms

3.2.2 Block

A block is a data structure which is comprised of data forming the block header and transactions. The interesting field for the thesis is the gasLimit field which will be discussed like the transaction gasLimit in section X.

```
1  > web3.eth.getBlock(5284738)
2  { difficulty: BigNumber { s: 1, e: 15, c: [
3        32,
4        85319757566868
5      ]
6    },
7    extraData: '0x7869786978697869',
8    gasLimit: 7995219,
9    gasUsed: 1547361,
10   hash: '0
        x61ff0118470fdda14815bdc26f6e4fb29effc55369f3d6985e1433f782686403
        ',
11   logsBloom: '0
        x000208000002040002000400000000000001004000000000008000200000000840008004002200
        ',
12   miner: '0xf3b9d2c81f2b24b0fa0acaaa865b7d9ced5fc2fb',
13   mixHash: '0
        x29b6efa55ad0298b0c90f21e9e23d572977ffb3c5064a9816a69bb2bf2a9effd
        ',
14   nonce: '0xabed128000fed25e',
15   number: 5284738,
16   parentHash: '0
        xb7063b9c7b05c95c35a329717e44875829cc740b2e0749e03d54806dcf34b520
        ',
17   receiptsRoot: '0
        xe5e176557b9f40394917191095b706a2a331742f0dc93a10e1d59b5e297ee0b5
        ',
```

```
18    sha3Uncles: '0
          x1dcc4de8dec75d7aab85b567b6ccd41ad312451b948a7413f0a142fd40d49347
          ',
19    size: 7789,
20    stateRoot: '0
          x1c62917ac72a2b76e00053efbb7af0d6949e86cafb3f983812d763715c6c9905
          ',
21    timestamp: 1521484243,
22    totalDifficulty: BigNumber { s: 1, e: 21, c: [
23        31406307,
24        78318927526632
25      ]
26    },
27    transactions: [ '0
          x6a5d9e470bbff3eb476e20647fbe66e0cec7795291efd6301e6028865d0d4201
          ',
28        '0
              xbe1c3e767e34d5d668ea50d3400b2e11a663479f931c225eda5e1d314e012589
              ', ...
29    ],
30    transactionsRoot: '0
          xb0a066469d74fe1f450c5fa8a1f59c5b7305feb6336d0d59f347a2b2c7a8c579
          ',
31    uncles: []
32  }
```

3.2.3 Blockchain

Blocks refer to the previous blocks recursively until the genesis block (first block in existence), forming a chain of blocks. The set of rules which allow an actor to add a valid block to the blockchain is called a *consensus algorithm*. In order to have consensus in distributed systems, all participating nodes must have the same version (often called history) of the system (blockchain). A malicious node could create an arbitrary block crediting them with any amount of Ether. In order to avoid that, consensus algorithms elect a network participant to decide on the contents of the next block, in a fair manner. This process is often called mining, due to the popularity of the Proof of Work consensus algorithm which allows nodes called *miners* to propose a new block if they solve a hard to compute problem. Consensus algorithms require their problem to be easy to verify however, as when somebody solves the problem and broadcasts it to the network, its solution must be verified swiftly in order to get accepted and propagated to the rest of the network, or rejected. The process of mining and how consensus is achieved is considered outside the scope of this Master Thesis.

3.2.4 Blockchain Types

Blockchains are inspectable and public. Any entity can setup a node, download the full blockchain history and view all the transactions caused by anyone participating in that netwokr. This is one of the main benefits of using a blockchain, transparency.

We categorize blockchains in two kinds (different authors might have different classifications):

1. Public or Permissionless: Low barrier to entry, transparent and immutable.

Figure 3.1: Blockchain = chain of blocks

2. Private or Permissioned: Federated participation, can obscure certain pieces of data, ability to modify and revert past transactions if needed.

Vitalik Buterin goes indepth in the advantages and disadvantages between private and public blockchains in [18]. Due to the scalability and privacy restrictions of public blockchains, corporations that are looking to include blockchain technology in their processes are looking for a solution NOW, when the research and development is still not at that level. As a result, permissioned blockchains as JP Morgan's Quorum [35], Hyperledger or Corda have arised, with aims to solve these problems.

3.2.5 Transactions as State Transitions

In Bitcoin, the state is created through the Unspent Transaction Outputs set, which defines the amount of BTC a user can spend. As Ethereum does not use UTXO but an account model, there needs to be a way to monitor the state. This is done through a data structure called Patricia State Trie [36] which provides an efficient mapping of key and value pairs where the key is the address of the Ethereum account and the value is the Recursive Length Prefix encoding [25] of the account's data.

Whenever a transaction gets successfully mined, the world state gets updated accordingly.

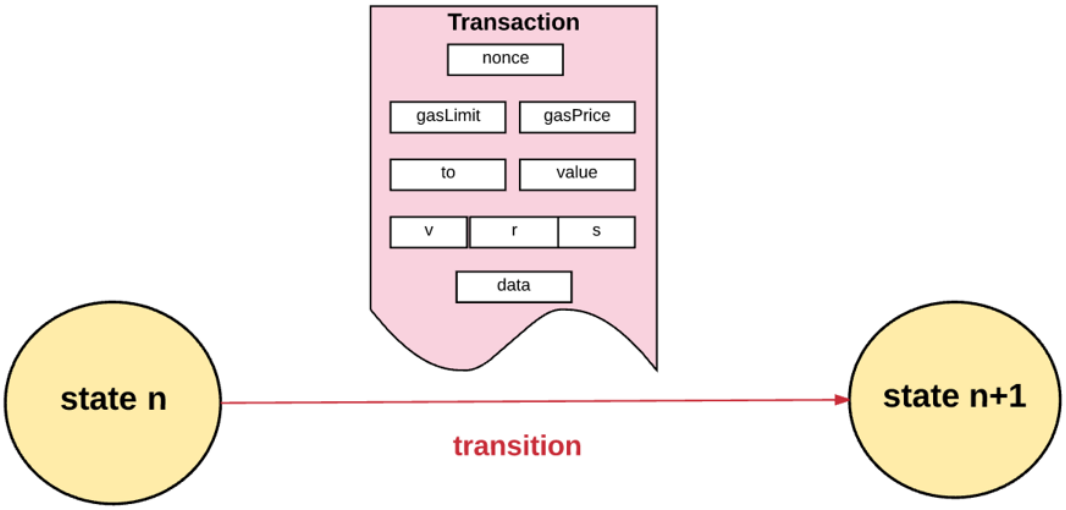

Figure 3.2: After each transaction the state gets updated

3.2.6 Ethereum Virtual Machine

The Ethereum Virtual Machine is the runtime environment for Ethereum. It is a Turing Complete State machine, allowing arbitrarily complex computations to be executed on it. Ethereum nodes validate blocks and also run the EVM, which means executing the code that is triggered by the transactions (discussed in Section X). Since all nodes redundantly process all transactions and contract executions this process, this can be used by an attacker to maliciously flood the network with transactions and cause multiple computers around the world to perform costly computations forever. There needs to be a computational cost. In Ethereum it is called gas and to the end user it manifests itself as the fees needed for a transaction (be it value transfer or contract call) to complete successfully.

3.2.7 Gas

Every computational step on Ethereum costs gas. The simplest transaction which involves transfering Ether from one account to another costs 21000 gas. Calling functions of a contract involves additional operations whose costs can be estimated through the costs described in [11, 43].

[INSERT GAS / WEI / ETHER denominations]

When refering to blocks, the gasLimit is the cumulative gas that is needed by all transactions included in that block. This is analogous to the block size in Bitcoin and effectively limits the amount of transactions that can be confirmed per block.

Every unit of gas costs a certain amount of *gasPrice* which is set by the sender of the transaction. It is the case that:

$$totalTransactionCost = gasPrice * gasLimit \tag{3.1}$$

Miners are rational players who are looking to maximize their profit. As a result, they include transactions which have higher transaction cost first and transactions with very low transaction fees take longer to confirm.

This effectively creates a fee market where actors increase the gasPrice value to have them confirmed faster. In the times of network congestion such as popular Initial Coin Offerings [CITE] or mass-driven games such as CryptoKitties [CITE], the network has become very expensive to use and oftentimes unusable with transactions taking hours to confirm [CITE].

In the case of a successful transaction, the consumed gas from *gasLimit* goes to miners, while the rest of the gas gets refunded to the sender. After the completion, the world state gets updated.

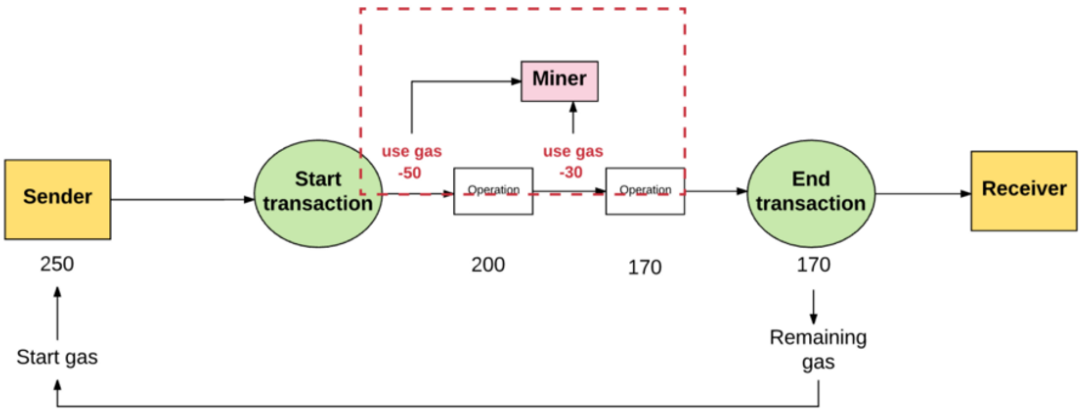

Figure 3.3: Successful transaction (from [30])

A transaction can fail for reasons such as not being given enough gas for its computations, or some exception occuring during its execution. In this case, any gas consumed goes to the miners and any changes that would happen are reverted. This is similar to the SQL transaction commit-rollback pattern.

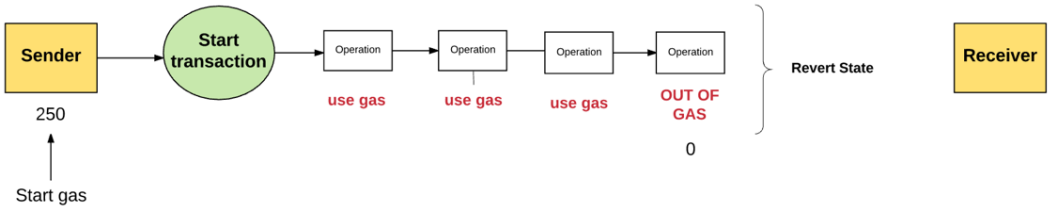

Figure 3.4: Out of gas transaction (from [30])

3.3 Programming in Ethereum

The EVM has its own language called EVM bytecode [REPHRASE]. Programmers often write in higher-level languages such as Solidity and then compile to lower level code.

3.3.1 Programming Languages

Programmers can write Ethereum Smart Contracts in languages which have compilers designed to compile to EVM bytecode. Such languages are Solidity, Serpent, LLL or Vyper.

Solidity is the most supported language in the ecosystem and although often comparable to Javascript, we argue that Smart Contracts remind more of C++ or Java, due to their object oriented design.

Due to the nascence of these languages and the security mistakes that have occured due to them providing programmers with powerful state-changing functions,

```
pragma solidity ^0.4.16;

contract TestContract {

  string private myString = "foo";
  uint private lastUpdated = now;

  function getString() view external returns (string, uint) {
    return (myString, lastUpdated);
  }

  function setString (string _string) public {
    myString = _string;
    lastUpdated = block.timestamp;
  }
}
```

Figure 3.5: Basic Solidity Smart Contract

there is also progress towards creating functional programming languages such as Bamboo or ones that are formally verifiable.

A compiler is needed to output both the EVM Bytecode and the Application Binary Interface (ABI) so that a third party library can interact with the Smart Contract.

3.3.2 Tooling

The following section describes tools and software that are often used by Ethereum users and developers to interact with the network.

Client (Node) Implementations and Testnets

Ethereum's official implementations are Geth (golang) and cpp-ethereum (C++). Third party implementations such as Parity (Rust), Pyethereum (Python) and EthereumJ (Java) also exist. The most used kind of node implementations are Geth (compatible with Rinkeby testnet) and Parity (compatibly with Kovan testnet).

Smart contracts are immutable once deployed which means that their code cannot change. In addition, they also cost to be deployed, which means that development can get expensive and inefficient. For that, public test networks (testnets) exist which allow for testing free of charge. Kovan and Rinkeby are functioning with the Proof of Authority [40] consensus algorithm, compared to Ropsten running the Proof of Work [24] which is the same as the Ethereum main network's (with less difficulty).

Comparison between test networks:

1. Kovan: Proof of Authority consensus supported by Parity nodes only
2. Rinkeby: Proof of Authority consensus supported by Geth nodes only
3. Ropsten: Proof of Work consensus, supported by all node implementations, provides best simulation to the main network

In addition, before deploying to a testnet, developers are encouraged to run their own local testnets in order to further their development processes. Geth and Parity allow for setting up private testnets, however the go-to tool for this process is ganache[1] (formerly known as testrpc).

Web3

Web3 is the library used for interacting with an Ethereum node. The most feature-rich implementation is Web3.js[2] which is also used for building web interfaces for Ethereum Decentralized Applications (DApps). Implementations for other programming languages are being worked on such as Web3.py[3]. We showcase an example of connecting and fetching the latest block from Ropsten and Mainnet using Web3.js and Web3.py. The full specifications of each library's API can be found in their documentation[4][5]

```
node
    > Web3 = require('web3');
> INFURA_API = process.env.INFURA_API; // Infura is a third party service that allows us to connect to their Ethereum node without setting up our own. > web3 = new Web3(new Web3.providers.HttpProvider("https://mainnet.infura.io/" + INFURA_API));
> web3.eth.blockNumber;
5289236
```

```
$ ipython
In [1]: from web3 import Web3, HTTPProvider
In [2]: import os
In [3]: INFURA_API = os.environ['INFURA_API']
In [4]: w3 = Web3(HTTPProvider('https://ropsten.infura.io/'+INFURA_API))
In [5]: w3.eth.blockNumber
Out[5]: 2872088
```

Truffle

Truffle is the industry standard framework for smart contract development framework written in Node.JS. It allows for easy deployment and initialization smart contracts along with writing test suites utilizing the Mocha testing framework. Latest versions come together with a debugger and a local testnet like ganache.

Docker

Explain docker...

[1] http://truffleframework.com/ganache
[2] https://github.com/ethereum/web3.js
[3] https://github.com/ethereum/web3.py
[4] https://github.com/ethereum/wiki/wiki/JavaScript-API
[5] https://web3py.readthedocs.io/en/stable/

4 Blockchain Scalability

4.1 Bottlenecks in Scalability

A blockchain's scalability is often measured in transactions per second. A block gets appended to the chain every 15 seconds on avereage in Ethereum, and can contain only a finite amount of transactions. As a result, transaction throughput is bound by the frequency of new blocks and by the number of transactions in them.

Proof-of-Work has been the only consensus algorithm to date that has proven to be effective against attackers, while still relatively maintaining the decentralization of the network. Due to faster block times, it can handle 7 transactions per second (tx/s), which is better than bitcoin's 3 tx/s however still not comparable to Visa's 2000 consistent tx/s or 60000 at peak. As a result, creating scalable blockchain architectures has been a topic of interest.

We argue that there are two levels of scalability, scalability on contract and on network level. Better contract design can result in transactions which require less gas to execute, and thus allow for more transactions to fit in a block while also making it cheaper for the end user. It should be noted that as Ethereum's current blockGasLimit is set by the miners at 8003916, if all transactions in Ethereum were financial transactions (each costing 21000 gas), each block would be able to handle 381 transactions per block, which is 25 tx/s, which is still not comparable to traditional payment operators.

4.2 Network Level Scalability

A naive solution in achieving scalability involves increasing the size of each block, or in Ethereum terms the *blockGasLimit*. This solution is not sustainable as it compromises decentralization, due to increased network and hardware costs. Bigger blocks require more disk space for storing the blockchain, better bandwith for the block propagation and more processing power on a node to verify the computations in a block. This eventually requires computers with datacenter-level network connections and processing power which are not accessible to the average consumer, thus damaging decentralization which is the core value proposition of blockchain. The blockGasLimit can be voted on by miners[1].

Long term solutions in Ethereum are categorized in:

1. Sidechains: First described in [15], sidechains (side-blockchains) are running in 'parallel' to the mainchain, while using a sort of mechanism to benefit from the security of the main blockchain (mainchain). This allows them to

[1] `https://www.etherchain.org/tools/gasLimitVoting`

implement consensus rules which are more flexible and customized to their use-case, allowing for potentially infinite scalability.

2. Proof of Stake: Proof of Work provides security at the cost of energy consumed by miners. Alternative consensus algorithms such as Proof of Stake (PoS), are more friendly to the environment than Proof of Work[22]. Instead of consuming energy, PoS involves validators who are 'staking' their ETH and by modeling their incentives and appropriately punishing malicious behavior, the network can have the same security as PoW. Ethereum is planning to transition to PoS, however there is no clear date when this is going to happen as this is still under heavy research.

3. Sharding: Due to the architecture of the EVM, it is not parallelizable. Sharding refers to having nodes which validate different parts of the blockchain, allowing for parallelizability on computations.

4. State channels: In the case of micropayments which involve a number of transactions between parties, there is no need to make every transaction on the blokcchain. The proposed technique involves exchanging signed messages offchain and settling when the transactions are finished. As a result, a transaction is done to open the state channel, and another to settle it.

4.3 Contract Level Scalability

In a recent study [20], after evaluating 4240 smart contracts, it is found that over 70% of them are under-optimized with respect to gas from the compiler. In this section we explore how gas gets computed and ways we can save on gas and transaction costs.

4.3.1 Gas Costs

An Ethereum transaction's gas costs are split in:

1. **Transaction Costs:** The cost of sending data to the blockchain. There are 4 items which make up the full transaction cost:
   (a) The base cost of a transaction (21000 gas)
   (b) The cost of a contract deployment (32000 gas)
   (c) The cost for every zero byte of data or contracts for a transaction.
   (d) The cost of every non-zero byte of data or contracts for a transaction.

2. **Execution Costs:** The cost of computational operations which are executed as a result of the the transaction, as described in detail in [43, 11]

[INSERT TABLE ON GAS COSTS SHOWING SSTORE ETC]

Gas costs get translated to transaction fees. As a result, a contract should be designed to minimize its operational gas costs in order to minimize its transaction fees. In addition, as gas is a unit for computational costs, less gas consumed results in

less burden on the nodes validating the smart contracts which can lead to increased scalability.

From the gas cost table, it can be seen that the most expensive operations involve SSTORE operations. The focus of this section will be to explore ways to decrease gas costs on Smart Contracts, either through better practices or by handcrafting optimizations for specific use cases.

It should be noted, that non-standard methods have been proposed for reducing fees incurred by gas costs. A recent construction[32] describes a method for buying gas at low cost periods and saving it in order to spend it when prices are higher at times when the network is congested. The economic applications of gas arbitrage are outside the scope of this Master Thesis.

General rules that should be followed for saving gas costs:

1. Enable compiler optimizations (although can lead to unexpected scenarios [6])

2. Reuse contracts through libraries[28]

3. Setting a variable back to zero refunds 15000 gas through SSTORE, so if a variable is going to be unused it is considered good practice to call delete on it.

4. Use 'bytes32' instead of 'string' for strings that are of known size. 'bytes32' always fit in an EVM word, while 'string' types can be arbitrarily long and thus require more gas for saving their length. [NEEDSCITATION]

5. Do not save large amounts of data on a blockchain. Instead, save a hash to prove their existence at a lower point in time.

As described in [20] there is a lot of room for further compiler optimizations. Future Solidity compiler versions are addressing some already[2][3][4]

The EVM operates on 32 byte words [CITE] implying that a SSTORE command is needed to store 32 bytes of data. The compiler is able to tightly pack data together, which means that 2 128 bit storage variables can be efficiently stored with 1 SSTORE command. The *optimize* flag of the Solidity compiler needs to be activated to access this feature when programming in Solidity.

[2] `https://github.com/ethereum/solidity/issues/3760`
[3] `https://github.com/ethereum/solidity/issues/3716`
[4] `https://github.com/ethereum/solidity/issues/3691`

```
pragma solidity ^0.4.21;

contract Packing {

    uint64  a;
    uint64  b;
    uint64  c;
    uint64  d;
    uint128 e;
    uint128 f;

    function set() public {
        a = 1;
        b = 2;
        c = 3;
        d = 4;
        e = 5;
        f = 6;
    }
}
```

```
$ solc --optimize --asm Packing.sol | grep sstore | wc-l
2
$ solc --asm Packing.sol | grep sstore | wc -l
6
```

Figure 4.1: Running the optimizer in storage variables less than 256 bytes results in 2 SSTORE commands instead of 6 which a significant saving in gas costs

4.3.2 Gas Savings Case Study

In order to illustrate our findings and compare accross different scenarios, we will perform a Solidity benchmarking test based on a use-case of a Solidity Smart Contract which describes a game. The contract must allows a user to register as a player if they are not already registered and allow them to create a character with some traits. Table X describes these traits:

Table 4.1: Required variables and size. Sizes add up to 256 bits

Name	Type	Comment
playerID	uint16	Game supports up to 65535 players
creationTime	uint32	Game supports timestamps up to 2**32 = 02/07/2106 @ 6:28am (UTC)
class	uint4	Game supports up to 16 classes
race	uint4	Game supports up to 16 classes
strength	uint16	Stats can be up to 65535
agility	uint16	Stats can be up to 65535
wisdom	uint16	Stats can be up to 65535
metadata	bytes19	Utilize the rest of the word for metadata

The size of the variables is selected so that all the information required to describe a 'Character' can fit in a 256 bit word.

For each of the following implementations we will examine the deployment gas costs, as well as the gas costs for calling the 'CreateCharacter' function:

1. Tightly packed structures for setting data

2. Bit masking encoding for setting data
3. Bit masking encoding utilizing libraries, influenced by [38].

The full contracts of each contract can be found in the Appendix. For each test described, the optimizer was run 0, 1, 100, 500 and 50000 times.

GameTightlyPacked.sol

We're utilizing a structure here and by taking advantage of the optimizer packing everything in a word we can perform a full write to structure with only X gas

GameByteMasking.sol

Here we create a new character by shifting variables. This concept can be though as a 'virtualstruct'. Essentially instead of creating a 'struct' as Soldiity expects it and let the compiler do the parsing, we do it ourselves. That way, we achieve gas costs which are substantially lower.

Table 4.2: Gas costs for Byte masking method wihtout Library

Optimizer Runs	Register	CreateCharacter	Constructor
0	70003	66620	551800.0
1	69943	66365	378022.0
100	69811	65924	402120.0
500	69604	65855	419559.0
500000	69598	65855	432537.0

:

In addition, as we essentially do the optimization ourselves, the deployed bytecode is smaller. This is not exactly intuitive, as it'd be expected that the solidity compiler is able to pack everything perfectly. It turns out[5] that the compiler is not very efficient and as a result this method is far more efficient. With this method we are able to store and fetch all the data in a very efficient way, which costs X% gas less than the previous implementation. However, this method does not allow for a readable and maintainable interface. In order to export every functionality it is needed to convert the 'uint' variables to bytes to perform the bit operations on functions. This creates undesired overhead and thus is avoided.

GameByteMaskingLib.sol

It is important to consider code reusability, in the case another developer wanted to develop on the same structure, they should not need to deploy the core functionality of the 'Character' structure each time. Utilizing the 'using X for Y' syntax, we can export the library's API in a format that is similar to calling functions on struct's in Golang [6].

The are two ways to export functions when creating Solidity APIs:

1. Internal: The library's bytecode is inlined to the main contract's code. This results in larger bytecode during deployment, however each of the contract's function are immediately jumping and returning to the Library's code, like any function. In this case, only the main contract gets deployed.

[5] https://github.com/figs999/Ethereum/blob/master/Solc.aComedyInOneAct

[6] `golangtutorials.blogspot.de/2011/06/methods-on-structs.html`

2. Public: This is a more complex process:
   (a) The library contract gets compiled and deployed
   (b) The main contract gets compiled and has placeholder slots in the bytecode.
   (c) The placeholder gets replaced by the deployed library's address
   (d) Any function call that requires the library utilizes the 'delegatecall' opcode.

The usage of the former can be done for separating the code and creating a more well done repository. The latter's usability cna be seen with more general purpose functions such as error-checked functions for mathematic operations. That way, instaed of everyone having to deploy their own version, they can use the already deployed one. The tradeoff comes between deployment costs and calling each function. When the bytecode is inlined, the jumping is done internally, while delegatecall requires additional resources. Finally there is a security gain, such as when everyone uses the same version of an audited library compared to everyone deploying their own. We opt for the internal approach, because cheaper and does not make sense to deploy, i.e. not enough people will care about it.

The final version is split in two files, a library file and a main file. [EXPLAIN LIBRARIES].

4.3.3 Results

It can be seen that in all cases the optimizer's first iteration creates significant gas savings. However, the more optimizer-runs were done, the more gas cost was spent during deployment, however the cost of 'CreateCharacter' went down. Code in Solidity is either optimized for size, and thus costs less to deploy, or for runtime costs, which costs more to deploy but each function costs less [4].

We described a technique which relies on the compiler's optimizer to pack the data in a struct and do the gas savings, however is simpler and more elegant. The second and third technique are more complex and allow for further gas optimizations. The second technique is more efficient however lacks reusability and is less maintanable. On the other hand, utilizing libraries however we can export a user-friendly API for reusing our code for anyone who has the same use case as us. This technique will be utilized in the Design and implementation section.

5 Ethereum and Security

The Ethereum platform itself has proven to be robust and reliable as a blockchain as it has been resistant to both censorship and double-spend attacks. In this chapter we discuss vulnerabilities that have been found in the network's implementation which resulted in Denial of Service-like attacks and the blockchain's state being bloated with junk data. Afterwards, we discuss the security of smart contracts and the best practices that need to be applied in order to have a proper workflow. We contribute to the existing literature by evaluating the usage of the tools 'Slither' and 'Echidna' towards finding smart contract vulnerabilities and edge cases.

5.1 Past Attacks

5.1.1 Network Level Attacks

September October 2016 Spam Attacks During the period of September-October 2016, an attacker was able to spam the Ethereum network's state by creating 19 million accounts. The attack was made possible by a mispricing in the SUICIDE opcode of smart contracts, allowing an attacker to create a large amount of transactions that created the accounts at a low cost. The creation of these accounts bloated the blockchain's state which resulted in clients being unable to synchronize in time, effectively causing a Denial of Service attack to the network [29]. As a response, two hard-forks[1] were proposed [16, 17]. Tangerine Whistle solved the gas pricing issue and at a later point, Spurious Dragon cleared the world stated from the accounts created by the spam attack.

Eclipse Attacks on Ethereum [34] describes 'eclipse' attacks on Ethereum, a type of attack which was considered to be harder to perform on Ethereum nodes. The researchers communicated the potential effects of the attack and the vulnerabilities were fixed in geth v1.8[2]. This vulnerability was not abused in the wild, and as a result there was no need for a hard-fork. It should be noted, that other client implementations such as parity or cpp-ethereum were not found to be vulnerable, which shows that having a diverse set of implementations of a protocol can contribute to the network's security.

[1] A non-backwards compatible upgrade mechanism that creates new rules for a blockchain, usually to improve the system

[2] Most popular implementation of Ethereum in golang

5.1.2 Smart Contract Attacks

Contrary to the network itself, Smart Contracts have proven to be quite vulnerable in the past. The biggest hack was the 'DAO hack' which involved more than 50 million dollars in value. The breaking point then was that the network hard-forked (similarly to the HF during the spam attacks) into a state that reverted the results of the hack. This was not widely accepted by the community, and a part of the Ethereum chain with the hack is still being maintained today as 'Ethereum Classic' [1].

In 2017, two large-scale attacks were done on Parity's[3] wallet, resulting in approximately 30 million dollars being stolen in July 2017[3]. The fix to this hack introduced another vulnerability in the library's code which was exploited in November 2017 which resulted which resulted in 150 million dollars of funds being locked in the smart contract forever [5]. A number of proposals were made [8] in order to recover the locked funds. All of these would require an 'irregular state change' similar to what happened with the DAO[4] which was considered bad practice, considering the precedent that the DAO incident caused.

5.2 Smart Contract Security

Due to the high financial amounts often involved with smart contracts, security audits from internal and external parties are considered a needed step before deployment to production. It is also being practiced that companies with public smart contracts also engage in bug-bounties, where they encourage users to interact with versions of their contracts deployed on a testnet, in order to identify any other vulnerabilities. Comprehensive studies on identifying the security, privacy and scalability of smart contracts [13] as well as taxonomies aiming to organize past smart contract vulnerabilities have been done [14, 23] have been done, however due to the rapid evolution of the field they get outdated very soon.

There is a need for auditors and developers to use automated auditing tools on their smart contracts and also use the latest version of the Solidity Compiler. As an example, none of the tools mentioned in [23] were able to detect the 'Uninitialized Storage Pointer' vulnerability[5], however the Solidity Compiler was later updated to throw a Warning if this vulnerability exists.

5.2.1 Automated Tools

Auditing smart contracts significantly more effective when the source code is available. Taking into account the tools which have not been examined in our literature, we came in contact with TrailOfBits, a security auditing firm, and used their suite of tools to extend the already built taxonomies.

[3]The ParityTech team developed a popular multisig-wallet smart contract which held the funds gathered by many ICOs

[4] 12 million ETH were moved from the "Dark DAO" and "Whitehat DAO" contracts into the WithdrawDAO recovery contract[2]

[5]`https://github.com/ethereum/solidity/issues/2628`. This particular vulnerability has been exploited in Smart Contract honeypots as discussed in Section X

We utilized the tool Slither[6] to audit smart contracts which had their source code available. As our concern is primarily in auditing and ensuring smart contracts that have yet to be deployed, we process all the smart contracts with the latest version of the Solidity compiler, v0.4.21, which provides verbose warnings and errors. [CITE]

As Slither is a static analyzer and works on the code, its modules (called 'detectors') are to find certain coding patterns which can be considered harmful to the smart contract. This includes detecting popular past contract vulnerabilities such as Reentrancy or the Parity library selfdestruct bug, however it's not limited to that as new functionalities can be added through its scriptable API. We describe its modules:

Constant/View functions that write to state: It is planned to make constant and view functions unable to modify state variables by default in the next Solidity compiler versions, however until that happens, it should be enforced manually by developers. It ensures that the code functions as advertised.

Misnamed constructors that allow modification of 'owner'-like variables: A constructor in a smart contract is run once at contract creation and usually sets an 'owner' variable which allows the contract's deployer to have some extra functionality on the contract. In past cases, constructors were not named properly and were callable by adversaries, leading to smart contracts being drained of funds (Rubixi)

Reentrancy bugs: After TheDAO brought reentrancy and race-to-empty[7] to the spotlight, all vulnerability scanners for Ethereum smart contracts are able to detect this vulnerability.

Deletion of struct with mapping: Deleting a struct with a mapping inside resets the contents of the struct, however it does not clear the contents of a mapping. This has not been reported as an exploit in the wild[8], however it can be critical in the case of a banking DApp that keeps tracks of balances. A full Proof of Concept is given Appendix A.

Variable Shadowing: This is a unique feature of Slither that has not been implemented in other scanners (has been used in honeypot contracts)

Similar Naming between State Variables: Warns useres in the case two state variables with same length have very similar names, leading to more clear variable naming in order to avoid misconceptions and typos.

Unimplemented Function Detection: This ensures that the implementation of an interface stays compliant and does not diverge from the intended implementation.

Unused State Variables: Detects state variables that are not used in any operations and suggests their removal. Makes code simpler and less gas intensive.

Unprotected Function Detection: Detects public functions which have no modifiers and do not perform any assertions on state variables. The current implementation can impose false positives, however it does not have false negatives. This is able to find the Parity Wallet hack.

Wrong Event Prefix: As per the best practices, the names of 'events' should

[6]Currently not open-sourced. TrailOfBits shared it with us to use it in the thesis.

[7]`http://vessenes.com/more-ethereum-attacks-race-to-empty-is-the-real-deal/`

[8]TrailOfBits have found this bug in audits

be capitalized. After a discussion on Github[9], using 'emit' for events is going to be a mandatory for Solidity 0.5.0 and onwards.

It is seen that Slither can be used both for finding known vulnerabilities, but also to avoid common coding anti-patterns and mistkaes. Due to its highly scriptable API we can extend it to include more rules. We contributed to the Slither repository by adding support for detecting 'tx.origin' and 'block.blockhash' usage. The usage of 'tx.origin' should be avoided unless necessary, and as stated in the Solidity documentation can incur in loss of funds[10] 'block.blockhash' has been misused in smart contracts and ended up in 400 ETH being stolen from the SmartBillions contract [CITE]. We also contributed to the improvement of the accuracy of the modules 'UnimplementedFunctionDetection'. Figure X shows a comparison of Slither after our contributions to the other analysis tools from [23]. [CREATE GRAPH WITH SLITHER FINDING VULNS SAME AS OTHER TOOLS]

5.2.2 Honeypot Smart Contracts

As of March 2018, no novel critical vulnerabilities have been identified in smart contracts. Smart Contracts that are architected to look vulnerable to known exploits started surfacing, when their true purpose is stealing the funds of aspiring hackers. These contract honeypots are funded with an initial small amount of ether (0.5 to 2 ether). Hackers who attempt to exploit them need to first deposit some amount (depending on the honeypot's implementation) before trying to drain the contract. Each honeypot has a well-hidden mechanism to prevent the attacker from draining the funds, essentially locking up any funds that get deposited by individuals other than the contracts deployer.

[9] `https://github.com/ethereum/solidity/issues/2877`
[10] `http://solidity.readthedocs.io/en/v0.4.21/security-considerations.html`

```
1  // contract address: 0xd8993F49F372BB014fB088eaBec95cfDC795CBF6
2  pragma solidity ^0.4.17;
3
4  contract Gift_1_ETH
5  {
6
7      bool passHasBeenSet = false;
8
9      function()payable{}
10
11     function GetHash(bytes pass) constant returns (bytes32) {return
           sha3(pass);}
12
13     bytes32 public hashPass;
14
15     function SetPass(bytes32 hash)
16     payable
17     {
18         if(!passHasBeenSet&&(msg.value >= 1 ether))
19         {
20             hashPass = hash;
21         }
22     }
23
24     function GetGift(bytes pass) returns (bytes32)
25     {
26
27         if( hashPass == sha3(pass))
28         {
29             msg.sender.transfer(this.balance);
30         }
31         return sha3(pass);
32     }
33
34     function PassHasBeenSet(bytes32 hash)
35     {
36         if(hash==hashPass)
37         {
38            passHasBeenSet=true;
39         }
40     }
41 }
```

Figure 5.1: Example honeypot

The above contract was initialized with 1 ether at its balance. An attack can drain the contract by calling the *GetGift* function with the correct password. Due to the attacker not knowing the password, they proceed to change it, using the *SetPass* function, which requires at least a 1 ether deposit, which is acceptable since the attacker will get that back. This also requires that the 'passHasBeenSet' variable is false, or that the PassHasBeenSet function has not been called yet.

A naive attacker would inspect the contract's transactions in Etherscan[11] and after notice that no transaction refering to 'PassHasBeenSet' has been made, and thus proceed to attack the contract and change the password, only to find that

[11] https://etherscan.io/address/0xd8993f49f372bb014fb088eabec95cfdc795cbf6

the password did not get changed. A transaction where a contract calls another contract's function is called a 'Message Call'. Etherscan shows this kind of calls as 'Internal Transactions', only when they include values of more than 0 ether. In this case, 'PassHasBeenSet' does not accept Ether and thus cannot be detected in Etherscan. The contract's owner called 'PassHasBeenSet' from another contract and as a result the password is not changeable. Detecting that the 'passHasBeenSet' variable had been set to true can be done by inspecting the storage of the smart contract, which is always public.

```
1
2 $ ipython
3 In [1]: from web3 import Web3, HTTPProvider
4 In [2]: import os
5 In [3]: INFURA_API = os.environ['INFURA_API']
6 In [4]: w3 = Web3(HTTPProvider('https://mainnet.infura.io/'+
    INFURA_API))
7 In [5]: w3.eth.getStorageAt(w3.toChecksumAddress('0
    xd8993F49F372BB014fB088eaBec95cfDC795CBF6'),  0)
8 Out[5]: HexBytes('0
    x0000000000000000000000000000000000000000000000000000000000000001
    ')
```

An extensive analysis of smart contracts as honeypots is made in [31] which was released to accompany the research of this Master Thesis.

5.2.3 Towards more secure smart contracts

It is apparent that since smart contracts being unmodifiable after deployment, there is no way of patching any vulnerabilities. Testing platforms have been setup so that developers can practice and test their skills. A developer should keep their code as simple as possible, while providing test coverage for as many scenarios as possible. Using audited and tested code for parts of contracts that have already been implemented (eg. an $ERC20$ token contract) ensures that these parts of the code are going to be secured. Following the best practices as described by the industrýs most sophisticated auditors[12]. Finally, developers should be looking for confluence between the results of different automated analyzers and turn their efforts there.

[12] https://consensys.github.io/smart-contract-best-practices/known_attacks/

6 Blockchain and the Energy Market

Price of energy, consumer does not know always what they pay, or what they gain from their renewables

List relevant projects in energy sector

6.1 Advantages of Blockchain

Transparency, full history of meter readings, price calculation, billing of inhouse energy departments. This can be extended for EV car payment microtransactions and so on.

6.2 Our Use-case

Describe meters, billing and so on

7 Design and Implementation

7.1 Business Logic

Explain company structure

7.2 Smart Contracts

7.2.1 Contract Registry

7.2.2 Meter Management

7.2.3 Cost - Profit Management

7.2.4 Access Control

We define a Smart Contract that is to be used for access control. Is influenced by Aragon There is NO private data, just functions that can be called by certain individuals A proper access control model needs to be implemented so that only authorized users can access certain functions. Explain the Smart Contracts suite

7.3 Monitoring Server

Explain monitoring server

7.3.1 REST API

Explain rest api usage

7.3.2 Python Client

Explain python implementation of rest api

7.3.3 web3.py interaction

Explain how web3.py interacts with monitoring server and sends data to Smart Contracts

8 Conclusion

8.1 Results

We are able to create blabla

8.2 Related Work

8.2.1 Scalability

We do not provide contributions towards network level Scalability as it is a far more complex issue than what . To date, there have been proposals [12] which illustrate smart contract techniques that consume less gas and let an application's backend do the heavy lifting. LINK TO PLASMA, TO COSMOS, TO LOOM TO ALL SCALING SOLUTIONS. There is also the case of permissioned blockchains which are able to function with a cryptocurrency that backs them such as Hyperledger Fabric[1] [42].

8.2.2 Security

Tools that are able to analyze and search for vulnerabilities only from contract bytecode have been developed[33, 26, 21]. The recent study[23] on the available tools that evaluate smart contract security[2] illustrates improvements that can be done to them, and provides an evaluation of each tool. Of these, Oyente and Securify are able to perform direct analysis on a contract's bytecode. Given the contract's source code, Smartcheck is able to vastly outperform other tools, detecting all vulnerabilities proposed in the given taxonomy as well as yielding the least false positives. We provide a rough summary of two tools that are not analyzed in the previous taxonomies or in our Automated Tools section.

These tools utilize symbolic execution. Although useful, raw bytecode analysis is not sufficient here are often false positives and cases where analyzing bytecode is not enough [9].

MAIAN

Maian [27] was developed for [26] and is able to detect greedy, prodigal and suicidal contracts which either lock funds indefinitely, leak them to arbitrary users, or are killable by any user MAIAN's features are useful and provide useful insight for

[1] `https://www.hyperledger.org/projects/fabric`
[2] Oyente, Remix, SmartCheck, Securify

creating detection mechanisms that can be incorporated in other tools, however the results of the study are considered skewed for the following reasons[3]:

- All contracts compiled with solc versions earlier than 0.3.6 are considered 'greedy' in absense of a 'withdraw' function due to the fact that functions did not require the 'payable' modifier in order to accept ether.
- Many smart contracts deployed on the Ethereum mainnet are used for testing. When ether was inexpensive, the main network was feasible to be used as its own testnet.
- The only contract which is cited in the paper is one which never received any ether [4]
- No peer-review in the paper

Mythril

Mythril [21] is a tool developed by ConsenSys[5]. Its unique feature allows it to directly connect to Ethereum and evaluate a deployed contract at any ethereum network. It allows for direction inspection of contract storage which can be used to evaluate a contract's state. As an example, the aforementioned contract honeypot in Section X could be swiftly inspected and it would be immediately noticed that the 'passHasBeenSet' variable is true.

```
1 $ myth --storage 0,10 -a 0x75041597d8f6e869092d78b9814b7bcdeeb393b4
      --rpc infura-mainnet
2 0x0: 0
    x0000000000000000000000000000000000000000000000000000000000000001

3 0x1: 0
    x262a262b32c44fdf8b75e8180c6bec05873b60a425126bb77e1059b01f6d3513

4 0x2: 0
    x0000000000000000000000000000000000000000000000000000000000000000

5 0x3: 0
    x0000000000000000000000000000000000000000000000000000000000000000

6 0x4: 0
    x0000000000000000000000000000000000000000000000000000000000000000

7 0x5: 0
    x0000000000000000000000000000000000000000000000000000000000000000

8 0x6: 0
    x0000000000000000000000000000000000000000000000000000000000000000

9 0x7: 0
    x0000000000000000000000000000000000000000000000000000000000000000
```

[3]Opinions influenced by relevant critique on Twitter by TrailOfBits `https://twitter.com/dguido/status/966795086704062465`

[4]`https://etherscan.io/address/0x4671ebe586199456ca28ac050cc9473cbac829eb`

[5]`https://new.consensys.net/`

```
10 0x8: 0
       x0000000000000000000000000000000000000000000000000000000000000000

11 0x9: 0
       x0000000000000000000000000000000000000000000000000000000000000000
```

Solium

Solium [7] is a linter for Solidity. It performs static analysis on the code by analyzing its abstract syntax tree and is able to identify and fix styling and security issues according to preconfigured rules. The plugin for security[6] can be used to further identify security issues in smart contracts according to best-practices as set by the community and by leading companies.

8.2.3 Energy Billing and Accounting on Blockchain

An proposal for billing and accounting models is seen on[41], however it is oriented towards a cloud-management use case and does not implement or go in-depth in a sophisticated smart contract architecture.

8.3 Future Work

The main issue with our curernt implementation is that instead of having a direct push from each meter (or any IoT device) to the blockchain, we need to pull the data from the aforementioned monitoring server, and then push it again. This introduces latencies and single points of failure, however, this was done due to our corporate setup. An improvement would be to setup a microcontroller on each that would be executing a binary that pings readings to the blockchain. even better, run a node on each IOt device, however requires too much power, maybe in the far future. We explore Ethereum platform due to its abundance in developers and stay in it. There are other smart contract platforms however they lack developer tools, are not battle tested and are potentially centralized. As there is a bigger issue with scaling, the whole infrastructure could be transferred to a permissioned in-house blockchain, however we wanted to stay within the scope of keeping it as transparent as possible.

FIN.

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